Ballistic and dynamic mechanical characterisation of 5t prototype cast of a new locally developed armour steel alloy.

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Ballistic and dynamic mechanical characterisation of 5t prototype cast of a new locally developed armour steel alloy.

by

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Synopsis

The ballistic performance was investigated with rigorous testing of the new armour steel alloy, a tempered variant and a benchmark material. Mechanical testing included Hopkinson pressure bar tests, high temperature, notched tests and standard quasi-static tensile tests.

The combination of a commercial prototype cast steel and ballistic testing with NATO standard soft projectiles allowed a uniquely practical perspective when comparing results. The ballistic test procedure reported the same minimum thickness values, for STANAG level 1 kinetic energy threats, than the suggested values of the manufacturer and comparison to the new alloy was thus established. Dynamic material characterisation is only accurate within the testing range. Using a single material model to predict critical strength and failure over large strain-rate and temperature ranges is only possible if the material response is consistent. A few scaling problems during specimen testing resulted in a challenging data set with subsequent numerical characterisation difficulty.

Ballistic performance was however found to correlate well with high strain-rate tensile tests.

KEYWORDS: Ballistic testing; High strain-rate testing; High temperature testing;

Publications to date

Bester, Jacques N., and Waldo E. Stumpf. "Plasticity and Ballistic Characterization of a New Armour Steel." In Dynamic Behavior of Materials, Volume 1, pp. 109-122. Springer New York, 2013.

Acknowledgements

It is the glory of God to conceal a thing: but the honour of kings is to search out a matter. Proverbs 25:2

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CHAPTER 1

General introduction

This chapter contains a general introduction and defines the frame of reference within which the author performed this body of work. The next 6 chapters document the literature review and the author's contribution as a postgraduate student in the Department of Materials Science and Metallurgical Engineering at the University of Pretoria.

1.1 Alloy development background

The Damascus Armour Development Consortium was formed under the Innovation Fund project number T70044, with the goal of investigating the commercial viability of an air hardenable armour alloy based on recent studies at the University of Pretoria [7], [8], [9] and [10]. The following objectives were formulated:

- To develop an air hardenable ductile armour alloy that can be used as the base for the development of a flexible body armour insert.
- To develop thin and flexible armour steel inserts for use in conjunction with existing soft body armour, to defeat the Level III A special, Tokarev and all lesser handgun threats.
- To develop air hardened armour plates with a thickness ranging from 4 – 8 mm with ballistic properties equivalent to or better than the existing global benchmark plates used, with a view to utilization as armour plate for light armoured vehicles.
- To commercialize and market the above two products.

The commercialisation of the alloy would require a significant portion of the total funds allocated for the project. Laboratory casts, prepared at SAMS Special Alloys &

Metallurgical Serv. CC on the NECSA site, was therefore used for initial evaluation of the candidate alloys before the 5t prototype cast was ordered. A technical report [11] was issued and contains detailed discussions of the alloy development methodology, project progress and strategy as well as ballistic and mechanical characterisation of the candidate alloys. The alloy development requirements were as follow:

- The requirement that the steel must be air hardenable up to $\sim$ 10 mm plate thickness. In order to achieve this objective, the hardenabilty of the alloys must be sufficiently high.
- The plate properties must be equivalent to or better than the current market leader(s).
- The general principles of the findings in the study by Maweja [9] would be employed (low M_s, low R_p/R_m, etc).

This resulted in five experimental alloys defined in table 1.1. Alloy #1 was selected as the commercial 5t prototype and cast at CARRS STAINLESS STEEL, a division of ELG Haniel Metals Ltd. in Wadsley Bridge, Sheffield, England. Subsequent rolling was performed at BOHLER Bleche GmbH & Co KG in Murzzuschlag, Austria, to nominal thickness's of 7, 8 and 10 mm. A number of 300 x 300 mm sample plates were cut and sent back by air for testing while the rest of the material was shipped to Pretoria in South Africa for further initial testing.

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	B,ppm	V	Ti	Al	Cu
#1	0.3	2.73	0.01	0.004	1.09	3.60	1.02	0.60	6.5	0.04	0.008	0.01	0.18
#2	0.44	1.40	0.01	0.002	0.43	3.25	1.62	0.66	N.A	0.04	0.01	0.01	0.20
#3	0.48	2.43	0.01	0.002	1.30	3.79	1.72	0.66	N.A	0.04	-	0.013	0.18
#4	0.53	0.97	0.007	0.001	0.87	4.1	0.45	0.44	N.A	0.01	0.02	0.017	0.83
#5*	0.42	3.01	0.01	0.001	1.15	3.45	1.38	0.63	10	0.04	-	-	0.22

* - Contains 0.24% Co

Table 1.1: Chemical composition (mass percentage) of the experimental alloys

Material testing and evaluation of the prototype cast consisted of the following activities performed more or less in this sequence with a few carried out in parallel. Ballistic, mechanical and weld testing was performed on the 300 x 300 mm sample plates as proof of concept with subsequent complete testing of the rest of the material. Each test is only briefly addressed here, as complete reports were generated by the Damascus Armour Development Consortium.

- A rigorous ballistic characterisation was performed on Alloy # 1, a tempered variant and a benchmark material. The procedure and results are discussed in detail in chapter 6. The improved ballistic performance of alloy # 1 above the benchmark material was confirmed.

- Mechanical tensile testing of Alloy # 1 was performed and the results correlated well with the expected values. Some specimen preparation difficulties were encountered due to the material's hardness. Round tensile specimens could not be manufactured and typical laser cut or water jet cut flat specimens reported lower elongations than expected. This was later found to be caused by rolling defects in the surface of the material and testing machine control problems. Wire electric discharge machining (EDM) prepared specimens with surface ground faces reported appropriate elongation values. Tensile test results from all the prototype plates are discussed in chapter 3.

- Dynamic mechanical testing consisted of tensile and compressive Split Hopkinson Pressure Bar (SHPB) tests performed at the Blast Impact and Survivability Research Unit BISRU at the University of Cape Town. The test procedure, signal processing and results are discussed in detail in chapter 4. SHPB tests correlated well with the ballistic results.

- Welding tests were performed with an austenitic filler material type E307. Standard welding procedures were followed without any preheating required for plate thickness's below 30 mm. Proper edge preparation and a low-hydrogen practice resulted in sound structurally integral weld joints. This allows for standard manufacturing procedures in light armoured personnel vehicles manufactured in South Africa.

- Bending sensitivity of the prototype alloy # 1 was extensively investigated with surface treatment, edge treatments, cutting processes, temper treatments and rolling orientation that were assessed. Each parameter was evaluated at certain bend radius to plate thickness ratios. Bend radii ratios of 7 – 8 could be lowered to 4 – 5.5 by grinding the outside surface of the bend test coupon. The benchmark material requires bend radius ratios of 6 – 7.

- Standard Charpy impact tests were conducted on the prototype alloy # 1 and benchmark material over a range of temperatures in the rolling direction and perpendicular to the rolling direction. No distinct ductile to brittle transition behaviour was observed in either material; and Alloy # 1 reported lower impact energy values.

- Low temp fracture toughness was evaluated with single specimen J integral tests. The lower martensite transformation temperatures of -35° C to -40° C limited testing to -30° C and 20° C. J integral results were used to calculate fracture toughness values of $K_j = 93.5[\frac{MPa}{\sqrt{m}}]$ for Alloy # 1 and $K_j = 155.7[\frac{MPa}{\sqrt{m}}]$ for the benchmark material. These values correlate with the Charpy impact test results.

It is clear from the broad range of material tests, that the performance of prototype cast alloy # 1 was broadly comparable to the benchmark material and that all the

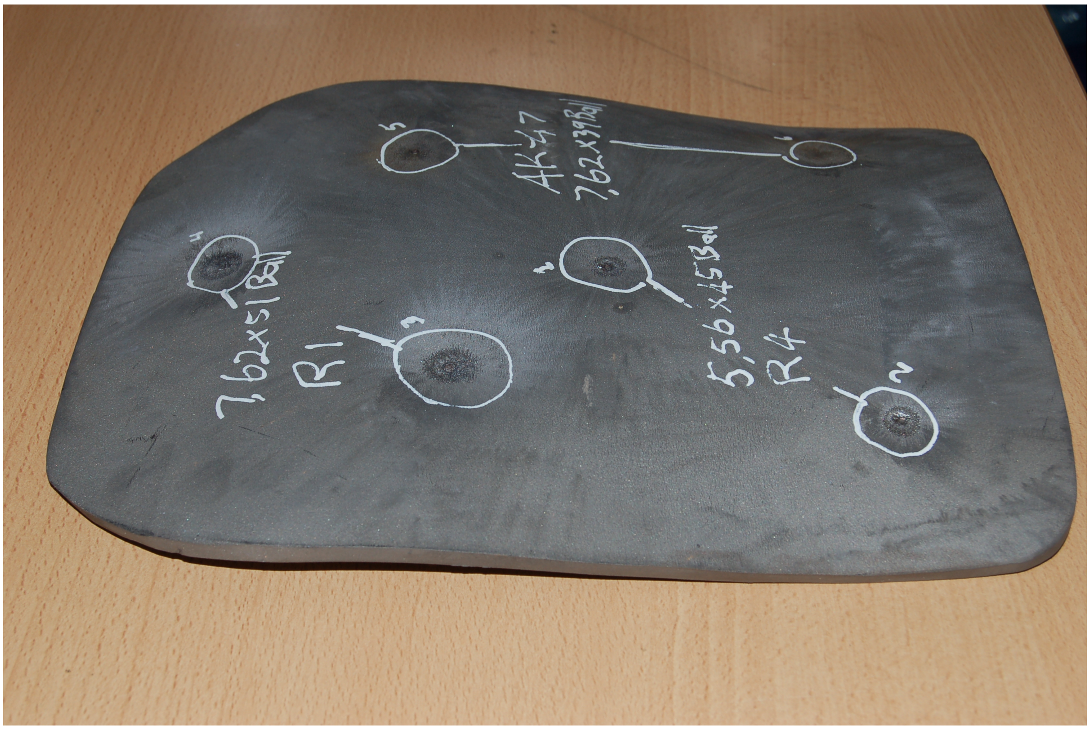

Figure 1.1: Shaped breast plate insert

manufacturability requirements were met.

The work of the Damascus Armour Development Consortium resulted in a patent [12] and the air hardenable concept was further developed into a prototype shaped breast plate insert shown in figure 1.1.

1.2 This investigation

The author's involvement with the Damascus Armour Development Consortium started as an employee at MegChem Engineering and Drafting Services (Pty) Ltd., a member of the consortium. He was tasked with the mechanical tensile testing of some of the candidate laboratory casts and later with the ballistic characterisation of the prototype cast.

A numerical investigation of the new alloy was proposed by the author as an additional means of explaining the ballistic performance and underlying mechanical requirements of armour materials. The proposal was approved by the consortium as well as the academic institution, the University of Pretoria, for a Masters of Engineering research topic. This initiated the dynamic material tests discussed in chapter 4 and high temperature tensile tests addressed in chapter 3. The numerical evaluation procedure and characterisation results themselves are reported in chapter 5.

1.2.1 Objectives

This investigation is focused on the ballistic and dynamic characterisation of the new Alloy # 1 prototype 5 ton cast by investigating the following objectives:

1. To characterise the ballistic performance of alloy # 1, a tempered variant and the benchmark material according to a rigorous statistical procedure.

2. To perform mechanical testing over a sufficient range of strain rates, temperatures and pressures to fit the Johnson-Cook material model [13] and fracture criteria [3].

3. To characterise the material model using simultaneous numerical optimisation.

4. To explain the improved ballistic performance in terms of the numerical characterisation.

It should be noted that the benchmark material is not identified beyond the brinell hardness grade. The Damascus Armour Development consortium gave instruction to the student not to identify critical ballistic performance of the benchmark material. Ballistic armour characterisation with defined projectiles is typically performed under classified research programs or by military and defence contractors at great expense. The sensitive data generated on the benchmark material by this project is therefore protected.

1.2.2 Specimen design

Five types of mechanical test specimens were used in this investigation. Variation in orientation, strain-rate, temperature and stress tri-axiality are defined in table 1.2. Detailed discussion of each specimen design is presented in the applicable chapter and the drawings used for the manufacture of the specimens are included in appendix A.

Test type #	Orientation	Temperature	Tri-axiality ratio	Strain-rate $[mm/mm/s]$
Type-1	Tensile	23 °C	0.333	0.15
Type-2	Tensile	23 °C – 800 °C	0.333	0.15
Type-3	Tensile	23 °C	0.333 – 1	0.15
Type-4	Tensile	23 °C	0.333	100 – 1000
Type-5	Compression	23 °C	0.333	100 – 1000

Table 1.2: Test type definition

CHAPTER 2

Literature review

This chapter contains a literature review of ballistic impact in general, numerical simulation and metallurgical requirements. Specific attention is given to ballistic testing using commercial projectiles.

2.1 Literature review

Ballistic performance investigations are typically characterised from either the projectile or armour point of view. Projectile development ranges from the launch dynamics and barrel interaction to flight stability and path prediction. The projectile shape is determined by these considerations. Increased perforation requirements are based on the kinetic energy, and energy density at the point of impact. Launch velocity, density and hardness is typically increased and contact area reduced. The effectiveness of these improvements are seen in the widespread use of the "sabot" type armour piercing rounds. Similar considerations were followed in the development of the shaped charge anti-tank round or rocket propelled grenade. Recently the development of an electrically powered electromagnetic projectile launcher or rail gun, drastically increased the launch velocity and effective range. All sub-artillery calibre weapons are however limited by production cost and fixed cartridge capacities. Improvements in perforation performance is therefore also limited to increased hardness as the further development of small arms projectiles seems to have ceased after World War two.

Terminal ballistics on the other hand is concerned with the interaction of projectile and target. The result is usually the protection or loss of life or equipment. The mitigation of projectile and blast impact events has been the focus of various extensive research programs. Development of advanced armour systems in light armoured vehicles has to be effective against a range of armour piercing projectiles, blast and shock loading as well as improvised explosive devices with increasingly insidious flier plates or long range shaped charges. High strength and high hardness steel alloys seem to be the most cost effective and widely used when compared to aluminium, titanium, composite, steel with add-on ceramic or reactive armour systems.

2.1.1 Ballistic impact characterisation

Impact classification and characterisation of the results has historically been grouped into various kinetic energy regimes with associated material behaviours.

- Low velocity [$\sim$ 1 m/s] impacts result in elastic interaction as seen with a bouncing ball.
- Intermediate impact velocities [$\sim$ 10 m/s] are seen in vehicle collisions and result in elastic, plastic material deformation and ductile failure.
- High impact velocities [$\sim$ 100 m/s] observed with small arm ballistic impact result in elastic and plastic stress waves with complete disintegration of the projectile and various failure modes for the target.
- Hyper velocity [$>$ 1000 m/s] impact events or blast and shock wave loading is observed in high energy ordinance systems or meteor impacts. The extreme kinetic energy results in shock waves and hydro-dynamic behaviour of materials.

This investigation is aimed at the high velocity impact regime with specific attention given to ballistic testing of steel plates with small arms projectiles.

The evaluation of impact events above the ballistic limit of a target results in only a reduction of the impact velocity of the projectile. Momentum conservation [1] allows for a remarkably accurate prediction of the critical perforation velocity as shown in figure 2.1 . This relationship is widely used in analytical [14] and numerical [15] ballistic limit characterisation studies. The lack of any material strength description however renders this approach less accurate.

Various review publications [14] and [16] on high velocity impacts report on the complex interaction of a projectile and target. Ballistic performance mapping of a single projectile and single material over the ballistic range is seen in figure 2.2 and typical perforation modes for steel plates, is shown in figure 2.3. A few extensively researched review papers [17],[18] and [19] offer a complete summary of impact response, analytical and numerical models and experimental results. Various other projectile shapes, velocity regimes and perforation modes are discussed with some analytical formulation of the ballistic behaviour. Most of these relationships however only account for the target material's strength in terms of the ultimate tensile strength.

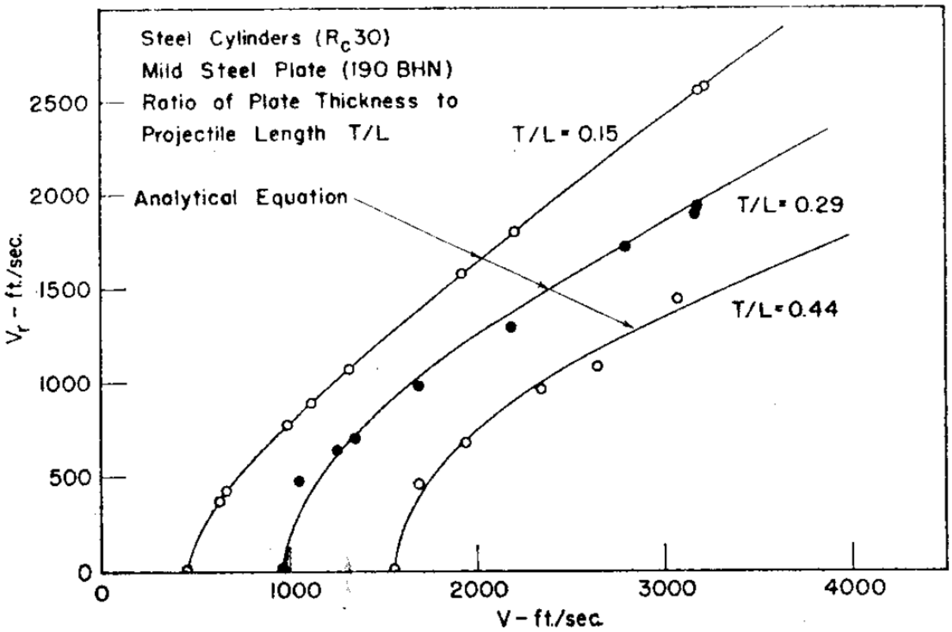

Figure 2.1: Postperforation velocity of cylindrical fragments.[1]

Armour material plastic behaviour, phase changes and effect of adiabatic heating on these mechanisms have not been incorporated into analytical models. Additional challenges in different failure modes range from Hugenoit tensile wave fracture, spalling, dynamic brittle cracking and mixed mode ductile tearing. It is therefore plain to the realise that interaction of some of these failure modes [20] greatly increases the challenge of characterising the critical perforation velocity.

The use of numerical methods and specifically, explicitly solved finite element models, allow for the integration of known material behaviour with complex interaction scenarios [16] and [17]. Long rod penetrators at oblique angles seem to to have been accurately modelled.

The behaviour of materials over this large range of velocity regimes was neatly summarised by Meyers [21] with chapters discussing elastic, plastic and shock waves. Shock wave-induced phase transformations and explosive material interactions as well as experimental techniques are also discussed and offer practical solutions in civilian and military applications. Dekel [22] reports on all aspects of terminal ballistics with chapters on experimental techniques, material models for numerical characterisation, penetration mechanics and defeat mechanisms.

This investigation is aimed at the plugging perforation shown in figure 2.5. Advanced analytical models of plugging perforation based on previous work [23] were presented in [24] and [25]. Strain rate effects were included in [24] and a condition was obtained for differentiating localised adiabatic shear plugging from simple shear plugging. A simplified regression-based approach was discussed by Munusamy et al. [25] using standard material parameters. These solutions seem to improve the ease of use in analytical procedures.

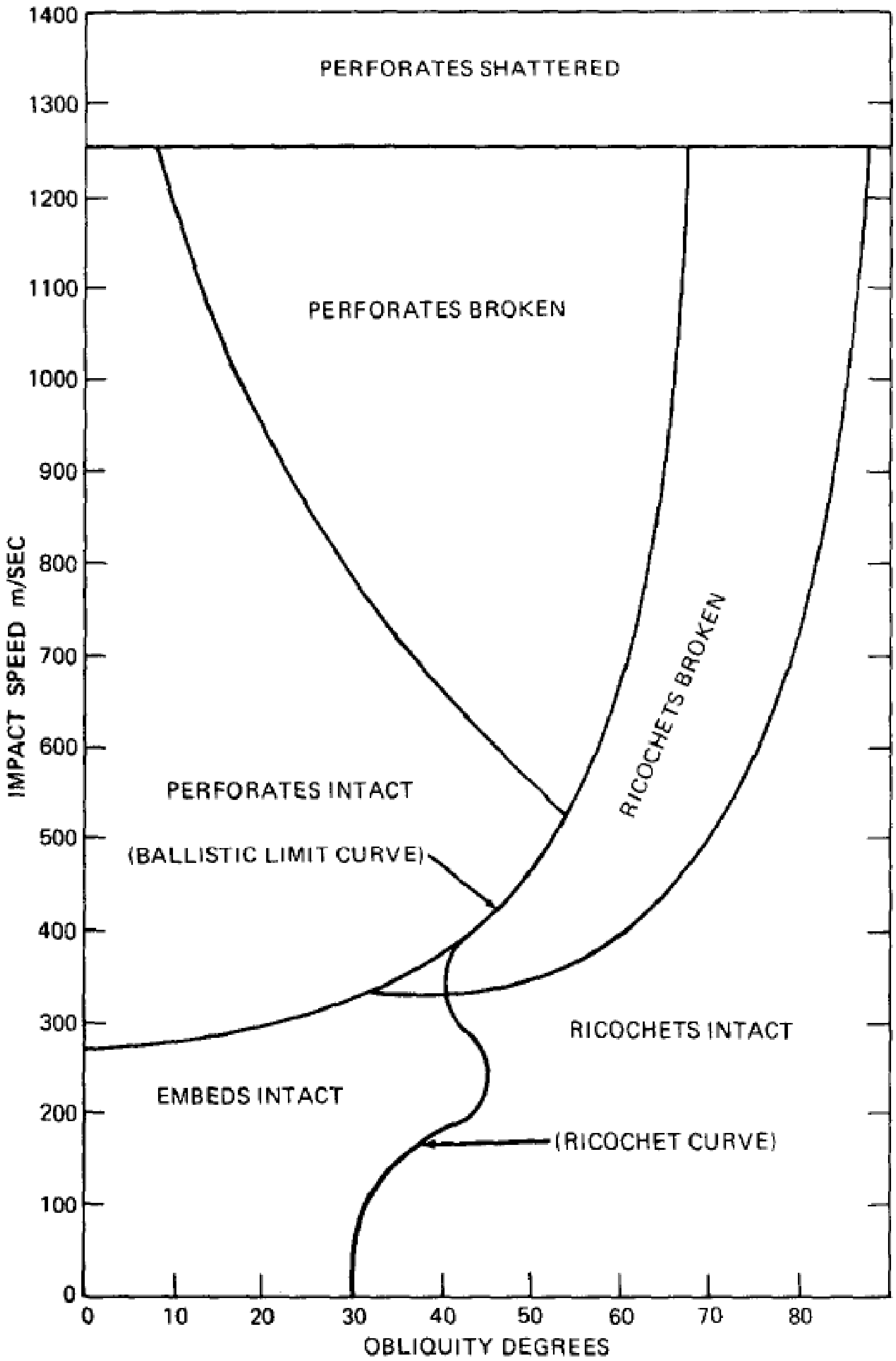

Figure 2.2: Ballistic limit curve of a 6.35 mm diameter ogival-nosed projectile and 6.35 mm aluminium alloy target element[14]

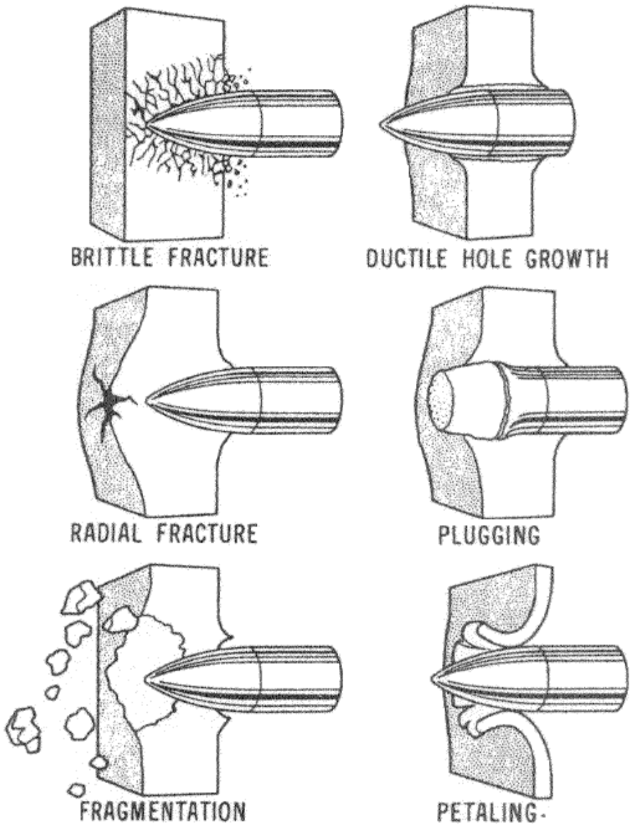

Figure 2.3: Ballistic perforation modes [16]

Direct empirical correlation is however still required and testing can therefore not be eliminated.

The process behind adiabatic shear localisation, or adiabatic wave trapping has long been understood from 1933, as latent heat from cold working by Taylor [26], measured in 1986, temperature profile across shear bands at nominal strain rates of 1000 [1/s] by unique infra-red radiation reflection from the inside surface of a Kolsky torsion bar specimen by Hartley [27] and more recently in 1994, thermal scanning by Noble [28].

For a simplified, flat nosed projectile, the axis-symmetric mode of deformation is driven from initial contact by the stress concentration on the edge of the projectile. High stresses lead to plastic deformation and heat is generated. The rise in local temperature softens the material, lowering its strength and due to increased plastic deformation, even more heat is generated. This sends it towards the inexorable adiabatic wave trap and the typical plug perforation. Soft projectile impact results in similar plug perforation failure although the projectile deformation is vastly different. It should be noted that for a soft projectile the plug diameter is related to plate thickness rather than projectile calibre.

Its effect was well documented by Stock et al. [29] and Woodward [30] in plugging and perforation evaluations with various similar analytical solutions, one shown in figure 2.4 have been proposed [2]. The relationship between adiabatic shear instability and

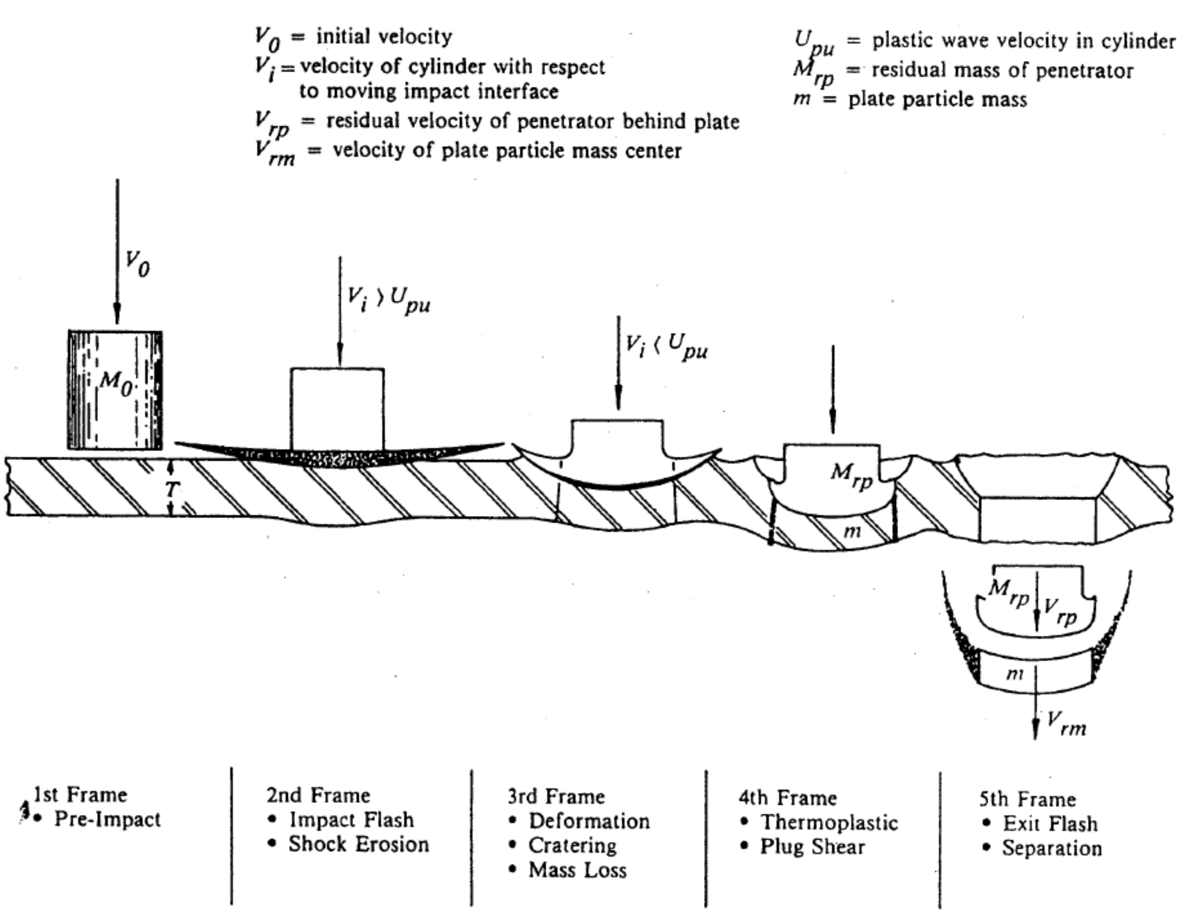

Figure 2.4: Ballistic plate plugging. [2]

material properties was established by Staker [31]. Adiabatic wave trapping was identified as the failure mode plugging with an analytical failure model proposed by Chen [32]. Experimental verification is however required for any new material. The effect of thermal coupling to the plastic wave by Klepaczko [33] showed promising results in simplified FE studies. Adiabatic shear was separated from the following ductile fracture by Teng [34] and showed that hot spots act as initiation sites for cracks. This numerical model is however sensitive to element size and smaller elements predicted higher temperatures. Solberg tested various steel types and impactor nose shapes and could show that phase transformation occurs in certain conditions [35]. Adiabatic shear localisation is also observed in boron carbide ceramics [36]. Almost all of these studies indicate that increased plastic deformation should also increase the local temperature and might exceed the dynamic phase transformation temperature.A complete material model of a new alloy should therefore include thermal, strength and phase transformations.

Any delay in temperature driven material softening should however contribute to enhanced ballistic resistance against plugging.

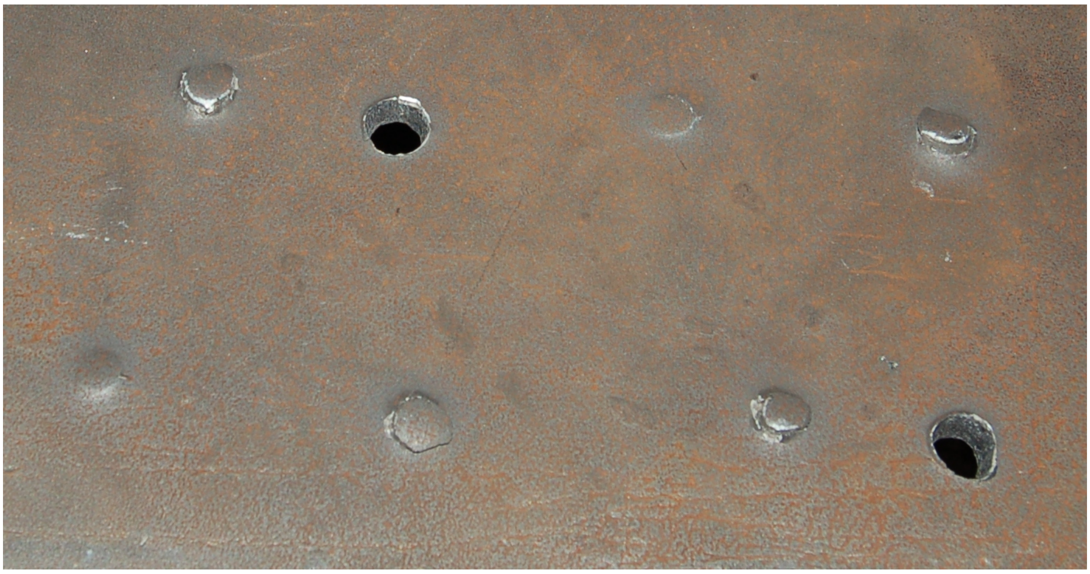

Figure 2.5: Typical plugging failure

2.1.2 Numerical simulation of ballistic impact

Numerical solutions offer a multiplicity of material behaviour models and almost any conceivable loading scenario. A few noteworthy publications have been included as a frame of reference for current ballistic impact simulation capabilities.

Advanced shielding design for the Columbus module of the International Space Station [37] was evaluated by Clegg et al. by coupling orthotropic constitutive behaviour with a non-linear equation of state for multi-layered composite shields. Reasonable correlation was found with impact tests performed between 3.0 and 6.5 km/s.

The plugging perforation simulation mode was most notably advanced by a computational model [38] by Borvik et al. which coupled a constitutive model with ductile damage from the principle of adiabatic heating which is driven by plastic strain. This model was characterised with material tests alone and was found to show reasonable agreement with experimental observations [15] from gas-gun penetration tests.

The effect of impactor nose shape on perforation performance on thin aluminium plate was investigated by Gupta et al. [39] and revealed an element size effect on the numerical results.

Improvements in the fracture locus by Wierzbicki et al. [40] allowed for increased modelling accuracy of perforation. A parametric study of several factors controlling the failure process resulted in an expression for crack length versus indentation depth. Six fracture models were also evaluated by Wierzbicki et al. [41] in high velocity perforation. Only the two models formulated with triaxiality and equivalent plastic strain to failure, were capable of realistic predictions. This reveals the increased shear sensitivity of certain materials.

Enhanced crack tip procedures developed by Unosson et al. [42], by scaling strain rates

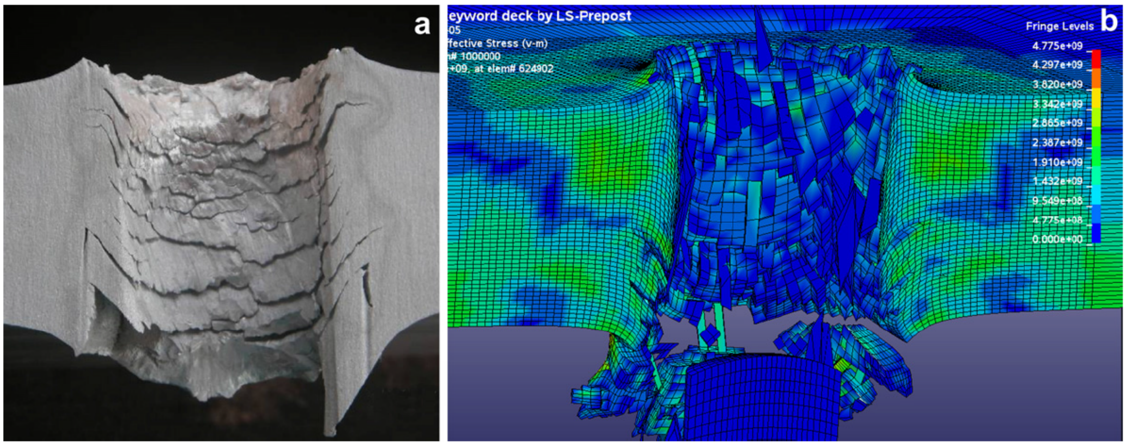

Figure 2.6: Section of an aluminium 6061 tartget after perforation: a Picture from a test, b computation result.[46]

at integration points to the crack tip, reduced mesh dependency. The protection performance effect of a double-layered metal shield was evaluated by Borvik and Wierzbicki et al.[43] against four projectile types. Ballistic resistance could be improved for a flat-nosed projectile. The perforation process of mild steel sheets by a hemispherical projectile was evaluated by Rusinek et al. using three constitutive relationships with the friction effect that was also included [44].

A review of numerical algorithms and material models used in high-velocity impact simulations over the previous 44 years was published by Johnson [45]. The progress of code development, element use and material formulations were also discussed by the author. Development code capabilities for explosive formed penetrators and material erosion with enhanced contact and sliding, was noted. The use of Meshless particles and improved material models for metals, ceramics, concrete, fabrics and composites were tracked. Challenges and progress in hyper-velocity impact problems were also discussed. The use of specialised numerical models in the simulation of ballistic impact and other high energy events seems to be most useful in applied research of specific problems but then always accompanied with experimental verification.

An improved ballistic model with the second and third stress invariants was presented by Chocron [46] with compelling correlation to plugging fracture, as shown in figure 2.6. The effect of weld-induced residual stresses was investigated by Flores-Johnson [47] and found to have an adverse effect on the ballistic performance.

The Johnson-Cook material model [3] is used in dual phase material modeling [48], the evaluation of energy absorption [49] and fracture modelling of high performance armour steel [50].

The model consists of a von Mises flow rule shown in equation 2.1, an element damage counter that is used to deactivate an element when $D = 1$, equation 2.2 defined as the ratio of incremental equivalent plastic strain $\Delta\varepsilon$ to the equivalent strain to failure ε^f

calculated according to equation 2.3, with the dimensionless strain rate $\dot{\varepsilon^*}$ and homologous temperature T^* defined in equations 2.4 and 2.5 respectively.

$$\sigma = [A + B\varepsilon^n][1 + C \ln \dot{\varepsilon^*}][1 - T^{*m}] \tag{2.1}$$

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{2.2}$$

$$\varepsilon^f = [D_1 + D_2 e^{D_3 \sigma^*}][1 + D_4 \ln \dot{\varepsilon^*}][1 + D_5 T^*] \tag{2.3}$$

with,

$$T^* = \frac{T - T_{Room}}{T_{Melt} - T_{Room}} \tag{2.4}$$

$$\dot{\varepsilon^*} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \tag{2.5}$$

The widespread use of the Johnson-Cook model is shown in a publication history graph figure 2.7, drawn from Scopus data. A marked increase between the year 2005 and 2010, is interesting and could be related to the commercial implementation of the model into the most prominent explicit solver based finite element codes. Its inclusion into AUTODYN in 1994, LS-DYNA in 1998 and ABACUS in 2000 allows enough time for academic institutions to include explicit finite element modelling into the curriculum and also some time for subsequent post graduate students to include the model in their work. The sharp drop in number of publications after 2015 is simply due to the future publishing date of certain publications.

A combined temperature and strain rate model with fracture prediction capability is a uniquely practical option for structural analysts. The relatively simple experimental procedure and implementation allows for a wider segment of structural simulation use outside of academic research.

A few limitations should, however, be noted when using this model to predict prominent plastic failure. The model is based on thermally activated dislocation glide alone and is restricted to strain rates $\leqslant 10^5 s^{-1}$ as discussed by Preston et al. [51]. The marked difference between the plane stress and axial symmetric fracture strain shown in figure 2.8 was most notably improved by Wierzbicki et al. [4] and can be seen in figure 2.9. These two figures show the fracture strain to be a function of stress tri-axiality σ^* or ratio of mean stress to equivalent stress σ_m/σ_{vm} in figure 2.8. The range of two possible Johnson Cook fits are shown in contrast to experimental data points. Fracture strain is presented in figure 2.9 as a function of both stress tri-axiality η and lode angle θ. Lode angle is related to the third deviatoric stress invariant ξ through $\xi = cos(3\theta)$.

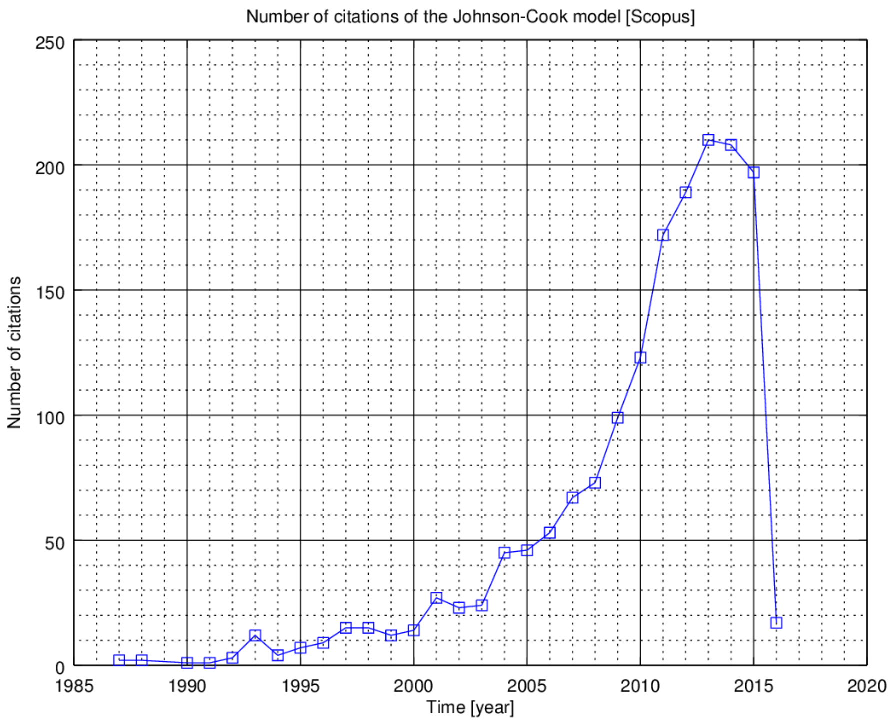

Figure 2.7: Citation history for Johnson-Cook material model [3]

Further work by Bai and Wierzbicki [5] elegantly simplified the fracture locus into a surface by including the third stress invariant, the lode angle shown in figure 2.10. The stress tri-axiality limit of $-\frac{1}{3}$ in shear failure is also clearly missed by the Johnson-Cook fracture locus as shown in figure 2.10 by Bao and Wierzbicki [6].

Another model, the material threshold strength MTS constitutive model developed by Follansbee and Kocks [52], is based on more fundamental material characteristics if compared to the phenomenological models and could be considered as an alternative to the Johnson-Cook model.

The aforementioned studies were mostly concerned with plugging perforation due to geometrically biased and or high hardness projectiles. These types of impacts do not present much of a challenge for standard contact algorithms and the simplified interaction between target and projectile consists mostly of momentum transfer. Reasonable comparison is therefore observed between numerical simulation and armour piercing round penetration tests. The ballistic characterisation of softer projectiles requires additional capabilities to handle large displacements, friction, pressure and temperature transference over the contact face. Adaptive re-meshing [53] attempts to solve the large displacement problem and it's adverse effect on element quality by re-meshing at certain intervals.

The fluid-like hydro-dynamic behaviour of typical lead projectiles due to the comparable low UTS of only ~ 10 MPa, is best modelled with Eulerian flow codes. Interaction of Euler and Lagrangian elements in coupled procedures however, leads to interpolation

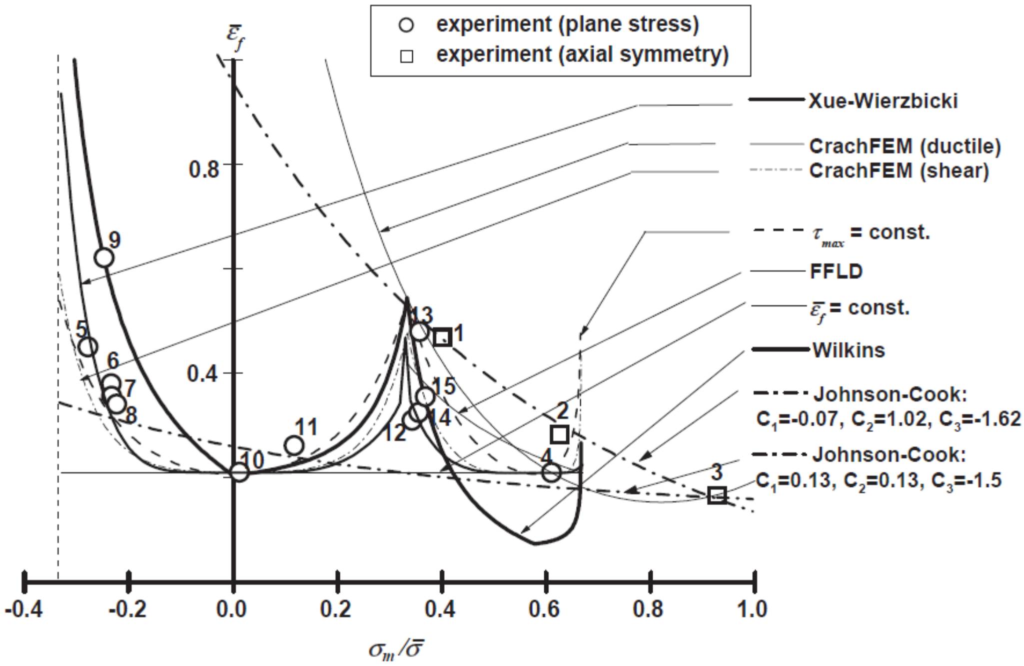

Figure 2.8: Johnson-Cook compared to plate stress and axial symmerty.[4]

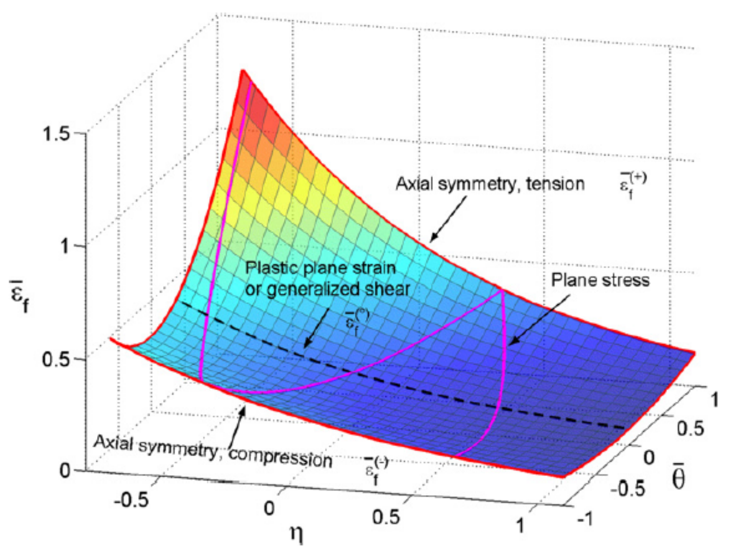

Figure 2.9: Material fitted 3D asymmeric fracture locus.[5]

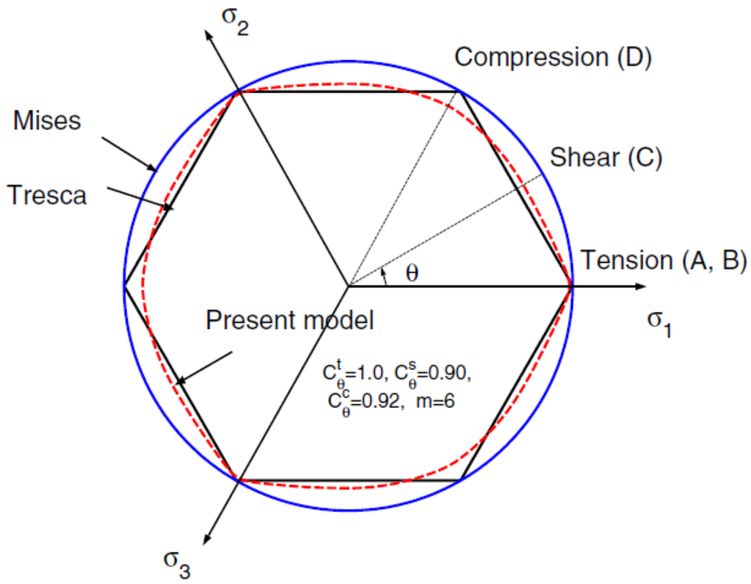

Figure 2.10: Three yield loci in the devatoric stress plane.[5]

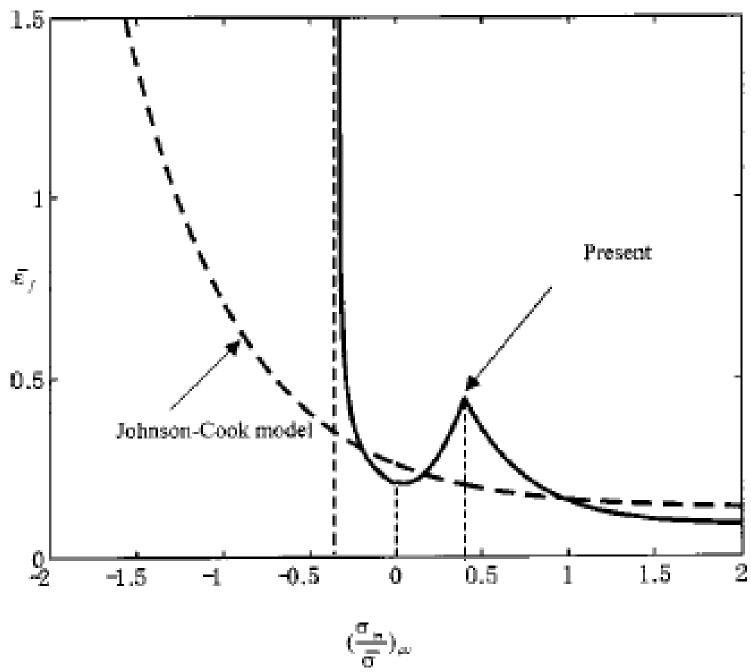

Figure 2.11: Johnson-Cook comparison to ductile crack fracture locus.[6]

errors and loss of energy. These challenges contribute to the difficulty of modelling soft projectile interactions.

A new class of numerical methods is discussed by Schwer et al. [54] for an aluminium projectile impacting aluminium target plates. Updated simulation procedures of Lagrange with erosion, Multi-Material Arbitrary Lagrange Euler technique and the Smooth Particle Hydrodynamics, were presented. A progressive failure model is proposed for improved results. Hybrid particle-finite element algorithms [55] and the Optimal Transportation Meshfree procedure [56] seem to show promise in improved contact interaction and fragmentation simulations. Accurate simulation, is therefore, still outside current numerical capabilities.

Advancements in various fields might lead to the development of accurate simulation of soft projectile interactions. Some promising advancements are noted here. Physics-based modelling of brittle fracture [57], meshfree and particle methods [58], atomistic damage mechanism [59] and multi-scale material modelling [60] and multi-scale plasticity [61] might contribute to a complete solution in future.

Material characterisation of all the materials involved in the numerical impact simulation is fitted to data from a series of mechanical tests. Quasi static, high temperature and notched tensile tests are simply performed on servo hydraulic tensile test machines. A variation in strain rate is however much more challenging and requires specialised dynamic testing equipment. The Kolsky bar or split Hopkinson bar is used for these tests. Various numerical investigations into ballistic impact [49], [62], [63] and [64] simply use the equipment with little further development as the procedure has been somewhat standardised. The microstructural material response due to high strain deformation [65] and strain rate effects on aluminium [66] and various other high strain rate material effects have been investigated. Specialised split Hopkinson bar development is only performed by field specific laboratories. The preeminent blast and impact research laboratory in South Africa is the Blast and Survivability Research Group at the University of Cape Town. their work includes bar normal mode corrected measurements [67], intermediate strain rate techniques [68], dynamic friction investigation [69] and the measurement of blast effects on a clamped plate, evaluated with a Hopkinson bar [70]. The group was therefore approached for assistance with the high strain rate material tests.

2.1.3 Metallurgical requirements

Developments in the critical material requirements for advanced alloys consisting of martensite with some retained austenite (RA) [7] is summarised in this section. The ballistic characterisation consisted of profile measurements of the sectioned target plate and the following detailed metallurgical investigations:

- Thin foil transmission electron microscopy before ballistic testing confirmed the presence of retained austenite.

- The martensite start temperature was also measured before ballistic testing.
- X-ray diffraction analysis of the retained austenite was performed on samples cut from the impact region after ballistic impact.
- Scanning electron microscopy of the cracks.
- Thin foil transmission electron microscopy for the presence of retained austenite after ballistic impact.
- Micro hardness profiles were also measured across the impact region.

The ballistic parameter (BP) used is defined in equation (2.6), as the ratio of the volume fraction of retained austenite (RA) to the exponential function of the plate thickness δ in mm.

$$BP = \frac{RA}{e^{\delta}} \tag{2.6}$$

Geometric observations of three deformation zones were made similarly to [14] and are shown in figure 2.12. The effect of various volume fractions of retained austenite (RA) on the size of these zones is shown in figure 2.13. Each zone is visually identified as follows, zone 1 consists of the flat area behind the impact, zone 2 defines the mid point of deformation of the dome and zone 3 defines the unaffected material. Increasing the volume fraction of retained austenite (RA) also increases the diameter of zone 2 and zone 3. More material is therefore involved in the impact event.

The study developed a total number of 23 alloys following a sequenced step optimisation procedure. Candidate alloys in the first round influenced the alloy specification of the next round with increased ballistic performance at every step. One such step consisted of the solution of a constrained optimisation problem. The objective function was defined as the ratio of yield strength to ultimate tensile strength (YS/UTS) , which is the measure of work hardening capacity and constraint functions, the Charpy impact energy and tensile strength at room temperature. The optimisation problem was solved with polynomial functions defined in terms of the normalised tempering and austenitisation temperatures. Results from this problem constituted the basis for the next round of alloys as well as metallurgical investigations. The specification for the next round of armour steels was updated at every step. The following guidelines were used as the starting point for this investigation. Each item is shortly discussed in terms of the general effect on ballistic performance.

- The volume fraction of retained austenite (RA) should be between 2 % to 7 %. This fraction results in the location of the retained austenite on the martensite plate

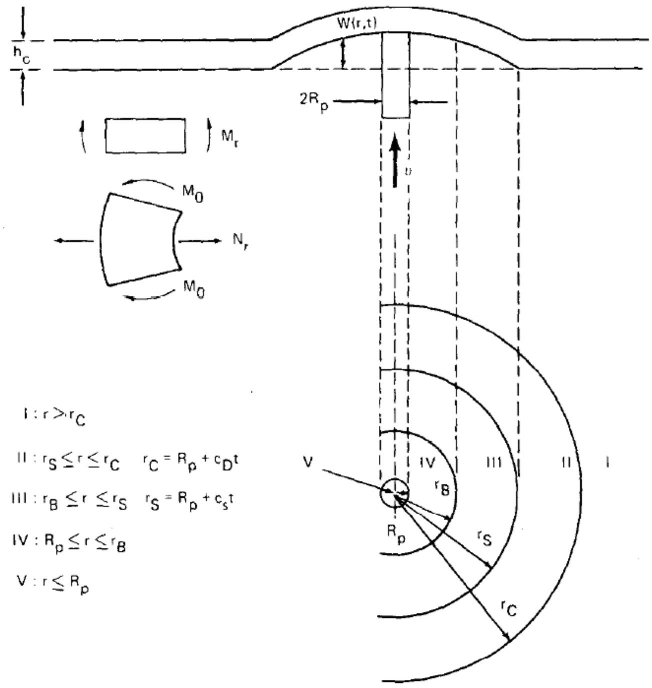

Figure 2.12: Model of plastic bending and membrane deformation of a plate due to impact by a blunt projectile [14]

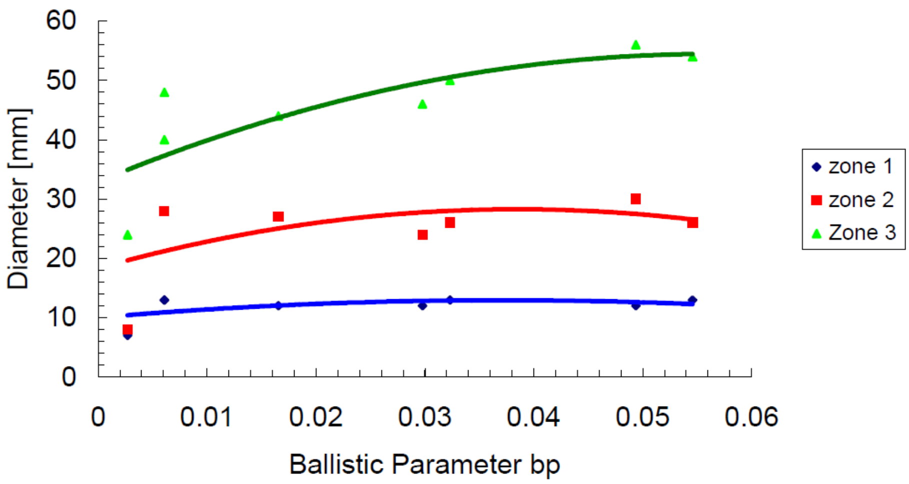

Figure 2.13: Variation of three concentric ballistic influenced zones with the BP parameter [7].Zones defined on previous page

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inter-faces and was found to be more effective in lowering the ratio of YS/UTS [7]. Additional kinetic energy is absorbed during ballistic impact by the phase transformation of retained austenite to deformation induced martensite.

- A ratio of yield strength to ultimate tensile strength (YS/UTS) of lower than 0.6 results in high work hardening and consequently a delay in destabilisation.
- Martensite start temperatures lower than 210°C to enhance the formation of plate martensite over lath martensite [7].

2.1.4 Ballistic Testing

The use of experimental specific projectiles and gas-gun launchers allow ballistic research laboratories greater control and increased accuracy in achieving an initial velocity. Direct comparison of these idealised projectiles with commercial produced projectiles is in most cases not possible. Subsequent comparison of ballistic performance between evaluated armour systems can then only be conducted on a comparative basis.

Specific threat characterisation with projectile geometry variations [71] and other associated statistical variations are only possible with direct testing. A short review of publications with specific ballistic projectiles is presented in this section.

A single publication was found using the 12.7 mm M-8 API projectile [72] to investigate the effect of perforated plates in impact mitigation.

Several publications use the 7.62 mm AP projectile. Titanium alloy development [73], perforated steel plates [74], high hardness steel armor [75], multi-layered metallic plates [76] and high strength aluminium 7xxx plates [77] were evaluated. An evaluation of dual phase steel [78] indicated that increased martensite also increases ballistic resistance. Ceramic evaluation [79] and an angle effect study [80] was also performed. A performance comparison of various armour piercing projectiles [81] was presented. The military application of β titanium alloys [82] an evaluation of transparent-armour systems [83] and another high strength steel investigation was published [84].

Only a few publications report the use of a 7.62 ball type projectile. Comparison with the 7.62 APM2 projectile is made in the evaluation of aluminium plates [85]. Various layered armour plate solutions are investigated [86] according to the STANAG 4569 specification, which includes the 7.62 x 51 mm and the 5.56 x 45 mm ball projectiles. Stainless austenitic steels [87] and titanium alloys [88] are evaluated and a recent study included the 7.62 mm ball projectile in a penetration study of granular materials [89].

The lack of soft projectile testing on advanced steel alloys should be noted and investigated further.

This investigation follows the NATO projectile threat classification according to the STANAG 4569 kinetic energy rating [90]. Elevation [0°] and azimuth [0-360°] angles relate the two planar incident angles the projectile path traces with the target plane. This angular variation is required as certain projectiles perforate thicker plates at an angle other than the 0°incident. In this study however, only the 0°azimuth is evaluated for various projectile velocities as shown in section 2.

CHAPTER 3

Quasi-static material tests

This chapter contains the quasi-static, high temperature and notched material test results from tests performed at the Eskom research, testing development laboratories in Johannesburg. Each test is briefly discussed and results are summarised.

3.1 Introduction

All quasi-static tensile tests where performed on a servo hydraulic tensile test machine shown in figure 3.1, according to the test specification ASTM A 370: Standard Test Methods and Definitions for Mechanical Testing of Steel Products: The furnace used in the high temperature quasi-static tensile tests is shown in figure 3.2 with the high temperature extensometer shown in figure 3.3.

A mechanical extensometer was used to accurately capture the material's yield point. To avoid damage to the extensometer, it was removed at a hold point during the test before the test continued to specimen failure. Load, machine displacement, extensometer displacement and temperature values were continually recorded during the test. Standard outputs also included stress, extensometer strain and machine compliance corrected strain. All these values are summarised in the standard result table at 0.2% offset, maximum values and specimen fracture. The tensile modulus was also recorded using two separate procedures. All test reports are included in Appendix C.

The following three sections deal with the quasi-static, high temperature and notched test results respectively. Exported test data were cropped at the fracture point and a correction was made for the extensometer removal and all stress strain data was then compiled into comparison figures and was saved for specimen number in a test type data file.

Figure 3.1: Servo hydraulic tensile test machine.

Figure 3.2: Tensile specimen heating oven.

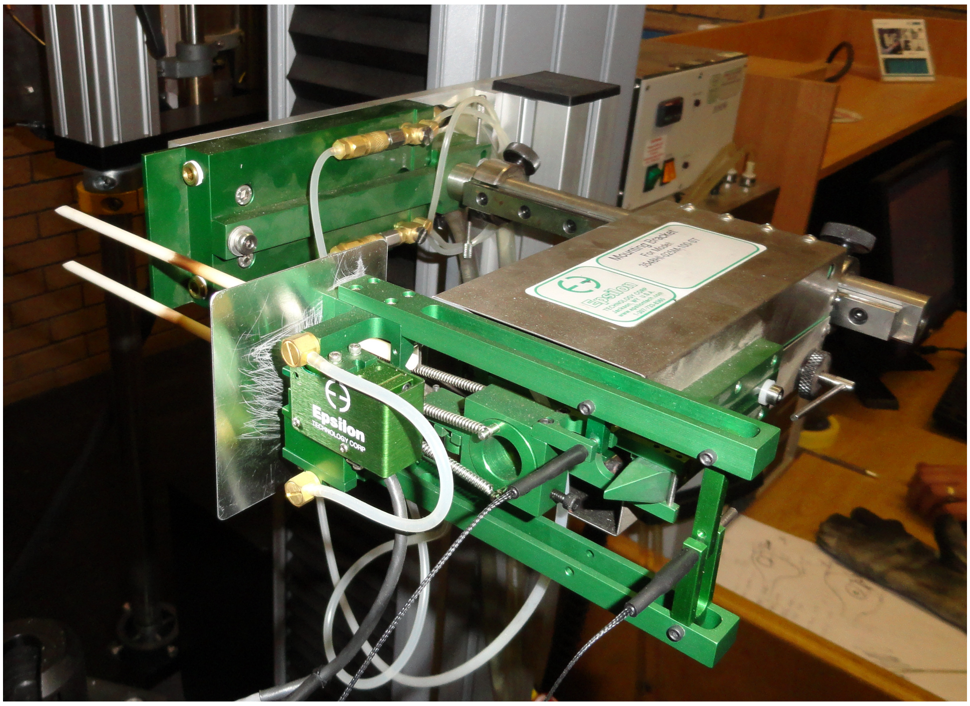

Figure 3.3: High temperature extensometer.

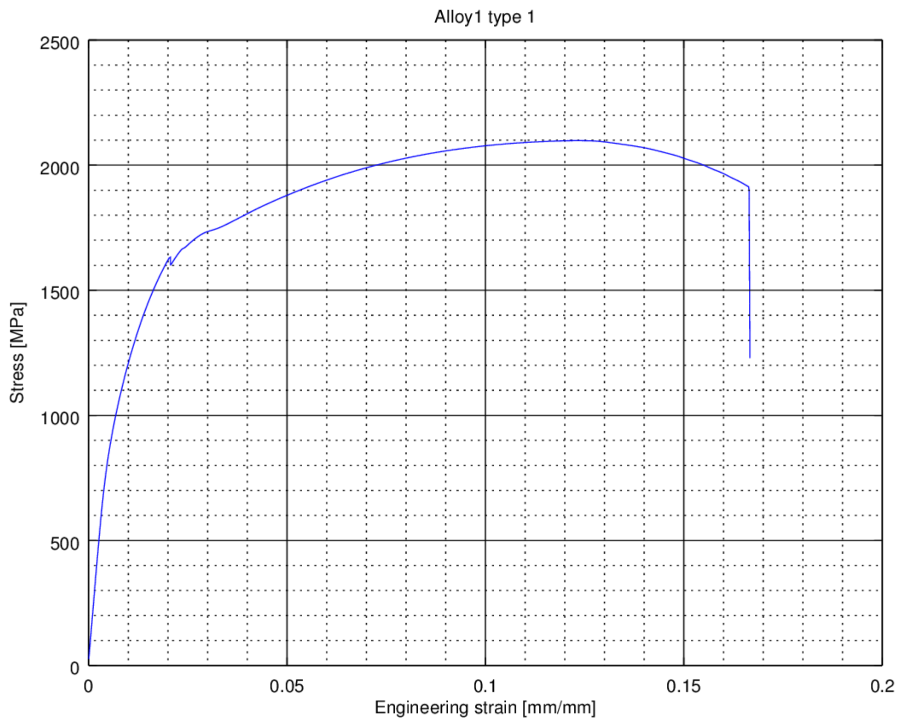

Figure 3.4: Raw tensile test results for Alloy #1, as received condition.

3.2 Quasi-static tensile tests

The quasi-static tensile tests consisted of 36 specimens with initial cross sectional dimensions, maximum load, ultimate tensile strength and elongation recorded in table 3.1. Rolling sensitivity was investigated with the first 6 specimens with a slight decrease in elongation noticed for the transverse orientation without any reduction in UTS. The effect of re-austenising at 900°C was investigated with the following 4 specimens and no measurable deviation was observed. The rest of the specimens were comprised of duplicate plate number tests to evaluate any rolling inconsistencies. An average UTS of 2104.95 MPa was reported with a standard deviation of only 72.13 MPa. Elongation results averaged at 13.6 % with a 3.2% standard deviation. The re-austenised and transverse tensile results are included in these averages and indicate little sensitivity to orientation and initial quench temperature.

The following figures show the exported test data (figure 3.4), a zoomed view of the transition point from extensometer to machine compliance corrected strain (figure 3.5) and the transition modified and failure cropped curve (figure 3.6), exported to the data file. The Octave file used for the modification and cropping is included in Appendix C.

The Alloy #1 quasi-static test group is summarised in figure 3.7 and compared to the benchmark material in figure 3.8. Limited benchmark material only allowed for the notch test series and only two specimens can therefore be compared. A secondary unfortunate error can be observed in figure 3.8 as an apparent x-axis scale discrepancy

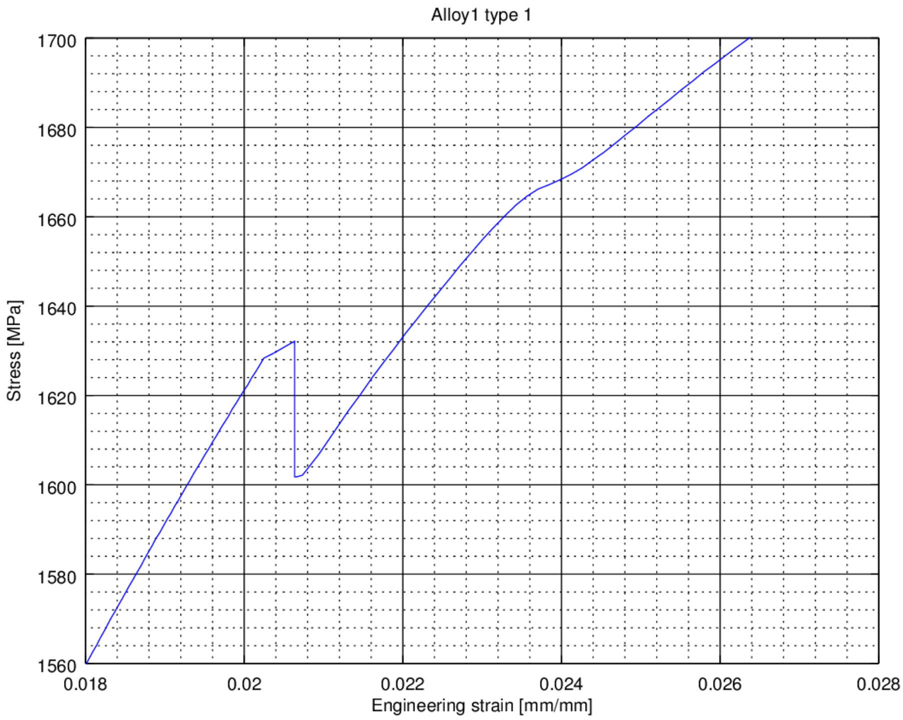

Figure 3.5: Raw tensile results for Alloy #1 as received - Zoomed view of yield point transfer.

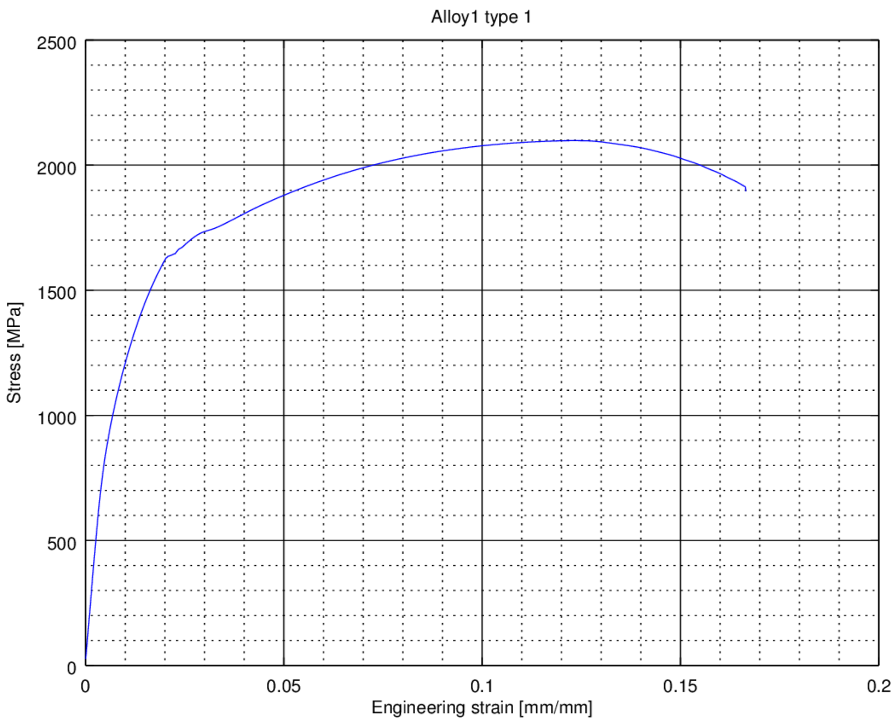

Figure 3.6: Corrected tensile results for Alloy #1 as received.

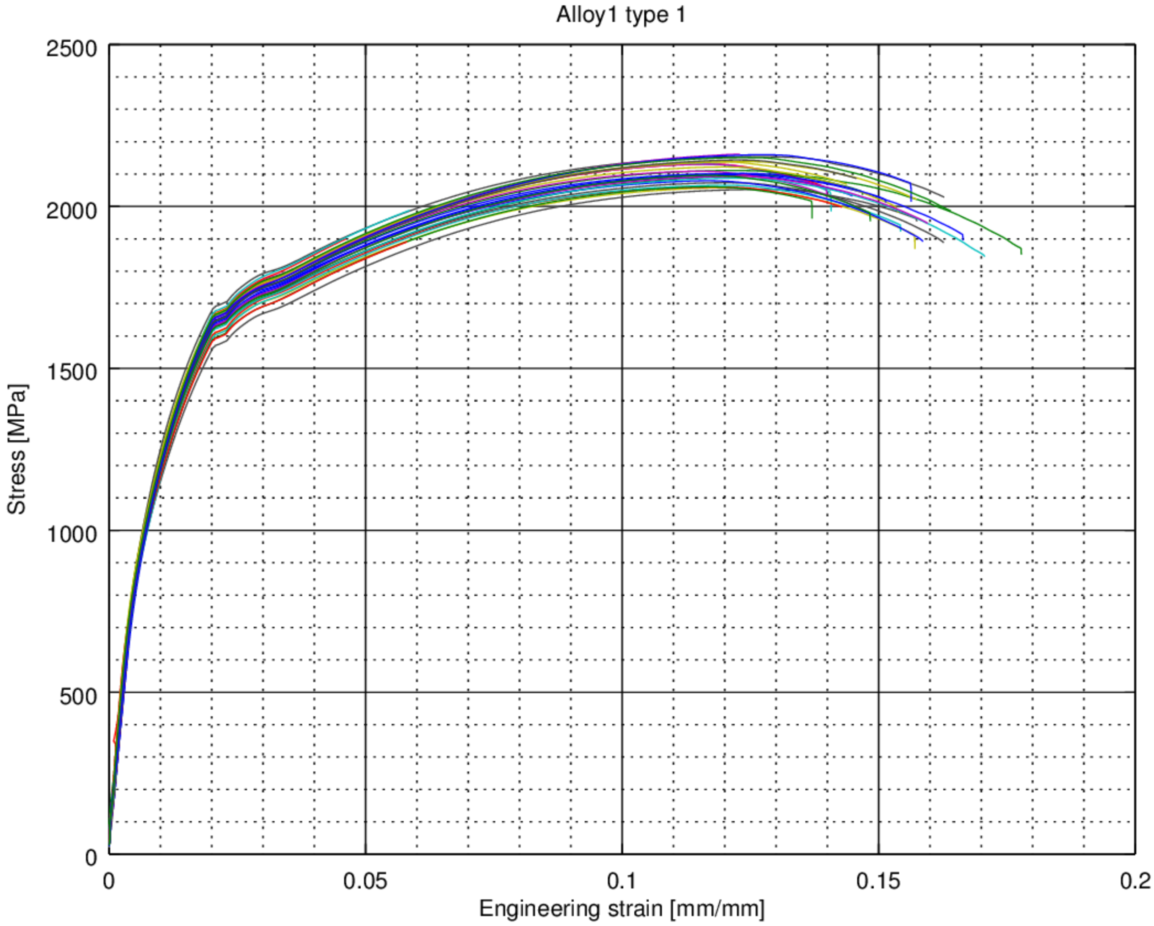

Figure 3.7: Quasi-static room temperature tensile result summary for Alloy #1 as received.

between the two materials. This is due to the video extensometer used for the notched series. Internal machine compliance correction could not be properly calibrated due to the limited number of specimens. This also explains why the total elongation value was not captured as the tensile test machine was set to report channel strain 1 and not strain 2, the video extensometer.

The high work hardening behaviour of alloy #1 is observed between 1% and 2% elongation with a consistent secondary work hardening range between 3% and 8%. Necking is observed around 13% and failure shortly thereafter. This behaviour is consistent with a high strength high work hardening material.

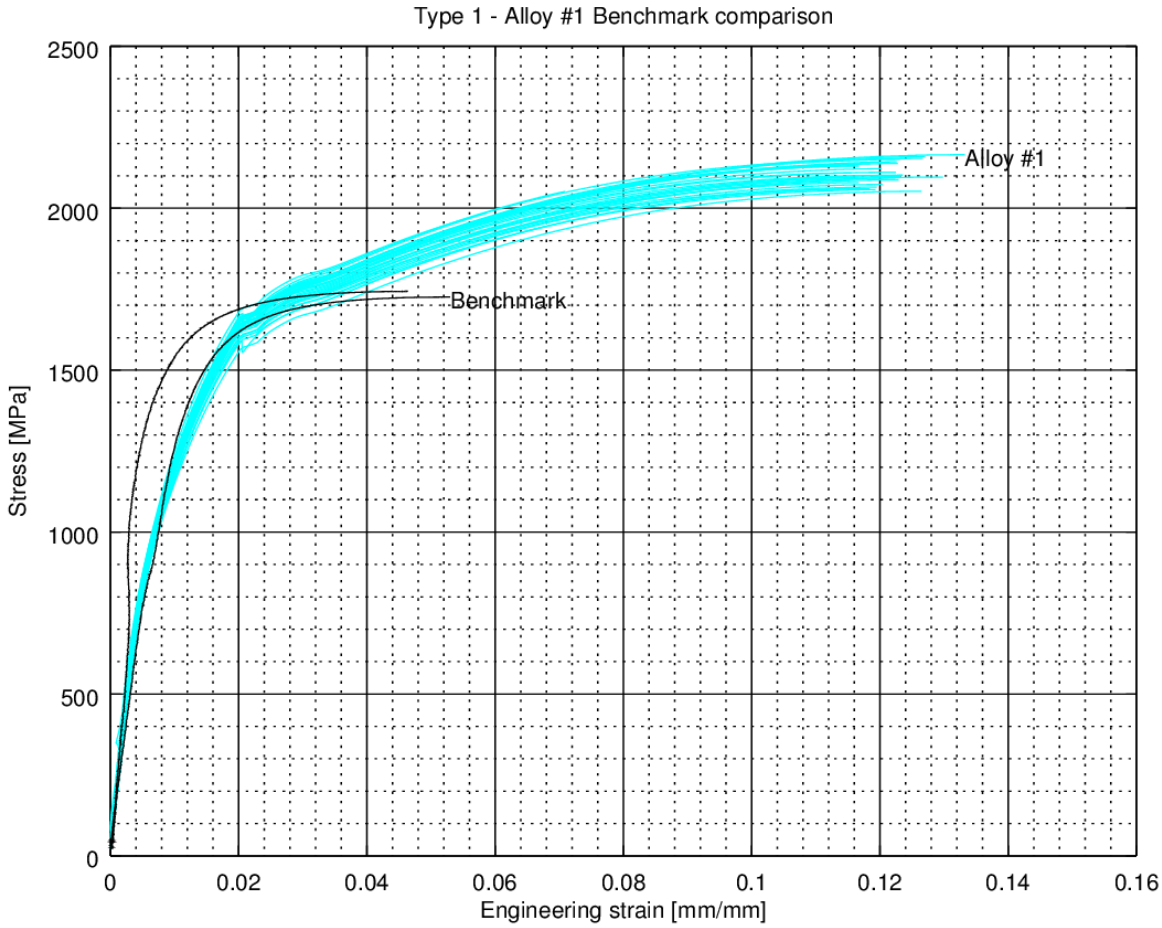

Figure 3.8: Quasi-static room temperature tensile results comparison for Alloy #1 and the benchmark material.

Specimen number #	t [mm]	w [mm]	Fmax [kN]	UTS [Mpa]	Elongation [%]
15 P 1 *	6.030	6.060	79.03	2162.84	
15 P 2	6.025	6.060	76.61	2098.24	16.65
15 P 3	6.035	6.050	76.53	2096.04	17.77
15 T 1	6.028	6.070	77.99	2131.46	14.06
15 T 2	6.030	6.065	77.95	2131.41	14.07
15 T 3	6.025	6.070	77.91	2130.33	13.99
7RA900 1	6.005	6.150	75.99	2057.63	15.7
7RA900 2	6.005	6.020	75.94	2100.69	15.08
4RA900 1	5.810	6.050	71.02	2020.45	4.06
4RA900 2	5.800	6.030	74.02	2116.43	10.54
18 1	6.000	6.050	74.51	2052.62	15.74
18 2	6.000	6.040	74.08	2044.15	12.95
16 1	5.660	6.050	71.94	2100.87	14.48
16 2	5.790	6.050	73.95	2111.08	14.68
14 1	5.780	6.040	71.92	2060.08	14.28
14 2	5.810	6.050	72.6	2065.40	15.42
13 1	5.790	6.030	73.62	2108.63	14.75
13 2	5.800	6.030	74.21	2121.86	15.38
12 1	5.680	6.050	71.25	2073.39	16.26
12 2	5.790	6.010	72.36	2079.44	15.86
11 1	5.760	6.040	71.69	2060.63	13.7
11 2	5.780	6.050	68.35	1954.59	7.05
10 1	6.000	6.060	75.91	2087.73	17.07
10 2	5.990	6.010	75.35	2093.06	15.95
9 1	6.010	6.050	77.73	2137.76	14.38
9 2	6.010	6.050	78.31	2153.71	16.27
8 1	6.010	6.070	76.69	2102.21	15.13
8 2	6.010	6.060	76.34	2096.07	14.83
7 1	6.010	6.005	71.63	1984.76	5.88
7 2	6.010	6.040	74.46	2051.22	7.09
3 1	6.050	6.050	79.26	2165.43	13.55
3 2	6.050	6.040	78.15	2138.63	15.74
2 1	6.050	6.060	78.45	2139.76	14.57
2 2	6.050	6.050	79.05	2159.69	15.63
1 1	6.050	6.080	79.12	2150.94	16.41
1 2	6.040	6.050	78.17	2139.18	14.04
B1N0	5.960	6.050	62.23	1725.83	-
B2N0	5.980	6.060	63.18	1743.44	-

Specimen numbers are arranged according to mill plate number and coupon number.
* *P* and *T* indicate parallel and transverse orientation to the rolling direction. All other coupons where tested parallel to the rolling direction.

Table 3.1: Quasi-static test summary

3.3 High temperature tensile tests

The high temperature test group consisted of two materials evaluated at 8 different temperatures from 100°C - 800°C in 100°C increments. The high temperature extensometer had to be removed at a hold point during the test and this transition was consequently recorded. A similar modification procedure to that discussed in the aforementioned section was used and included in Appendix C.

Direct comparison of all the high temperature tests is made in figures 3.9 - 3.11. One of the Alloy # 1 tests showed an initial calibration anomaly. The Alloy # 1 curves seem to be consistently located above the benchmark curves. This is clarified in figure 3.12 by comparing UTS at testing temperatures for the two materials. A clear delay in thermal softening is observed for Alloy # 1 between 300°C and 500°C with an ultimate tensile strength $\sim$ 60% higher than the benchmark material at 500°C.

The relative high alloy content required for air hardening ability could point to this thermal resilience. An austenite transformation temperature AC_1 of 675 °C is reported in the Damascus technical report [11] for Alloy # 1. It should be noted that the transformation temperature was measured on a near stress-free specimen and also without any plastic deformation. The maximum mechanical strength advantage is however observed for the 500 °C test, 175 °C below the transformation line. Martensite micro structure degradation below the AC_1 line, in a high stress condition, could explain the apparent similar strength reported at 600 °C and also the delay in thermal softening. Fine plate and lenticular martensite structures act as a grain refinement mechanism inside the original austenite grains. This in turn contributes to limit dislocation movement and increase mechanical strength in the macro scale. How the thermal, mechanical and transformation energy balances interact in a dynamic loading scenario seems to be essential for a complete understanding of this material.

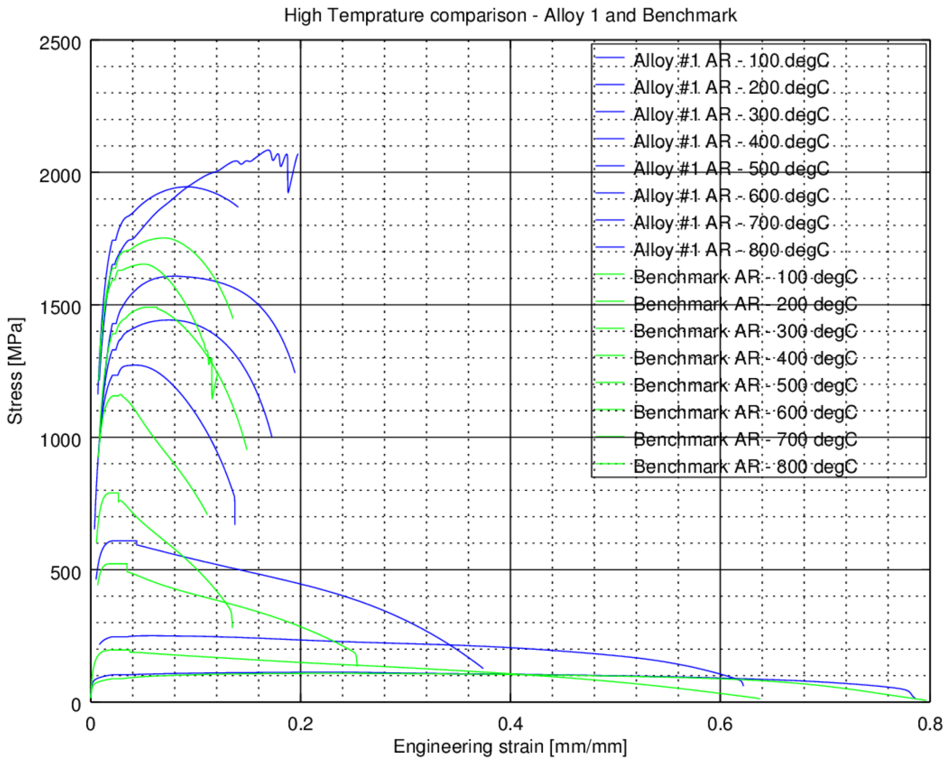

Figure 3.9: High temperature tensile test results for Alloy #1 AR and Benchmark AR.

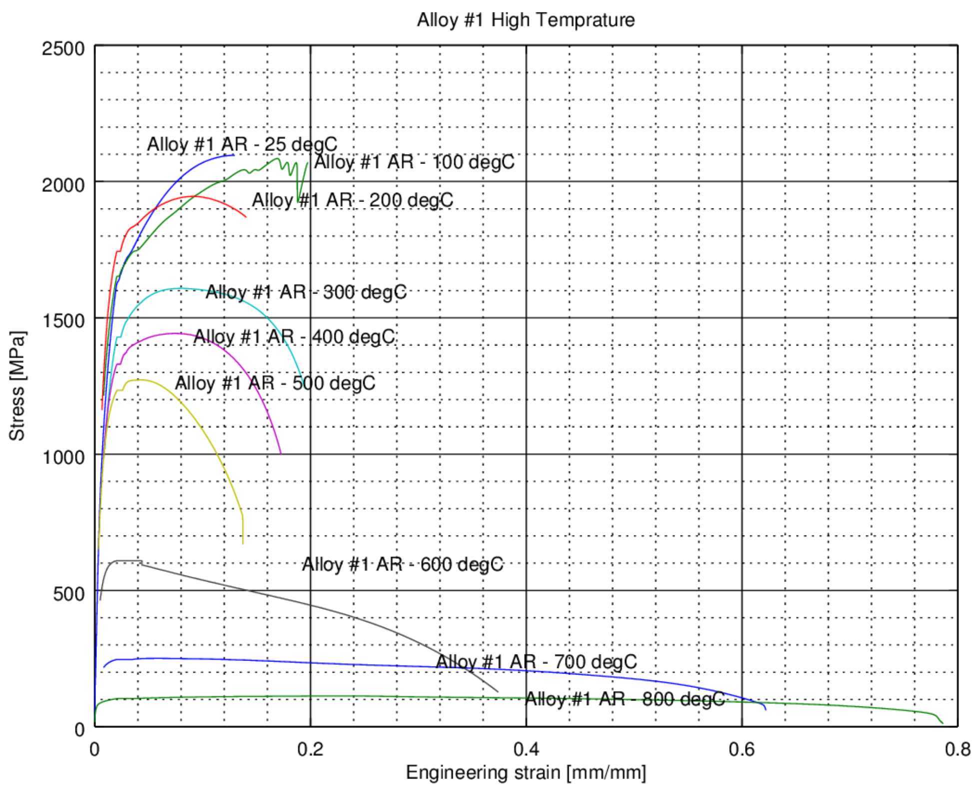

Figure 3.10: High temperature tensile test results for Alloy #1 AR.

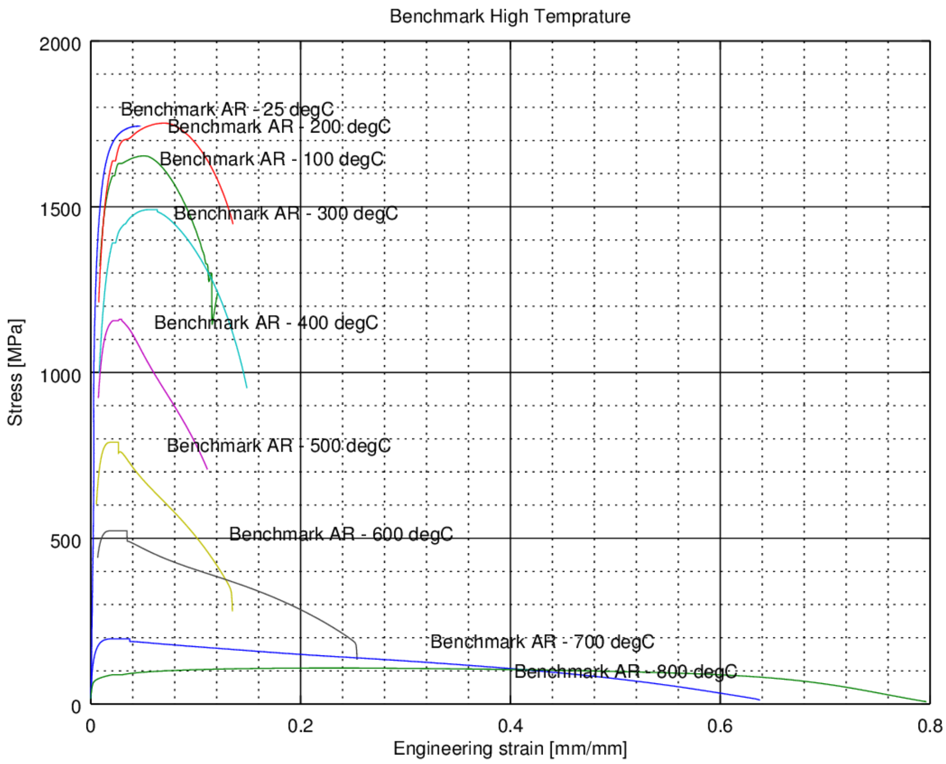

Figure 3.11: High temperature tensile test results for Benchmark AR.

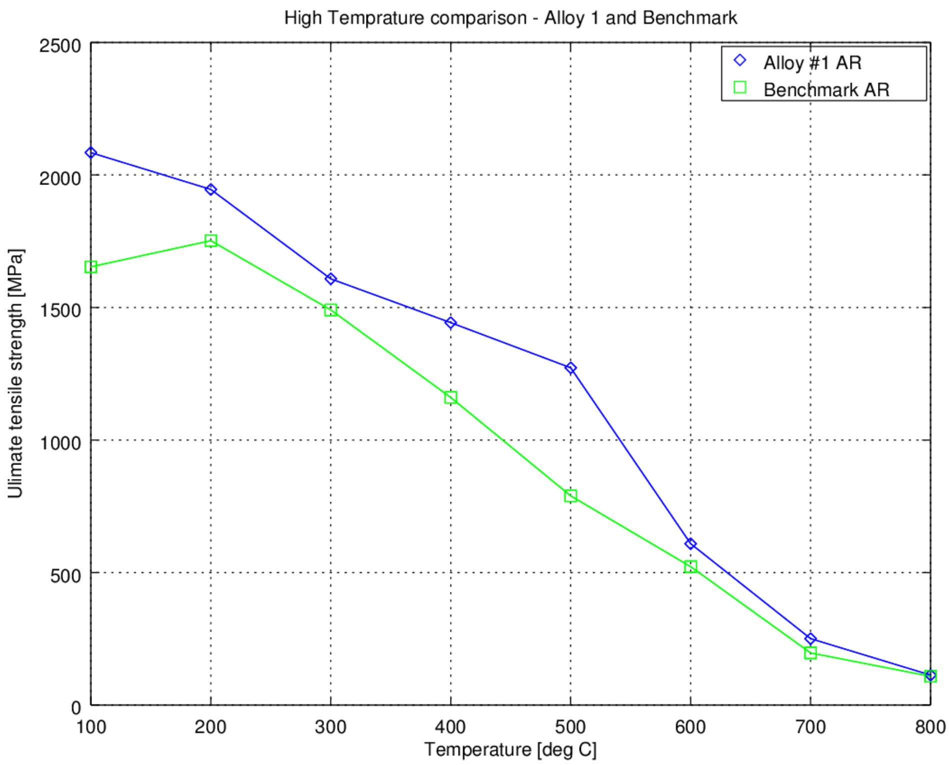

Figure 3.12: Ultimate tensile trength comparison at temperature for Alloy #1 AR and Benchmark AR.

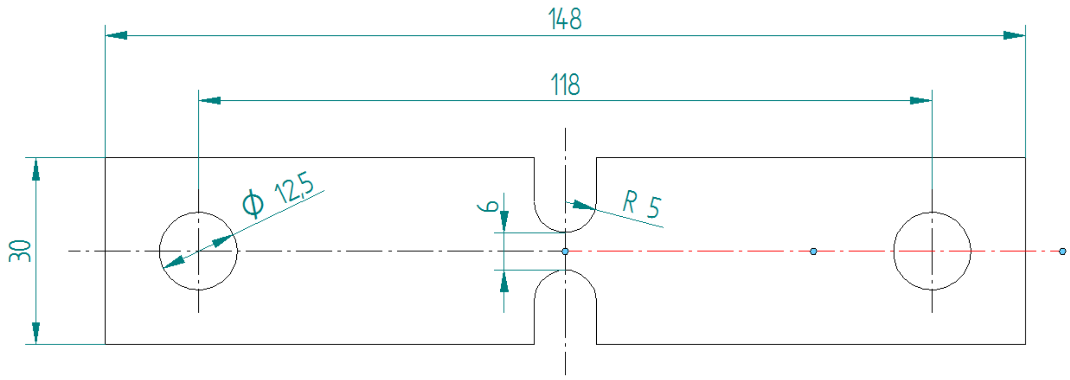

Figure 3.13: Notched tensile test specimen design.

3.4 Notched tensile tests

The notched tensile test specimen design, shown in figure 3.13, increased the notch effect by reducing the notch radius in the middle of the specimen. Radius values of 5 mm, 2 mm, 1 mm, 0.5 mm and 0.15 mm as well as a neutral specimen were included in this evaluation. Two complete sets were prepared for Alloy #1 and the benchmark material. Some difficulty with another testing machine resulted however in the loss of one Alloy # 1 notch set. The use of an extensometer was not required for this set. Failure point cropping and direct result comparison was again performed by an Octave script included in Appendix C.

The complete set of respective results is shown in figure 3.15. Only one set of blue lines represent Alloy # 1 with two complete sets (green lines) for the benchmark material. The typical round specimens used in these type of notched investigations allow for a fairly straight forward comparison of notch radius to peak stress tri-axiality with the well known Bridgman equation [91]. Stress tri-axiality is defined as the ratio of the hydrostatic stress to the equivalent stress or:

$$\sigma^* = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_{vm}} = \frac{\sigma_m}{\sigma_{vm}} \tag{3.1}$$

This can easily be calculated in a finite element environment. A simplified model of the 1 mm radius specimen is shown in figure 3.14 with symmetry constraint planes located on all three coordinate planes. The single planar notch on the one face locates the peak stress tri-axiality away from the center point towards the middle of the notch. An elastic reference tri-axiality was calulated for every notch specimen geometry and used in figure 3.17 for notch sensitivity comparison.

The benchmark material reports higher fracture strain values at every notch increment. This indicates a more severe notch sensitivity for Alloy # 1.

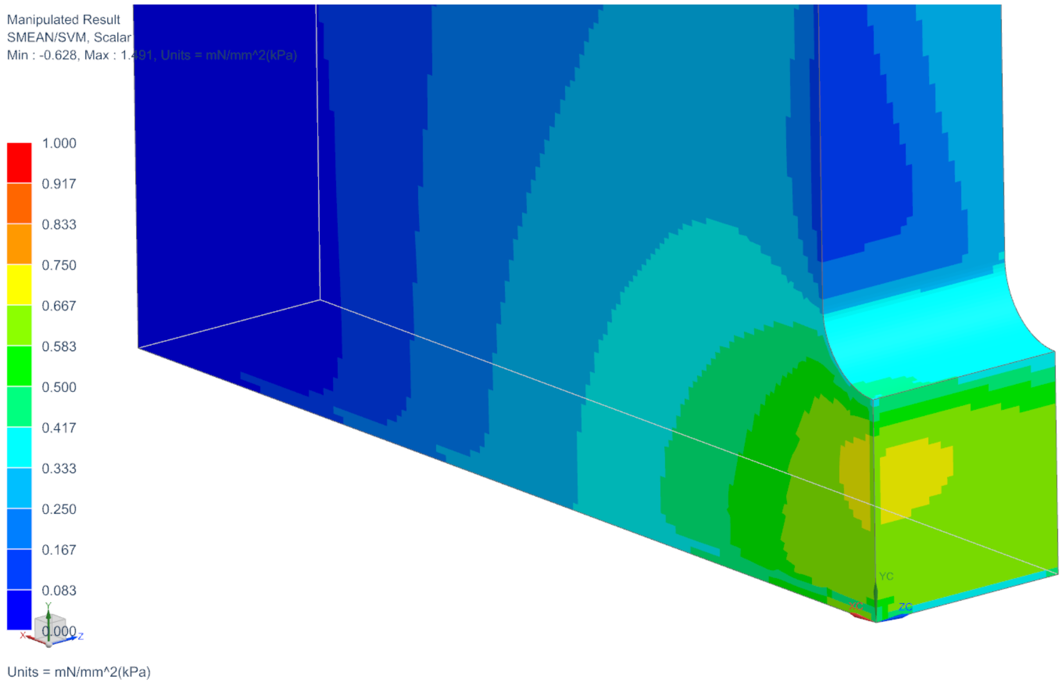

Figure 3.14: Stress tri-axiality ratio for Notch R = 1 mm

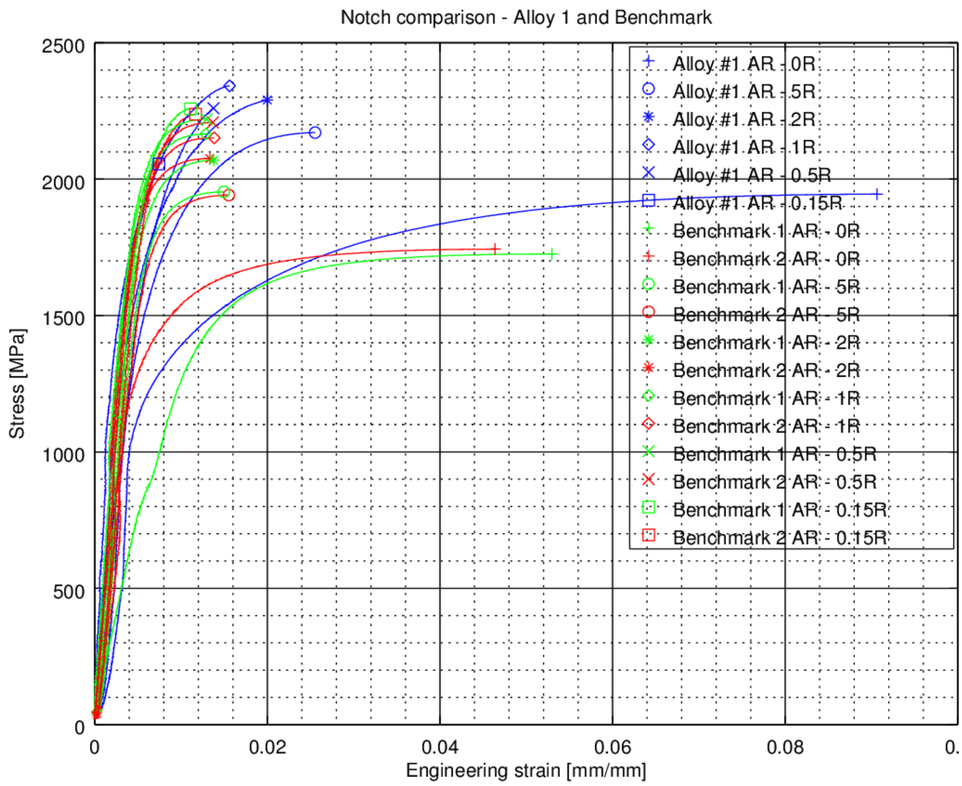

Figure 3.15: Notched tensile results for Alloy #1 and Benchmark specimen 1. and 2

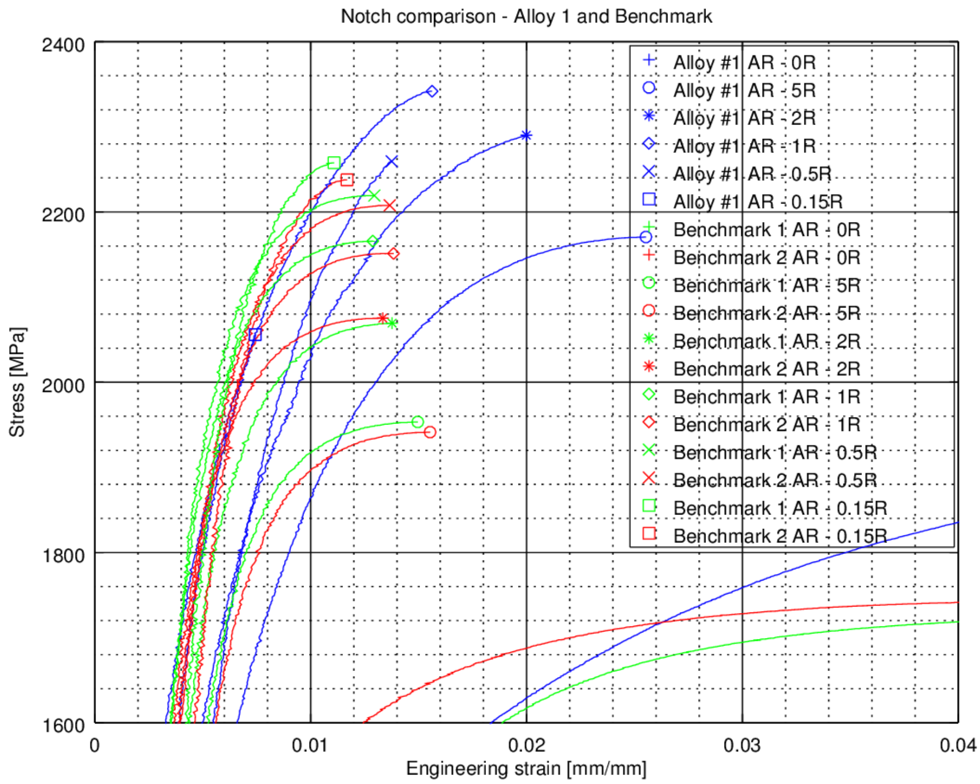

Figure 3.16: Notched comparison Alloy #1 and Benchmark specimen 1 and 2. - Zoomed view

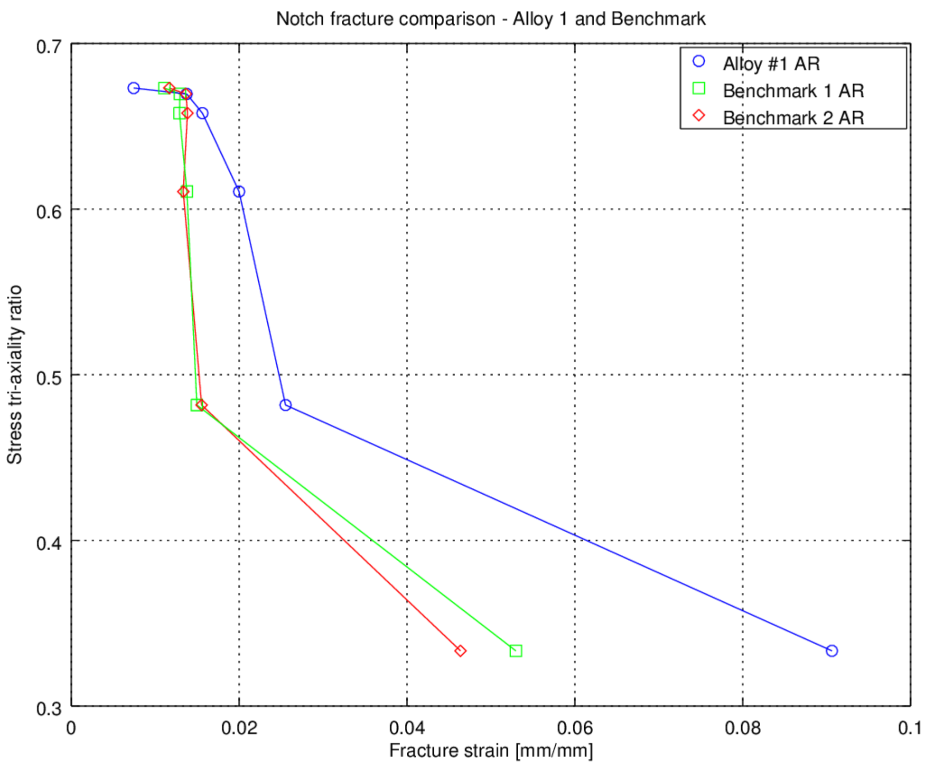

Figure 3.17: Notch sensitivity of Alloy #1 and Benchmark specimen 1. and 2.

3.5 Summary points

The following points summarise the conclusions from this chapter:

- Quasi-static tensile tests show little statistical variation for Alloy #1 and limited benchmark tests restrict direct comparison as these tests where recorded using a point video strain measurement3.7. The higher ultimate tensile strength of Alloy #1 should be noted.

- The delay in thermal softening of Alloy #1, figure3.12, could be attributed to the predominant martensitic structure as discussed in section 3.3.

- Notched tensile tests are compared in figure 3.16. It seems that Alloy #1 would accommodate more deformation at elevated stress triaxiality as the blue line is above the green and red for most of the graph. This is however misleading as the square shape of the specimens only allows for a single plain notch and therefore only a mild increase in stress triaxiality. It should be noted that the 0.15 mm notch comparison best approximates a real life crack and at this point the benchmark material performs better. Additional work not included in this report on the fracture toughness at lowered temperatures revealed the severe crack sensitivity of Alloy #1 over all temperatures tested.

CHAPTER 4

High strain rate material tests.

This chapter contains the high strain-rate material test results performed on a Split Hopkinson Pressure Bar at the Blast Impact and Survivability Research Unit BISRU at the University of Cape Town.

The bar configurations and specimen design are presented followed by a summary of the test theory and calculation procedure and then the results. It should be noted that the equipment and testing procedure was developed by Cloete and Stander [92].

4.1 Split Hopkinson Pressure Bar tensile configuration

The standard tensile configuration of the Split Hopkinson Pressure Bar [93] developed at BISRU was used for the type 4 tests. A general layout drawing of the tensile configuration is shown in section view in figure 4.1.

The cylindrical striker forms a closed high pressure chamber over the gas gun barrel. Note the barrel plug, pressure cap and seals along with the Teflon bush sliding freely to allow smooth acceleration of the striker towards the right as high pressure air is released from the gas gun. The pre-set pressure regulator of the gas gun is used to adjust the total impact energy. Once the transfer cap impacts the flange, a tensile wave is generated in the input bar proportional to the momentum of the cylindrical striker. A smooth transfer of the wave is facilitated by placing a dynamic contact dampening element in the form of four small balls of temporary adhesive on the transfer flange every few tests. The stress waves are recorded at 10 MHz in both the input and output bars by means of strain gauges located in the middle of each bar. This reduces the effect of reflected

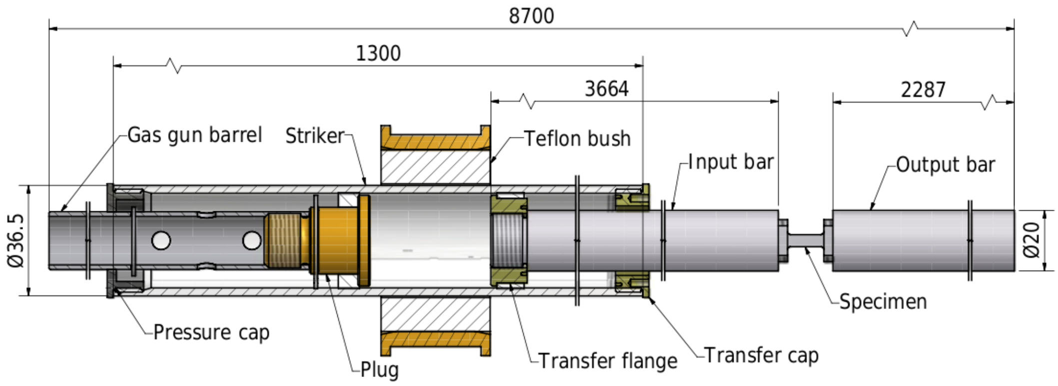

Figure 4.1: Tensile configuration of Split Hopkinson Pressure Bar.[93]

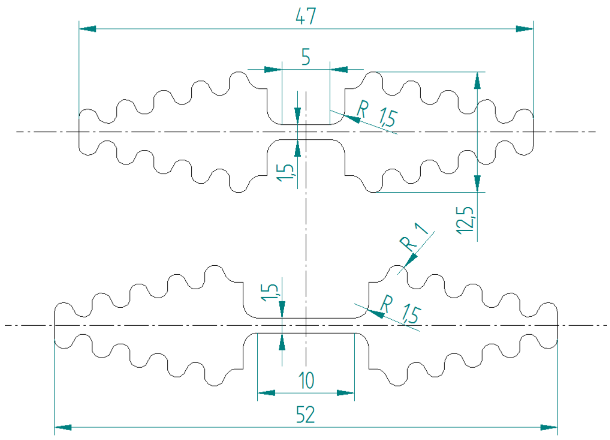

Figure 4.2: Type 4 specimen design.

waves interfering with test measurements. The striker, input and output bars are made from aluminium and supported in several locations along the length to reduce transverse deformation under own weight.

The specimen design is influenced by the elastic limit of the bars and the input energy or the gas gun's capacity, or in wave terms, the height and length of the elastic wave. The experimental configuration should always exceed the requirements of the tested material to ensure a successful set of results. The comparative strength of the new Alloy # 1 and fixed bar size of the current tensile configuration, limited the type 4 specimens to a cross section of $1.5 \times 1.5 = 2.25\ mm^2$, shown in figure 4.2.

The specimen was connected to the bars using a novel split taper threaded adapter, with a special fern tree cut-out on the inside, as shown in figure 4.3 to 4.5. Longitudinal slots in the adapter allow for a tight fit to the specimen. The adaptor is then snap-fitted onto the test specimen before assembly into the pressure bar. Use of a tapered thread further simplified the assembly by reducing the number of rotations to tighten the adaptor. Compact design and use of titanium in the adapter minimized inertial effects on the test results.

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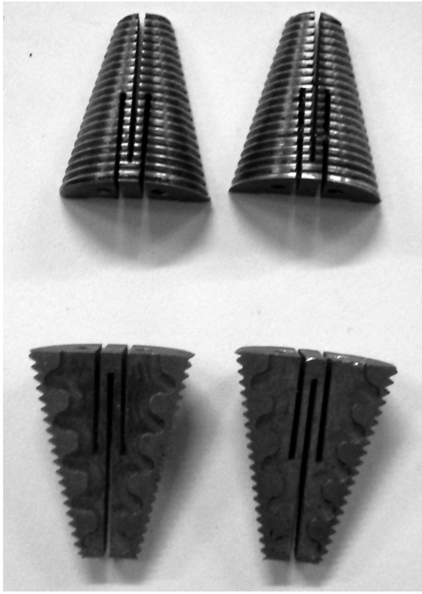

Figure 4.3: Taper threaded specimen connection adaptor.

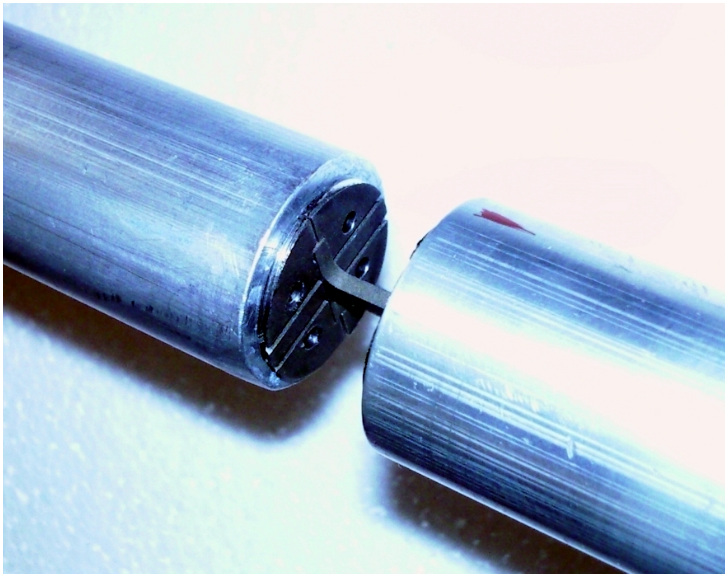

Figure 4.4: Specimen with adaptor assembly in Split Hopkinson Pressure Bar.

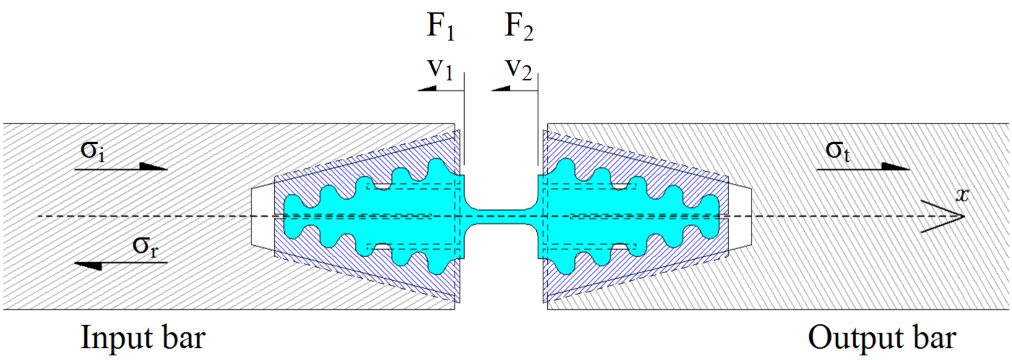

Figure 4.5: Tensile configuration with wave directions.

4.2 SHPB theory

The classic Split Hopkinson Pressure Bar test has been developed over the part 50 years into a widely used and well documented [94] material testing technique. This section contains the test theory and forms the reference for the following two sections where the measured signals are related to engineering stress strain curves for the test specimens.

The general one-dimensional elastic wave equation [95],

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{4.1}$$

can be written as follows for the incident and reflected waves,

$$u = f(x - c_b t) + g(x - +c_b t) = u_i + u_r \tag{4.2}$$

Differentiating equation 4.2 with respect to x, the strain in the bar is given by,

$$\varepsilon_{bi} = \frac{\partial u}{\partial x} = f' + g' = \varepsilon_i + \varepsilon_r \tag{4.3}$$

and differentiating equation 4.2 with respect to t and using equation 4.3 gives,

$$v_1 = \frac{\partial u}{\partial t} = c_{b1}(f' + g') = c_{b1}(\varepsilon_i + \varepsilon_r) \tag{4.4}$$

As no reflected wave is present in the output bar, the velocity is,

$$v_2 = c_{b2}\varepsilon_t \tag{4.5}$$

The instantaneous increase in specimen length, strain and strain rate can thus be calculated as follows:

$$\triangle\ u = \int v_1 dt - \int v_2 dt \tag{4.6}$$

$$\varepsilon_s = \frac{\triangle\ u}{l_0} \tag{4.7}$$

$$\dot{\varepsilon_s} = \frac{v_1 + v_2}{l_{si}} \tag{4.8}$$

where l_0 and l_{si} are the specimen original and instantaneous lengths respectively. As the bars remain elastic, the forces in each bar are calculated as,

$$F_1 = A_{b1} E_{b1} (\varepsilon_i + \varepsilon_r) \tag{4.9}$$

$$F_2 = A_{b2} E_{b2} \varepsilon_{b2} \tag{4.10}$$

Engineering stress is then simply calculated as follows;

$$\sigma_s = \frac{F_i}{A_s} \tag{4.11}$$

Engineering stress, strain and strain-rate were calculated and are reported in the following two sections.

4.3 Type 4 test calculation and results

The strain signal recording consisted of several reflections of the stress waves over a 5 s period. This was to ensure that the impact event was captured as the experiment was manually triggered after the recording had been started. The result was however that 80 % of the captured data needed to be eliminated before the calculation starts.

Test data that would be typically processed in Excel, required some patience when manipulating 50 000 cells. As multiple specimens would be processed, it was decided that an Octave script would rather be used. Octave is well suited for vector operations and iterative data reading and writing tasks.

A simple signal offset correction and crop was performed before the calculation was started. Using the Octave script, all 20 type 4 recorded strain signals were cropped in less than 5 minutes. Details of this script are shown in Appendix D along with the calibration variables for the tensile SHPB configuration.

The calculation and reporting process was separated into three parts and dealt with in each of the following Octave files. Firstly the individual specimen results were calculated and saved in result files. The second part recalled all the result files for direct comparison and in the third part a manual sectioning of the data was performed to eliminate noisy and dynamically unstable sections before the type 4 results were saved for material characterisation.

4.3.1 Individual specimen calculation

The first Octave file is **THPB do.m**. It reads the single wave offset corrected signals for the incident, transmitted and reflected waves and used the calibration factors for the aluminium bars to calculate the specimen engineering stress, strain and strain-rate. A sample calculation is shown in the following few figures with notes. The Octave file THPB do.m and calibration files are included in Appendix D.

The calculation started with three strain waves (figure 4.6) and used equations 4.4 and 4.5 to calculate the two bar end velocities (figure 4.7). The bar end acceleration (figure 4.8) and displacements (figure 4.9) were simply calculated by numerical integration and differentiation.

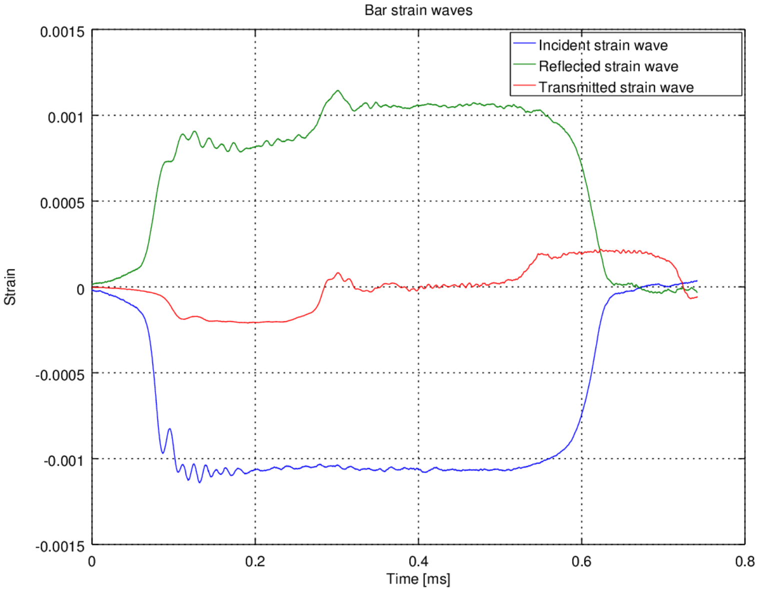

Figure 4.6: THPB do: Bar strain waves.

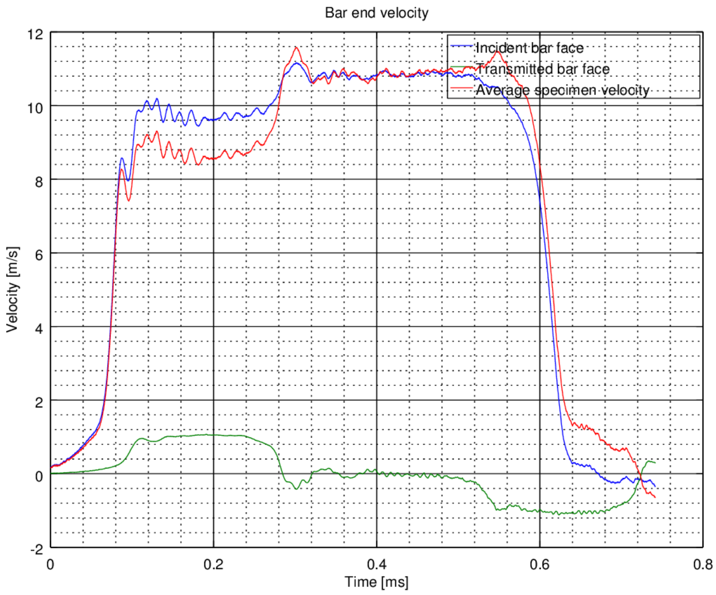

Figure 4.7: THPB do: Bar end velocity.

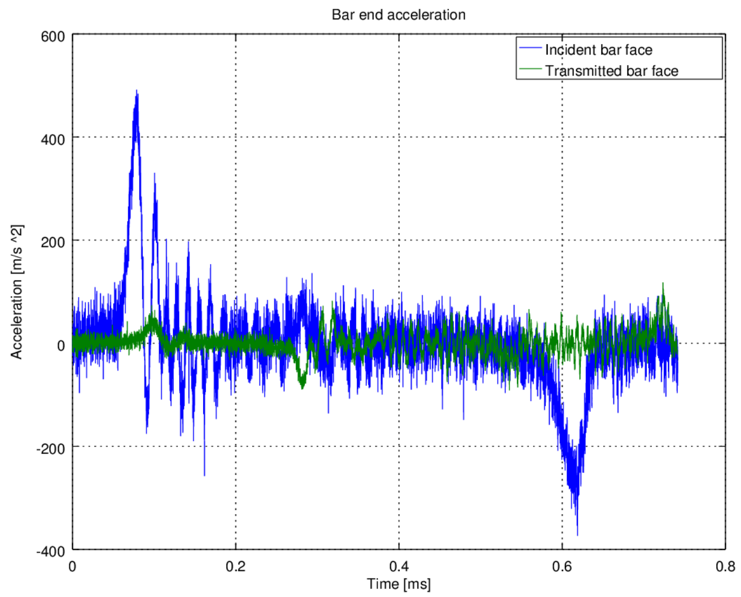

Figure 4.8: THPB do: Bar end acceleration.

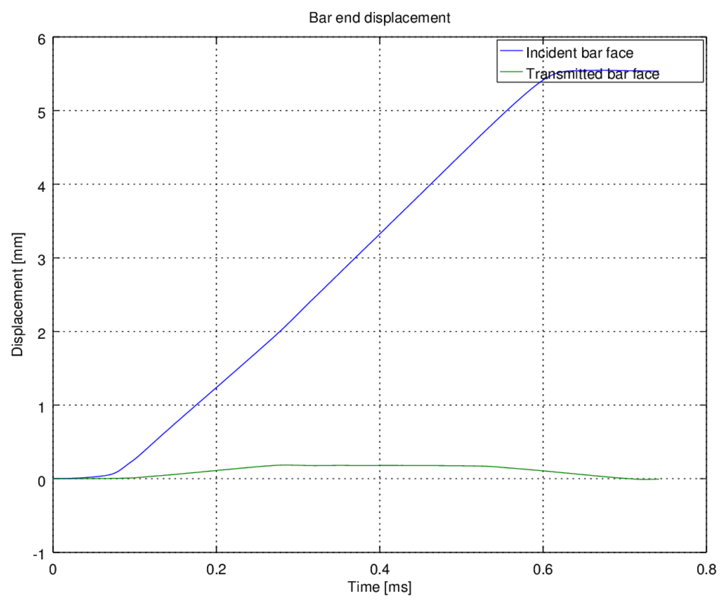

Figure 4.9: THPB do: Bar end displacement.

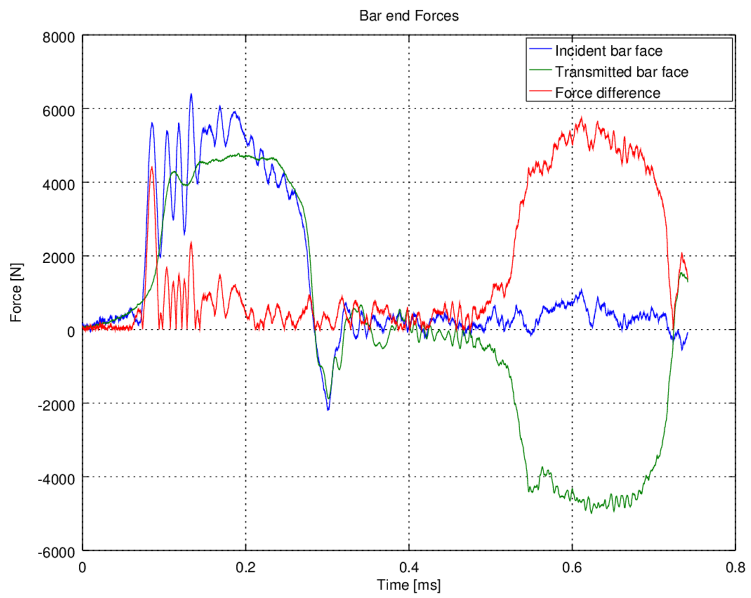

Figure 4.10: THPB do: Bar end forces.

The bar end forces were calculated using equations 4.9 and 4.10 and are shown in figure 4.10 together with a force difference curve to indicate when a point of equilibrium was reached between the two bars.

The engineering strain was calculated using equation 4.7 and was found to increase over time in figure 4.11. Strain rate was calculated using equation 4.8 and is shown in figure 4.12.

Using both force curves in figure 4.10 and equation 4.11, the engineering stress was calculated and reported in figure 4.13. For all the tested specimens a noisy stress curve was observed when using the incident bar force curve. To avoid numerically smoothing or taking an average it was decided to simply use the transmitted force signal in reporting all the dynamic plasticity results for every test specimen.

4.3.2 Comparison of results

The second Octave file is **THPB plot results.m**. It reads all the saved result files for the type 4 tests and plots engineering stress strain and strain-rate for comparison between each specimen and then re-plots all the stress strain curves on a single figure with curve colours for every material, for direct comparison. These figures are shown on the following pages for the new Alloy # 1 in figures 4.14 and 4.15, for the tempered variant of Alloy # 1T in figures 4.16 and 4.17 and for the benchmark material in figures 4.18 and 4.19. The direct comparison plot is shown in figure 4.20. The Octave file is included in Appendix D.

The validity of high strain rate testing in the tensile configuration can be evaluated with the following minimum requirements. Was the projectile energy sufficient to plas-

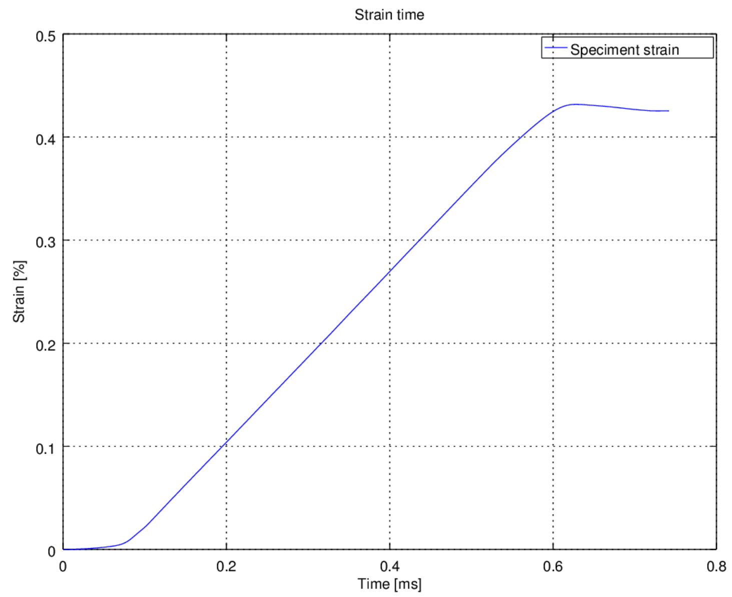

Figure 4.11: THPB do: Strain time.

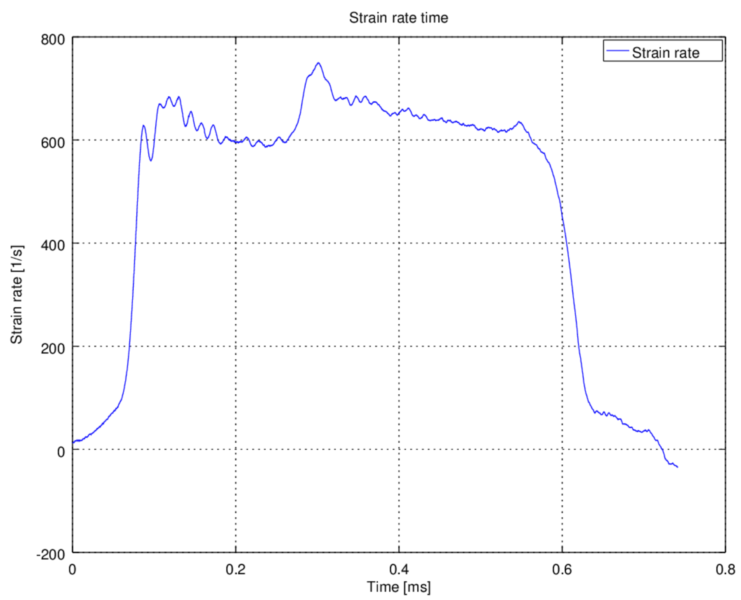

Figure 4.12: THPB do: Strain rate time.

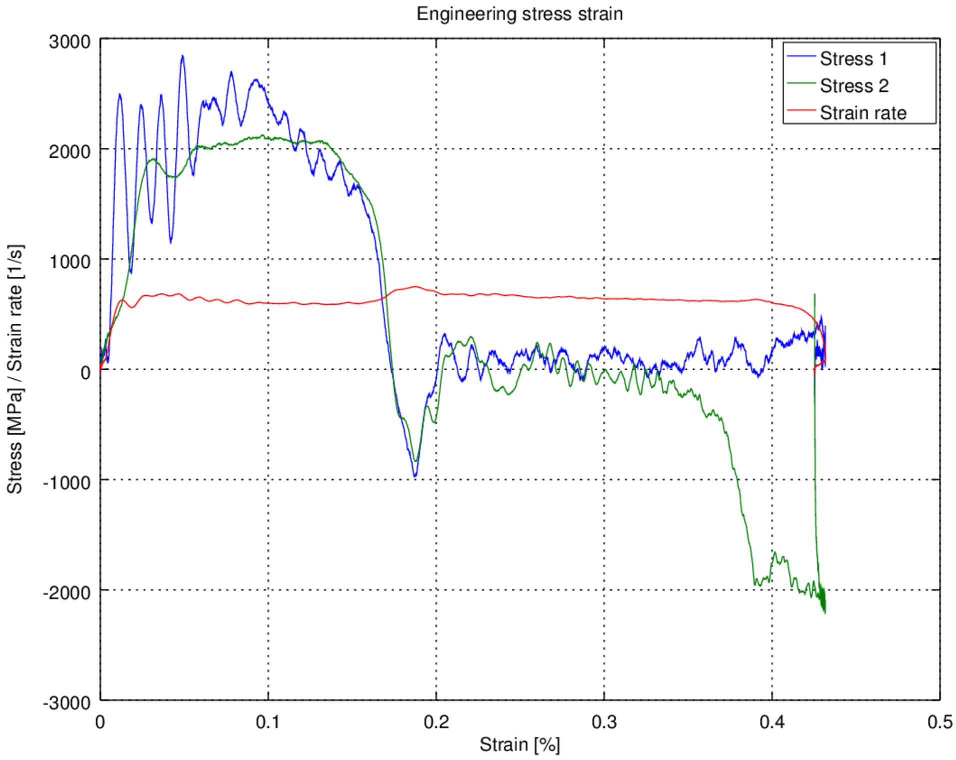

Figure 4.13: THPB do: Engineering stress strain.

tically deform the specimen past the ultimate load capability and unto failure? Did the strain-rate remain constant over most of the test? Did the effective load on the specimen reach a steady state before the onset of plastic deformation?

These questions can be answered by observing the strain rate figures (4.14, 4.16 and 4.18). It should be noted that the launch pressure was purposefully kept the same across all three materials as similar strength material should resist the tensile wave and lead to comparable strain rates. This was the case as the Alloy #1 and the tempered variant of Alloy # 1T reported strain rates between 600 and 1000 [1/s], however the benchmark material fractured almost without any plastic deformation at the highest pressure and a dynamic unstable loading is shown for the second pressure. The strain rate range of only 500 to 750 [1/s] is observed for the benchmark material and the dynamic unstable oscillations shown in figure 4.19 indicate that the specimen was dynamically overloaded. A redesign of the benchmark material specimen would have allowed for a larger force capacity and thus comparable strain rate testing. This was however not possible as limited time and funding constrained the dynamic testing.

Comparison of figures 4.15, 4.17 and 4.19 show a consistent plastic elongation for both Alloy #1 and the tempered variant Alloy # 1T before the failure localisation starts. The benchmark material is slightly misrepresented here as the loads where applied in an oscillating wave and the plastic elongation portion of the curve could not be captured.

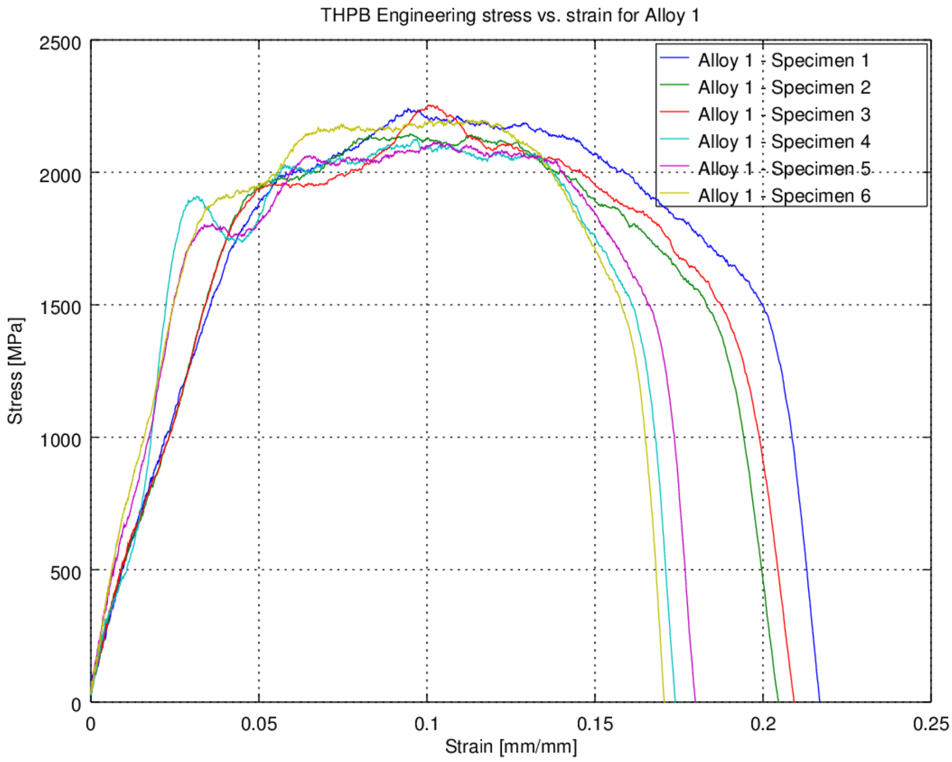

Figure 4.14: Type 4 - Alloy # 1 stress strain comparison [MPa]

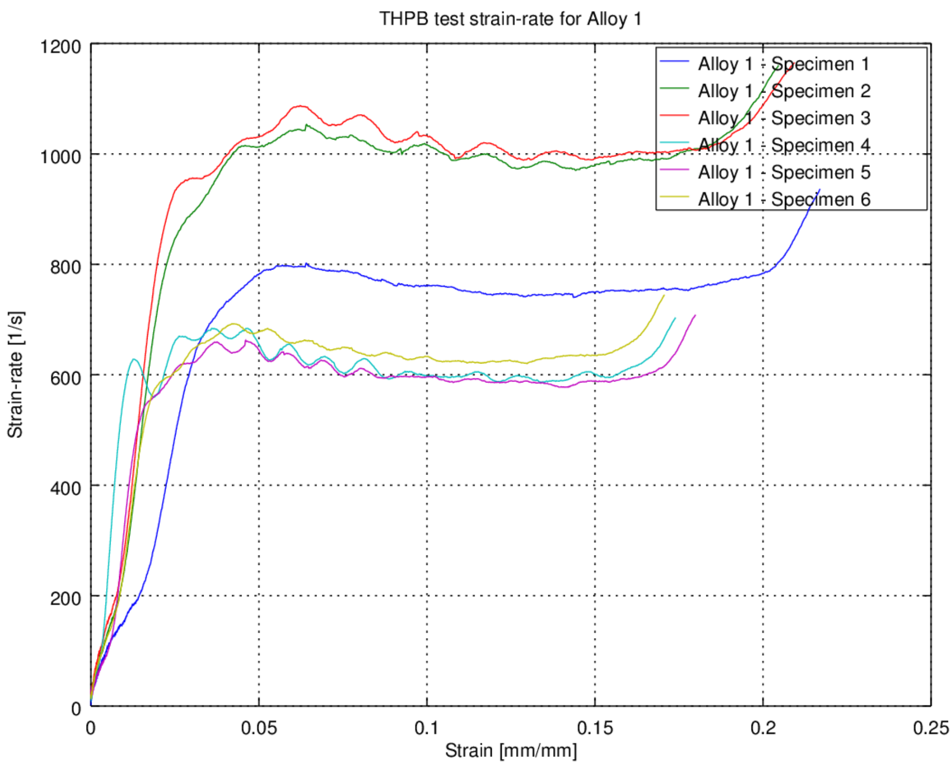

Figure 4.15: Type 4 - Alloy # 1 strain-rate comparison [mm/mm/s]

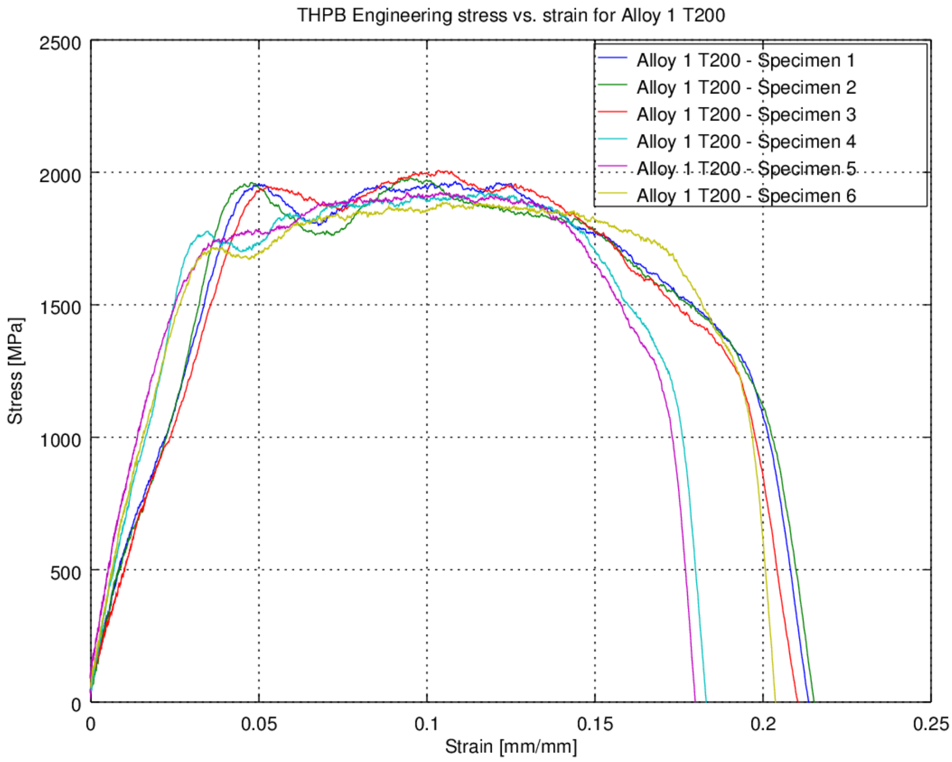

Figure 4.16: Type 4 - Alloy # 1 T200 stress strain comparison [MPa]

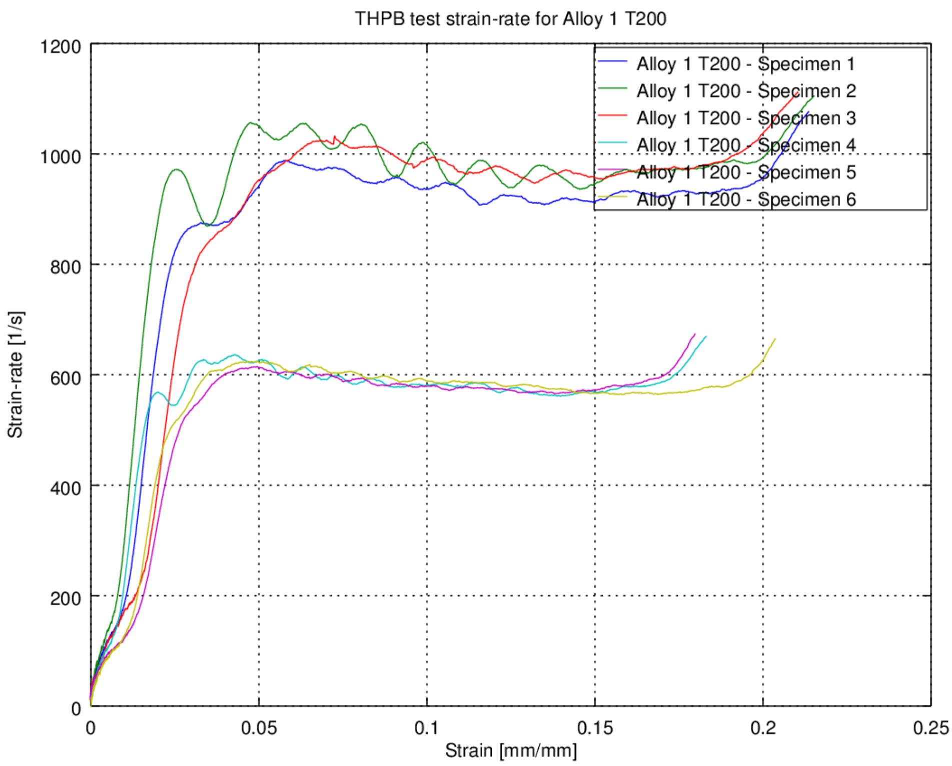

Figure 4.17: Type 4 - Alloy # 1 T200 strain-rate comparison [mm/mm/s]

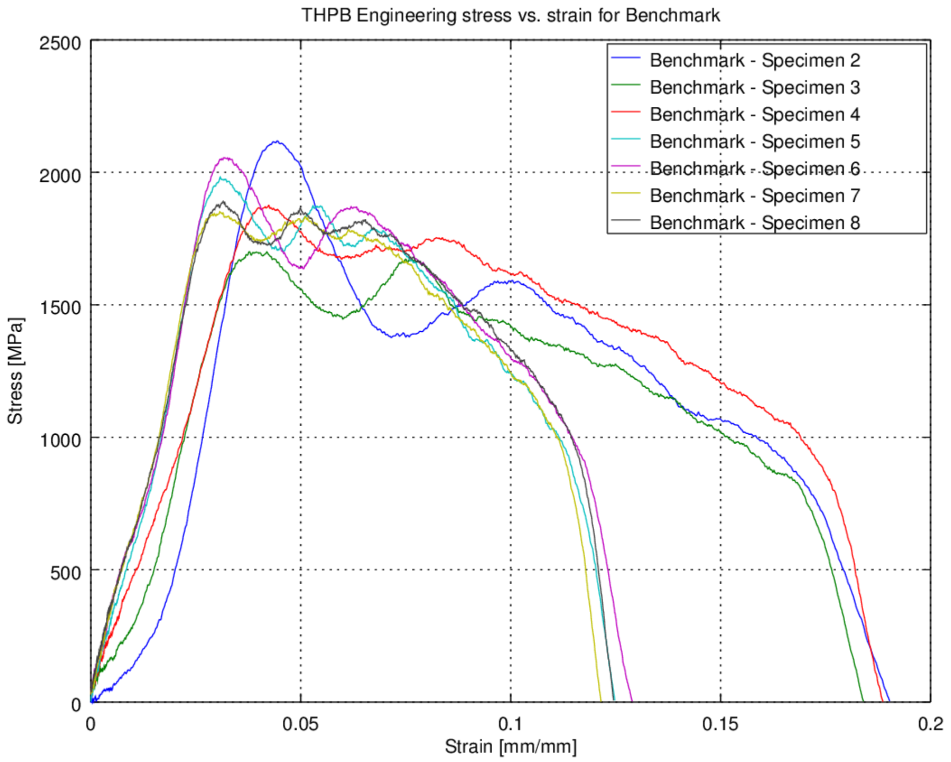

Figure 4.18: Type 4 - Benchmark stress strain comparison [MPa]

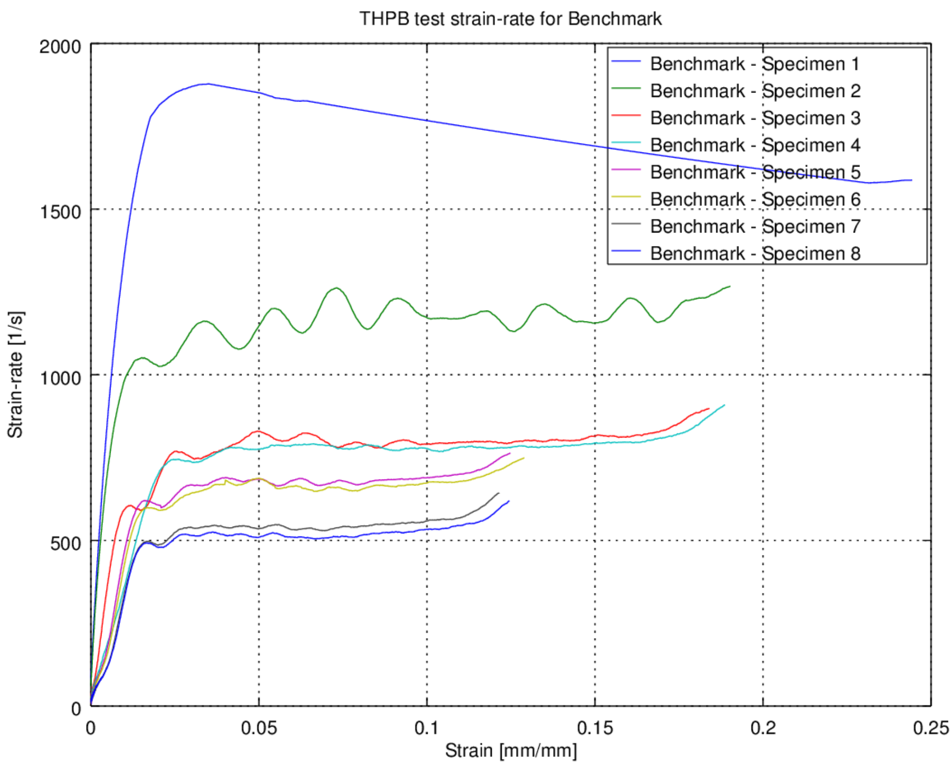

Figure 4.19: Type 4 - Benchmark strain-rate comparison [mm/mm/s]

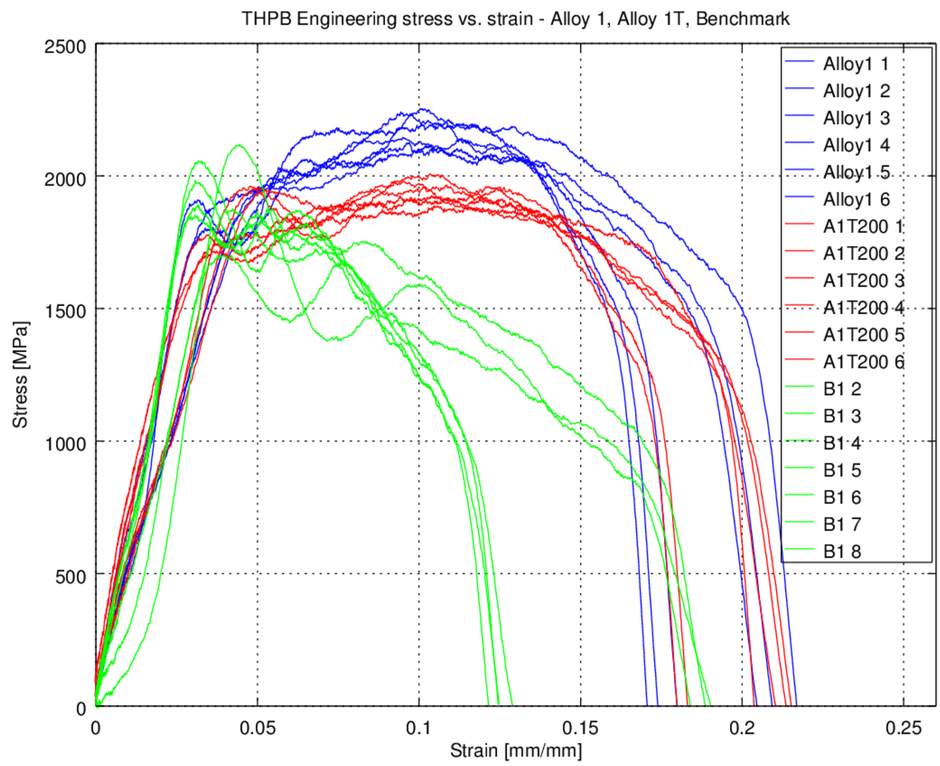

Figure 4.20: Type 4 - Material comparison [MPa]

4.3.3 Result clipping

The third Octave file is **Plot all T4.m**. This script reads all the result files and cuts noisy sections from the first part of the curve and any data past the fracture point. Fracture is taken as the point of sudden slope change in the curve. Each specimen's stress and strain result was saved into a unique identification name and all the type 4 test results were saved into a single file named **Type4.dat**. The Octave file is included in Appendix D.

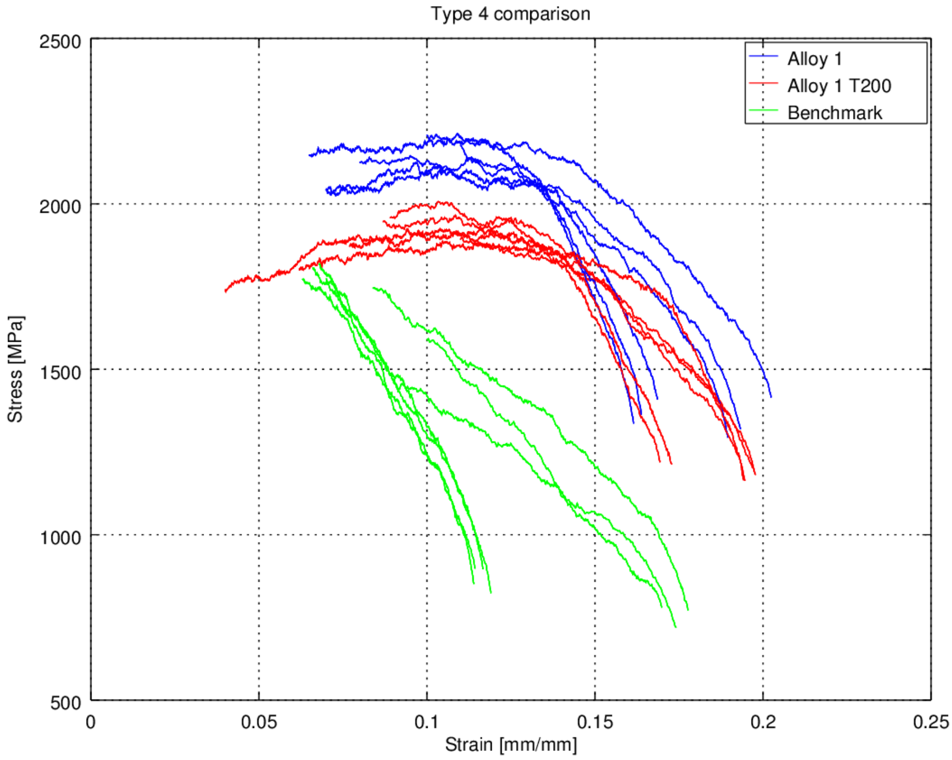

Figure 4.21: Type 4 - Clipped result comparison.

4.4 Type 5 test calculation and results

The compression configuration of the Split Hopkinson Pressure Bar consists simply of two hardened steel bars and a typical cylindrical striker. Test specimens were limited to a 5 mm Ø cylinder 5 mm long to avoid any damage to the pressure bars.

A similar data zero and crop procedure was followed for the compression configuration and is shown in Appendix D.

4.4.1 Individual specimen calculation

The result calculation, direct comparison and sectioning were performed with similar octave files than discussed in the aforementioned section. It should be noted that the direction arrow that were shown in figure 4.10 are reversed for the compression configuration of the test.

The first file, **CHPB do.m**, starts with three strain waves (figure 4.22) and used equations 4.4 and 4.5 to calculate the two bar end velocities (figure 4.23). The bar end acceleration (figure 4.24) and displacements (figure 4.25) were simply calculated by numerical integration and differentiation.

The bar end forces were calculated using equations 4.9 and 4.10 are shown in figure 4.26 along with a force difference curve to indicate when a point of equilibrium is reached

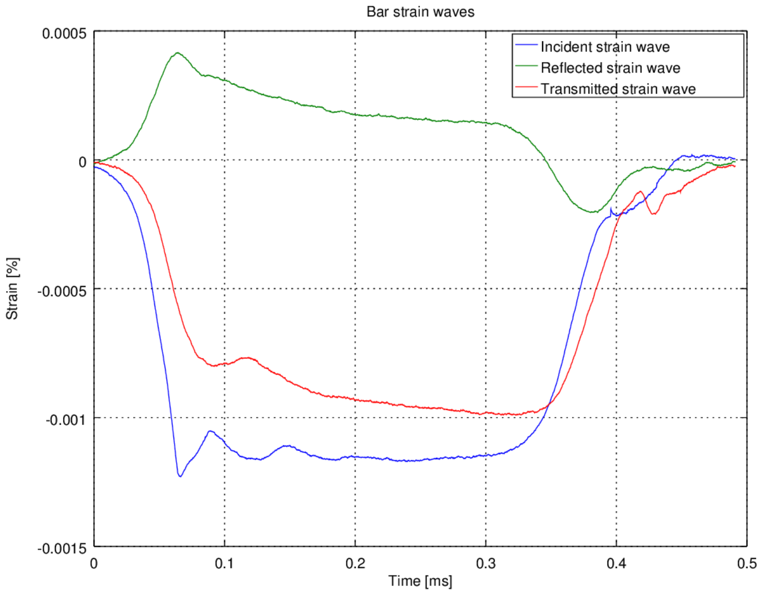

Figure 4.22: CHPB do: Bar strain waves.

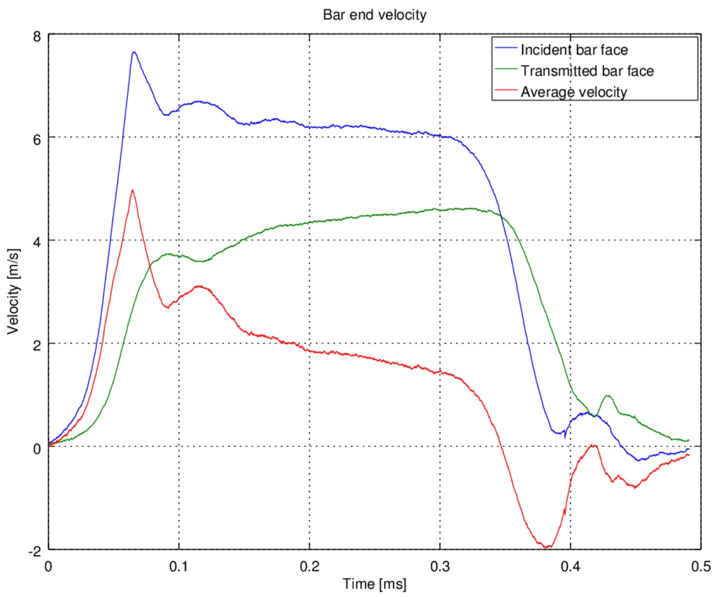

Figure 4.23: CHPB do: Bar end velocity.

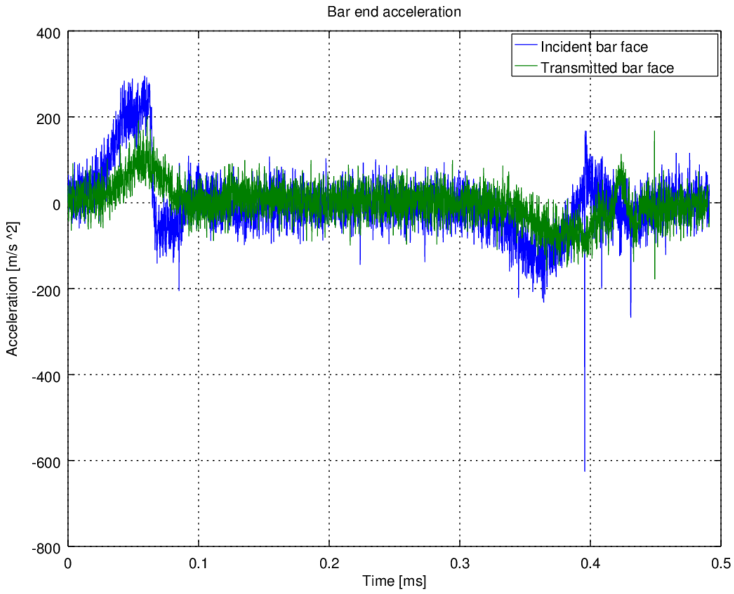

Figure 4.24: CHPB do: Bar end acceleration.

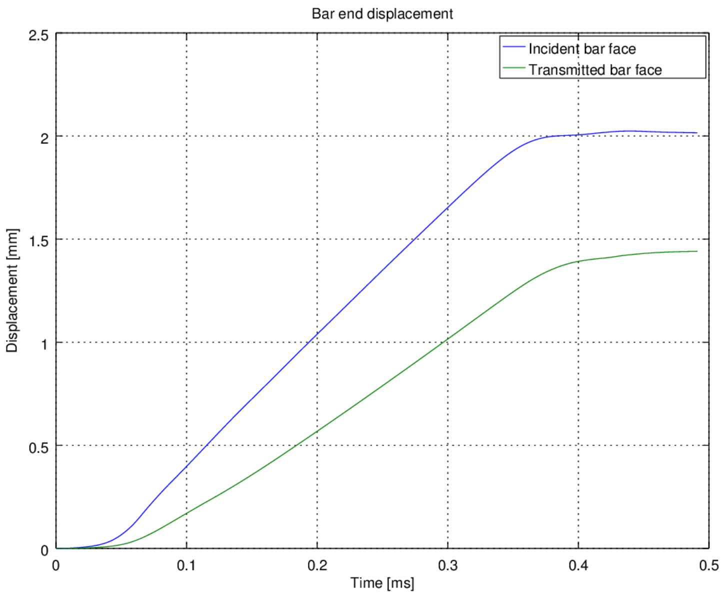

Figure 4.25: CHPB do: Bar end displacement.

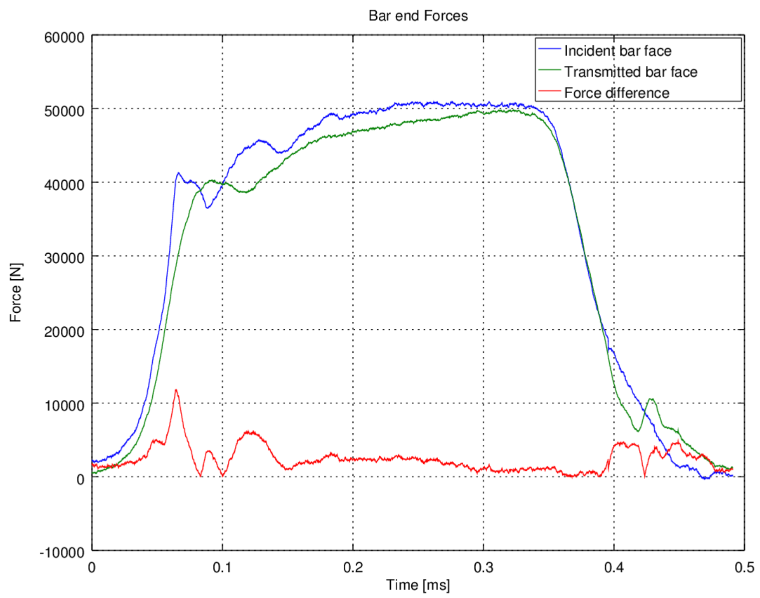

Figure 4.26: CHPB do: Bar end forces.

between the two bars.

The engineering strain was calculated using equation 4.7 and was shown to increase over time in figure 4.27. The strain rate was calculated using equation 4.8 and is shown in figure 4.28.

Using both force curves in figure 4.26 and equation 4.11 the engineering stress was calculated and reported in figure 4.29. For all the tested specimens a noisy stress curve was observed when the incident bar force curve was used. To avoid numerically smoothing or taking an average it was decided to simply use the transmitted force signal in reporting all the dynamic plasticity results for every test specimen.

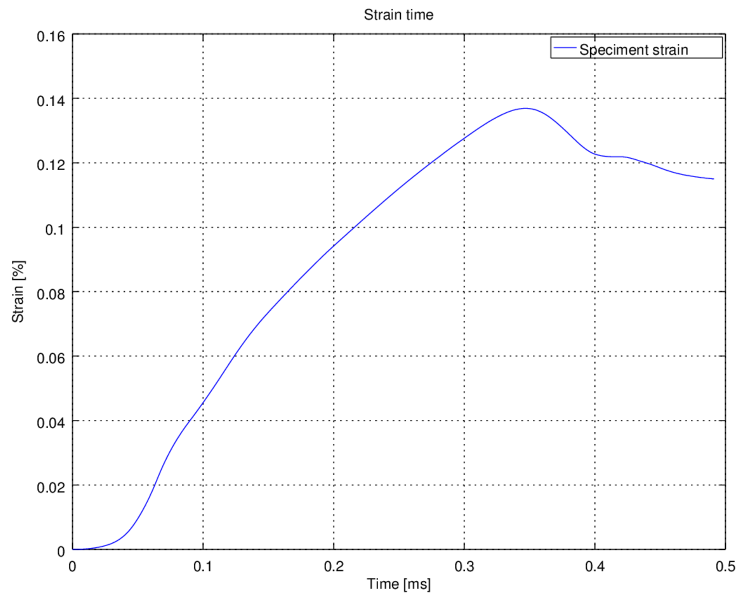

Figure 4.27: CHPB do: Strain time.

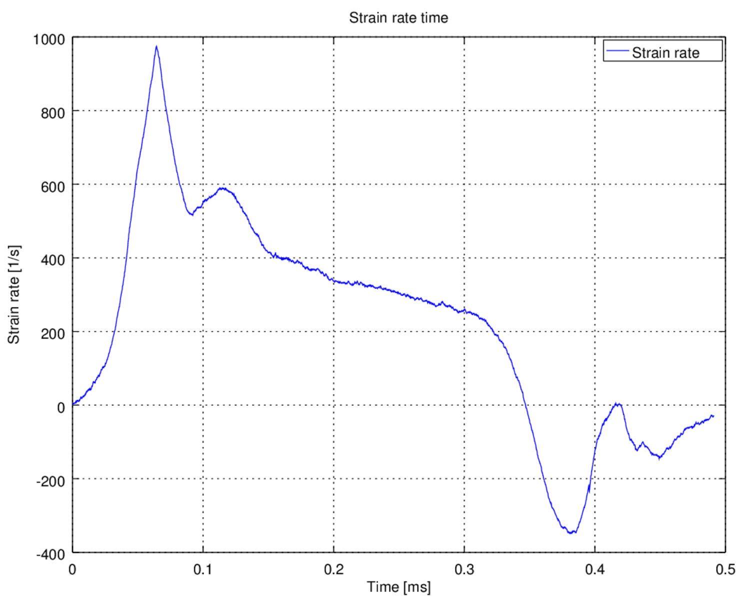

Figure 4.28: CHPB do: Strain rate time.

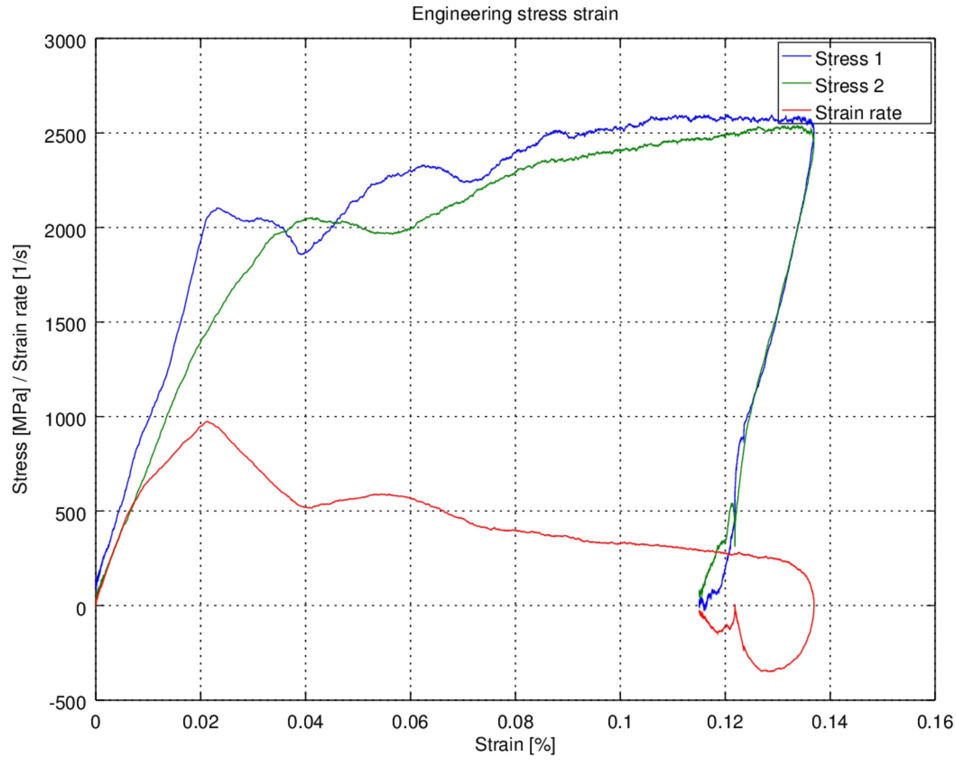

Figure 4.29: CHPB do: Engineering stress strain.

4.4.2 Comparison of results

Direct comparison of the results are made in the Octave file **CHPB plot results.m**. These figures are shown on the following pages for the new Alloy # 1 in figure 4.30 and figure 4.31, for the tempered variant of Alloy # 1T in figure 4.32 and figure 4.33 and for the benchmark material in figure 4.34 and figure 4.35. The direct comparison plot is shown in figure 4.36. The Octave file is included in Appendix D.

The usefulness of high strain rate test data from a compression test can be evaluated by similar questions as asked in section 4.3. Did the impact load deform the specimen with sufficient plastic deformation? Was the loading applied in a steady state manner?

Friction on the ends of the specimen results in a self constricting effect and an increase of cross section. This ever increasing load curve is failure independent and only the plastic behaviour of the material can be studied. All three materials report strain rates between 300 and 700 [1/s] with a clear dynamic oscillation around the start of plastic deformation for almost all except the slowest impact. The tempered Alloy # 1T specimen tested at the highest impact velocity fractured during the test.

The dynamic strength increase as strain rate is increased seems clear in figure 4.36 with Alloy # 1 and the tempered variant of Alloy # 1T almost insensitive and the benchmark material showing incremental increases in hardening. A redesign of the Alloy # 1 specimen could have allowed for testing over a larger strain range and possibly

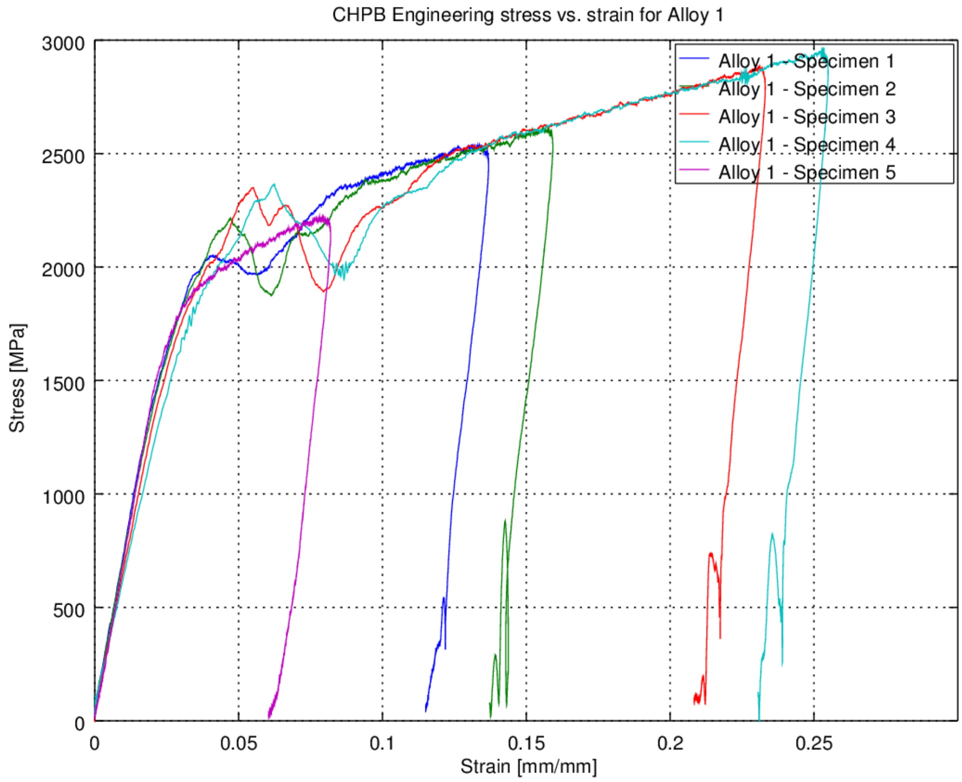

Figure 4.30: Type 5 - Alloy # 1 stress strain comparison [MPa] of 5 specimens each tested at increasing pressures.

increased strain rates. This was discussed with the Damascus Armour Development Consortium as increased stain rates would require a much shorter Taylor bar, with a total length of less than 1m. Instrumentation and data recording costs terminated this avenue of investigation. It should also be noted that the limited amount of Alloy # 1 material also constrained any additional or parallel investigations.

4.4.3 Result clipping

The clipping procedure was performed on the results with the Octave file **Plot all T5.m**. This script read all the result files and cut noisy sections from the first part of the curve. A drop in compression results was simply the end of energy transfer from the incident bar and did not coincide with any material behaviour. This drop was therefore removed from the test data. Each specimen's stress and strain result were saved with a unique identification name and all the type 5 test results were saved into a single file named **Type5.dat**. The Octave file is included in Appendix D.

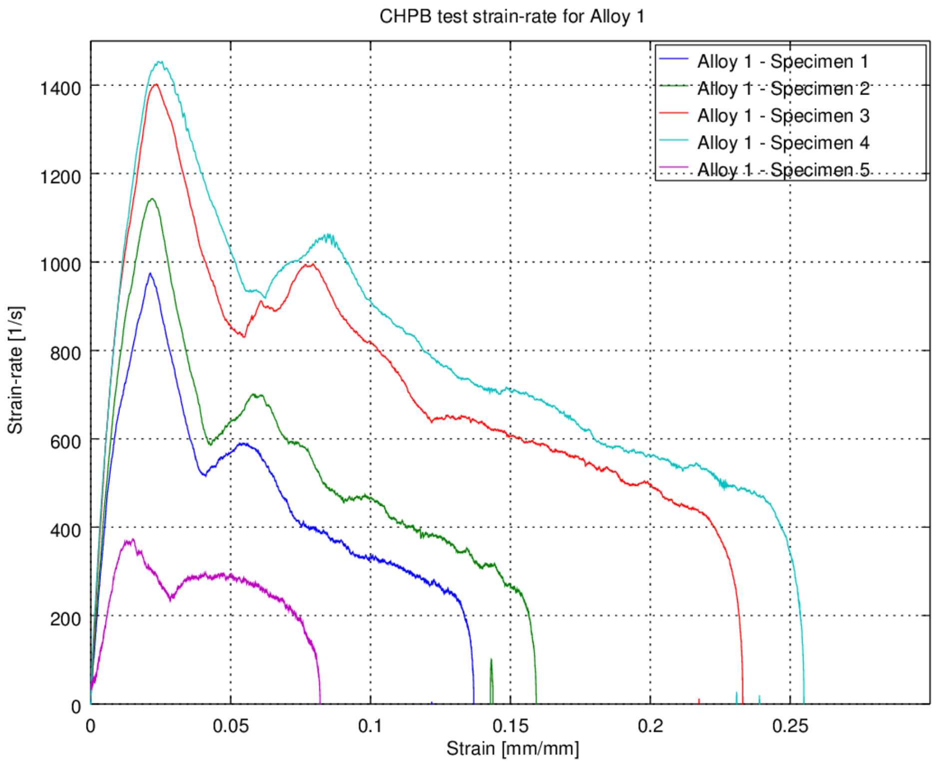

Figure 4.31: Type 5 - Alloy # 1 strain-rate comparison (mm/mm/s) of 5 specimens each tested at increasing pressures.

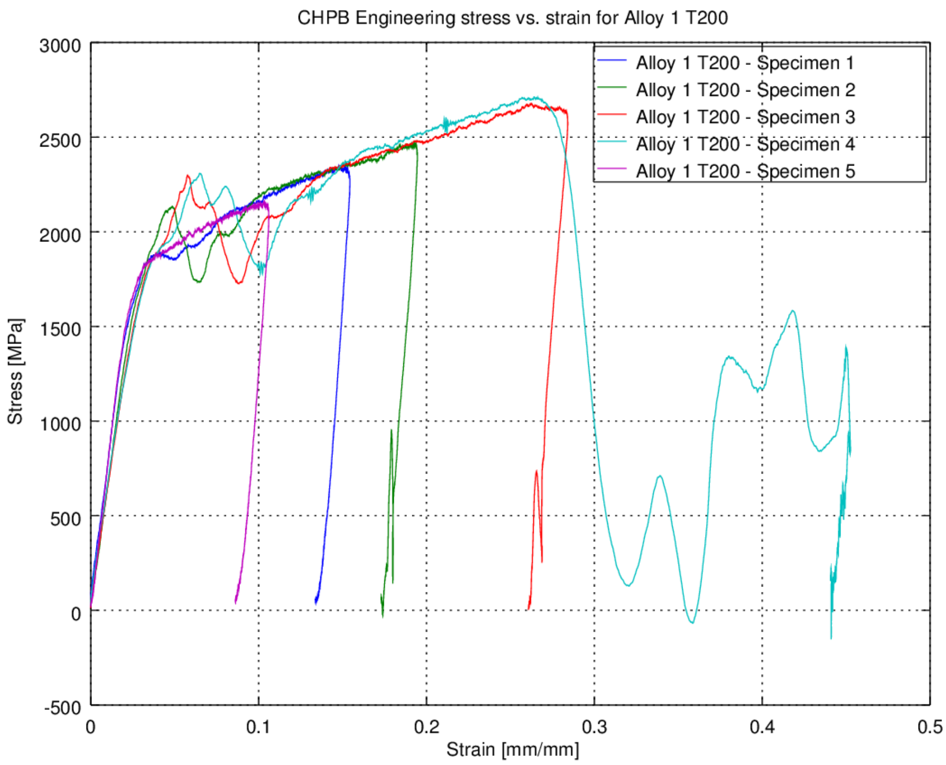

Figure 4.32: Type 5 - Alloy # 1 T200 stress strain comparison [MPa]

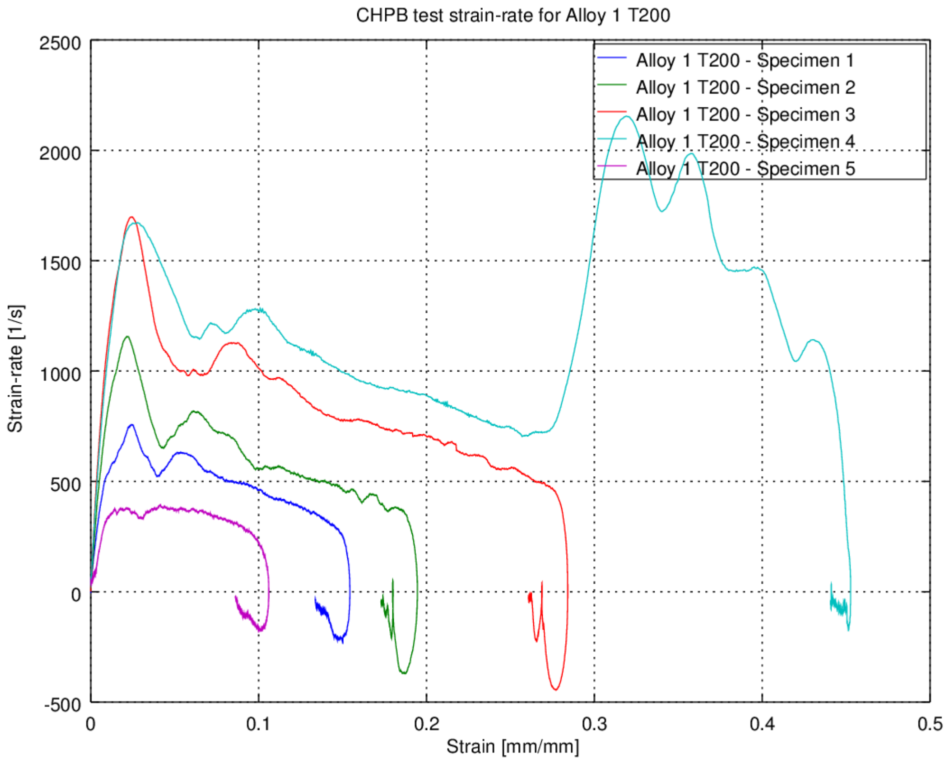

Figure 4.33: Type 5 - Alloy # 1 T200 strain-rate comparison [mm/mm/s]

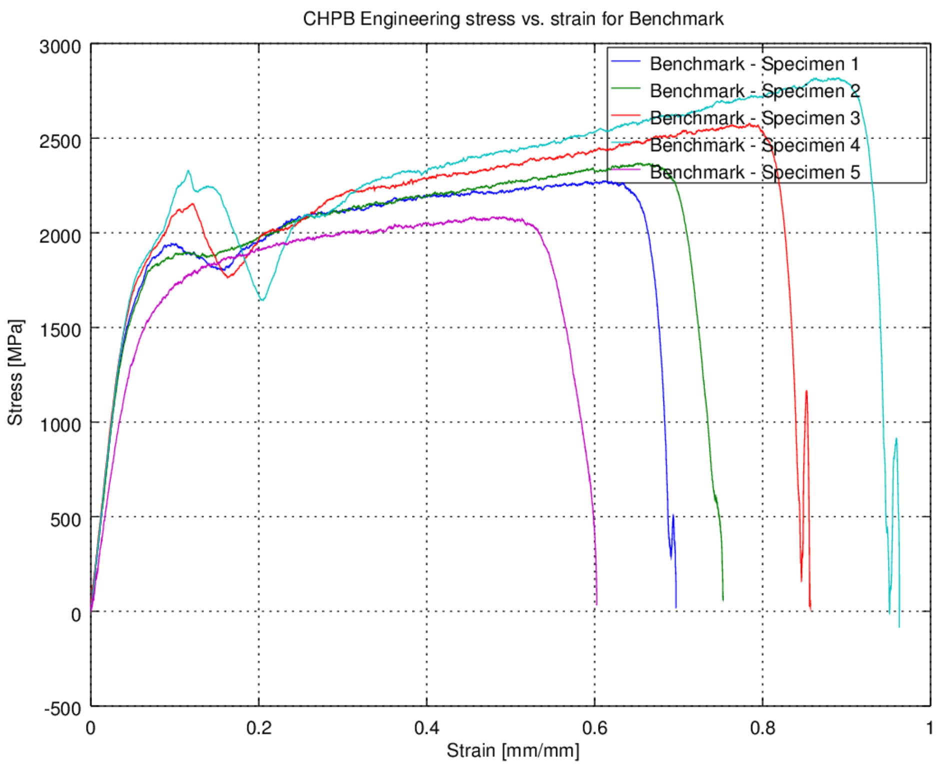

Figure 4.34: Type 5 - Benchmark stress strain comparison [MPa]

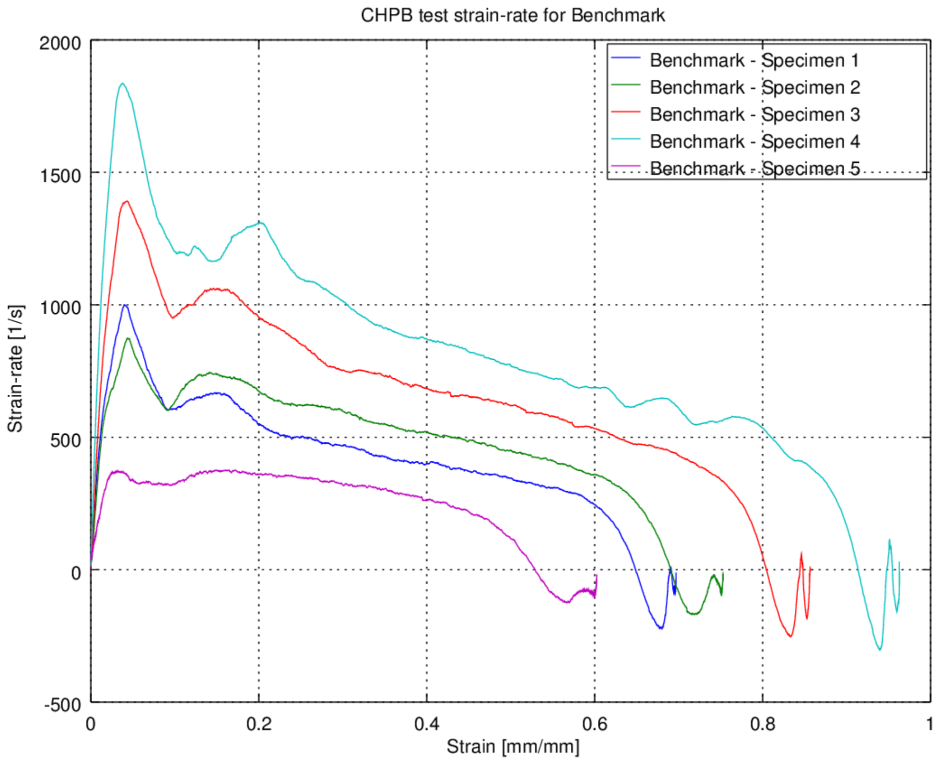

Figure 4.35: Type 5 - Benchmark strain-rate comparison [mm/mm/s]

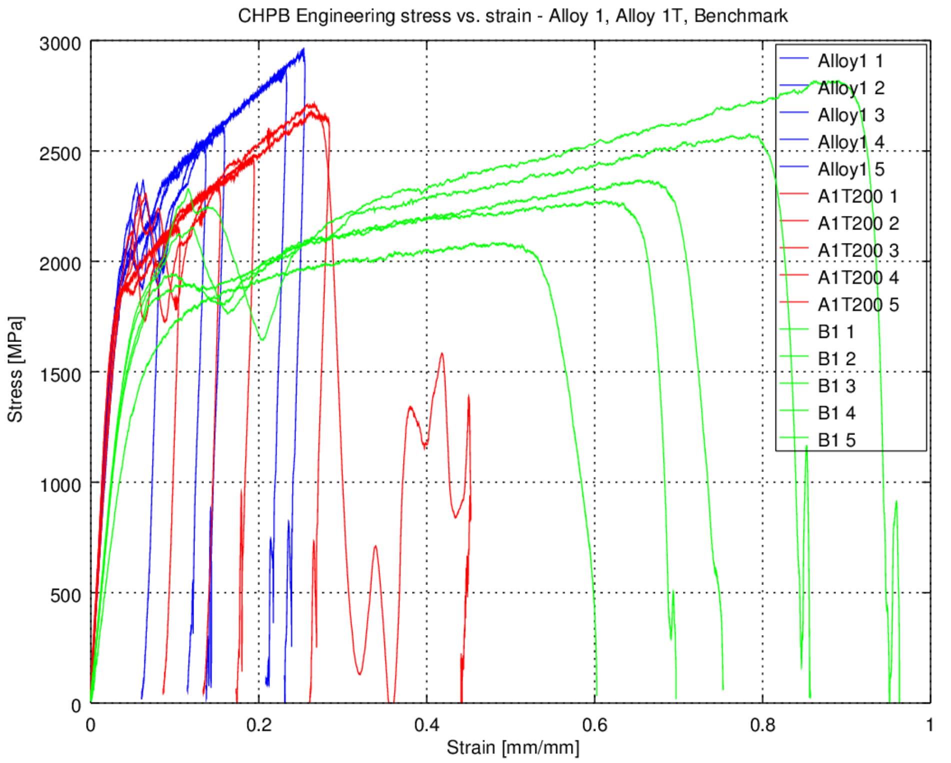

Figure 4.36: Type 5 - Material comparison [MPa]

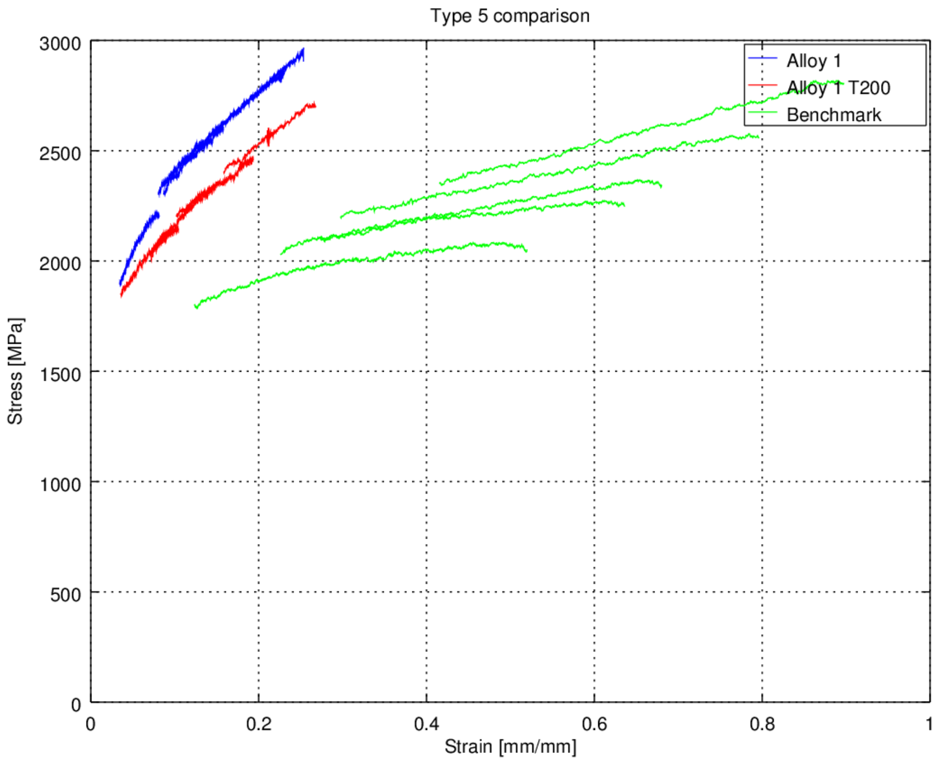

Figure 4.37: Type 5 - Clipped result comparison.

4.5 True fracture strain measurement

A microscopic investigation of the fracture face of all three materials revealed typical ductile behaviour with prominent cut and cone formations as shown in figures 4.39. Four side views of another specimen are shown in figures 4.40 - 4.42. The measurements recorded from these photos along with measurements for the rest of the specimens are summarised in table 4.1 and used to calculate the true fracture strain as follows:

$$\varepsilon_{fr} = \ln \frac{A_0}{A_n} = \ln \frac{d_0^2}{d_n^2} \tag{4.12}$$

With A_0 the initial cross-sectional area, A_n the necked area calculated with the average neck width d_n. Fracture strain values are listed in table 4.1 with material averages as follows:

- Alloy #1 = 0.544
- Alloy #1T = 0.658
- Benchmark = 0.823

Direct comparison of these values to the engineering strain shown in figure 4.20 is not possible. It is however observed that the average fracture strain of the benchmark material is $\sim$ 50% higher than the new alloy.

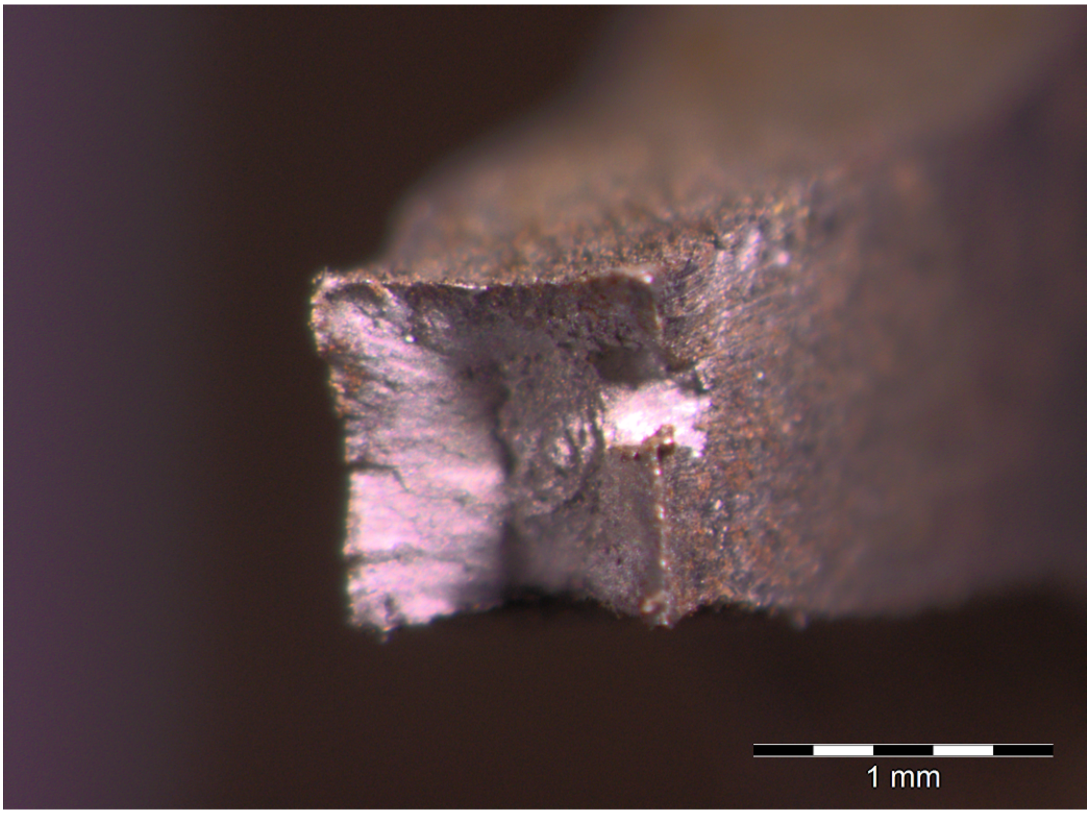

Figure 4.38: Typical fracture face of tenisle specimen.

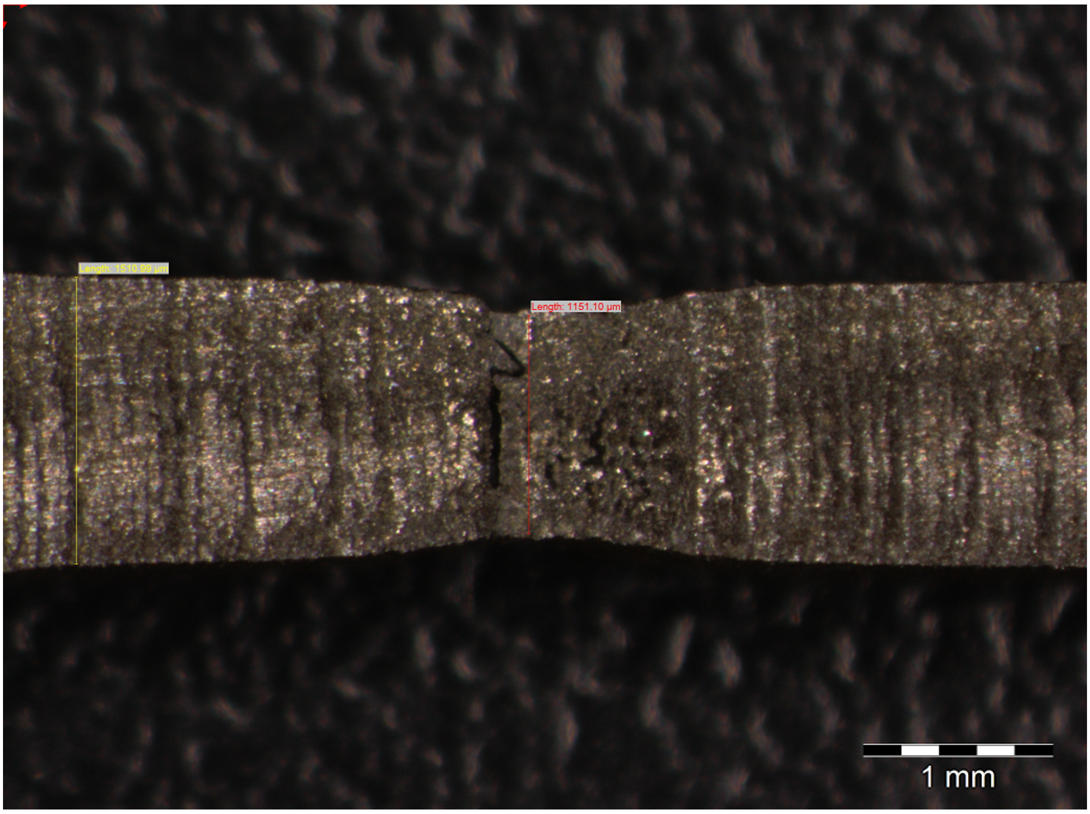

Figure 4.39: Alloy 1 specimen 5 1 Necking view 1/4

Specimen number	Neck dimention [mm]					
	Side 1	Side 2	Side 3	Side 4	Average	Fracture strain
A1 5 1	1.175	1.151	1.151	1.162	1.160	0.515
A1 5 2	1.176	1.201	1.069	1.128	1.144	0.543
A1 5 3	1.221	1.228	1.090	1.069	1.152	0.528
A1 10 1	1.170	1.170	1.083	1.114	1.134	0.559
A1 10 2	1.201	1.221	1.052	1.069	1.136	0.556
A1 10 3	1.156	1.149	1.121	1.097	1.131	0.565
A1T 5 1	1.135	1.151	1.041	1.044	1.093	0.634
A1T 5 2	1.149	1.149	1.031	1.003	1.083	0.651
A1T 5 3	1.118	1.142	1.024	1.048	1.083	0.651
A1T 10 1	1.052	1.104	1.017	1.017	1.048	0.718
A1T 10 2	1.163	1.093	1.038	1.045	1.085	0.648
A1T 10 3	1.152	1.135	1.010	1.045	1.086	0.647
B1 5 1	1.017	1.017	0.903	0.896	0.958	0.896
B1 5 2	1.024	1.010	1.017	0.972	1.006	0.799
B1 5 3	1.017	1.003	0.965	0.986	0.993	0.825
B1 5 4	1.014	1.019	1.014	1.008	1.014	0.784
B1 10 1	1.076	0.990	0.893	0.952	0.978	0.856
B1 10 2	1.024	1.017	0.972	0.986	1.000	0.811
B1 10 3	1.038	1.014	0.997	1.000	1.012	0.787
B1 10 4	1.003	0.965	1.022	0.976	0.992	0.827

Table 4.1: Measured reduction in area true fracture strain.

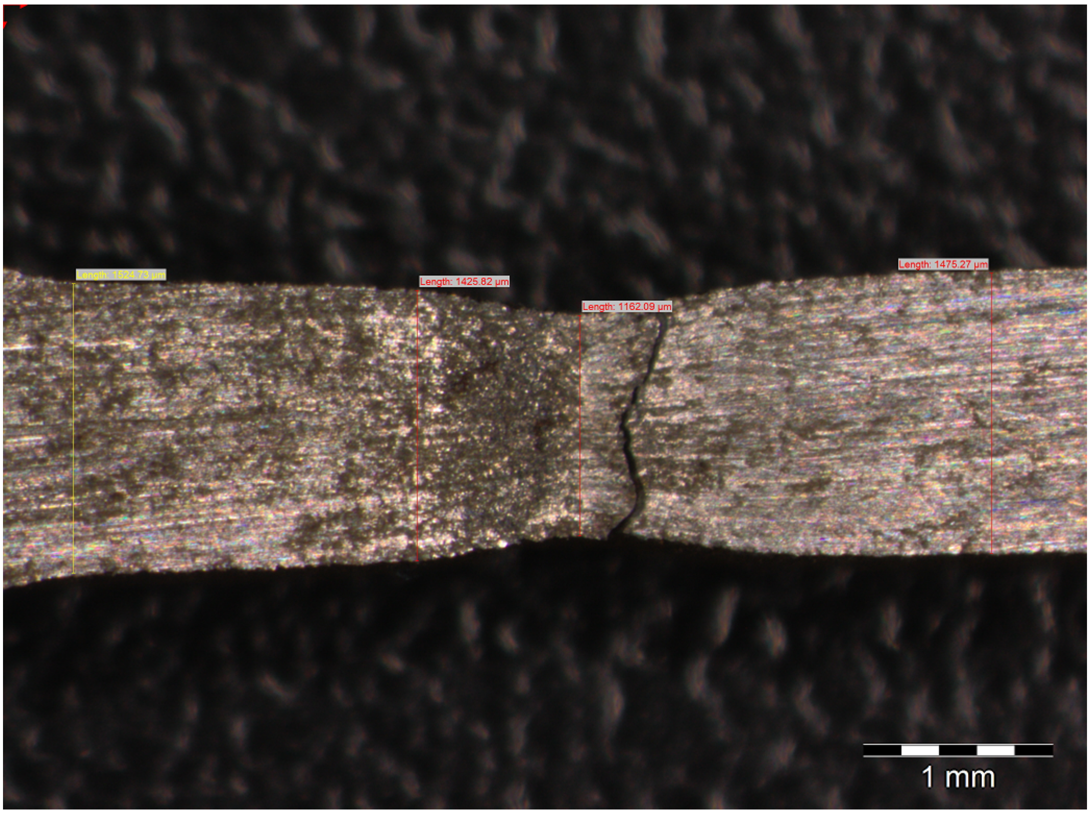

Figure 4.40: Alloy 1 specimen 5 1 Necking view 2/4

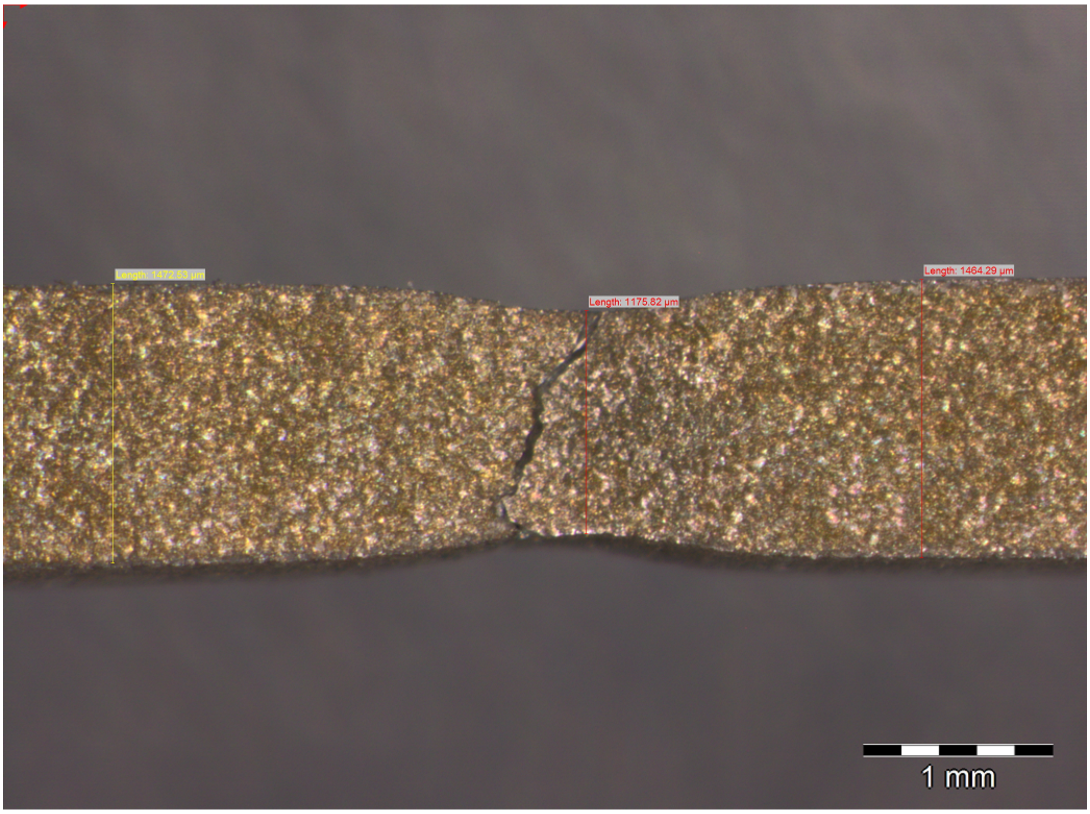

Figure 4.41: Alloy 1 specimen 5 1 Necking view 3/4

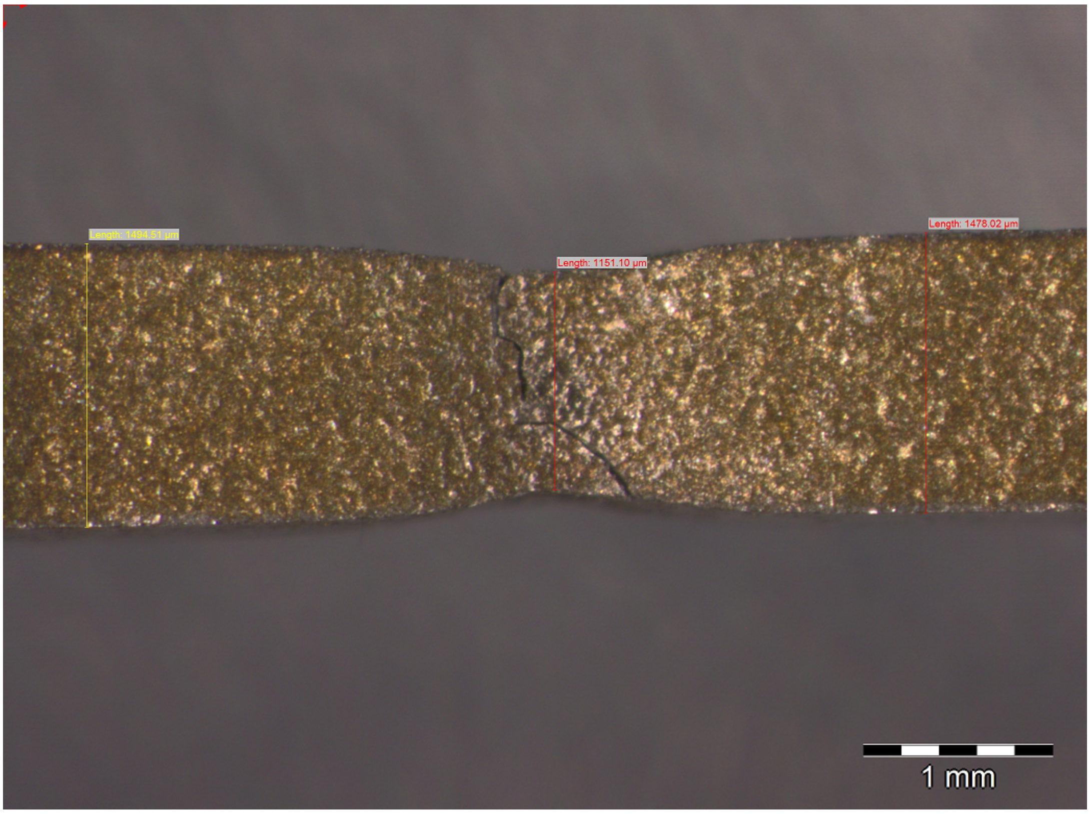

Figure 4.42: Alloy 1 specimen 5 1 Necking view 4/4

4.6 Discussion of results

The high strain rate results for the new Alloy # 1, the tempered variant and the benchmark alloy are summarised in figures 4.20 and 4.36. Alloy # 1 shows a higher strength than the tempered variant with the benchmark reporting the lowest strength. Fracture strain values for the three materials are summarised in table 4.1. The benchmark material reported the highest true fracture strain with the tempered variant ∼ 20% lower and Alloy # 1 ∼ 34% lower.

In both the tensile and compression tests strain rates in the range of 200 - 1000 s^{-1} were observed. This seems to be high enough for adiabatic heating to occur and reveals the high temperature strength of the new alloy as well as retained stability as necking is delayed. Tempering lowers the strength somewhat but seems to have little effect on the fracture strain.

4.6.1 Summary points

The following points summarise the conclusions from this chapter:

- High strain rate tensile results, figure 4.21, show the general trend that Alloy #1 reports higher ultimate strength, followed be the tempered variant and then the benchmark. It should also be noted that the benchmark material tests were performed at higher relative strength specific impact energies and the transient loading effect could not be removed numerically or by retesting with larger specimens. Clipped results therefore only show a small section of the benchmark material strength curve. This is unfortunate as the dynamic ultimate strength of the benchmark material was not recorded.

- Compression test results, figure 4.37, in high strain rate loading reveal that Alloy #1 seems to be insensitive to strain rate effects. This could however not be verified over a larger strain rate range as the increased plastic deformation is tied to the adiabatic heating and possible residual austenite transformation. Dynamic effects are again observed with the benchmark material results.

CHAPTER 5

Numerical material characterisation

This chapter contains the numerical characterisation and comparison between the new Alloy # 1 and the benchmark.

5.1 Introduction

The purpose of this chapter is to fit the Johnson Cook model on the two sets of material test data and to compare the model parameters. Firstly all the test data are presented and discussed. The numerical characterisation procedure is then explained and results presented.

All the material test data are summarised in the following figures (5.1 - 5.4) for the two materials, with a zoomed view of engineering strain <0.2 [mm/mm]. Each test type is identified by the colours defined in table 5.1.

The following observations were made from figures 5.1 and 5.2 for Alloy # 1:

- Prominent work hardening behaviour for the type-1 and type-2 tests.
- Comparatively little plasticity during post-necking for type-1.
- Increasing plasticity during post-necking for type-2.
- Reduction of the engineering fracture strain op to 500°C (type-2).
- Dramatic increase of engineering fracture strain for 600°C - 800°C (type-2).
- Almost no post-necking plasticity for the type-3 tests. Only the reference and 5 mm radius specimen failed past necking.
- No dynamically stable results are available for both the type-4 and type-5 tests in the work hardening strain range.

- Only a small increase in strength at high strain-rates.
- Increased plasticity post-necking for type-4.
- Short sections are reported for the type-5 tests. The range of dynamically stable results related directly to the input energy of the test. This also affects the strain rate of the tests and effectively constrains the results.

Similar observations were made from figure 5.3 and 5.4 for the benchmark material.

- No type-1 test specimens where available at the time of testing. The two reference specimens from the type-3 tests are used in the numerical material characterisation.
- The work hardening behaviour is less conspicuous for the benchmark material for the type-1 and type-2 tests.
- Lower ultimate tensile strength values are reported.
- The post-necking plasticity is comparatively large and represents more than 50% of the plastic range.
- Reduction of the engineering fracture strain op to 400°C (type-2).
- Dramatic increase of engineering fracture strain for 500°C - 800°C (type-2).
- Clear post-necking plasticity for almost all type-3 tests. Only the 0.15 mm radius specimen failed before necking.
- No dynamically stable results are available for both the type-4 and type-5 tests before necking.
- Clear strength increase is seen in the type-5 tests as the strain-rate is increased. It should also be noted that similar pressure values were used for both materials in the type-5 tests. The dramatic increase in reported engineering strain observed for the benchmark material indicates a lower total energy absorption capacity as a similar amount of kinetic energy was applied to alloy #1 and resulted in less plastic deformation.

5.2 Characterisation procedure

The numerical material characterisation procedure is presented in the following simplified example. Each component is introduced and used in a simple error calculation before the optimisation procedure is discussed. The example code (Eval 0.m) is included below and discussed in detail.

Test type #	Description	Colour
Type-1	Quasi-static room temperature tensile test	Cyan
Type-2	Quasi-static high temperature tensile test	Red
Type-3	Quasi-static room temperature notched tensile test	Black
Type-4	High strain-rate room temperature tensile test	Green
Type-5	High strain-rate room temperature compression test	Magenta

Table 5.1: Test type colour identification

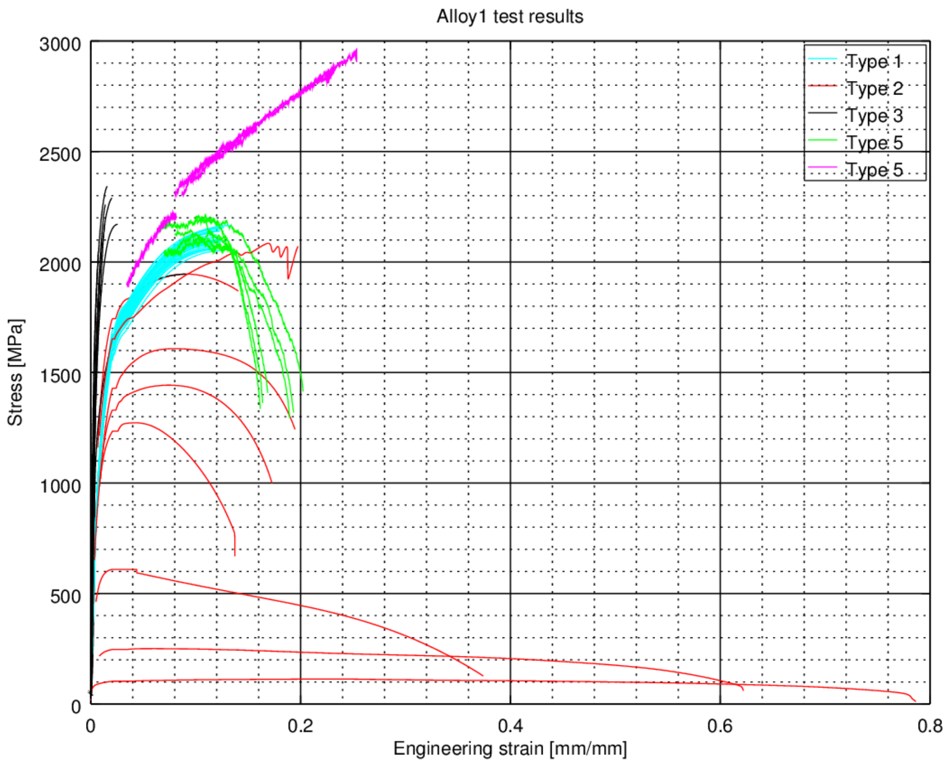

Figure 5.1: All Alloy #1 test results.

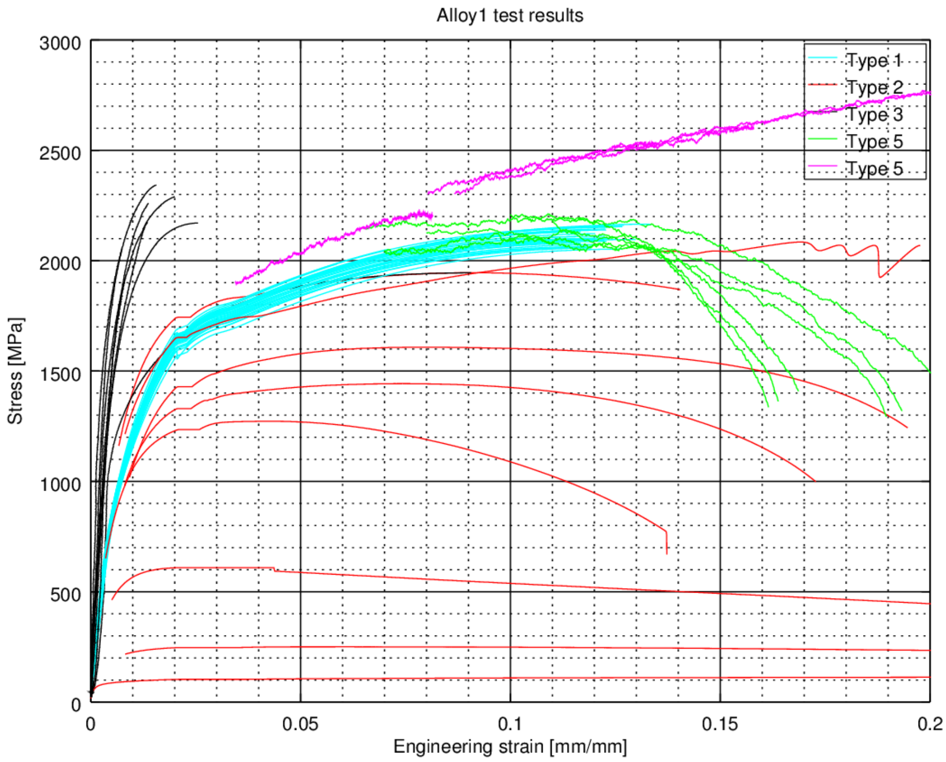

Figure 5.2: All Alloy #1 test results - Zoomed view

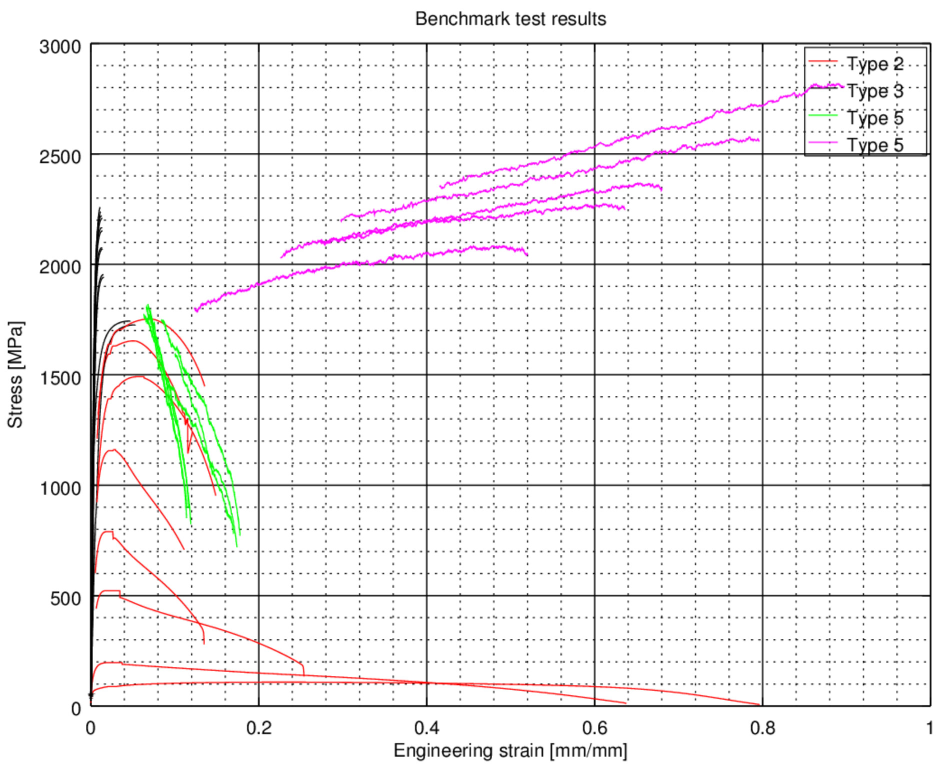

Figure 5.3: All Benchmark test results.

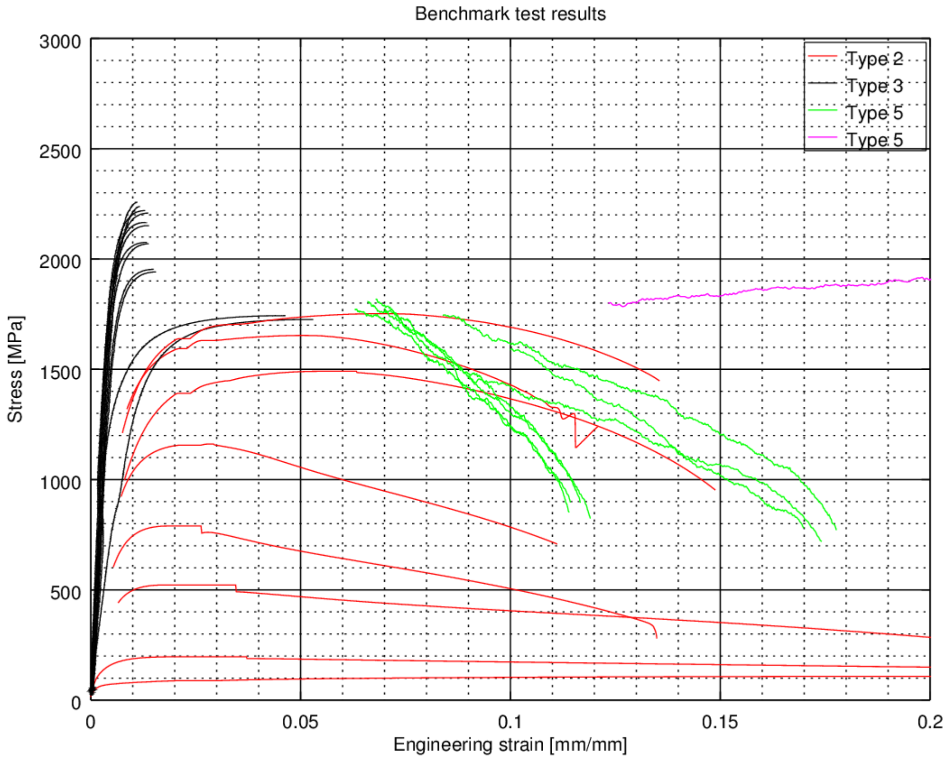

Figure 5.4: All Benchmark test results - Zoomed view

A few data points (figure 5.5) are used as the test data set and reasonable initial material parameters for equation 5.1, defines the start condition. The aim of the evaluation algorithm (Eval 0.m) is to calculate the error between stress values of the data points and the predicted analytical stress values calculated with equation 5.1.

$$\sigma = A + B\varepsilon^n \tag{5.1}$$

Eval 0.m is defined as a function in the Octave environment and requires the input MatProp, a [3 x 1] vector defining the three material parameters, A, B and n. A normalisation correction is performed for the first two parameters and the data set is explicitly defined (line 11). The strain range is generated (line 13) and equation 5.1 is used to calculate the analytical test values (line 16). A total root mean square error is calculated with equation 5.2 and returned as the standard function out. In the last section of the function a figure of the fixed data and the analytical curve is plotted. This plot is updated every time the function is called. The initial value plot is shown in figure 5.5.

$$Error = \sqrt{\frac{\sum_0^N (\sigma_{data_i} - \sigma_{analytical_i})^2}{N}} \tag{5.2}$$

Eval 0.m:

```
1 function Error = Eval_0(MatProp)
```

```

% This script evaluates the stress curve calculated with
% MatProp values and calculates the RMS error using the
% fixed data points.

A = MatProp(1)*1000;
B = MatProp(2)*1000;
n = MatProp(3);

Data_stress = [1600 1800 1950 2025 2075 2100];

Strain = linspace(0.02,0.12,6);
Stress = zeros(1,length(Strain));

Stress = A .+ B .*Strain.^n;

Error = sqrt((sum(Data_stress .- Stress).^2)/(6))

figure(1)
plot(Strain,Data_stress,"bd",Strain,Stress,"k")
axis([0 0.14 0 2500])
title("Data points with Johnson Cook curve");
xlabel("Engineering strain [mm/mm]");
ylabel("Engineerin stress [MPa]");
grid on
drawnow

fflush(stdout);
```

The basic components required to complete the numerical procedure have been addressed and can be summarised as follows:

1. The evaluation algorithm [Eval]
2. Material parameter values vector [MatProp]
3. Evaluation error scalar [Error]
4. Experimental data [Test Data]

These components are defined in the optimisation flow diagram shown in figure 5.6 with the test data component simply read into the evaluation algorithm as a second input. One additional component required in a minimisation scheme, the minimiser, is

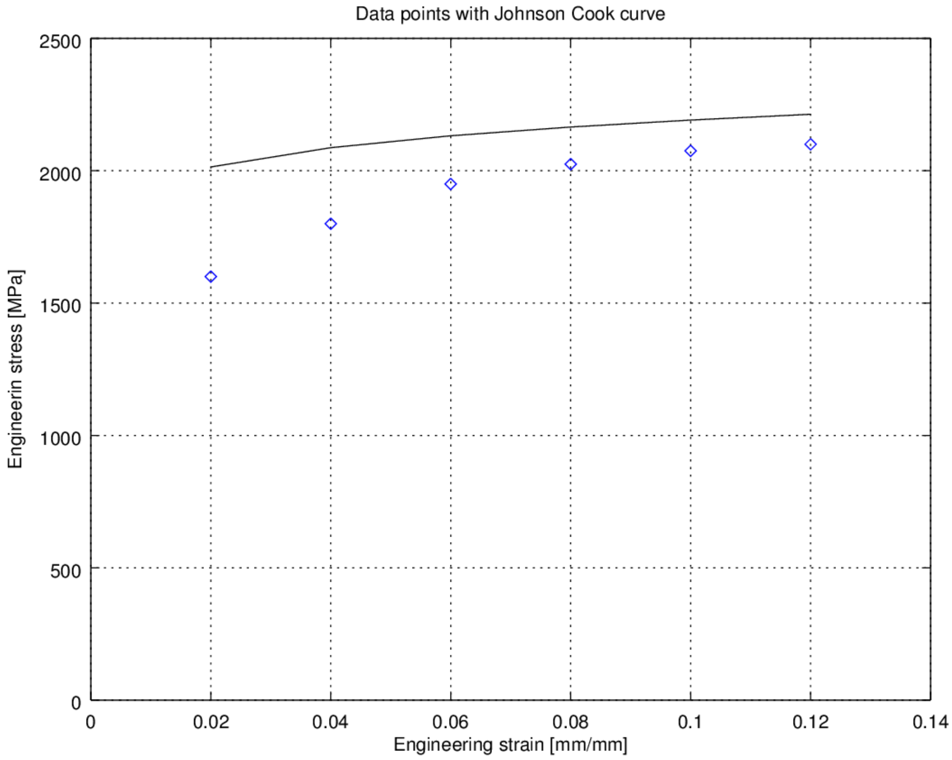

Figure 5.5: Initial Johnson-Cook curve with data points.

Fmin. The purpose of the minimiser is to modify the MatProp variable vector to move the analytical line closer to the data points. For this data set and the full set of measured material results, the internal Octave function **fminsearch.m** was used. This function iterates input values using the Nelder & Mead Simplex algorithm to minimise the output and is well suited to functions with discontinuities.

With the optimisation procedure defined and each component identified, the execution can be discussed. The characterisation is typically initialised by another small script **A1 run 0.m** shown below, and best illustrated by the terminal display of the Error value as the procedure iterates, also included below. The error value is displayed every time the evaluation algorithm is called. The minimiser iterates 92 times with large initial fluctuations as the problem is explored and finally converges. Converged material parameters are reported in line 93 with the updated plot in figure 5.7.

A1 run 0.m:

```
% This script is used to define initial values,
% and to call the optimization algorithm fminsearch:

x=[1 1.5 0.1]
x = fminsearch('Eval_0',x)
print(1,'Eval_min.png','-dpng')
```

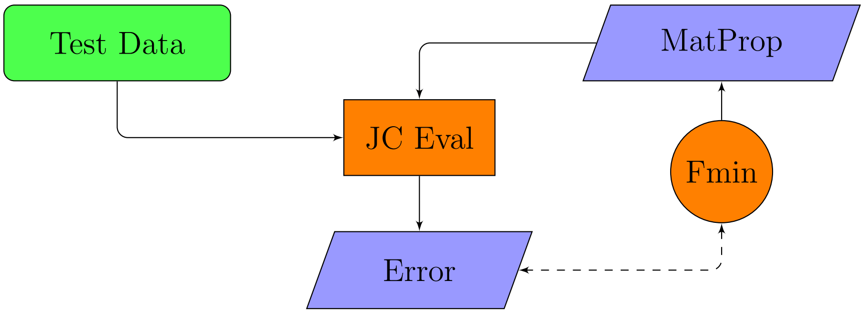

Figure 5.6: Optimisation flow diagram

```
>> A1_run_0_0
x = 1.00000 1.50000 0.10000
Error = 511.86
Error = 2509.9
Error = 662.31
Error = 1311.1
Error = 4092.9
Error = 775.82
Error = 5.5634e+004
Error = 958.76
Error = 680.98
Error = 429.59
Error = 1362.5
Error = 1.0701e+004
Error = 779.72
Error = 403.58
Error = 528.57
Error = 660.53
Error = 2997.5
Error = 217.00
Error = 152.90
Error = 441.10
Error = 491.60
Error = 200.30
Error = 260.06
Error = 184.94
Error = 88.741
Error = 213.47
Error = 319.42
Error = 50.808
Error = 216.08
Error = 98.805
Error = 176.94
Error = 69.566
Error = 159.57
Error = 38.617
Error = 135.91
Error = 35.760
Error = 100.93
Error = 26.819
Error = 70.171
Error = 20.359
Error = 60.808
Error = 14.602
Error = 51.360
Error = 14.530
Error = 40.307
Error = 10.033
Error = 27.161
Error = 8.4912
Error = 23.736
Error = 5.1692
Error = 19.266
Error = 6.1732
Error = 16.365
Error = 3.4348
Error = 10.141
Error = 3.8415
Error = 9.3968
Error = 2.2936
Error = 7.0342
Error = 2.1414
Error = 6.0313
Error = 1.3736
Error = 4.4514
Error = 1.4633
Error = 3.7895
Error = 0.77519
Error = 2.6080
Error = 0.95747
Error = 2.2572
Error = 0.53312
Error = 1.8503
Error = 0.56750
Error = 1.4991
Error = 0.34393
Error = 0.98284
Error = 0.33613
Error = 0.92814
Error = 0.19360
Error = 0.65697
Error = 0.23559
Error = 0.54032
Error = 0.12296
Error = 0.44629
Error = 0.14059
Error = 0.37641
Error = 0.082594
Error = 0.23692
Error = 0.085971
Error = 0.22035
Error = 0.050366
x = 1.36133 1.49360 0.35383
```

This flow diagram forms the basis of the full numerical characterisation procedure. Any number of data test sets could be called by the evaluation algorithm and compared to the material model.

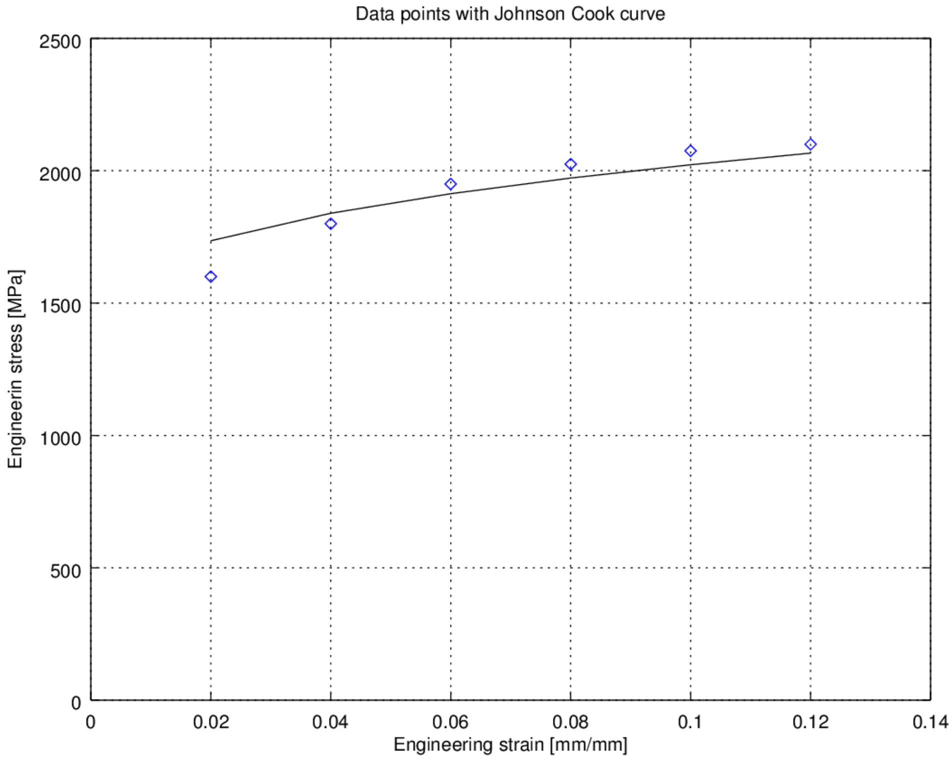

Figure 5.7: Converged Johnson-Cook curve with data points.

5.3 Analytical characterisation results

The complete Johnson-Cook plasticity model [13] as shown in equations 5.3 - 5.5, was implemented in the full numerical characterisation procedure. An external function was used for the Johnson-Cook plasticity calculation and simply lengthened the material parameter values vector to [5 x 1]. The minimiser **Fminsearch.m** remained unaffected, iteration solving time required was however slightly lengthened and the total number of iterations increased greatly.

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon^*}][1 - T^{*m}] \tag{5.3}$$

with,

$$T^* = \frac{T - T_{Room}}{T_{Melt} - T_{Room}} \tag{5.4}$$

$$\dot{\varepsilon^*} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \tag{5.5}$$

One additional challenge was the fluctuation of strain range for the measured data between tests and even between specimens. Almost all the test results end at other fracture points and the high strain-rate tests only start after a while. Calculating errors with corresponding analytical values is essential and was ensured by interpolating the analytical strain range to the measured strain range for every curve.

Reference strain-rates and temperatures were explicitly defined for the various curves used in the evaluation algorithm. The specific test data curve, interpolation range and error calculation were manually modified with every change of input set.

The minimiser function as many others, requires initial values to be close enough to the required solution to avoid divergence. Various evaluation algorithms were investigated with only the most basic sets allowing successful convergence. This difficulty might indicate that the Johnson-Cook material model alone could be insufficient to fully capture the whole range of material behaviour. On the other hand it might also indicate that the measured results are incomplete for an adequate representation over the entire range of variables. Shortcomings as discussed in the aforementioned sections indicate that this could be the major contributor.

The broad range of material tests over temperature and strain rate and stress tri-axiality, resulted in a fairly challenging characterisation problem. One major limitation in using an analytical solution was that results of post-necking could not be used. Result data files as defined in sections 3.2, 3.3, 3.4, 4.3 and 4.4 were modified to remove all post-necking results. This eliminated the entire high strain-rate tensile test set for the benchmark material and large sections of other result curves. It should also be noted that the tri-axiality results only influence the fracture strain portion of the Johnson-Cook material model and were excluded.

Some of the successful Octave evaluation files as well as convergence report files are included in Appendix E. The report files consist of the material parameters for every iteration with the current error value included after the last parameter and marked between two vertical bars as |Error |.

5.3.1 Model characterisation results

The converged results of three evaluation algorithms are discussed in this section. Firstly the new Alloy # 1 with quasi-static, high temperature and high strain-rate compression test results, type 1, 2 and 5, are shown in figure 5.8. Secondly the benchmark material, also with test results type 1, 2 and 5 in figure 5.9, and lastly the benchmark material with only type 1 and 2 are shown in figure 5.10. Root mean square errors for the three converged evaluation algorithms are respectively, 79 MPa, 144 MPa and 137 MPa. The five Johnson-Cook material parameters, A, B, n, C, and m are summarised in table 5.2.

Direct comparison of the material parameters in table 5.2 reveal some of the plastic behaviour characteristics:

- A direct comparison between Alloy # 1 and the benchmark material for high strain-rate and high temperature can only be made with the first fit. Comparable values are shown for both materials. The characterisation procedure seems to be accurate enough to distinguish the material type behaviour.

- The basic plasticity parameters for Alloy # 1 report the yield strength as 614.7 MPa and the true necking strain as 0.23.
- For the benchmark fit 1, with the yield strength of 1641 MPa, seems appropriate. The true fracture strain of 1.36 is however completely unrealistic.
- Benchmark fit 2 predicts a negative yield strength value and is clearly inappropriate.
- The negative strain-rate parameter C for benchmark fit 2, is simply due to the lack of any results over the variable.

	A	B	n	C	m
Alloy # 1	614.700	2629.249	0.238801	0.018676	1.183291
Benchmark fit 1	1641.709	960.119	1.365485	0.016927	0.907908
Benchmark fit 2	-2449.186	5121.717	0.051305	-4.210536	0.918130

Table 5.2: Summary of converged material parameters

The following observations were made for the new Alloy # 1 from figure 5.8:

- The prominent work hardening behaviour of the measured data is followed by the fitted curves.
- A reasonable fit is shown for both the quasi-static and high temperature tests.
- High temperature softening is observed in the fitted curves with some under-approximation at the highest temperatures.
- The fairly accurate representation of the measured data under 0.02 [mm/mm] is replaced by a clear overestimation as the engineering strain increases. The levelling off noticed in the test data can not be approximated by the Johnson-Cook plasticity model.

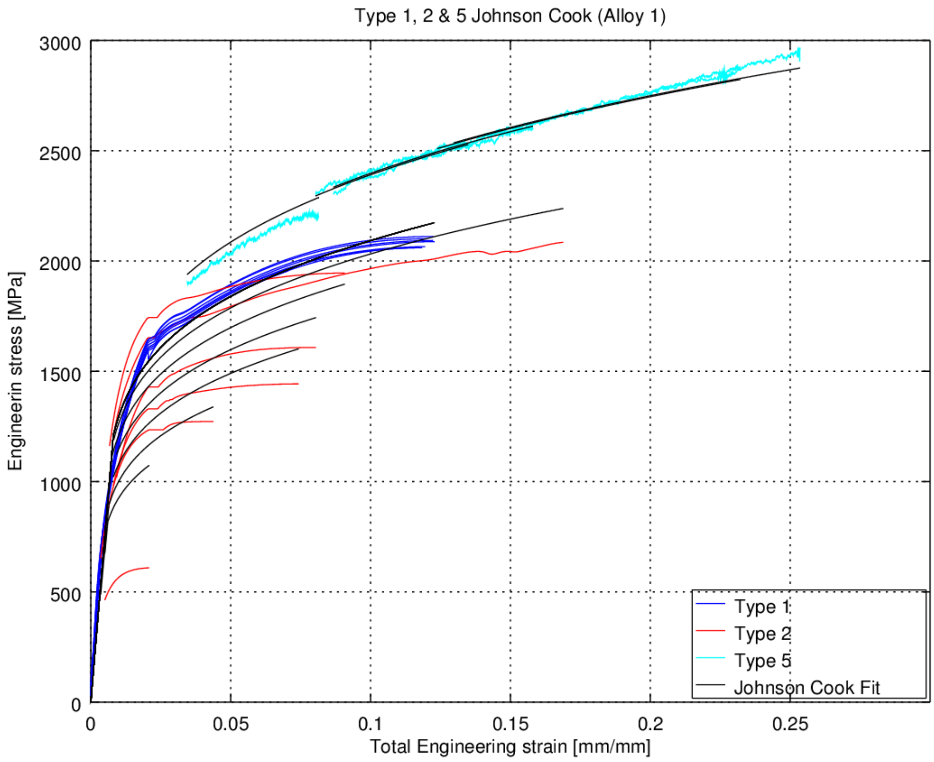

Figure 5.8: Johnson-Cook fit for Alloy # 1

Material characterisation of the benchmark alloy was considerably more challenging due to the comparatively poorly scaled material test results. This is clearly illustrated below. Some observations are firstly made on the results in figure 5.9:

- An unexpected concave plastic behaviour.
- No clear strain-rate differentiation for the high strain-rate variation.
- An almost linear representation of the initial plasticity.

These observations were made from figure 5.10:

- Reasonable fit for the quasi-static test data.
- High temperature softening in the fitted curves with some under-approximation at the highest temperatures.
- The representation of the measured data under 0.02 [mm/mm] is replaced by a clear overestimation as the engineering strain increases. The levelling off noticed in test data can not be approximated by the Johnson-Cook plasticity model.

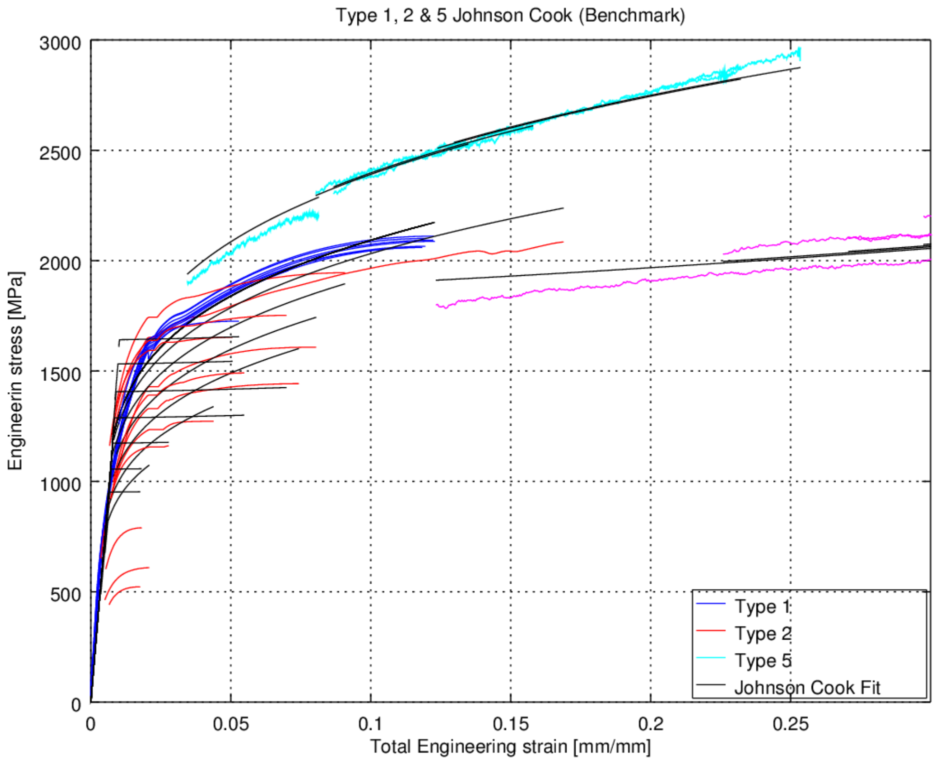

Figure 5.9: Johnson-Cook fit 1 for the Benchmark steel

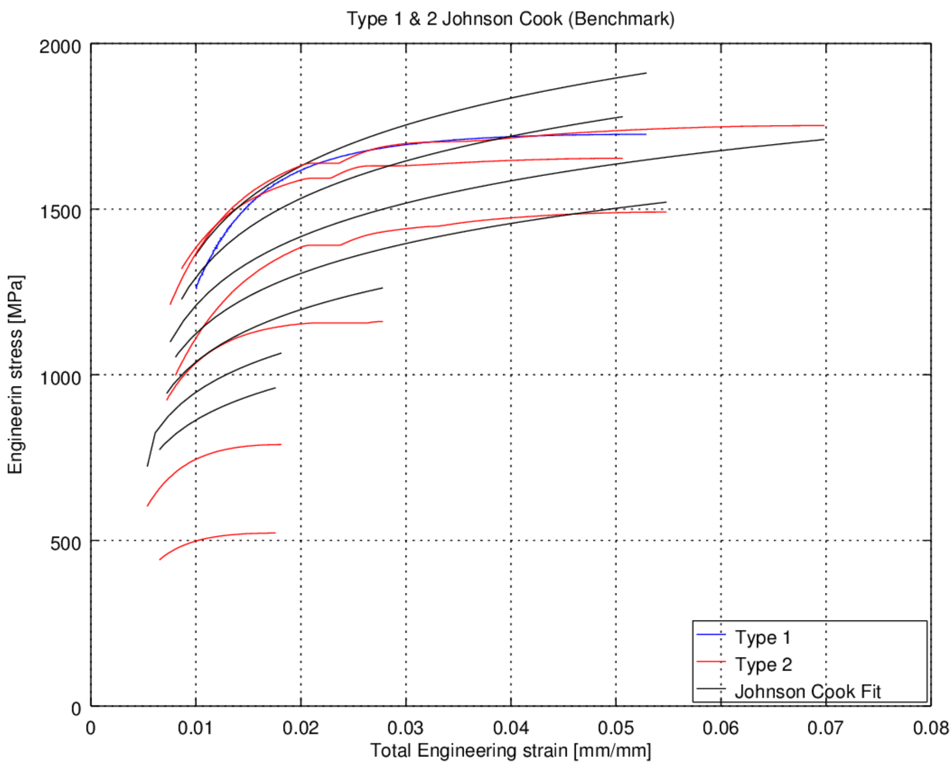

Figure 5.10: Johnson-Cook fit 2 for the Benchmark steel

5.4 Conclusion

The validity and accuracy of the numerical material characterisation results are assessed by direct comparison with four other published steel alloy groups. A bainitic steel T24, two dual-phase steels DP500 and DP700, a high strength weldable steel Weldox 460e and two armour steel alloys, Armox 500T and Armox 600T are included in table 5.3. Ballistic performance potential is defined by the A/B parameter calculated in the second last column as it approximates the ratio of yield strength to ultimate tensile strength (YS/UTS) discussed in section 2.1.

Material	A	B	n	C	m	A/B	Citation
Alloy #1	615	2629	0.239	0.01868	1.183	0.234	-
Benchmark fit 1	1642	960	1.365	0.01693	0.908	1.710	-
T24 steel (High T)	100	78	0.274	0.08000	0.585	1.282	[96]
DP500	470	703	0.700	0.01900	1.20	0.669	[97]
DP700	699	740	0.780	0.00900	1.50	0.945	[97]
Weldox 460 E	490	807	0.730	0.01200	0.94	0.607	[98]
Armox 500T	849	1340	0.092	0.00541	0.87	0.634	[99]
Armox 600T	944	1700	0.119	0.00962	0.805	0.555	[99]

Table 5.3: Summary of converged material parameters

General comparison of the Johnson-Cook material properties show that most of the parameters fall within the same order of magnitude. This is expected as this high alloy steel should compare well with other high alloy steels. Alloy #1 seem to relate better than the benchmark steel, as the work hardening exponent n for the benchmark seems unrealistically high. This might be expected as a limited number of tests were used for the bechmark material characterisation. The normalised temperature exponent m seem to vary by alloy group.

The historical ballistic performance parameter, hardness, is still in widespread use, and may be approximated by B. This arranges the new Alloy #1 at the top of the list and suggests a ballistic performance better that Armox 600T. A refined ballistic performance parameter, the ratio of yield strength to ultimate tensile strength (YS/UTS), is aproximated by A/B. This measure also indicated that the new Alloy #1 might out perform Armox 600T.

Both of these results could be inaccurate as they are based on only one aspect of the total energy absorption potential of the material. Hardness relates to the UTS of a material and thus defines the maximum applied load a certain component might be able to resist. The the ratio of yield strength to ultimate tensile strength (YS/UTS) as a ballistic parameter indicates the amount of work hardening a material might develop during deformation. This implies a certain amount of work due to plastic deformation. A complete ballistic performance parameter should include the work hardening of the material as well as some measure of the amount of energy absorbed during localisation and failure. Total plastic deformation energy at high enough strain rates might be a complete ballistic performance parameter.

It should be noted that in addition to the apparent difficulty in fitting the Johnson-Cook material model, the majority of high strain rate test results were captured in the post-necking range of the test. This wealth of data can only be included in the evaluation procedure by simulating each test in an explicit finite element model with adiabatic heat generation. Various other material models should be considered by comparing total RMS error values. This inverse finite element model procedure could use the high strain rate test alone to characterise the material model for ballistic performance.

Such a rigorous finite element based fit error evaluation procedure is beyond the scope of this study and would however, require significant additional time. It should also be noted that the second half of the mechanical impact problem, the soft projectile interaction with the target, is critical to a rigorous and complete solution. This remains a challenging simulation problem as the fluid structure interaction should be sensitive to phase changes, surface texture and all the failure modes of both the projectile and target.

CHAPTER 6

Ballistic characterisation

This chapter contains the ballistic characterisation of Alloy # 1. The ballistic test equipment and capabilities are described followed by the evaluation procedure and practical limitations and is followed by a summary of the results and a few observations.

6.1 Introduction

The purpose of this part of the investigation is an improved understanding of the ballistic performance of experimental alloy # 1 and how this relates to the observed constants found from the strain rate tests. Two benchmark materials of hardness grades 500 and 600 and a 200° C tempered variant of alloy # 1 are also included.

Standardized ballistic acceptance criteria simply classify a system or component as acceptable or unacceptable for a specific threat. The margin or factor of safety and variation around any value can only be defined with repeated tests and statistical analysis. A complete ballistic performance map of the material with statistical variation would be prohibitively expensive, it was therefore proposed that an extended V_{50} method be used.

The V_{50} ballistic limit, or the 50 % probability of perforation, was determined at various plate thicknesses for each of the materials. Each V_{50} average value consists of as many impacts as practically possible.

This study includes two projectile types, 37 test plates and more than 650 test shots performed over a 4 month period.

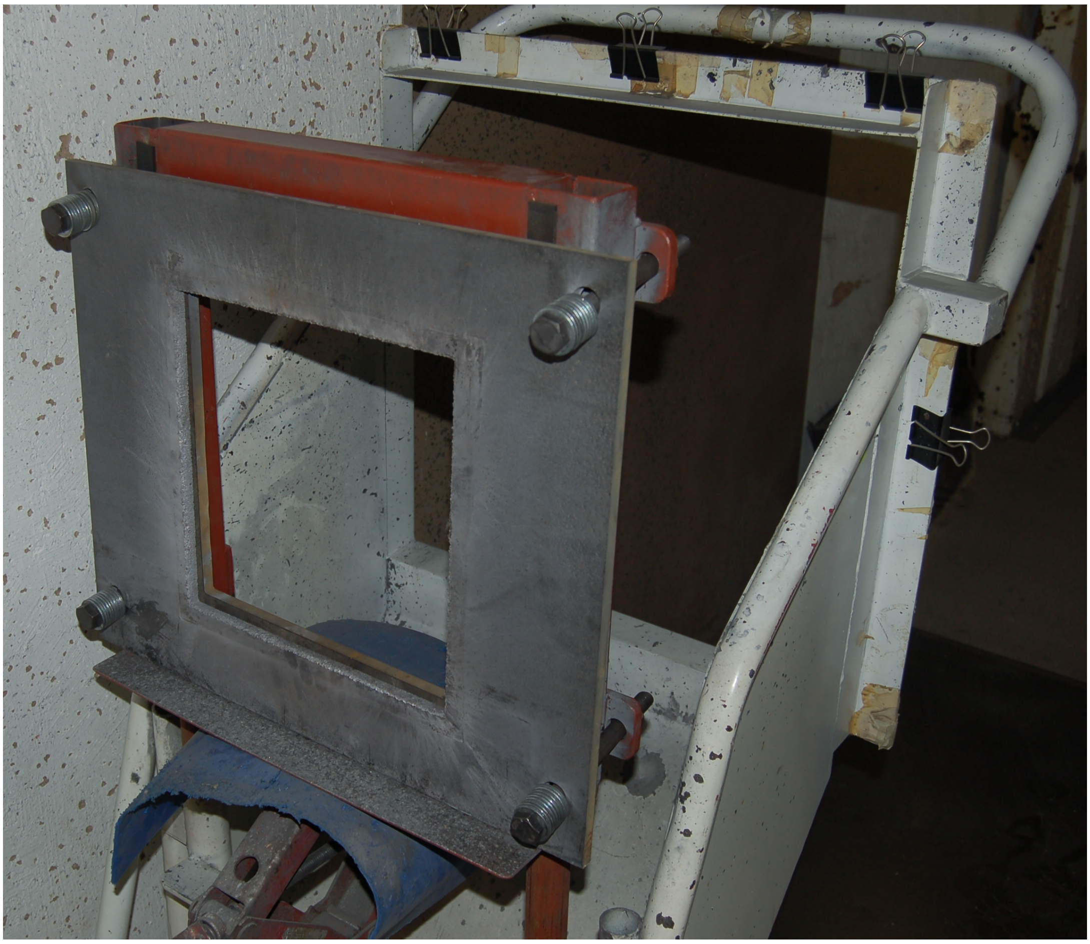

Figure 6.1: Plate test frame.

6.2 Ballistic test equipment

The unique ballistic testing capability of the SABS Ballistic Laboratory is shown in this section. All the laboratory equipment used for this investigation was photographed and discussed. A short summary of the velocity range for two calibre rounds is shown.

6.2.1 Ballistic laboratory equipment

A standard glass panel test frame was modified slightly by replacing the clamp brackets with a single clamp plate. Two locating plates are positioned behind the clamp plate and bolted onto the support frame with 4 x M16 bolts, figure 6.1. During testing the test plate is slid into position from the top and the bolts are hand tightened.

A typical test plate is seen clamped into the test frame in Figures 6.2 to 6.4 before and after the test. The equipment used during the test is seen in Figures 6.5 to 6.14. As the cartridge charge is continuously varied during the test, the round is therefore only loaded right before the shot is taken. Accurate velocity and propellant measurement is therefore essential (Figures 6.5 to 6.8). The testing range is equipped with a remotely triggered pneumatic firing mechanism and interchangeable high pressure barrels (Figures

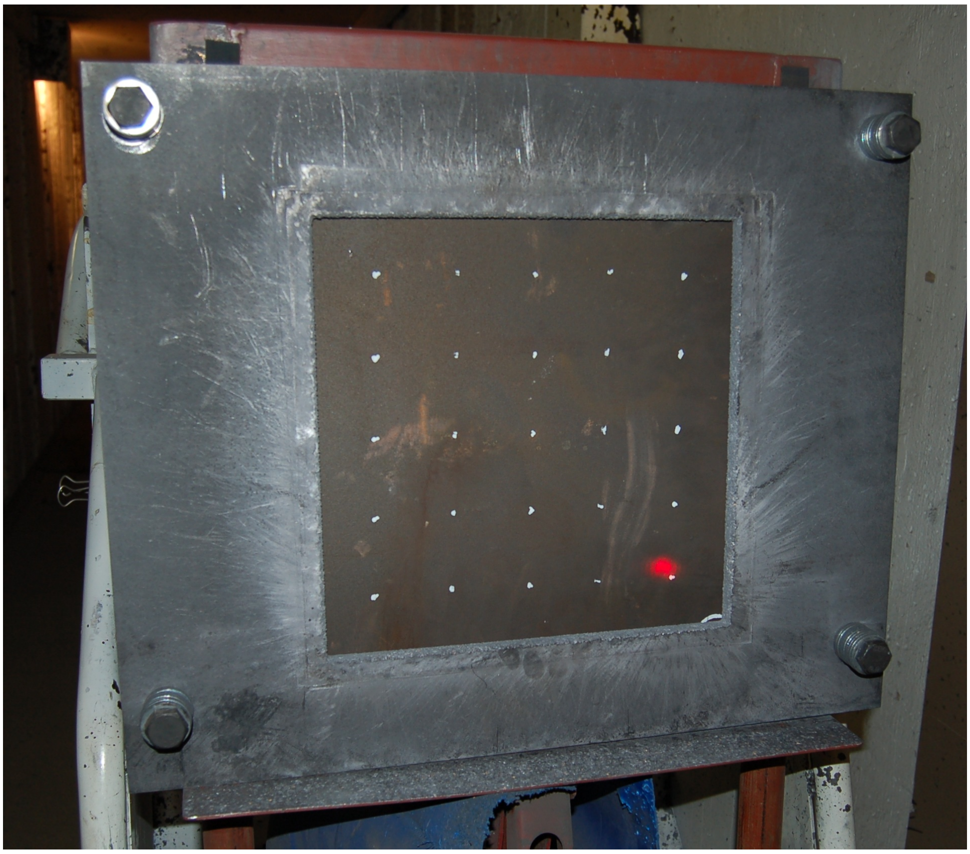

Figure 6.2: Test plate with planned shot positions.

6.13 and 6.14) with laser sight and adjustable support frame (Figures 6.9 to 6.12).

6.2.2 Velocity range capability

The combination of a high pressure barrel and adjustable cartridge charge result in an increased testing range of about 120% above the STANAG 4569 limits. This sets the SABS ballistic laboratory apart from any other rifle based testing range in South Africa and is illustrated for 5.56 mm and 7.62 mm calibre rounds in Figures 6.15 and 6.16 respectively with red and orange lines included to show the applicable STANAG velocity limits (833 m/s and 947 m/s ± 20 m/s). These figures show the velocity range as the cartrige charge, measured in troy grain, is increased. The type of propellant was not changed.

6.3 V_{50} Evaluation procedure

The V_{50} calculation as defined below (from Annex F in [90]) is used as the starting point in this evaluation and compared with ballistic limits defined in [100] and summarized in Table 6.1. A minimum number of 6 shots are required to establish a V_{50} value. As the first plates received were 300 mm x 300 mm it was decided to shoot on a 50 mm

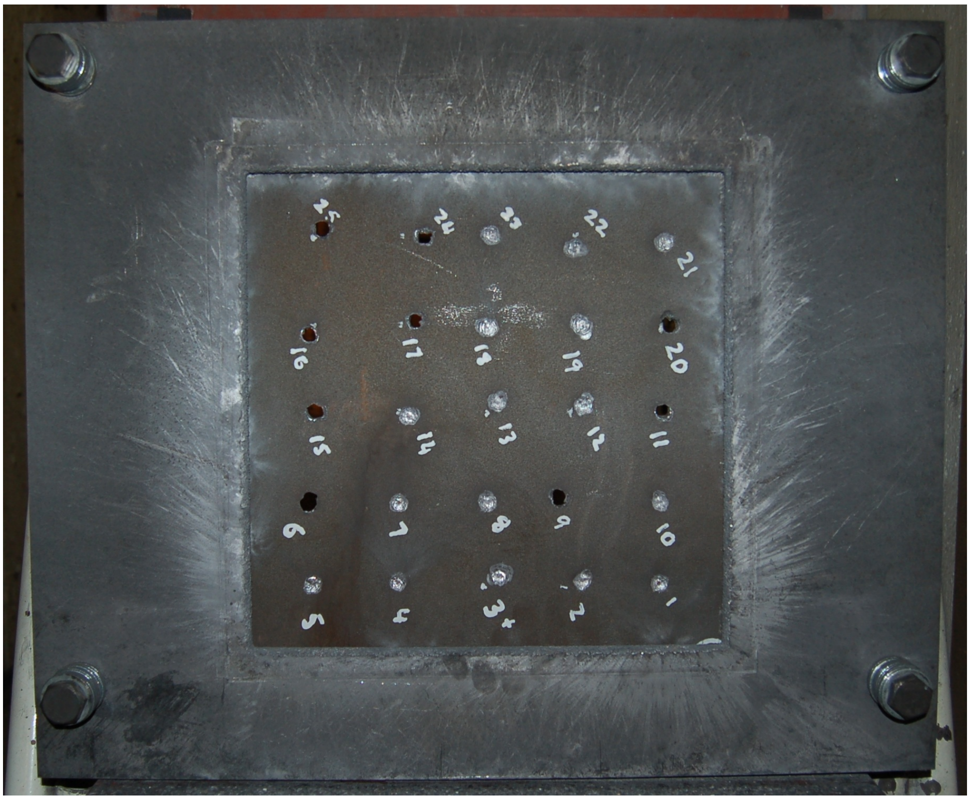

Figure 6.3: Test plate # 30 front.

Figure 6.4: Test plate # 30 back.

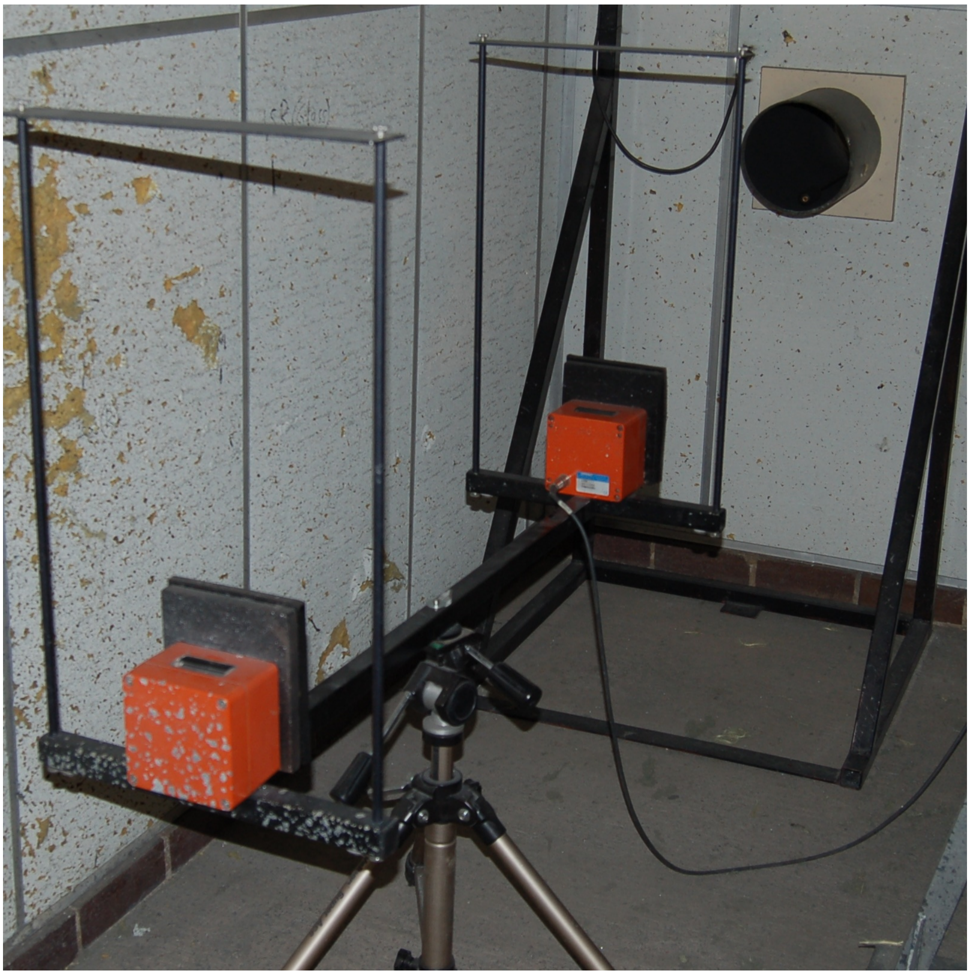

Figure 6.5: Chronograph 1.5m from muzzle end.

Figure 6.6: Chronograph display unit measuring projectile velocity [m/s].

Figure 6.7: Electronic propellant dispenser.

Figure 6.8: Reloading press.

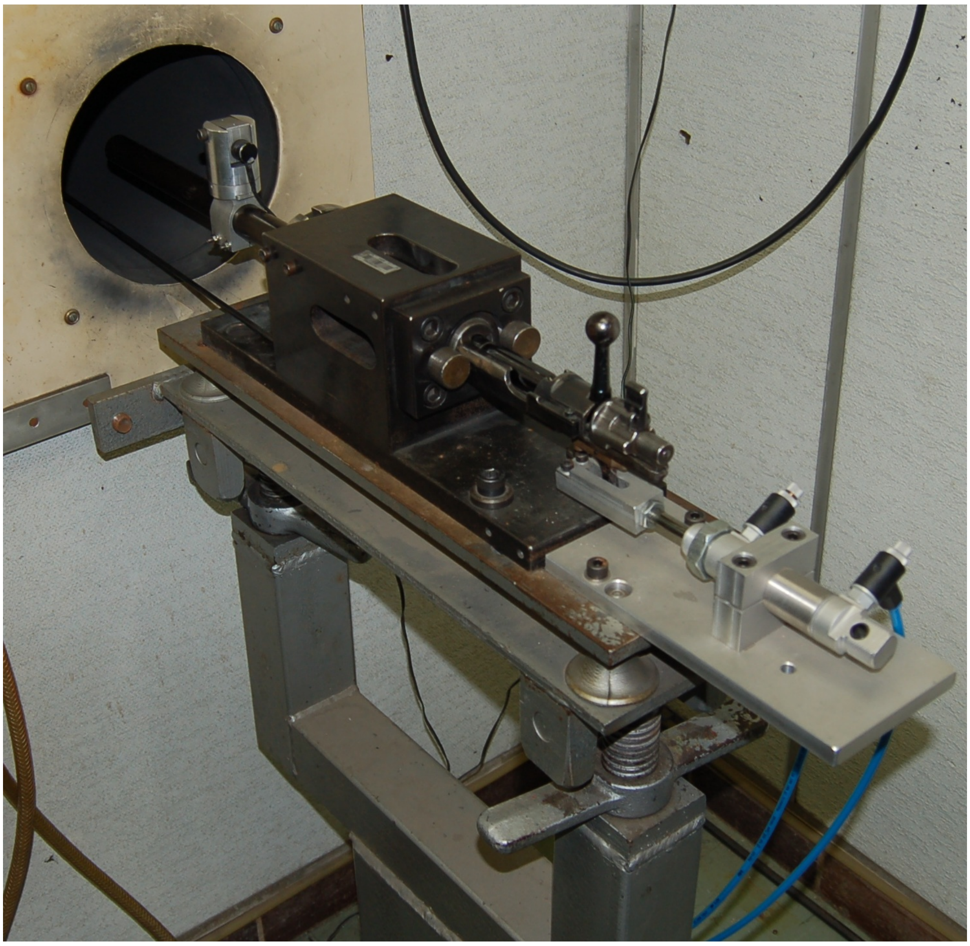

Figure 6.9: Ballistic test block with pneumatic trigger.

Figure 6.10: Lazer sight.

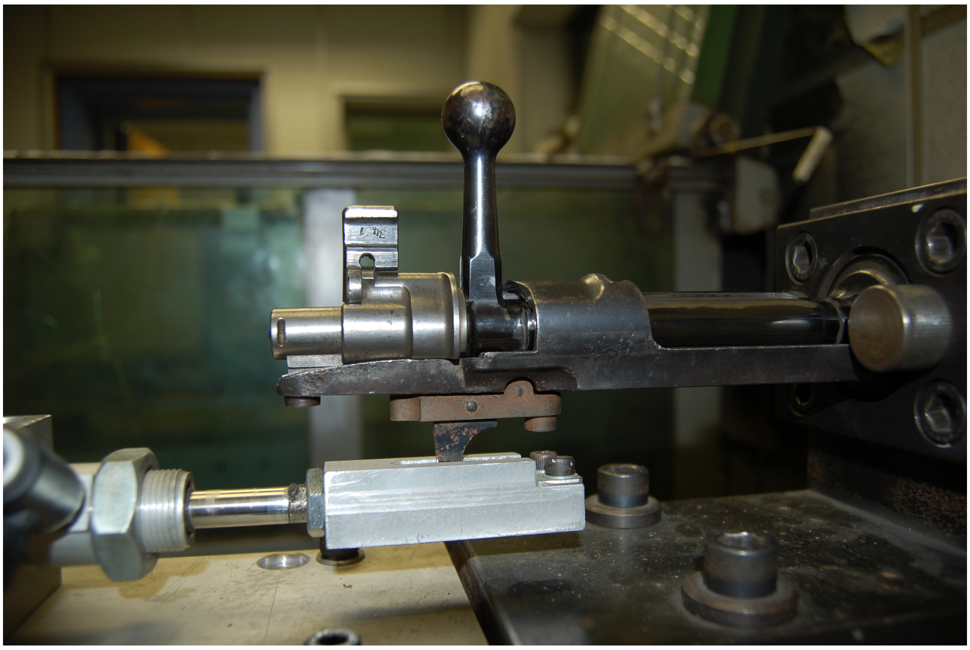

Figure 6.11: Detail view of trigger mechanism.

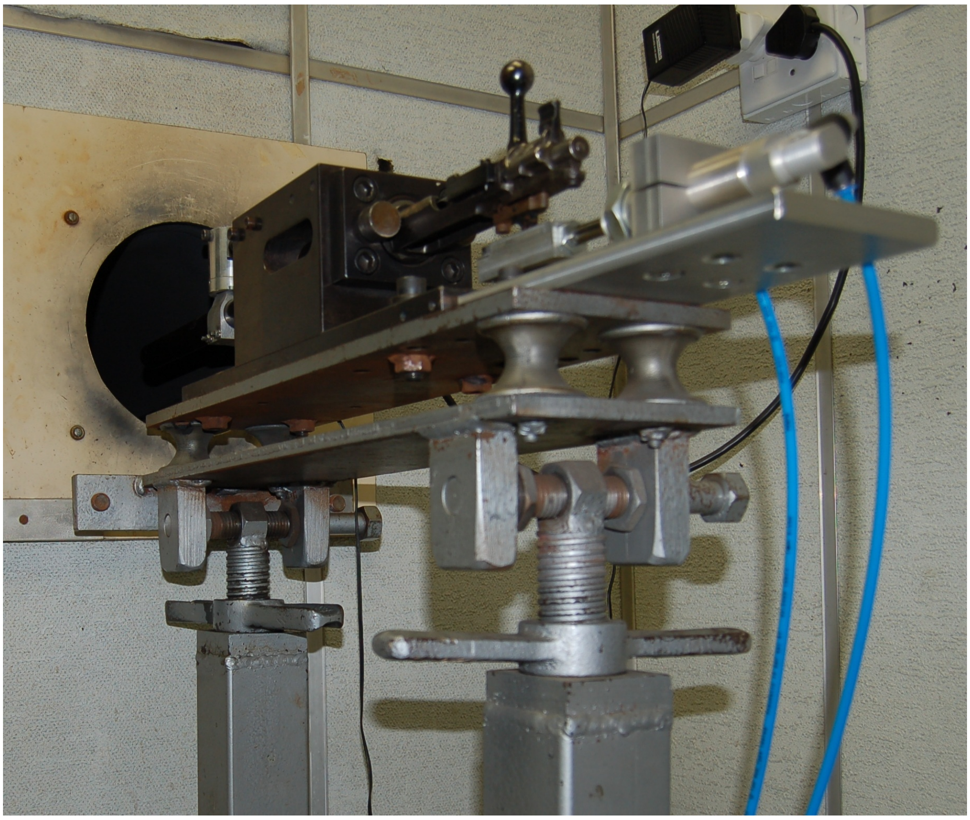

Figure 6.12: Ballistic test block with adjustable support frame.

Figure 6.13: High pressure test barrel [5.56mm] - Side view.

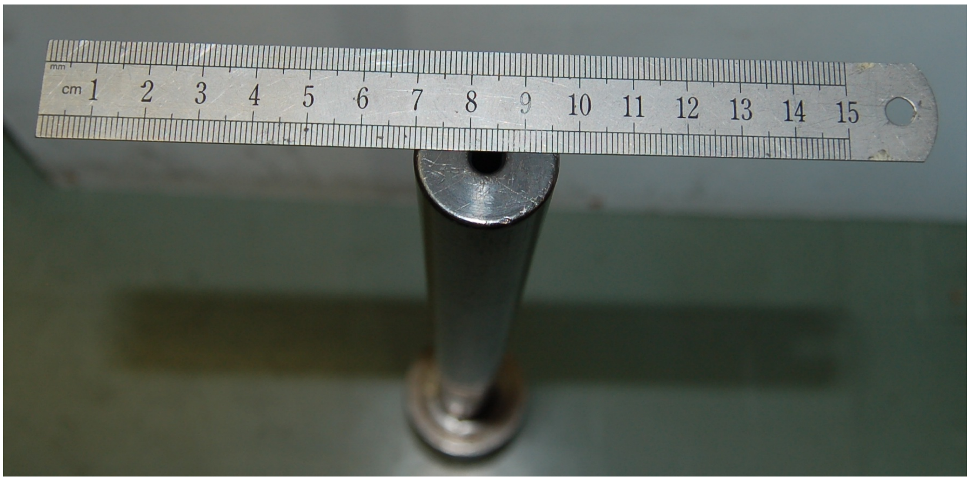

Figure 6.14: High pressure test barrel [5.56mm] - End view.

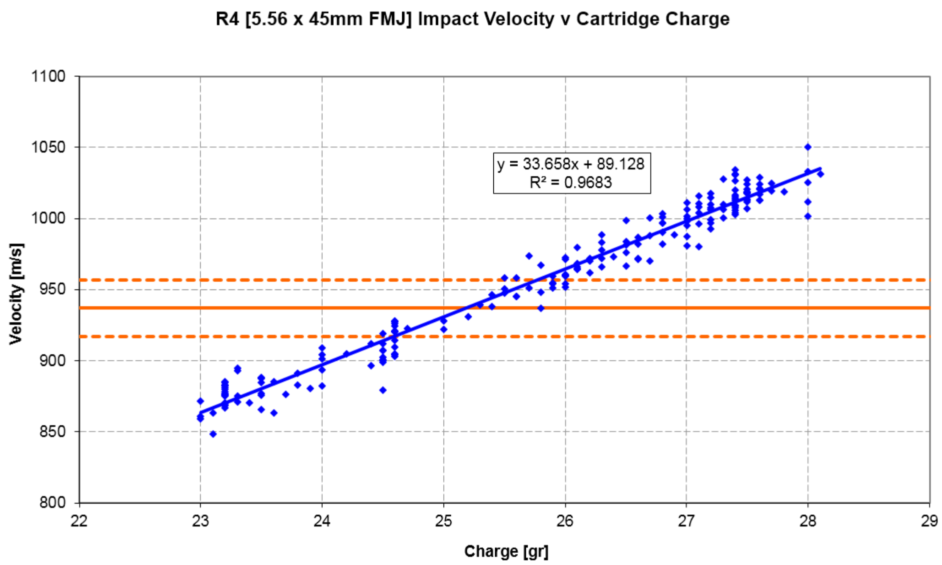

Figure 6.15: Impact velocity range for 5.56 x 45 mm FMJ. Orange lines show the STANAG test velocity limit of 833 m/s ± 20 m/s

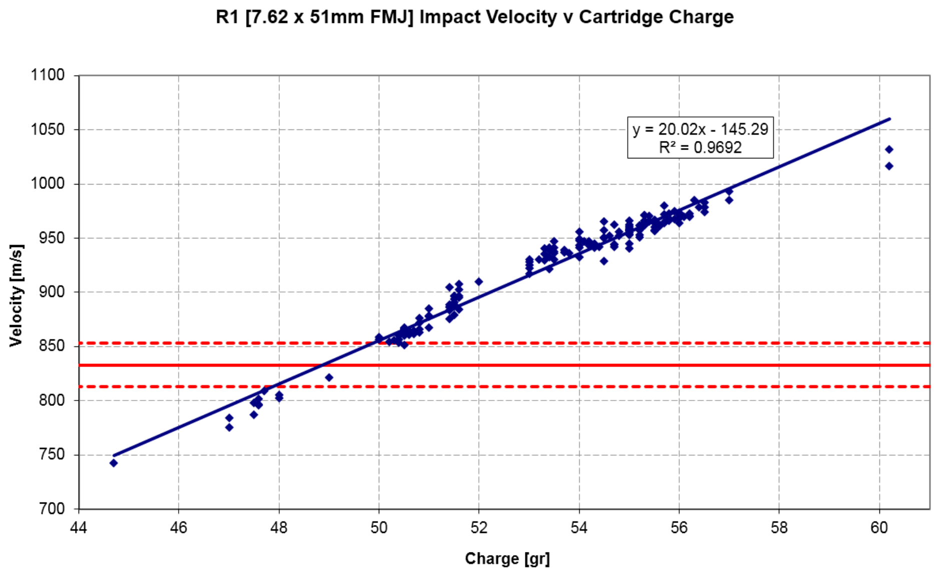

Figure 6.16: Impact velocity range for 7.62 x 51 mm FMJ.Orange lines show the STANAG test velocity limit of 947 m/s ± 20 m/s

grid to increase the number of shots per plate. This pattern results in 25 shots per plate and allowing for inaccuracy, a calculated V_{50} value consisting of 20 shots evenly spaced around the entire plate.

6.3.1 Test requirements and definitions

The experimental alloy # 1 had been developed to effectively stop any projectile from level 1 threat group as defined in Table 6.1.

Of the three projectiles included in level 1, the 5.56 mm x 45 M193 [R4] round is the most challenging to stop for steel plate armour. The SS109 round is the equivalent American round and could not be included in this evaluation due to limited availability. The 7.62 mm x 51 NATO ball [R1] round is included, however, in this investigation to reveal any spall or brittle fracture ballistic failure sensitivity.

The standard witness system defined in [90] consists of a 0.5 mm aluminium plate positioned 150 mm from the back face of the test plate, as it should extend over a large enough area to detect any fragments. Characterization of impacts near the ballistic limit of the material is defined as partial penetration if light is not observed to pass through the witness plate or alternatively, is classified as complete penetration if the light passes through the witness plate.

For this investigation a more conservative approach was followed. Initially damage was evaluated using a modified witness system as follows: The aluminium plate was replaced with a sheet of paper clamped to a witness frame behind the test plate support frame. This complicated the evaluation process and greatly increased the time interval for each shot as every hole had to be marked on the paper before the next shot could be taken and

Level	KE Threat				
	Ammunitions	Supplier / Specific test ammunitions	V proof [m/s] ± 20 m/s	Azimuth	Elev.
5	25 mm x 137 APDS-T, PMB 073	Oerlikon-Contraves, 121.5g W alloy core (150g with sabot)	1258	± 30°	0°
4	14.5 mm x 114 API/B32	CIS1 Chicom, ARL Drawing number 3200 (Figure C.7.), 63.4g steel core	911	0 - 360°	0°
3	7.62 mm x 51 AP (WC Core)	Bofos Carl Gustaf FFV AP M993 pr AP8 Nammo, 8.4 g W alloy core	930	0 - 360°	0°
	7.62 mm x 54R B32 API	Barnaul Machine Tool or CIS Russia, AP 713, 10.0 g	854	0 - 360°	0°
2	7.62 mm x 39 API BZ	Chicom, CIS State arsenals, 7.77g steel core	695	0 - 360°	0°
1	7.62 mm x 51 NATO ball	Ball M80, copper jacket, 9.65 g lead core or C21, 9.5 g, DM41 with tomac jacket and lead core, projectile weight: 9.45 g	833	0 - 360	0
	5.56 mm x 45 NATO SS109	SS109, 4.0 g, M855, DM11, tomac jacket, steel and lead core, projectile weigth: 4 g	900	0 - 360°	0°
	5.56 mm x 45 M193	M 193, Ball 3.56 g	937	0 - 360°	0°

Table 6.1: KE Threat levels - STANAG 4569

Figure 6.17: Definition of partial perforation.

a new paper was needed every few shots. In addition to this it was observed that some of the projectiles did not even pierce the paper as the witness paper was located about 400 mm from the back of the test plate and was clearly too small. The impact evaluation was therefore simplified further to a visual inspection of the test plate's rear face. An impact event above the ballistic limit results in a clear hole through the plate and is classified as complete perforation CP. With the impact velocity well below the ballistic limit, almost no damage was observed on the back face of the test plate with only slight bulging in some instances. These types of impacts were classified as non-perforation NP. Impact events near the ballistic limit of the plate resulted in partial perforations PP as seen in Figure 6.17. An impact classification summary is shown in Table 2.

The partial perforation was classified according to the development of the shear band crack on the back surface.

Complete perforation [CP]	Shear band crack $> 180°$
Partial perforation [PP]	Shear band crack $< 180°$
Non perforation [NP]	No visible crack

Table 6.2: Partial preforation classification.

This classification could be overly conservative for some CP events on thick plates, however with thinner plates only a few PP classifications were observed.

6.3.2 Test procedure and classification

Before the test started 2 rounds were fired on a blank piece of paper to warm up the barrel and set the laser sight. Once the 50 mm grid was marked and the test plate was clamped into position, the barrel was positioned to the correct level for the test. The test plate was moved up and down during the test using the adjustable test frame (Figure 6.1). The first few shots were used to establish a test range with at least one CP and one NP. Once the test range was known, the charge was varied only slightly to influence the impact velocity. The aim of this section of the test was to vary the impact velocity such that approximately half of the shots produced NP and the other half CP with all shots within the velocity range of approximately 40 m/s. This process proved to be challenging for some tests and a reduced number of shots had to be used to calculate the V_{50} value.

During the test the following values were recorded:

1. Shot number. (Also marked on the plate.)
2. Cartridge charge [grain]
3. Muzzle velocity [m/s]
4. Impact result [CP, PP or NP]

A complete record of al the ballistic tests are included in appendix B. Calculating the V_{50} value consisted of the following steps:

1. All the test data were entered into a spreadsheet and all shots sorted in descending order for complete perforations and ascending order for the non-perforations.
2. All the shots were verified to be within $V_{Crit} \pm 20\ m/s$ and the group was reduced if any values were outside the 40 m/s velocity range.
3. Equal numbers of shots were grouped and the average taken. The number of shots and their minimum and maximum values were reported.
4. The average muzzle velocity was adjusted to the V_{50} value by subtracting the velocity drop over 13.5 m for the specific calibre (Table 6.3).

Ammunition	Velocity drop factor	Distance [m]	Total reduction [m/s]
7.62 x 51 mm NATO Ball	0.76 [m/s]/m	13.5	10.260
5.56 x 45 mm M193	1.23 [m/s]/m	13.5	16.605

Table 6.3: Velocity reduction for each projectile.

6.4 Ballistic results

A total number of 25 plates were tested with the 5.56 x 45 mm M193 calibre round. The results are presented in Figure 6.18 with the upper STANAG limit in dotted lines and listed in Table 6.4. The data range bars have been removed from alloy # 1 data points to clarify the result.

Alloy # 1 is positioned between Benchmark 600 and Benchmark 500 as expected. The 190°C tempered Alloy #1 performed significantly worse than the air cooled plate. One interesting inconsistency is observed on the Alloy #1 line with an apparent plateau between 7.6 mm and 8.6 mm.

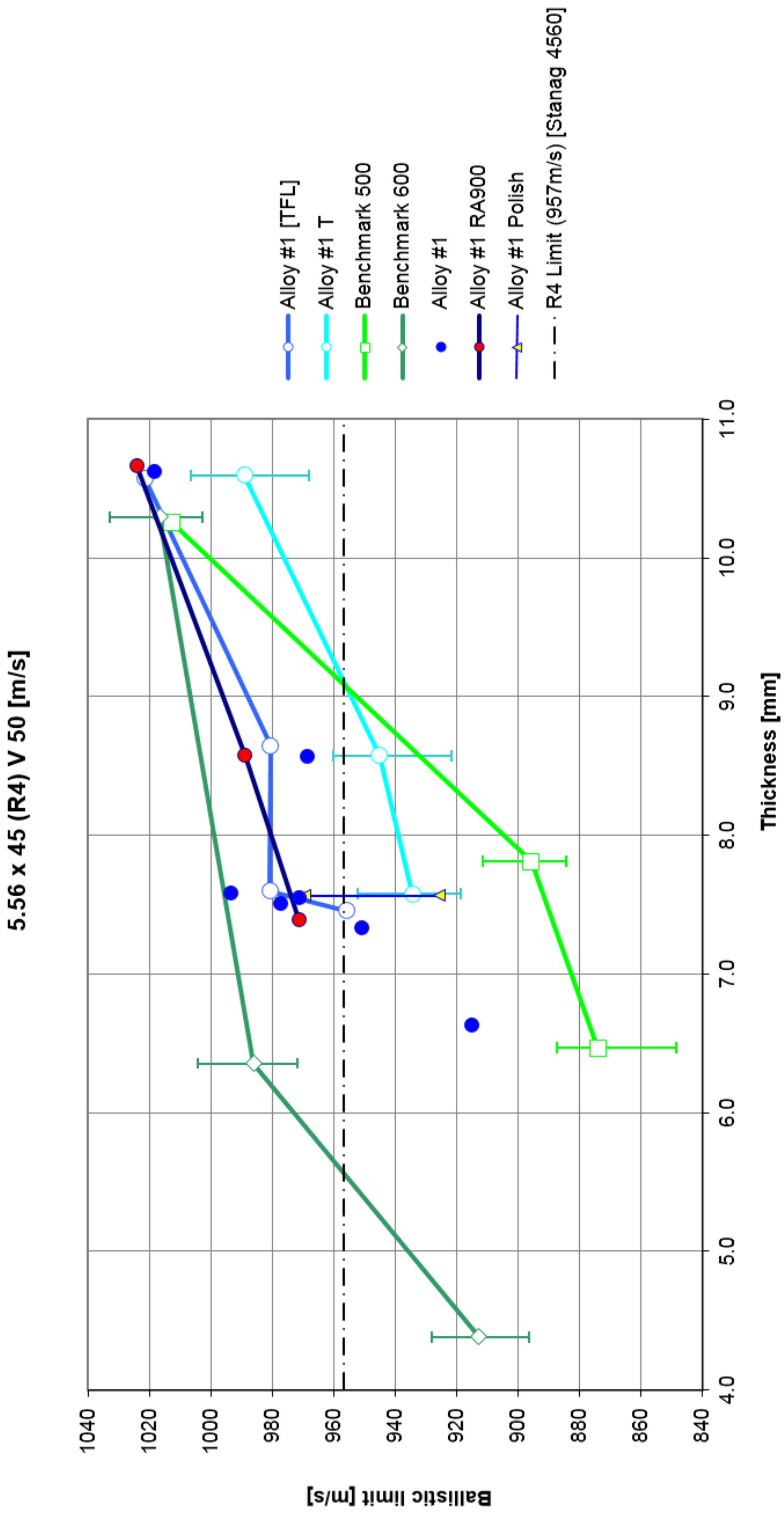

Figure 6.18: V_{50} results for 5.56 x 45 mm M193 round.

Six plates from the original air-couriered material are included, these where the designated TFL plates, ranging in thickness from 6.5 mm to 10.5 mm. A reasonable correlation is seen between the TFL type and the remaining plates (Blue dots), with a ballistic limit range between plates of around 40 m/s for similar thicknesses.

The ballistic performance effect of re-austenization at 900°C (Red dots) is not as clear as a temper treatment at 200°C (Turquoise line) and simply confirms that all the new material plates had been properly solution treated before air cooling.

One curious result is the ballistic performance effect of the surface finish on the front side of the plate (Yellow triangles). A reduction in ballistic limit of 44 m/s is seen with the front face polished compared to the rear face. The ballistic limit of the plate with the rear face polished is similar to plates without any polished faces.

Only 12 plates were tested with the 7.62 x 51 mm M80 calibre round. Complete perforation of the 10 mm thick Bechmark 600 plate was not possible with current equipment. The results are presented in Figure 6.19 with the upper STANAG limit in dotted lines and listed in Table 6.5.

Alloy # 1 is again positioned between the Benchmark grades. The plate thicknesses tested resulted in V_{50} values almost 100 m/s above the threat limit. Additional testing with thinner plates should be conducted to extend the limit line past the threat limit. The reduction in performance of the 200°C tempered plate seems to be smaller for the 7.62 mm calibre round.

The general ballistic performance of the three materials all follow the trend that a thicker plate requires a higher impact velocity to perforate. For the 5.56 x 45mm projectile the failure mode was consistently observed to be plugging with several plugs collected. The plug dimension ratio discussed in section 2, $Diameter_{Plug} \approx t_{Plate}$, was noted on almost all plugs collected. This geometric constraint on the failure mode points to an interaction of the projectile and target during momentum transfer that follows some rule. Future work in numeric modelling of the projectile during impact could help explain this phenomenon.

The occurrence of spalling failure along with plugging for the 7.62 x 51 mm projectile explains some of the variation in the ballistic performance. The relevance of test results well above the ballistic limit of the projectile is also questionable as thinner plates with V_{50} values closer to the level 1 threat limit could have been more appropriate. Standard plate rolling thicknesses do however discretize the evaluation resolution and it was therefore decided not to expand this test range.

6.4.1 Summary points

The following points summarise the conclusions from this chapter:

- The ballistic results for the 5.56 x 45 mm projectile seem to show less statistical

Plate no.	Thickness [mm]	V_{50} [m/s]	+	-	No. Shots
TFL 1/3 [2210124] TP1	7.45	955.96	17.93	17.91	18
TFL 3/1 [2210124] TP2	7.59	980.88	14.21	9.74	10
TFL 5/1 [2208934] TP3	8.65	980.72	19.97	15.88	18
TFL 3/2 [2210125] TP4	10.57	1021.62	6.72	19.21	10
Alloy #1 T SM12 TP22	7.58	934.50	17.70	15.57	22
Alloy #1 T SM10 TP25	8.57	945.33	15.01	23.59	22
Alloy #1 T SM1 TP26	10.59	989.17	17.62	21.14	20
Alloy #1 SM12 TP33	6.63	915.33	15.48	20.53	18
Alloy #1 SM11 TP39	7.34	950.83	22.28	17.67	16
Alloy #1 SM15 TP29	7.55	971.24	18.66	9.84	18
Alloy #1 SM12 TP30	7.58	993.49	18.11	9.09	20
Alloy #1 SM13 TP31	7.51	977.26	15.34	21.00	20
Alloy #1 SM7 TP40	8.57	968.82	22.58	14.92	20
Alloy #1 SM3 TP32	10.62	1018.58	18.51	17.59	18
Alloy #1 RA900 SM12 TP34	7.39	971.46	11.34	9.97	18
Alloy #1 RA900 SM7 TP35	8.58	988.92	21.58	13.26	22
Alloy #1 RA900 SM3 TP36	10.67	1024.19	18.41	14.29	24
SM12 TP37 Back Polished	7.56	969.57	14.82	18.12	12
SM12 TP37 Front Polished	7.56	925.70	13.35	14.41	6
Benchmark 500 TP16	6.47	874.27	13.04	25.75	22
Benchmark 500 TP12	7.81	895.86	15.79	11.23	12
Benchmark 500 TP13	10.25	1012.66	2.24	2.26	8
Benchmark 600 TP15	4.38	912.89	15.24	16.25	22
Benchmark 600 PT14	6.35	986.22	18.27	14.30	20
Benchmark 600 TP17	10.29	1016.62	16.57	13.93	24

Table 6.4: Ballistic test summary for 5.56 x 45 mm M193.

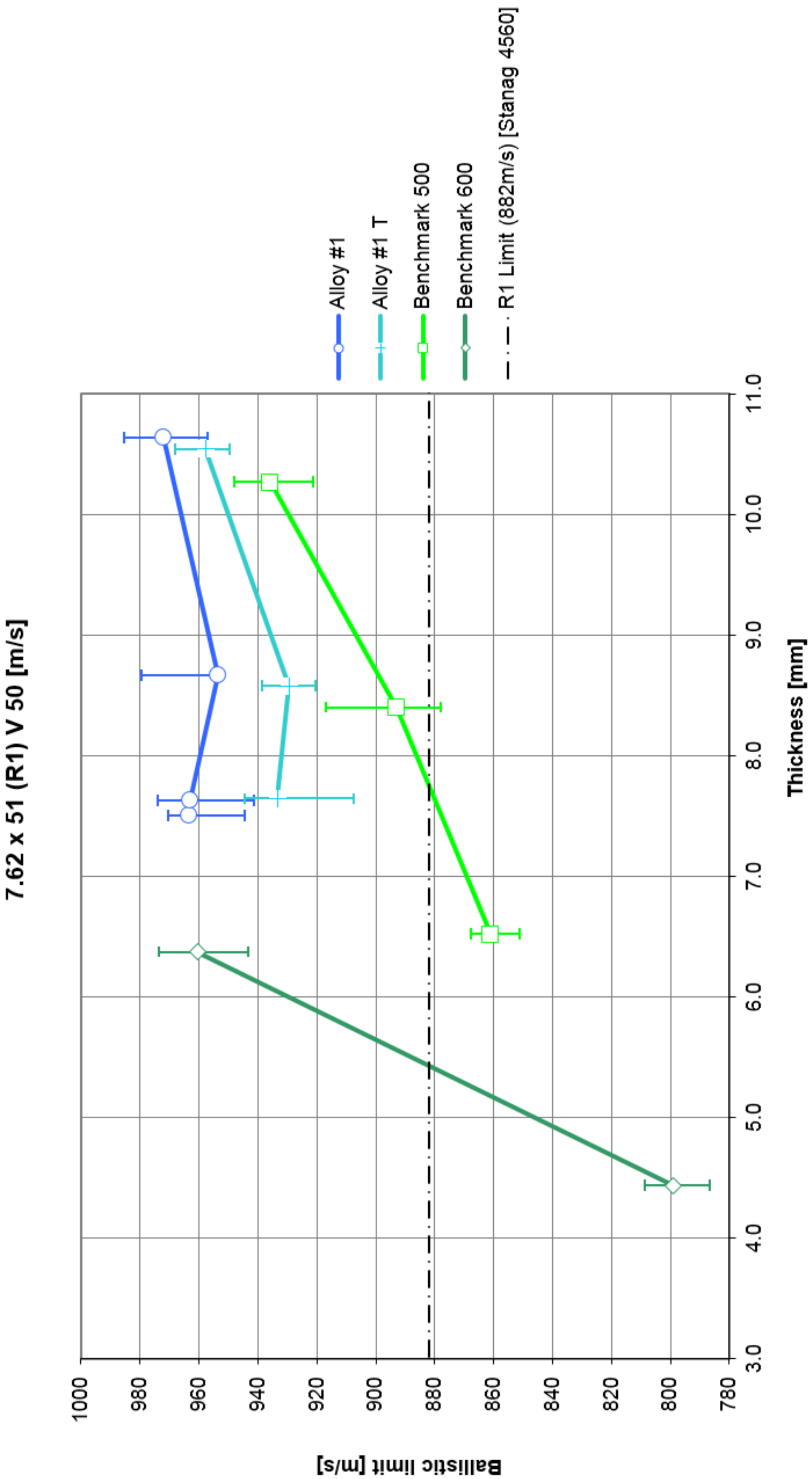

Figure 6.19: V_{50} results for 7.62 x 51 mm M80 round.

scatter than those for the 7.62 x 51 mm projectile. Plate thickness well above the ballistic limit of 7.62 x 51 mm was however evaluated and the scatter could be attributed to spall failure occurrence at some impacts.

- The limiting projectile in the STANAG level 1 kinetic threat group is the 5.56 x 45 mm projectile. The benchmark material's minimum thickness requirement for level 1 is defined in the product data sheet as 9 mm. Ballistic results produced by the procedure in the aforementioned chapter, Figure 6.18, shown a minimum thickness required for the benchmark material as 9 mm. This correlation verifies the ballistic test procedure.

Plate no.	Thickness [mm]	V_{50} [m/s]	+	-	No. Shots
Alloy #1 SM12 TP38	6.75	913.47	10.24	10.74	22
TFL 1/2 [2210124] TP5	7.50	963.70	6.72	19.21	18
TFL 3/2 [2210124] TP6	7.63	962.97	10.83	21.84	16
TFL 5/2 [2208934] TP7	8.67	953.52	26.12	1.31	14
TFL 3/3 [2210125] TP8	10.64	972.03	13.23	15.08	8
Alloy #1 T SM12 TP23	7.64	933.35	10.95	25.93	10
Alloy #1 T SM10 TP24	8.58	929.45	8.97	8.96	24
Alloy #1 T SM1 TP27	10.54	957.84	10.37	8.13	22
Benchmark 500 TP19	6.52	861.21	6.49	9.99	22
Benchmark 500T TP9	8.40	892.98	23.89	14.90	22
Benchmark 500T TP10	10.27	935.98	11.98	14.53	14
Benchmark 600 TP18	4.44	799.19	9.42	12.51	8
Benchmark 600 TP11	6.37	960.45	12.96	16.97	18

Table 6.5: Ballistic test summary for 7.62 x 51 mm M80.

CHAPTER 7

Conclusion and recommendations

This chapter summarises the findings of this study and makes recommendations for further research and investigation.

7.1 Conclusions

The focus of this investigation as set out in section 1.2.1 was quite ambitious, specifically objective 4 stated: To explain the improved ballistic performance in terms of the numerical characterisation.

It should however be noted that the ballistic characterization (objective 1), clearly differentiated all three materials tested. The material testing over temperature, strain-rate and notch intensity ranges (objective 2), was completed according to the initial plan and indicated general differenced between Alloy # 1 and the benchmark material.

The limited success of the numerical characterisation study (objective 3) confirms the general indication that Alloy # 1 should show favourable ballistic performance. This is indicated by the low ratio of yield strength to ultimate tensile strength (YS/UTS). The mechanism of improved ballistic performance (objective 4), could however not be explained.

Material tests for the benchmark material were limited and inappropriately scaled for the high strain rate tests. A redesign of the benchmark specimens with another round of dynamic testing could have revealed the initial plastic transition and work hardening. This section of the tensile curve is essential for a proper numerical fit using the Joohnson-Cook model. The material characterisation of alloy #1 could also have been improved by less quasi-static tests and more slightly varied high strain rate tests. Various sized compression specimens could be used in successive impacts to increase total plastic deformation and tensile specimens loaded past the necking point but not past failure could be used to construct a true stress strain curve.

Direct comparison of true stress strain curves would reveal the total plastic strain energy absorbed by the materials and include strain energy used in the austenite to martensite transformation. Rigorous ballistic and mechanical tests performed in this study nonetheless reveal interesting insight into the material behaviour. Key test results are listed below:

1. The 5t prototype cast of alloy # 1 proved to be a superior ballistic resistant material. A thickness of only 7.4 mm was required to effectively resist a STANAG Level 1 threat, compared to the 9 mm required by the benchmark material.

2. Higher strength was observed at high (400°C - 600°C) temperatures.

3. Higher strength and increased plasticity was observed at high (300 $mm/mm/s$ - 1000 $mm/mm/s$) strain rates.

4. Notch sensitivity in the new armour plate steel seems to be less important for resisting ballistic perforation.

A final observation on the tests results should be made, i.e. the high strain rate test correlated well with ballistic performance and could be used to calculate the total energy absorption capacity of the material. This procedure would be less expensive than a complete ballistic evaluation and would allow for an appropriate mechanical behaviour comparison early in the alloy development process.

7.2 Recommendations

The effect of residual austenite (RA) and it's energy requirements in the transformation to fresh martensite in Alloy # 1 has not been included in this study. An energy based transformation model, implemented into a commercial code should allow for a complete evaluation of the ballistic performance.

Development and progression of this fresh martensite is critically dependent of the local shape and planar orientation of every volume of residual austenite inside every grain. Mirco-scale modelling of this transformation would however require the shape and position of the residual austenite as well as existing martensite to be defined. A stress field could then be applied and local transformation modelled with volumetric increases and resulting stress relaxation. Meso-scale models could help explain this phenomenon with various original austenite grain boundaries in place and would also require more orientation and relative positioning information. Both of these models would then also require some input based on the initial air quenching to fully characterise internal grain residual stresses.

Macro-scale modelling of the impact is clearly the only course of action available for any practical solution. It is therefore proposed that a volume faction model consisting of a linear combination of material properties be used. Mechanical strength, thermal response and ductile failure could be fitted for pure austenite an martensite and combined by volume fraction for any ratio. Chemical driving force and mechanical energy applied to the material should then be independently considered as the transformation criteria. If transformation would occur an incremental volume increase could be included for identified elements and iterated until a time step convergence point is reached.

Such a procedure would require a reasonable theoretical model, capable of handling the relationship between mechanical assisted martensite transformation and thermally driven transformation for an adiabatic heating condition. These two mechanisms initiate and terminate at fixed temperatures for any alloy and it could thus be assumed that if the volumetric correction is iterated and every time step already includes this effect, that the high strain rate simply results in heat generated by the plastic deformation.

Any change in the material due to transformation would trigger a volumetric correction and in turn a local stress release, more deformation energy could then be absorbed by all surrounding elements consequently increasing mechanical load capacity.

First steps towards a numerical model capable of modelling soft projectile impact could included the following:

1. The numerical characterisation of the material requires a finite element based evaluation procedure to effectively capture the post necking behaviour.

2. A material model based on the Material Threshold Strength type is proposed for future work.

3. Thermal softening should be included in the implementation.

4. A damage model based on the Johnson-Cook fracture strain model should be included.

5. Particle based methods could begin to describe the soft projectile interaction.

With the above material energy models and modified numerical procedures in place, various volume fractions of residual austenite (RA) should be evaluated numerically for ballistic impact. Maximal dynamic energy absorption would be reported and an optimal volume fraction of RA could then be predicted.

Surface roughness and texture could also contribute to internal pressure inflection of the projectile and thus increased energy dissipation early in the momentum transfer during impact. This could be investigated apart from the material transformation and should remain an experimental study until a rigorous numerical solution has been developed.

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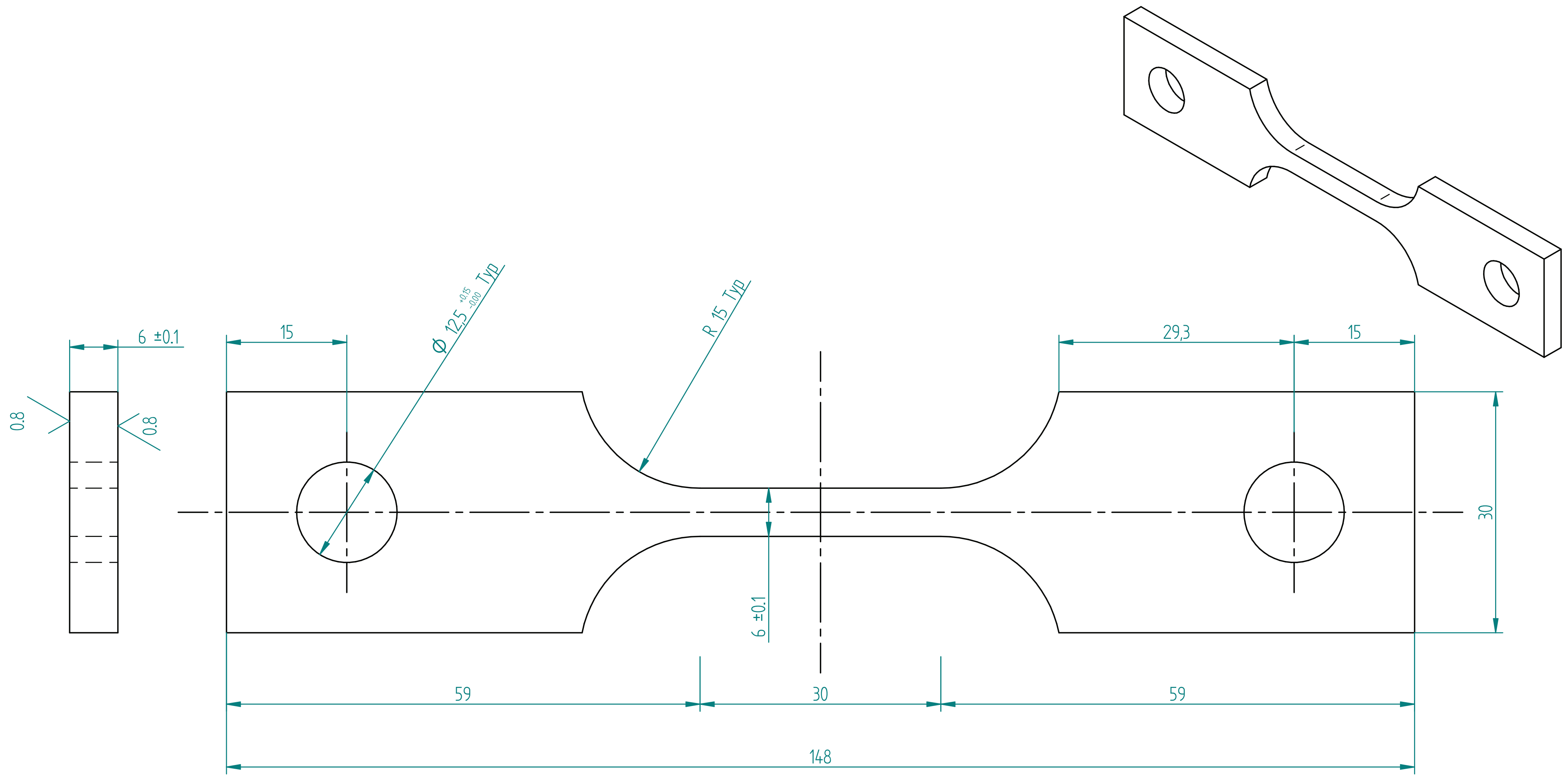
CHAPTER 8

Appendix A

This appendix includes all the material test specimen drawings.



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CAD FILE NAME:

DRG SIZE A3 PROJECTION

MEGCHEM JOB NO : MC2410688-

CLIENT JOB NO

DRAWN DATE

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FAX: +27 17 620 2330

DIMENSIONS IN mm UNLESS OTHERWISE STATED

DRAWING NUMBER MC2410688-2010-8-28-001

Material: Alloy 1 Plate 7.5mm
Quantity: 8

Type 1 tensile

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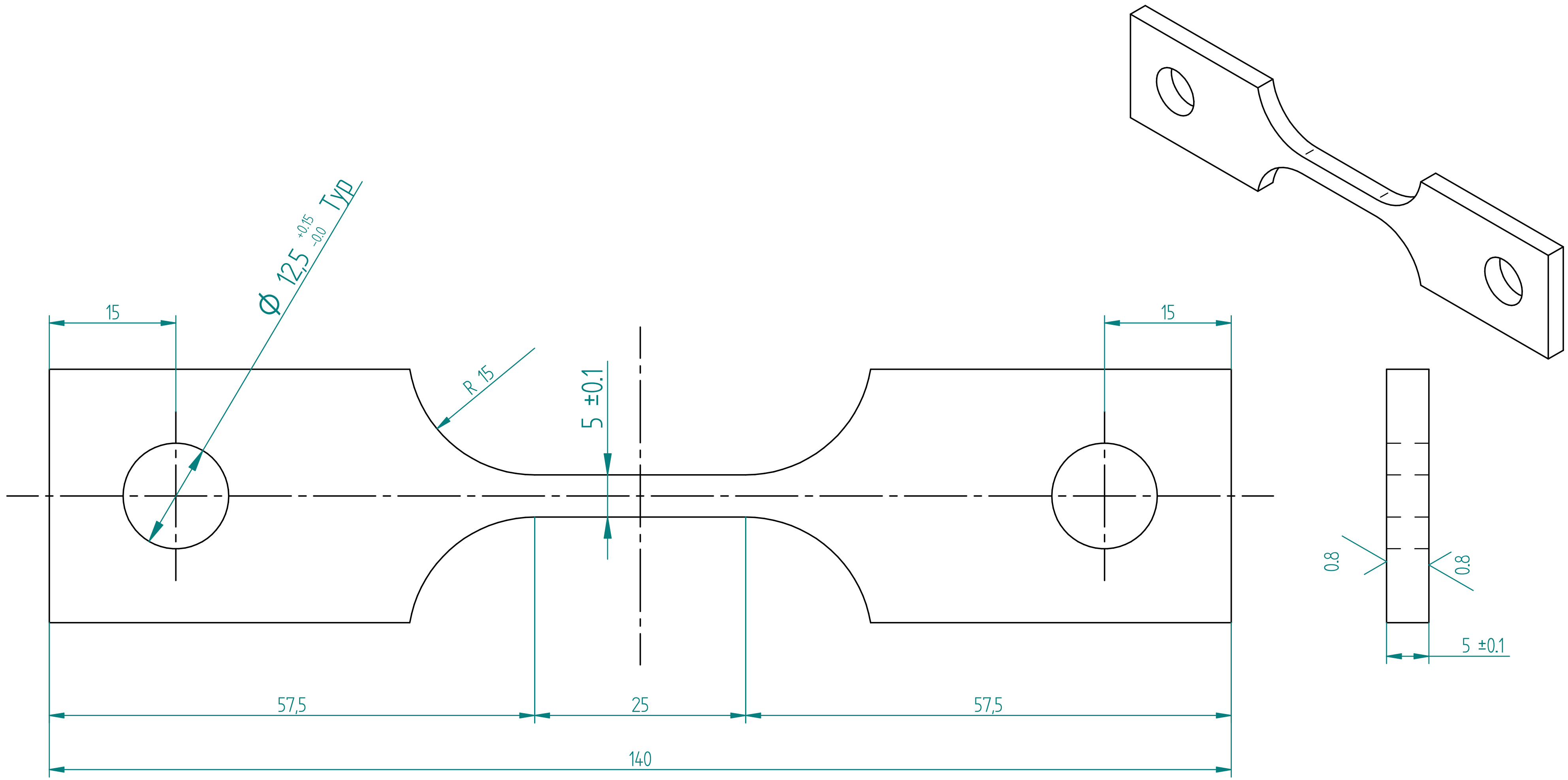

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PROJECTION

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DIMENSIONS IN mm
UNLESS OTHERWISE STATED

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2011-3-29

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Quantity: See lab request

Type 2 tensile

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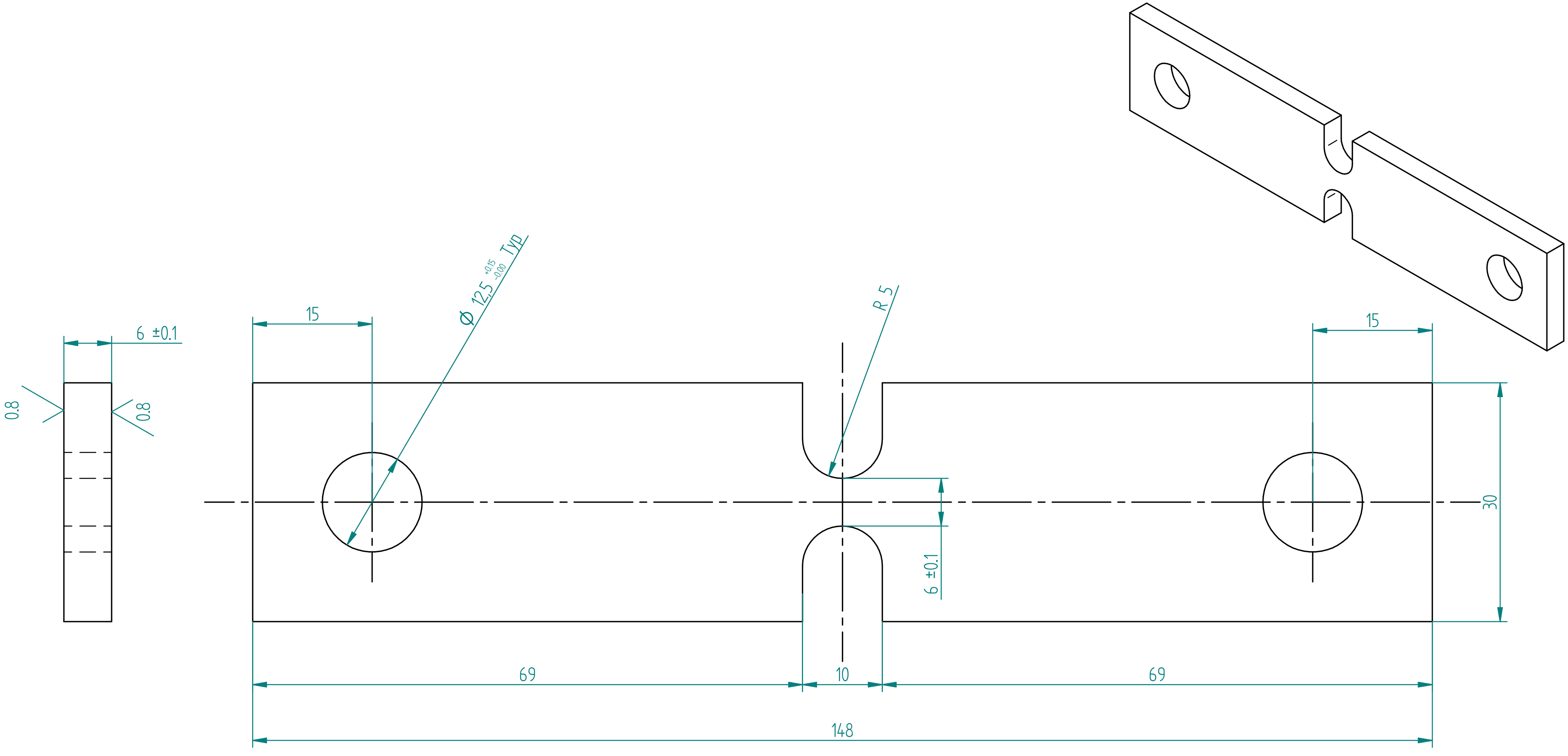

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MEGCHEM JOB NO : MC2410688-

CLIENT JOB NO

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DIMENSIONS IN mm
UNLESS OTHERWISE STATED

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Material: Alloy 1 Plate 7.5mm
Quantity: 2

Type 3_5 tensile

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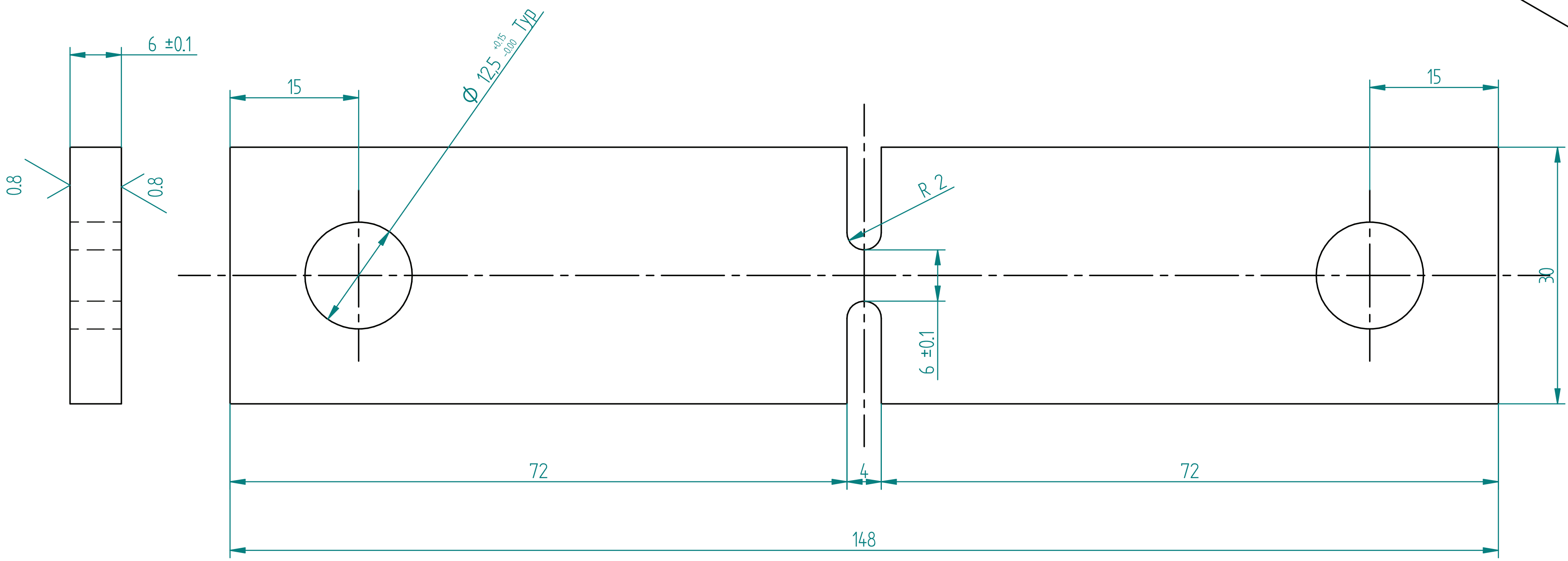

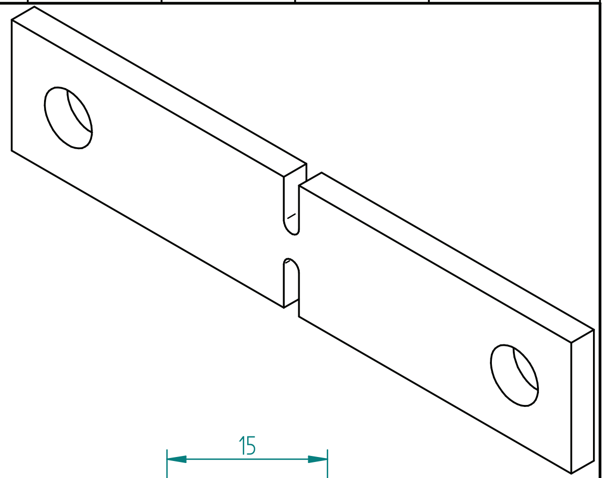

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DRG SIZE A3 PROJECTION

MEGCHEM JOB NO : MC2410688-

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DIMENSIONS IN mm UNLESS OTHERWISE STATED

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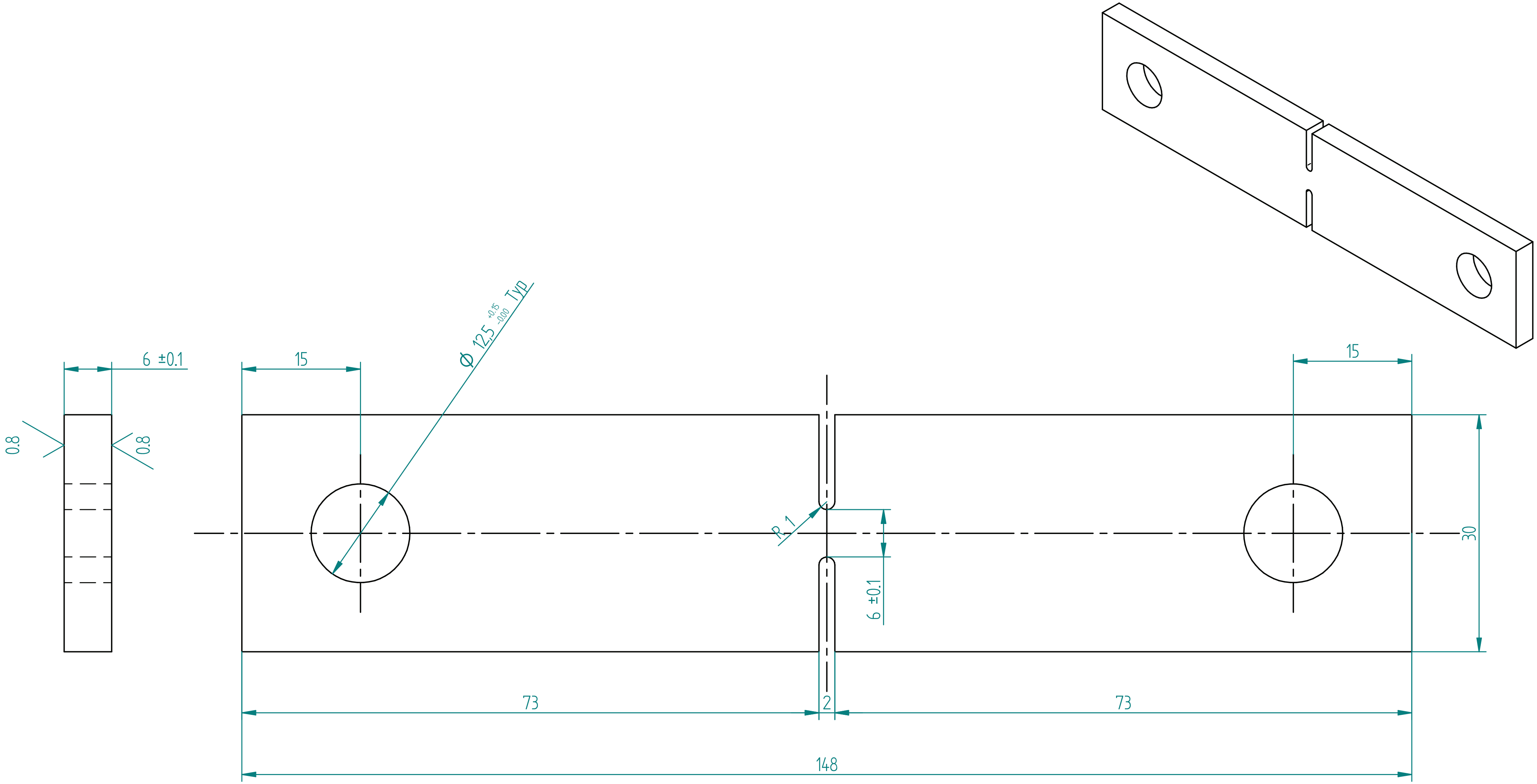
Material: Alloy 1 Plate 7.5mm
Quantity: 2

Type 3_2 tensile

SHT OF REV



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DRG SIZE A3

PROJECTION

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DIMENSIONS IN mm UNLESS OTHERWISE STATED

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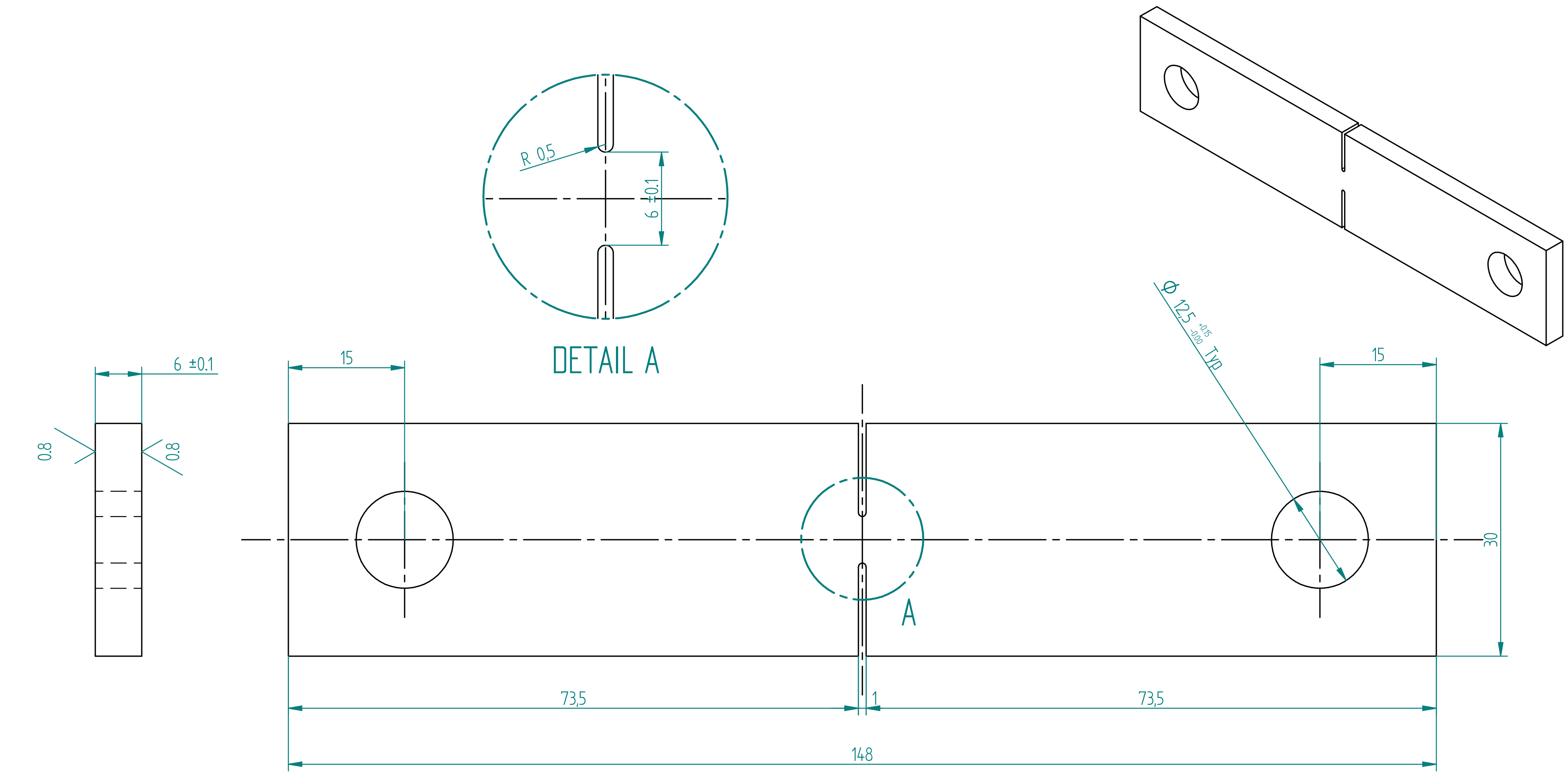
Material: Alloy 1 Plate 7.5mm
Quantity: 2

Type 3_1 tensile

SHT OF REV



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MEGCHEM JOB NO : MC2410688-

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DIMENSIONS IN mm UNLESS OTHERWISE STATED

DRAWING NUMBER MC2410688-
2010-8-28-005

Material: Alloy 1 Plate 7.5mm
Quantity: 2

Type 3_0.5 tensile

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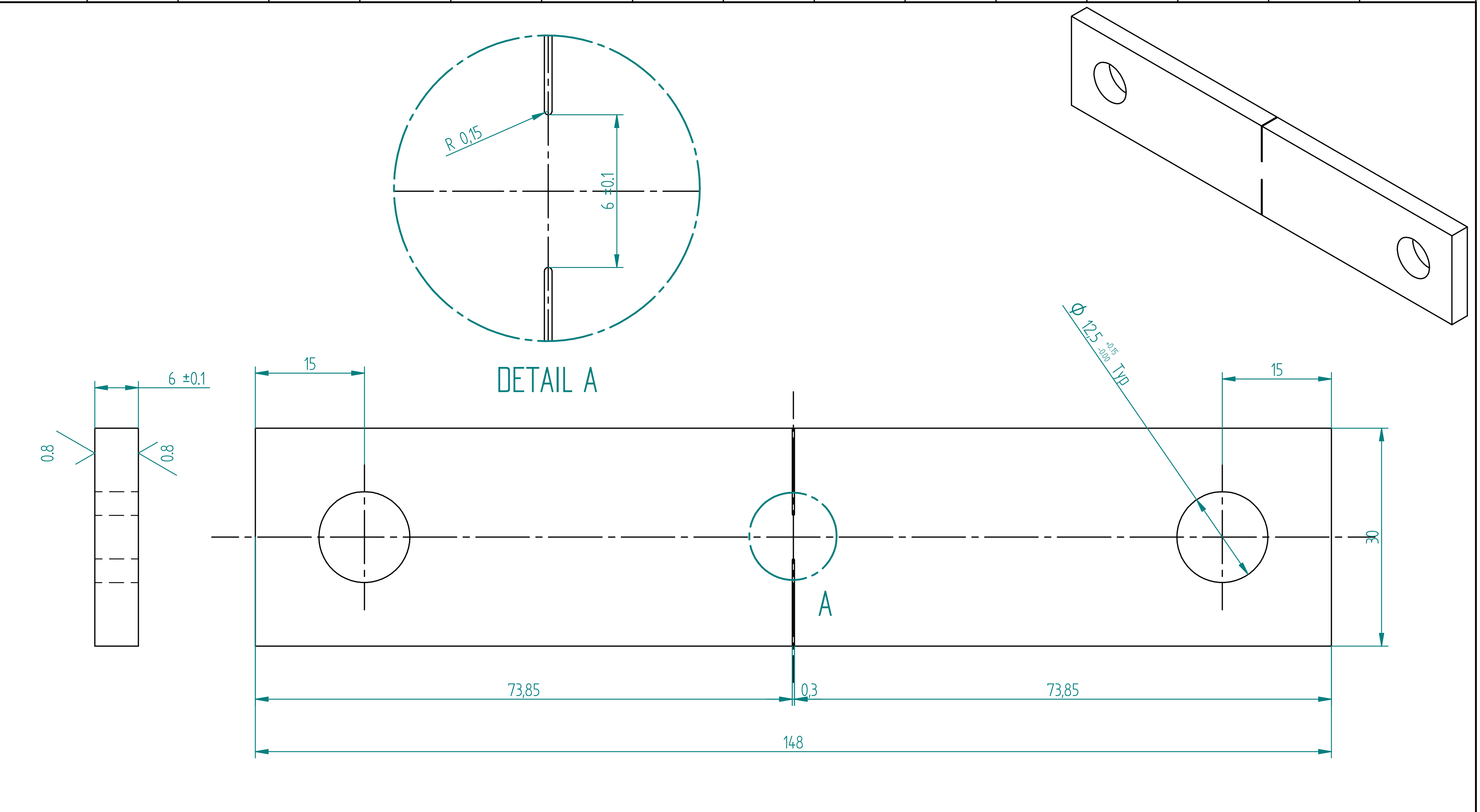

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DIMENSIONS IN mm
UNLESS OTHERWISE STATED
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Material: Alloy 1 Plate 7.5mm
Quantity: 2

Type 3_0.15 tensile

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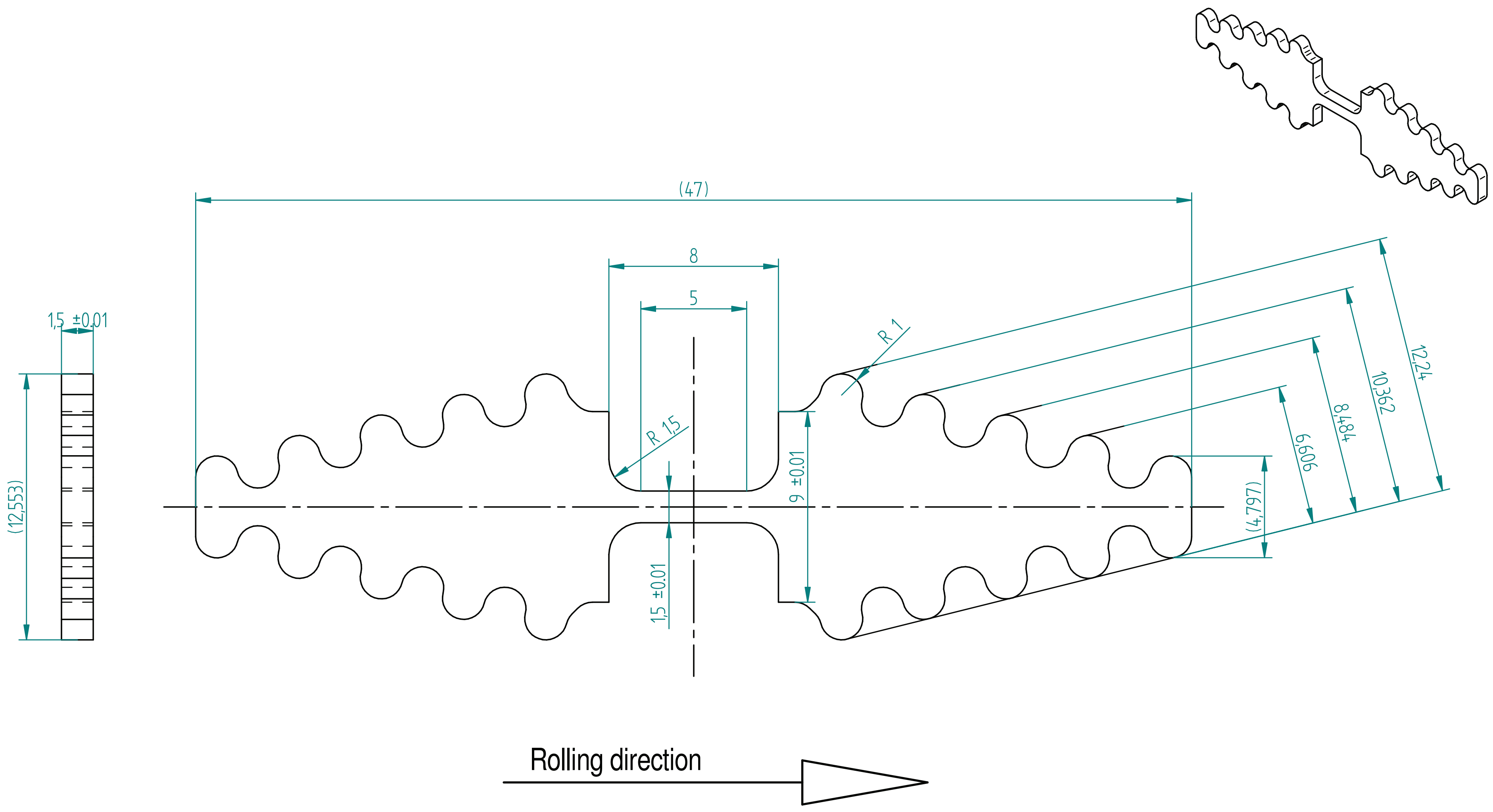

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Quantity:

Type 4_5 tensile

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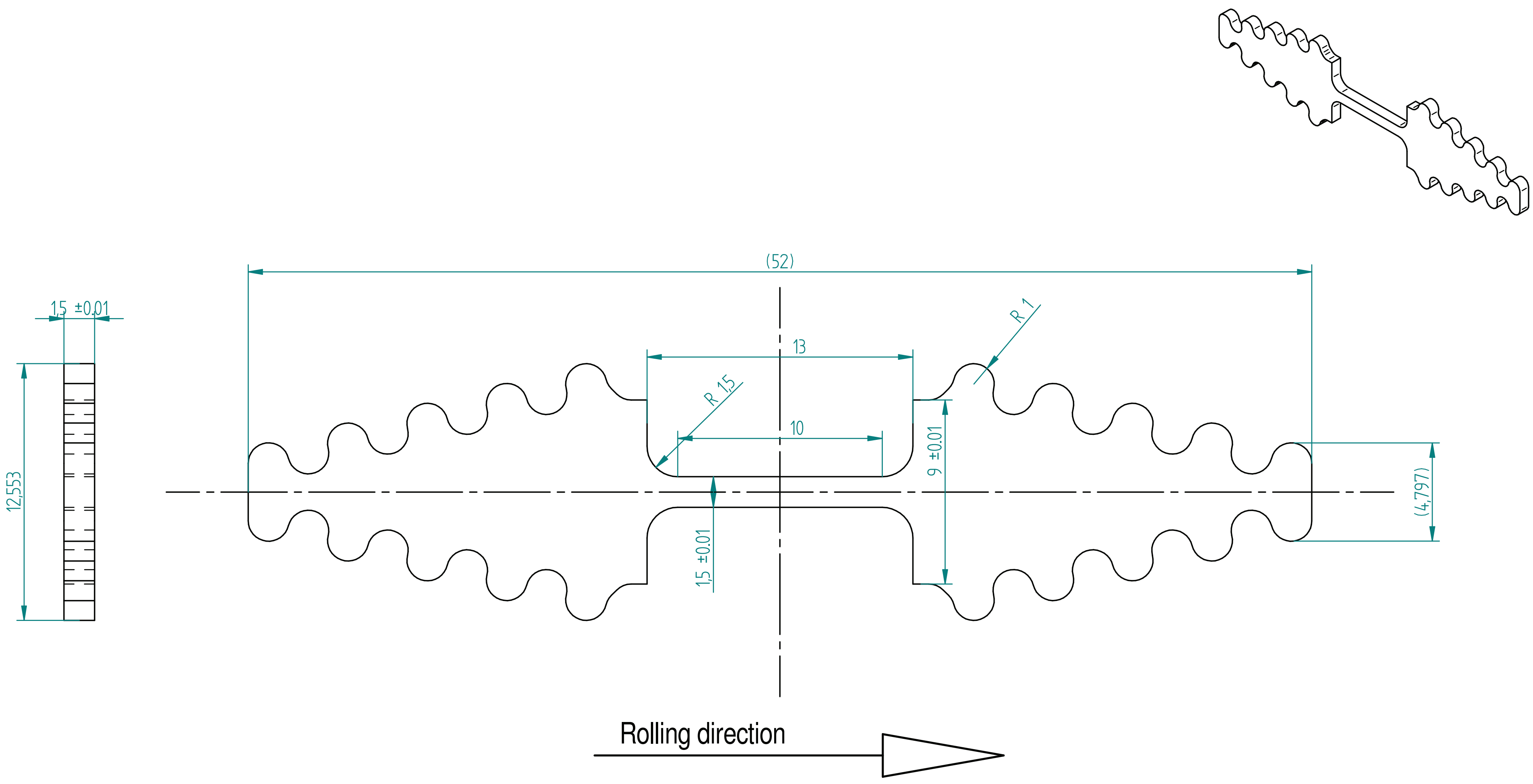

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DIMENSIONS IN mm UNLESS OTHERWISE STATED

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2010/10/21

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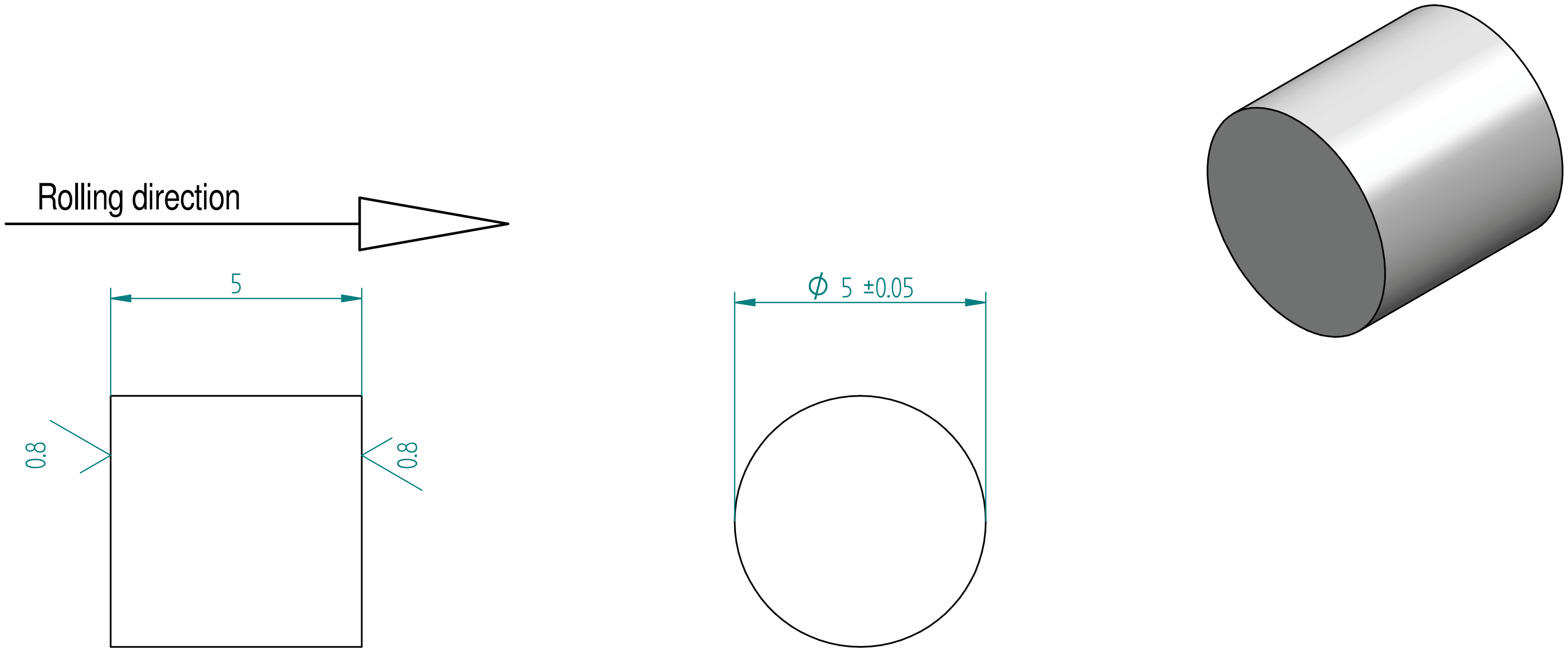

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DIMENSIONS IN mm UNLESS OTHERWISE STATED

DRAWING NUMBER MC2410688-2010-9-6-002

Material: Alloy #1
Quantity: 1

Type 5 compression

SHT OF REV

CHAPTER 9

Appendix B

This appendix includes all the ballistic test results and show sorted data for every test plate.

Date	2010-06-29			
Plate	ˉFL 1/3 [2210124] TP1			
Nominal Thickness	7.5 mm	**16.61**	V drop over 13.5m	
Distance	15 m			
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation (12)		
7	26.3	1004.9	Perforated	1	0	1004.9		
22	26.3	999.6	Perforated	1	0	999.6		
8	26.3	994.13	Perforated	1	0	994.13	46.62	
10	25.7	990.49	Perforated	1	0	990.49	**35.84**	1
6	26.2	988.73	Perforated	1	0	988.73	32.71	1
21	26.3	988.73	Perforated	1	0	988.73	24.32	1
9	26.1	985.13	Perforated	1	0	985.13	18.2	1
3	25.8	983.77	Perforated	1	0	983.77	16.18	1
4	25.9	976.18	Perforated	1	0	976.18	8.31	1
19	25.9	970.78	Perforated	1	0	970.78	2.35	1
18	25.8	964.97	Perforated	1	0	964.97	-9.69	1
12	25.6	961.72	Perforated	1	0	961.72	-13.32	1
1	25.2	947.51	Non-Perforation	0	947.51	0		
14	25.4	954.65	Non-Perforation	0	954.65	0		
15	25.3	956.02	Non-Perforation	0	956.02	0		
13	25.5	964.41	Non-Perforation	0	964.41	0		
11	25.5	966.93	Non-Perforation	0	966.93	0		
17	25.7	967.59	Non-Perforation	0	967.59	0		
20	25.9	967.87	Non-Perforation	0	967.87	0		
5	26	968.43	Non-Perforation	0	968.43	0		
2	25.5	974.66	Non-Perforation	0	974.66	0		
16	25.6	975.04	Non-Perforation	0	975.04	0		

	Min	947.51	966.1777778	978.944444	**V 50 =**	**956.0 m/s**	
22	Max	1004.9					
	D	57.39	938.05	973.89	**+**	17.9	
					-	17.9	
					Number of Shots	18	

Date	2010-06-30		
Plate	'FL 3/1 [2210124] TP2		
Nominal Thickness	7.5	16.61	V drop over 13.5m
Distance	15		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (9)	Perforation (15)			
15	27.4	1048.1	Perforated	1	0	1048.1			
16	27.3	1044.2	Perforated	1	0	1044.2			
18	27.2	1033.9	Perforated	1	0	1033.9			
17	27.3	1026.4	Perforated	1	0	1026.4			
14	27.2	1022.9	Perforated	1	0	1022.9			
11	27	1017.9	Perforated	1	0	1017.9			
8	27.2	1015.5	Perforated	1	0	1015.5		62.12	
9	27	1014.5	Perforated	1	0	1014.5		52.78	
19	27.2	1013.6	Perforated	1	0	1013.6		50.95	
20	27.1	1013	Perforated	1	0	1013		42.5	
21	27	1011.7	Perforated	1	0	1011.7		**23.95**	1
22	26.8	1006.8	Perforated	1	0	1006.8		17.19	1
12	27	997.41	Perforated	1	0	997.41		4.85	1
13	27.1	996.71	Perforated	1	0	996.71		-1.99	1
23	26.6	988.34	Perforated	1	0	988.34		-16.96	1
3	25.8	953.38	Non-Perforation	0	953.38	0			
2	25.6	961.72	Non-Perforation	0	961.72	0			
1	25.4	962.65	Non-Perforation	0	962.65	0			
4	26	970.5	Non-Perforation	0	970.5	0			
6	26.6	987.75	Non-Perforation	0	987.75	0			
24	26.4	989.61	Non-Perforation	0	989.61	0			
5	26.5	992.56	Non-Perforation	0	992.56	0			
7	26.8	998.7	Non-Perforation	0	998.7	0			
10	26.9	1005.3	Non-Perforation	0	1005.3	0			
	Min	953.38			994.8	1000.2	**V 50 =**	**980.9 m/s**	
24	Max	1048.1							
	D	94.72			971.15	995.10	**+**	14.2	
							-	9.7	

Number of Shots 10

Date 2010-06-30
Plate FL 5/1 [2208934] TP3
Nominal Thickness 8.5 16.61 V drop over 13.5m
Distance 15
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					14	12		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		
1	27.5	1043.6	Perforated	1	0	1043.6	67.04	
2	27	1027.7	Perforated	1	0	1027.7	51.14	
3	26.8	1020	Perforated	1	0	1020	41.91	
23	26.8	1017.3	Perforated	1	0	1017.3	**36.62**	1
26	26.7	1016.8	Perforated	1	0	1016.8	35.35	1
5	26.5	1015.4	Perforated	1	0	1015.4	32.8	1
22	26.8	1013.4	Perforated	1	0	1013.4	26.82	1
24	26.8	1013.3	Perforated	1	0	1013.3	26.62	1
25	26.7	1004.6	Perforated	1	0	1004.6	15.77	1
19	26.6	1003.4	Perforated	1	0	1003.4	7.38	1
7	26.1	982.51	Perforated	1	0	982.51	-15.2	1
11	26	977.04	Perforated	1	0	977.04	-21.46	1
10	25.9	971.54	Non-Perforation	0	971.54	0		
8	26	976.18	Non-Perforation	0	976.18	0		
13	26	976.56	Non-Perforation	0	976.56	0		
16	26.2	978.09	Non-Perforation	0	978.09	0		
12	26.1	980.68	Non-Perforation	0	980.68	0		
14	26.1	981.45	Non-Perforation	0	981.45	0		
17	26.3	982.6	Non-Perforation	0	982.6	0		
6	26.2	986.58	Non-Perforation	0	986.58	0		
21	26.7	986.68	Non-Perforation	0	986.68	0		
9	26	988.83	Non-Perforation	0	988.83	0		
15	26.1	996.02	Non-Perforation	0	996.02	0		
18	26.5	997.71	Non-Perforation	0	997.71	0		
20	26.6	998.5	Non-Perforation	0	998.5	0		
4	26.5	1000.6	NA Same spot	N				

	Min	971.54	989.8	1004.9	**V 50 =**	**980.7 m/s**	
26	Max	1043.6					
	D	72.06	964.85	1000.70	**+**	20.0	
					-	15.9	

Number of Shots 18

Date	2010-06-30			
Plate	ˉFL 3/2 [2210125] TP4			
Nominal Thickness	10.5		16.61	V drop over 13.5m
Distance	15			
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (6)	Perforation (6)		
2	28	1066.8	Perforated	1	0	1066.8	48.6	
12	28.1	1047.7	Perforated	1	0	1047.7	**24**	1
4	27.6	1040.9	Perforated	1	0	1040.9	11.4	1
7	27.5	1040.8	Perforated	1	0	1040.8	6.2	1
10	27.6	1037.9	Perforated	1	0	1037.9	-3.2	1
6	27.5	1035.4	Perforated	1	0	1035.4	-15.2	1
11	28	1018.2	Non-Perforation	0	1018.2	0		
5	27.5	1023.7	Non-Perforation	0	1023.7	0		
8	27.4	1029.5	Non-Perforation	0	1029.5	0		
1	27.5	1034.6	Non-Perforation	0	1034.6	0		
3	27.7	1041.1	Non-Perforation	0	1041.1	0		
9	27.4	1050.6	Non-Perforation	0	1050.6	0		

	Min	1018.2	1035.9	1040.5	**V 50 = 1021.6 m/s**	
12	Max	1066.8				
	D	48.6	1007.10	1031.10	**+**	9.5
					-	14.5
				Number of Shots		10

Date 2010-06-30
Plate ˉFL 1/2 [2210124] TP5
Nominal Thickness 7.5 10.26 V drop over 13.5m
Distance 15
Caliber 7.62mm M80 R1 **V proof = 862m/s (143gr) +-20**

Shot number	Charge [grain]	Velocity [m/s]	Impact Result	Barrel		Non-Perforation (14)	Perforation (9)		
14	55.4	980.68	Perforated		1	0	980.68	25.93	1
10	56	978.28	Perforated		1	0	978.28	10.32	1
22	55.3	976.28	Perforated		1	0	976.28	7.01	1
15	55.4	976.18	Perforated		1	0	976.18	4.27	1
12	55.5	976.09	Perforated		1	0	976.09	3.99	1
11	56	974.18	Perforated		1	0	974.18	-1.81	1
21	55.3	974.09	Perforated		1	0	974.09	-2.57	1
4	55	972.86	Perforated	0.30-06	1	0	972.86	-8.21	1
7	55	971.35	Perforated		1	0	971.35	-10.29	1
1	44	855.65	Non-Perforation		0	855.65	0		
2	46	899.85	Non-Perforation		0	899.85	0		
3	48	930.15	Non-Perforation	0.308	0	930.15	0		
5	53	935.63	Non-Perforation		0	935.63	0		
6	54	953.47	Non-Perforation		0	953.47	0		
8	55	954.75	Non-Perforation		0	954.75	0		
17	55.2	967.96	Non-Perforation		0	967.96	0		
19	55.2	969.27	Non-Perforation		0	969.27	0		
23	55.3	971.91	Non-Perforation		0	971.91	0		
18	55.2	972.1	Non-Perforation		0	972.1	0		
9	55	975.99	Non-Perforation		0	975.99	0		
13	55.5	976.66	Non-Perforation		0	976.66	0		
16	55.3	981.07	Non-Perforation		0	981.07	0		
20	55.3	981.64	Non-Perforation		0	981.64	0		

	Min	855.65	972.4	975.6	**V 50 =**	**963.7 m/s**
23	Max	981.64				
	D	125.99	944.49	970.42	+	6.7
					-	19.2

Number of Shots 18

Date	2010-07-02		
Plate	'FL 3/2 [2210124] TP6		
Nominal Thickness	7.5	10.26	V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation		
					10	10		
10	57	995.22	Perforated	1	0	995.22		
12	56.4	988.83	Perforated	1	0	988.83	56.34	
11	56.5	984.06	Perforated	1	0	984.06	**32.67**	1
16	55.8	983.09	Perforated	1	0	983.09	20.25	1
13	56.2	983	Perforated	1	0	983	16.35	1
14	56.1	979.91	Perforated	1	0	979.91	12.6	1
15	55.9	978.09	Perforated	1	0	978.09	5.61	1
17	55.5	974.18	Perforated	1	0	974.18	-0.66	1
19	55.2	971.72	Perforated	1	0	971.72	-3.7	1
4	55	965.62	Perforated	1	0	965.62	-15.45	1
1	53	932.49	Non-Perforation	0	932.49	0		
2	54	951.39	Non-Perforation	0	951.39	0		
7	55.2	962.84	Non-Perforation	0	962.84	0		
20	55	966.65	Non-Perforation	0	966.65	0		
18	55.2	967.31	Non-Perforation	0	967.31	0		
6	54.7	972.48	Non-Perforation	0	972.48	0		
8	55.5	974.84	Non-Perforation	0	974.84	0		
5	54.5	975.42	Non-Perforation	0	975.42	0		
9	56	981.07	Non-Perforation	0	981.07	0		
3	55	967.87	Na Overlap with clamp plate					

	Min	932.49	969.0	977.5	**V 50 =**	**963.0**	**m/s**
20	Max	995.22					
	D	62.73	941.13	973.80	**+**	10.8	
					-	21.8	

Number of Shots 16

Date	2010-07-02	**2010-08-04**	Test plate 7
Plate	FL 5/2 [2208934] TP7		
Nominal Thickness	8.5		10.26 V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation	< 40 ?		
					15	8			
23	60.2	1026.8	Perforated	1	0	1026.8		65.82	
1	55	963.21	Perforated	1	0	963.21		0.74	1
16	54.8	962.56	Perforated	1	0	962.56		-3.62	1
9	54.2	956.02	Perforated [UNFAIR <mm]	1	0	956.02		-11.47	1
2	54.7	954.11	Perforated	1	0	954.11		-14.23	1
7	54.7	951.84	Perforated	1	0	951.84		-24.06	1
5	55	950.75	Perforated	1	0	950.75		-34.57	1
8	54.5	938.88	Perforated	1	0	938.88		-51.02	1
6	44.7	752.96	Non-Perforation	0	752.96	0			
12	54.4	951.84	Non-Perforation	0	951.84	0			
15	54.7	954.38	Non-Perforation	0	954.38	0			
11	54.3	955.02	Non-Perforation	0	955.02	0			
10	54.2	957.49	Non-Perforation	0	957.49	0			
13	54.5	960.06	Non-Perforation	0	960.06	0			
4	54.5	960.71	Non-Perforation	0	960.71	0			
19	55.2	960.98	Non-Perforation	0	960.98	0			
14	54.6	962.47	Non-Perforation	0	962.47	0			
17	54.8	966.18	Non-Perforation	0	966.18	0			
3	54.5	967.49	Non-Perforation	0	967.49	0			
18	55	968.34	Non-Perforation	0	968.34	0			
20	55.4	975.9	Non-Perforation	0	975.9	0			
22	55.9	985.32	Non-Perforation	0	985.32	0			
21	55.7	989.9	Non-Perforation	0	989.9	0			

	Min	752.96		973.7	953.9	**V 50 =**	**953.5 m/s**	
23	Max	1026.8				D	71.5	
	D	273.84	952.21		979.64	+	26.12	
						-	1.31	
						Number of shots		14

Date	2010-08-04		Test plate 8
Plate	FL 3/3 [2210125] TP8		
Nominal Thickness	10		10.26	V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

					4	6			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**		
1	60.2	1041.7	Perforated	1	0	1041.7		1041.7	
2	57	1003.2	Perforated	1	0	1003.2		1003.2	
8	56.3	995.52	Perforated	1	0	995.52		28.31	1
6	56.5	993.35	Perforated	1	0	993.35		23.55	1
5	56.5	988.53	Perforated	1	0	988.53		8.81	1
9	56.2	980.3	Perforated	1	0	980.3		-3.57	1
10	55.5	967.21	Non-Perforation	0	967.21	0			
3	55	969.8	Non-Perforation	0	969.8	0			
7	56.2	979.72	Non-Perforation	0	979.72	0			
4	56	983.87	Non-Perforation	0	983.87	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			

	Min	967.21	975.2		989.4	**V 50 =**	**972.0 m/s**
10	Max	1041.7				D	90.0
	D	74.49		956.95	985.26	+	13.23
						-	15.0774999999990

Number of shots 8

Date	2010-08-04		Test plate 9	
Plate	B 500T TP9			
Nominal Thickness	8.5		10.26	V drop over 13.5m
Distance	15			
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**		

					12	11		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
1	53	927.13	Perforated	1	0	927.13	38.79	1
3	52	919.96	Perforated	1	0	919.96	30.68	1
16	51.6	917.85	Perforated	1	0	917.85	24.11	1
10	51.4	915	Perforated	1	0	915	20.62	1
20	51.6	912.74	Perforated	1	0	912.74	17.24	1
5	51.5	907.19	Perforated	1	0	907.19	10.73	1
14	51.5	906.95	Perforated	1	0	906.95	10.01	1
18	51.6	906.54	Perforated	1	0	906.54	8.95	1
19	51.6	905.22	Perforated	1	0	905.22	6.26	1
21	51.5	903.83	Perforated	1	0	903.83	4.79	1
7	51.5	897.42	Perforated	1	0	897.42	-3.89	1
12	51.4	885.58	Non-Perforation	0	885.58	0		
4	51	888.34	Non-Perforation	0	888.34	0		
15	51.5	889.28	Non-Perforation	0	889.28	0		
9	51.4	893.74	Non-Perforation	0	893.74	0		
17	51.6	894.38	Non-Perforation	0	894.38	0		
2	51	895.5	Non-Perforation	0	895.5	0		
11	51.4	896.46	Non-Perforation	0	896.46	0		
23	51.4	896.94	Non-Perforation	0	896.94	0		
22	51.5	897.59	Non-Perforation	0	897.59	0		
6	51.4	898.96	Non-Perforation	0	898.96	0		
13	51.5	899.04	Non-Perforation	0	899.04	0		
8	51.5	901.31	Non-Perforation	0	901.31	0		
	Min	885.58			895.6	910.9	**V 50 =**	**893.0 m/s**
23	Max	927.13					D	11.0
	D	41.55			878.08	916.87	+	23.89
							-	14.90
							Number o	22

Date	2010-08-05	Test plate 10	
Plate	B 500T TP10		
Nominal Thickness	10	10.26	V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

					7	8		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
1	55	968.34	Perforated	1	0	968.34		
3	54	958.22	Perforated	1	0	958.22	26.51	1
9	53.5	957.21	Perforated	1	0	957.21	17.63	1
11	53.4	951.75	Perforated	1	0	951.75	11.37	1
8	53.5	951.39	Perforated	1	0	951.39	11.01	1
14	53.3	950.75	Perforated	1	0	950.75	10.1	1
12	53.4	949.4	Perforated	1	0	949.4	6.98	1
5	53.5	947.69	Perforated	1	0	947.69	1.86	1
10	53.4	931.71	Non-Perforation	0	931.71	0		
6	53.3	939.58	Non-Perforation	0	939.58	0		
4	53.5	940.38	Non-Perforation	0	940.38	0		
15	53.2	940.38	Non-Perforation	0	940.38	0		
2	53	940.65	Non-Perforation	0	940.65	0		
7	53.4	942.42	Non-Perforation	0	942.42	0		
13	53.3	945.83	Non-Perforation	0	945.83	0		
					0	0		
					0	0		
					0	0		
					0	0		
					0	0		
					0	0		
					0	0		
					0	0		

	Min	931.71	940.1	952.3	**V 50 =**	**936.0 m/s**	
15	Max	968.34			D	54.0	
	D	36.63	921.45	947.96	+	11.98	
					-	14.53	
					Number o	14	

Date	2010-08-05	Test plate 11	
Plate	B 600T TP11		
Nominal Thickness	6.5	10.26	V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

					-1	1	
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**
1	54	966	Perforated	1	0	966	
2	53	938.62	Non-Perforation	0	938.62	0	-953.74
3	53.5	946.52	Non-Perforation	0	946.52	0	-951.2
4	53.7	946.7	Non-Perforation	0	946.7	0	0
5	53.7	949.4	Non-Perforation	0	949.4	0	0
6	53.8	946.07	Non-Perforation	0	946.07	0	0
7	54	959.42	Non-Perforation	0	959.42	0	0
8	54.1	957.49	Non-Perforation	0	957.49	0	0
9	54.2	953.74	Non-Perforation	0	953.74	0	
10	54.3	951.2	Non-Perforation	0	951.2	0	
11				0	0	0	
12				0	0	0	
13				0	0	0	
14				0	0	0	
15				0	0	0	
16					0	0	
17					0	0	
18					0	0	
19					0	0	
20					0	0	
21					0	0	
22					0	0	
23					0	0	
24							
25							
	Min	938.62			272.1	0.0	**V 50 = 125.8 m/s**
	Max	966					D -756.2
	D	27.38			951.20	0.00	+ -125.81
							- -825.39

Number of shots 0

Date	2010-08-05			
Plate	B 500 PT12			
Nominal Thickness	8.5		16.61	V drop over 13.5m
Distance	15			
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

					15	10			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
1	27	1003.7	Perforated	1	0	1003.7		111.16	
3	26	987.75	Perforated	1	0	987.75		94.73	
2	26.5	983.09	Perforated	1	0	983.09		86.31	
4	25	944.64	Perforated	1	0	944.64		45.2	
8	24.4	928.25	Perforated	1	0	928.25		27.02	1
7	24.6	921.57	Perforated	1	0	921.57		19.86	1
25	24	910.33	Perforated	1	0	910.33		2.64	1
17	23.5	904.9	Perforated	1	0	904.9		-16.33	1
15	23.5	904.32	Perforated	1	0	904.32		-19.72	1
10	24	898.64	Perforated	1	0	898.64		-27.03	1
21	23.6	879.66	Non-Perforation	0	879.66	0			
20	23.5	882.22	Non-Perforation	0	882.22	0			
13	23.4	887.15	Non-Perforation	0	887.15	0			
19	23.3	887.31	Non-Perforation	0	887.31	0			
18	23.4	891.43	Non-Perforation	0	891.43	0			
14	23.5	892.54	Non-Perforation	0	892.54	0			
22	23.7	893.02	Non-Perforation	0	893.02	0			
24	23.9	896.78	Non-Perforation	0	896.78	0			
11	23.8	899.44	Non-Perforation	0	899.44	0			
16	23.5	901.23	Non-Perforation	0	901.23	0			
12	23.6	901.71	Non-Perforation	0	901.71	0			
23	23.8	907.69	Non-Perforation	0	907.69	0			
9	24.2	921.23	Non-Perforation	0	921.23	0			
6	24.5	924.04	Non-Perforation	0	924.04	0			
5	24	925.67	Non-Perforation	0	925.67	0			
	Min	879.66			913.6	911.3	**V 50 =**	**895.9 m/s**	
25	Max	1003.7					d	-61.1	
	D	124.04			884.63	911.65	+	15.79	
							-	11.23	
								Number o	12

Date 2010-08-05
Plate B 500 PT13
Nominal Thickness 10.2 16.61 V drop over 13.5m
Distance 15
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					11	4			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
2	27.2	1031.5	Perforated	1	0	1031.5		4.5	1
6	27.2	1026.6	Perforated	1	0	1026.6		-5.7	1
5	27.2	1023.8	Perforated	1	0	1023.8		-10.3	1
10	27.3	1022.7	Perforated	1	0	1022.7		-13.4	1
15	28	1028.4	Non-Perforation	0	891.43	0			
9	27.2	1009.1	Non-Perforation	0	1009.1	0			
11	27.3	1016.9	Non-Perforation	0	1016.9	0			
7	27.1	1020.3	Non-Perforation	0	1020.3	0			
1	27	1023	Non-Perforation	0	1023	0			
12	27.4	1024.2	Non-Perforation	0	1024.2	0			
8	27.1	1024.9	Non-Perforation	0	1024.9	0			
3	27.1	1027	Non-Perforation	0	1027	0			
4	27.1	1032.3	Non-Perforation	0	1032.3	0			
13	27.5	1034.1	Non-Perforation	0	1034.1	0			
14	27.7	1036.1	Non-Perforation	0	1036.1	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
				0	0	0			
	Min	1009.1			1032.4	1026.2	**V 50 =**	**1012.7 m/s**	
15	Max	1036.1					d	55.7	
	D	27			1010.40	1014.90	+	2.24	
							-	2.26	
								Number of	8

Date 2010-08-05
Plate B 600 PT14
Nominal Thickness 6.3 16.61 V drop over 13.5m
Distance 15
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					10	10			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
11	26.9	1021.10	Perforated	1	0	1021.1		32.57	1
15	26.9	1020.40	Perforated	1	0	1020.4		27.55	1
13	26.9	1014.80	Perforated	1	0	1014.8		20.96	1
16	26.8	1007.10	Perforated	1	0	1007.1		9.19	1
1	27.0	1005.60	Perforated	1	0	1005.6		7.59	1
3	26.8	1005.60	Perforated	1	0	1005.6		7.2	1
8	26.8	1003.70	Perforated	1	0	1003.7		4.7	1
17	26.7	1003.00	Perforated	1	0	1003		3.4	1
19	26.6	1001.90	Perforated	1	0	1001.9		1.5	1
5	26.7	1001.10	Perforated	1	0	1001.1		-2.6	1
7	26.7	988.53	Non-Perforation	0	988.53	0			
12	26.8	992.85	Non-Perforation	0	992.85	0			
2	26.5	993.84	Non-Perforation	0	993.84	0			
18	26.6	997.91	Non-Perforation	0	997.91	0			
6	26.6	998.01	Non-Perforation	0	998.01	0			
10	26.8	998.40	Non-Perforation	0	998.4	0			
20	26.5	999.00	Non-Perforation	0	999	0			
9	26.7	999.60	Non-Perforation	0	999.6	0			
4	26.6	1000.40	Non-Perforation	0	1000.4	0			
14	26.8	1003.70	Non-Perforation	0	1003.7	0			
					0	0			
					0	0			
					0	0			
					0	0			
					0	0			
	Min	988.53			997.2	1008.4	**V 50 =**	**986.2 m/s**	
20	Max	1021.1					d	29.2	
	D	32.57			971.93	1004.50	+	18.27	
							-	14.30	
								Number o	20

Date 2010-09-09
Plate B 600 TP15
Nominal Thickness 4 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					14	11		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
11	24.6	944.73	Perforated	1	0	944.73	31.49	1
21	24.6	943.75	Perforated	1	0	943.75	28.08	1
24	24.6	942.77	Perforated	1	0	942.77	26.26	1
16	24.6	940.91	Perforated	1	0	940.91	23.9	1
6	24.7	939.14	Perforated	1	0	939.14	19.94	1
5	25.0	938.88	Perforated	1	0	938.88	19.51	1
10	24.6	937.30	Perforated	1	0	937.3	16.49	1
18	24.6	937.30	Perforated	1	0	937.3	16.4	1
20	24.6	936.68	Perforated	1	0	936.68	13.15	1
13	24.5	935.81	Perforated	1	0	935.81	9.88	1
7	24.6	931.10	Perforated	1	0	931.1	2.85	1
1	23.0	877.73	Non-Perforation	0	877.73	0		
2	23.5	893.66	Non-Perforation	0	893.66	0		
23	24.5	895.90	Non-Perforation	0	895.9	0		
8	24.4	913.24	Non-Perforation	0	913.24	0		
15	24.5	915.67	Non-Perforation	0	915.67	0		
14	24.5	916.51	Non-Perforation	0	916.51	0		
4	24.5	917.01	Non-Perforation	0	917.01	0		
12	24.5	919.20	Non-Perforation	0	919.2	0		
17	24.6	919.37	Non-Perforation	0	919.37	0		
3	24.0	920.81	Non-Perforation	0	920.81	0		
25	24.6	920.90	Non-Perforation	0	920.9	0		
22	24.5	923.53	Non-Perforation	0	923.53	0		
19	24.6	925.93	Non-Perforation	0	925.93	0		
9	24.5	928.25	Non-Perforation	0	928.25	0		

	Min	877.73	920.0381818	938.942727	**V 50 =**	**912.9 m/s**	
25	Max	944.73					
	D	67	896.64	928.13	+	15.24	
					-	16.25	
					No. of shots		22

Date	2010-09-09
Plate	B 500 TP16
Nominal Thickness	6 mm
Distance	15 m
Caliber	5.56mm M193 [R4]

16.61 V drop over 13.5m

V proof = 937m/s +-20

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (11)	Perforation (14)	< 40 ?	
2	24.0	917.94	Perforated	1	0	917.94		
11	23.3	911.16	Perforated	1	0	911.16		
10	23.3	909.26	Perforated	1	0	909.26		
3	23.5	903.92	Perforated	1	0	903.92	**38.8**	1
19	23.2	901.71	Perforated	1	0	901.71	26.1	1
21	23.2	901.23	Perforated	1	0	901.23	21.3	1
17	23.2	899.20	Perforated	1	0	899.2	15.9	1
22	23.2	899.20	Perforated	1	0	899.2	14.2	1
14	23.2	898.96	Perforated	1	0	898.96	13.8	1
8	23.2	897.59	Perforated	1	0	897.59	11.4	1
25	23.2	894.69	Perforated	1	0	894.69	7.46	1
20	23.2	893.58	Perforated	1	0	893.58	5.32	1
4	23.2	892.78	Perforated	1	0	892.78	1.22	1
24	23.2	892.54	Perforated	1	0	892.54	-4	1
7	23.1	865.13	Non-Perforation	0	865.13	0		
5	23.0	875.66	Non-Perforation	0	875.66	0		
6	23.1	879.89	Non-Perforation	0	879.89	0		
12	23.2	883.31	Non-Perforation	0	883.31	0		
15	23.2	884.96	Non-Perforation	0	884.96	0		
23	23.2	885.19	Non-Perforation	0	885.19	0		
13	23.2	886.21	Non-Perforation	0	886.21	0		
18	23.2	887.23	Non-Perforation	0	887.23	0		
1	23.0	888.26	Non-Perforation	0	888.26	0		
9	23.2	891.56	Non-Perforation	0	891.56	0		
16	23.2	896.54	Non-Perforation	0	896.54	0		

	Min	865.13	883.9945455	897.763636	**V 50 = 874.3 m/s**	
25	Max	917.94				
	D	52.81	848.53	887.32	+	13.04
					-	25.75
					No. of	22

Date	2010-09-09			
Plate	B 600 TP17			
Nominal Thickness	10 mm		16.61	V drop over 13.5m
Distance	15 m			
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (13)	Perforation (12)	< 40 ?	
3	28.0	1049.80	Perforated	1	0	1049.8	30.5	1
17	27.4	1047.50	Perforated	1	0	1047.5	26.9	1
7	27.6	1045.50	Perforated	1	0	1045.5	23	1
19	27.4	1042.80	Perforated	1	0	1042.8	17.4	1
4	28.0	1042.10	Perforated	1	0	1042.1	16.5	1
12	27.6	1037.10	Perforated	1	0	1037.1	8.9	1
11	27.5	1036.90	Perforated	1	0	1036.9	7.4	1
5	27.8	1035.10	Perforated	1	0	1035.1	4.8	1
6	27.6	1033.30	Perforated	1	0	1033.3	2.7	1
21	27.4	1032.10	Perforated	1	0	1032.1	-0.9	1
14	27.6	1029.70	Perforated	1	0	1029.7	-5.1	1
13	27.6	1029.30	Perforated	1	0	1029.3	-7.2	1
1	27.0	1016.20	Non-Perforation	0	1016.2	0		
25	27.4	1019.30	Non-Perforation	0	1019.3	0		
24	27.4	1020.60	Non-Perforation	0	1020.6	0		
10	27.4	1022.50	Non-Perforation	0	1022.5	0		
22	27.4	1025.40	Non-Perforation	0	1025.4	0		
18	27.4	1025.60	Non-Perforation	0	1025.6	0		
15	27.5	1028.20	Non-Perforation	0	1028.2	0		
8	27.5	1029.50	Non-Perforation	0	1029.5	0		
2	27.5	1030.30	Non-Perforation	0	1030.3	0		
16	27.4	1030.60	Non-Perforation	0	1030.6	0		
20	27.4	1033.00	Non-Perforation	0	1033	0		
9	27.5	1034.80	Non-Perforation	0	1034.8	0		
23	27.4	1036.50	Non-Perforation	0	1036.5	0		
	Min	1016.2			1028.025	1038.43333	**V 50 = 1016.6 m/s**	
25	Max	1049.8						
	D	33.6			1002.70	1033.20 +	16.57	
						-	13.93	
							No. of s	24

Date 2010-09-09
Plate B 600 TP18
Nominal Thickness 4 10.26 V drop over 13.5m
Distance 15
Caliber 7.62mm M80 R1 **V proof = 862m/s (143gr) +-20**

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation	< 40 ?	
					5	7		
1	51.0	887.79	Perforated	1	0	887.79	887.8	
2	50.0	868.74	Perforated	1	0	868.74	868.7	
3	49.0	831.74	Perforated	1	0	831.74	**46.5**	
9	47.7	818.87	Perforated	1	0	818.87	21.93	1
5	48.0	815.20	Perforated	1	0	815.2	9.2	1
4	48.0	812.42	Perforated	1	0	812.42	6.03	1
11	47.6	811.69	Perforated	1	0	811.69	3.61	1
6	47.0	785.24	Non-Perforation	0	785.24	0		
7	47.5	796.94	Non-Perforation	0	796.94	0		
10	47.6	806.00	Non-Perforation	0	806	0		
8	47.6	806.39	Non-Perforation	0	806.39	0		
12	47.5	808.08	Non-Perforation	0	808.08	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		

	Min	785.24	804.4	814.5	**V 50 =**	**799.2 m/s**
12	Max	887.79				
	D	102.55	786.68	808.61 +	9.42	
				-	12.51	
					No. of s	8

Date	2010-09-09		
Plate	B 500 TP19		
Nominal Thickness	6	10.26	V drop over 13.5m
Distance	15		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		12 Non-Perforation	13 Perforation	**< 40 ?**	
21	50.8	886.53	Perforated	1	0	886.53	886.5	
19	50.8	881.68	Perforated	1	0	881.68	**87.27**	
9	50.5	877.96	Perforated	1	0	877.96	16.48	1
3	51.0	877.27	Perforated	1	0	877.27	13.19	1
8	50.5	876.58	Perforated	1	0	876.58	12.27	1
20	50.8	876.50	Perforated	1	0	876.5	10.92	1
4	50.5	875.96	Perforated	1	0	875.96	9.11	1
10	50.5	875.66	Perforated	1	0	875.66	8.73	1
23	50.6	874.74	Perforated	1	0	874.74	4.49	1
22	50.7	874.51	Perforated	1	0	874.51	4.04	1
14	50.5	873.90	Perforated	1	0	873.9	2.59	1
18	50.8	873.21	Perforated	1	0	873.21	1.9	1
17	50.7	871.76	Perforated	1	0	871.76	0.07	1
1	47.0	794.41	Non-Perforation	0	794.41	0		
24	50.5	861.48	Non-Perforation	0	861.48	0		
12	50.4	864.08	Non-Perforation	0	864.08	0		
5	50.2	864.31	Non-Perforation	0	864.31	0		
6	50.3	865.58	Non-Perforation	0	865.58	0		
2	50.0	866.85	Non-Perforation	0	866.85	0		
11	50.4	866.93	Non-Perforation	0	866.93	0		
7	50.4	870.25	Non-Perforation	0	870.25	0		
15	50.5	870.47	Non-Perforation	0	870.47	0		
16	50.6	871.31	Non-Perforation	0	871.31	0		
25	50.4	871.31	Non-Perforation	0	871.31	0		
13	50.5	871.69	Non-Perforation	0	871.69	0		

	Min	794.41	867.7	875.3	**V 50 = 861.2 m/s**		
25	Max	886.53					
	D	92.12	851.22	867.70	+	6.49	
					-	9.99	
						No. of s	22

Date 2010-09-09 Test plate 11
Plate B 600 TP11
Nominal Thickness 6.5 10.26 V drop over 13.5m
Distance 15
Caliber 7.62mm M80 R1 **V proof = 862m/s (143gr) +-20**

					16	9			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
13	56.0	983.67	Perforated	1	0	983.67		29.93	1
23	55.7	982.13	Perforated	1	0	982.13		24.64	1
24	55.8	978.57	Perforated	1	0	978.57		19.15	1
15	55.8	977.04	Perforated	1	0	977.04		13.18	1
16	55.5	976.37	Perforated	1	0	976.37		8.69	1
21	55.7	973.81	Perforated	1	0	973.81		3.31	1
20	55.6	971.44	Perforated	1	0	971.44		-1.51	1
14	55.5	966.93	Perforated	1	0	966.93		-8.11	1
1	54.0	966.00	Perforated	1	0	966		-10.09	1
2	53.0	938.62	Non-Perforation	0	938.62	0			
11	54.0	942.33	Non-Perforation	0	942.33	0			
6	53.8	946.07	Non-Perforation	0	946.07	0			
3	53.5	946.52	Non-Perforation	0	946.52	0			
4	53.7	946.70	Non-Perforation	0	946.7	0			
5	53.7	949.40	Non-Perforation	0	949.4	0			
10	54.3	951.20	Non-Perforation	0	951.2	0			
9	54.2	953.74	Non-Perforation	0	953.74	0			
8	54.1	957.49	Non-Perforation	0	957.49	0			
7	54.0	959.42	Non-Perforation	0	959.42	0			
12	55.0	963.86	Non-Perforation	0	963.86	0			
17	55.5	967.68	Non-Perforation	0	967.68	0			
18	55.5	970.50	Non-Perforation	0	970.5	0			
19	55.6	972.95	Non-Perforation	0	972.95	0			
22	55.7	975.04	Non-Perforation	0	975.04	0			
25	55.8	976.09	Non-Perforation	0	976.09	0			
	Min	938.62			966.3	975.1		**V 50 = 960.4 m/s**	
25	Max	983.67							
	D	45.05			943.48	973.41	+	12.96	
							-	16.97	
								No. of s	18

Date 2010-10-19
Plate Alloy #1 T SM12 TP22
Nominal Thickness 7.5 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation		
					11	14	**< 40 ?**	
1	26.0	1000.00	CP	1	0	1000		
3	25.2	976.66	CP	1	0	976.66		
2	25.6	975.00	CP	1	0	975		
22	24.6	968.81	CP	1	0	968.81	33.27	1
14	24.7	966.93	CP	1	0	966.93	29.86	1
19	24.7	965.25	CP	1	0	965.25	27.69	1
6	24.8	963.30	CP	1	0	963.3	25.67	1
5	25.1	960.62	CP	1	0	960.62	22.97	1
25	24.6	959.51	CP	1	0	959.51	21.07	1
18	24.7	958.77	CP	1	0	958.77	15.02	1
23	24.6	958.13	CP	1	0	958.13	12.5	1
17	24.7	953.11	CP	1	0	953.11	3.62	1
7	24.5	952.20	PP	1	0	952.2	-0.73	1
11	24.7	946.52	PP	1	0	946.52	-9.05	1
8	24.5	935.54	NP	0	935.54	0		
13	24.6	937.07	NP	0	937.07	0		
24	24.6	937.56	NP	0	937.56	0		
16	24.7	937.63	NP	0	937.63	0		
9	24.6	937.65	NP	0	937.65	0		
20	24.6	938.44	NP	0	938.44	0		
15	24.7	943.75	NP	0	943.75	0		
10	24.6	945.63	NP	0	945.63	0		
12	24.7	949.49	NP	0	949.49	0		
21	24.6	952.93	NP	0	952.93	0		
4	25.0	955.57	NP	0	955.57	0		

	Min	935.54	942.8418182	959.3772727	**V 50 =**	**934.5 m/s**	
25	Max	1000					
	D	64.46	918.94	952.21	**+**	17.70	
					-	15.57	
					no. of shots		22

Date 2010-10-19
Plate Alloy #1 T SM12 TP23
Nominal Thickness 7.5 mm 10.26 V drop over 13.5m
Distance 15 m
Caliber 7.62mm M80 R1 **V proof = 862m/s (143gr) +-20**

					9	16		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
14	55.0	967.49	CP	1	0	967.49		
15	54.9	963.86	CP	1	0	963.86		
17	54.8	963.02	CP	1	0	963.02		
13	55.0	960.89	CP	1	0	960.89		
8	54.8	960.15	CP	1	0	960.15		
7	55.0	957.67	CP	1	0	957.67		
18	54.8	957.58	CP	1	0	957.58		
16	54.9	956.39	CP	1	0	956.39	94.25	
21	54.4	954.47	CP	1	0	954.47	85.66	
20	54.6	953.38	CP	1	0	953.38	70.61	
19	54.7	951.48	CP	1	0	951.48	56.14	
22	54.2	946.43	CP	1	0	946.43	28.75	1
9	54.6	946.34	CP	1	0	946.34	6.14	1
23	54.0	946.07	CP	1	0	946.07	-4.86	1
24	53.8	942.77	CP	1	0	942.77	-11.16	1
25	53.5	937.21	CP	1	0	937.21	-17.35	1
1	50.0	862.14	NP	0	862.14	0		
2	50.5	868.81	NP	0	868.81	0		
3	51.0	882.77	NP	0	882.77	0		
4	51.5	895.34	NP	0	895.34	0		
5	52.5	917.68	NP	0	917.68	0		
6	54.0	940.20	NP	0	940.2	0		
10	55.5	950.93	NP	0	950.93	0		
12	54.8	953.93	NP	0	953.93	0		
11	54.7	954.56	NP	0	954.56	0		

	Min	862.14	943.46	943.764	**V 50 =**	**933.4 m/s**
25	Max	967.49				
	D	105.35	907.42	944.30	**+**	10.95
					-	25.93

no. of shots 10

Date 2010-10-19
Plate Alloy #1 T SM10 TP24
Nominal Thickness 8.5 mm 10.26 V drop over 13.5m
Distance 15 m
Caliber 7.62mm M80 R1 **V proof = 862m/s (143gr) +-20**

					12	13		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
1	55.0	961.54	CP	1	0	961.54		
23	53.7	948.68	CP	1	0	948.68	17.93	1
2	54.0	948.50	CP	1	0	948.5	16.1	1
24	53.8	948.32	CP	1	0	948.32	15.13	1
18	53.7	946.61	CP	1	0	946.61	12.47	1
21	53.7	945.27	PP	1	0	945.27	10.51	1
25	53.8	945.18	CP	1	0	945.18	9.81	1
19	53.7	941.62	CP	1	0	941.62	5.9	1
10	53.6	940.38	CP	1	0	940.38	4.05	1
11	53.6	940.03	CP	1	0	940.03	1.86	1
6	53.5	938.70	PP	1	0	938.7	-1.06	1
5	53.6	937.03	CP	1	0	937.03	-5.92	1
15	53.6	934.06	PP	1	0	934.06	-11.12	1
3	53.0	930.75	NP	0	930.75	0		
16	53.6	932.40	NP	0	932.4	0		
20	53.7	933.19	NP	0	933.19	0		
17	53.6	934.14	NP	0	934.14	0		
12	53.5	934.76	NP	0	934.76	0		
8	53.5	935.37	NP	0	935.37	0		
4	53.5	935.72	NP	0	935.72	0		
14	53.5	936.33	NP	0	936.33	0		
7	53.4	938.17	NP	0	938.17	0		
9	53.6	939.76	NP	0	939.76	0		
22	53.7	942.95	NP	0	942.95	0		
13	53.5	945.18	NP	0	945.18	0		

	Min	930.75	936.56	942.865	**V 50 =**	**929.5 m/s**	
25	Max	961.54					
	D	30.79	920.49	938.42	**+**	8.97	
					-	8.96	
					no. of shots		24

Date 2010-10-19
Plate Alloy #1 T SM10 TP25
Nominal Thickness 8.5 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber **V proof = 937m/s +-20**

					11	14		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
7	26.3	989.22	CP	1	0	989.22		
13	26.0	987.17	CP	1	0	987.17	987.17	
5	26.1	982.41	PP	1	0	982.41	982.41	
6	26.2	976.95	CP	1	0	976.95	38.6	1
1	26.0	973.71	PP	1	0	973.71	30.76	1
9	26.2	972.01	PP	1	0	972.01	19.27	1
10	26.2	970.97	PP	1	0	970.97	15.68	1
2	26.0	970.03	CP	1	0	970.03	13.37	1
12	26.0	969.56	PP	1	0	969.56	12.9	1
3	26.0	968.90	PP	1	0	968.9	8.56	1
8	26.2	967.49	CP	1	0	967.49	4.75	1
18	25.7	958.41	CP	1	0	958.41	-6.38	1
14	25.8	957.95	PP	1	0	957.95	-7.77	1
19	25.7	951.57	CP	1	0	951.57	-17.24	1
23	25.5	938.35	NP	0	938.35	0		
22	25.5	942.95	NP	0	942.95	0		
20	25.6	952.74	NP	0	952.74	0		
24	25.6	955.29	NP	0	955.29	0		
17	25.6	956.66	NP	0	956.66	0		
21	25.6	956.66	NP	0	956.66	0		
16	25.6	960.34	NP	0	960.34	0		
25	25.6	962.74	NP	0	962.74	0		
11	26.0	964.79	NP	0	964.79	0		
15	25.8	965.72	NP	0	965.72	0		
4	26.1	968.81	NP	0	968.81	0		

	Min	938.35	956.8227273	967.05	**V 50 =**	**945.3 m/s**	
25	Max	989.22					
	D	50.87	921.75	960.35	**+**	15.01	
					-	23.59	
						no. of shots	22

Date 2010-10-19
Plate Alloy #1 T SM1 TP26
Nominal Thickness 10 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber **V proof = 937m/s +-20**

					11	14		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
9	27.4	1039.60	PP	1	0	1039.6	1039.6	
8	27.5	1037.40	CP	1	0	1037.4	1037.4	
5	27.6	1033.40	CP	1	0	1033.4	1033.4	
3	27.5	1023.90	PP	1	0	1023.9	55.75	
10	27.3	1023.40	PP	1	0	1023.4	38.76	1
6	27.6	1019.10	PP	1	0	1019.1	28.31	1
14	27.2	1018.40	PP	1	0	1018.4	26.24	1
4	27.5	1016.00	PP	1	0	1016	21.67	1
15	27.2	1014.90	PP	1	0	1014.9	16.7	1
16	27.1	1012.50	PP	1	0	1012.5	13.3	1
18	27.0	1010.70	PP	1	0	1010.7	10.6	1
12	27.2	1004.60	PP	1	0	1004.6	-3	1
17	27.0	1003.20	PP	1	0	1003.2	-10.8	1
23	26.7	988.34	PP	1	0	988.34	-35.06	1
1	26.0	968.15	NP	0	968.15	0		
20	26.6	984.64	NP	0	984.64	0		
24	26.8	990.79	NP	0	990.79	0		
22	26.7	992.16	NP	0	992.16	0		
21	26.7	994.33	NP	0	994.33	0		
19	26.8	998.20	NP	0	998.2	0		
25	26.8	999.20	NP	0	999.2	0		
13	27.2	1000.10	NP	0	1000.1	0		
11	27.2	1007.60	NP	0	1007.6	0		
2	27.0	1014.00	NP	0	1014	0		
7	27.5	1023.40	NP	0	1023.4	0		
	Min	968.15			1000.442	1011.114	**V 50 = 989.2 m/s**	
25	Max	1039.6						
	D	71.45			968.04	1006.80	**+** 17.62	
							- 21.14	

no. of shot: 20

Date	2010-10-19		
Plate	Alloy #1 T SM1 TP27		
Nominal Thickness	10 mm	10.26	V drop over 13.5m
Distance	15 m		
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**	

					14	11		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
21	59.6	978.47	CP	1	0	978.47	18.5	1
1	60.0	977.90	CP	1	0	977.9	17.84	1
23	59.6	975.71	CP	1	0	975.71	14.63	1
25	59.6	974.38	PP	1	0	974.38	12.29	1
22	59.6	973.81	CP	1	0	973.81	11.53	1
24	59.6	973.62	CP	1	0	973.62	9.02	1
12	59.0	967.40	CP	1	0	967.4	2.06	1
13	59.1	966.74	PP	1	0	966.74	-1.13	1
3	59.0	966.46	CP	1	0	966.46	-2.53	1
18	59.4	964.88	CP	1	0	964.88	-5.43	1
9	59.0	963.86	CP	1	0	963.86	-8.53	1
4	58.5	951.39	NP	0	951.39	0		
2	58.0	954.20	NP	0	954.2	0		
6	58.7	955.93	NP	0	955.93	0		
14	59.1	959.97	NP	0	959.97	0		
8	58.9	960.06	NP	0	960.06	0		
7	58.8	961.08	NP	0	961.08	0		
5	58.6	962.09	NP	0	962.09	0		
10	59.0	962.28	NP	0	962.28	0		
11	59.0	964.60	NP	0	964.6	0		
15	59.1	965.34	NP	0	965.34	0		
17	59.3	967.87	NP	0	967.87	0		
16	59.2	968.99	NP	0	968.99	0		
19	59.5	970.31	NP	0	970.31	0		
20	59.5	972.39	NP	0	972.39	0		
	Min	951.39			964.9981818	971.2027273	**V 50 =**	**957.8 m/s**
25	Max	978.47						
	D	27.08			949.71	968.21	**+** 10.37	
							- 8.13	
							no. of shots	22

Date	2011-04-20		
Plate	Alloy #1 SM15 TP29		
Nominal Thickness	7.5 mm	16.61	V drop over 13.5m
Distance	15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (16)	Perforation (10)	< 40 ?	
1	28.0	1042.30	cp	1	0	1042.3	66.12	
25	26.6	1006.50	cp	1	0	1006.5	28.5	1
3	27.0	1004.20	cp	1	0	1004.2	25.25	1
17	26.4	999.90	cp	1	0	999.9	20.25	1
5	26.4	994.13	cp	1	0	994.13	12.58	1
14	26.4	991.57	cp	1	0	991.57	9.93	1
26	26.5	989.9	cp	1	0	989.9	5.36	1
15	26.5	987.07	cp	1	0	987.07	0.19	1
4	26.5	980.01	cp	1	0	980.01	-7.74	1
8	26.4	977.33	cp	1	0	977.33	-14.24	1
2	26.0	950.03	np	0	950.03	0		
6	26.2	965.44	np	0	965.44	0		
22	26.4	973.14	np	0	973.14	0		
7	26.3	974.18	np	0	974.18	0		
21	26.4	975.14	np	0	975.14	0		
19	26.3	976.18	np	0	976.18	0		
16	26.5	978.00	np	0	978	0		
24	26.5	978.95	pp	0	978.95	0		
10	26.3	979.65	np	0	979.65	0		
9	26.4	981.55	pp	0	981.55	0		
12	26.3	981.64	np	0	981.64	0		
20	26.3	984.54	pp	0	984.54	0		
13	26.4	986.88	pp	0	986.88	0		
11	26.3	987.75	np	0	987.75	0		
23	26.5	991.57	pp	0	991.57	0		
18	26.3	975.52	X			0		
	Min	950.03			983.3922222	992.29	**V 50 =**	**971.2 m/s**
26	Max	1042.3						
	D	92.27			961.40	989.90	**+** 18.66	
							- 9.84	
							no. of shots	18

Date	2011-04-20		
Plate	Alloy #1 SM12 TP30		
Nominal Thickness	7.5 mm	16.61	V drop over 13.5m
Distance	15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation (15)	Perforation (10)	**< 40 ?**	
25	27.6	1028.20	cp	1	0	1028.2	27.2	1
24	27.4	1018.40	cp	1	0	1018.4	14.6	1
17	27.0	1017.00	cp	1	0	1017	13.1	1
9	27.0	1015.10	cp	1	0	1015.1	11	1
16	27.0	1011.90	cp	1	0	1011.9	7.6	1
20	26.9	1010.80	cp	1	0	1010.8	4.3	1
11	26.9	1010.30	cp	1	0	1010.3	2.4	1
14	26.8	1008.50	cp	1	0	1008.5	-1.1	1
6	26.8	1006.90	cp	1	0	1006.9	-7.8	1
15	26.9	1003.60	cp	1	0	1003.6	-11.7	1
4	26.6	985.42	pp	0	985.42	0		
5	26.7	992.75	pp	0	992.75	0		
1	26.6	994.63	np	0	994.63	0		
10	26.9	995.22	np	0	995.22	0		
8	26.8	998.50	np	0	998.5	0		
2	26.5	1001.00	pp	0	1001	0		
3	26.5	1003.80	np	0	1003.8	0		
7	26.8	1003.90	pp	0	1003.9	0		
18	26.9	1004.10	pp	0	1004.1	0		
22	27.0	1004.30	np	0	1004.3	0		
12	26.9	1006.50	np	0	1006.5	0		
13	26.8	1007.90	pp	0	1007.9	0		
21	27.0	1009.60	np	0	1009.6	0		
23	27.2	1014.70	np	0	1014.7	0		
19	26.9	1015.30	np	0	1015.3	0		

	Min	985.42	1007.11	1013.07	**V 50 = 993.5 m/s**
25	Max	1028.2			
	D	42.78	984.40	1011.60	**+** 18.11
					- 9.09
					no. of shot: 20

Date 2011-04-20
Plate Alloy #1 SM13 TP31
Nominal Thickness 7 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					11	15			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
2	26.8	1009.20	cp	1	0	1009.2		36.34	1
17	26.9	1009.10	cp	1	0	1009.1		35.96	1
21	26.9	1009.00	cp	1	0	1009		35.67	1
18	26.9	1007.90	cp	1	0	1007.9		31.72	1
19	26.9	1003.10	cp	1	0	1003.1		21.65	1
22	26.9	1000.50	cp	1	0	1000.5		12.55	1
23	26.8	999.80	cp	1	0	999.8		7.83	1
24	26.8	999.00	cp	1	0	999		6.54	1
14	26.8	998.70	cp	1	0	998.7		3.48	1
12	26.7	998.10	cp	1	0	998.1		-0.2	1
11	26.7	996.61	cp	1	0	996.61			
20	26.9	996.31	cp	1	0	996.31			
26	26.6	995.52	cp	1	0	995.52			
7	26.6	994.13	cp	1	0	994.13			
25	26.7	989.02	cp	1	0	989.02			
1	26.5	972.86	np	0	972.86	0			
6	26.5	973.14	np	0	973.14	0			
9	26.5	973.33	pp	0	973.33	0			
3	26.6	976.18	pp	0	976.18	0			
13	26.7	981.45	np	0	981.45	0			
5	26.5	987.95	np	0	987.95	0			
8	26.6	991.97	np	0	991.97	0			
15	26.8	992.46	np	0	992.46	0			
16	27.0	995.22	pp	0	995.22	0			
10	26.6	998.30	np	0	998.3	0			
4	26.5	982.71	X						
	Min	972.86			984.286	1003.44	**V 50 =**	**977.3 m/s**	
26	Max	1009.2							
	D	36.34			956.26	992.60	**+**	15.34	
							-	21.00	
								no. of shots	20

Date	2011-04-20		
Plate	Alloy #1 SM3 TP32		
Nominal Thickness	10 mm	16.61	V drop over 13.5m
Distance	15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation	< 40 ?	
					13	13		
9	28.5	1074.00	cp	1	0	1074	1074	
7	28.4	1071.70	cp	1	0	1071.7	64.8	
14	28.3	1063.60	cp	1	0	1063.6	55.3	
16	28.2	1057.70	cp	1	0	1057.7	41.4	
15	28.3	1053.70	cp	1	0	1053.7	36.1	1
12	28.4	1053.00	cp	1	0	1053	28.4	1
2	28.2	1047.60	cp	1	0	1047.6	22.7	1
13	28.4	1046.90	cp	1	0	1046.9	21.8	1
17	28.1	1044.90	cp	1	0	1044.9	17.1	1
1	28.0	1041.70	cp	1	0	1041.7	13.1	1
3	27.8	1036.90	cp	1	0	1036.9	8.1	1
20	27.5	1030.50	cp	1	0	1030.5	1.5	1
6	27.6	1024.80	cp	1	0	1024.8	-22.2	1
24	27.1	1006.90	np	0	1006.9	0		
26	27.3	1008.30	np	0	1008.3	0		
23	27.2	1016.30	np	0	1016.3	0		
25	27.2	1017.60	np	0	1017.6	0		
5	27.6	1024.60	np	0	1024.6	0		
22	27.3	1024.90	pp	0	1024.9	0		
11	28.3	1025.10	np	0	1025.1	0		
4	27.6	1027.80	np	0	1027.8	0		
19	27.6	1028.60	np	0	1028.6	0		
18	27.8	1028.80	pp	0	1028.8	0		
21	27.4	1029.00	pp	0	1029	0		
10	28.4	1047.00	pp	0	1047	0		
8	28.3	1046.90	x					
	Min	1006.9			1028.155556	1042.222222	**V 50 =**	**1018.6 m/s**
26	Max	1074						
	D	67.1			1001.00	1037.10	**+**	18.51
							-	17.59
							no. of shots	18

Date	2011-05-04		
Plate	Alloy #1 SM12 TP33		
Nominal Thickness	6 mm	16.61	V drop over 13.5m
Distance	15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

					10	15		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
10	25.5	947.87	cp	1	0	947.87	52.93	
16	25.5	947.42	cp	1	0	947.42	36.01	1
17	25.4	946.79	cp	1	0	946.79	32.96	1
15	25.5	946.70	cp	1	0	946.7	31.62	1
13	25.4	944.02	cp	1	0	944.02	27.93	1
20	25.3	940.91	cp	1	0	940.91	20.86	1
9	25.5	940.20	cp	1	0	940.2	16.24	1
11	25.4	938.70	cp	1	0	938.7	12.54	1
21	25.2	937.21	cp	1	0	937.21	3.07	1
14	25.5	937.03	cp	1	0	937.03	1.84	1
1	25.0	935.81	cp	1	0	935.81		
18	25.4	934.14	cp	1	0	934.14		
19	25.4	933.10	cp	1	0	933.1		
25	24.8	930.93	cp	1	0	930.93		
22	25.0	930.84	cp	1	0	930.84		
2	24.0	894.94	np	0	894.94	0		
5	24.8	911.41	np	0	911.41	0		
3	24.5	913.83	np	0	913.83	0		
6	25.0	915.08	np	0	915.08	0		
4	24.7	916.09	np	0	916.09	0		
24	24.8	920.05	np	0	920.05	0		
7	25.2	923.96	np	0	923.96	0		
8	25.3	926.16	np	0	926.16	0		
23	25.0	934.14	np	0	934.14	0		
12	25.4	935.19	pp	0	935.19	0		
	Min	894.94			921.7677778	942.1088889	**V 50 =**	**915.3 m/s**
25	Max	947.87						
	D	52.93			894.81	930.82	**+**	15.48
							-	20.53
							no. of shot:	18

Date 2011-05-04
Plate Alloy #1 RA900 SM12 TP34
Nominal Thickness 7 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					15	10			
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**		**< 40 ?**	
1	28.0	1025.00	cp	1	0	1025		48.91	
18	26.6	999.40	cp	1	0	999.4		21.31	1
16	26.6	998.80	cp	1	0	998.8		20.71	1
15	26.7	996.61	cp	1	0	996.61		17.85	1
13	26.8	996.22	cp	1	0	996.22		14.67	1
2	27.0	989.12	cp	1	0	989.12		4.38	1
21	26.4	987.95	cp	1	0	987.95		1.76	1
3	26.8	987.75	cp	1	0	987.75		-1.96	1
17	26.6	987.66	cp	1	0	987.66		-3.03	1
5	26.5	982.41	cp	1	0	982.41		-8.97	1
7	26.3	968.52	np	0	968.52	0			
6	26.3	973.14	np	0	973.14	0			
4	26.5	975.14	np	0	975.14	0			
10	26.4	975.23	np	0	975.23	0			
23	26.5	975.42	np	0	975.42	0			
11	26.5	976.09	np	0	976.09	0			
20	26.4	978.09	np	0	978.09	0			
24	26.5	978.09	np	0	978.09	0			
22	26.4	978.76	np	0	978.76	0			
9	26.3	981.55	pp	0	981.55	0			
8	26.3	984.74	np	0	984.74	0			
25	26.5	986.19	np	0	986.19	0			
12	26.6	989.71	np	0	989.71	0			
14	26.8	990.69	pp	0	990.69	0			
19	26.5	991.38	pp	0	991.38	0			
	Min	968.52			984.3555556	991.7688889	**V 50 =**	**971.5 m/s**	
25	Max	1025							
	D	56.48			961.49	982.80	**+**	11.34	
							-	9.97	
								no. of shots	18

Date 2011-05-04
Plate Alloy #1 RA900 SM7 TP35
Nominal Thickness 8 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					14	11		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
2	28.0	1027.10	cp	1	0	1027.1	34.84	1
25	28.0	1023.90	cp	1	0	1023.9	31.15	1
3	27.4	1022.50	cp	1	0	1022.5	28.56	1
6	27.3	1018.10	cp	1	0	1018.1	23.77	1
10	27.0	1015.70	cp	1	0	1015.7	19.88	1
4	27.2	1012.70	cp	1	0	1012.7	14.99	1
12	27.0	1006.30	cp	1	0	1006.3	6.1	1
11	27.0	1005.40	cp	1	0	1005.4	4.3	1
5	27.2	1004.90	cp	1	0	1004.9	1.2	1
17	26.8	999.70	cp	1	0	999.7	-4.4	1
18	26.8	999.20	cp	1	0	999.2	-10.9	1
24	26.6	978.95	np	0	978.95	0		
21	26.5	981.93	np	0	981.93	0		
23	26.6	992.16	np	0	992.16	0		
16	26.8	992.26	np	0	992.26	0		
19	26.8	992.75	np	0	992.75	0		
22	26.6	993.94	np	0	993.94	0		
20	26.7	994.33	np	0	994.33	0		
13	27.0	995.82	np	0	995.82	0		
9	27.0	997.71	pp	0	997.71	0		
1	27.0	1000.20	np	0	1000.2	0		
7	27.0	1001.10	np	0	1001.1	0		
8	27.0	1003.70	np	0	1003.7	0		
15	26.9	1004.10	np	0	1004.1	0		
14	27.0	1010.10	np	0	1010.1	0		

	Min	978.95	998.7281818	1012.318182	**V 50 =**	**988.9**	**m/s**
25	Max	1027.1					
	D	48.15	975.66	1010.50	**+**	21.58	
					-	13.26	
						no. of shots	22

Date	2011-05-04			
Plate	Alloy #1 RA900 SM3 TP36			
Nominal Thickness		10 mm	16.61	V drop over 13.5m
Distance		15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

					13	12		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
10	28.8	1059.20	cp	1	0	1059.2	32.7	1
11	28.6	1057.70	cp	1	0	1057.7	30.8	1
5	28.8	1057.50	cp	1	0	1057.5	28.7	1
6	28.9	1056.40	cp	1	0	1056.4	26.3	1
7	29.0	1051.70	cp	1	0	1051.7	21.4	1
14	28.3	1048.60	cp	1	0	1048.6	18.2	1
4	28.7	1046.40	cp	1	0	1046.4	14	1
9	28.8	1045.80	cp	1	0	1045.8	12.3	1
3	28.6	1044.50	cp	1	0	1044.5	8.9	1
8	28.8	1044.40	cp	1	0	1044.4	8	1
16	28.2	1039.70	cp	1	0	1039.7	0.3	1
22	27.9	1035.70	cp	1	0	1035.7	-5.4	1
24	27.9	1023.50	np	0	1023.5	0		
23	27.9	1026.50	np	0	1026.5	0		
25	27.9	1026.90	np	0	1026.9	0		
21	27.8	1028.80	np	0	1028.8	0		
19	28.0	1030.10	pp	0	1030.1	0		
1	28.0	1030.30	np	0	1030.3	0		
20	28.0	1030.40	np	0	1030.4	0		
12	28.0	1032.40	np	0	1032.4	0		
13	28.2	1033.50	pp	0	1033.5	0		
17	28.2	1035.60	pp	0	1035.6	0		
18	28.1	1036.40	pp	0	1036.4	0		
15	28.2	1039.40	pp	0	1039.4	0		
2	28.5	1041.10	pp	0	1041.1	0		

	Min	1023.5	1032.616667	1048.966667	**V 50 =**	**1024.2 m/s**
25	Max	1059.2				
	D	35.7	1009.90	1042.60	**+**	18.41
					-	14.29
					no. of shot	24

Date 2011-05-04
Plate SM12 TP37 Back Polished
Nominal Thickness 7 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					6	9		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
1	27.0	1001.00	cp	1	0	1001	32.94	1
2	26.8	999.40	cp	1	0	999.4	28.71	1
6	26.7	994.73	cp	1	0	994.73	19.4	1
11	26.5	993.35	cp	1	0	993.35	15.35	1
12	26.5	991.40	cp	1	0	991.4	11.1	1
9	26.6	990.30	cp	1	0	990.3	-1.27	1
5	26.6	990.00	cp	1	0	990		
8	26.6	986.78	cp	1	0	986.78		
15	26.4	982.90	cp	1	0	982.9		
14	26.4	968.06	pp	0	968.06	0		
13	26.4	970.69	np	0	970.69	0		
3	26.5	975.33	np	0	975.33	0		
10	26.5	978.00	np	0	978	0		
7	26.7	980.30	pp	0	980.3	0		
4	26.7	991.57	pp	0	991.57	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		

	Min	968.06	977.325	995.03	**V 50 =**	**969.6 m/s**	
15	Max	1001					
	D	32.94	951.46	984.40	**+**	14.82	
					-	18.12	
					no. of shots		12

Date	2011-05-04		
Plate	SM12 TP37 Front Polished		
Nominal Thickness	7 mm	16.61	V drop over 13.5m
Distance	15 m		
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**	

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation	< 40 ?	
					18	7		
17	26.6	987.75	cp	1	0	987.75		
19	26.0	982.03	cp	1	0	982.03		
18	26.2	980.00	cp	1	0	980		
16	26.4	976.75	cp	1	0	976.75		
20	25.8	955.66	cp	1	0	955.66	27.76	1
22	25.6	952.47	cp	1	0	952.47	19.72	1
23	25.5	947.06	cp	1	0	947.06	9.06	1
25	25.2	927.90	np	0	927.9	0		
24	25.3	932.75	np	0	932.75	0		
21	25.5	938.00	np	0	938	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		
				0	0	0		

	Min	927.9	932.8833333	951.73	**V 50 =**	**925.7 m/s**	
25	Max	987.75					
	D	59.85	911.30	939.06	**+**	13.35	
					-	14.41	
						no. of shots	6

Date	2011-05-04				
Plate	Alloy #1 SM12 TP38				
Nominal Thickness	6.3	mm	10.26	V drop over 13.5m	
Distance	15	m			
Caliber	7.62mm M80 R1	**V proof = 862m/s (143gr) +-20**			

					14	11		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
18	53.2	933.97	cp	1	0	933.97	20.98	1
16	53.4	933.45	cp	1	0	933.45	19.54	1
15	53.4	933.36	cp	1	0	933.36	18.53	1
12	53.3	933.10	cp	1	0	933.1	16.34	1
17	53.3	930.23	cp	1	0	930.23	11.53	1
10	53.0	924.98	cp	1	0	924.98	3.07	1
11	53.2	923.31	cp	1	0	923.31	1.05	1
24	52.7	922.68	cp	1	0	922.68	-0.34	1
1	53.0	922.26	cp	1	0	922.26	-2.04	1
14	53.3	922.17	cp	1	0	922.17	-2.3	1
22	52.8	920.56	cp	1	0	920.56	-8.38	1
2	51.0	880.51	np	0	880.51	0		
3	52.0	903.51	np	0	903.51	0		
8	52.8	912.08	np	0	912.08	0		
5	52.4	912.99	np	0	912.99	0		
4	52.5	913.91	np	0	913.91	0		
23	52.7	914.83	np	0	914.83	0		
20	52.9	916.76	np	0	916.76	0		
7	52.6	918.70	pp	0	918.7	0		
25	53.0	921.91	pp	0	921.91	0		
6	52.6	922.26	pp	0	922.26	0		
21	52.9	923.02	pp	0	923.02	0		
19	53.0	924.30	np	0	924.3	0		
9	53.0	924.47	pp	0	924.47	0		
13	53.3	928.94	pp	0	928.94	0		

	Min	880.51	920.19	927.2790909	**V 50 =**	**913.5 m/s**	
25	Max	933.97					
	D	53.46	902.73	923.71	**+**	10.24	
					-	10.74	
						no. of shots	22

Date	2011-05-05			
Plate	Alloy #1 SM11 TP39			
Nominal Thickness	7 mm		16.61	V drop over 13.5m
Distance	15 m			
Caliber	5.56mm M193 [R4]	**V proof = 937m/s +-20**		

Shot number	Charge [grain]	Velocity [m/s]	Impact Result		Non-Perforation	Perforation	< 40 ?	
					14	11		
1	27.0	1000.40	cp	1	0	1000.4	61.78	
6	26.6	996.61	cp	1	0	996.61	50.36	
15	26.4	989.81	cp	1	0	989.81	40.95	
14	26.5	989.71	cp	1	0	989.71	39.95	1
4	26.7	988.73	cp	1	0	988.73	33.62	1
5	26.6	978.86	cp	1	0	978.86	23.11	1
16	26.2	978.57	cp	1	0	978.57	22	1
17	26.1	970.69	cp	1	0	970.69	13.11	1
22	26.0	969.46	cp	1	0	969.46	10.32	1
18	26.0	968.52	cp	1	0	968.52	8.37	1
21	26.0	965.72	cp	1	0	965.72	-8.85	1
3	26.5	922.17	np	0	922.17	0		
20	25.8	934.67	np	0	934.67	0		
23	25.9	938.26	np	0	938.26	0		
10	25.6	938.62	np	0	938.62	0		
25	25.8	946.25	np	0	946.25	0		
11	25.6	948.86	np	0	948.86	0		
7	25.5	949.76	np	0	949.76	0		
9	25.5	955.11	np	0	955.11	0		
12	25.6	955.75	np	0	955.75	0		
19	26.0	956.57	np	0	956.57	0		
24	25.9	957.58	np	0	957.58	0		
8	25.5	959.14	np	0	959.14	0		
13	25.7	960.15	np	0	960.15	0		
2	26.0	974.57	np	0	974.57	0		
	Min	922.17			958.57875	976.2825	**V 50 =**	**950.8 m/s**
25	Max	1000.4						
	D	78.23			933.16	973.11	**+** 22.28	
							- 17.67	
							no. of shots	16

Date 2011-05-05
Plate Alloy #1 SM7 TP40
Nominal Thickness 8 mm 16.61 V drop over 13.5m
Distance 15 m
Caliber 5.56mm M193 [R4] **V proof = 937m/s +-20**

					15	10		
Shot number	**Charge [grain]**	**Velocity [m/s]**	**Impact Result**		**Non-Perforation**	**Perforation**	**< 40 ?**	
21	26.9	1008.00	cp	1	0	1008	37.5	1
19	26.7	1001.90	cp	1	0	1001.9	30.36	1
25	27.0	1001.00	cp	1	0	1001	29.37	1
22	26.8	997.51	cp	1	0	997.51	25.5	1
24	26.9	995.92	cp	1	0	995.92	22.11	1
3	26.6	994.23	cp	1	0	994.23	17.38	1
20	26.8	993.54	cp	1	0	993.54	11.51	1
4	26.4	985.51	cp	1	0	985.51	1.26	1
2	26.5	978.19	cp	1	0	978.19	-7.71	1
7	26.2	975.61	cp	1	0	975.61	-12.92	1
1	26.0	962.47	np	0	962.47	0		
16	26.4	964.32	np	0	964.32	0		
9	26.2	965.34	np	0	965.34	0		
12	26.2	969.93	np	0	969.93	0		
17	26.5	970.50	np	0	970.5	0		
5	26.3	971.54	np	0	971.54	0		
11	26.2	971.63	np	0	971.63	0		
14	26.3	972.01	np	0	972.01	0		
6	26.2	973.81	np	0	973.81	0		
23	26.8	976.85	np	0	976.85	0		
8	26.3	982.03	pp	0	982.03	0		
15	26.4	984.25	np	0	984.25	0		
13	26.3	985.90	pp	0	985.9	0		
10	26.2	988.53	np	0	988.53	0		
18	26.7	x	cp					

	Min	962.47	977.705	993.141	**V 50 =**	**968.8 m/s**	
25	Max	1008					
	D	45.53	953.90	991.40	**+**	22.58	
					-	14.92	
						no. of shots	20

CHAPTER 10

Appendix C

This appendix includes all the standard ESKOM research testing and development laboratory test reports.

10.1 Quasistatic tensile test reports

Eskom Holdings SOC Limited
Research, Testing and Development
629 5214
Private Bag 40175
CLEVELAND
2022

Equiries: J.Calitz
Tel: 011
Fax: 086 665 3398

TEST CERTIFICATE

Univeristy of Pretoria
ATT: J. Bester

CERTIFICATE NUMBER	RTD/CER/12/136
Sample Description	Flat specimen machined from plate material No. 15
Date received	14 February 2012
Date tested	14 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	1
Test temperature	24 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

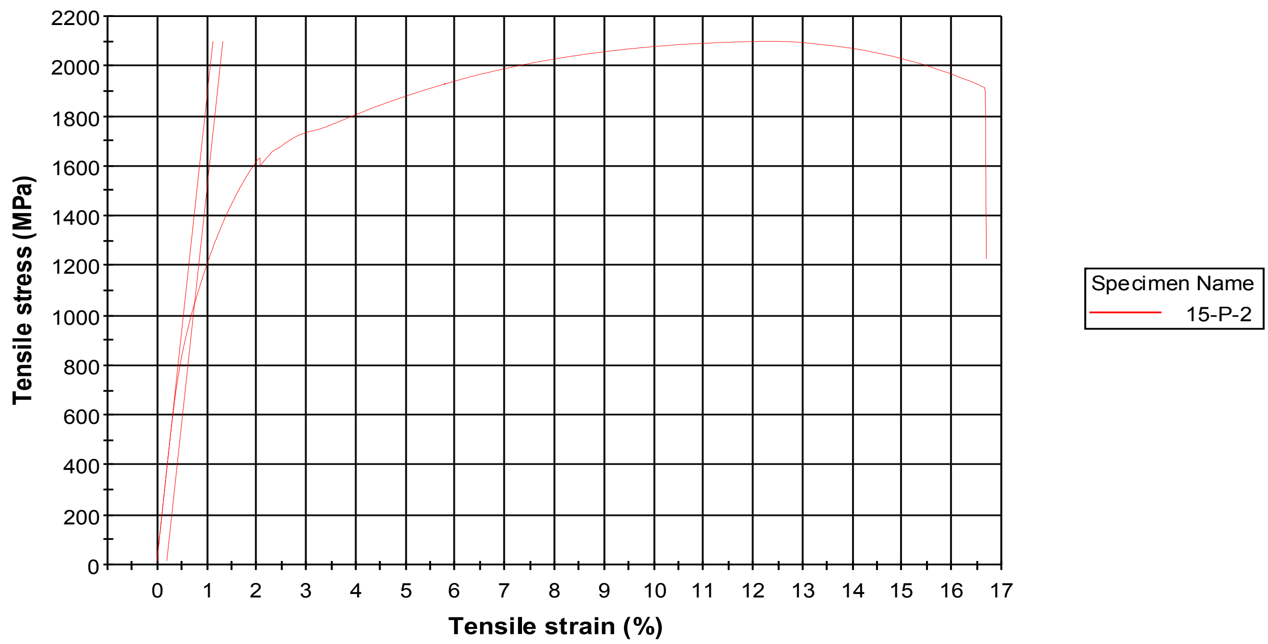
Table 1

	Specimen I.D.	E (Segment 100 - 600) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
1	15-P-2	185.25	189.90	1054.30	2096.54	12.32	16.65
2	15-P-3	181.55	202.12	1035.41	2094.80	12.98	17.77
3	15-T-1	187.42	192.80	1029.92	2131.39	11.62	14.06
4	15-T-2	193.29	198.71	1026.34	2131.47	11.39	14.07
5	15-T-3	188.74	196.98	1040.08	2130.33	11.67	13.99
6	7RA900-1	187.12	191.53	1011.87	2056.03	11.93	15.70
7	7RA900-2	199.59	210.94	1029.27	2099.83	10.08	15.08
8	4RA900-1	196.90	205.97	1019.89	2020.48	4.06	4.06
9	4RA900-2	240.61	235.83	1140.77	2413.38	10.53	10.54
10	18-1	197.80	208.14	945.59	2051.21	12.65	15.74
11	18-2	-----	197.87	-----	2040.65	11.89	12.95
12	16-1	198.69	200.98	1032.39	2100.87	11.97	14.48
13	16-2	188.00	195.52	1042.52	2111.16	12.25	14.68
14	14-1	205.01	212.98	959.42	2060.03	11.84	14.28
15	14-2	187.84	204.62	956.39	2063.65	11.95	15.42
16	13-1	184.69	193.81	1063.00	2106.98	11.55	14.75
17	13-2	184.87	193.87	1072.46	2120.17	12.02	15.38
18	21-1	173.59	168.38	1087.94	2072.00	12.04	16.26
19	12-2	167.07	177.39	1158.74	2077.74	11.67	15.86
20	11-1	198.55	225.10	944.71	2060.63	11.77	13.70
21	11-2	207.46	232.98	928.17	1942.64	7.05	7.05
22	10-1	182.79	186.17	1023.75	2086.37	12.29	17.07
23	10-2	177.37	176.51	1088.28	2091.79	12.23	15.95
24	9-1	197.20	199.62	1049.13	2137.82	11.84	14.38
25	9-2	190.79	201.81	1071.03	2152.56	12.66	16.27

	Specimen I.D.	E (Segment 100 - 600) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
26	8-1	167.53	168.21	1071.24	2102.17	12.35	15.13
27	8-2	175.30	176.06	1049.88	2094.30	11.66	14.83
28	7-1	174.68	174.49	1060.55	1967.74	5.87	5.88
29	7-2	177.61	178.53	1054.73	2039.15	7.09	7.09
30	3-1	194.80	203.13	1008.41	2165.29	13.32	13.55
31	3-2	209.21	224.89	1002.91	2136.80	12.28	15.74
32	2-1	175.17	183.86	1041.21	2143.23	12.26	14.57
33	2-2	173.32	177.39	1055.66	2157.42	12.70	15.63
34	1-1	197.09	212.82	1004.64	2149.34	12.31	16.41
Mean		189.30	197.06	1035.17	2100.17	11.30	13.97
Standard Deviation		14.49	17.39	50.76	74.93	2.09	3.25

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

Stress versus Strain



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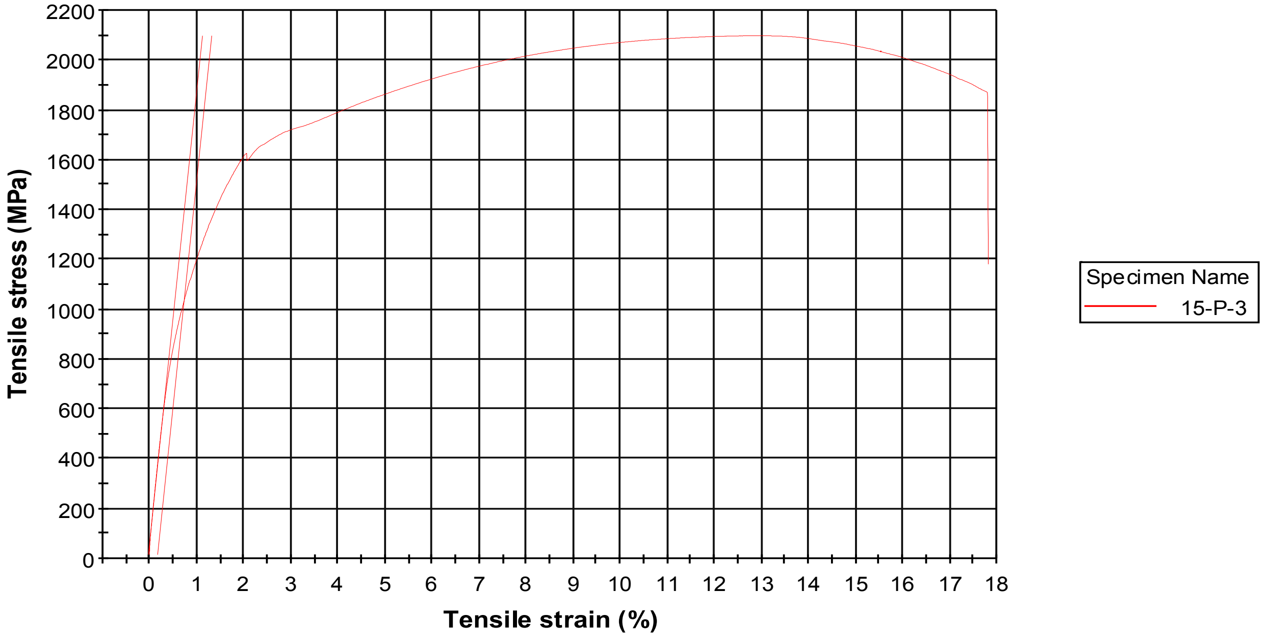
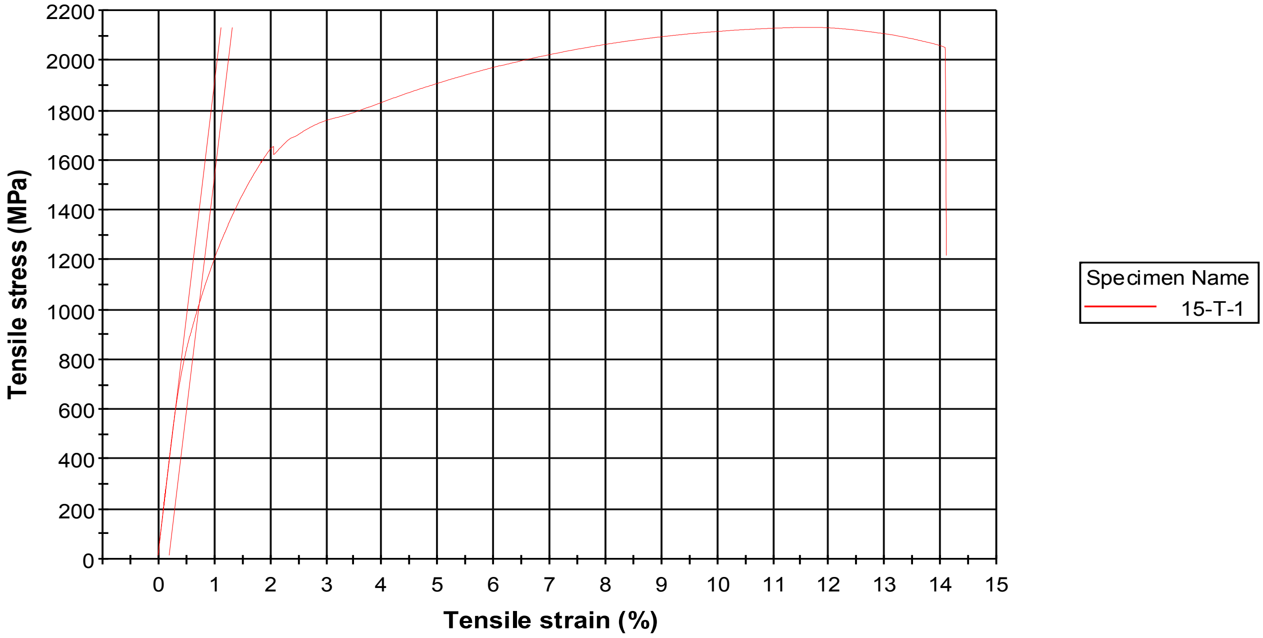
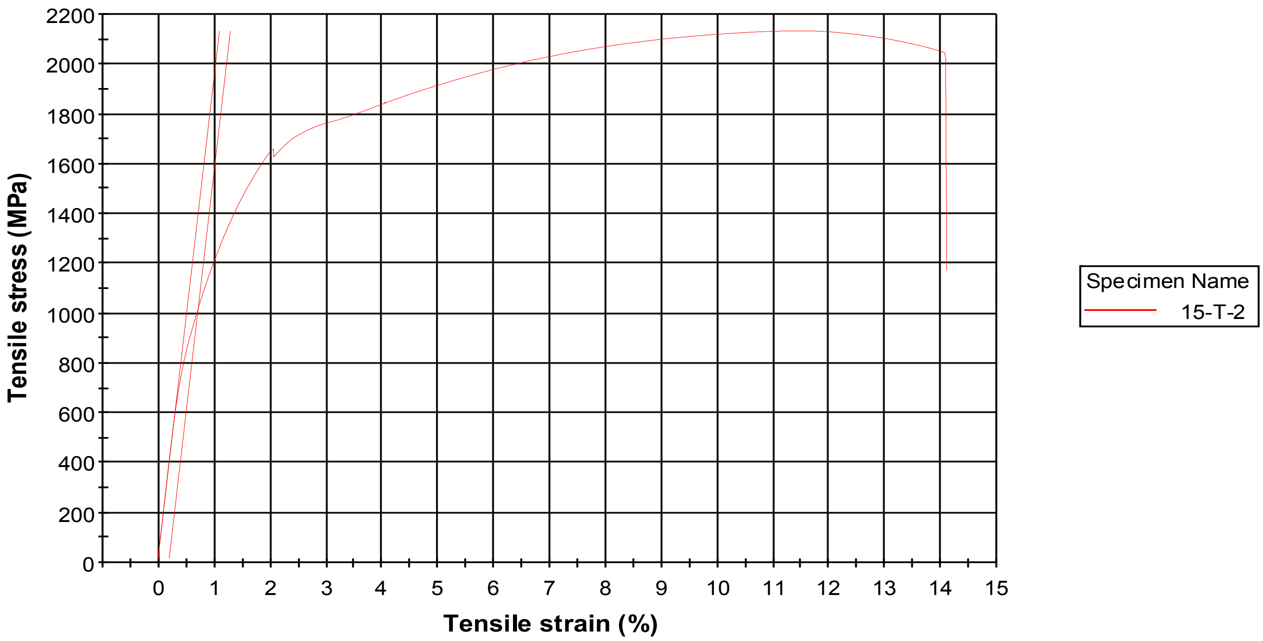
Stress versus Strain



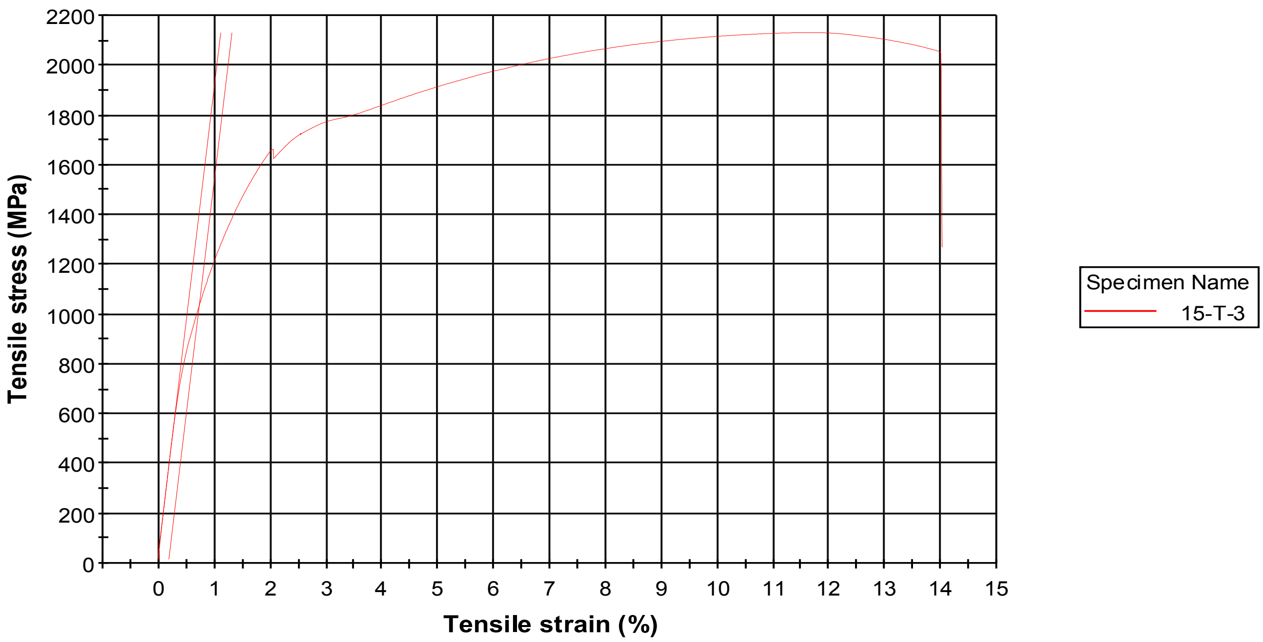
Stress versus Strain



Stress versus Strain



Stress versus Strain



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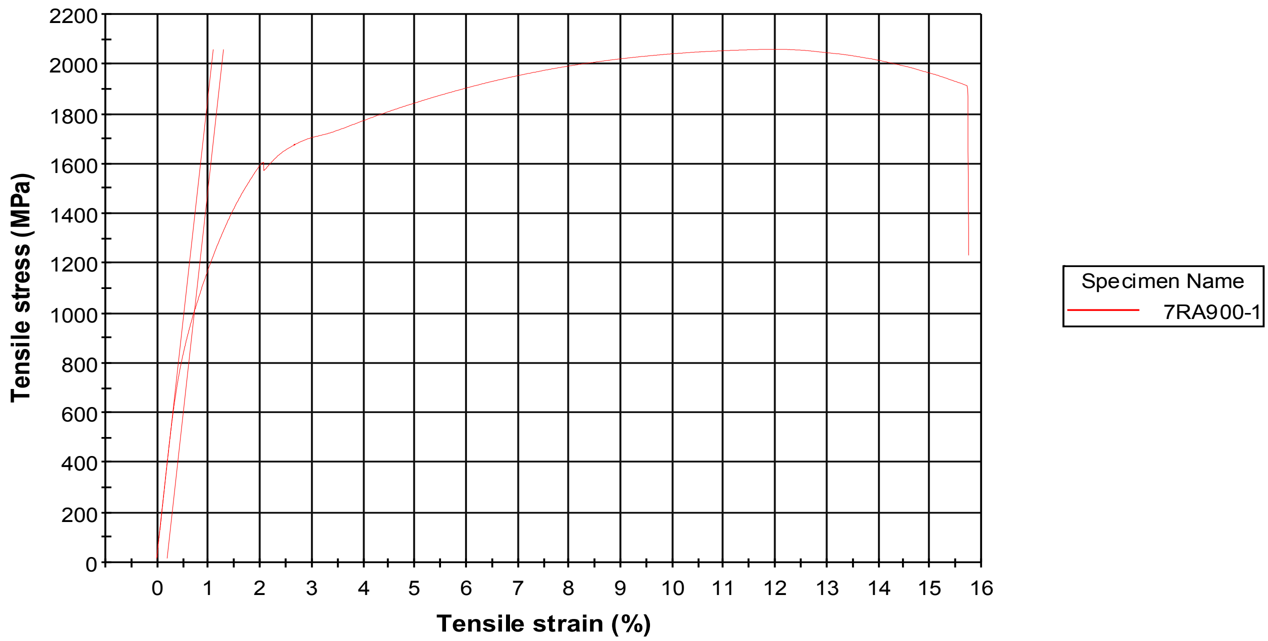

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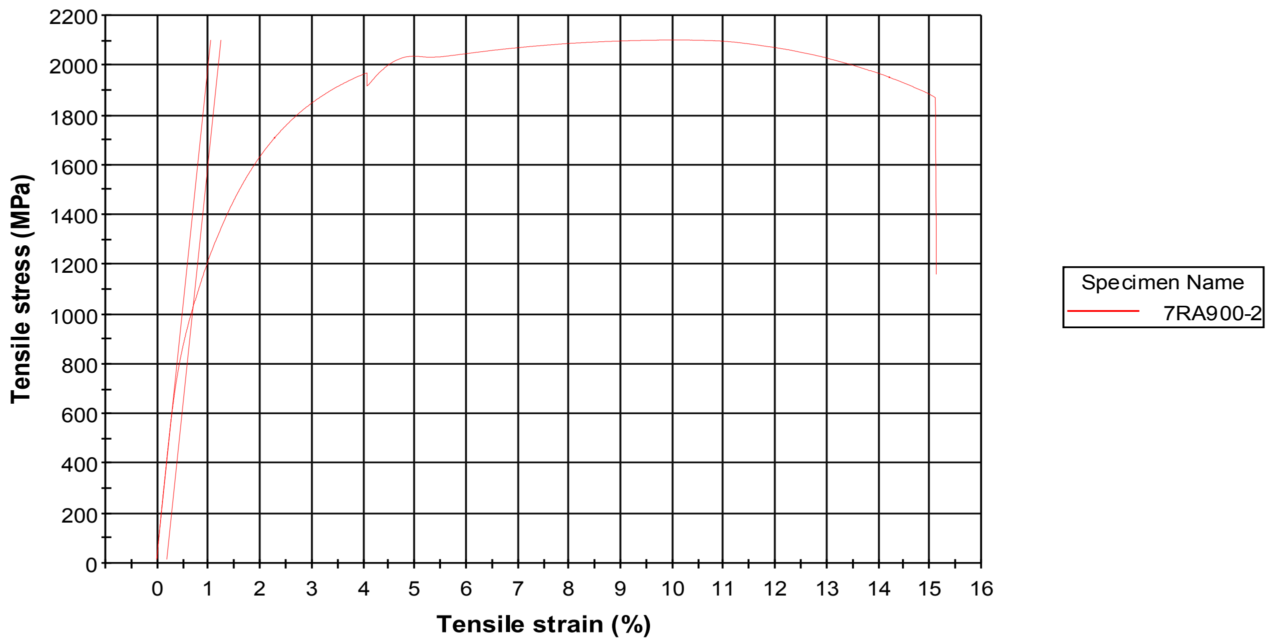

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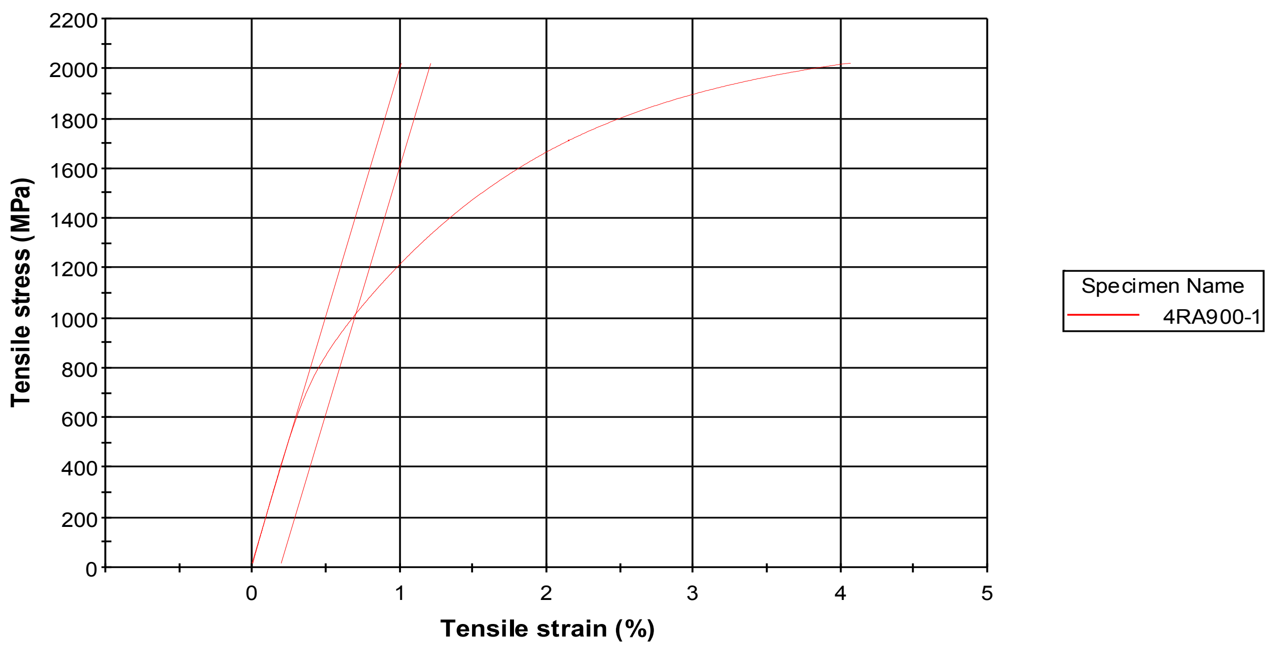

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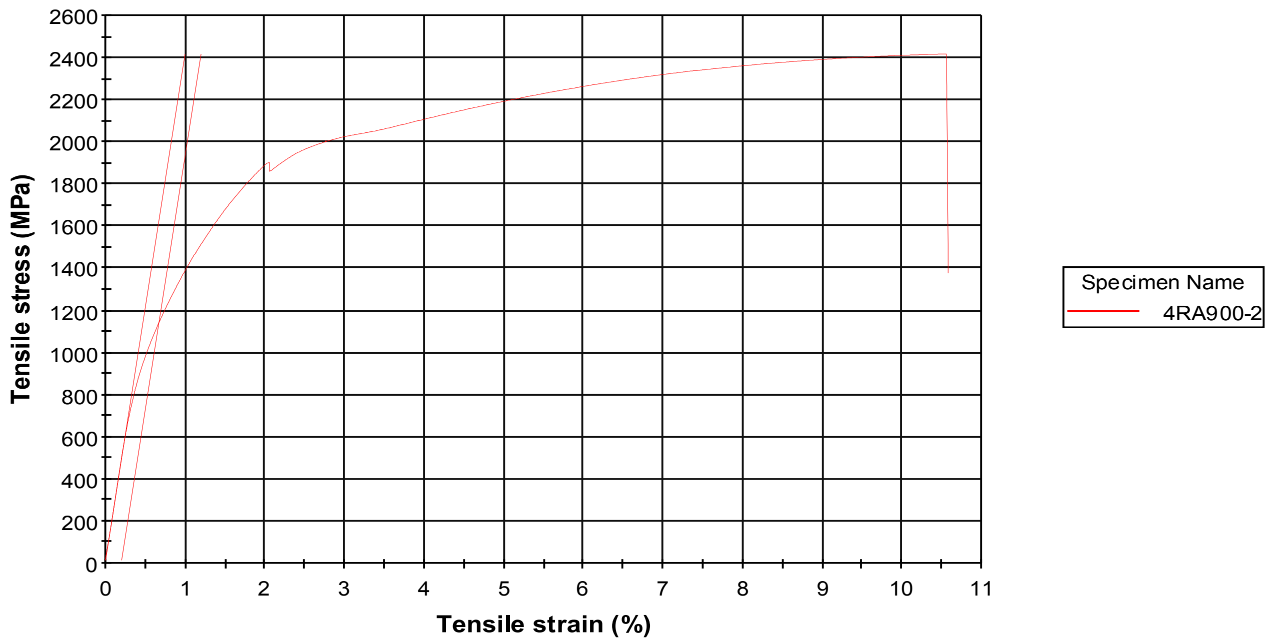

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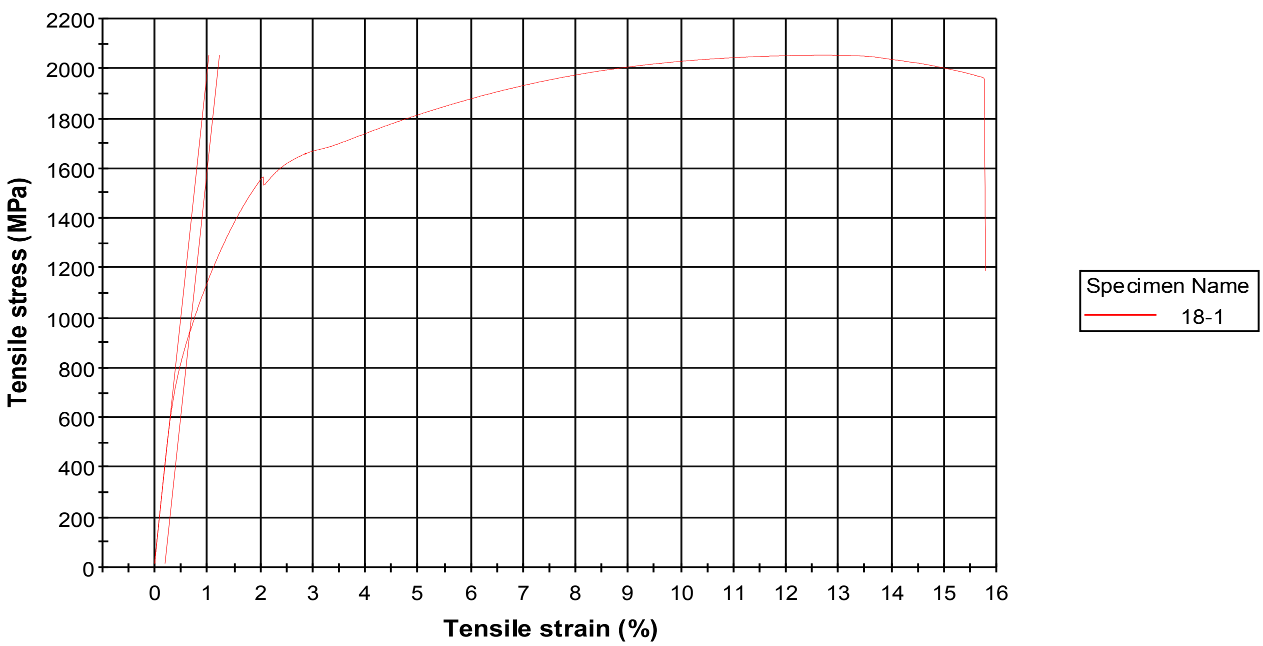
Stress versus Strain



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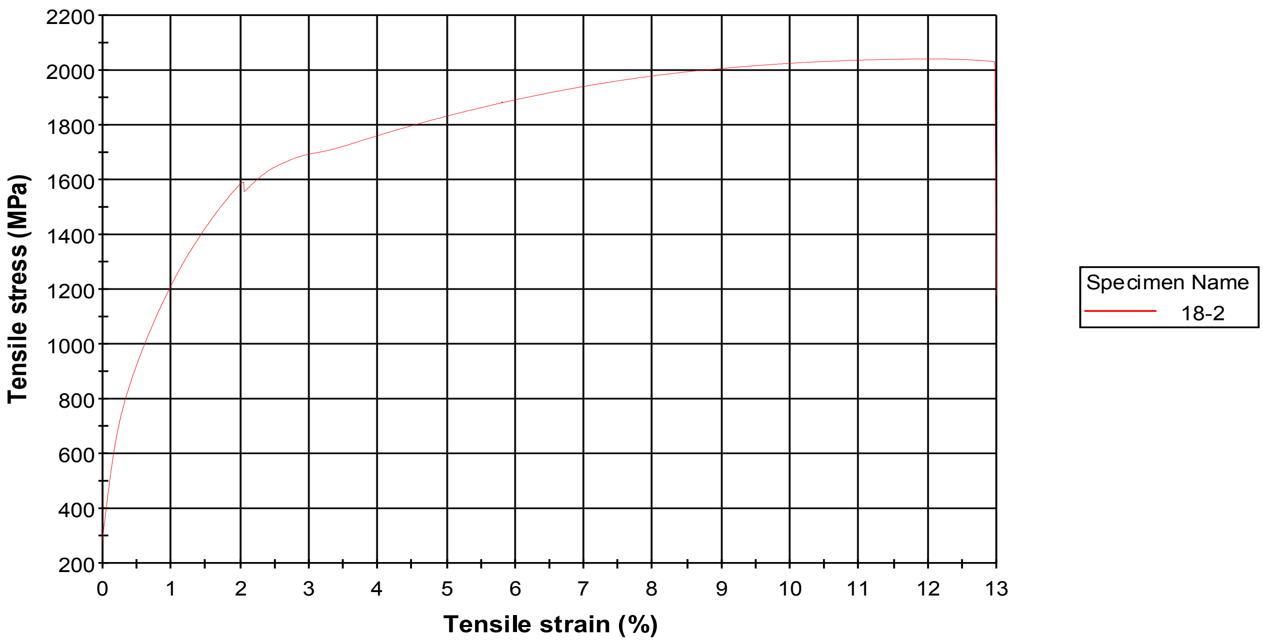

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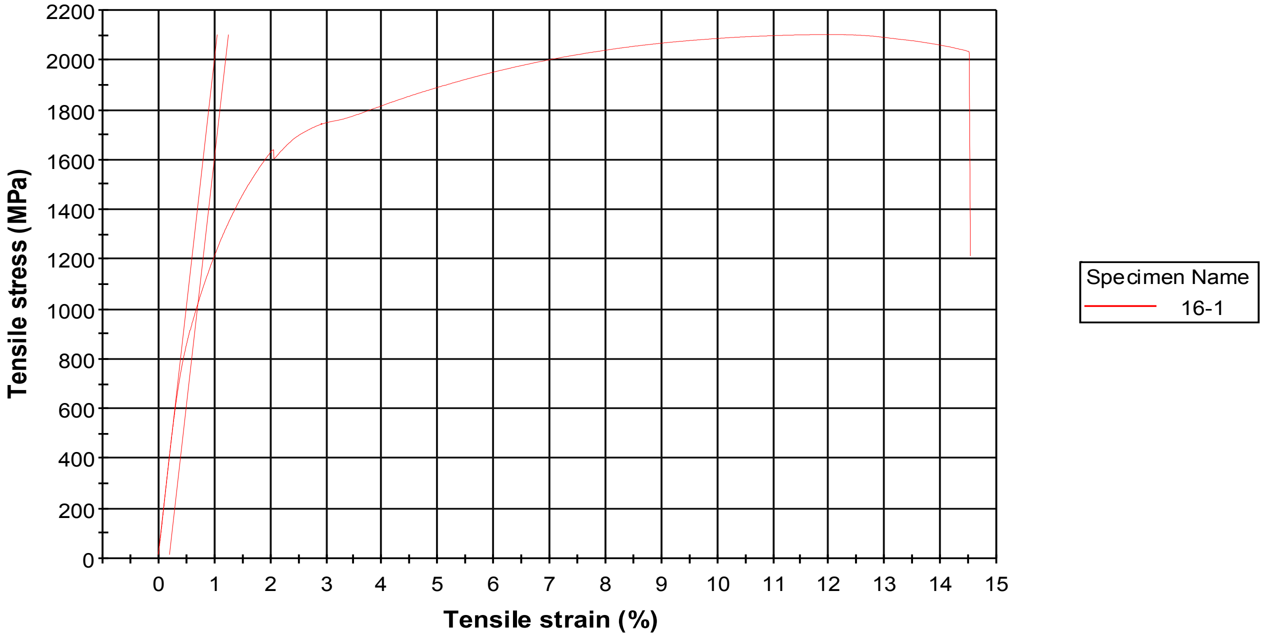

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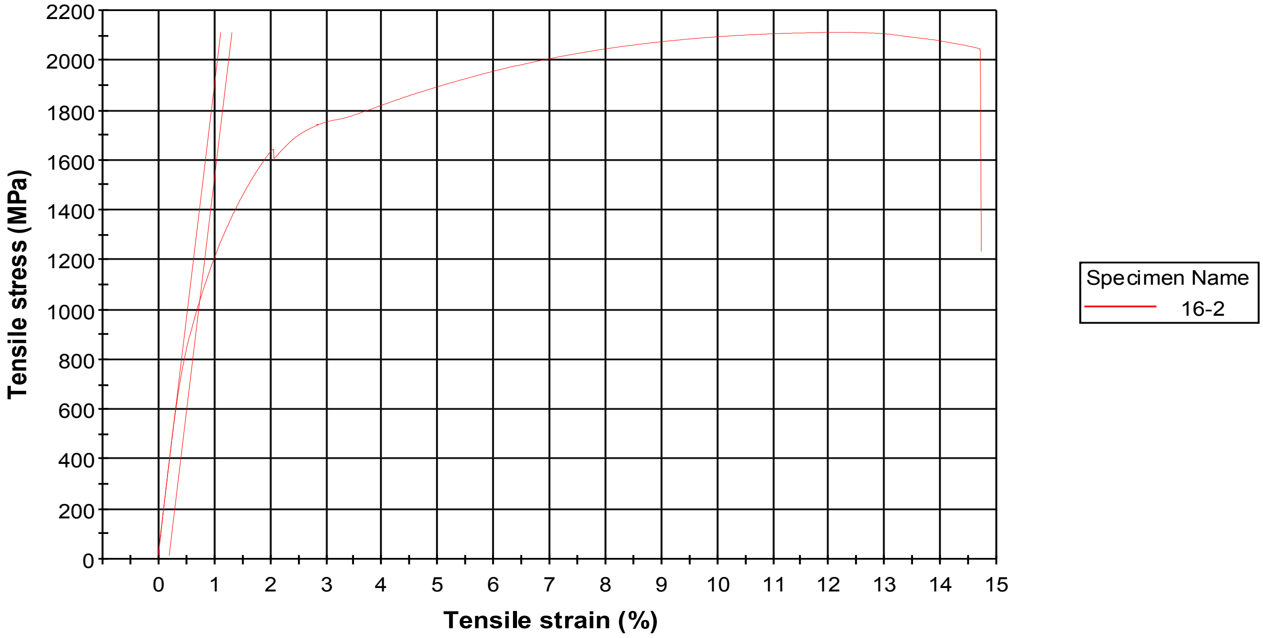

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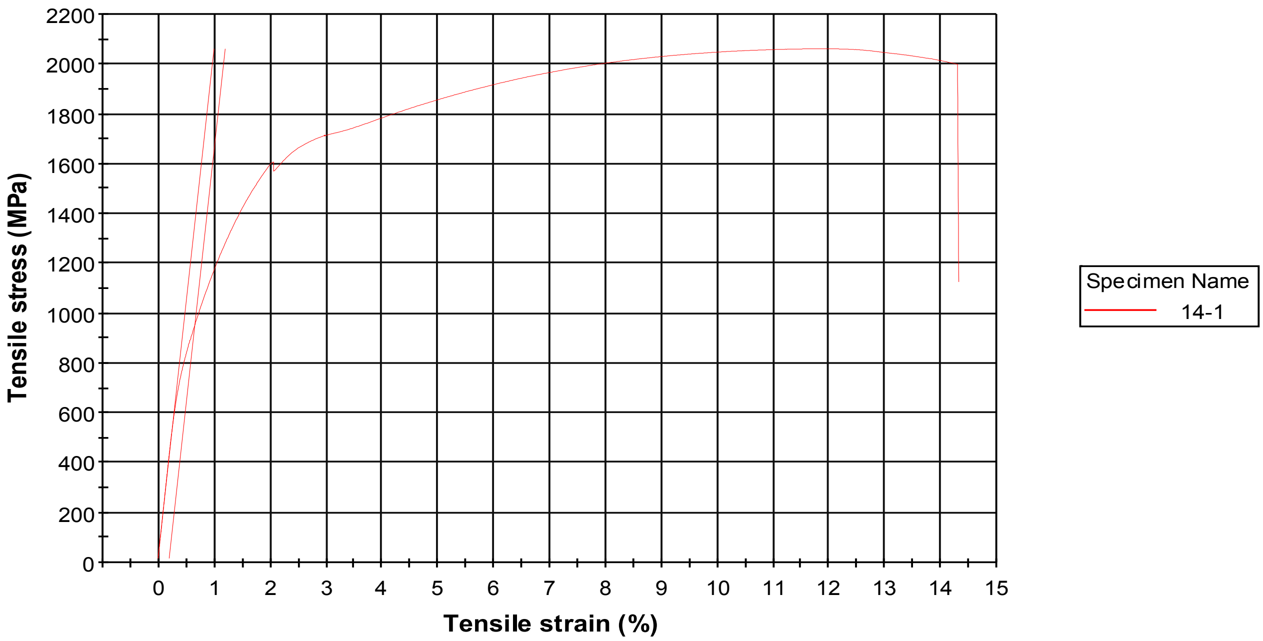

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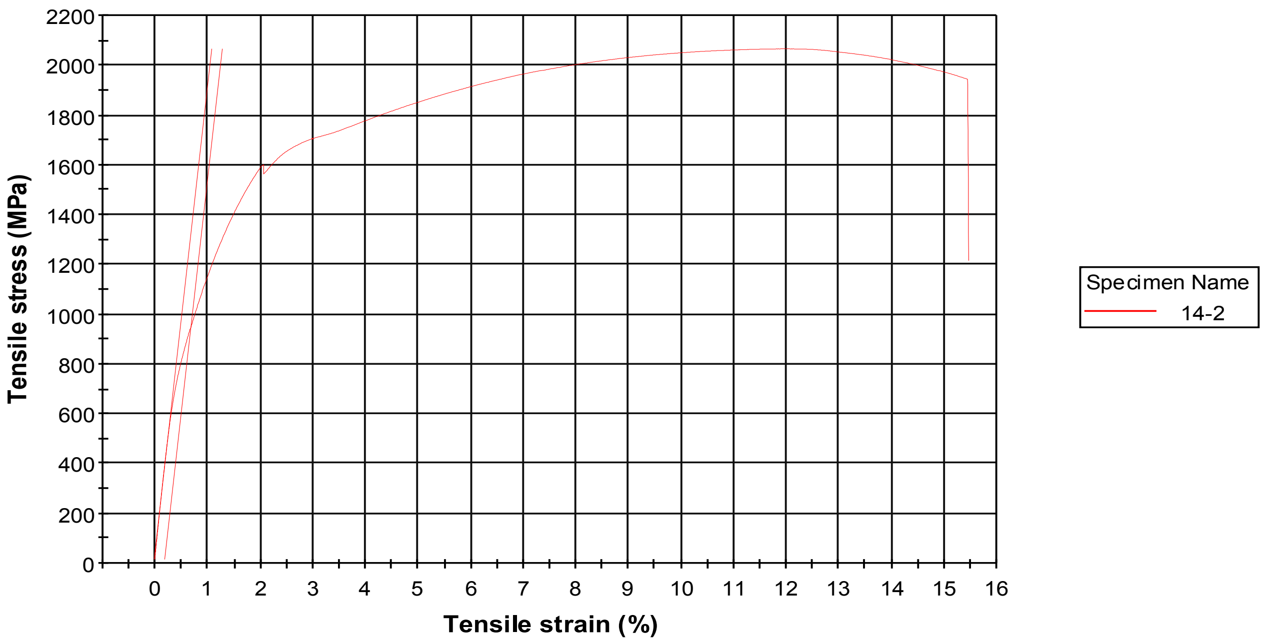

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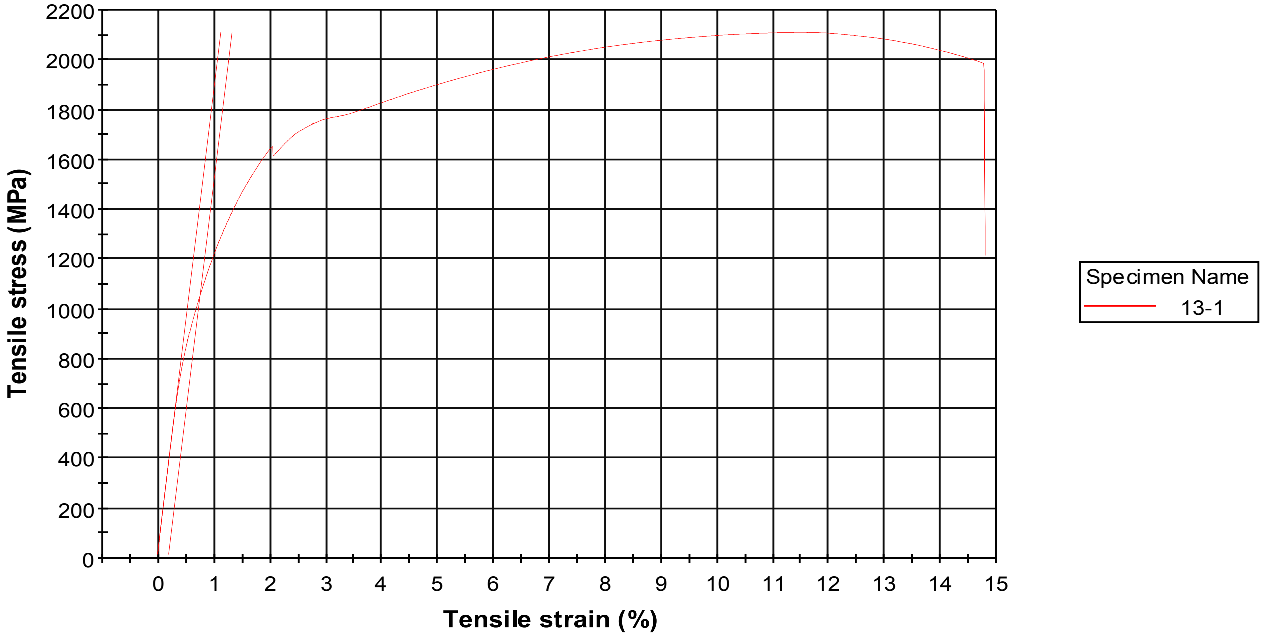
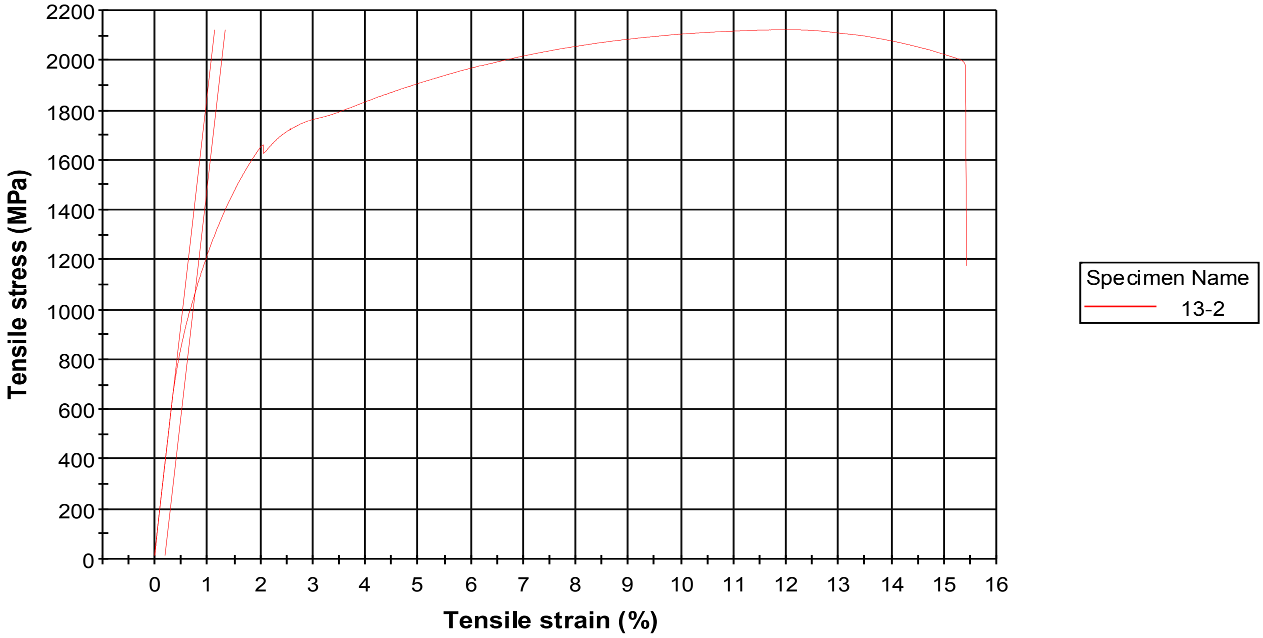


Stress versus Strain



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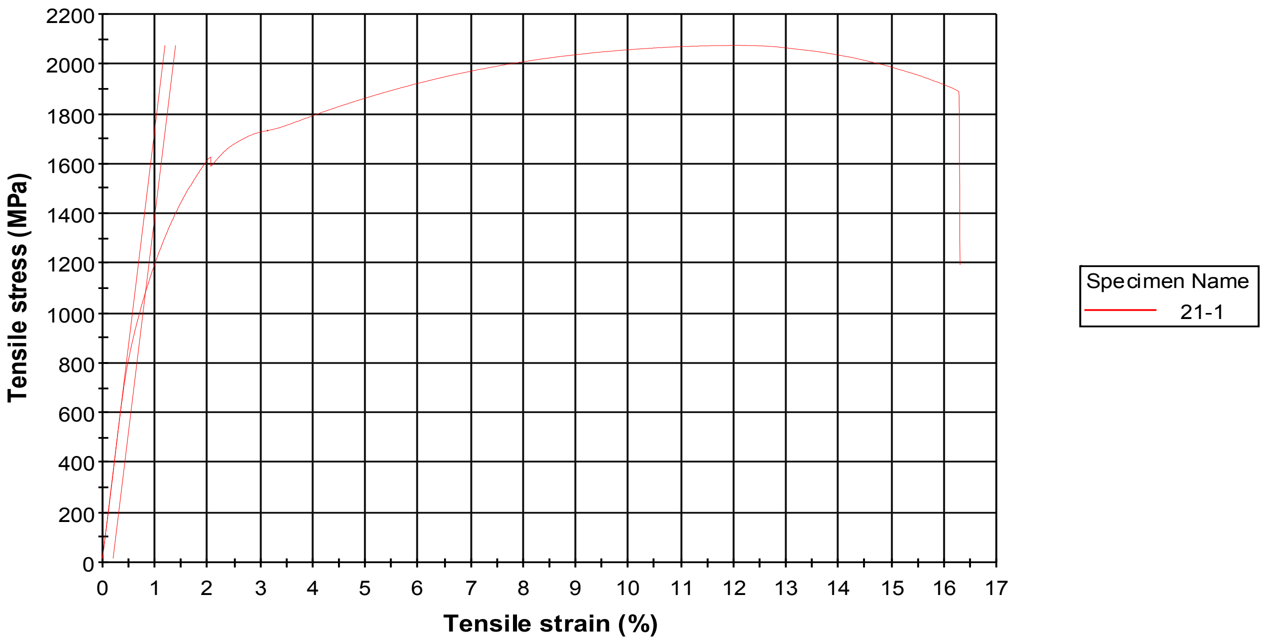
Stress versus Strain



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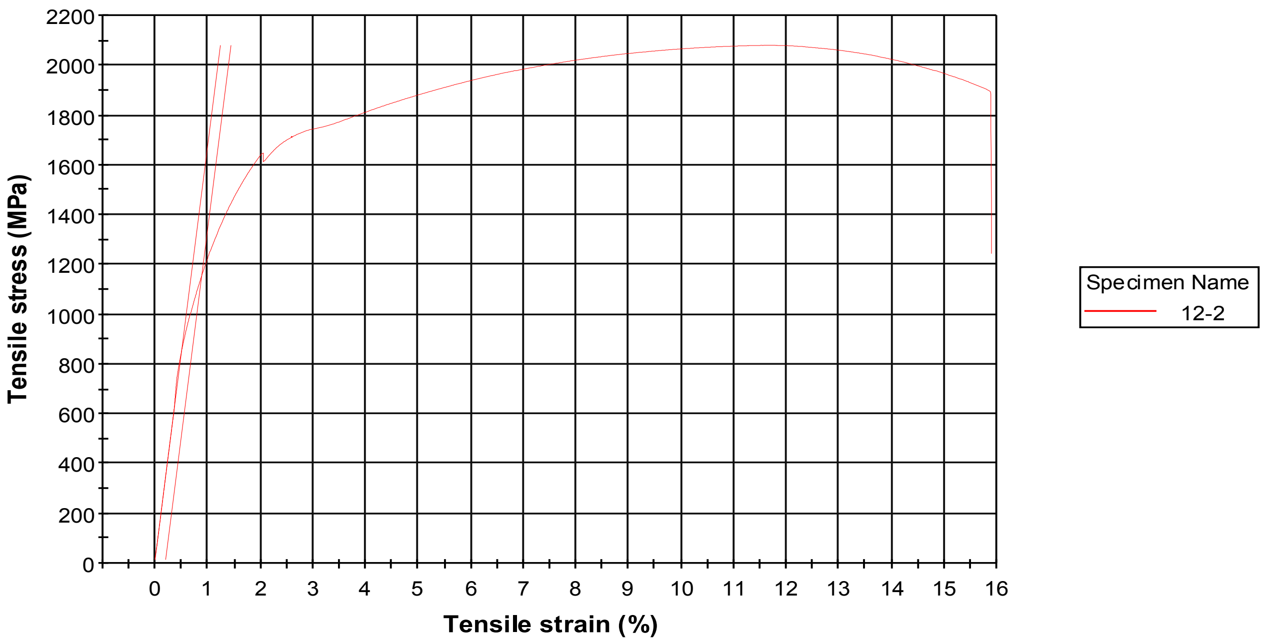

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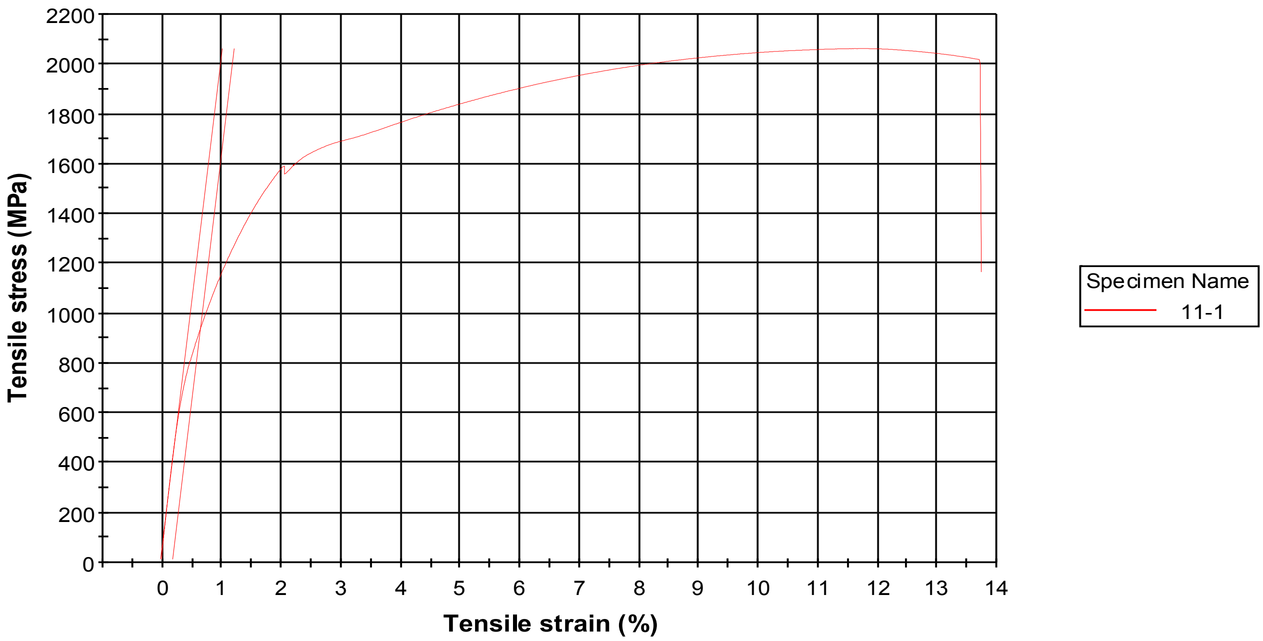

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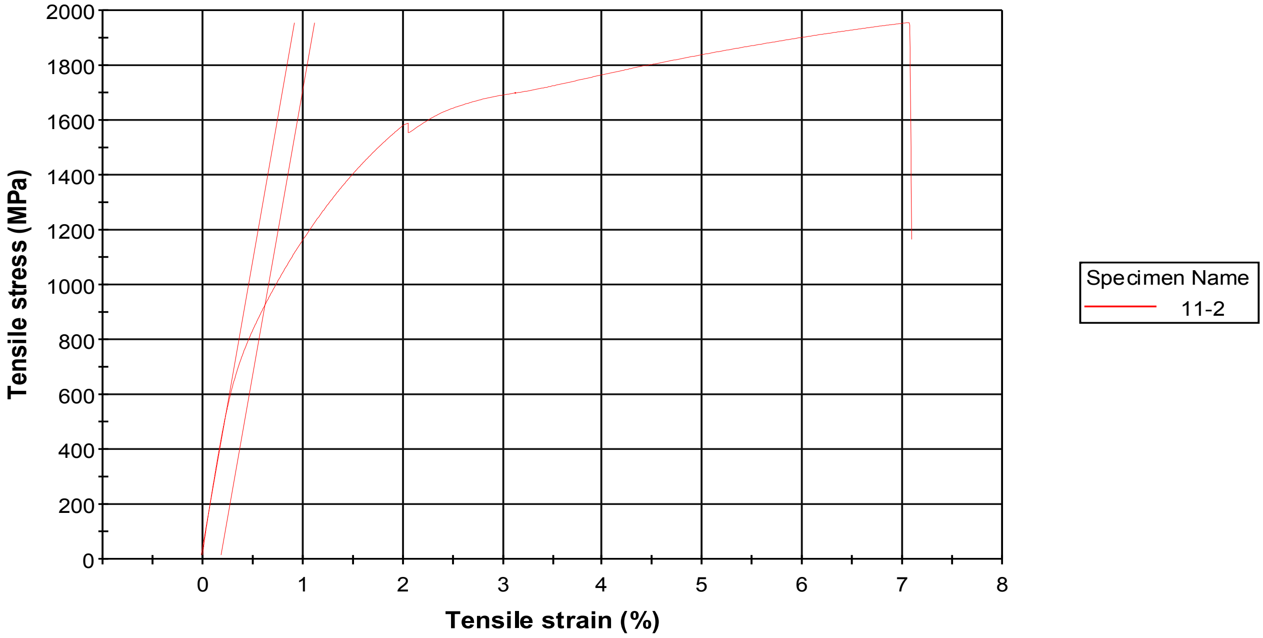

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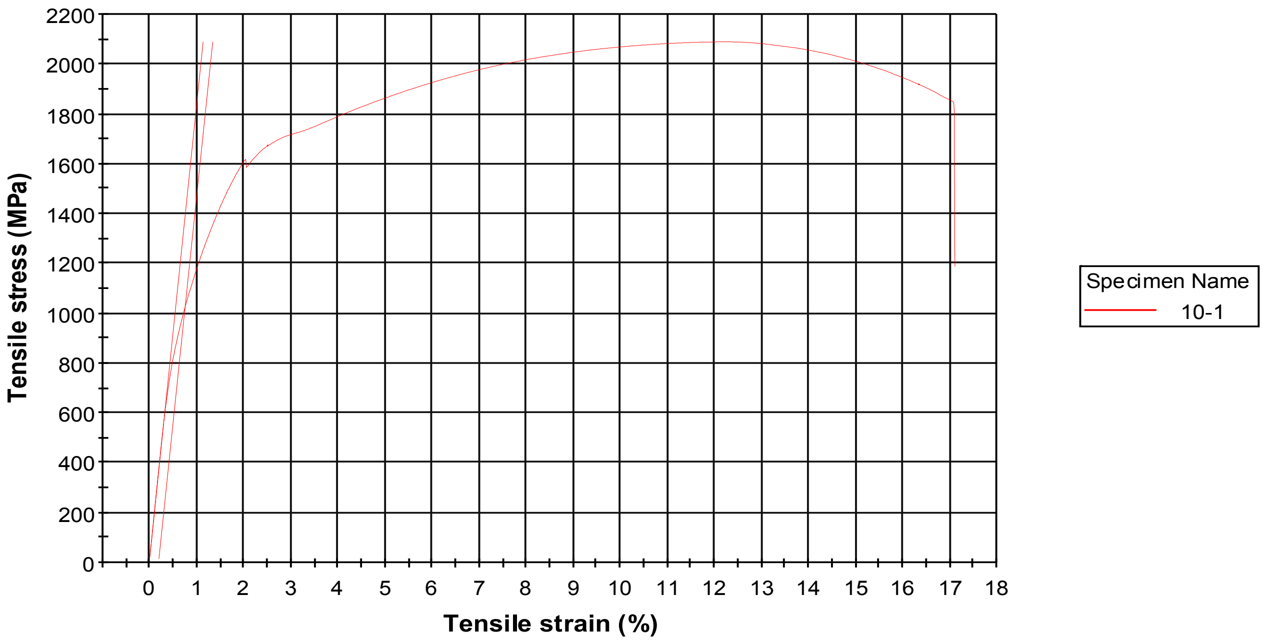

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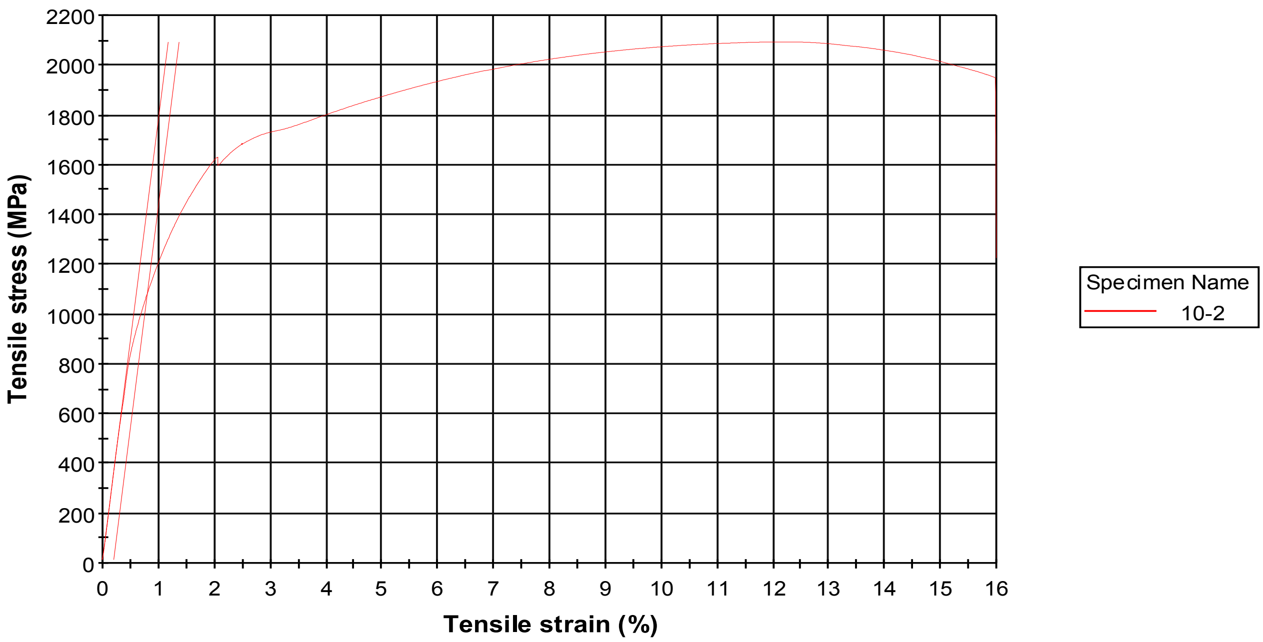

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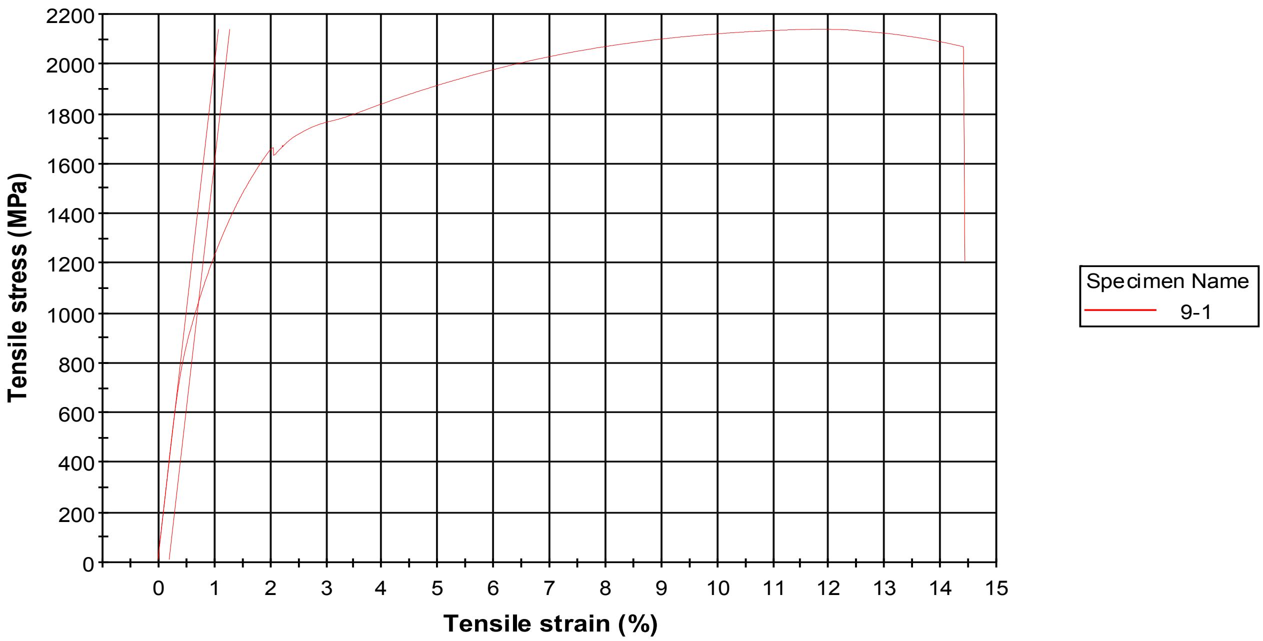

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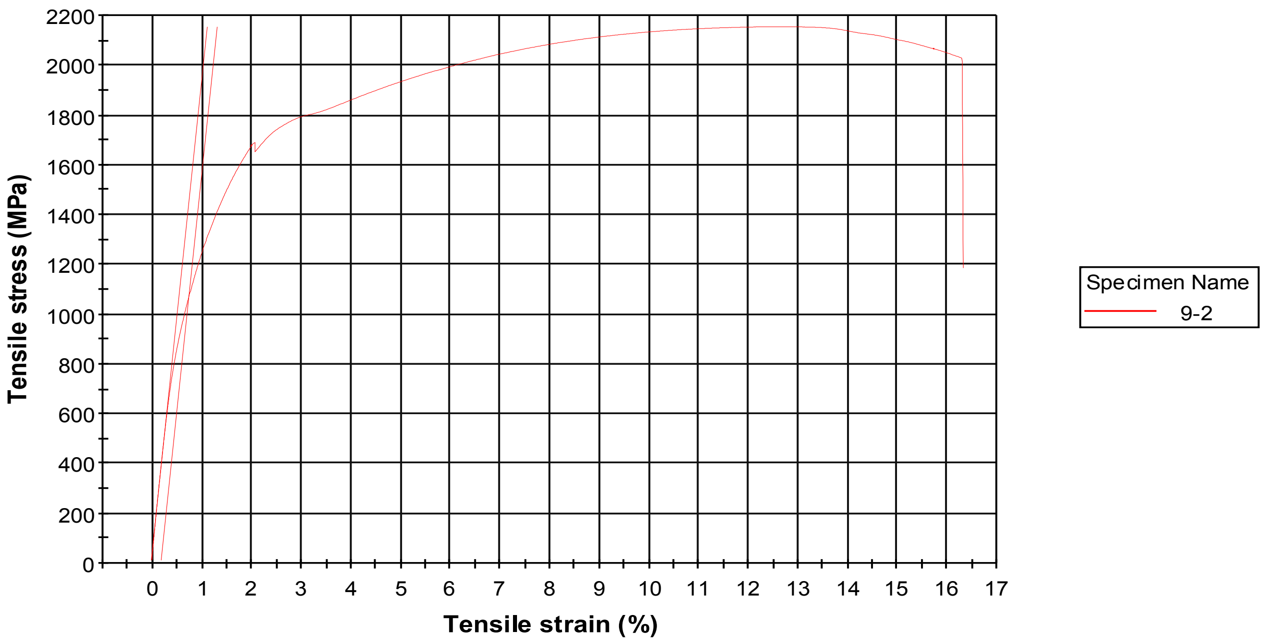

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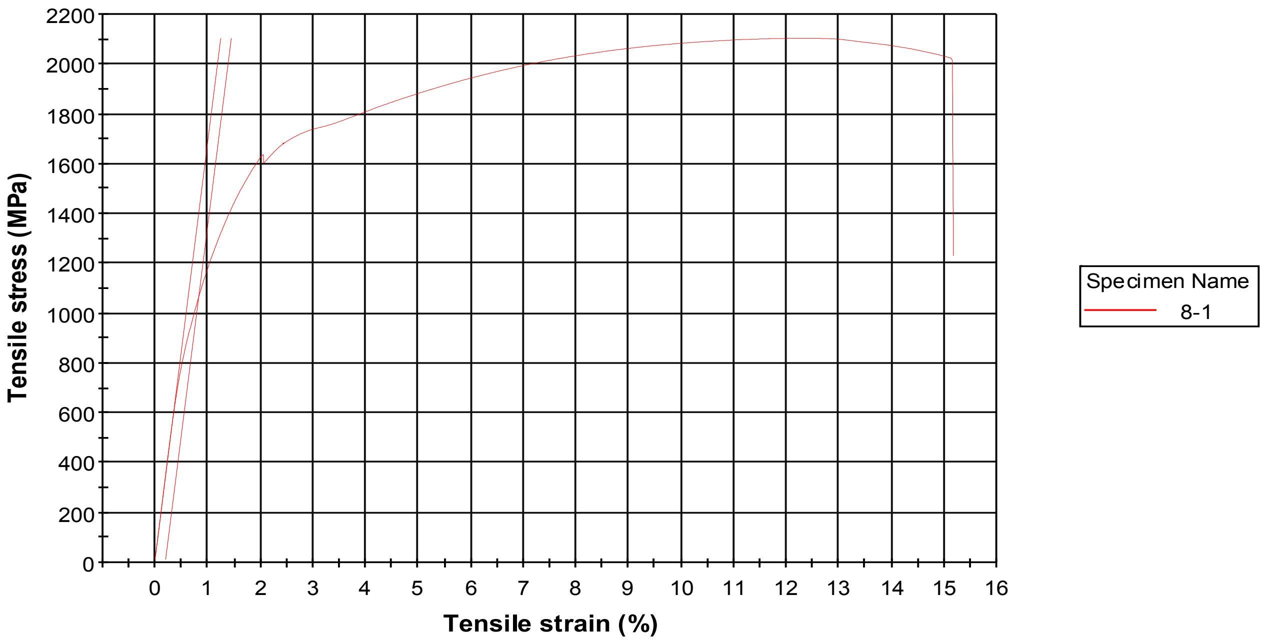

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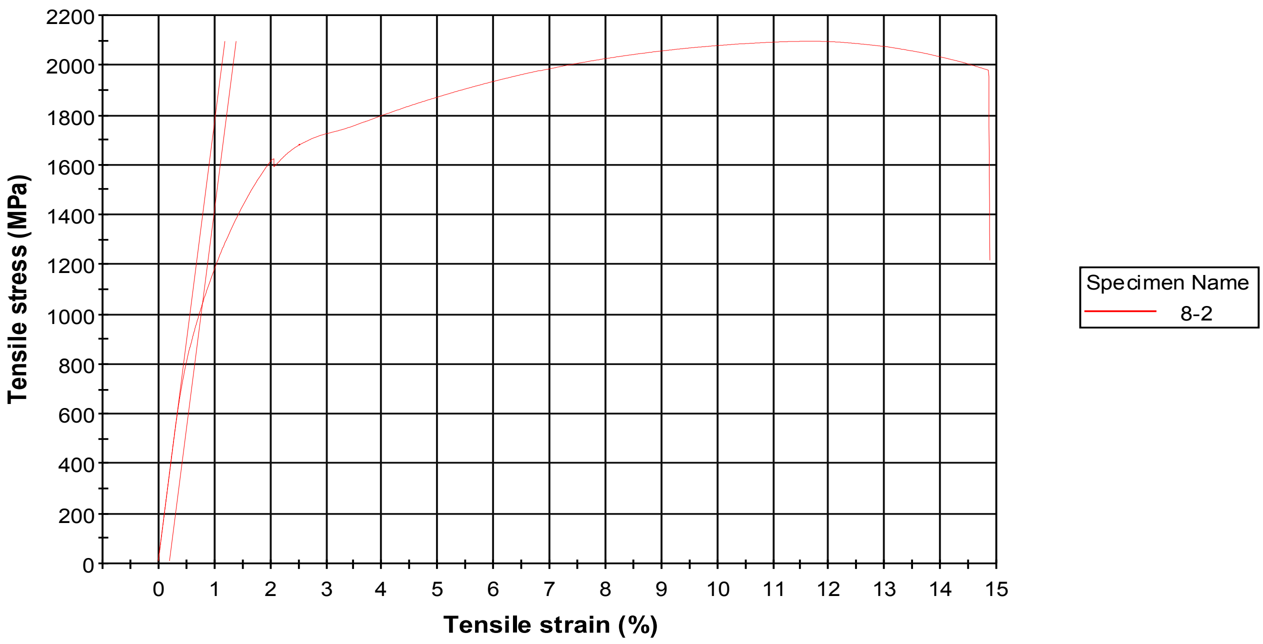

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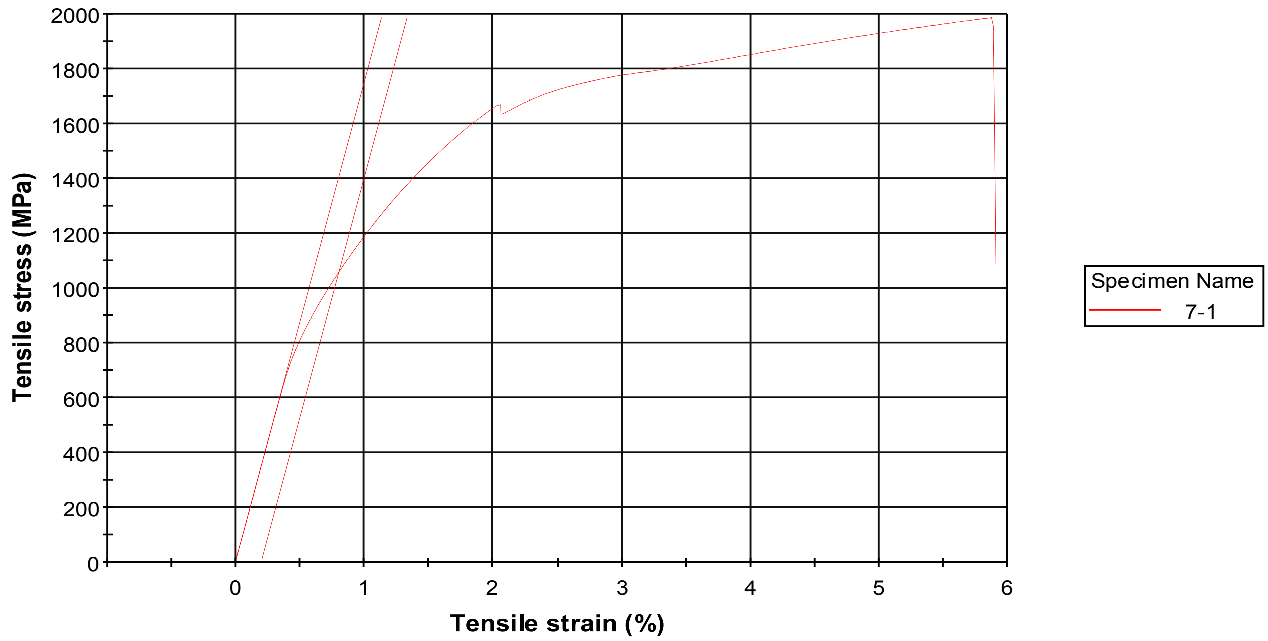
Stress versus Strain



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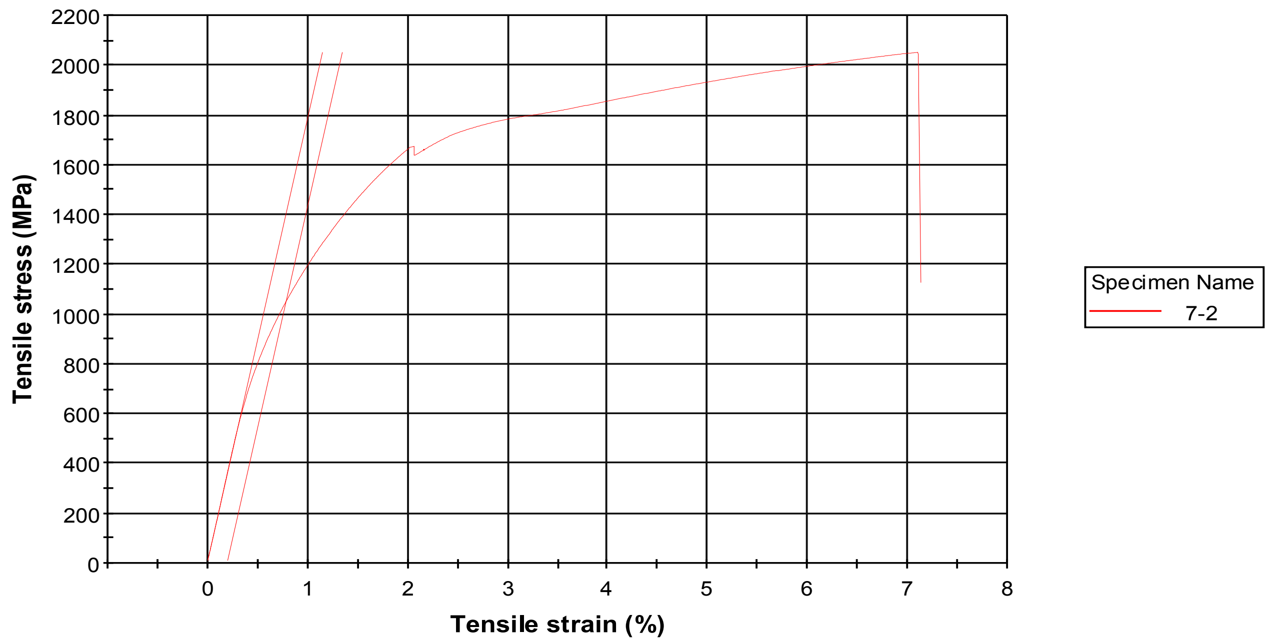

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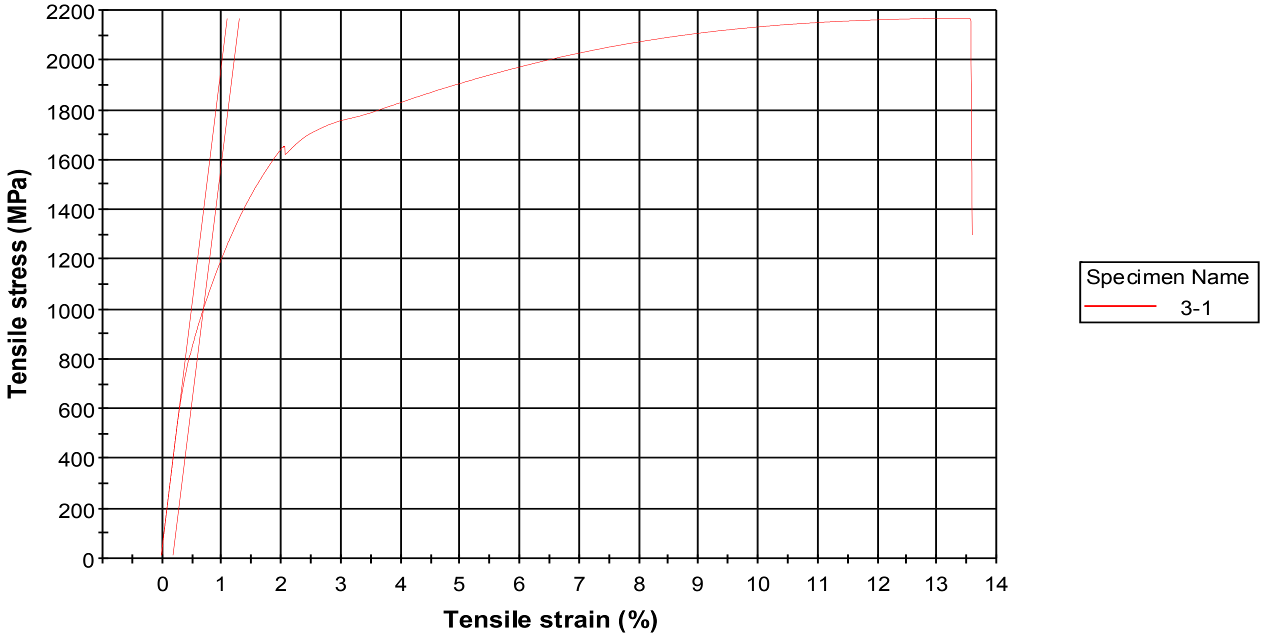

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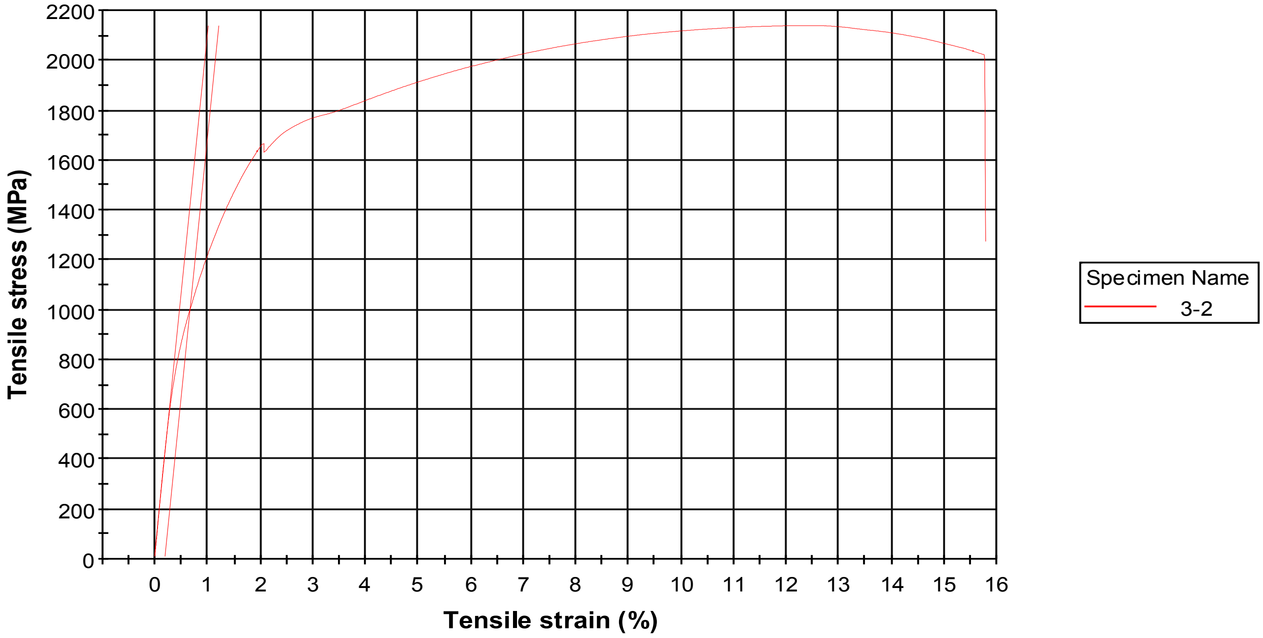

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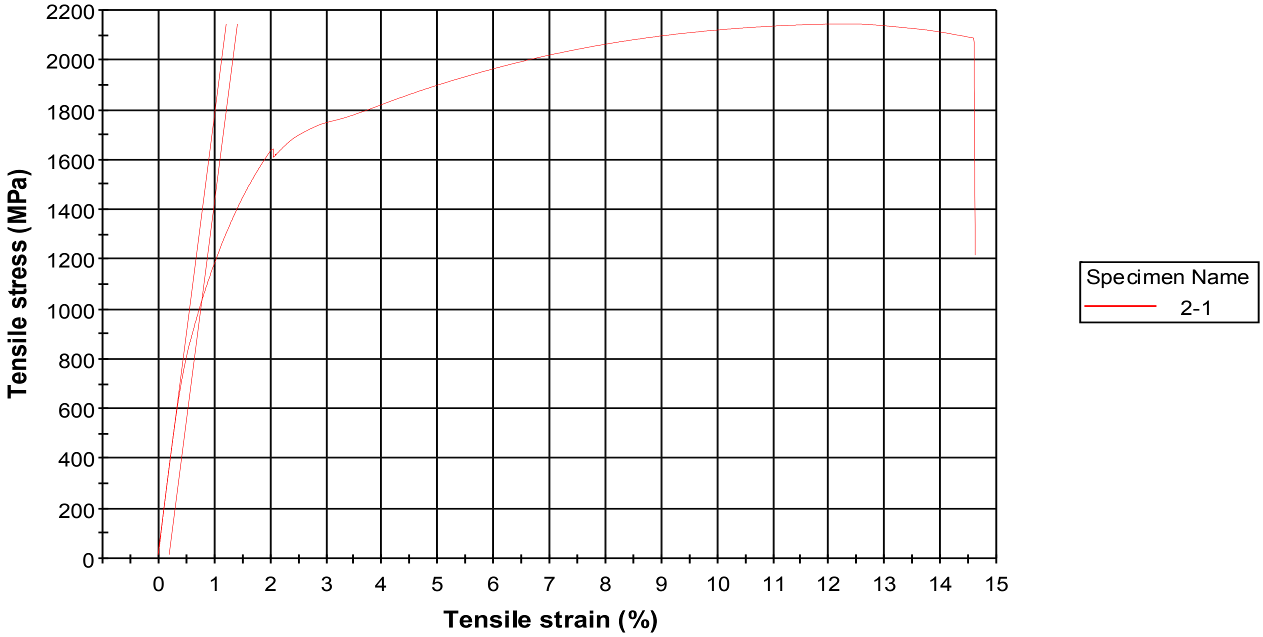

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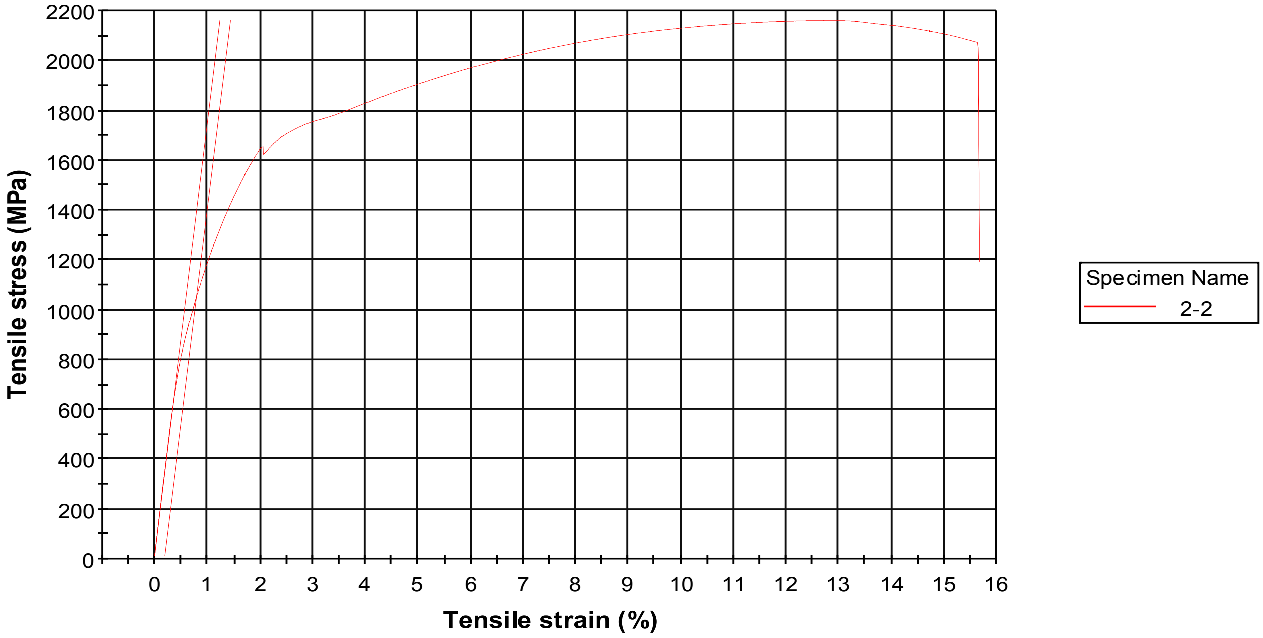

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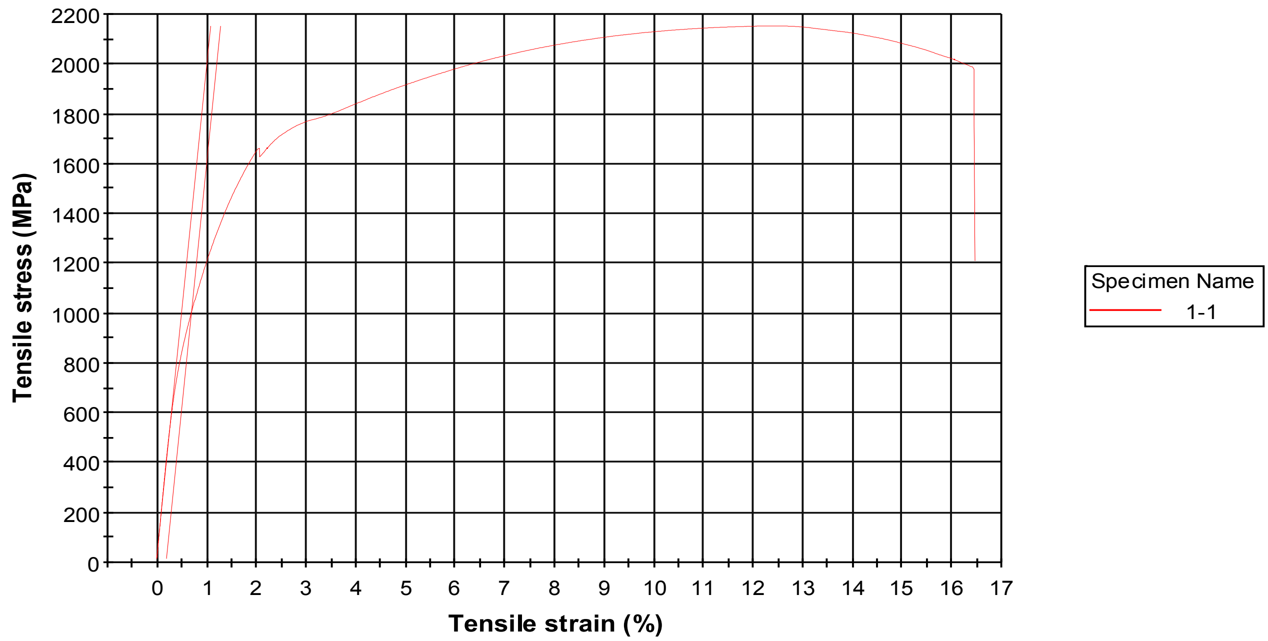

Results Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
1	15-P-2	38.49	76.61	69.22	27.78	15.43
2	15-P-3	37.80	76.53	68.27	29.74	16.54
3	15-T-1	37.68	77.99	75.07	17.18	12.78
4	15-T-2	37.54	77.95	74.01	18.34	12.80
5	15-T-3	38.04	77.91	74.81	17.89	12.69
6	7RA900-1	37.37	75.99	70.14	27.20	14.49
7	7RA900-2	37.21	75.94	67.57	29.60	13.96
8	4RA900-1	35.85	71.02	71.02	0.97	2.82
9	4RA900-2	34.94	74.02	74.02	-6.03	9.29
10	18-1	34.32	74.51	70.94	18.93	14.57
11	18-2	-----	74.08	73.71	11.60	11.64
12	16-1	35.35	71.94	69.59	19.57	13.26
13	16-2	36.52	73.95	71.65	16.95	13.38
14	14-1	33.49	71.92	69.75	16.50	13.10
15	14-2	33.62	72.60	68.28	22.83	14.14
16	13-1	37.11	73.62	69.32	21.38	13.47
17	13-2	37.51	74.21	69.29	27.40	14.15
18	21-1	37.39	71.25	64.89	27.51	15.05
19	12-2	40.32	72.36	65.83	27.20	14.73
20	11-1	32.87	71.69	69.55	11.14	12.46
21	11-2	32.46	68.35	68.35	6.00	5.88
22	10-1	37.22	75.91	67.11	32.51	15.87
23	10-2	39.18	75.35	70.12	21.97	14.75
24	9-1	38.15	77.73	75.20	19.36	13.15
25	9-2	38.94	78.31	73.76	23.77	14.96
26	8-1	39.08	76.69	73.72	17.98	13.69
27	8-2	38.24	76.34	72.12	21.85	13.51

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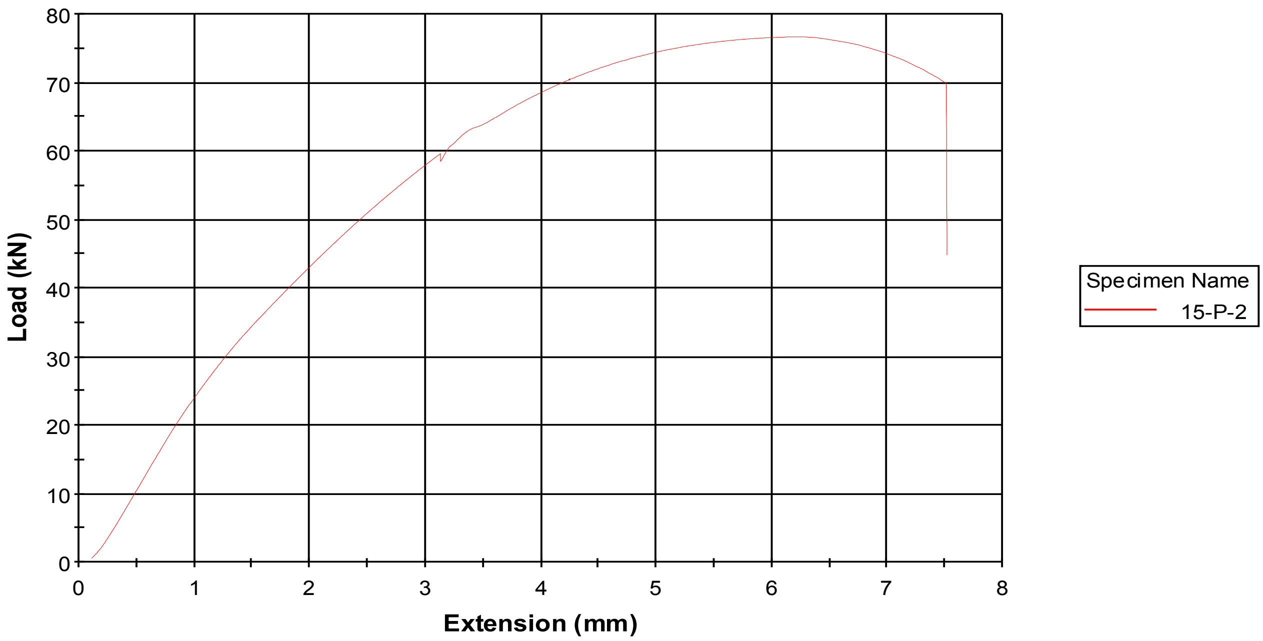
	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
28	7-1	38.28	71.63	70.52	4.69	4.62
29	7-2	38.29	74.46	74.46	4.92	5.69
30	3-1	36.91	79.26	79.24	10.93	12.19
31	3-2	36.65	78.15	73.89	12.51	14.53
32	2-1	38.11	78.45	76.37	18.11	13.13
33	2-2	38.64	79.05	75.15	20.04	14.24
34	1-1	36.95	79.12	73.04	24.64	15.13
Mean		36.99	75.14	71.47	18.32	12.71

Load versus Extension



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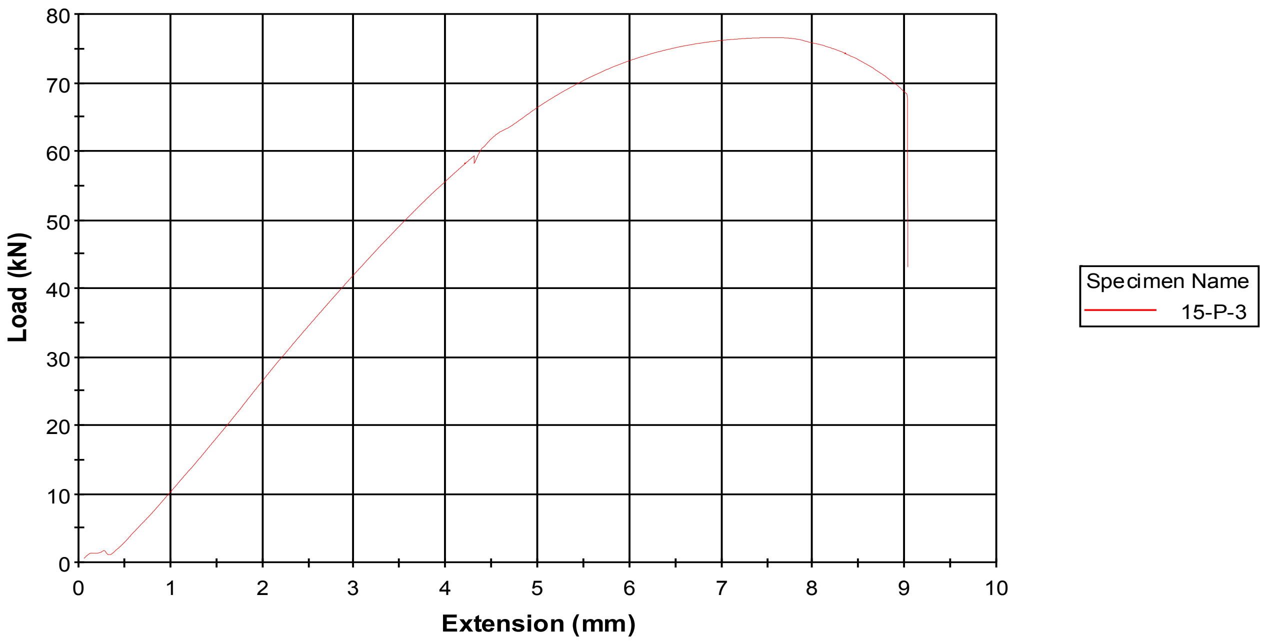

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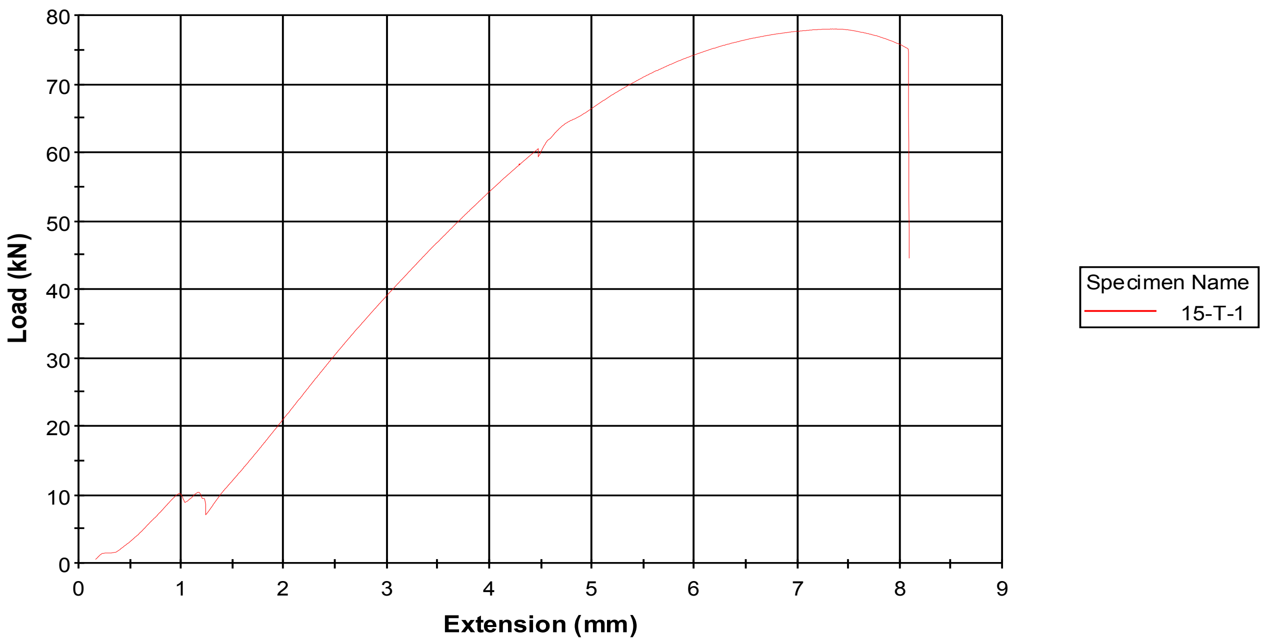

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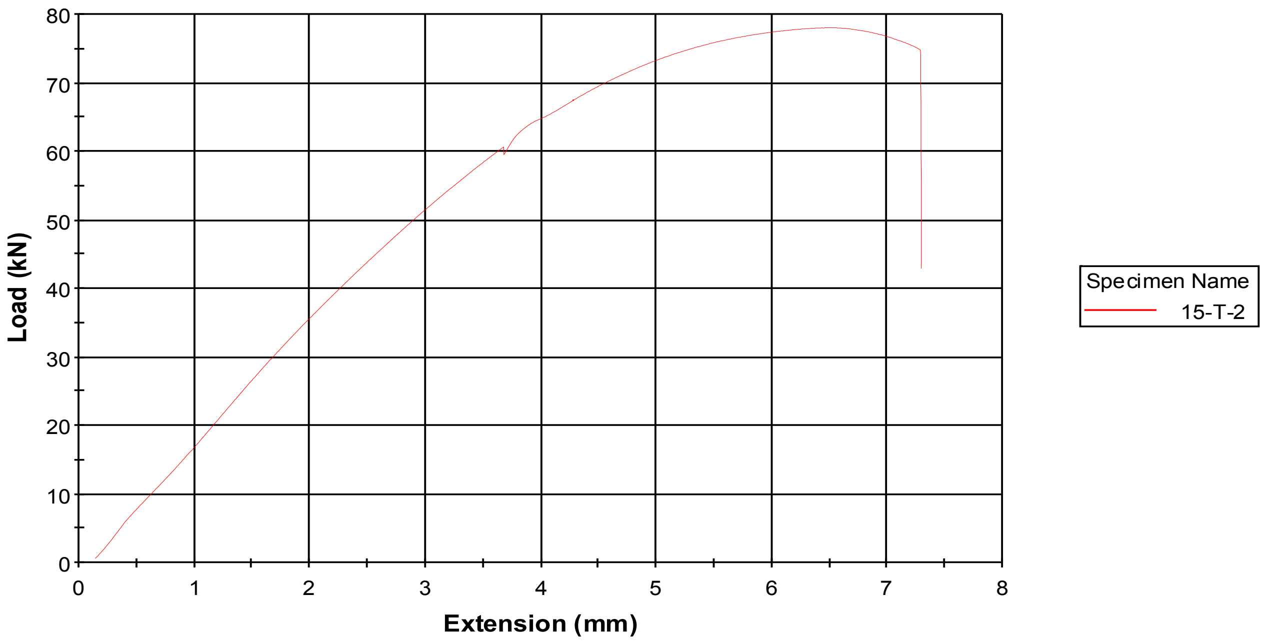

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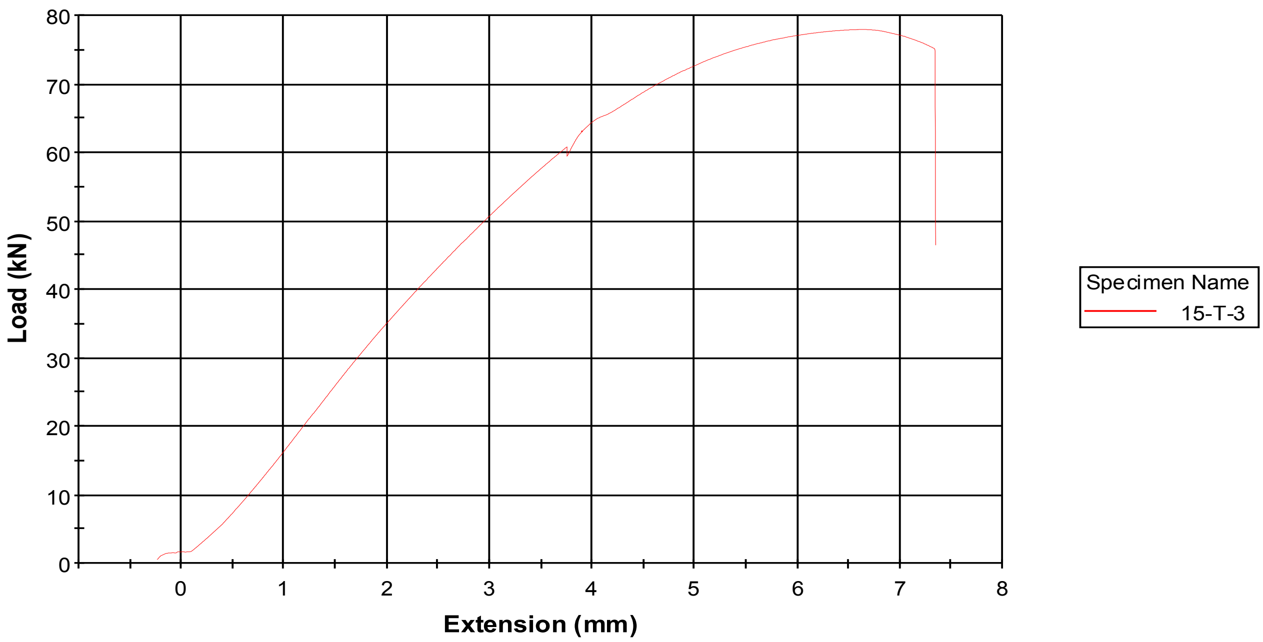

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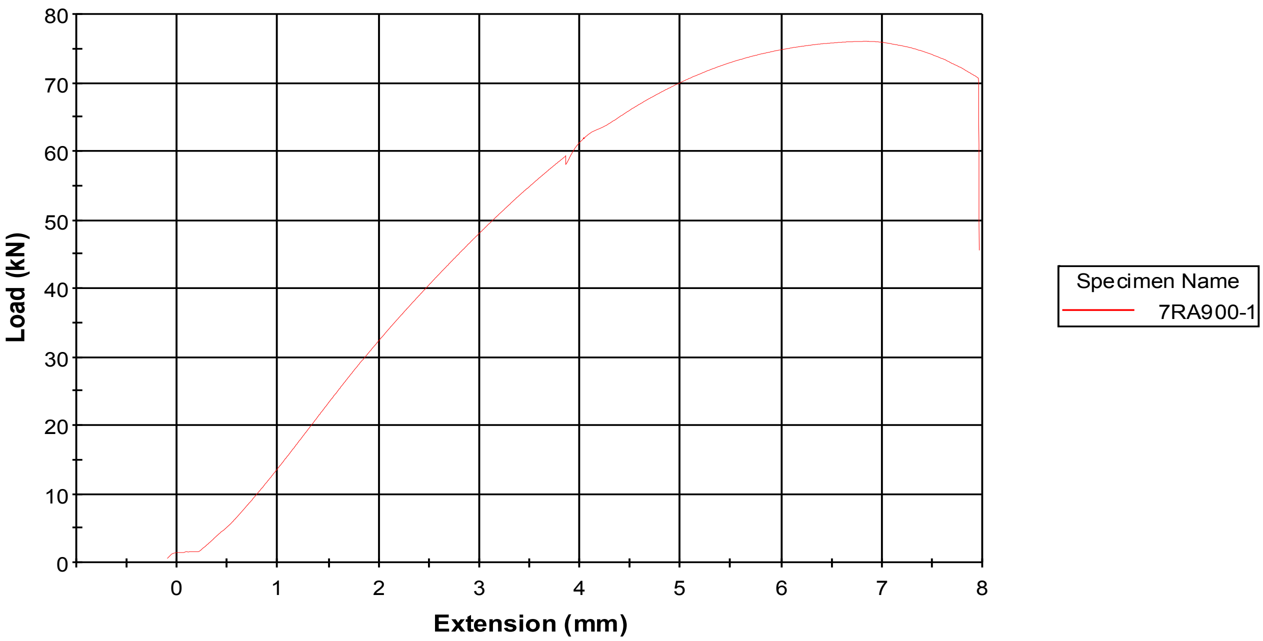

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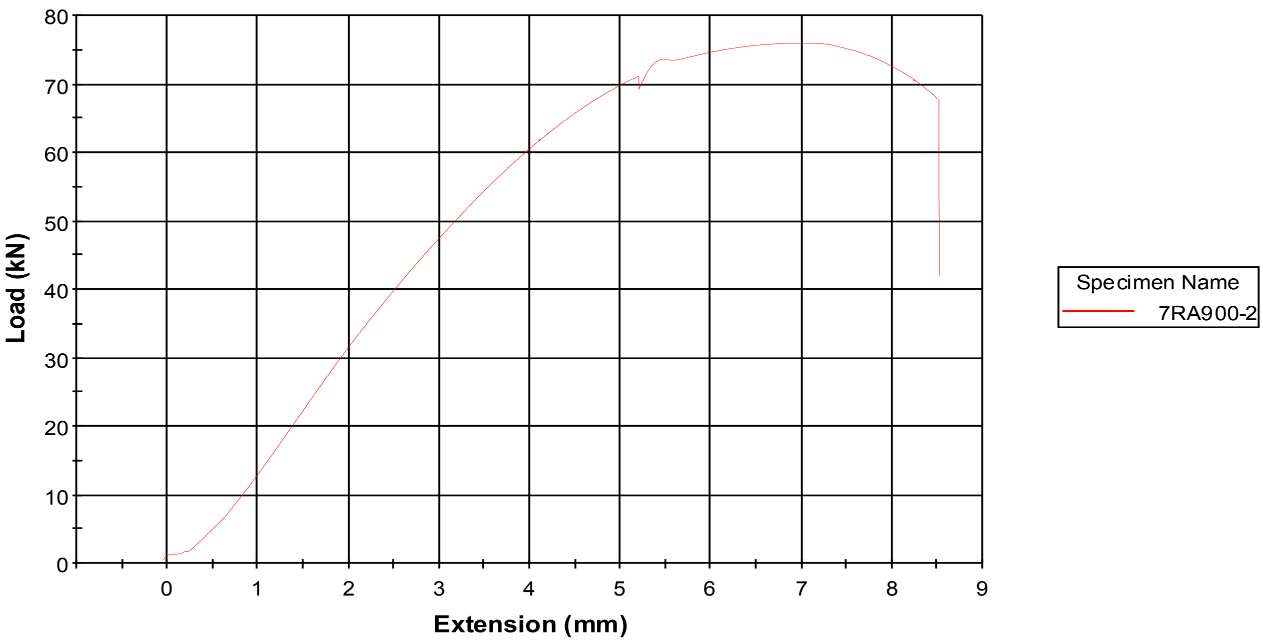

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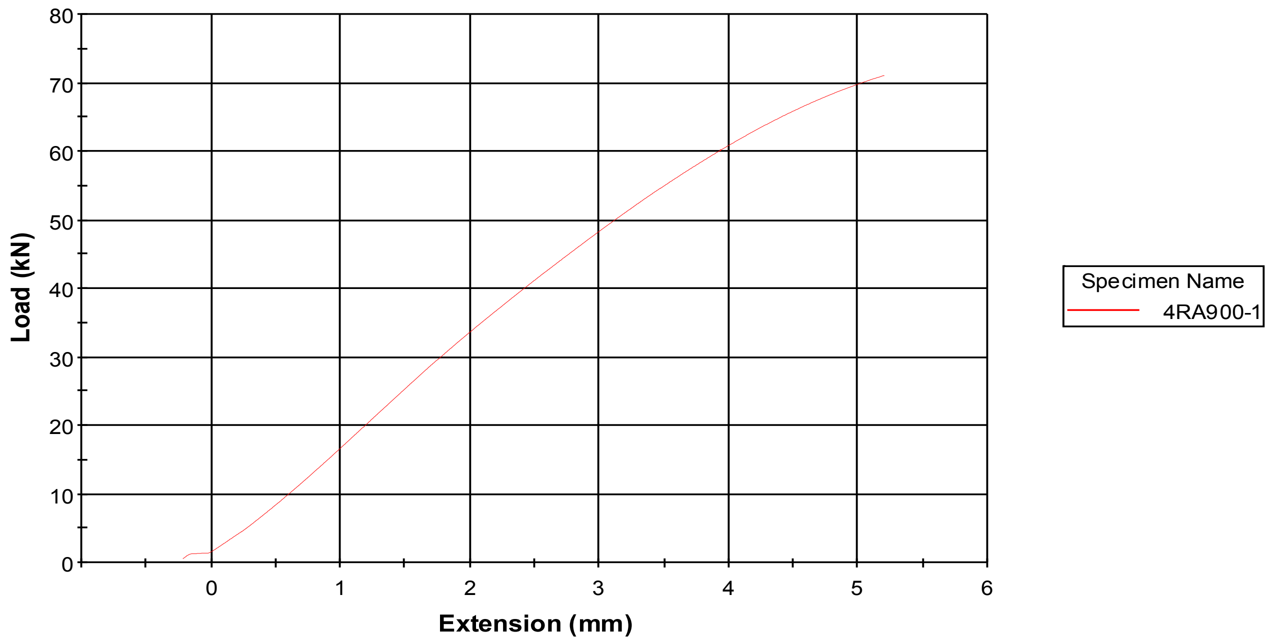

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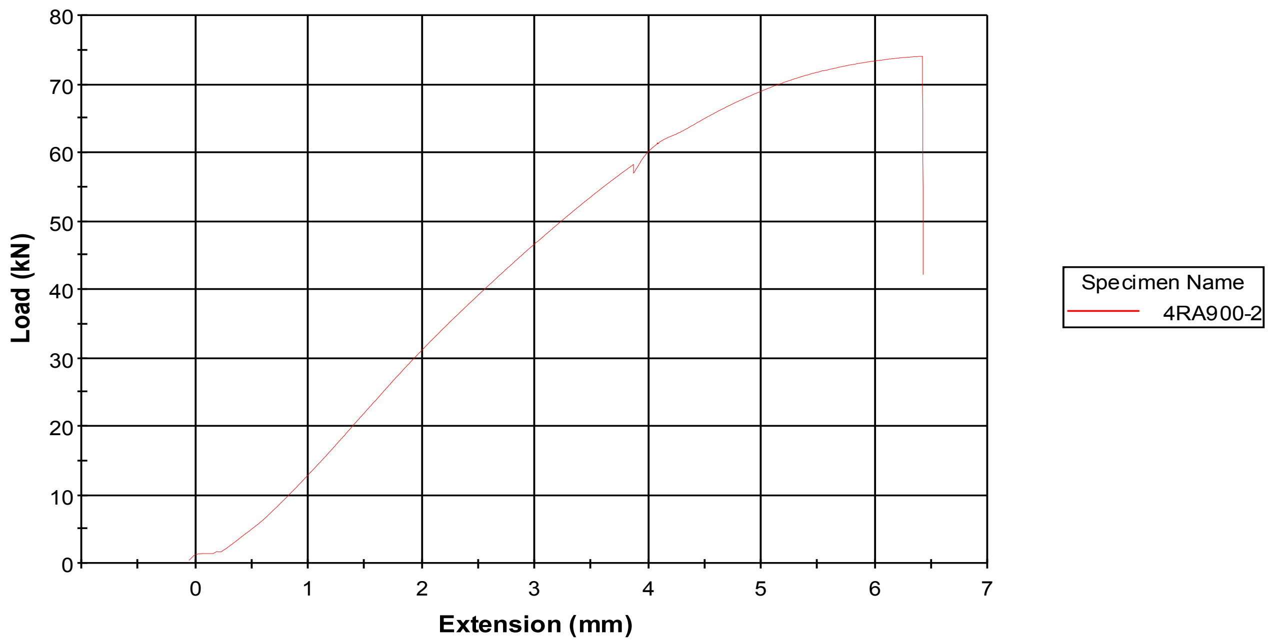

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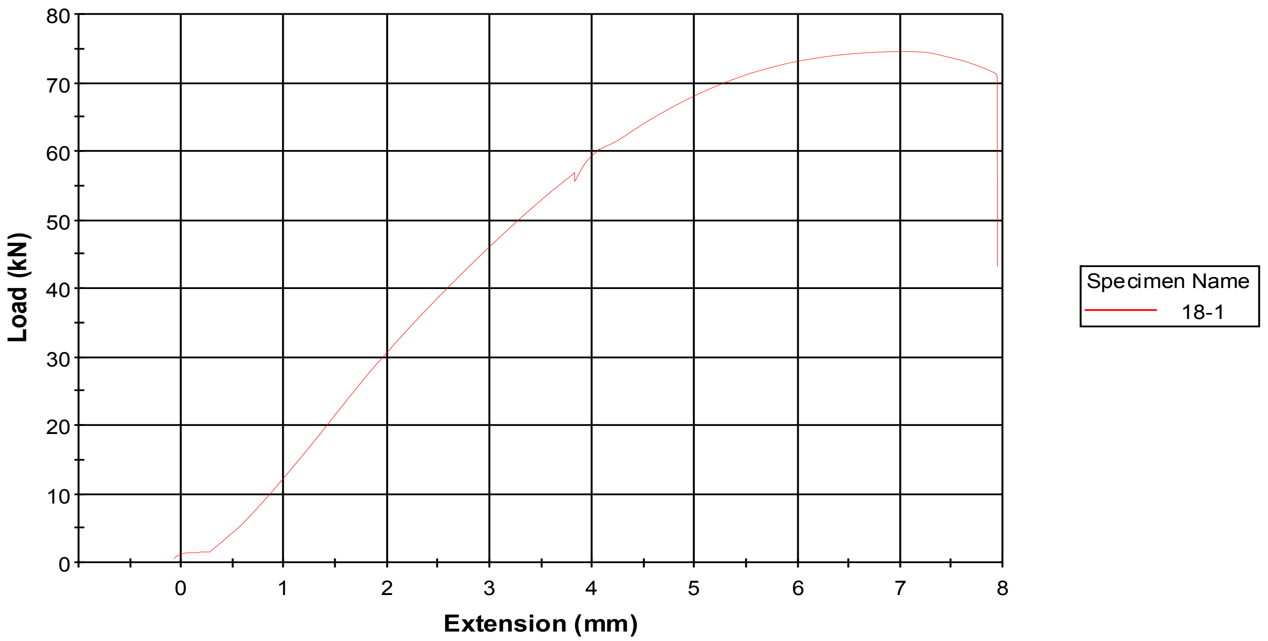

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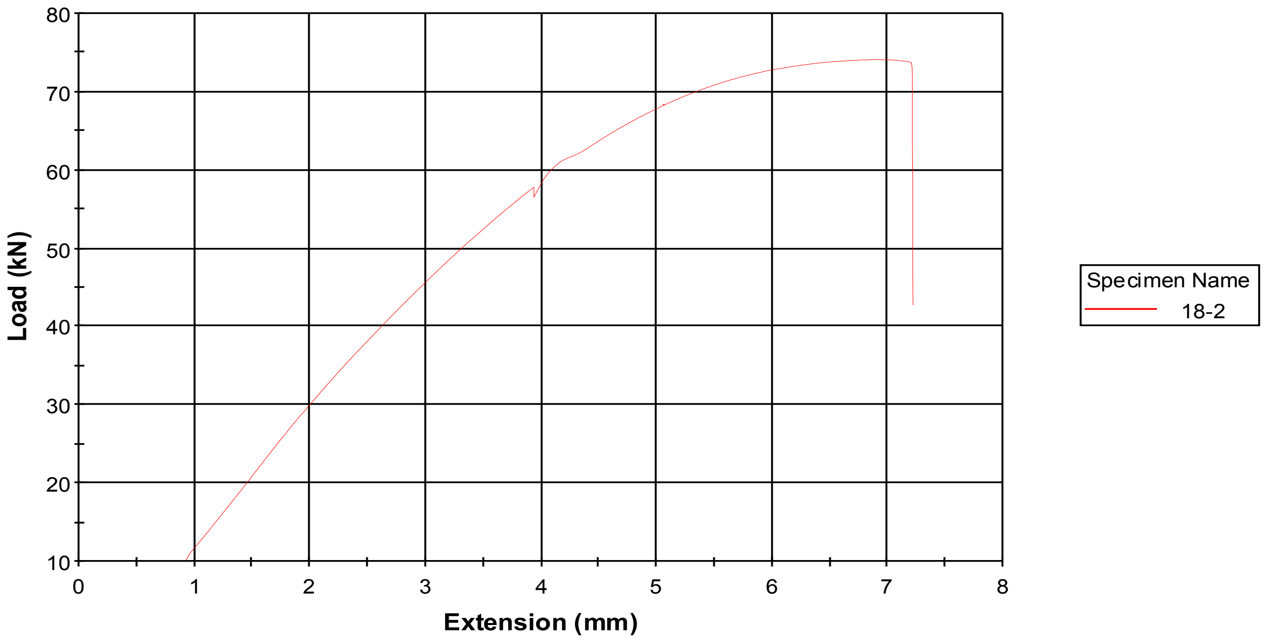

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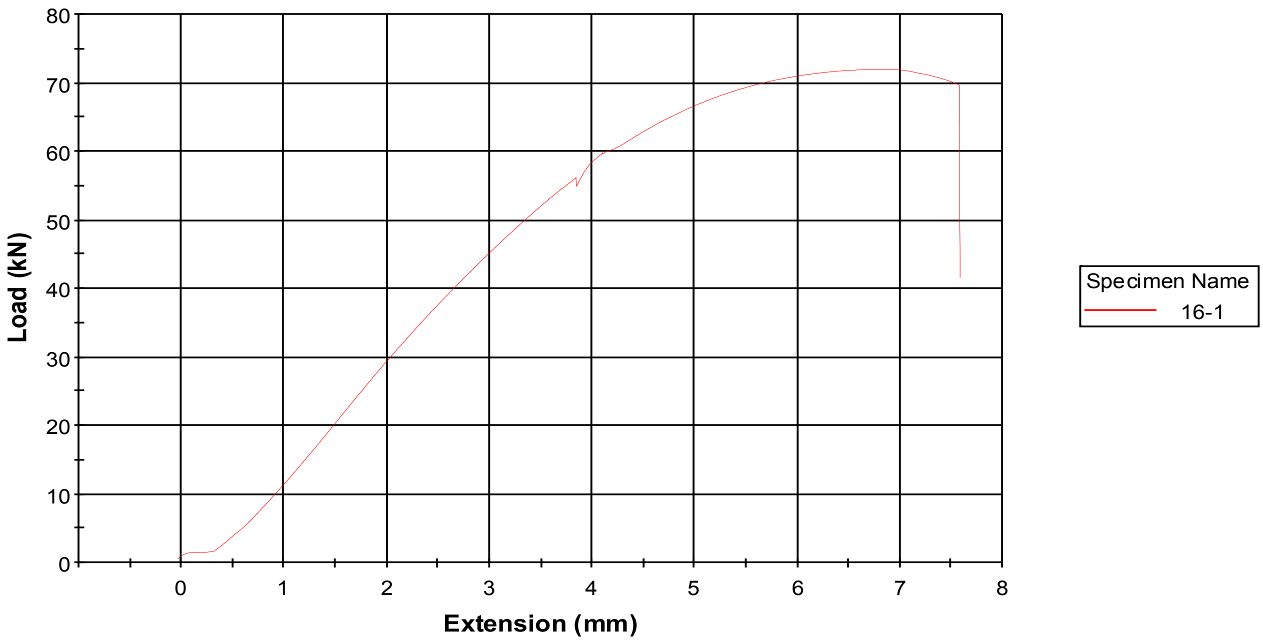

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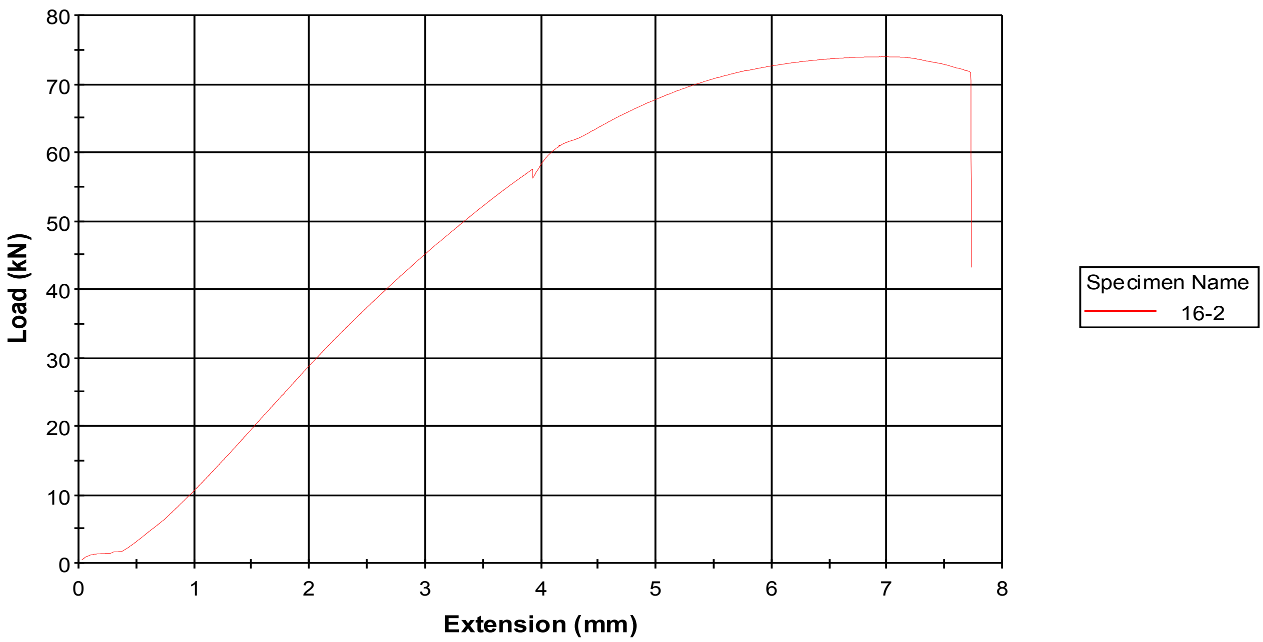

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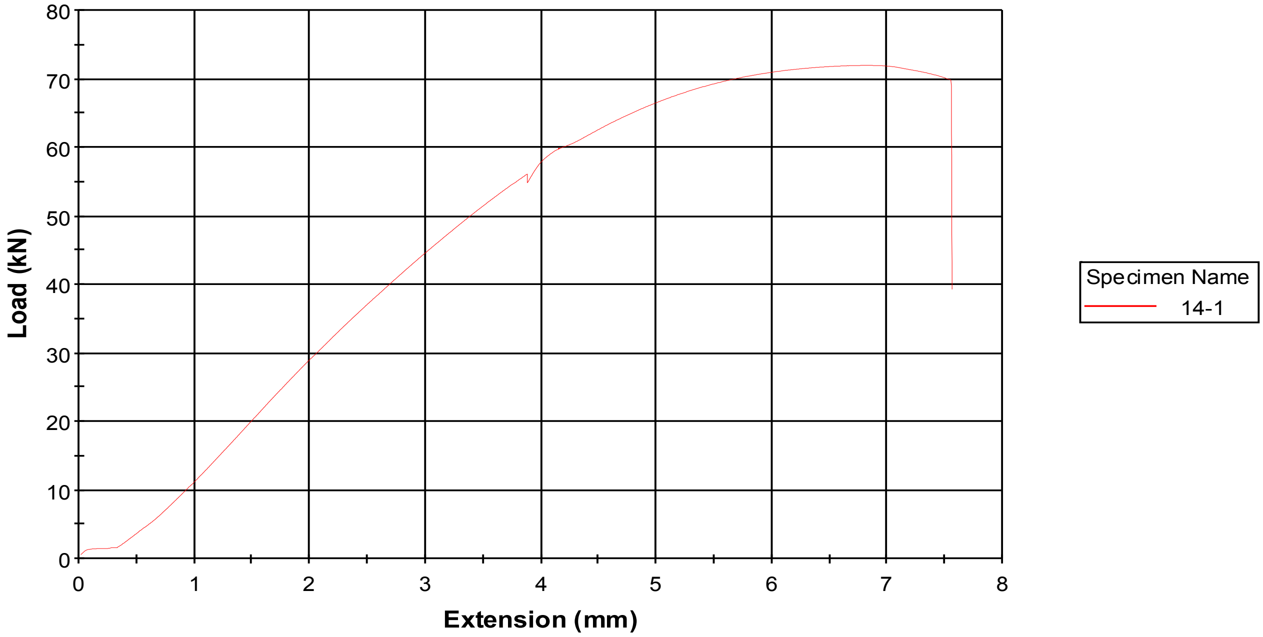

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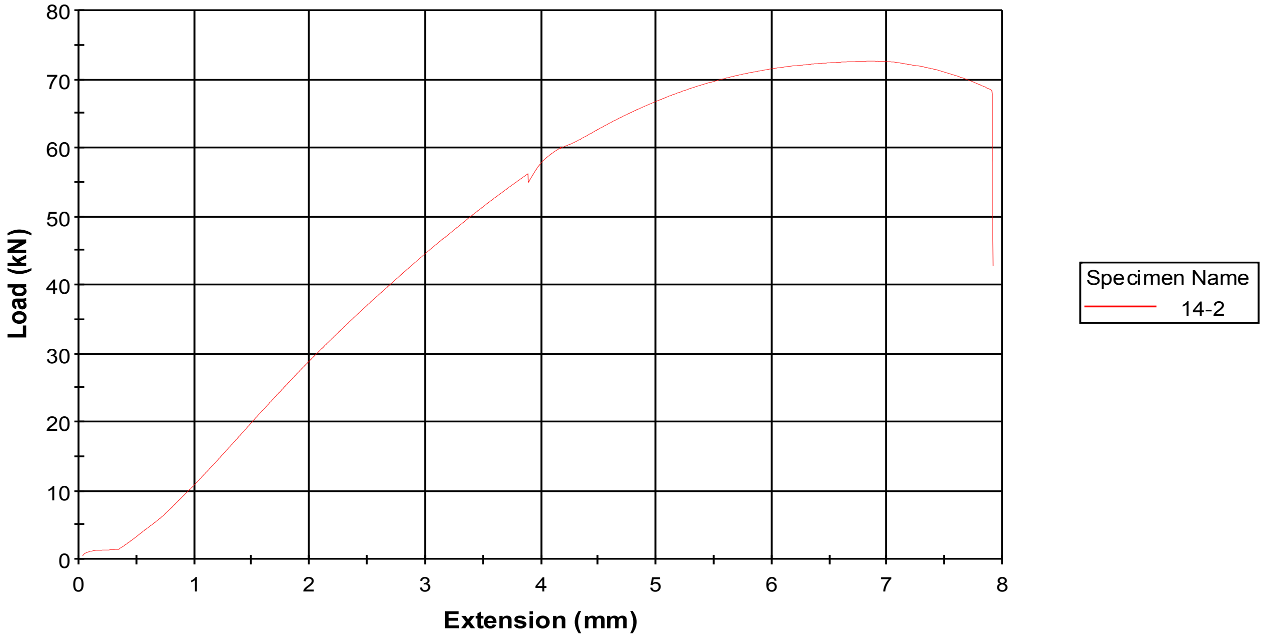

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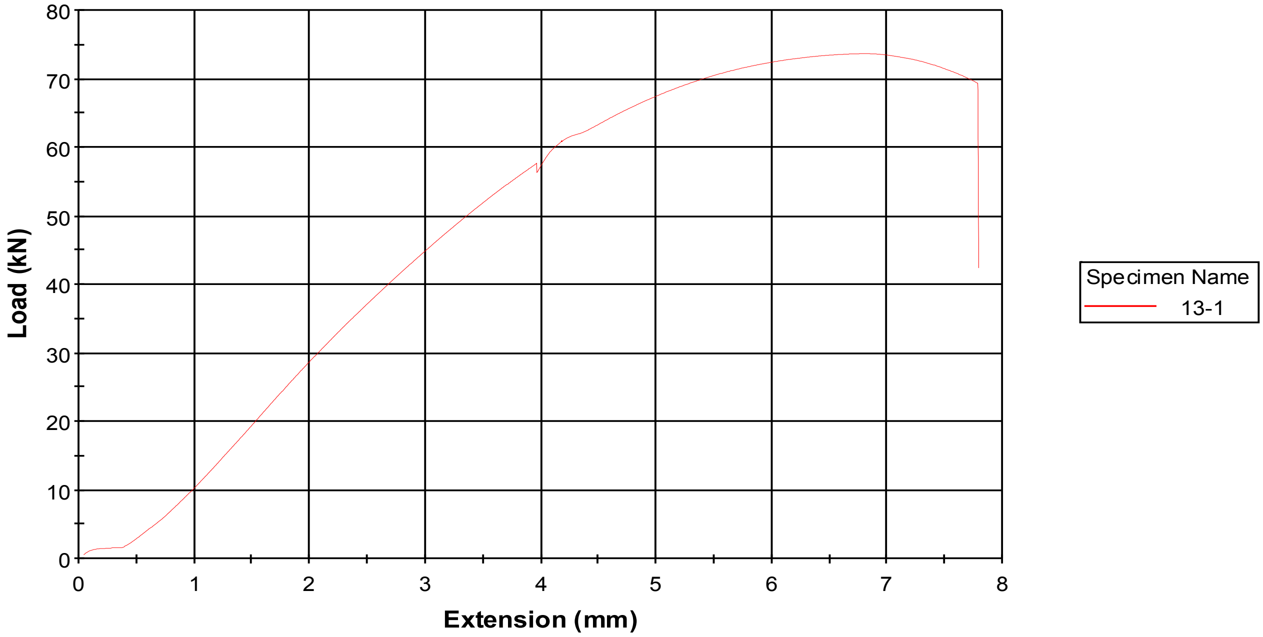

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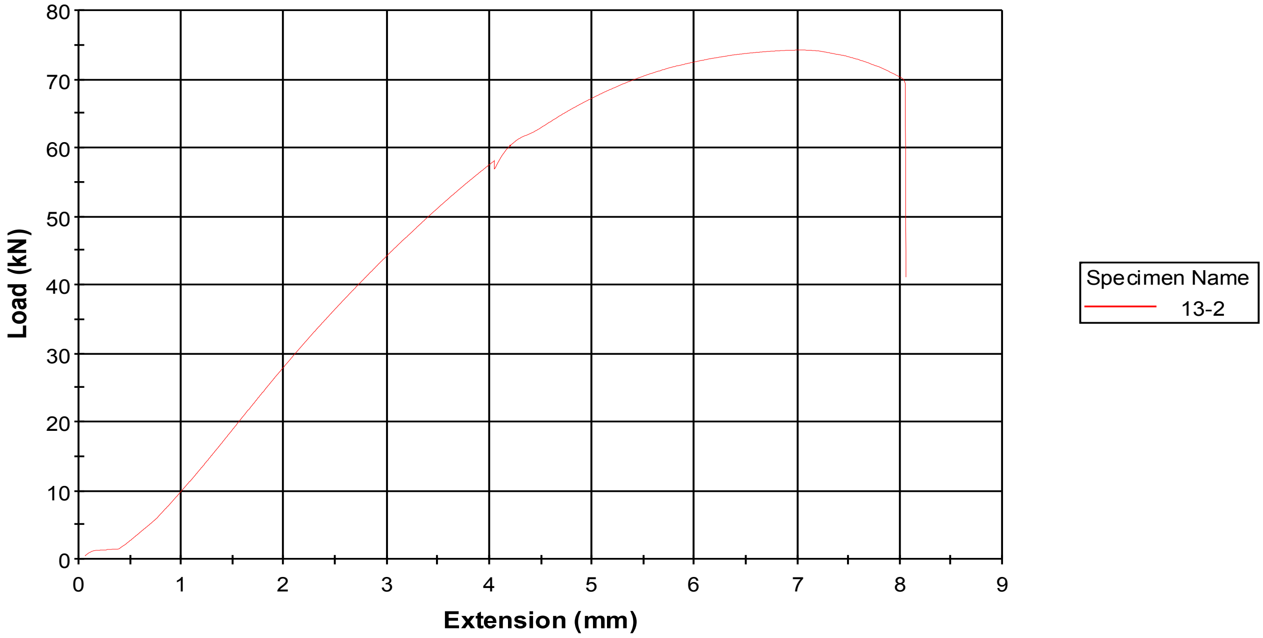

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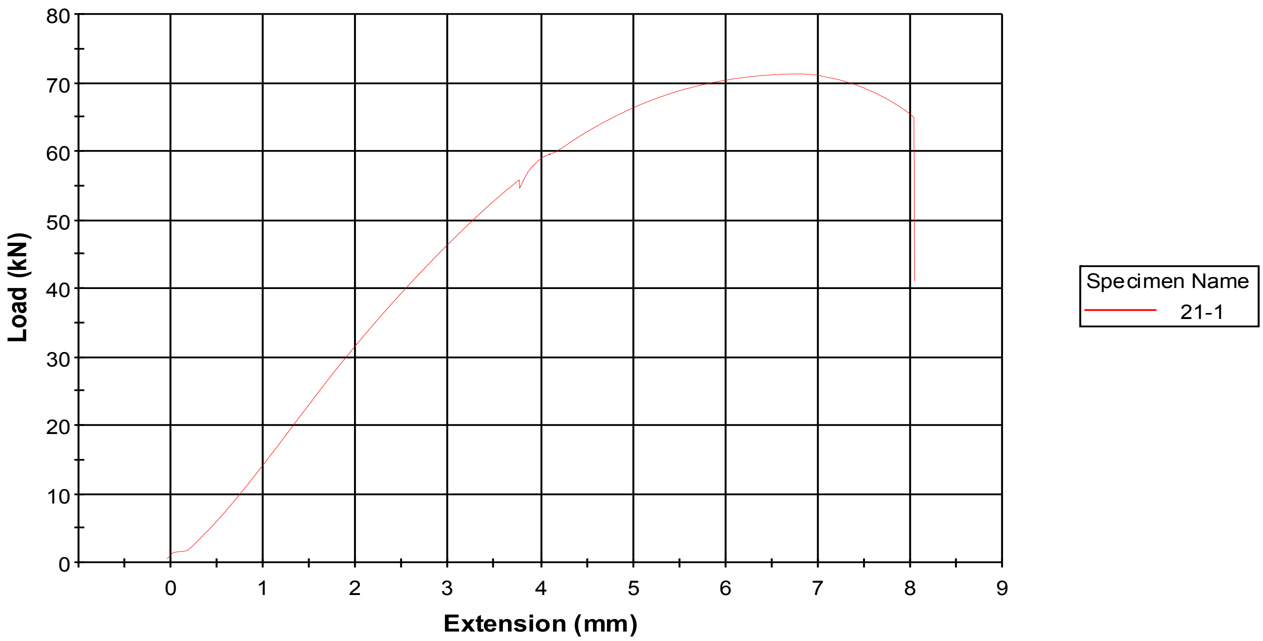
Load versus Extension



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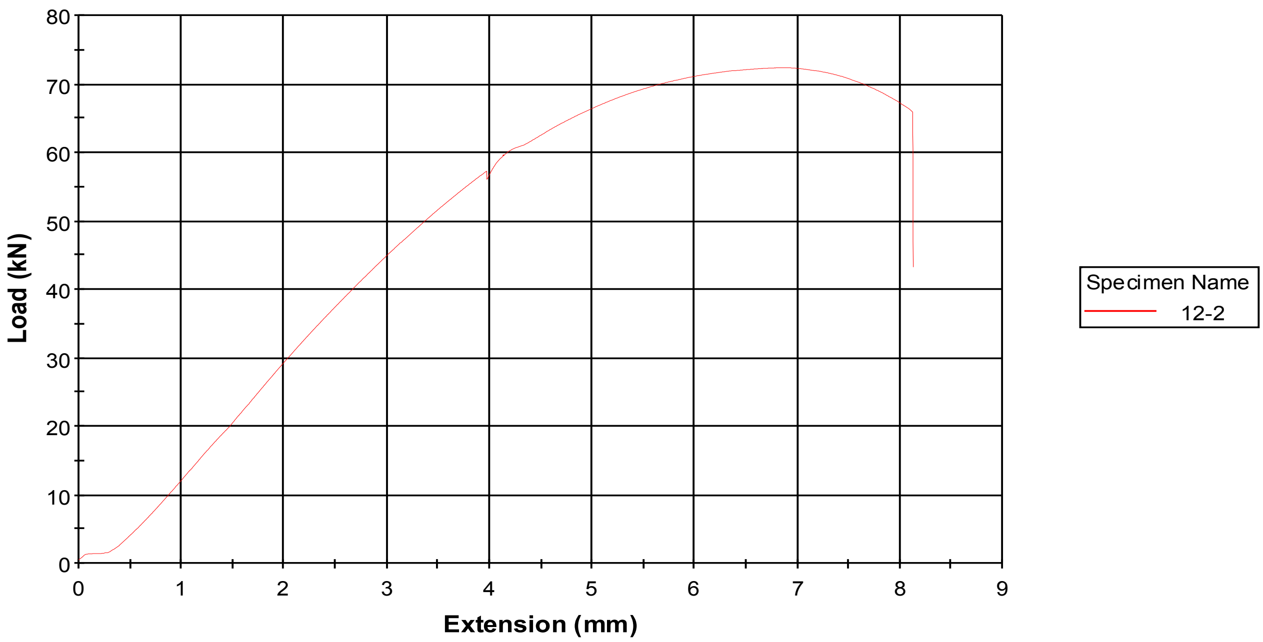

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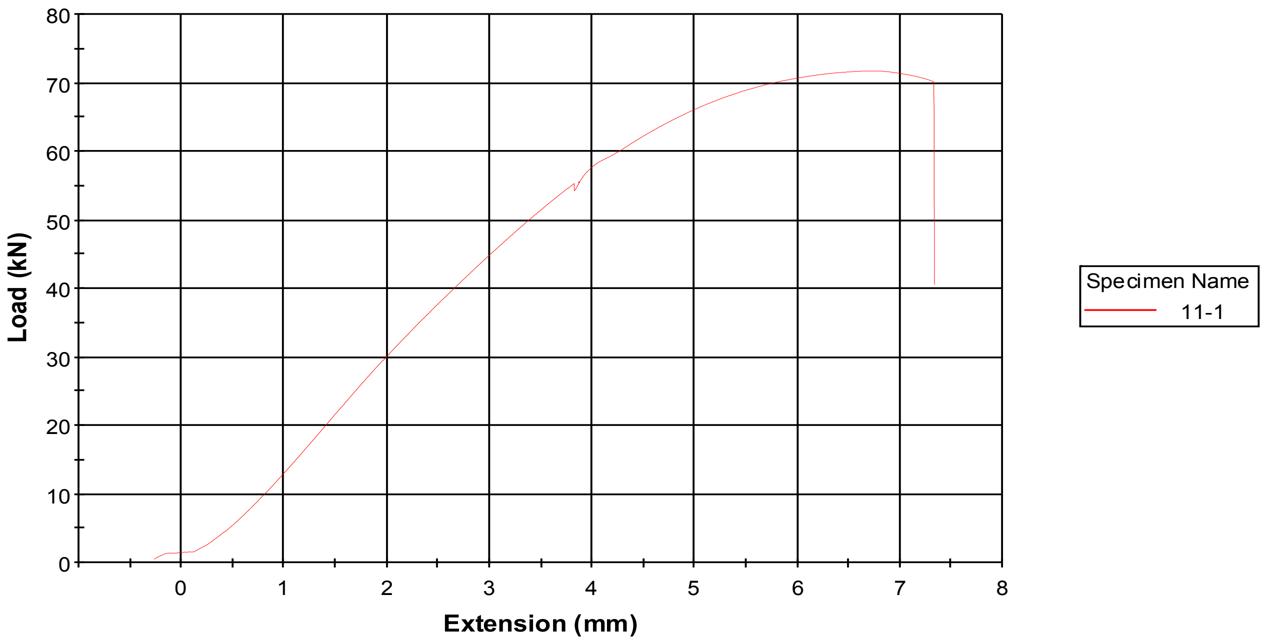

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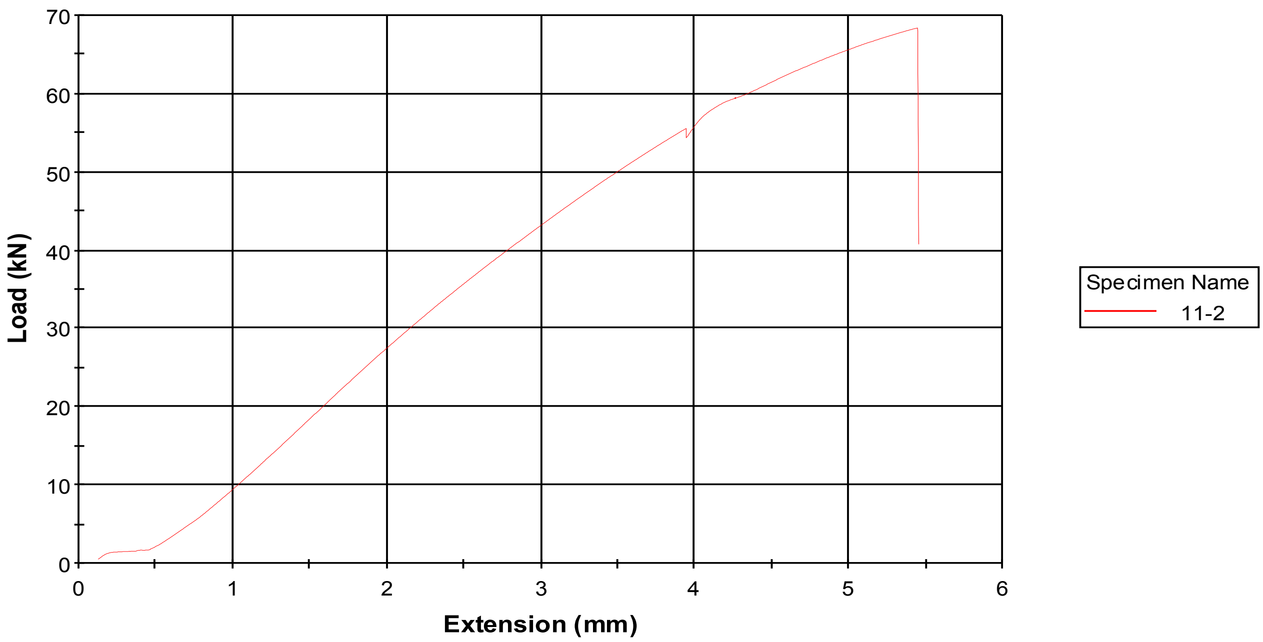

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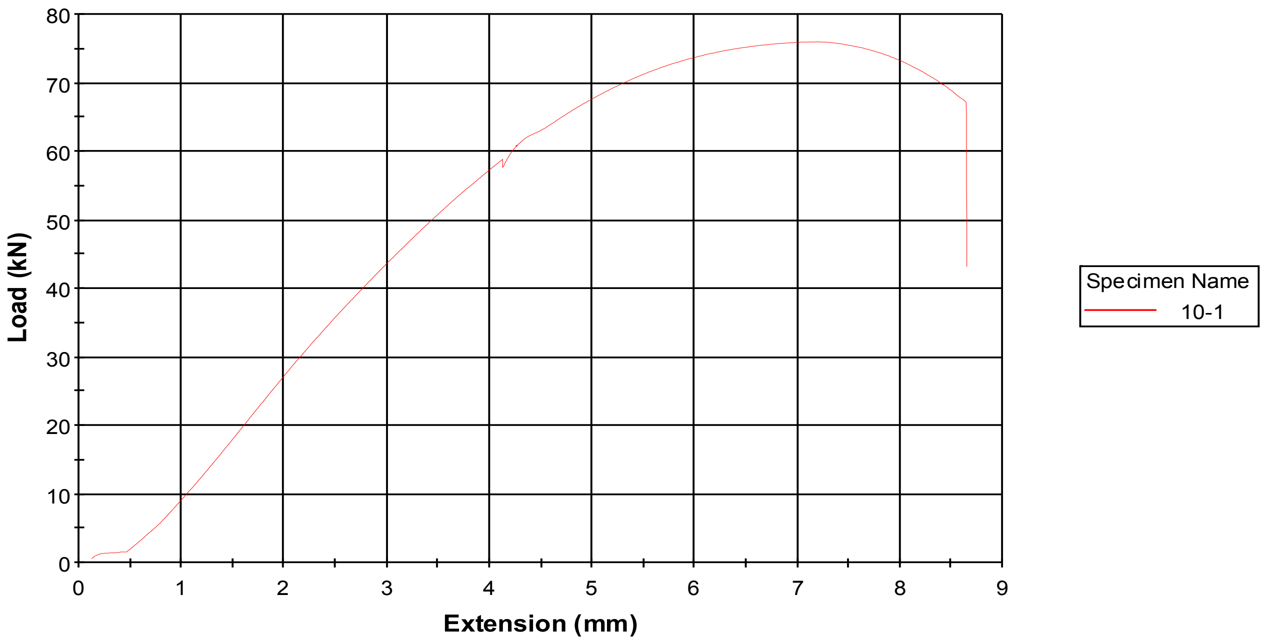

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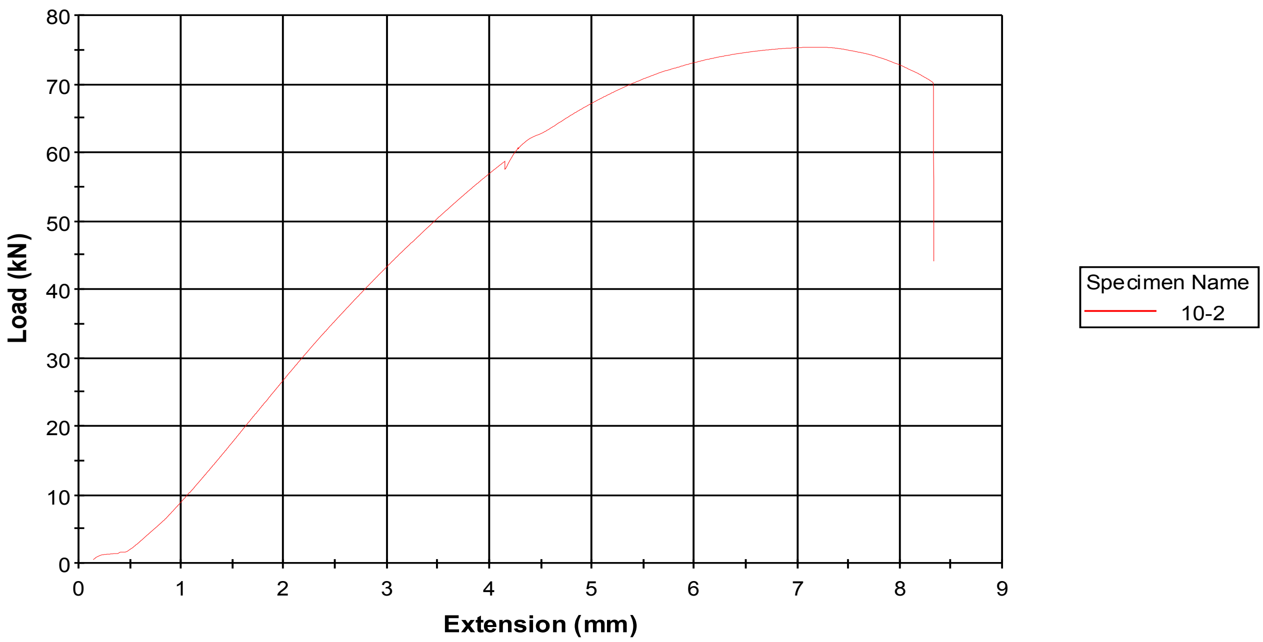

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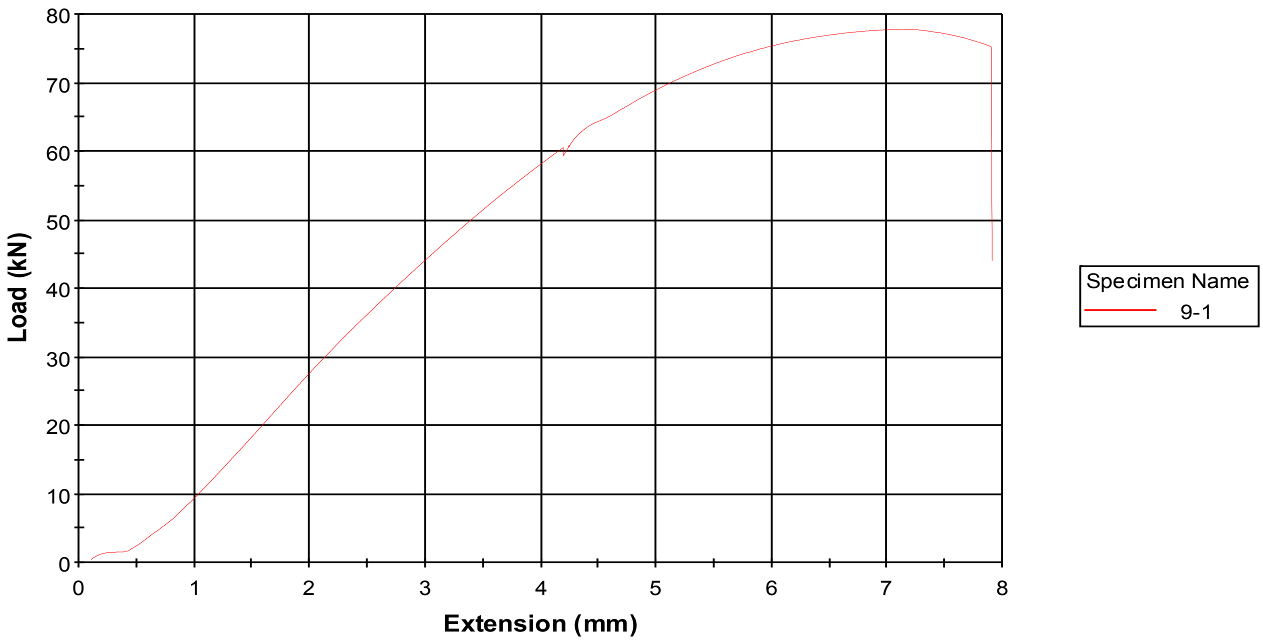

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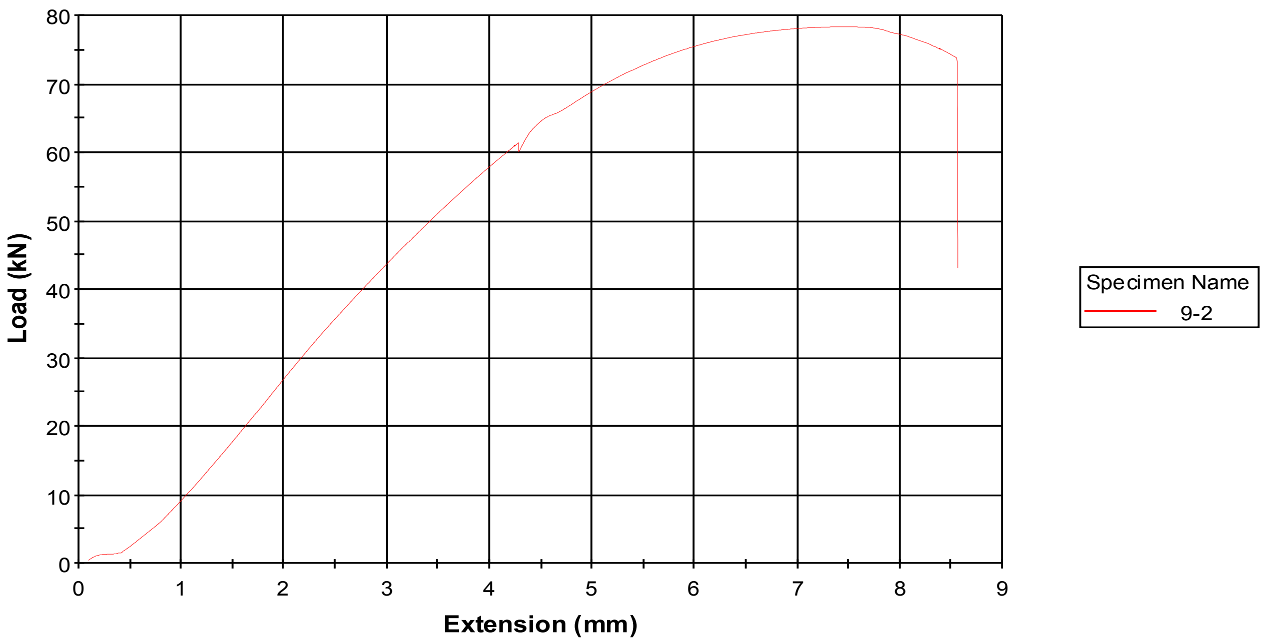

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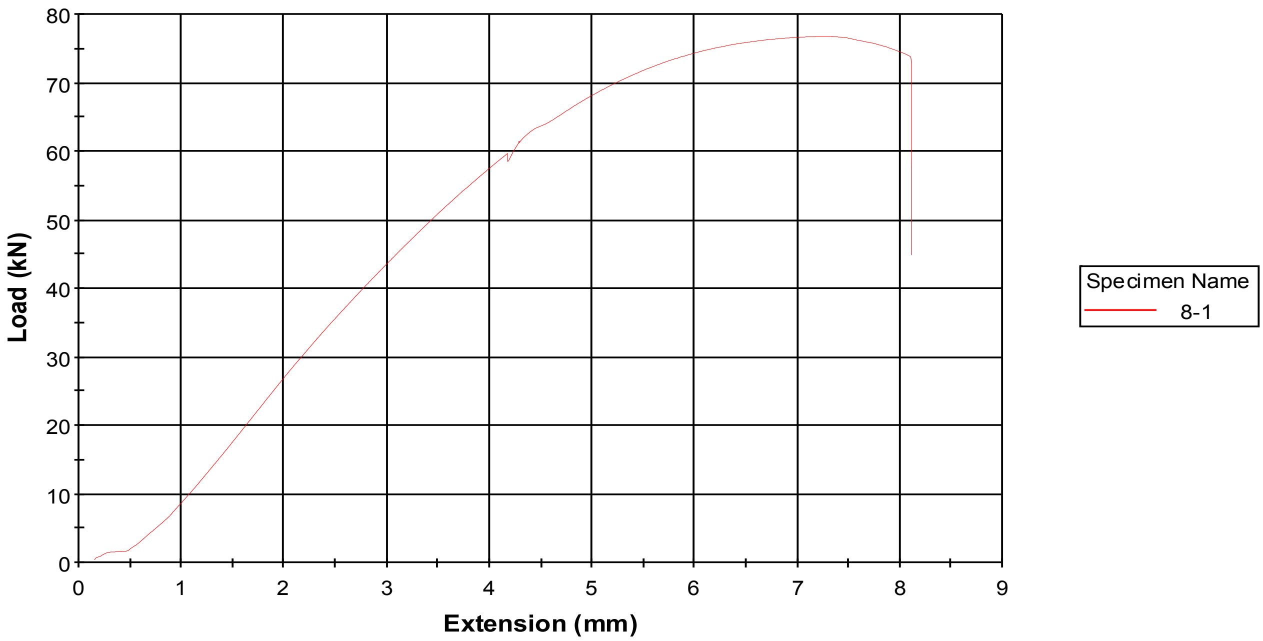

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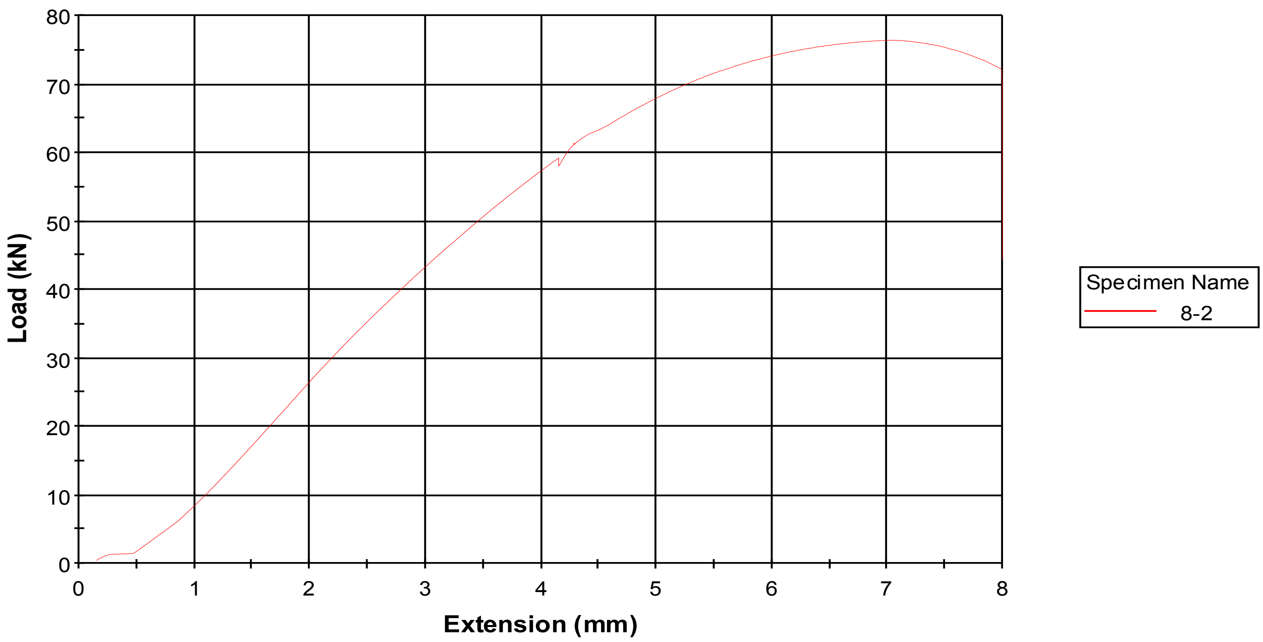

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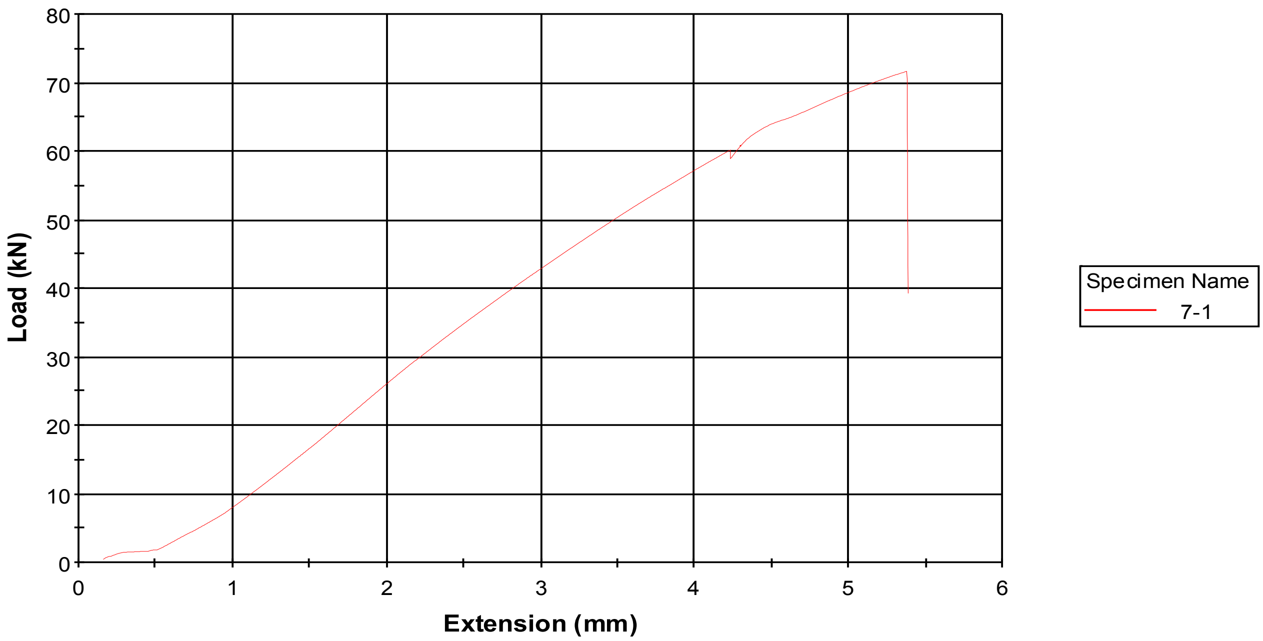
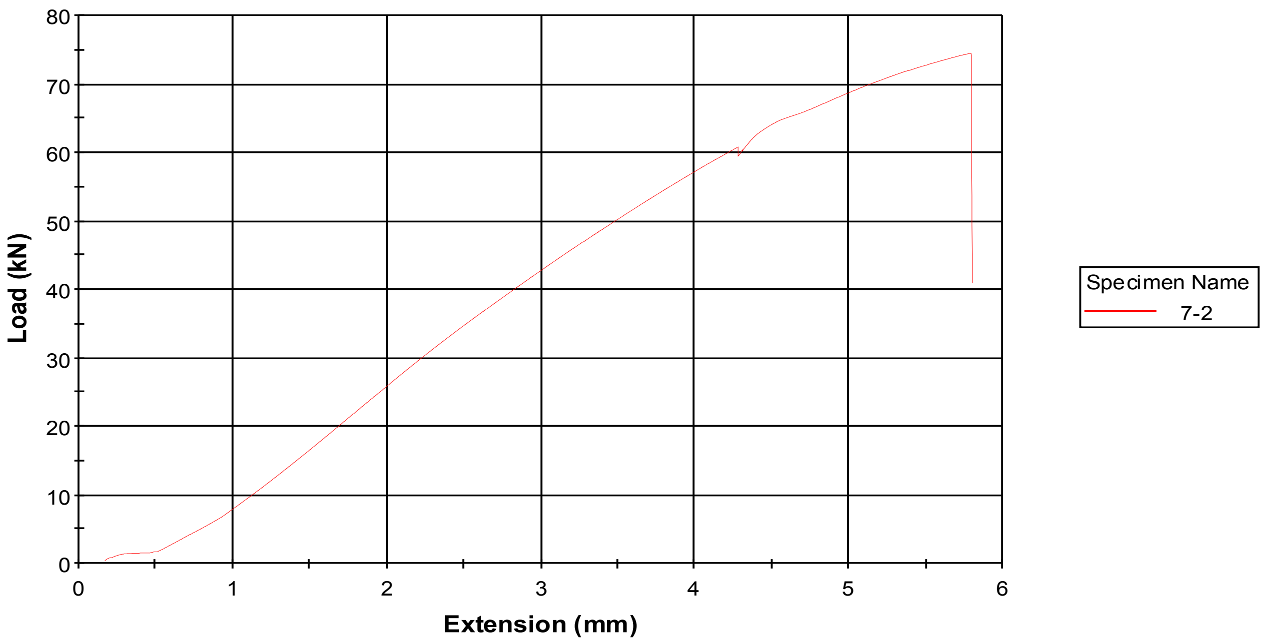
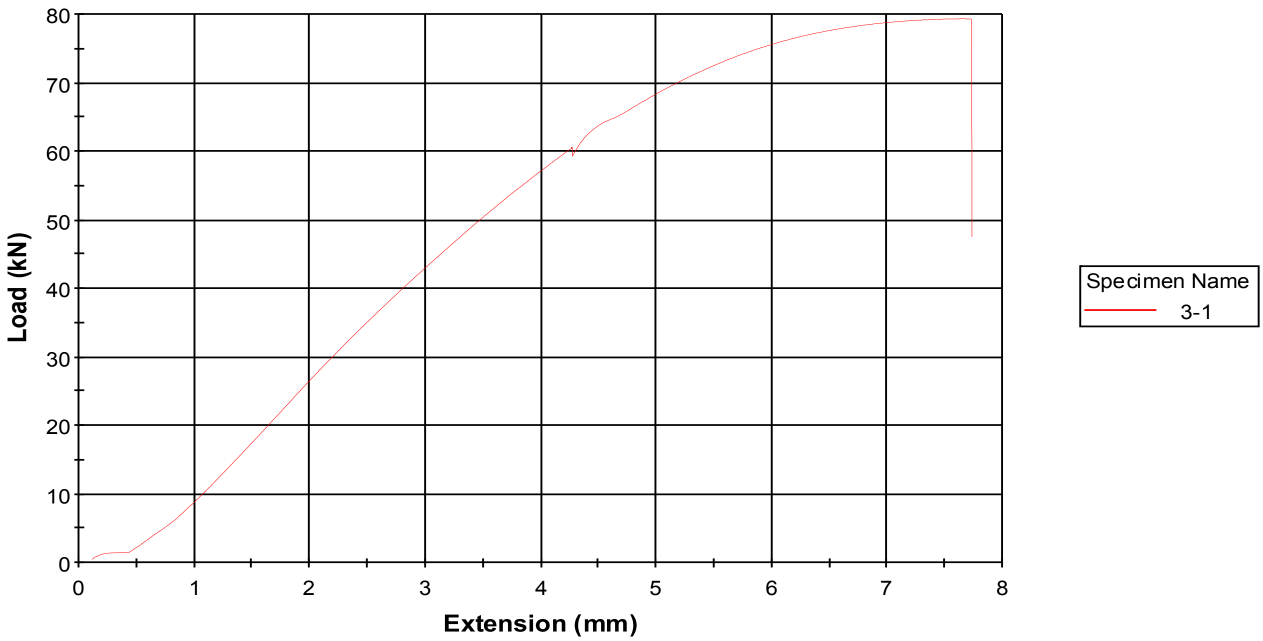
Load versus Extension



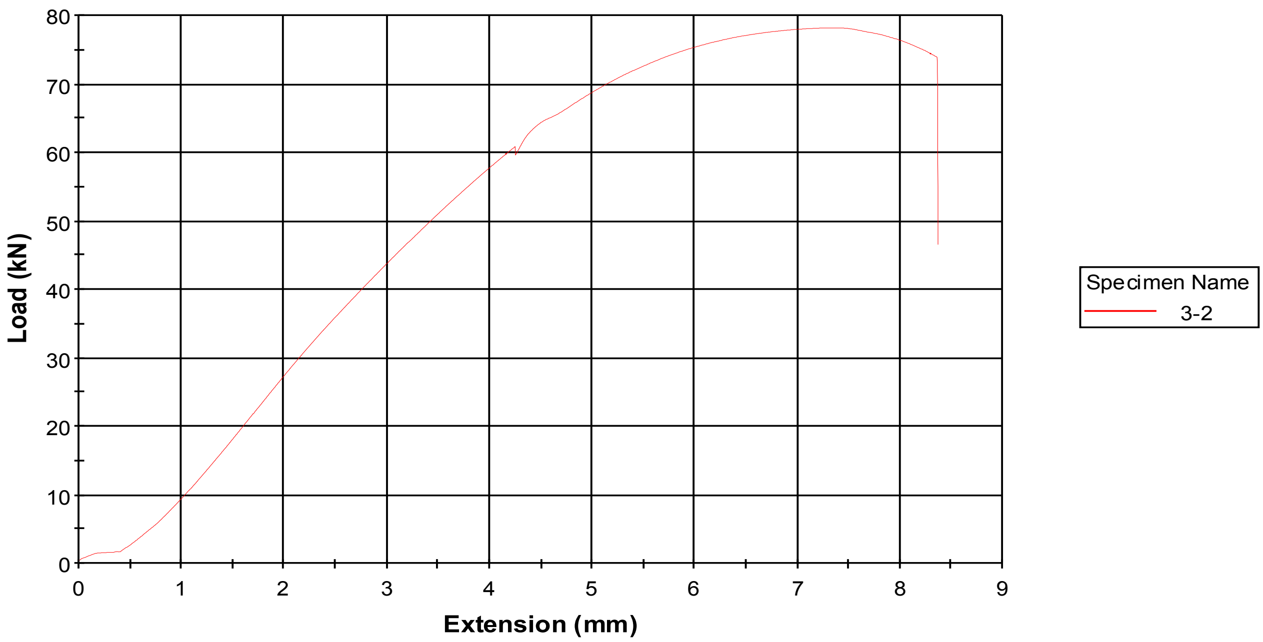
Load versus Extension



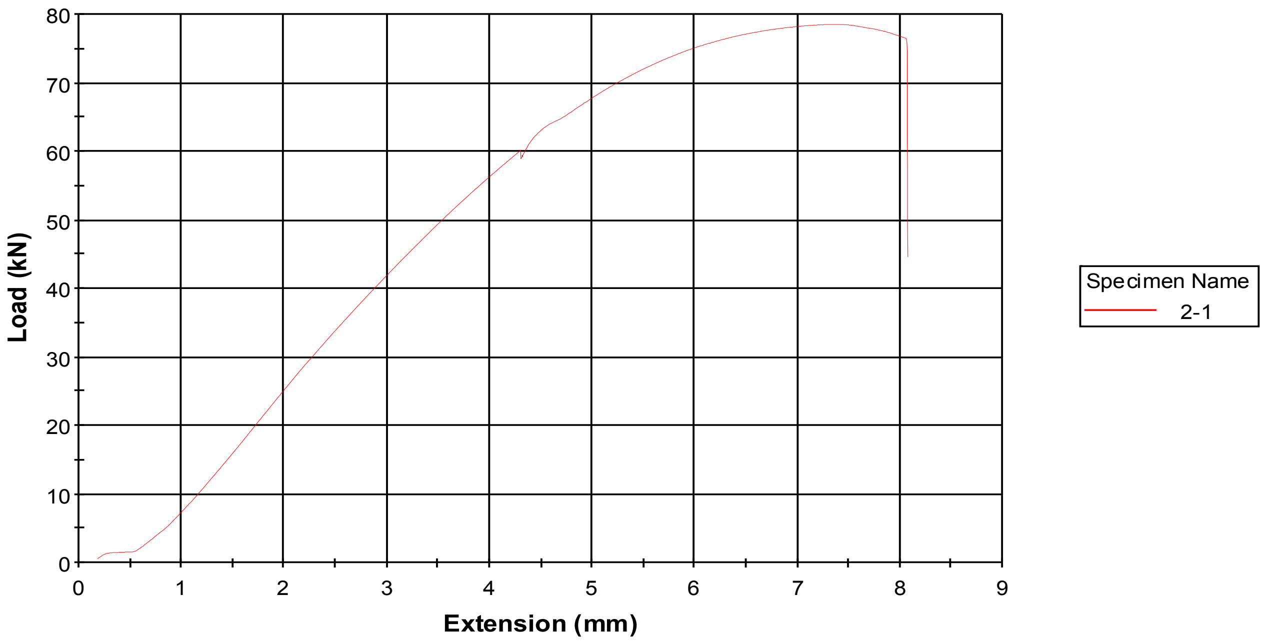
Load versus Extension



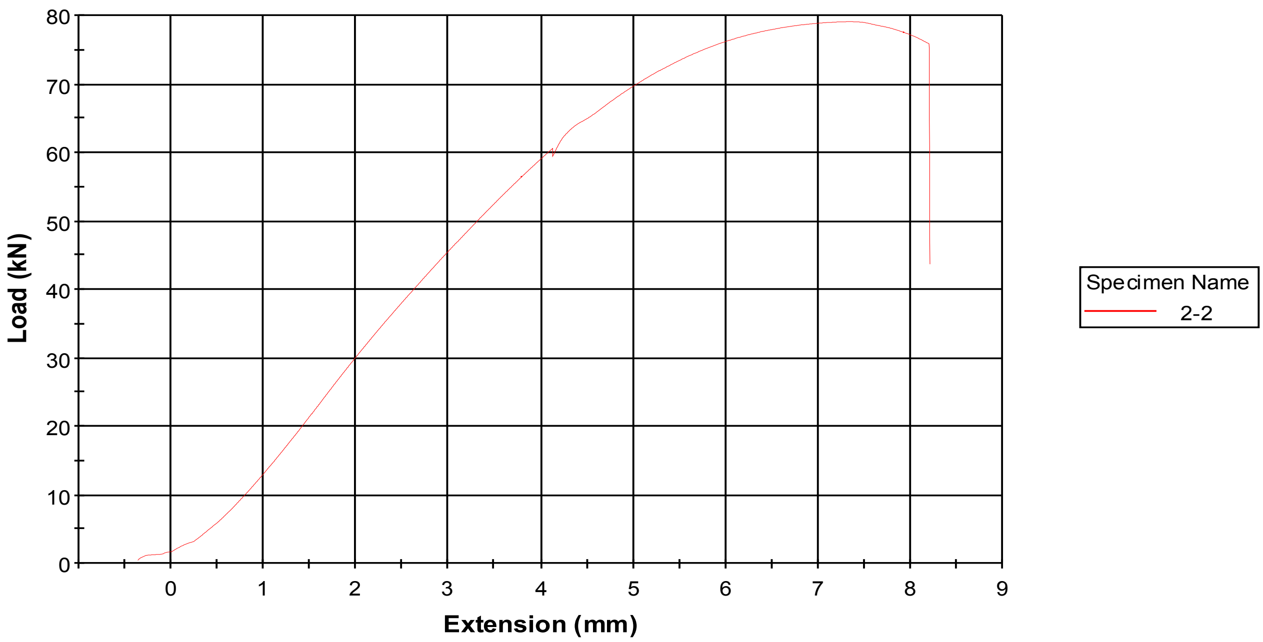
Load versus Extension



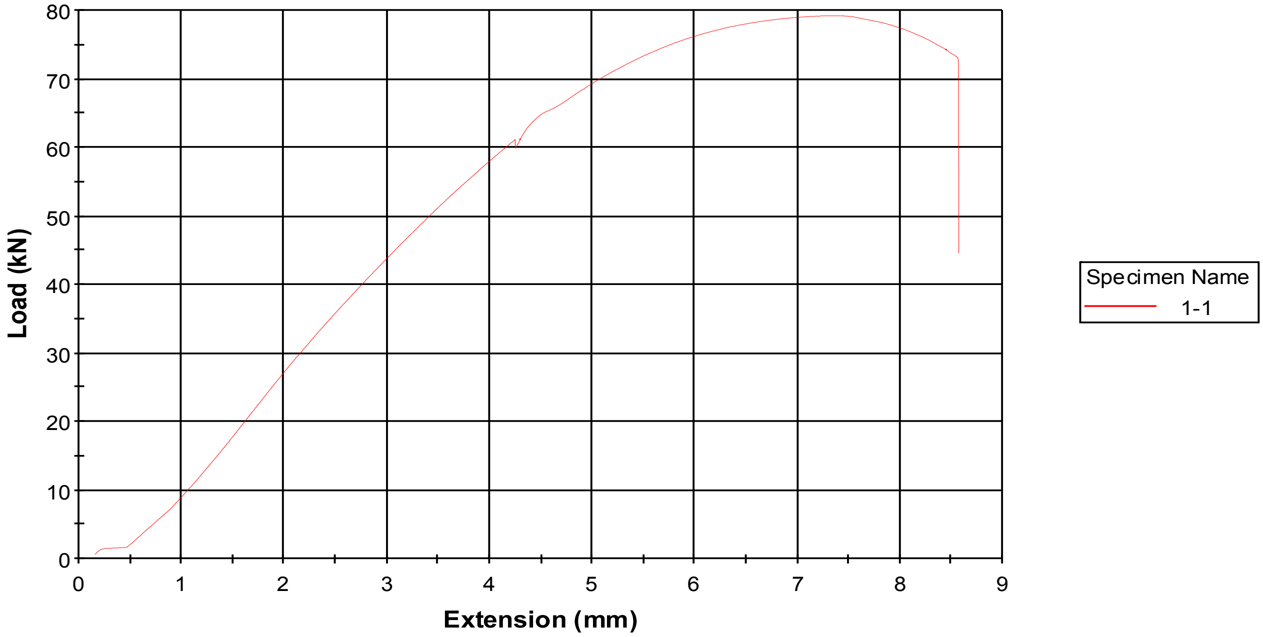
Load versus Extension



Load versus Extension



Load versus Extension



COMMENTS:

J. CALITZ — Date: ....

Senior Consultant [Pr. Technologist (Eng) - Metallurgy]

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Copies to:

J. Calitz — RT&D

10.2 High teperature test reports

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TEST CERTIFICATE

Univeristy of Pretoria
ATT: J. Bester

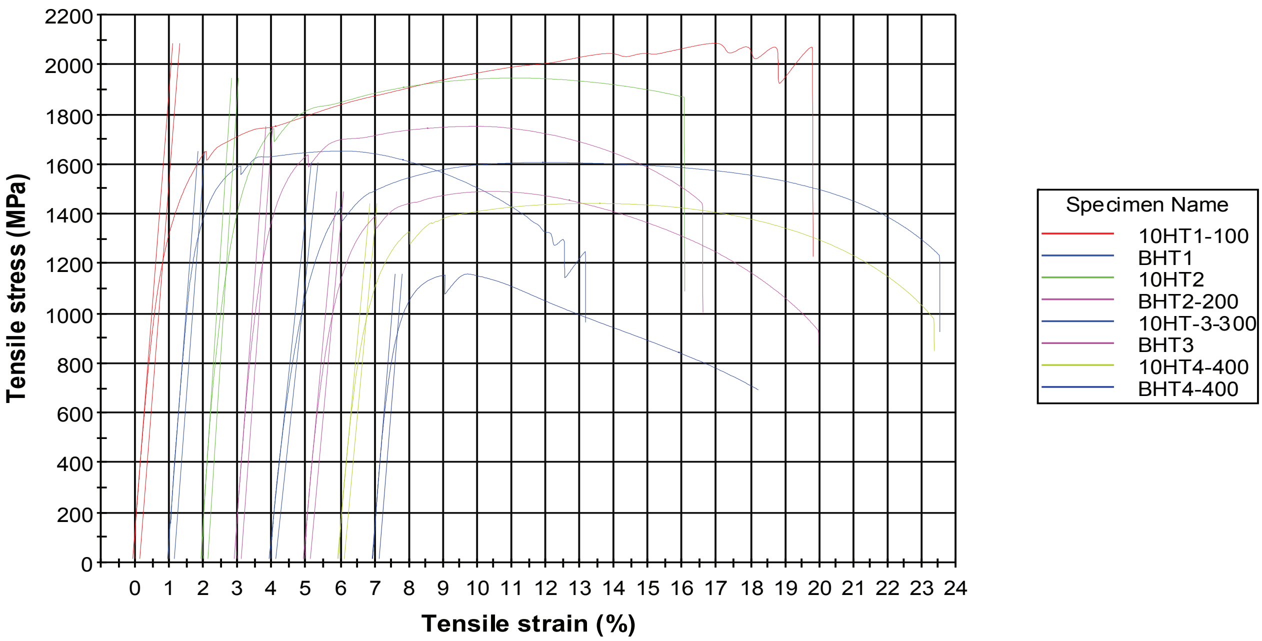
CERTIFICATE NUMBER	RTD/CER/12/139
Sample Description	Flat specimen machined from plate material No. 10 and benchmark.
Date received	14 February 2012
Date tested	15 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	100 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 100 - 600) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
1	10HT1-100	176.78	214.12	1212.86	2084.42	16.89	19.76
2	BHT1	185.48	195.94	1318.15	1653.04	5.06	12.15
3	10HT2	215.52	308.37	1160.01	1945.41	9.08	14.05
4	BHT2-200	188.31	286.27	1210.92	1751.74	6.98	13.58
5	10HT-3-300	128.91	177.37	1016.62	1607.58	8.05	19.53
6	BHT3	151.56	223.26	996.23	1490.87	5.48	15.00
7	10HT4-400	149.93	192.97	980.91	1442.92	7.43	17.38
8	BHT4-400	169.94	189.58	922.67	1159.71	2.78	11.26
Mean		170.80	223.48	1102.30	1641.96	7.72	15.34
Standard Deviation		27.04	48.11	141.19	291.84	4.19	3.23

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

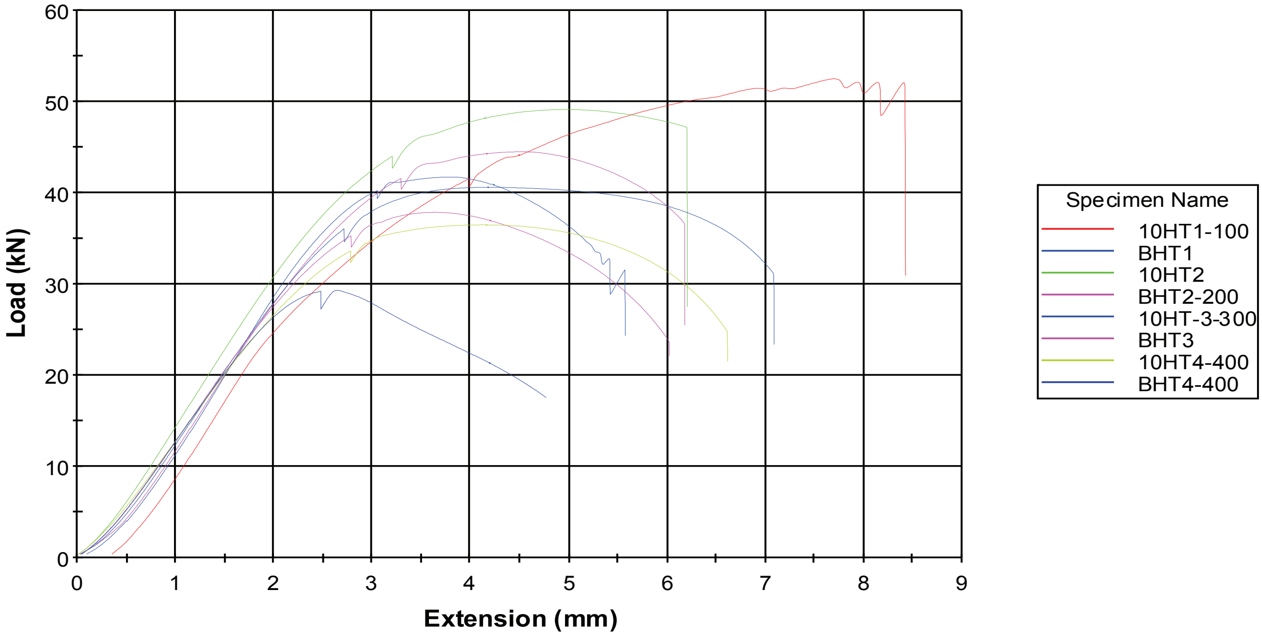
Stress versus Strain



Results Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
1	10HT1-100	30.53	52.48	52.07	17.05	18.40
2	BHT1	33.28	41.75	31.57	51.49	11.42
3	10HT2	29.29	49.13	47.18	18.02	12.84
4	BHT2-200	30.76	44.51	36.66	38.42	12.64
5	10HT-3-300	25.67	40.61	30.93	45.78	18.37
6	BHT3	25.30	37.87	23.72	54.50	14.23
7	10HT4-400	24.82	36.51	24.85	50.20	16.60
8	BHT4-400	23.34	29.37	17.63	1.19	10.78
Mean		27.88	41.53	33.07	34.58	14.41

Load versus Extension



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Univeristy of Pretoria
ATT: J. Bester

CERTIFICATE NUMBER	RTD/CER/12/140
Sample Description	Flat specimen machined from plate material No. 10 and benchmark.
Date received	14 February 2012
Date tested	17 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	500 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 100 - 200) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
1	10HT5-500	357.09	431.68	650.52	1271.99	4.38	13.71
2	BHT5-500	168.31	232.47	602.17	726.83	1.81	13.49
3	10HT6-600	123.55	222.96	461.69	595.75	2.11	37.55
4	BHT6-600	95.69	98.57	440.29	433.81	1.76	25.39
5	10HT7-700	20.44	123.97	216.80	250.49	5.84	62.34
6	BHT7-700	-----	75.89	-----	186.73	2.09	63.92
7	10HT8-800	-----	71.44	-----	112.97	22.81	78.78
8	BHT8-800	-----	40.93	-----	108.42	22.81	79.78
Mean		153.02	162.24	474.30	460.88	7.95	46.87
Standard Deviation		126.11	129.37	169.58	398.61	9.28	27.76

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

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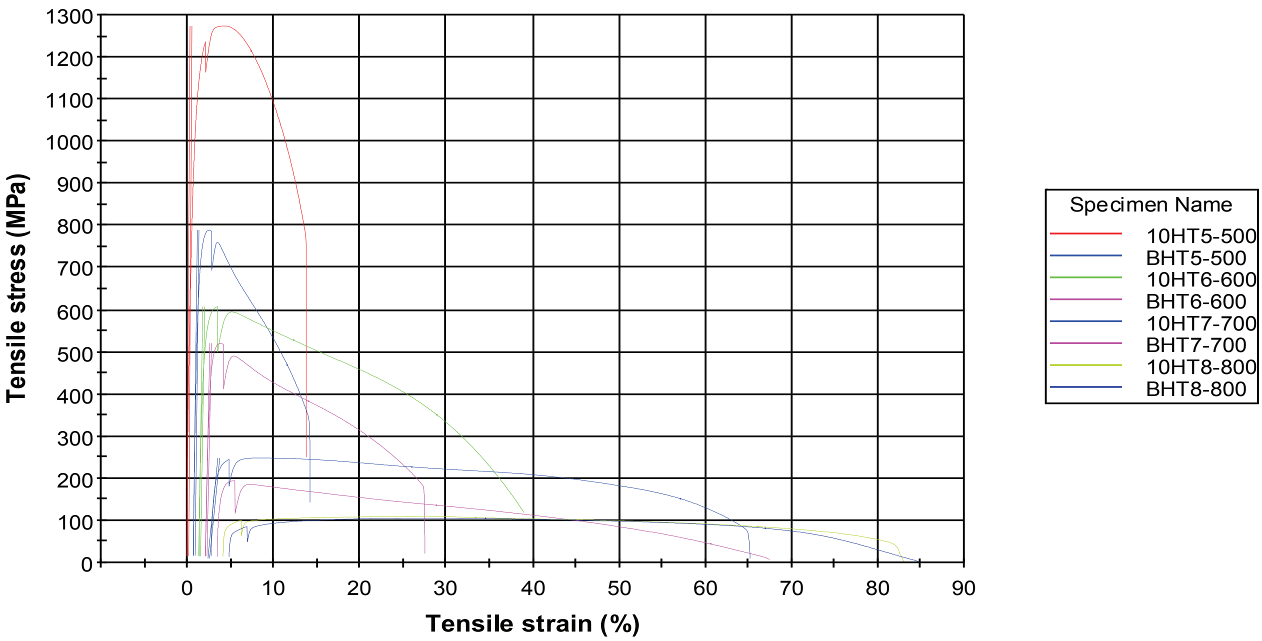
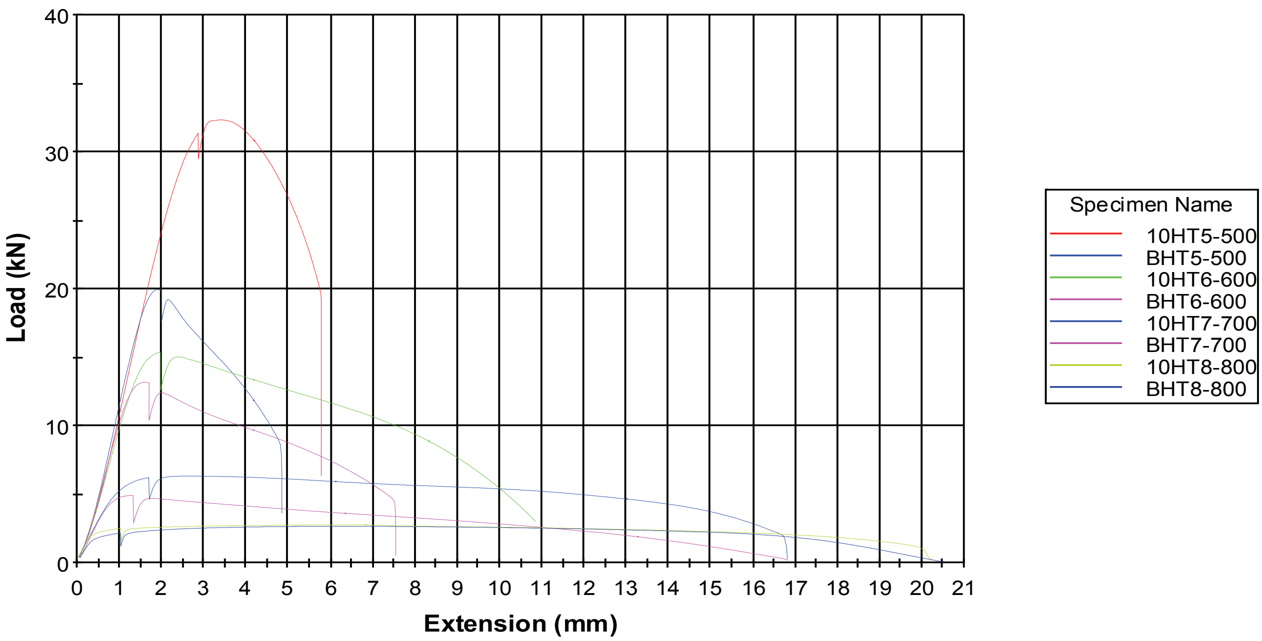
Stress versus Strain



Results Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
1	10HT5-500	16.52	32.33	19.62	54.59	13.12
2	BHT5-500	15.24	19.97	7.07	65.49	13.24
3	10HT6-600	11.68	15.41	3.09	80.41	37.41
4	BHT6-600	11.14	13.22	2.88	73.04	25.25
5	10HT7-700	5.53	6.39	0.83	76.10	62.27
6	BHT7-700	-----	4.99	0.25	91.40	63.90
7	10HT8-800	-----	2.86	0.15	64.71	78.77
8	BHT8-800	-----	2.74	0.14	92.84	79.76
Mean		12.02	12.24	4.25	74.82	46.71

Load versus Extension



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Sample Description	Flat specimen machined from plate material No. 10 and benchmark.
Date received	14 February 2012
Date tested	17 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	500 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 30 - 50) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
5	10HT7-700	145.49	123.97	156.97	250.49	5.84	62.34
6	BHT7-700	88.11	75.89	144.84	186.73	2.09	63.92
7	10HT8-800	57.96	71.44	81.08	112.97	22.81	78.78
8	BHT8-800	26.60	40.93	69.88	108.42	22.81	79.78
Mean		79.54	78.06	113.19	164.65	13.39	71.21
Standard Deviation		50.63	34.33	44.07	67.55	10.99	9.35

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

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Stress versus Strain

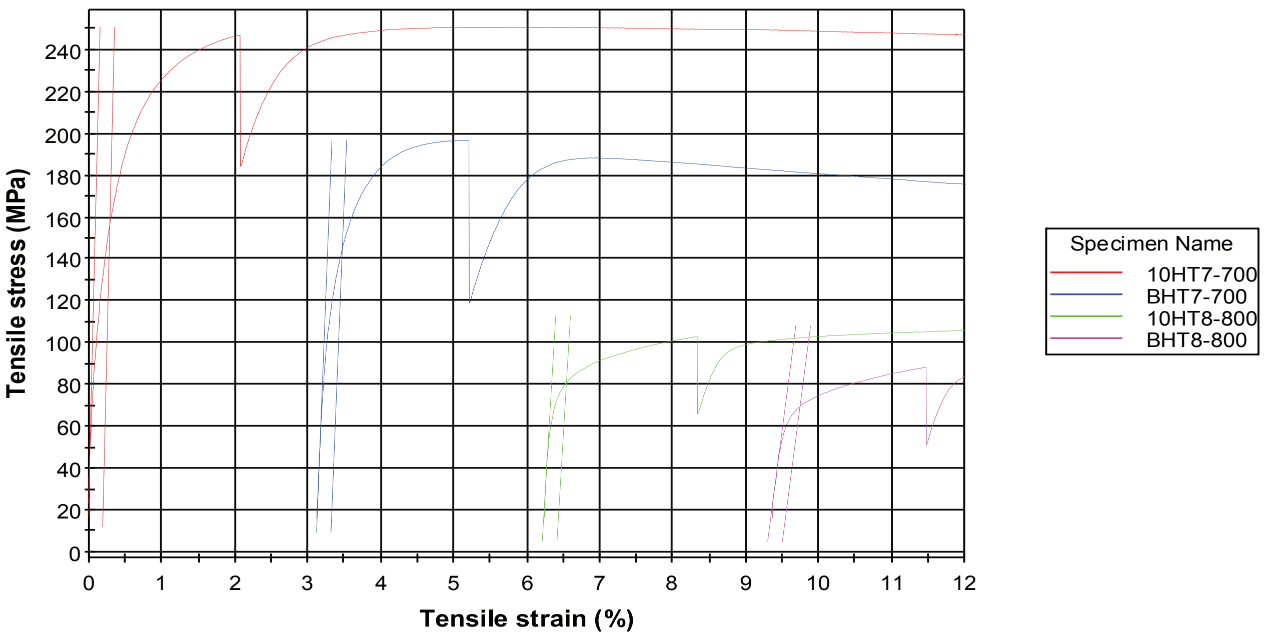
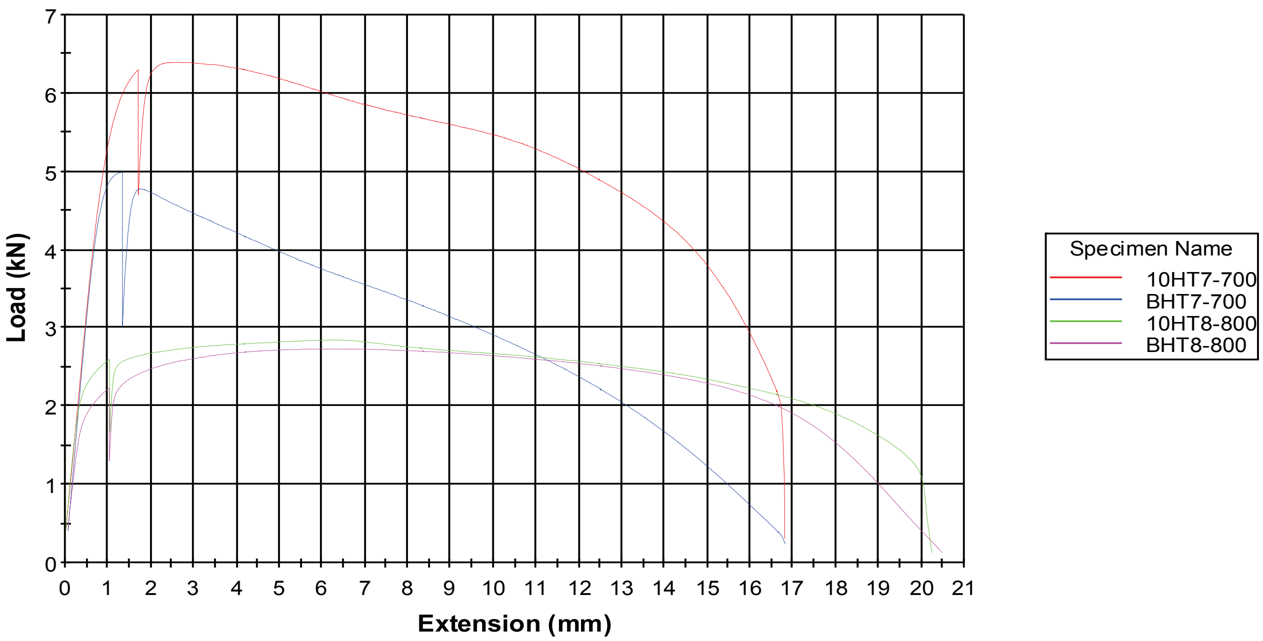


Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
5	10HT7-700	4.00	6.39	0.83	76.10	62.27
6	BHT7-700	3.67	4.99	0.25	91.40	63.90
7	10HT8-800	2.05	2.86	0.15	64.71	78.77
8	BHT8-800	1.77	2.74	0.14	92.84	79.76
Mean		2.87	4.25	0.34	81.26	71.17

Load versus Extension



COMMENTS:

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10.3 Notched test reports

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TEST CERTIFICATE

Univeristy of Pretoria
ATT: J. Bester

CERTIFICATE NUMBER	RTD/CER/12/139
Sample Description	Flat specimen machined from plate material No. 10 and benchmark.
Date received	14 February 2012
Date tested	15 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	100 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 100 - 600) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
1	10HT1-100	176.78	214.12	1212.86	2084.42	16.89	19.76
2	BHT1	185.48	195.94	1318.15	1653.04	5.06	12.15
3	10HT2	215.52	308.37	1160.01	1945.41	9.08	14.05
4	BHT2-200	188.31	286.27	1210.92	1751.74	6.98	13.58
5	10HT-3-300	128.91	177.37	1016.62	1607.58	8.05	19.53
6	BHT3	151.56	223.26	996.23	1490.87	5.48	15.00
7	10HT4-400	149.93	192.97	980.91	1442.92	7.43	17.38
8	BHT4-400	169.94	189.58	922.67	1159.71	2.78	11.26
Mean		170.80	223.48	1102.30	1641.96	7.72	15.34
Standard Deviation		27.04	48.11	141.19	291.84	4.19	3.23

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

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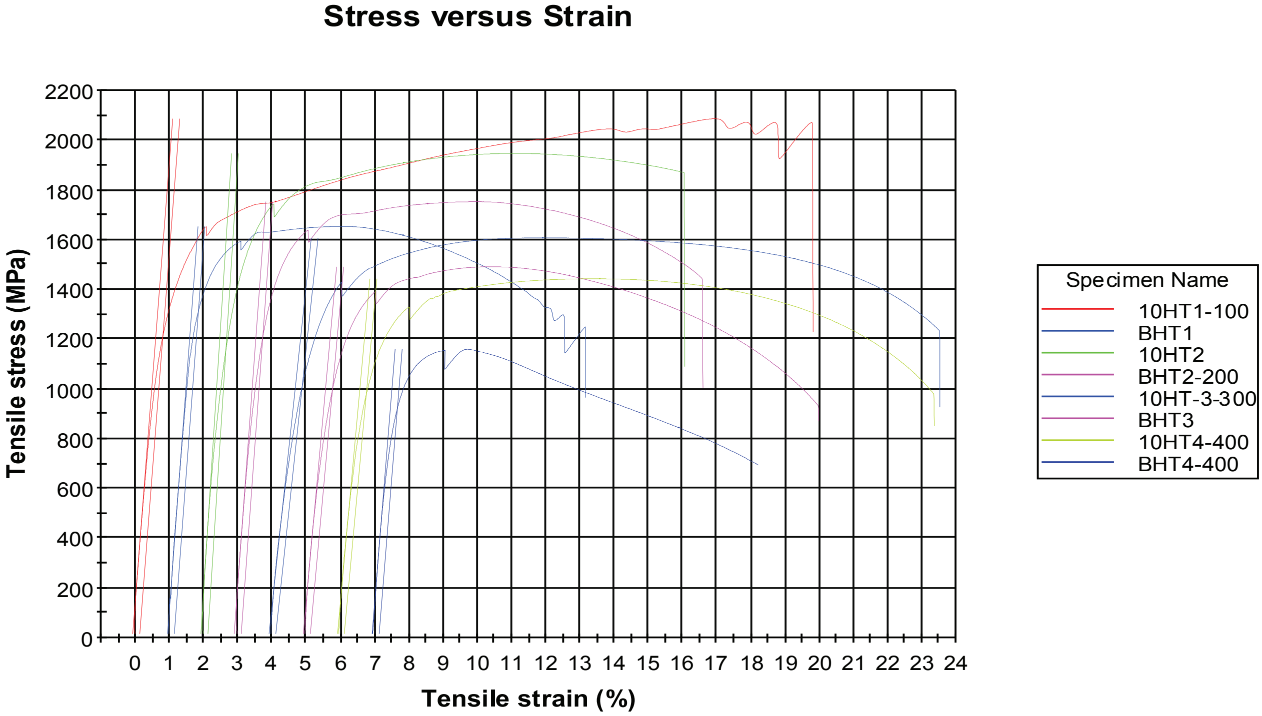
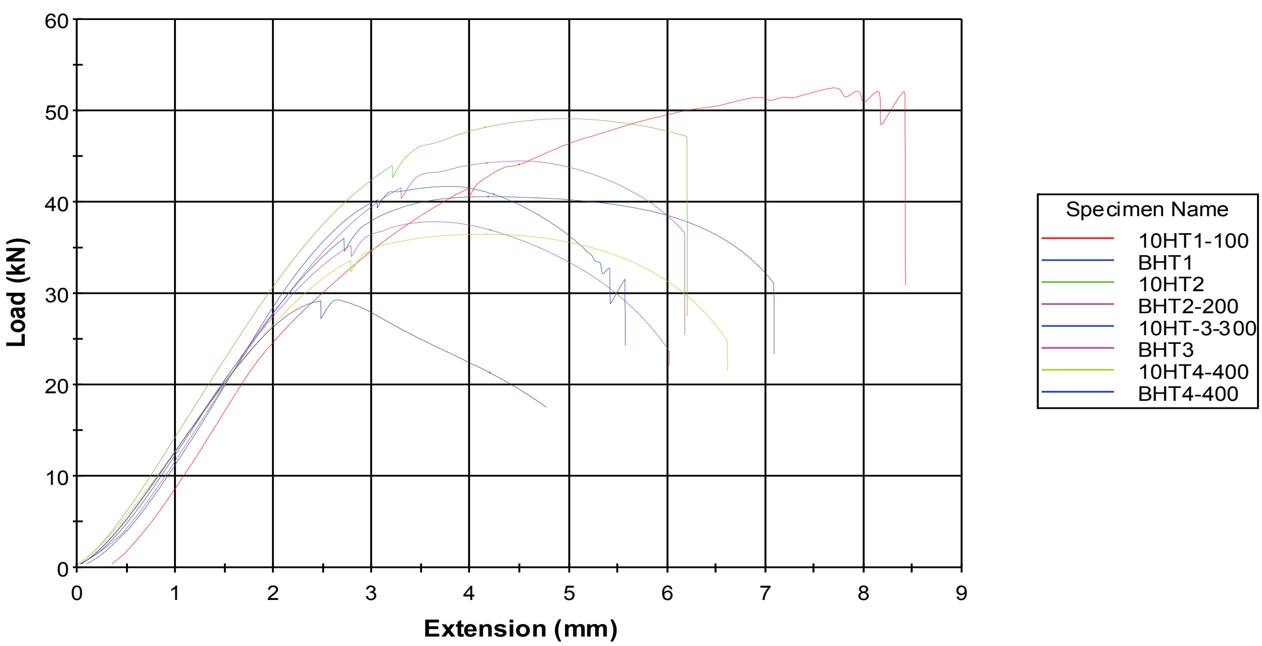


Results Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
1	10HT1-100	30.53	52.48	52.07	17.05	18.40
2	BHT1	33.28	41.75	31.57	51.49	11.42
3	10HT2	29.29	49.13	47.18	18.02	12.84
4	BHT2-200	30.76	44.51	36.66	38.42	12.64
5	10HT-3-300	25.67	40.61	30.93	45.78	18.37
6	BHT3	25.30	37.87	23.72	54.50	14.23
7	10HT4-400	24.82	36.51	24.85	50.20	16.60
8	BHT4-400	23.34	29.37	17.63	1.19	10.78
Mean		27.88	41.53	33.07	34.58	14.41

Load versus Extension



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J. CALITZ

Date: ....

Senior Consultant [Pr. Technologist (Eng) - Metallurgy]

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TEST CERTIFICATE

Univeristy of Pretoria
ATT: J. Bester

CERTIFICATE NUMBER	RTD/CER/12/140
Sample Description	Flat specimen machined from plate material No. 10 and benchmark.
Date received	14 February 2012
Date tested	17 February 2012
Method description	ASTM A 370 – 2006 Standard test methods and definitions for mechanical testing of steel products. Flat specimens with dynamic extensometer at ambient temperature.
User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	500 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 100 - 200) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
1	10HT5-500	357.09	431.68	650.52	1271.99	4.38	13.71
2	BHT5-500	168.31	232.47	602.17	726.83	1.81	13.49
3	10HT6-600	123.55	222.96	461.69	595.75	2.11	37.55
4	BHT6-600	95.69	98.57	440.29	433.81	1.76	25.39
5	10HT7-700	20.44	123.97	216.80	250.49	5.84	62.34
6	BHT7-700	-----	75.89	-----	186.73	2.09	63.92
7	10HT8-800	-----	71.44	-----	112.97	22.81	78.78
8	BHT8-800	-----	40.93	-----	108.42	22.81	79.78
Mean		153.02	162.24	474.30	460.88	7.95	46.87
Standard Deviation		126.11	129.37	169.58	398.61	9.28	27.76

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
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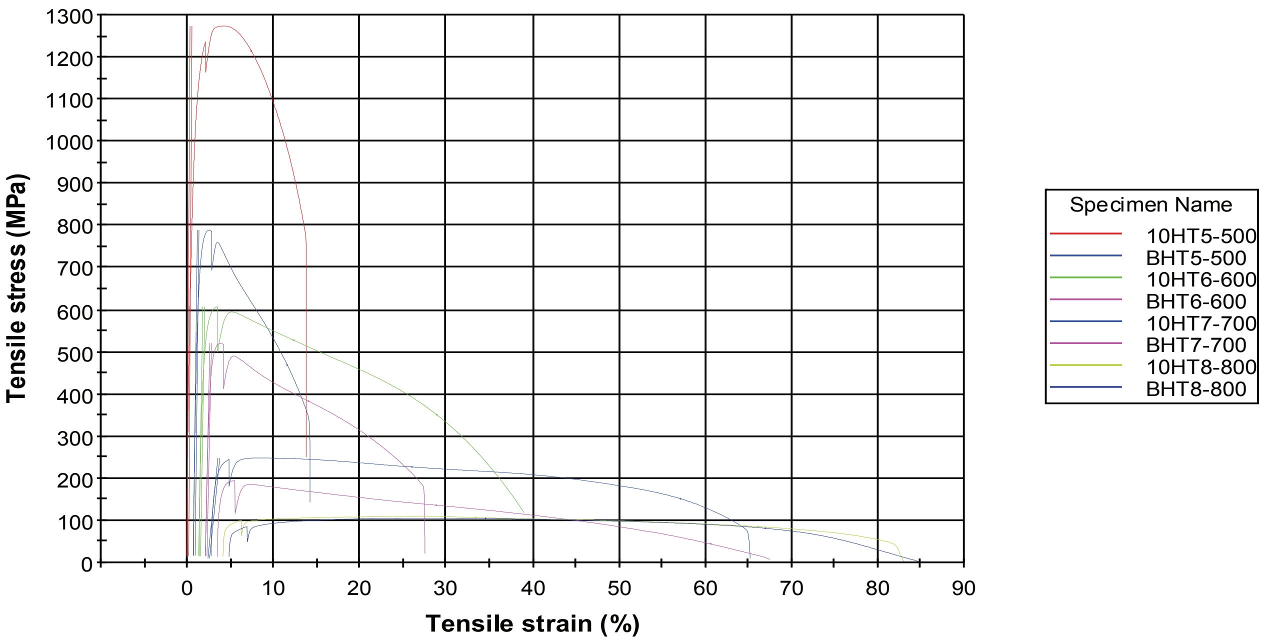
Stress versus Strain



Results Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
1	10HT5-500	16.52	32.33	19.62	54.59	13.12
2	BHT5-500	15.24	19.97	7.07	65.49	13.24
3	10HT6-600	11.68	15.41	3.09	80.41	37.41
4	BHT6-600	11.14	13.22	2.88	73.04	25.25
5	10HT7-700	5.53	6.39	0.83	76.10	62.27
6	BHT7-700	-----	4.99	0.25	91.40	63.90
7	10HT8-800	-----	2.86	0.15	64.71	78.77
8	BHT8-800	-----	2.74	0.14	92.84	79.76
Mean		12.02	12.24	4.25	74.82	46.71

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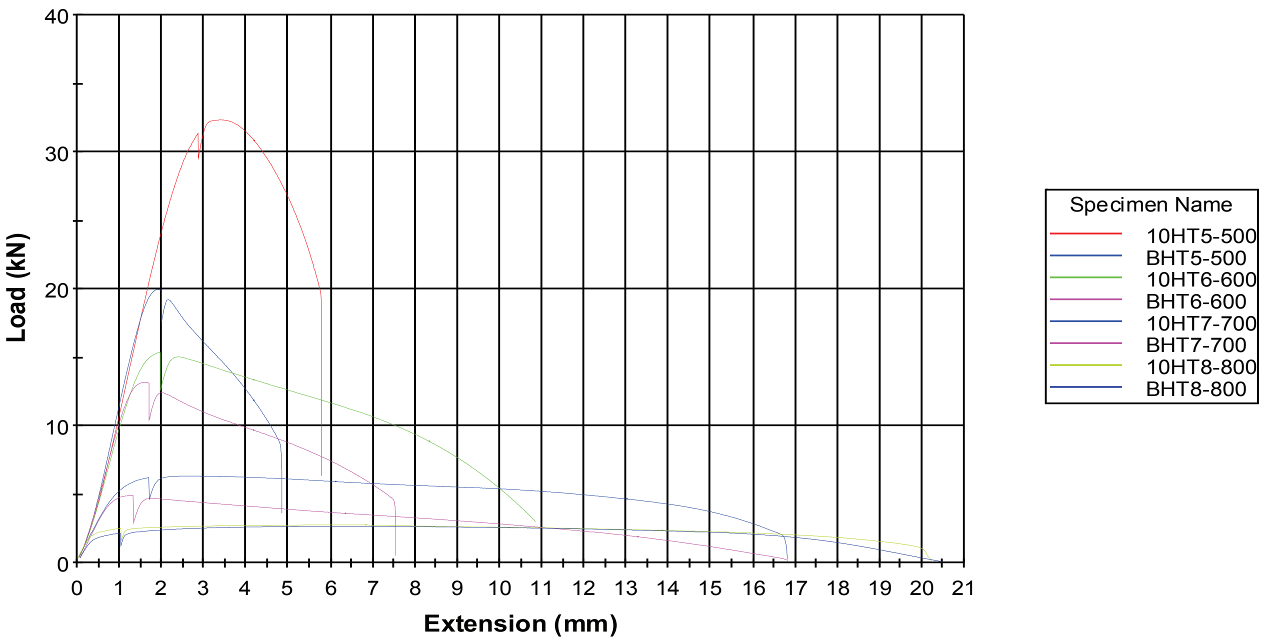
Load versus Extension



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User I.D.	J. Calitz
Number of specimens in sample	8
Test temperature	500 - 800 Degree C
Tensile direction	Longitudinal
Rate 1	2.50000 mm/min

Table 1

	Specimen I.D.	E (Segment 30 - 50) (GPa)	E (Automatic Young's) (GPa)	Rp 0.2 % (MPa)	Rm (MPa)	Agt (%)	At (%)
5	10HT7-700	145.49	123.97	156.97	250.49	5.84	62.34
6	BHT7-700	88.11	75.89	144.84	186.73	2.09	63.92
7	10HT8-800	57.96	71.44	81.08	112.97	22.81	78.78
8	BHT8-800	26.60	40.93	69.88	108.42	22.81	79.78
Mean		79.54	78.06	113.19	164.65	13.39	71.21
Standard Deviation		50.63	34.33	44.07	67.55	10.99	9.35

E = Modulus of elasticity
Rp 0.2% = Proof strength, non-proportional extension (offset 0.2%)
Rm = Tensile strength
Agt = Percentage total elongation at maximum force
At = Percentage total elongation at fracture

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Stress versus Strain

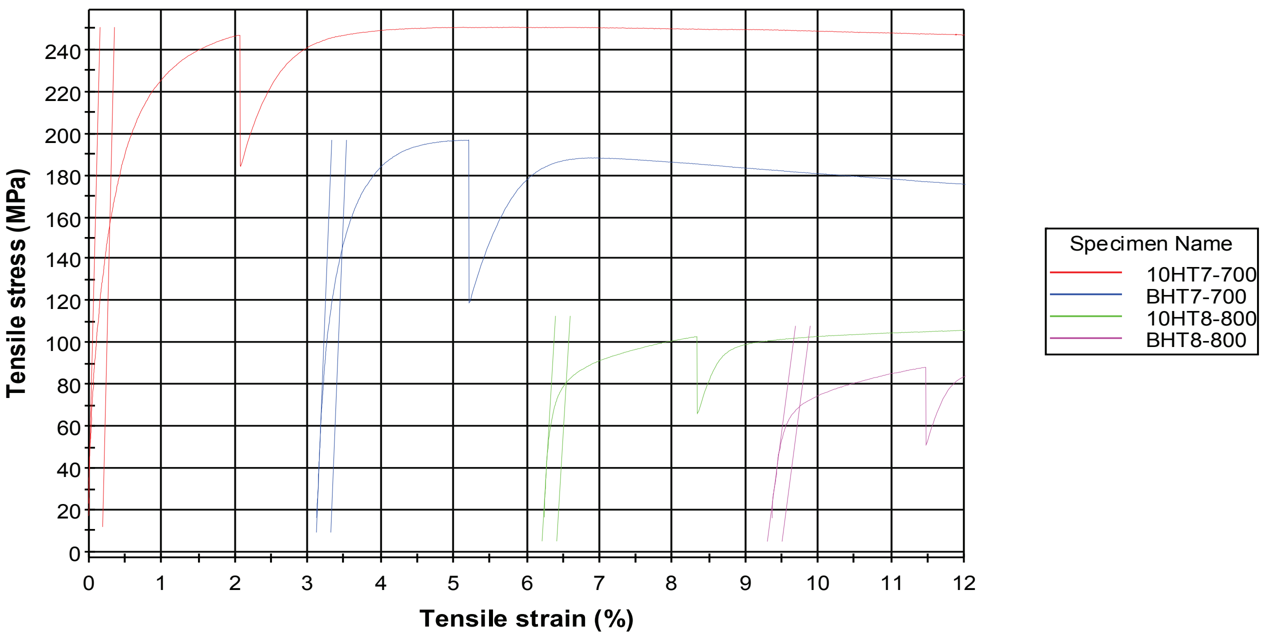
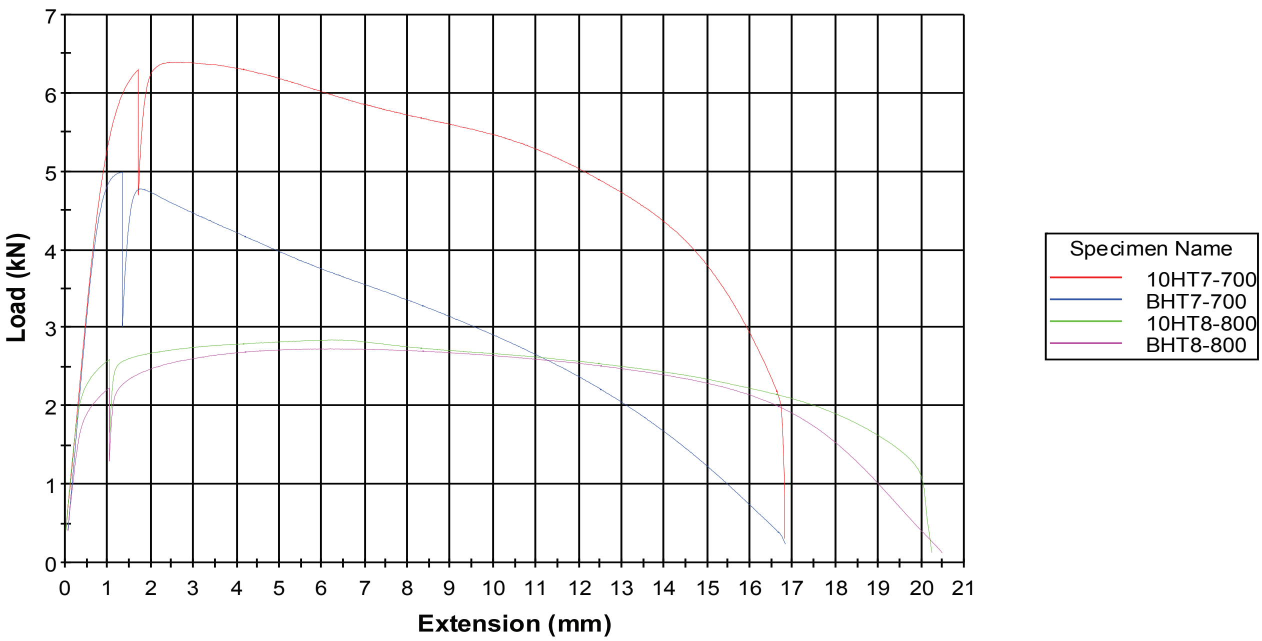


Table 2

	Specimen I.D.	Load at Yield (Offset 0.2 %) (kN)	Max Load (kN)	Load at Break (kN)	Reduction in area (%)	% Elongation at Break (%)
5	10HT7-700	4.00	6.39	0.83	76.10	62.27
6	BHT7-700	3.67	4.99	0.25	91.40	63.90
7	10HT8-800	2.05	2.86	0.15	64.71	78.77
8	BHT8-800	1.77	2.74	0.14	92.84	79.76
Mean		2.87	4.25	0.34	81.26	71.17

Load versus Extension



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Date: ....

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CHAPTER 11

Appendix D

This appendix includes the Octave code files used in material test result comparison and processing.

11.1 Octave code used for quasi-static, high temperature and notched tests

This section includes all the Octave code files used in the result comparison for the quasi-static, high temperature and notched tests.

11.1.1 Quasi-static tests code

TestDataRead T1.m

```
% This script is used to read and crop the tensile test data for
    type 1.
% Only the (plastic) tensile strain {Engineering stress, Machine
    Compliance corrected}
% and the tensile stress {Engineering stress F/A0} are saved for
    later use.

% The following Columns are read:
% Column D − Tensile stress [Mpa]
% Column G − Tensile strain [%]
% Data only start in the 27th row.
% Data ends at the tensile break stress [MPa] {B9}
% Save stress and strain in new .dat file type(N)
    _report_specimen_number {T*_001}

for RD = 34

  Data_in=csvread(strcat('Type_1_RD',num2str(RD),'.csv'));

  % Read the tensile break stress
  Break_stress=Data_in(9,2);
  % Read the Yield stress
  Sy=Data_in(7,2);
  start_cut=0;
  end_cut=0;
  % Read Auto tensile Modulus
  E_auto=Data_in(22,2);

  % Find break stress index
  for i0=1:100
    if Data_in((length(Data_in)−i0),4)<=Break_stress
    end_cut=i0;
    end
  end
  %end_cut=12;

  Data_L = length(Data_in);
  % Find Yield stress index
  for i00=1:1000
```

```
      if Data_in(i00,4)<=Sy
      start_cut=i00;
      end
    end

    start_cut=30;

    Data_strain=zeros((length(Data_in)-end_cut-start_cut),1);
    Data_stress=Data_strain;

    for i=1:length(Data_strain)
      Data_strain(i)=(Data_in((i+start_cut),7))/100;
      %-Data_in((i+start_cut),4)/E_auto...
      %-Data_in((start_cut),7))/100;
      if (Data_strain(i)<=0)
        Data_strain(i)=0;
      end
      Data_stress(i)=Data_in((i+start_cut),4);
      if (i < Data_L/1.5)
        if (i >= 2)
          if (Data_stress(i) < Data_stress(i-1))
            Data_stress(i) = Data_stress(i-1) + 1;
          end
        end
      end
    end

    figure(1)
    plot(Data_strain,Data_stress,"o",
    Data_in(:,7)./100,Data_in(:,4));
    %axis([0 0.2 0 2500])
    grid on
    drawnow

    [out] = strcat('T1_',num2str(RD),'.dat');

    save(out,'Data_strain','Data_stress');
    clear all
end

Plot_all_T1
```

Plot all T1.m

```
% Read stress strain data from dat files and plot

load T1_1.dat;
S_T1_001=Data_stress;
e_T1_001=Data_strain;
clear Data_strain Data_stress

load T1_2.dat;
S_T1_002=Data_stress;
e_T1_002=Data_strain;
clear Data_strain Data_stress

load T1_3.dat;
S_T1_003=Data_stress;
e_T1_003=Data_strain;
clear Data_strain Data_stress

load T1_4.dat;
S_T1_004=Data_stress;
e_T1_004=Data_strain;
clear Data_strain Data_stress

load T1_5.dat;
S_T1_005=Data_stress;
e_T1_005=Data_strain;
clear Data_strain Data_stress

load T1_6.dat;
S_T1_006=Data_stress;
e_T1_006=Data_strain;
clear Data_strain Data_stress

load T1_7.dat;
S_T1_007=Data_stress;
e_T1_007=Data_strain;
clear Data_strain Data_stress

load T1_8.dat;
S_T1_008=Data_stress;
e_T1_008=Data_strain;
```

```
clear Data_strain Data_stress

load T1_9.dat;
S_T1_009=Data_stress;
e_T1_009=Data_strain;
clear Data_strain Data_stress

load T1_10.dat;
S_T1_010=Data_stress;
e_T1_010=Data_strain;
clear Data_strain Data_stress

load T1_11.dat;
S_T1_011=Data_stress;
e_T1_011=Data_strain;
clear Data_strain Data_stress

load T1_12.dat;
S_T1_012=Data_stress;
e_T1_012=Data_strain;
clear Data_strain Data_stress

load T1_13.dat;
S_T1_013=Data_stress;
e_T1_013=Data_strain;
clear Data_strain Data_stress

load T1_14.dat;
S_T1_014=Data_stress;
e_T1_014=Data_strain;
clear Data_strain Data_stress

load T1_15.dat;
S_T1_015=Data_stress;
e_T1_015=Data_strain;
clear Data_strain Data_stress

load T1_16.dat;
S_T1_016=Data_stress;
e_T1_016=Data_strain;
clear Data_strain Data_stress
```

```
load T1_17.dat;
S_T1_017=Data_stress;
e_T1_017=Data_strain;
clear Data_strain Data_stress

load T1_18.dat;
S_T1_018=Data_stress;
e_T1_018=Data_strain;
clear Data_strain Data_stress

load T1_19.dat;
S_T1_019=Data_stress;
e_T1_019=Data_strain;
clear Data_strain Data_stress

load T1_20.dat;
S_T1_020=Data_stress;
e_T1_020=Data_strain;
clear Data_strain Data_stress

load T1_21.dat;
S_T1_021=Data_stress;
e_T1_021=Data_strain;
clear Data_strain Data_stress

load T1_22.dat;
S_T1_022=Data_stress;
e_T1_022=Data_strain;
clear Data_strain Data_stress

load T1_23.dat;
S_T1_023=Data_stress;
e_T1_023=Data_strain;
clear Data_strain Data_stress

load T1_24.dat;
S_T1_024=Data_stress;
e_T1_024=Data_strain;
clear Data_strain Data_stress
```

```
load T1_25.dat;
S_T1_025=Data_stress;
e_T1_025=Data_strain;
clear Data_strain Data_stress

load T1_26.dat;
S_T1_026=Data_stress;
e_T1_026=Data_strain;
clear Data_strain Data_stress

load T1_27.dat;
S_T1_027=Data_stress;
e_T1_027=Data_strain;
clear Data_strain Data_stress

load T1_28.dat;
S_T1_028=Data_stress;
e_T1_028=Data_strain;
clear Data_strain Data_stress

load T1_29.dat;
S_T1_029=Data_stress;
e_T1_029=Data_strain;
clear Data_strain Data_stress

load T1_30.dat;
S_T1_030=Data_stress;
e_T1_030=Data_strain;
clear Data_strain Data_stress

load T1_31.dat;
S_T1_031=Data_stress;
e_T1_031=Data_strain;
clear Data_strain Data_stress

load T1_32.dat;
S_T1_032=Data_stress;
e_T1_032=Data_strain;
clear Data_strain Data_stress

load T1_33.dat;
```

```
S_T1_033=Data_stress;
e_T1_033=Data_strain;
clear Data_strain Data_stress

load T1_34.dat;
S_T1_034=Data_stress;
e_T1_034=Data_strain;
clear Data_strain Data_stress

load T3_9.dat;
S_T1_035=Data_stress;
e_T1_035=Data_strain;
clear Data_strain Data_stress

load T3_10.dat;
S_T1_036=Data_stress;
e_T1_036=Data_strain;
clear Data_strain Data_stress

figure(1)
plot(e_T1_001,S_T1_001,"c",
        e_T1_002,S_T1_002,"c",
        e_T1_003,S_T1_003,"c",
        e_T1_004,S_T1_004,"c",
        e_T1_005,S_T1_005,"c",
        e_T1_006,S_T1_006,"c",
        %e_T1_007,S_T1_007,
        %e_T1_008,S_T1_008,
        %e_T1_009,S_T1_009,
        e_T1_010,S_T1_010,"c",
        %e_T1_011,S_T1_011,
        e_T1_012,S_T1_012,"c",
        e_T1_013,S_T1_013,"c",
        e_T1_014,S_T1_014,"c",
        e_T1_015,S_T1_015,"c",
        e_T1_016,S_T1_016,"c",
        e_T1_017,S_T1_017,"c",
        e_T1_018,S_T1_018,"c",
        e_T1_019,S_T1_019,"c",
        e_T1_020,S_T1_020,"c",
        e_T1_021,S_T1_021,"c",
```

```
          e_T1_022,S_T1_022,"c",
          e_T1_023,S_T1_023,"c",
          e_T1_024,S_T1_024,"c",
          e_T1_025,S_T1_025,"c",
          e_T1_026,S_T1_026,"c",
          e_T1_027,S_T1_027,"c",
          e_T1_028,S_T1_028,"c",
          e_T1_029,S_T1_029,"c",
          e_T1_030,S_T1_030,"c",
          e_T1_031,S_T1_031,"c",
          e_T1_032,S_T1_032,"c",
          e_T1_033,S_T1_033,"c",
          e_T1_034,S_T1_034,"c",
          e_T1_035,S_T1_035,"k",
          e_T1_036,S_T1_036,"k");
grid minor on
title("Type 1 - Alloy #1 Benchmark comparison");
xlabel("Engineering strain [mm/mm]")
ylabel("Stress [MPa]")
text(max(e_T1_035),max(S_T1_035),'Benchmark');
text(max(e_T1_030),max(S_T1_030),'Alloy #1');

save Type1.dat
print(1,'Type1-compare','-dpng');
clear all
```

11.1.2 High temperature tests code

TestDataRead T2.m

```
% This script is used to read and crop the tensile test data for
    type 2.
% Only the (plastic) tensile strain {Engineering stress, Machine
    Compliance corrected}
% and the tensile stress {Engineering stress F/A0} are saved for
    later use.

% The following Columns are read:
% Column D - Tensile stress [Mpa]
% Column G - Tensile strain [%]
% Data only start in the 27th row.
% Data ends at the tensile break stress [MPa] {B9}
% Save stress and strain in new .dat file type(N)
    _report_specimen_number {T*_001}

for RD = 1:16

  Data_in=csvread(strcat('Type_2_RD',num2str(RD),'.csv'));

  fx = [3 4 3 3 3 3 3 5 ...
        3 5.8 8 8 10 10 3 3];
  sc = [1000 1000 1000 1000 1000 1000 1000 500 ...
         1000 500 500 300 300 500 500 500];

  % Read the tensile break stress
  Break_stress=Data_in(9,2);
  % Read the Yield stress
  Sy=Data_in(7,2);
  start_cut=0;
  end_cut=0;
  % Read Auto tensile Modulus
  E_auto=Data_in(22,2);

  % Find break stress index
  for i0=1:100
    if Data_in((length(Data_in)-i0),4)<=Break_stress
    end_cut=i0;
    end
  end
```

```
Data_L = length(Data_in);
% Find Yield stress index
for i00=1:sc(RD)
   if Data_in(i00,4)<=Sy
   start_cut=i00;
   end
end

%start_cut=30;

Data_strain=zeros((length(Data_in)-end_cut-start_cut),1);
Data_stress=Data_strain;

for i=1:length(Data_strain)
   Data_strain(i)=Data_in((i+start_cut),7);
   %-Data_in((i+start_cut),4)/E_auto...
   %-Data_in((start_cut),7);
   if (Data_strain(i)<=0)
      Data_strain(i)=0;
   end
   Data_stress(i)=Data_in((i+start_cut),4);
   if (i < Data_L/fx(RD))
      if (i >= 2)
         if (Data_stress(i) < Data_stress(i-1))
            Data_stress(i) = Data_stress(i-1);
         end
      end
   end
end

figure(1)
plot(Data_strain,Data_stress,"o",
Data_in(:,7),Data_in(:,4));
%axis([0 0.2 0 2500])
grid on
drawnow

[out] = strcat('T2_',num2str(RD),'.dat');

save(out,'Data_strain','Data_stress');
```

```
    clear all
end

Plot_all_T2
```

Plot all T2.m

```
% Read stress strain data from dat files and plot

clear all
close all

load T2_1.dat;
S_T2_001=Data_stress;
e_T2_001=Data_strain;
clear Data_strain Data_stress

load T2_2.dat;
S_T2_002=Data_stress;
e_T2_002=Data_strain;
clear Data_strain Data_stress

load T2_3.dat;
S_T2_003=Data_stress;
e_T2_003=Data_strain;
clear Data_strain Data_stress

load T2_4.dat;
S_T2_004=Data_stress;
e_T2_004=Data_strain;
clear Data_strain Data_stress

load T2_5.dat;
S_T2_005=Data_stress;
e_T2_005=Data_strain;
clear Data_strain Data_stress

load T2_6.dat;
S_T2_006=Data_stress;
e_T2_006=Data_strain;
clear Data_strain Data_stress

load T2_7.dat;
S_T2_007=Data_stress;
e_T2_007=Data_strain;
clear Data_strain Data_stress

```

```
load T2_8.dat;
S_T2_008=Data_stress;
e_T2_008=Data_strain;
clear Data_strain Data_stress

load T2_9.dat;
S_T2_009=Data_stress;
e_T2_009=Data_strain;
clear Data_strain Data_stress

load T2_10.dat;
S_T2_010=Data_stress;
e_T2_010=Data_strain;
clear Data_strain Data_stress

load T2_11.dat;
S_T2_011=Data_stress;
e_T2_011=Data_strain;
clear Data_strain Data_stress

load T2_12.dat;
S_T2_012=Data_stress;
e_T2_012=Data_strain;
clear Data_strain Data_stress

load T2_13.dat;
S_T2_013=Data_stress;
e_T2_013=Data_strain;
clear Data_strain Data_stress

load T2_14.dat;
S_T2_014=Data_stress;
e_T2_014=Data_strain;
clear Data_strain Data_stress

load T2_15.dat;
S_T2_015=Data_stress;
e_T2_015=Data_strain;
clear Data_strain Data_stress

load T2_16.dat;
```

```
S_T2_016=Data_stress;
e_T2_016=Data_strain;
clear Data_strain Data_stress

load T1_2.dat;
S_T1_002=Data_stress;
e_T1_002=Data_strain;
clear Data_strain Data_stress

load T3_9.dat;
S_T3_009=Data_stress;
e_T3_009=Data_strain;
clear Data_strain Data_stress

load T3_10.dat;
S_T3_010=Data_stress;
e_T3_010=Data_strain;
clear Data_strain Data_stress

figure(1)
plot(e_T1_002,S_T1_002,
  e_T2_001,S_T2_001,
        e_T2_003,S_T2_003,
        e_T2_005,S_T2_005,
        e_T2_007,S_T2_007,
        e_T2_009,S_T2_009,
        e_T2_011,S_T2_011,
        e_T2_013,S_T2_013,
        e_T2_015,S_T2_015);
grid minor on
text(max(e_T1_002)/3,1.025*max(S_T1_002),' Alloy #1 AR - 25 degC');
text(max(e_T2_001),max(S_T2_001),' Alloy #1 AR - 100 degC');
text(max(e_T2_003),max(S_T2_003),' Alloy #1 AR - 200 degC');
text(max(e_T2_005)/2,max(S_T2_005),' Alloy #1 AR - 300 degC');
text(max(e_T2_007)/2,max(S_T2_007),' Alloy #1 AR - 400 degC');
text(max(e_T2_009)/2,max(S_T2_009),' Alloy #1 AR - 500 degC');
text(max(e_T2_011)/2,max(S_T2_011),' Alloy #1 AR - 600 degC');
text(max(e_T2_013)/2,max(S_T2_013),' Alloy #1 AR - 700 degC');
text(max(e_T2_015)/2,max(S_T2_015),' Alloy #1 AR - 800 degC');
title("Alloy #1 High Temprature");
xlabel("Engineering strain [mm/mm]")
```

```
ylabel("Stress [MPa]")

figure(2)
plot(e_T3_010,S_T3_010,
  e_T2_002,S_T2_002,
         e_T2_004,S_T2_004,
         e_T2_006,S_T2_006,
         e_T2_008,S_T2_008,
         e_T2_010,S_T2_010,
         e_T2_012,S_T2_012,
         e_T2_014,S_T2_014,
         e_T2_016,S_T2_016);
grid minor on
text(max(e_T3_010)/2,1.035*max(S_T3_010),' Benchmark AR - 25 degC');
text(max(e_T2_002)/2,max(S_T2_002),' Benchmark AR - 100 degC');
text(max(e_T2_004)/2,max(S_T2_004),' Benchmark AR - 200 degC');
text(max(e_T2_006)/2,max(S_T2_006),' Benchmark AR - 300 degC');
text(max(e_T2_008)/2,max(S_T2_008),' Benchmark AR - 400 degC');
text(max(e_T2_010)/2,max(S_T2_010),' Benchmark AR - 500 degC');
text(max(e_T2_012)/2,max(S_T2_012),' Benchmark AR - 600 degC');
text(max(e_T2_014)/2,max(S_T2_014),' Benchmark AR - 700 degC');
text(max(e_T2_016)/2,max(S_T2_016),' Benchmark AR - 800 degC');

title("Benchmark High Temprature");
xlabel("Engineering strain [mm/mm]")
ylabel("Stress [MPa]")

figure(3)
plot(e_T2_001,S_T2_001,"b",
         e_T2_003,S_T2_003,"b",
         e_T2_005,S_T2_005,"b",
         e_T2_007,S_T2_007,"b",
         e_T2_009,S_T2_009,"b",
         e_T2_011,S_T2_011,"b",
         e_T2_013,S_T2_013,"b",
         e_T2_015,S_T2_015,"b",
         e_T2_002,S_T2_002,"g",
         e_T2_004,S_T2_004,"g",
         e_T2_006,S_T2_006,"g",
         e_T2_008,S_T2_008,"g",
         e_T2_010,S_T2_010,"g",
```

```
        e_T2_012,S_T2_012,"g",
        e_T2_014,S_T2_014,"g",
        e_T2_016,S_T2_016,"g");
grid minor on
title("High Temprature comparison - Alloy 1 and Benchmark");
xlabel("Engineering strain [mm/mm]")
ylabel("Stress [MPa]")
legend(strcat(' Alloy #1 AR - 100 degC'),strcat(' Alloy #1 AR - 200 degC'),strcat(' Alloy #1 AR - 300 degC'),strcat(' Alloy #1 AR - 400 degC'),strcat(' Alloy #1 AR - 500 degC'),strcat(' Alloy #1 AR - 600 degC'),strcat(' Alloy #1 AR - 700 degC'),strcat(' Alloy #1 AR - 800 degC'), ...
    strcat(' Benchmark AR - 100 degC'),strcat(' Benchmark AR - 200 degC'),strcat(' Benchmark AR - 300 degC'),strcat(' Benchmark AR - 400 degC'),strcat(' Benchmark AR - 500 degC'),strcat(' Benchmark AR - 600 degC'),strcat(' Benchmark AR - 700 degC'),strcat(' Benchmark AR - 800 degC'));

T = [100 200 300 400 500 600 700 800]';

UTS_A1 = [max(S_T2_001);
          max(S_T2_003);
          max(S_T2_005);
          max(S_T2_007);
          max(S_T2_009);
          max(S_T2_011);
          max(S_T2_013);
          max(S_T2_015)];

UTS_B1 = [max(S_T2_002);
          max(S_T2_004);
          max(S_T2_006);
          max(S_T2_008);
          max(S_T2_010);
          max(S_T2_012);
          max(S_T2_014);
          max(S_T2_016)];

figure(4)
hold on
plot(T,UTS_A1,"bd",T,UTS_B1,"gs");
```

```
grid on
title("High Temprature comparison - Alloy 1 and Benchmark");
xlabel("Temperature [deg C]")
ylabel("Ulimate tensile strength [MPa]")
legend(strcat(' Alloy #1 AR'),strcat(' Benchmark AR'));
plot(T,UTS_A1,"b",T,UTS_B1,"g");
hold off

save Type2.dat
print(1,'Type2-A1','-dpng');
print(2,'Type2-B','-dpng');
print(3,'Type2','-dpng');
print(4,'Type2_compare','-dpng');
```

11.1.3 Notched tests code

TestDataRead T3.m

```
% This script is used to read and crop the tensile test data for
    type 3.
% Only the (plastic) tensile strain {Engineering stress, Machine
    Compliance corrected}
% and the tensile stress {Engineering stress F/A0} are saved for
    later use.

% The following Columns are read:
% Column D - Tensile stress [Mpa]
% Column G - Tensile strain [%]
% Data only start in the 27th row.
% Data ends at the tensile break stress [MPa] {B9}
% Save stress and strain in new .dat file type(N)
    _report_specimen_number {T*_001}

for RD = 1:20

  Data_in=csvread(strcat('Type_3_RD',num2str(RD),'.csv'));

  % Read the tensile break stress
  Break_stress=Data_in(9,2);
  % Read the Yield stress
  Sy=Data_in(7,2);
  start_cut=0;
  end_cut=0;
  % Read Auto tensile Modulus
  E_auto=Data_in(22,2);

  % Find break stress index
  for i0=1:100
    if Data_in((length(Data_in)-i0),4)<=Break_stress
    end_cut=i0;
    end
  end
  end_cut=12;

  Data_L = length(Data_in);
  % Find Yield stress index
  for i00=1:500
```

```
    if  Data_in(i00,4)<=Sy
    start_cut=i00;
    end
  end

  start_cut=30;

  Data_strain=zeros((length(Data_in)-end_cut-start_cut),1);
  Data_stress=Data_strain;

  for  i=1:length(Data_strain)
    Data_strain(i)=Data_in((i+start_cut),7)...
    %-Data_in((i+start_cut),4)/E_auto...
    -Data_in((start_cut),7);
    if  (Data_strain(i)<=0)
      Data_strain(i)=0;
    end
    Data_stress(i)=Data_in((i+start_cut),4);
  end

  figure(1)
  plot(Data_strain,Data_stress,"o",
  Data_in(:,7),Data_in(:,4));
  %axis([0  0.2  0  2500])
  grid  on
  drawnow

  [out] = strcat('T3_',num2str(RD),'.dat');

  save(out,'Data_strain','Data_stress');
  clear  all
end

Plot_all_T3
```

Plot all T3.m

```
% Read stress strain data from dat files and plot

clear all
close all

load T3_1.dat;
S_T3_001=Data_stress;
e_T3_001=Data_strain;
clear Data_strain Data_stress

load T3_2.dat;
S_T3_002=Data_stress;
e_T3_002=Data_strain;
clear Data_strain Data_stress

load T3_3.dat;
S_T3_003=Data_stress;
e_T3_003=Data_strain;
clear Data_strain Data_stress

load T3_4.dat;
S_T3_004=Data_stress;
e_T3_004=Data_strain;
clear Data_strain Data_stress

load T3_5.dat;
S_T3_005=Data_stress;
e_T3_005=Data_strain;
clear Data_strain Data_stress

load T3_6.dat;
S_T3_006=Data_stress;
e_T3_006=Data_strain;
clear Data_strain Data_stress

load T3_7.dat;
S_T3_007=Data_stress;
e_T3_007=Data_strain;
clear Data_strain Data_stress

```

```
load T3_8.dat;
S_T3_008=Data_stress;
e_T3_008=Data_strain;
clear Data_strain Data_stress

load T3_9.dat;
S_T3_009=Data_stress;
e_T3_009=Data_strain;
clear Data_strain Data_stress

load T3_10.dat;
S_T3_010=Data_stress;
e_T3_010=Data_strain;
clear Data_strain Data_stress

load T3_11.dat;
S_T3_011=Data_stress;
e_T3_011=Data_strain;
clear Data_strain Data_stress

load T3_12.dat;
S_T3_012=Data_stress;
e_T3_012=Data_strain;
clear Data_strain Data_stress

load T3_13.dat;
S_T3_013=Data_stress;
e_T3_013=Data_strain;
clear Data_strain Data_stress

load T3_14.dat;
S_T3_014=Data_stress;
e_T3_014=Data_strain;
clear Data_strain Data_stress

load T3_15.dat;
S_T3_015=Data_stress;
e_T3_015=Data_strain;
clear Data_strain Data_stress

load T3_16.dat;
```

```
S_T3_016=Data_stress;
e_T3_016=Data_strain;
clear Data_strain Data_stress

load T3_17.dat;
S_T3_017=Data_stress;
e_T3_017=Data_strain;
clear Data_strain Data_stress

load T3_18.dat;
S_T3_018=Data_stress;
e_T3_018=Data_strain;
clear Data_strain Data_stress

load T3_19.dat;
S_T3_019=Data_stress;
e_T3_019=Data_strain;
clear Data_strain Data_stress

load T3_20.dat;
S_T3_020=Data_stress;
e_T3_020=Data_strain;
clear Data_strain Data_stress

figure(1)
hold on
plot(max(e_T3_001),S_T3_001(length(S_T3_001)),'b+',
        max(e_T3_002),S_T3_002(length(S_T3_002)),'bo',
        max(e_T3_003),S_T3_003(length(S_T3_003)),'b*',
        max(e_T3_004),S_T3_004(length(S_T3_004)),'bd',
        max(e_T3_005),S_T3_005(length(S_T3_005)),'bx',
        max(e_T3_006),S_T3_006(length(S_T3_006)),'bs',
        %max(e_T3_007),S_T3_007(length(S_T3_007)),'bd',
        %max(e_T3_008),S_T3_008(length(S_T3_008)),'bh',
        max(e_T3_009),S_T3_009(length(S_T3_009)),'g+',
        max(e_T3_010),S_T3_010(length(S_T3_010)),'r+',
        max(e_T3_011),S_T3_011(length(S_T3_011)),'go',
        max(e_T3_012),S_T3_012(length(S_T3_012)),'ro',
        max(e_T3_013),S_T3_013(length(S_T3_013)),'g*',
        max(e_T3_014),S_T3_014(length(S_T3_014)),'r*',
        max(e_T3_015),S_T3_015(length(S_T3_015)),'gd',
```

```
        max(e_T3_016),S_T3_016(length(S_T3_016)),'rd',
        max(e_T3_017),S_T3_017(length(S_T3_017)),'gx',
        max(e_T3_018),S_T3_018(length(S_T3_018)),'rx',
        max(e_T3_019),S_T3_019(length(S_T3_019)),'gs',
        max(e_T3_020),S_T3_020(length(S_T3_020)),'rs');
grid minor on
title("Notch comparison - Alloy 1 and Benchmark");
xlabel("Engineering strain [mm/mm]")
ylabel("Stress [MPa]")
legend(strcat(' Alloy #1 AR - 0R'),
       strcat(' Alloy #1 AR - 5R'),
       strcat(' Alloy #1 AR - 2R'),
       strcat(' Alloy #1 AR - 1R'),
       strcat(' Alloy #1 AR - 0.5R'),
       strcat(' Alloy #1 AR - 0.15R'),
      %strcat(' Alloy #1 AR - 0.5R'),
      %strcat(' Alloy #1 AR - 0.15R'),
       strcat(' Benchmark 1 AR - 0R'),
       strcat(' Benchmark 2 AR - 0R'),
       strcat(' Benchmark 1 AR - 5R'),
       strcat(' Benchmark 2 AR - 5R'),
       strcat(' Benchmark 1 AR - 2R'),
       strcat(' Benchmark 2 AR - 2R'),
       strcat(' Benchmark 1 AR - 1R'),
       strcat(' Benchmark 2 AR - 1R'),
       strcat(' Benchmark 1 AR - 0.5R'),
       strcat(' Benchmark 2 AR - 0.5R'),
       strcat(' Benchmark 1 AR - 0.15R'),
       strcat(' Benchmark 2 AR - 0.15R'));

plot(e_T3_001,S_T3_001,"b",
        e_T3_002,S_T3_002,"b",
        e_T3_003,S_T3_003,"b",
        e_T3_004,S_T3_004,"b",
        e_T3_005,S_T3_005,"b",
        e_T3_006,S_T3_006,"b",
%       e_T3_007,S_T3_007,"b",
%       e_T3_008,S_T3_008,"b",
        e_T3_009,S_T3_009,"g",
        e_T3_010,S_T3_010,"r",
        e_T3_011,S_T3_011,"g",
```

```
        e_T3_012,S_T3_012,"r",
        e_T3_013,S_T3_013,"g",
        e_T3_014,S_T3_014,"r",
        e_T3_015,S_T3_015,"g",
        e_T3_016,S_T3_016,"r",
        e_T3_017,S_T3_017,"g",
        e_T3_018,S_T3_018,"r",
        e_T3_019,S_T3_019,"g",
        e_T3_020,S_T3_020,"r");

%axis([0 0.04 1600 2400])
S_star = [0.333334123    0.481737569    0.610591469    0.657946195
        0.669525841    0.673093648]';

e_A1 = [max(e_T3_001);
        max(e_T3_002);
        max(e_T3_003);
        max(e_T3_004);
        max(e_T3_005);
        max(e_T3_006)];

e_B1 = [max(e_T3_009);
        max(e_T3_011);
        max(e_T3_013);
        max(e_T3_015);
        max(e_T3_017);
        max(e_T3_019)];

e_B2 = [max(e_T3_010);
        max(e_T3_012);
        max(e_T3_014);
        max(e_T3_016);
        max(e_T3_018);
        max(e_T3_020)];

figure(2)
hold on
plot(e_A1,S_star,"bo",
            e_B1,S_star,"gs",
     e_B2,S_star,"rd");
grid on
```

```
title("Notch fracture comparison - Alloy 1 and Benchmark");
ylabel("Stress tri-axiality ratio")
xlabel("Fracture strain [mm/mm]")
legend(strcat(' Alloy #1 AR'),strcat(' Benchmark 1 AR'),strcat('
    Benchmark 2 AR'));
plot(e_A1,S_star,"b",
              e_B1,S_star,"g",
       e_B2,S_star,"r");
hold off

save Type3.dat
print(1,'Type3','-dpng');
print(2,'Type3_compare','-dpng');
clear all
```

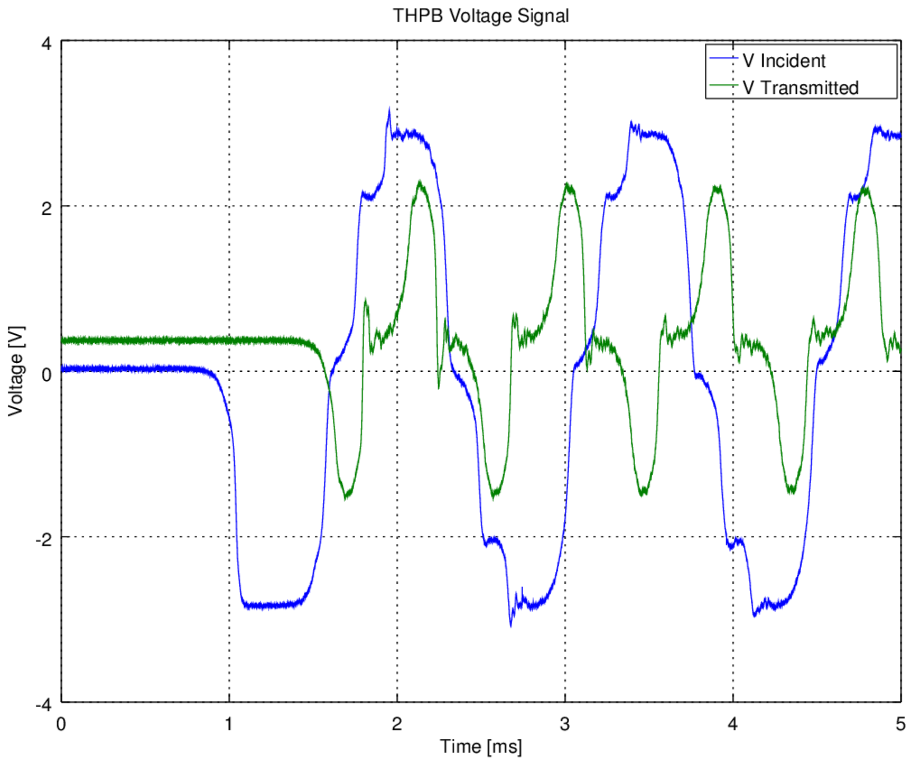

Figure 11.1: Typical recorded strain signal.

11.2 Octave code used for high strain rate tests

This section includes all the Octave code files used for the signal processing in the high strain-rate tests.

11.2.1 Octave code files used for the Tensile Split Hopkinson Pressure Bar tests

THPB shift.m

This script corrects the measured strain signal 11.1 for voltage offsets 11.2, shift the transmitted and reflected waves and crops all three signals to a single wave length 11.3. The total measured signal length of 50 000 data points is reduced to around 8000.

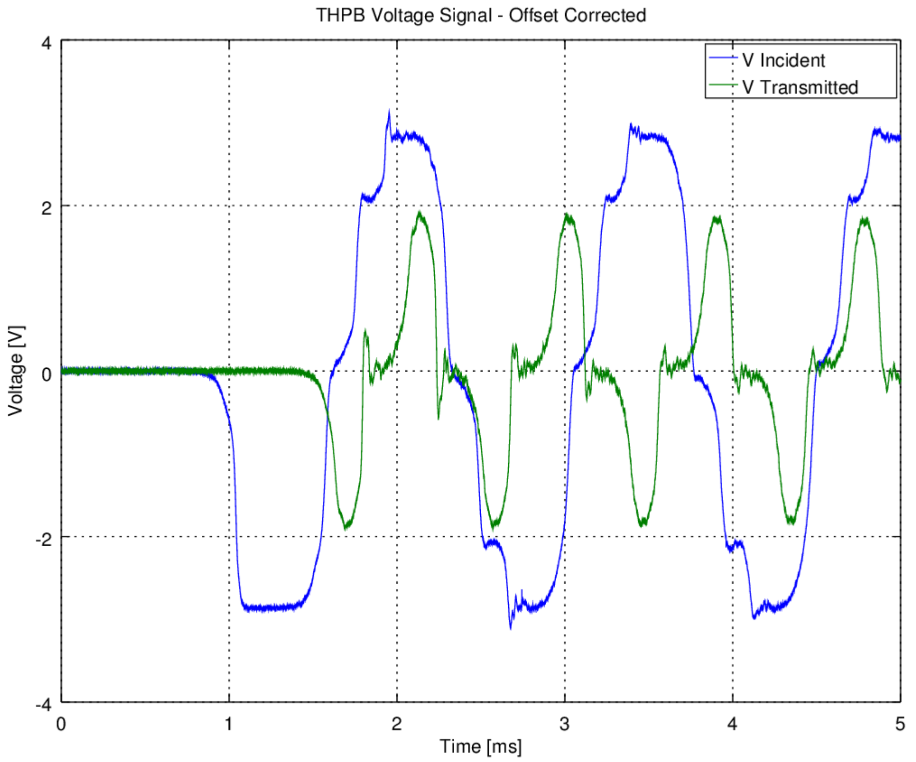

Figure 11.2: Offset corrected strain signal.

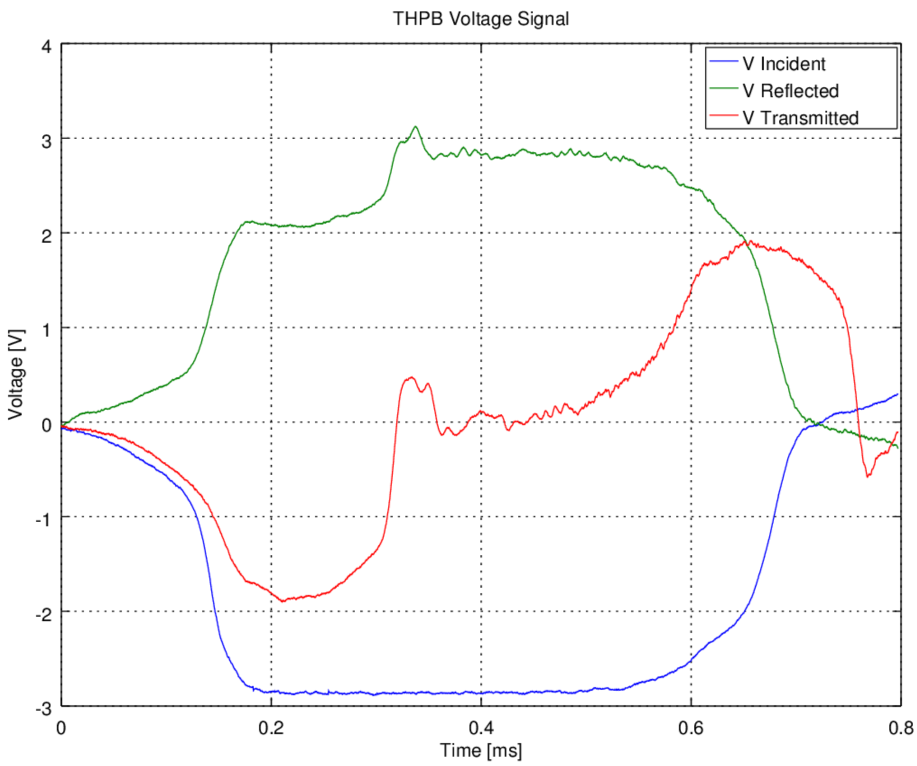

Figure 11.3: Single wave signal.

THPB shift.m

```
% This script is used to crop & zero the strain guage signal.
% The Incident, Transmitted and Reflected Voltage signals are then
    saved
% as Octave variables in a smaller file.dat

% The signal is imported from the following csv file:
% Only the first two columbs are used.

tic

Signal=csvread('Alloy_1_5_1.mat.csv');

Vinc=Signal(:,1);
Vtrans=Signal(:,2);
clear('Signal');

% Sample rate = 10Mhz
% Time step = 1/(10e6) = 0.1 [micro s] = 1e-4 [ms]

Time_step=1e-4;
T_Signal=linspace(0,Time_step*length(Vinc),length(Vinc))';

% Verify voltage signal vertical offset average over offset time [ms
    ]
figure(1)
plot(T_Signal,Vinc,T_Signal,Vtrans);
title('THPB Voltage Signal');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Transmitted');
grid on

disp(' ')

Vinc_offset_t=0.6
Vinc_idx=Vinc_offset_t/Time_step;
Vinc_offset=sum(Vinc(1:Vinc_idx))/Vinc_idx;

Vinc=Vinc.-Vinc_offset;

```

```
Vtrans_offset_t=1.2
Vtrans_idx=Vtrans_offset_t/Time_step;
Vtrans_offset=sum(Vtrans(1:Vtrans_idx))/Vtrans_idx;

disp ('Verify if the offset average is taken over a constant section
    using Fig 1.')
disp (' ')

Vtrans=Vtrans.-Vtrans_offset;

figure(2)
plot(T_Signal,Vinc,T_Signal,Vtrans);
title('THPB Voltage Signal - Offset Corrected');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Transmitted');
grid on

% Shift signal to start of incident wave.
Vinc_noise=max(Vinc(1:Vinc_idx))-min(Vinc(1:Vinc_idx));

i1=1;
err1=0;
err2=0;

while (err1>=0)
        err1=Vinc(i1)+2*Vinc_noise;
        i1=i1+1;
end

Time_shift=i1;
%                          ^^^ Modify to start of reflected wave.

while (err2<=0)
        err2=Vinc(i1);
        i1=i1+1;
end
Signal_length=1.1*(i1-Time_shift);

% The bar calibration and signal offset values are
% defined in the following script:
```

```
SHPB_CAL_AL;

% Crop incident and transmitted voltage signals and
% shift reflected signal.

v_inc=zeros(1,Signal_length)';
v_ref=v_inc;
v_trans=v_inc;
t_wave=linspace(0,Time_step*Signal_length,Signal_length)';

v_ref_offset=round(Ref_bar_offset/Time_step)
v_trans_offset=round(Trans_bar_offset/Time_step)

for i2=1:Signal_length
        v_inc(i2)=Vinc(i2+Time_shift);
        v_ref(i2)=Vinc(i2+Time_shift+v_ref_offset);
        v_trans(i2)=Vtrans(i2+Time_shift+v_trans_offset);
        i2=i2+1;
end

figure(3)
plot(t_wave,v_inc,t_wave,v_ref,t_wave,v_trans);
title('THPB Voltage Signal');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Reflected','V Transmitted');
grid on

clear Vinc;
clear Vtrans;
clear T_Signal;

%save Alloy_1_5_1.dat

toc
disp (' ')
```

SHPB CAL AL.m

```
% SHPB Calibration data for Aluminium bars.

% Incident bar total length = 3665mm
% From strain guage to specimen = 1834mm
% Diameter = 19.05mm
% Grade 7075 T6

Inc_bar_rho=2795;
Inc_bar_E=72.95227e9;
Inc_bar_C=(Inc_bar_E/Inc_bar_rho)^0.5;

Inc_bar_Dia=19.05;
Inc_bar_Area=0.25*pi*Inc_bar_Dia^2;
Inc_bar_D_end=1834;

Inc_bar_V_in=1.51;
Inc_bar_K_GF=2.14;

Inc_bar_K=4/(1000*4*Inc_bar_K_GF*Inc_bar_V_in);

Inc_bar_K_theory=Inc_bar_K*Inc_bar_E/1e6;

Inc_bar_offset=0;
Ref_bar_offset=2*Inc_bar_D_end/Inc_bar_C;

% Transmitted bar total length ~= 2250mm
% From strain guage to specimen = 1128mm
% Diameter = 19.975mm

Trans_bar_rho=2799;
Trans_bar_E=72.7295e9;
Trans_bar_C=(Trans_bar_E/Trans_bar_rho)^0.5;

Trans_bar_Dia=19.975;
Trans_bar_Area=0.25*pi*Trans_bar_Dia^2;
Trans_bar_D_end=1129;

Trans_bar_V_in=4.01;
Trans_bar_K_GF=2.14;

```

```
Trans_bar_K=4/(1000*4*Trans_bar_K_GF*Trans_bar_V_in);

Trans_bar_K_theory=Trans_bar_K*Trans_bar_E/1e6;

Trans_bar_offset=Trans_bar_D_end/Trans_bar_C+Inc_bar_D_end/Inc_bar_C
    ;
```

SHPB CAL FeC.m

```
% SHPB Calibration data for Steel bars. [Updated 31-5-2011]

% Incident bar total length = 3000mm
% From strain guage to specimen = 1480mm (3000-1480 = 1520) <<< To
    be verified.
% Diameter = 19mm

Inc_bar_rho=8151;
Inc_bar_C=4665;
Inc_bar_E=Inc_bar_rho*Inc_bar_C^2;

Inc_bar_Dia=19;
Inc_bar_Area=0.25*pi*Inc_bar_Dia^2;
Inc_bar_D_end=1520;

Inc_bar_V_in=1.25;
Inc_bar_K_GF=2.11;

Inc_bar_K=4/(1000*4*Inc_bar_K_GF*Inc_bar_V_in);

Inc_bar_K_theory=Inc_bar_K*Inc_bar_E/1e6;

Inc_bar_offset=0;
Ref_bar_offset=2*Inc_bar_D_end/Inc_bar_C;

% Transmitted bar total length ~= 3000mm
% From strain guage to specimen = 1495mm
% Diameter = 19mm

Trans_bar_rho=8151;
Trans_bar_C=4665;
Trans_bar_E=Trans_bar_rho*Trans_bar_C^2;

Trans_bar_Dia=19;
Trans_bar_Area=0.25*pi*Trans_bar_Dia^2;
Trans_bar_D_end=1495;

Trans_bar_V_in=1.25;
Trans_bar_K_GF=2.11;

```

```
Trans_bar_K=4/(1000*4*Trans_bar_K_GF*Trans_bar_V_in);

Trans_bar_K_theory=Trans_bar_K*Trans_bar_E/1e6;

Trans_bar_offset=Trans_bar_D_end/Trans_bar_C+Inc_bar_D_end/Inc_bar_C
    ;
```

THPB do.m

```
% This script is used to convert the three strain guage
% signals v_inc, v_ref, v_trans from the script THPB_shift
% to stress & strain rate vs strain data.

% Load voltage signals and relevant variables from 'file.dat'

load Alloy_1_10_1.dat

% Specimen dimentions L0= {L+2*1.5}
specimen_L0=13;
specimen_A=1.5^2;
disp ("**********************************")
disp ("Verify if L0=8mm  for _5_")
disp ("        and L0=13mm for _10_ ")
disp ("**********************************")

% Generate strain signals with calibrated offset values for incident,
% reflected and transmitted waves. e=K*V

e_inc=Inc_bar_K.*v_inc;
e_ref=Inc_bar_K.*v_ref;
e_trans=Trans_bar_K.*v_trans;

figure(1)
plot(t_wave,e_inc,t_wave,e_ref,t_wave,e_trans);
title('Bar strain waves');
xlabel('Time [ms]');
ylabel('Strain');
legend('Incident strain wave','Reflected strain wave','Transmitted strain wave');
grid on

print(1,'Bar strain waves','-dpng');

% Generate face velocity, displacement & acceleration.
% Also face forces, stress & strains

inc_face_v=zeros(length(e_inc):1);
inc_face_d=inc_face_v;
```

```
inc_face_a=inc_face_v;

trans_face_v=inc_face_v;
trans_face_d=inc_face_v;
trans_face_a=inc_face_v;

specimen_length=inc_face_v;
e_rate=inc_face_v;

inc_F=inc_face_v;
trans_F=inc_face_v;
Err_F=inc_face_v;

strain=inc_face_v;
stress_1=inc_face_v;
stress_2=inc_face_v;

Results=zeros(length(e_inc):3);

i1=1;
i2=0;
i3=0;

for i1=1:Signal_length
        inc_face_v(i1)=Inc_bar_C*(e_ref(i1)-e_inc(i1));
        trans_face_v(i1)=-Trans_bar_C*(e_trans(i1));
        if (i1==1)
                inc_face_d(i1)=Time_step*inc_face_v(i1);
                trans_face_d(i1)=Time_step*trans_face_v(i1);
        else
                inc_face_d(i1)=Time_step*inc_face_v(i1)+inc_face_d(
                    i2);
                trans_face_d(i1)=Time_step*trans_face_v(i1)+
                    trans_face_d(i2);
                inc_face_a(i1)=(inc_face_v(i1)-inc_face_v(i2))/
                    Time_step;
                trans_face_a(i1)=(trans_face_v(i1)-trans_face_v(i2))
                    /Time_step;
        end
        specimen_length(i1)=specimen_L0+inc_face_d(i1)+trans_face_d(
            i1);
```

```
        e_rate(i1)=1000*(inc_face_v(i1)-trans_face_v(i1))/
            specimen_length(i1);
        strain(i1)=specimen_length(i1)/specimen_L0-1;
        inc_F(i1)=-Inc_bar_Area*1e-6*Inc_bar_E*(e_inc(i1)+e_ref(i1))
            ;
        trans_F(i1)=-Trans_bar_Area*1e-6*Trans_bar_E*(e_trans(i1));
        Err_F(i1)=abs(inc_F(i1)-trans_F(i1));
        stress_1(i1)=inc_F(i1)/specimen_A;
        stress_2(i1)=trans_F(i1)/specimen_A;
        if (i3==0)
                if (stress_2(i1)<=0)
                i3=i1;
                end
        end
        i1=i1+1;
        i2=i1-1;
end

strain_0=zeros(i3,1);
stress_1_0=strain_0;
stress_2_0=strain_0;
e_rate_0=strain_0;

i4=1;
for i4=1:i3
        strain_0(i4)=strain(i4);
        stress_1_0(i4)=stress_1(i4);
        stress_2_0(i4)=stress_2(i4);
        e_rate_0(i4)=e_rate(i4);
end

V_av = inc_face_v .- trans_face_v;

figure(2)
plot(t_wave,inc_face_v,t_wave,trans_face_v,t_wave,V_av);
title('Bar end velocity');
xlabel('Time [ms]');
ylabel('Velocity [m/s]');
legend('Incident bar face','Transmitted bar face','Average specimen
    velocity');
grid minor on
```

```
print(2,'Bar end velocity','-dpng');

figure(3)
plot(t_wave,inc_face_d,t_wave,trans_face_d);
title('Bar end displacement');
xlabel('Time [ms]');
ylabel('Displacement [mm]');
legend('Incident bar face','Transmitted bar face');
grid on

print(3,'Bar end displacement','-dpng');

figure(4)
plot(t_wave,inc_face_a,t_wave,trans_face_a);
title('Bar end acceleration');
xlabel('Time [ms]');
ylabel('Acceleration [m/s^2]');
legend('Incident bar face','Transmitted bar face');
grid on

print(4,'Bar end acceleration','-dpng');

figure(5)
plot(t_wave,inc_F,t_wave,trans_F,t_wave,Err_F);
title('Bar end Forces');
xlabel('Time [ms]');
ylabel('Force [N]');
legend('Incident bar face','Transmitted bar face','Force difference'
    );
grid on

print(5,'Bar end Forces','-dpng');

figure(6)
plot(t_wave,strain);
title('Strain time');
xlabel('Time [ms]');
ylabel('Strain [%]');
legend('Speciment strain');
grid on
```

```
print(6,'Strain time','-dpng');

figure(7)
plot(t_wave,e_rate);
title('Strain rate time');
xlabel('Time [ms]');
ylabel('Strain rate [1/s]');
legend('Strain rate');
grid on

print(7,'Strain rate time','-dpng');

figure(8)
plot(strain_0,stress_1_0,strain_0,stress_2_0,strain_0,e_rate_0);
plot(strain,stress_1,strain,stress_2,strain,e_rate);
title('Engineering stress strain');
xlabel('Strain [%]');
ylabel('Stress [MPa] / Strain rate [1/s]');
legend('Stress 1','Stress 2','Strain rate');
grid on

print(8,'Engineering stress strain','-dpng');

Results = zeros(length(strain_0),3);

Results(:,1)=strain_0;
%Results(:,2)=stress_1_0;
Results(:,2)=stress_2_0;
Results(:,3)=e_rate_0;

%csvwrite('Alloy_1_10_1_Results.csv',Results);
```

THPB plot results.m

```
% This script is used to plot all the results from the Tension Hopkinson
% Pressure Bar tests for the SHPB report.
% Result data is imported from the .csv files generatad by THPB_do.m
% All plots are printed to .png format and saved in ~/Octave_script

Res_A1_1=csvread('Alloy_1_5_1_Results.csv');
Res_A1_2=csvread('Alloy_1_5_2_Results.csv');
Res_A1_3=csvread('Alloy_1_5_3_Results.csv');
Res_A1_4=csvread('Alloy_1_10_1_Results.csv');
Res_A1_5=csvread('Alloy_1_10_2_Results.csv');
Res_A1_6=csvread('Alloy_1_10_3_Results.csv');

Res_A1T_1=csvread('Alloy_1T_5_1_Results.csv');
Res_A1T_2=csvread('Alloy_1T_5_2_Results.csv');
Res_A1T_3=csvread('Alloy_1T_5_3_Results.csv');
Res_A1T_4=csvread('Alloy_1T_10_1_Results.csv');
Res_A1T_5=csvread('Alloy_1T_10_2_Results.csv');
Res_A1T_6=csvread('Alloy_1T_10_3_Results.csv');

Res_A500_1=csvread('Benchmark_500_5_1_Results.csv');
Res_A500_2=csvread('Benchmark_500_5_2_Results.csv');
Res_A500_3=csvread('Benchmark_500_5_3_Results.csv');
Res_A500_4=csvread('Benchmark_500_5_4_Results.csv');
Res_A500_5=csvread('Benchmark_500_10_1_Results.csv');
Res_A500_6=csvread('Benchmark_500_10_2_Results.csv');
Res_A500_7=csvread('Benchmark_500_10_3_Results.csv');
Res_A500_8=csvread('Benchmark_500_10_4_Results.csv');

figure(1)
plot(Res_A1_1(:,1),Res_A1_1(:,2),
Res_A1_2(:,1),Res_A1_2(:,2),
Res_A1_3(:,1),Res_A1_3(:,2),
Res_A1_4(:,1),Res_A1_4(:,2),
Res_A1_5(:,1),Res_A1_5(:,2),
Res_A1_6(:,1),Res_A1_6(:,2));
title(strcat('THPB Engineering stress vs. strain for Alloy 1'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat(' Alloy 1 - Specimen 1'),strcat(' Alloy 1 - Specimen 2
```

```
'),strcat(' Alloy 1 - Specimen 3'),strcat(' Alloy 1 - Specimen 4'),strcat(' Alloy 1 - Specimen 5'),strcat(' Alloy 1 - Specimen 6'));
grid on
set(gca(),"xlim",[0,0.25],"ylim",[0,2500]);

figure(2)
plot(Res_A1_1(:,1),Res_A1_1(:,3),
Res_A1_2(:,1),Res_A1_2(:,3),
Res_A1_3(:,1),Res_A1_3(:,3),
Res_A1_4(:,1),Res_A1_4(:,3),
Res_A1_5(:,1),Res_A1_5(:,3),
Res_A1_6(:,1),Res_A1_6(:,3));
title(strcat('THPB test strain-rate for Alloy 1'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Strain-rate [1/s]'));
legend(strcat(' Alloy 1 - Specimen 1'),strcat(' Alloy 1 - Specimen 2'),strcat(' Alloy 1 - Specimen 3'),strcat(' Alloy 1 - Specimen 4'),strcat(' Alloy 1 - Specimen 5'),strcat(' Alloy 1 - Specimen 6'));
grid on

figure(3)
plot(Res_A1T_1(:,1),Res_A1T_1(:,2),
Res_A1T_2(:,1),Res_A1T_2(:,2),
Res_A1T_3(:,1),Res_A1T_3(:,2),
Res_A1T_4(:,1),Res_A1T_4(:,2),
Res_A1T_5(:,1),Res_A1T_5(:,2),
Res_A1T_6(:,1),Res_A1T_6(:,2));
title(strcat('THPB Engineering stress vs. strain for Alloy 1 T200'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat(' Alloy 1 T200 - Specimen 1'),strcat(' Alloy 1 T200 - Specimen 2'),strcat(' Alloy 1 T200 - Specimen 3'),strcat(' Alloy 1 T200 - Specimen 4'),strcat(' Alloy 1 T200 - Specimen 5'),strcat(' Alloy 1 T200 - Specimen 6'));
grid on
set(gca(),"xlim",[0,0.25],"ylim",[0,2500]);

figure(4)
```

```
plot(Res_A1T_1(:,1),Res_A1T_1(:,3),
Res_A1T_2(:,1),Res_A1T_2(:,3),
Res_A1T_3(:,1),Res_A1T_3(:,3),
Res_A1T_4(:,1),Res_A1T_4(:,3),
Res_A1T_5(:,1),Res_A1T_5(:,3),
Res_A1T_6(:,1),Res_A1T_6(:,3));
title(strcat('THPB test strain-rate for Alloy 1 T200'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Strain-rate [1/s]'));
legend(strcat(' Alloy 1 T200 - Specimen 1'),strcat(' Alloy 1 T200 - Specimen 2'),strcat(' Alloy 1 T200 - Specimen 3'),strcat(' Alloy 1 T200 - Specimen 4'),strcat(' Alloy 1 T200 - Specimen 5'),strcat(' Alloy 1 T200 - Specimen 6'));
grid on
set(gca(),"xlim",[0,0.25],"ylim",[0,1200]);

figure(5)
plot(Res_A500_2(1:1476,1),Res_A500_2(1:1476,2),
Res_A500_3(1:2202,1),Res_A500_3(1:2202,2),
Res_A500_4(1:2432,1),Res_A500_4(1:2432,2),
Res_A500_5(1:2196,1),Res_A500_5(1:2196,2),
Res_A500_6(1:2247,1),Res_A500_6(1:2247,2),
Res_A500_7(1:2589,1),Res_A500_7(1:2589,2),
Res_A500_8(1:2650,1),Res_A500_8(1:2650,2));
title(strcat('THPB Engineering stress vs. strain for Benchmark'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat(' Benchmark - Specimen 2'),strcat(' Benchmark - Specimen 3'),strcat(' Benchmark - Specimen 4'),strcat(' Benchmark - Specimen 5'),strcat(' Benchmark - Specimen 6'),strcat(' Benchmark - Specimen 7'),strcat(' Benchmark - Specimen 8'));
grid on
set(gca(),"ylim",[0,2500]);

figure(6)
plot(Res_A500_1(1:1357,1),Res_A500_1(1:1357,3),
Res_A500_2(1:1476,1),Res_A500_2(1:1476,3),
Res_A500_3(1:2202,1),Res_A500_3(1:2202,3),
Res_A500_4(1:2432,1),Res_A500_4(1:2432,3),
Res_A500_5(1:2196,1),Res_A500_5(1:2196,3),
Res_A500_6(1:2247,1),Res_A500_6(1:2247,3),
```

```
Res_A500_7(1:2589,1),Res_A500_7(1:2589,3),
Res_A500_8(1:2650,1),Res_A500_8(1:2650,3));
title(strcat('THPB test strain-rate for Benchmark'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Strain-rate [1/s]'));
legend(strcat(' Benchmark - Specimen 1'),strcat(' Benchmark -
    Specimen 2'),strcat(' Benchmark - Specimen 3'),strcat(' Benchmark
     - Specimen 4'),strcat(' Benchmark - Specimen 5'),strcat('
    Benchmark - Specimen 6'),strcat(' Benchmark - Specimen 7'),strcat
    (' Benchmark - Specimen 8'));
grid on

figure(7)
plot(Res_A1_1(:,1),Res_A1_1(:,2),'b',
Res_A1_2(:,1),Res_A1_2(:,2),'b',
Res_A1_3(:,1),Res_A1_3(:,2),'b',
Res_A1_4(:,1),Res_A1_4(:,2),'b',
Res_A1_5(:,1),Res_A1_5(:,2),'b',
Res_A1_6(:,1),Res_A1_6(:,2),'b',
Res_A1T_1(:,1),Res_A1T_1(:,2),'r',
Res_A1T_2(:,1),Res_A1T_2(:,2),'r',
Res_A1T_3(:,1),Res_A1T_3(:,2),'r',
Res_A1T_4(:,1),Res_A1T_4(:,2),'r',
Res_A1T_5(:,1),Res_A1T_5(:,2),'r',
Res_A1T_6(:,1),Res_A1T_6(:,2),'r',
Res_A500_2(1:1476,1),Res_A500_2(1:1476,2),'g',
Res_A500_3(1:2202,1),Res_A500_3(1:2202,2),'g',
Res_A500_4(1:2432,1),Res_A500_4(1:2432,2),'g',
Res_A500_5(1:2196,1),Res_A500_5(1:2196,2),'g',
Res_A500_6(1:2247,1),Res_A500_6(1:2247,2),'g',
Res_A500_7(1:2589,1),Res_A500_7(1:2589,2),'g',
Res_A500_8(1:2650,1),Res_A500_8(1:2650,2),'g');
title(strcat('THPB Engineering stress vs. strain - Alloy 1, Alloy 1T
    , Benchmark'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat(' Alloy1 1'),strcat(' Alloy1 2'),strcat(' Alloy1 3'),
    strcat(' Alloy1 4'),strcat(' Alloy1 5'),strcat(' Alloy1 6'),
    strcat(' A1T200 1'),strcat(' A1T200 2'),strcat(' A1T200 3'),
    strcat(' A1T200 4'),strcat(' A1T200 5'),strcat(' A1T200 6'),
    strcat(' B1 2'),strcat(' B1 3'),strcat(' B1 4'),strcat(' B1 5'),
```

```
    strcat(' B1 6'),strcat(' B1 7'),strcat(' B1 8'));
grid on
set(gca(),"xlim",[0,0.26],"ylim",[0,2500]);

figure(8)
plot(Res_A1_1(:,1),Res_A1_1(:,2),'b',
Res_A1T_1(:,1),Res_A1T_1(:,2),'r',
Res_A500_1(1:1357,1),Res_A500_1(1:1357,2),'g');
title(strcat('THPB Engineering stress vs. strain - Alloy 1, Alloy 1T
    , Benchmark'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat(' Alloy1 1'),strcat(' A1T200 1'),strcat(' B1 1'));
grid on
set(gca(),"xlim",[0,0.26],"ylim",[0,2500]);

print(1,'THPB_A1_ss','-dpng');
print(2,'THPB_A1_sr','-dpng');
print(3,'THPB_1T_ss','-dpng');
print(4,'THPB_1T_sr','-dpng');
print(5,'THPB_B1_ss','-dpng');
print(6,'THPB_B1_sr','-dpng');
print(7,'THPB_All','-dpng');
print(8,'THPB_3','-dpng');

clear all
```

Plot all T4.m

```
% Read stress strain data from dat files , trim for break stress and
    plot

Res = csvread('Alloy_1_5_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.1)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res) -i0),2) <= 1417)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;

S_T4_001 = Res(start_cut:end_cut,2);
e_T4_001 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1_5_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.08)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res) - i0),2) <= 1300)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_002 = Res(start_cut:end_cut,2);
e_T4_002 = Res(start_cut:end_cut,1);
clear Res;

```

```
Res = csvread('Alloy_1_5_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.11)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res) -i0),2) <= 1323)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_003 = Res(start_cut:end_cut,2);
e_T4_003 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1_10_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.07)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1370)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_004 = Res(start_cut:end_cut,2);
e_T4_004 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1_10_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.07)
```

```
            start_cut = i0;
            end
end
for i0 = 1:1000
            if (Res((length(Res)-i0),2) <= 1409)
            end_cut = i0;
            end
end
end_cut = length(Res)-end_cut;
S_T4_005 = Res(start_cut:end_cut,2);
e_T4_005 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1_10_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
            if (Res(i0,1)<= 0.065)
            start_cut = i0;
            end
end
for i0 = 1:1000
            if (Res((length(Res)-i0),2) <= 1339)
            end_cut = i0;
            end
end
end_cut = length(Res)-end_cut;
S_T4_006 = Res(start_cut:end_cut,2);
e_T4_006 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_5_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
            if (Res(i0,1) <= 0.087)
            start_cut = i0;
            end
end
for i0 = 1:1000
            if (Res((length(Res)-i0),2) <= 1190)
```

```
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_007 = Res(start_cut:end_cut,2);
e_T4_007 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_5_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.11)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1182)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_008 = Res(start_cut:end_cut,2);
e_T4_008 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_5_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.089)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1167)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_009 = Res(start_cut:end_cut,2);
```

```
e_T4_009 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_10_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.077)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1214)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_010 = Res(start_cut:end_cut,2);
e_T4_010 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_10_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.04)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1222)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_011 = Res(start_cut:end_cut,2);
e_T4_011 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Alloy_1T_10_3_Results.csv');
end_cut = 0;
```

```
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.062)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((length(Res)-i0),2) <= 1167)
        end_cut = i0;
        end
end
end_cut = length(Res)-end_cut;
S_T4_012 = Res(start_cut:end_cut,2);
e_T4_012 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_5_1_Results.csv');
S_T4_013 = Res(:,2);
e_T4_013 = Res(:,1);
clear Res;

Res = csvread('Benchmark_500_5_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.1)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((1476-i0),2) <= 721)
        end_cut = i0;
        end
end
end_cut = 1476-end_cut;
S_T4_014 = Res(start_cut:end_cut,2);
e_T4_014 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_5_3_Results.csv');
end_cut = 0;
```

```
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.09)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((2202-i0),2) <= 784)
        end_cut = i0;
        end
end
end_cut = 2202-end_cut;
S_T4_015 = Res(start_cut:end_cut,2);
e_T4_015 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_5_4_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.084)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((2432-i0),2) <= 776)
        end_cut = i0;
        end
end
end_cut = 2432-end_cut;
S_T4_016 = Res(start_cut:end_cut,2);
e_T4_016 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_10_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.07)
        start_cut = i0;
        end
```

```
end
for i0 = 1:1000
        if (Res((2196-i0),2) <= 900)
        end_cut = i0;
        end
end
end_cut = 2196-end_cut;
S_T4_017 = Res(start_cut:end_cut,2);
e_T4_017 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_10_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.068)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((2247-i0),2) <= 830)
        end_cut = i0;
        end
end
end_cut = 2247-end_cut;
S_T4_018 = Res(start_cut:end_cut,2);
e_T4_018 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_10_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.063)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((2589-i0),2) <= 854)
        end_cut = i0;
        end
```

```
end
end_cut = 2589-end_cut;
S_T4_019 = Res(start_cut:end_cut,2);
e_T4_019 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('Benchmark_500_10_4_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        if (Res(i0,1) <= 0.066)
        start_cut = i0;
        end
end
for i0 = 1:1000
        if (Res((2650-i0),2) <= 900)
        end_cut = i0;
        end
end
end_cut = 2650-end_cut;
S_T4_020 = Res(start_cut:end_cut,2);
e_T4_020 = Res(start_cut:end_cut,1);

clear Res;
clear end_cut;
clear i0;

figure(1)
hold on
plot(e_T4_001,S_T4_001,"b",
        e_T4_007,S_T4_007,"r",
  e_T4_014,S_T4_014,"g");
legend(strcat(' Alloy 1'),strcat(' Alloy 1 T200'),strcat(' Benchmark
    '));
plot(e_T4_002,S_T4_002,"b",
        e_T4_003,S_T4_003,"b",
        e_T4_004,S_T4_004,"b",
        e_T4_005,S_T4_005,"b",
        e_T4_006,S_T4_006,"b",
        e_T4_008,S_T4_008,"r",
        e_T4_009,S_T4_009,"r",
```

```
        e_T4_010,S_T4_010,"r",
        e_T4_011,S_T4_011,"r",
        e_T4_012,S_T4_012,"r",
        e_T4_015,S_T4_015,"g",
        e_T4_016,S_T4_016,"g",
        e_T4_017,S_T4_017,"g",
        e_T4_018,S_T4_018,"g",
        e_T4_019,S_T4_019,"g",
        e_T4_020,S_T4_020,"g");
grid on
title("Type 4 comparison");
xlabel('Strain [mm/mm]');
ylabel('Stress [MPa]');

print(1,'Type_4_data','-dpng');

save Type4.dat
clear all
```

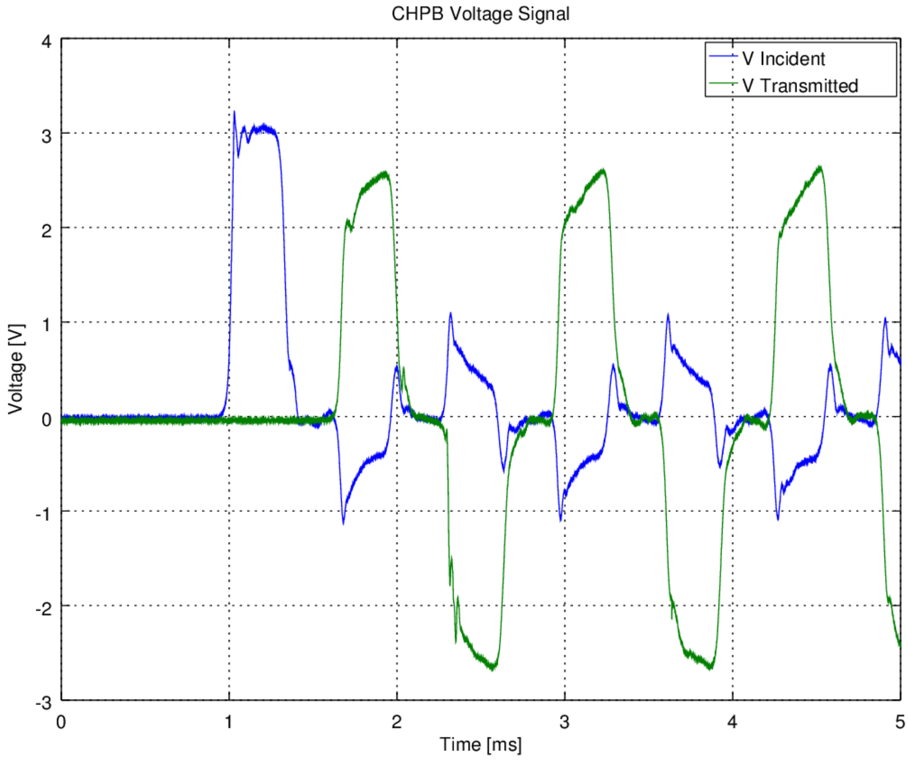

Figure 11.4: Typical recorded strain signal.

11.2.2 Octave code files used for the Compression Split Hopkinson Pressure Bar tests

CHPB shift.m

This script corrects the measured strain signal 11.3 for voltage offsets 11.4, shift the transmitted and reflected waves and crops all three signals to a single wave length 11.5. The total measured signal length of 50 000 data points is reduced to around 8000.

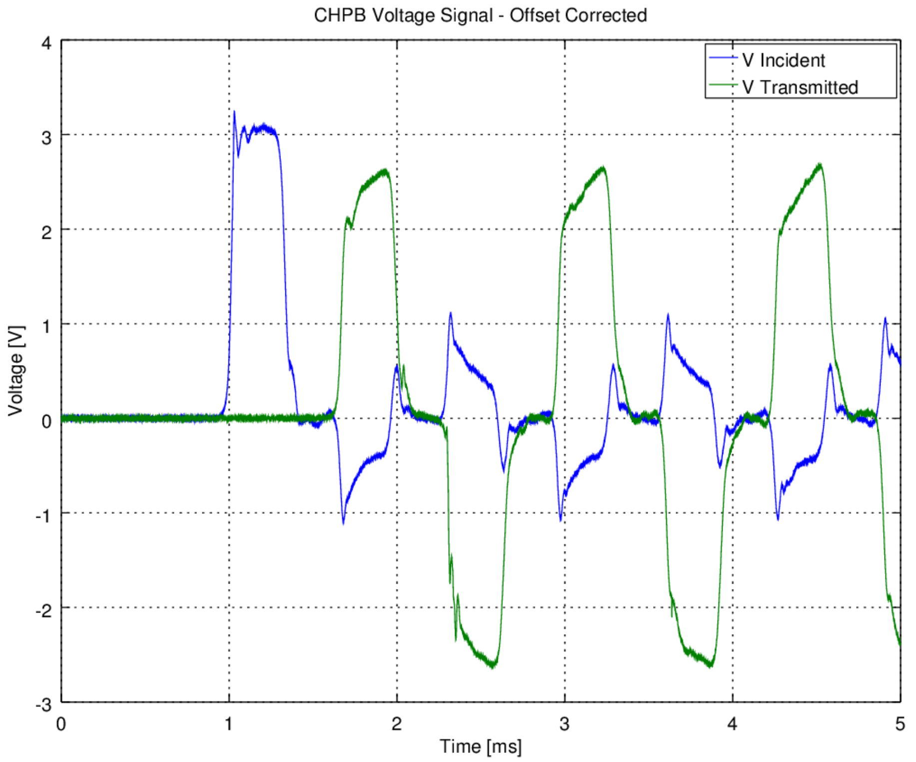

Figure 11.5: Offset corrected strain signal.

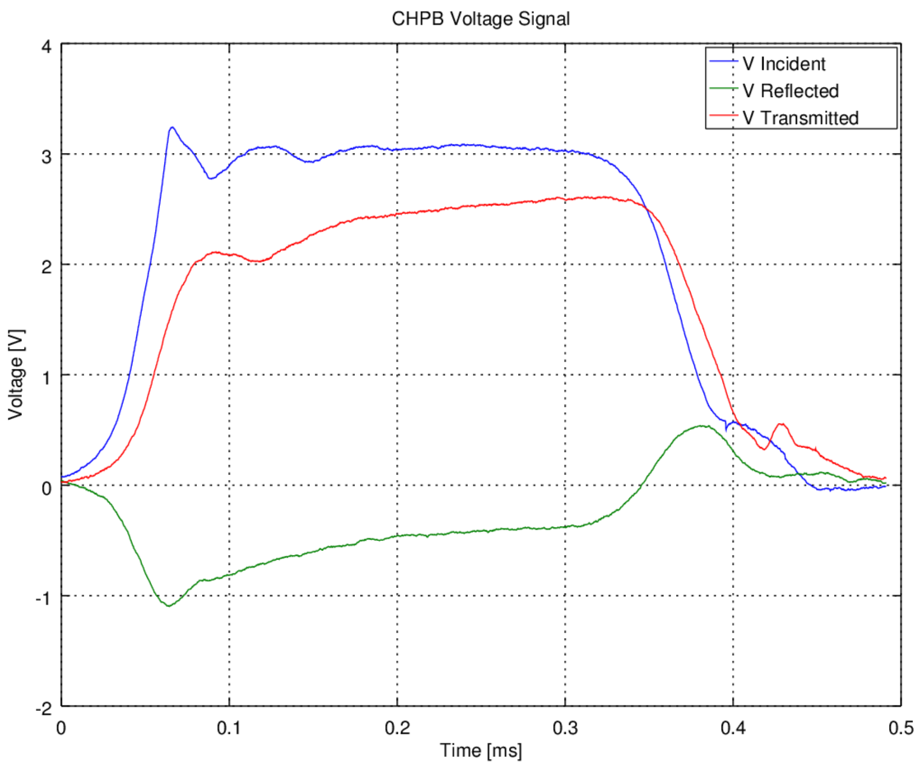

Figure 11.6: Single wave signal.

CHPB shift.m

```
% This script is used to crop & zero the strain guage signal
% The Incident, Transmitted and Reflected Voltage signals are then saved
% as Octave variables in a smaller file.dat

% The signal is imported from the following csv file:
% Only the first two columbs are used.

tic

Signal = csvread('RC_Alloy_1_1.mat.csv');

Vinc = Signal(:,1);
Vtrans = Signal(:,2);
clear('Signal');

% Sample rate = 10Mhz
% Time step = 1/(10e6) = 0.1 [micro s] = 1e-4 [ms]

Time_step = 1e-4;
T_Signal = linspace(0,Time_step*length(Vinc),length(Vinc))';

% Verify voltage signal vertical offset average over offset time [ms]
figure(1)
plot(T_Signal,Vinc,T_Signal,Vtrans);
title('CHPB Voltage Signal');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Transmitted');
grid on

disp (" ")

Vinc_offset_t = 0.6
Vinc_idx = Vinc_offset_t/Time_step;
Vinc_offset = sum(Vinc(1:Vinc_idx))/Vinc_idx;

Vinc = Vinc.-Vinc_offset;

```

```
Vtrans_offset_t = 1.2
Vtrans_idx = Vtrans_offset_t/Time_step;
Vtrans_offset = sum(Vtrans(1:Vtrans_idx))/Vtrans_idx;

Vtrans = Vtrans-Vtrans_offset;

disp ("Verify if the offset average is taken over a constant section using Fig 1.")
disp ("Use close (1) to close figures as required.")
disp (" ")

figure(2)
plot(T_Signal,Vinc,T_Signal,Vtrans);
title('CHPB Voltage Signal - Offset Corrected');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Transmitted');
grid on

% Shift signal to start of incident wave.
Vinc_noise = max(Vinc(1:Vinc_idx))-min(Vinc(1:Vinc_idx))

i1 = 1;
err1 = 0;
err2 = 0;

while (err1 <= 0)
        err1 = Vinc(i1)-2*Vinc_noise;
        i1 = i1+1;
end

Time_shift = i1
%              ^^^ Modify to start of reflected wave.
% Increase Vinc_noise factor (row 64) to reduce sensitivity.

disp ("Verify if the Time_shift correct for reflective wave start using Fig 3.")
disp ("Modify Time_shift offset in line 68 as required.")
disp (" ")

while (err2 >= 0)
```

```
        err2 = Vinc(i1);
        i1 = i1+1;
end

Signal_length = 1.1*(i1-Time_shift);

% The bar calibration and signal offset values are
% defined in the following script:
SHPB_CAL_FeC;

% Crop incident and transmitted voltage signals and
% shift reflected signal.

v_inc = zeros(1,Signal_length)';
v_ref = v_inc;
v_trans = v_inc;
t_wave = linspace(0,Time_step*Signal_length,Signal_length)';

v_ref_offset = round(Ref_bar_offset/Time_step);
v_trans_offset = round(Trans_bar_offset/Time_step);

i2 = 1;

for i2 = 1:Signal_length
        v_inc(i2) = Vinc(i2+Time_shift);
        v_ref(i2) = Vinc(i2+Time_shift+v_ref_offset);
        v_trans(i2) = Vtrans(i2+Time_shift+v_trans_offset);
        i2 = i2+1;
end

figure(3)
plot(t_wave,v_inc,t_wave,v_ref,t_wave,v_trans);
title('CHPB Voltage Signal');
xlabel('Time [ms]');
ylabel('Voltage [V]');
legend('V Incident','V Reflected','V Transmitted');
grid on

clear Vinc;
clear Vtrans;
clear T_Signal;
```

```
%save C_Alloy_1_1.dat

toc
disp (" ")
```

CHPB do.m

```
% This script is used to convert the three strain guage
% signals v_inc, v_ref, v_trans from the script THPB_shift
% to stress & strain rate vs strain data.

% Load voltage signals and relevant variables from 'file.dat'

load C_Alloy_1_1.dat

specimen_L0 = 5;
specimen_A = 0.25*pi*5^2;

% Generate strain signals with calibrated offset values for incident
    ,
% reflected and transmitted waves. e = K*V

e_inc = -Inc_bar_K.*v_inc;
e_ref = -Inc_bar_K.*v_ref;
e_trans = -Trans_bar_K.*v_trans;

figure(1)
plot(t_wave,e_inc,t_wave,e_ref,t_wave,e_trans);
title('Bar strain waves');
xlabel('Time [ms]');
ylabel('Strain [%]');
legend('Incident strain wave','Reflected strain wave','Transmitted
    strain wave');
grid on

print(1,'CHPB_Bar_strain_waves','-dpng');

% Generate face velocity, displacement & acceleration.
% Also face forces, stress & strains

inc_face_v = zeros(length(e_inc):1);
inc_face_d = inc_face_v;
inc_face_a = inc_face_v;

trans_face_v = inc_face_v;
trans_face_d = inc_face_v;
trans_face_a = inc_face_v;
```

```

specimen_length = inc_face_v;
e_rate = inc_face_v;

inc_F = inc_face_v;
trans_F = inc_face_v;
Err_F = inc_face_v;

strain = inc_face_v;
stress_1 = inc_face_v;
stress_2 = inc_face_v;

Results = zeros(length(e_inc):3);

i1 = 1;
i2 = 0;
i3 = 0;

for i1 = 1:Signal_length
        inc_face_v(i1) = Inc_bar_C*(e_ref(i1)-e_inc(i1));
        trans_face_v(i1) = -Trans_bar_C*(e_trans(i1));
        if (i1 == 1)
                inc_face_d(i1) = Time_step*inc_face_v(i1);
                trans_face_d(i1) = Time_step*trans_face_v(i1);
        else
                inc_face_d(i1) = Time_step*inc_face_v(i1)+inc_face_d
                   (i2);
                trans_face_d(i1) = Time_step*trans_face_v(i1)+
                   trans_face_d(i2);
                inc_face_a(i1) = (inc_face_v(i1)-inc_face_v(i2))/
                   Time_step;
                trans_face_a(i1) = (trans_face_v(i1)-trans_face_v(i2
                   ))/Time_step;
        end
        specimen_length(i1) = specimen_L0+inc_face_d(i1)-
           trans_face_d(i1);
        e_rate(i1) = 1000*(inc_face_v(i1)-trans_face_v(i1))/
           specimen_length(i1);
        strain(i1) = specimen_length(i1)/specimen_L0 -1;
        inc_F(i1) = -Inc_bar_Area*1e-6*Inc_bar_E*(e_inc(i1)+e_ref(i1
           ));
```

```
        trans_F(i1) = -Trans_bar_Area*1e-6*Trans_bar_E*(e_trans(i1))
            ;
        Err_F(i1) = abs(inc_F(i1)-trans_F(i1));
        stress_1(i1) = inc_F(i1)/specimen_A;
        stress_2(i1) = trans_F(i1)/specimen_A;
        if (i3 == 0)
                if (stress_2(i1) <= 0)
                i3 = i1;
                end
        end
        i1 = i1+1;
        i2 = i1-1;
end

strain_0 = zeros(i3:1);
stress_1_0 = strain_0;
stress_2_0 = strain_0;
e_rate_0 = strain_0;

i4 = 1;
for i4 = 1:i3
        strain_0(i4) = strain(i4);
        stress_1_0(i4) = stress_1(i4);
        stress_2_0(i4) = stress_2(i4);
        e_rate_0(i4) = e_rate(i4);
end

V_mean = inc_face_v .- trans_face_v;

figure(2)
plot(t_wave,inc_face_v,t_wave,trans_face_v,t_wave,V_mean);
title('Bar end velocity');
xlabel('Time [ms]');
ylabel('Velocity [m/s]');
legend('Incident bar face','Transmitted bar face','Average velocity'
    );
grid on

print(2,'CHPB_Bar_end_velocity','-dpng');

figure(3)
```

```
plot(t_wave,inc_face_d,t_wave,trans_face_d);
title('Bar end displacement');
xlabel('Time [ms]');
ylabel('Displacement [mm]');
legend('Incident bar face','Transmitted bar face');
grid on

print(3,'CHPB_Bar_end_displacement','-dpng');

figure(4)
plot(t_wave,inc_face_a,t_wave,trans_face_a);
title('Bar end acceleration');
xlabel('Time [ms]');
ylabel('Acceleration [m/s^2]');
legend('Incident bar face','Transmitted bar face');
grid on

print(4,'CHPB_Bar_end_acceleration','-dpng');

figure(5)
plot(t_wave,inc_F,t_wave,trans_F,t_wave,Err_F);
title('Bar end Forces');
xlabel('Time [ms]');
ylabel('Force [N]');
legend('Incident bar face','Transmitted bar face','Force difference'
    );
grid on

print(5,'CHPB_Bar_end_Forces','-dpng');

figure(6)
plot(t_wave,strain);
title('Strain time');
xlabel('Time [ms]');
ylabel('Strain [%]');
legend('Speciment strain');
grid on

print(6,'CHPB_Strain_time','-dpng');

figure(7)
```

```
plot(t_wave,e_rate);
title('Strain rate time');
xlabel('Time [ms]');
ylabel('Strain rate [1/s]');
legend('Strain rate');
grid on

print(7,'CHPB_Strain_rate_time','-dpng');

figure(8)
%plot(strain_0,stress_1_0,strain_0,stress_2_0,strain_0,e_rate_0);
plot(strain,stress_1,strain,stress_2,strain,e_rate);
title('Engineering stress strain');
xlabel('Strain [%]');
ylabel('Stress [MPa] / Strain rate [1/s]');
legend('Stress 1','Stress 2','Strain rate');
grid on

print(8,'CHPB_Engineering_stress_strain','-dpng');

Results = zeros(length(strain_0),3);

Results(:,1) = strain_0;
Results(:,2) = stress_2_0;
Results(:,3) = e_rate_0;

%csvwrite('C_Alloy_1_1_Results.csv',Results);
```

CHPB plot results.m

```
% This script is used to plot all the results from the Compession
    Hopkinson
% Pressure Bar tests for the SHPB report.
% Result data is imported from the .csv files generatad by CHPB_do.m
% All plots are printed to .png format and saved in ~/Octave_script

Res_A1_1 = csvread('C_Alloy_1_1_Results.csv');
Res_A1_2 = csvread('C_Alloy_1_2_Results.csv');
Res_A1_3 = csvread('C_Alloy_1_3_Results.csv');
Res_A1_4 = csvread('C_Alloy_1_4_Results.csv');
Res_A1_5 = csvread('C_Alloy_1_5_Results.csv');

Res_A1T_1 = csvread('C_Alloy_1T_1_Results.csv');
Res_A1T_2 = csvread('C_Alloy_1T_2_Results.csv');
Res_A1T_3 = csvread('C_Alloy_1T_3_Results.csv');
Res_A1T_4 = csvread('C_Alloy_1T_4_Results.csv');
Res_A1T_5 = csvread('C_Alloy_1T_5_Results.csv');

Res_A500_1 = csvread('C_Benchmark_500_1_Results.csv');
Res_A500_2 = csvread('C_Benchmark_500_2_Results.csv');
Res_A500_3 = csvread('C_Benchmark_500_3_Results.csv');
Res_A500_4 = csvread('C_Benchmark_500_4_Results.csv');
Res_A500_5 = csvread('C_Benchmark_500_5_Results.csv');

figure(1)
plot(Res_A1_1(:,1),Res_A1_1(:,2),
Res_A1_2(:,1),Res_A1_2(:,2),
Res_A1_3(:,1),Res_A1_3(:,2),
Res_A1_4(:,1),Res_A1_4(:,2),
Res_A1_5(:,1),Res_A1_5(:,2));
title(strcat(' CHPB Engineering stress vs. strain for Alloy 1'));
xlabel(strcat(' Strain [mm/mm] '));
ylabel(strcat(' Stress [MPa] '));
legend(strcat(' Alloy 1 - Specimen 1'),strcat(' Alloy 1 - Specimen 2
    '),strcat(' Alloy 1 - Specimen 3'),strcat(' Alloy 1 - Specimen 4'
    ),strcat(' Alloy 1 - Specimen 5'));
grid on
set(gca(),"xlim",[0,0.3],"ylim",[0,3000]);

figure(2)
```

```
plot(Res_A1_1(:,1),Res_A1_1(:,3),
Res_A1_2(:,1),Res_A1_2(:,3),
Res_A1_3(:,1),Res_A1_3(:,3),
Res_A1_4(:,1),Res_A1_4(:,3),
Res_A1_5(:,1),Res_A1_5(:,3));
title(strcat('CHPB test strain-rate for Alloy 1'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Strain-rate [1/s]'));
legend(strcat('Alloy 1 - Specimen 1'),strcat('Alloy 1 - Specimen 2'),strcat('Alloy 1 - Specimen 3'),strcat('Alloy 1 - Specimen 4'),strcat('Alloy 1 - Specimen 5'));
grid on
set(gca(),"xlim",[0,0.3],"ylim",[0,1500]);

figure(3)
plot(Res_A1T_1(:,1),Res_A1T_1(:,2),
Res_A1T_2(:,1),Res_A1T_2(:,2),
Res_A1T_3(:,1),Res_A1T_3(:,2),
Res_A1T_4(:,1),Res_A1T_4(:,2),
Res_A1T_5(:,1),Res_A1T_5(:,2));
title(strcat('CHPB Engineering stress vs. strain for Alloy 1 T200'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat('Alloy 1 T200 - Specimen 1'),strcat('Alloy 1 T200 - Specimen 2'),strcat('Alloy 1 T200 - Specimen 3'),strcat('Alloy 1 T200 - Specimen 4'),strcat('Alloy 1 T200 - Specimen 5'));
grid on
%set(gca(),"xlim",[0,0.5],"ylim",[0,3000]);

figure(4)
plot(Res_A1T_1(:,1),Res_A1T_1(:,3),
Res_A1T_2(:,1),Res_A1T_2(:,3),
Res_A1T_3(:,1),Res_A1T_3(:,3),
Res_A1T_4(:,1),Res_A1T_4(:,3),
Res_A1T_5(:,1),Res_A1T_5(:,3));
title(strcat('CHPB test strain-rate for Alloy 1 T200'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Strain-rate [1/s]'));
legend(strcat('Alloy 1 T200 - Specimen 1'),strcat('Alloy 1 T200 - Specimen 2'),strcat('Alloy 1 T200 - Specimen 3'),strcat('Alloy
```

```
1 T200 - Specimen 4'),strcat(' Alloy 1 T200 - Specimen 5'));
grid on
%set(gca(),"xlim",[0,0.28],"ylim",[0,2500]);

figure(5)
plot(Res_A500_1(:,1),Res_A500_1(:,2),
Res_A500_2(:,1),Res_A500_2(:,2),
Res_A500_3(:,1),Res_A500_3(:,2),
Res_A500_4(:,1),Res_A500_4(:,2),
Res_A500_5(:,1),Res_A500_5(:,2));
title(strcat(' CHPB Engineering stress vs. strain for Benchmark'));
xlabel(strcat(' Strain [mm/mm] '));
ylabel(strcat(' Stress [MPa] '));
legend(strcat(' Benchmark - Specimen 1'),strcat(' Benchmark -
    Specimen 2'),strcat(' Benchmark - Specimen 3'),strcat(' Benchmark
     - Specimen 4'),strcat(' Benchmark - Specimen 5'));
grid on
%set(gca(),"xlim",[0,0.5],"ylim",[0,3000]);

figure(6)
plot(Res_A500_1(:,1),Res_A500_1(:,3),
Res_A500_2(:,1),Res_A500_2(:,3),
Res_A500_3(:,1),Res_A500_3(:,3),
Res_A500_4(:,1),Res_A500_4(:,3),
Res_A500_5(:,1),Res_A500_5(:,3));
title(strcat(' CHPB test strain-rate for Benchmark'));
xlabel(strcat(' Strain [mm/mm] '));
ylabel(strcat(' Strain-rate [1/s] '));
legend(strcat(' Benchmark - Specimen 1'),strcat(' Benchmark -
    Specimen 2'),strcat(' Benchmark - Specimen 3'),strcat(' Benchmark
     - Specimen 4'),strcat(' Benchmark - Specimen 5'));
grid on
%set(gca(),"xlim",[0,0.4],"ylim",[0,2000]);

figure(7)
plot(Res_A1_1(:,1),Res_A1_1(:,2),'b',
Res_A1_2(:,1),Res_A1_2(:,2),'b',
Res_A1_3(:,1),Res_A1_3(:,2),'b',
Res_A1_4(:,1),Res_A1_4(:,2),'b',
Res_A1_5(:,1),Res_A1_5(:,2),'b',
Res_A1T_1(:,1),Res_A1T_1(:,2),'r',
```

```
Res_A1T_2(:,1),Res_A1T_2(:,2),'r',
Res_A1T_3(:,1),Res_A1T_3(:,2),'r',
Res_A1T_4(:,1),Res_A1T_4(:,2),'r',
Res_A1T_5(:,1),Res_A1T_5(:,2),'r',
Res_A500_1(:,1),Res_A500_1(:,2),'g',
Res_A500_2(:,1),Res_A500_2(:,2),'g',
Res_A500_3(:,1),Res_A500_3(:,2),'g',
Res_A500_4(:,1),Res_A500_4(:,2),'g',
Res_A500_5(:,1),Res_A500_5(:,2),'g');
title(strcat('CHPB Engineering stress vs. strain - Alloy 1, Alloy 1
    T, Benchmark'));
xlabel(strcat('Strain [mm/mm]'));
ylabel(strcat('Stress [MPa]'));
legend(strcat('Alloy1 1'),strcat('Alloy1 2'),strcat('Alloy1 3'),
    strcat('Alloy1 4'),strcat('Alloy1 5'),strcat('A1T200 1'),
    strcat('A1T200 2'),strcat('A1T200 3'),strcat('A1T200 4'),
    strcat('A1T200 5'),strcat('B1 1'),strcat('B1 2'),strcat('B1 3
    '),strcat('B1 4'),strcat('B1 5'));
grid on
set(gca(),"xlim",[0,1],"ylim",[0,3000]);

print(1,'CHPB_A1_ss','-dpng');
print(2,'CHPB_A1_sr','-dpng');
print(3,'CHPB_1T_ss','-dpng');
print(4,'CHPB_1T_sr','-dpng');
print(5,'CHPB_B1_ss','-dpng');
print(6,'CHPB_B1_sr','-dpng');
print(7,'CHPB_All','-dpng');

clear all
```

Plot all T5.m

```
% Read stress strain data from dat files , trim for break stress and
    plot

Res = csvread('C_Alloy_1_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2300
        start_cut = i1;
        end
        if Res(i0,2) >= 2522
        end_cut = i0;
        end
end
S_T5_001 = Res(start_cut:end_cut,2);
e_T5_001 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2300
        start_cut = i1;
        end
        if Res(i0,2) >= 2599
        end_cut = i0;
        end
end
S_T5_002 = Res(start_cut:end_cut,2);
e_T5_002 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
```

```
        if Res(i1,2) >= 2500
        start_cut = i1;
        end
        if Res(i0,2) >= 2870
        end_cut = i0;
        end
end
S_T5_003 = Res(start_cut:end_cut,2);
e_T5_003 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1_4_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2500
        start_cut = i1;
        end
        if Res(i0,2) >= 2948
        end_cut = i0;
        end
end
S_T5_004 = Res(start_cut:end_cut,2);
e_T5_004 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1_5_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 1900
        start_cut = i1;
        end
        if Res(i0,2) >= 2202
        end_cut = i0;
        end
end
S_T5_005 = Res(start_cut:end_cut,2);
e_T5_005 = Res(start_cut:end_cut,1);
```

```
clear Res;

Res = csvread('C_Alloy_1T_1_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2000
        start_cut = i1;
        end
        if Res(i0,2) >= 2345
        end_cut = i0;
        end
end
S_T5_006 = Res(start_cut:end_cut,2);
e_T5_006 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1T_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2200
        start_cut = i1;
        end
        if Res(i0,2) >= 2457
        end_cut = i0;
        end
end
S_T5_007 = Res(start_cut:end_cut,2);
e_T5_007 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1T_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2300
        start_cut = i1;
```

```
        end
        if Res(i0,2) >= 2677
        end_cut = i0;
        end
end
S_T5_008 = Res(start_cut:end_cut,2);
e_T5_008 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1T_4_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2400
        start_cut = i1;
        end
        if Res(i0,2) >= 2699
        end_cut = i0;
        end
end
S_T5_009 = Res(start_cut:end_cut,2);
e_T5_009 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Alloy_1T_5_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 1850
        start_cut = i1;
        end
        if Res(i0,2) >= 2147
        end_cut = i0;
        end
end
S_T5_010 = Res(start_cut:end_cut,2);
e_T5_010 = Res(start_cut:end_cut,1);
clear Res;
```

```
Res = csvread('C_Benchmark_500_1_Results.csv');
end_cut = 0;
for i0 = 1:length(Res)
        if Res(i0,2) >= 2247
        end_cut = i0;
        end
end
S_T5_011 = Res(start_cut:end_cut,2);
e_T5_011 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Benchmark_500_2_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2100
        start_cut = i1;
        end
        if Res(i0,2) >= 2343
        end_cut = i0;
        end
end
S_T5_012 = Res(start_cut:end_cut,2);
e_T5_012 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Benchmark_500_3_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2200
        start_cut = i1;
        end
        if Res(i0,2) >= 2555
        end_cut = i0;
        end
end
S_T5_013 = Res(start_cut:end_cut,2);
e_T5_013 = Res(start_cut:end_cut,1);
```

```
clear Res;

Res = csvread('C_Benchmark_500_4_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 2350
        start_cut = i1;
        end
        if Res(i0,2) >= 2804
        end_cut = i0;
        end
end
S_T5_014 = Res(start_cut:end_cut,2);
e_T5_014 = Res(start_cut:end_cut,1);
clear Res;

Res = csvread('C_Benchmark_500_5_Results.csv');
end_cut = 0;
start_cut = 0;
for i0 = 1:length(Res)
        i1 = length(Res)-i0+1;
        if Res(i1,2) >= 1800
        start_cut = i1;
        end
        if Res(i0,2) >= 2050
        end_cut = i0;
        end
end
S_T5_015 = Res(start_cut:end_cut,2);
e_T5_015 = Res(start_cut:end_cut,1);

clear Res;
clear end_cut;
clear i0;

figure(1)
hold on
plot(e_T5_001,S_T5_001,"b",
        e_T5_006,S_T5_006,"r",
```

```
  e_T5_011,S_T5_011,"g");
legend(strcat(' Alloy 1'),strcat(' Alloy 1 T200'),strcat(' Benchmark
    '));
plot(e_T5_002,S_T5_002,"b",
        e_T5_003,S_T5_003,"b",
        e_T5_004,S_T5_004,"b",
        e_T5_005,S_T5_005,"b",

        e_T5_007,S_T5_007,"r",
        e_T5_008,S_T5_008,"r",
        e_T5_009,S_T5_009,"r",
        e_T5_010,S_T5_010,"r",

        e_T5_012,S_T5_012,"g",
        e_T5_013,S_T5_013,"g",
        e_T5_014,S_T5_014,"g",
        e_T5_015,S_T5_015,"g");
hold off
grid on
title("Type 5 comparison");
xlabel('Strain [mm/mm]');
ylabel('Stress [MPa]');
axis([0 1 0 3000])
print(1,'Type_5_data','-dpng');

save Type5.dat
clear all
```

CHAPTER 12

Appendix E

This section includes all the Octave code files used for the Numerical material characterisation as well as iterative progress results.

JCook.m

```
function Stress = JCook(T,edot,Strain,MatProp);

A = MatProp(1)*1e3;
B = MatProp(2)*1e3;
n = MatProp(3);
c = MatProp(4);
m = MatProp(5);

Tmelt = 1793;
Troom = 297;
Tstar = (T-Troom)/(Tmelt - Troom);

for i=1:length(Strain)
        Stress(i) = (A+B*(Strain(i))^n)*(1+c*log(edot))*(1-Tstar^m);
end
```

Eval JC a1.m

```
function Error = Eval_JC_a1(MatProp)

load Type1.dat;
load Type2.dat;
%load Type3.dat;
%load Type4.dat;
load Type5.dat;

e1 = e_T1_012;
s1 = S_T1_012;
e2 = e_T1_013;
s2 = S_T1_013;
e3 = e_T1_014;
s3 = S_T1_014;
e4 = e_T1_015;
s4 = S_T1_015;
e5 = e_T1_020;
s5 = S_T1_020;
e6 = e_T1_021;
s6 = S_T1_021;
e7 = e_T1_022;
s7 = S_T1_022;
e8 = e_T1_023;
s8 = S_T1_023;

e9 = e_T2_001;
s9 = S_T2_001;
e10 = e_T2_003;
s10 = S_T2_003;
e11 = e_T2_005;
s11 = S_T2_005;
e12 = e_T2_007;
s12 = S_T2_007;
e13 = e_T2_009;
s13 = S_T2_009;
e14 = e_T2_011;
s14 = S_T2_011;

e15 = e_T5_001;
s15 = S_T5_001;
```

```
e16 = e_T5_002;
s16 = S_T5_002;
e17 = e_T5_003;
s17 = S_T5_003;
e18 = e_T5_004;
s18 = S_T5_004;
e19 = e_T5_005;
s19 = S_T5_005;

T = [297 297 297 297 297 297 297 297 ...
     373 473 573 673 778 873 ...
                    297 297 297 297 297];

edot = [0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 ...
                     0.15 0.15 0.15 0.15 0.15 0.15 ...
                     370 440 630 700 260];

EPSO = 0.15;

edot = edot./EPSO;

Strain(1,:) = linspace(0.001,1,1000);
Strain(2,:) = linspace(0.001,1,1000);
Strain(3,:) = linspace(0.001,1,1000);
Strain(4,:) = linspace(0.001,1,1000);
Strain(5,:) = linspace(0.001,1,1000);
Strain(6,:) = linspace(0.001,1,1000);
Strain(7,:) = linspace(0.001,1,1000);
Strain(8,:) = linspace(0.001,1,1000);
Strain(9,:) = linspace(0.001,1,1000);
Strain(10,:) = linspace(0.001,1,1000);
Strain(11,:) = linspace(0.001,1,1000);
Strain(12,:) = linspace(0.001,1,1000);
Strain(13,:) = linspace(0.001,1,1000);
Strain(14,:) = linspace(0.001,1,1000);
Strain(15,:) = linspace(0.001,1,1000);
Strain(16,:) = linspace(0.001,1,1000);
Strain(17,:) = linspace(0.001,1,1000);
Strain(18,:) = linspace(0.001,1,1000);
Strain(19,:) = linspace(0.001,1,1000);
```

```
Stress = zeros(length(T),length(Strain));

E = 200e3;

for i=1:length(T)
        Stress(i,:) = JCook(T(i),edot(i),Strain(i,:),MatProp);
  Strain(i,:) = Strain(i,:) .+ Stress(i,:)./E;
  Stress(i,1) = 0;
  Strain(i,1) = 0;
end

s1_int = interp1(Strain(1,:),Stress(1,:),e1);
s2_int = interp1(Strain(2,:),Stress(2,:),e2);
s3_int = interp1(Strain(3,:),Stress(3,:),e3);
s4_int = interp1(Strain(4,:),Stress(4,:),e4);
s5_int = interp1(Strain(5,:),Stress(5,:),e5);
s6_int = interp1(Strain(6,:),Stress(6,:),e6);
s7_int = interp1(Strain(7,:),Stress(7,:),e7);
s8_int = interp1(Strain(8,:),Stress(8,:),e8);
s9_int = interp1(Strain(9,:),Stress(9,:),e9);
s10_int = interp1(Strain(10,:),Stress(10,:),e10);
s11_int = interp1(Strain(11,:),Stress(11,:),e11);
s12_int = interp1(Strain(12,:),Stress(12,:),e12);
s13_int = interp1(Strain(13,:),Stress(13,:),e13);
s14_int = interp1(Strain(14,:),Stress(14,:),e14);
s15_int = interp1(Strain(15,:),Stress(15,:),e15);
s16_int = interp1(Strain(16,:),Stress(16,:),e16);
s17_int = interp1(Strain(17,:),Stress(17,:),e17);
s18_int = interp1(Strain(18,:),Stress(18,:),e18);
s19_int = interp1(Strain(19,:),Stress(19,:),e19);


Data_points=length(e1)+length(e2)+length(e3)+length(e4)+...
                        length(e5)+length(e6)+length(e7)+length(e8)
                            +...
                        length(e9)+length(e10)+length(e11)+length(
                            e12)+...
                        length(e13)+length(e14)+length(e15)+length(
                            e16)+...
                        length(e17)+length(e18)+length(e19);

```

```
Error = sqrt((sum((s1_int-s1).^2)+...
               sum((s2_int-s2).^2)+...
               sum((s3_int-s3).^2)+...
               sum((s4_int-s4).^2)+...
               sum((s5_int-s5).^2)+...
               sum((s6_int-s6).^2)+...
               sum((s7_int-s7).^2)+...
               sum((s8_int-s8).^2)+...
               sum((s9_int-s9).^2)+...
               sum((s10_int-s10).^2)+...
               sum((s11_int-s11).^2)+...
               sum((s12_int-s12).^2)+...
               sum((s13_int-s13).^2)+...
               sum((s14_int-s14).^2)+...
               sum((s15_int-s15).^2)+...
               sum((s16_int-s16).^2)+...
               sum((s17_int-s17).^2)+...
               sum((s18_int-s18).^2)+...
               sum((s19_int-s19).^2))/(Data_points))

Plot_on=1;
if (Plot_on == 1)
        figure(1)
  hold on
        plot(e1,s1,"b",
  e9,s9,"r",
  e15,s15,"c",
  e1,s1_int,"k");
  legend(strcat(' Type 1'),strcat(' Type 2'),strcat(' Type 5'),
     strcat(' Johnson Cook Fit'), 'location', 'southeast');

  plot(e2,s2,"b",e3,s3,"b",e4,s4,"b",...
               e5,s5,"b",e6,s6,"b",e7,s7,"b",e8,s8,"b",...
               e10,s10,"r",e11,s11,"r",e12,s12,"r",...
               e13,s13,"r",e14,s14,"r",e16,s16,"c",...
               e17,s17,"c",e18,s18,"c",e19,s19,"c",...
               e2,s2_int,"k",e3,s3_int,"k",e4,s4_int,"k",...
               e5,s5_int,"k",e6,s6_int,"k",e7,s7_int,"k",e8,s8_int
                  ,"k",...
               e9,s9_int,"k",e10,s10_int,"k",e11,s11_int,"k",e12,
                  s12_int,"k",...
```

```
                    e13,s13_int,"k",e14,s14_int,"k",e15,s15_int,"k",e16,
                        s16_int,"k",...
                    e17,s17_int,"k",e18,s18_int,"k",e19,s19_int,"k")
          axis([0 0.3 0 3000])
          title("Type 1, 2 & 5 Johnson Cook (Alloy 1)");
          xlabel("Total Engineering strain [mm/mm]");
          ylabel("Engineerin stress [MPa]");
          grid on
          drawnow
  hold off
end

[MatProp_out] = fopen('MatProp_basic_JC_A1.dat','a');
out = 0;
iter = [num2str(MatProp,'%10.8e '),' | ',num2str(Error,'%.5f'),'|'];
while (out == 0)
          line = fgets(MatProp_out);
          if ((line = -1))
                    w = fprintf(MatProp_out,'%s \n',iter);
                    out = 1;
          else
                    w = fprintf(MatProp_out,'%s \n',line);
          end
end
fclose('MatProp_basic_JC_A1.dat');

print(1,'Type_1_2_5_JC_A1','-dpng');
fflush(stdout);
```

Eval JC 1 B.m

```
function Error = Eval_JC_1_B(MatProp)

%load Type1.dat;
load Type2.dat;
load Type3.dat;
%load Type4.dat;
load Type5.dat;

e1 = e_T3_009';
s1 = S_T3_009';
%e2 = e_T3_010';
%s2 = S_T3_010';

e2 = e_T2_002;
s2 = S_T2_002;
e3 = e_T2_004;
s3 = S_T2_004;
e4 = e_T2_006;
s4 = S_T2_006;
e5 = e_T2_008;
s5 = S_T2_008;
e6 = e_T2_010;
s6 = S_T2_010;
e7 = e_T2_012;
s7 = S_T2_012;

e8 = e_T5_011;
s8 = S_T5_011;
e9 = e_T5_012;
s9 = S_T5_012;
e10 = e_T5_013;
s10 = S_T5_013;
e11 = e_T5_014;
s11 = S_T5_014;
e12 = e_T5_015;
s12 = S_T5_015;

T = [297 ...
     %297 ...
                    373 473 573 673 778 873 ...
```

```
                297 297 297 297 297];

edot = [0.15 ...
       %0.15 ...
                    0.15 0.15 0.15 0.15 0.15 0.15 ...
                    420 510 640 780 330];

EPSO = 0.15;

edot = edot./EPSO;

Strain(1,:) = linspace(0.001,1,1000);
Strain(2,:) = linspace(0.001,1,1000);
Strain(3,:) = linspace(0.001,1,1000);
Strain(4,:) = linspace(0.001,1,1000);
Strain(5,:) = linspace(0.001,1,1000);
Strain(6,:) = linspace(0.001,1,1000);
Strain(7,:) = linspace(0.001,1,1000);
Strain(8,:) = linspace(0.001,1,1000);
Strain(9,:) = linspace(0.001,1,1000);
Strain(10,:) = linspace(0.001,1,1000);
Strain(11,:) = linspace(0.001,1,1000);
Strain(12,:) = linspace(0.001,1,1000);

Stress = zeros(length(T),length(Strain));

E = 200e3;

for i=1:length(T)
        Stress(i,:) = JCook(T(i),edot(i),Strain(i,:),MatProp);
  Strain(i,:) = Strain(i,:) .+ Stress(i,:)./E;
  Stress(i,1) = 0;
  Strain(i,1) = 0;
end

s1_int = interp1(Strain(1,:),Stress(1,:),e1);
s2_int = interp1(Strain(2,:),Stress(2,:),e2);
s3_int = interp1(Strain(3,:),Stress(3,:),e3);
s4_int = interp1(Strain(4,:),Stress(4,:),e4);
s5_int = interp1(Strain(5,:),Stress(5,:),e5);
s6_int = interp1(Strain(6,:),Stress(6,:),e6);
```

```
s7_int = interp1(Strain(7,:),Stress(7,:),e7);
s8_int = interp1(Strain(8,:),Stress(8,:),e8);
s9_int = interp1(Strain(9,:),Stress(9,:),e9);
s10_int = interp1(Strain(10,:),Stress(10,:),e10);
s11_int = interp1(Strain(11,:),Stress(11,:),e11);
s12_int = interp1(Strain(12,:),Stress(12,:),e12);

Data_points=length(e1)+length(e2)+...
                        length(e3)+length(e4)+length(e5)+length(e6)
                            +...
                        length(e7)+length(e8)+length(e9)+length(e10
                            +...
      length(e11)+length(e12));

Error = sum((s1_int-s1).^2)+...
                sum((s2_int-s2).^2)+...
                sum((s3_int-s3).^2)+...
                sum((s4_int-s4).^2)+...
                sum((s5_int-s5).^2)+...
                sum((s6_int-s6).^2)+...
                sum((s7_int-s7).^2)+...
                sum((s8_int-s8).^2)+...
                sum((s9_int-s9).^2)+...
                sum((s10_int-s10).^2)+...
                sum((s11_int-s11).^2)+...
                sum((s12_int-s12).^2);

Error = sqrt(Error/(Data_points))

Plot_on=1;
if (Plot_on==1)
        figure(1)
  hold on
        plot(e1,s1,"b",
    e2,s2,"r",
    e8,s8,"m",
    e1,s1_int,"k");
legend(strcat(' Type 1'),strcat(' Type 2'),strcat(' Type 5'),strcat(
    ' Johnson Cook Fit'), 'location', 'southeast');

  plot(e3,s3,"r",e4,s4,"r",e5,s5,"r",e6,s6,"r",...
```

```
                    e7,s7,"r",...
        e9,s9,"m",e10,s10,"m",e11,s11,"m",e12,s12,"m",...
                    e2,s2_int,"k",...
                    e3,s3_int,"k",e4,s4_int,"k",e5,s5_int,"k",e6,s6_int
                        ,"k",...
                    e7,s7_int,"k",e8,s8_int,"k",e9,s9_int,"k",e10,
                        s10_int,"k",...
        e11,s11_int,"k",e12,s12_int,"k")

            %axis([0 0.8 0 3000])
            title("Type 1, 2 & 5 Johnson Cook (Benchmark)");
            xlabel("Total Engineering strain [mm/mm]");
            ylabel("Engineerin stress [MPa]");
            grid on
            drawnow
    hold off
end

[MatProp_out] = fopen('MatProp_basic_JC_1_B.dat','a');
out = 0;
iter = [num2str(MatProp,'%10.8e '),' | ',num2str(Error,'%.5f'),'|'];
while (out == 0)
            line = fgets(MatProp_out);
            if ((line = -1))
                    w = fprintf(MatProp_out,'%s \n',iter);
                    out = 1;
            else
                    w = fprintf(MatProp_out,'%s \n',line);
            end
end
fclose('MatProp_basic_JC_1_B.dat');

%print(1,'Type_1_2_5_JC_B','-dpng');
fflush(stdout);
```

Eval JC 2 B.m

```
function Error = Eval_JC_2_B(MatProp)

%load Type1.dat;
load Type2.dat;
load Type3.dat;
%load Type4.dat;
load Type5.dat;

e1 = e_T3_009';
s1 = S_T3_009';
%e2 = e_T3_010';
%s2 = S_T3_010';

e2 = e_T2_002;
s2 = S_T2_002;
e3 = e_T2_004;
s3 = S_T2_004;
e4 = e_T2_006;
s4 = S_T2_006;
e5 = e_T2_008;
s5 = S_T2_008;
e6 = e_T2_010;
s6 = S_T2_010;
e7 = e_T2_012;
s7 = S_T2_012;

%e8 = e_T5_015;
%s8 = S_T5_015;

T = [297 ...
    %297 ...
                    373 473 573 673 778 873];
                    %297 297 297 297 297];

edot = [0.15 ...
        %0.15 ...
                        0.15 0.15 0.15 0.15 0.15 0.15];
                        %420 510 640 780 330];

EPSO = 0.15;
```

```

edot = edot./EPSO;

Strain(1,:) = linspace(0.001,1,1000);
Strain(2,:) = linspace(0.001,1,1000);
Strain(3,:) = linspace(0.001,1,1000);
Strain(4,:) = linspace(0.001,1,1000);
Strain(5,:) = linspace(0.001,1,1000);
Strain(6,:) = linspace(0.001,1,1000);
Strain(7,:) = linspace(0.001,1,1000);

Stress = zeros(length(T),length(Strain));

E = 200e3;

for i=1:length(T)
        Stress(i,:) = JCook(T(i),edot(i),Strain(i,:),MatProp);
  Strain(i,:) = Strain(i,:) .+ Stress(i,:)./E;
  Stress(i,1) = 0;
  Strain(i,1) = 0;
end

s1_int = interp1(Strain(1,:),Stress(1,:),e1);
s2_int = interp1(Strain(2,:),Stress(2,:),e2);
s3_int = interp1(Strain(3,:),Stress(3,:),e3);
s4_int = interp1(Strain(4,:),Stress(4,:),e4);
s5_int = interp1(Strain(5,:),Stress(5,:),e5);
s6_int = interp1(Strain(6,:),Stress(6,:),e6);
s7_int = interp1(Strain(7,:),Stress(7,:),e7);

Data_points=length(e1)+length(e2)+...
                        length(e3)+length(e4)+length(e5)+length(e6)
                           +...
                        length(e7);

Error = sum((s1_int-s1).^2)+...
               sum((s2_int-s2).^2)+...
               sum((s3_int-s3).^2)+...
               sum((s4_int-s4).^2)+...
               sum((s5_int-s5).^2)+...
               sum((s6_int-s6).^2)+...
```

```
                    sum((s7_int-s7).^2);

Error = sqrt(Error/(Data_points))

Plot_on=1;
if (Plot_on==1)
        figure(1)
  hold on
        plot(e1,s1,"b",
    e2,s2,"r",
    e1,s1_int,"k");
  legend(strcat(' Type 1'),strcat(' Type 2'),strcat(' Johnson Cook
      Fit'), 'location', 'southeast');

  plot(e3,s3,"r",e4,s4,"r",e5,s5,"r",e6,s6,"r",...
                e7,s7,"r",...
                e2,s2_int,"k",...
                e3,s3_int,"k",e4,s4_int,"k",e5,s5_int,"k",e6,s6_int
                    ,"k",...
                e7,s7_int,"k")
  hold off
        %axis([0 0.8 0 3000])
        title("Type 1 & 2 Johnson Cook (Benchmark)");
        xlabel("Total Engineering strain [mm/mm]");
        ylabel("Engineerin stress [MPa]");
        grid on
        drawnow
end

[MatProp_out] = fopen('MatProp_basic_JC_2_B.dat','a');
out = 0;
iter = [num2str(MatProp,'%10.8e '),' | ',num2str(Error,'%.5f'),'|'];
while (out == 0)
        line = fgets(MatProp_out);
        if ((line = -1))
                w = fprintf(MatProp_out,'%s \n',iter);
                out = 1;
        else
                w = fprintf(MatProp_out,'%s \n',line);
        end
end
```

```
fclose('MatProp_basic_JC_2_B.dat');

fflush(stdout);
```

MatProp basic JC A1.dat

```
1.00000000e+000 2.00000000e+000 2.00000000e-001 1.00000000e-002 1.00000000e+000 |162.91574|
2.82419117e+000 2.40997761e+000 6.09977611e-001 4.19977611e-001 1.40997761e+000 |6896.62839|
1.40997761e+000 3.82419117e+000 6.09977611e-001 4.19977611e-001 1.40997761e+000 |4395.19828|
1.40997761e+000 2.40997761e+000 2.02419117e+000 4.19977611e-001 1.40997761e+000 |2266.28660|
1.40997761e+000 2.40997761e+000 6.09977611e-001 1.83419117e+000 1.40997761e+000 |12613.59793|
1.40997761e+000 2.40997761e+000 6.09977611e-001 4.19977611e-001 2.82419117e+000 |3619.41935|
1.81167199e+000 2.81167199e+000 1.01167199e+000 -1.15822700e+000 1.81167199e+000 |13729.75109|
1.51040121e+000 2.51040121e+000 7.10401206e-001 1.08608663e+000 1.51040121e+000 |8727.31191|
1.20498881e+000 2.20498881e+000 1.11209559e+000 2.14988805e-001 1.20498881e+000 |873.17036|
1.20498881e+000 2.20498881e+000 4.04988805e-001 2.14988805e-001 1.91209559e+000 |1879.59826|
1.20498881e+000 2.91209559e+000 4.04988805e-001 2.14988805e-001 1.20498881e+000 |2313.72397|
1.91209559e+000 2.20498881e+000 4.04988805e-001 2.14988805e-001 1.20498881e+000 |2985.13871|
1.20498881e+000 2.20498881e+000 4.04988805e-001 9.22095586e-001 1.20498881e+000 |7781.17388|
1.40583600e+000 2.40583600e+000 6.05835996e-001 -5.74113498e-001 1.40583600e+000 |6304.60884|
1.35562420e+000 2.35562420e+000 5.55624198e-001 -2.00061227e-001 1.35562420e+000 |2269.30813|
4.76140659e-001 2.46609015e+000 6.66090153e-001 -3.30267297e-002 1.46609015e+000 |1194.05971|
8.91708182e-001 1.58058120e+000 7.70530692e-001 -1.32232944e-001 1.57053069e+000 |1610.13537|
5.55506383e-001 1.82703539e+000 7.05857896e-001 3.09948402e-001 1.50585790e+000 |845.63639|
4.46348806e-001 1.82648941e+000 9.76840926e-001 -6.71177918e-002 7.86891432e-001 |1533.36367|
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1.01781385e+000 1.58793094e+000 7.18578497e-001 -4.43482444e-002 1.58035135e+000 |1036.91467|
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80	1.16257357e+000	1.96003086e+000	3.37990062e−001	2.62861915e−002	9.08498291e−001	|102.83785|
81	1.24550882e+000	1.95864741e+000	3.38528230e−001	1.94870818e−002	8.49109848e−001	|110.57505|
82	1.03137002e+000	1.86722749e+000	2.76715930e−001	2.71394632e−002	1.02167700e+000	|99.12920|
83	9.90444250e−001	1.79824938e+000	2.32140345e−001	2.32324559e−002	1.06508243e+000	|106.75371|
84	1.11954124e+000	1.91958549e+000	3.11527632e−001	2.55227576e−002	9.47644326e−001	|98.80697|
85	1.02088277e+000	1.90274217e+000	2.51204498e−001	2.45463391e−002	1.03145539e+000	|101.57311|
86	1.04779628e+000	1.89551596e+000	2.67606403e−001	2.46921492e−002	1.00951709e+000	|98.18442|
87	1.04054160e+000	1.96463303e+000	2.71715809e−001	2.08152654e−002	9.87230709e−001	|97.21967|
88	1.01509936e+000	2.02903781e+000	2.63522511e−001	1.73880720e−002	9.83798312e−001	|101.29178|
89	1.03908912e+000	1.93041235e+000	2.85887801e−001	2.67670254e−002	1.01293931e+000	|96.15644|
90	1.01967112e+000	1.94708375e+000	2.92182868e−001	2.94205387e−002	1.03252354e+000	|99.26819|
91	1.08873188e+000	1.98552835e+000	2.86138288e−001	2.09385858e−002	9.61538075e−001	|98.63889|
92	9.88236913e−001	1.95954749e+000	2.41170848e−001	2.07216227e−002	1.04112825e+000	|101.78820|
93	1.08671516e+000	1.92957599e+000	2.93938436e−001	2.43224739e−002	9.71015308e−001	|96.70100|
94	1.01823959e+000	1.87122369e+000	2.69680251e−001	2.66593497e−002	1.03102540e+000	|98.37063|
95	1.03586266e+000	1.89979985e+000	2.73794760e−001	2.52291587e−002	1.01365357e+000	|96.54570|
96	1.05440173e+000	1.96294963e+000	2.90687480e−001	2.31205902e−002	9.84700973e−001	|95.45476|
97	1.05770446e+000	1.99666647e+000	3.02228019e−001	2.23348106e−002	9.72292914e−001	|97.25269|
98	1.04935760e+000	1.95320558e+000	2.96011815e−001	2.57038804e−002	9.87109683e−001	|96.43438|
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100	1.04681343e+000	1.94991086e+000	2.79889934e−001	2.29219455e−002	9.90557239e−001	|95.45209|
101	1.00349466e+000	1.94893532e+000	2.76570280e−001	2.51745662e−002	1.02456900e+000	|95.72845|
102	1.04139996e+000	1.99836564e+000	2.97824164e−001	2.42460444e−002	9.86296915e−001	|94.67663|
103	1.04416861e+000	2.04764854e+000	3.09838865e−001	2.37544872e−002	9.72618589e−001	|95.07362|
104	1.02582942e+000	1.98273710e+000	2.81137929e−001	2.29915654e−002	1.00704436e+000	|93.79026|
105	1.01406532e+000	1.99750286e+000	2.73700986e−001	2.16354078e−002	1.01701170e+000	|93.87309|
106	1.02608838e+000	2.03236653e+000	2.86387216e−001	1.98757734e−002	9.82843691e−001	|97.24571|
107	1.03583894e+000	1.95590090e+000	2.86012655e−001	2.50442124e−002	1.00541540e+000	|94.65191|
108	1.07462055e+000	2.01662979e+000	2.99481688e−001	2.14160910e−002	9.63552562e−001	|94.16852|
109	1.03180100e+000	2.02408754e+000	2.88882171e−001	2.27882674e−002	9.94961225e−001	|92.20662|
110	1.02050064e+000	2.05465649e+000	2.87979517e−001	2.26221061e−002	1.00009135e+000	|90.87513|
111	1.02886420e+000	2.07902457e+000	3.02915551e−001	2.28669763e−002	9.92918604e−001	|91.41384|
112	1.02538725e+000	1.99383731e+000	2.70197293e−001	2.16794302e−002	1.01897726e+000	|94.55777|
113	1.02953625e+000	2.10075951e+000	2.87697359e−001	1.90437922e−002	9.91605186e−001	|92.25046|
114	1.04164753e+000	2.10559198e+000	3.10512746e−001	2.13543191e−002	9.67094501e−001	|92.90098|
115	9.79225025e−001	2.11838437e+000	2.85640775e−001	2.15929496e−002	1.02393597e+000	|89.02151|
116	9.31527263e−001	2.16926167e+000	2.78720319e−001	2.16813788e−002	1.05412768e+000	|87.27362|
117	1.00676503e+000	2.20621484e+000	3.13429211e−001	2.13920212e−002	9.85323229e−001	|88.96852|
118	9.65229817e−001	2.13837485e+000	2.77784036e−001	2.16881907e−002	1.04253192e+000	|87.20362|
119	9.27020959e−001	2.15476628e+000	2.61419680e−001	2.18551265e−002	1.08025063e+000	|88.27117|
120	9.51618531e−001	2.15825345e+000	2.96634094e−001	2.50564770e−002	1.03839193e+000	|91.15061|
121	9.21392314e−001	2.21167995e+000	2.78903320e−001	2.21090933e−002	1.05526784e+000	|84.86871|
122	8.67656373e−001	2.27800763e+000	2.66897205e−001	2.17301517e−002	1.08644246e+000	|82.96770|
123	9.65053118e−001	2.18035274e+000	2.73290020e−001	1.85890624e−002	1.02901473e+000	|89.44571|
124	8.73992001e−001	2.33422820e+000	2.76068799e−001	1.94102158e−002	1.07888465e+000	|82.12092|
125	8.00737682e−001	2.47401405e+000	2.70113441e−001	1.78042707e−002	1.11828131e+000	|80.13609|
126	8.63713348e−001	2.32599647e+000	2.89487664e−001	2.31293429e−002	1.08566791e+000	|87.37573|
127	7.64780763e−001	2.34804703e+000	2.39771855e−001	2.10213128e−002	1.16949728e+000	|83.09388|
128	8.68259411e−001	2.23708562e+000	2.43827078e−001	1.84407790e−002	1.10268435e+000	|91.54705|
129	8.64849864e−001	2.30376876e+000	2.78072517e−001	2.19572019e−002	1.08992202e+000	|83.38782|
130	7.73774537e−001	2.44762326e+000	2.54335302e−001	1.99990723e−002	1.14854231e+000	|82.15361|
131	6.63489870e−001	2.60220945e+000	2.45892092e−001	1.93166131e−002	1.20254223e+000	|79.98968|
132	5.12619897e−001	2.83412674e+000	2.29946121e−001	1.81308243e−002	1.28254739e+000	|87.87472|
133	6.83325826e−001	2.55619181e+000	2.32731441e−001	1.79913663e−002	1.20020022e+000	|90.14993|
134	8.19468854e−001	2.36687452e+000	2.66737248e−001	2.09657430e−002	1.11749157e+000	|80.79900|
135	8.05270163e−001	2.51944453e+000	2.81818260e−001	1.89050276e−002	1.09982267e+000	|79.84696|
136	8.25514863e−001	2.60514328e+000	3.02841463e−001	1.78468850e−002	1.06498537e+000	|82.91697|
137	6.77440070e−001	2.68605869e+000	2.60661333e−001	1.70661390e−002	1.18822958e+000	|79.04992|
138	5.82331919e−001	2.89008422e+000	2.57543397e−001	1.47341326e−002	1.23912314e+000	|82.14316|
139	7.32788119e−001	2.61181723e+000	2.75753648e−001	1.76240450e−002	1.14200463e+000	|82.26521|
140	7.63527933e−001	2.48867175e+000	2.59689889e−001	1.94053155e−002	1.14690789e+000	|79.74525|
141	6.64717433e−001	2.74128487e+000	2.60532758e−001	1.60332033e−002	1.18482190e+000	|80.01213|
142	6.29040506e−001	2.74105367e+000	2.53324292e−001	1.84862487e−002	1.21064840e+000	|81.89027|
143	7.57813388e−001	2.54077395e+000	2.65916154e−001	1.79747652e−002	1.14137308e+000	|79.00067|
144	8.02299137e−001	2.39357848e+000	2.65058333e−001	2.10339408e−002	1.12672828e+000	|80.40520|
145	6.99112859e−001	2.65435827e+000	2.61664152e−001	1.72833877e−002	1.17029850e+000	|79.03635|
146	8.17775895e−001	2.55351343e+000	2.86007823e−001	1.69372409e−002	1.09611046e+000	|80.05473|
147	7.02061376e−001	2.59003544e+000	2.55921025e−001	1.87217700e−002	1.17593429e+000	|78.97988|
148	6.34712087e−001	2.66451471e+000	2.39722760e−001	1.72755234e−002	1.22927466e+000	|82.43345|
149	7.62630644e−001	2.55571208e+000	2.71294385e−001	1.84976515e−002	1.13218567e+000	|78.97024|
150	6.76095402e−001	2.72210362e+000	2.66492931e−001	1.64121699e−002	1.17630055e+000	|79.74191|
151	6.97953535e−001	2.66374565e+000	2.64792170e−001	1.71604563e−002	1.16895239e+000	|78.97951|
152	7.70388651e−001	2.51579147e+000	2.67173821e−001	1.87890733e−002	1.12726799e+000	|79.09654|
153	7.00677215e−001	2.64349188e+000	2.62289455e−001	1.74968725e−002	1.17298918e+000	|78.81754|
154	7.49341605e−001	2.54314533e+000	2.66421124e−001	1.86572185e−002	1.14627535e+000	|78.90788|
155	6.87252362e−001	2.65767820e+000	2.62371110e−001	1.82388224e−002	1.17716167e+000	|78.98186|
156	7.04892619e−001	2.62845214e+000	2.63257371e−001	1.81728081e−002	1.16821452e+000	|78.78099|
157	7.44136871e−001	2.62378339e+000	2.75300777e−001	1.72722328e−002	1.13951255e+000	|79.56190|
158	7.12580250e−001	2.59847243e+000	2.60765963e−001	1.83593857e−002	1.16682885e+000	|78.73068|

159	7.54095398e−001	2.52396389e+000	2.64819149e−001	1.93131183e−002	1.14564504e+000	|78.98394|
160	7.11989001e−001	2.62880021e+000	2.64798915e−001	1.76986218e−002	1.16312555e+000	|78.78943|
161	6.69161632e−001	2.66123272e+000	2.55718746e−001	1.76563111e−002	1.19478771e+000	|78.85735|
162	6.50378682e−001	2.72103442e+000	2.56311056e−001	1.70963812e−002	1.20010298e+000	|79.56181|
163	7.24600874e−001	2.58761761e+000	2.63893607e−001	1.82670092e−002	1.15973226e+000	|78.71212|
164	7.52734352e−001	2.57350099e+000	2.70283379e−001	1.83415678e−002	1.13756843e+000	|78.89439|
165	6.90054812e−001	2.63929979e+000	2.59359904e−001	1.78276253e−002	1.18048289e+000	|78.74582|
166	7.16969807e−001	2.58956499e+000	2.62540849e−001	1.86333075e−002	1.16236445e+000	|78.72566|
167	7.07650344e−001	2.58856257e+000	2.59128163e−001	1.88054325e−002	1.17192364e+000	|78.72866|
168	7.15849816e−001	2.57295481e+000	2.59018023e−001	1.85842960e−002	1.16831831e+000	|78.67385|
169	7.21328414e−001	2.54520615e+000	2.56898349e−001	1.87900400e−002	1.16837021e+000	|78.75089|
170	7.41005624e−001	2.53556917e+000	2.62778738e−001	1.92321471e−002	1.15118411e+000	|78.87685|
171	7.02792515e−001	2.61336713e+000	2.60214613e−001	1.81787557e−002	1.17315820e+000	|78.68256|
172	7.14565092e−001	2.58235441e+000	2.61152139e−001	1.86281347e−002	1.16736989e+000	|78.68911|
173	7.22260898e−001	2.58978101e+000	2.63599530e−001	1.81111687e−002	1.16045360e+000	|78.74618|
174	7.11302982e−001	2.58886718e+000	2.60246004e−001	1.86318666e−002	1.16905613e+000	|78.68356|
175	7.10674705e−001	2.58849947e+000	2.59268905e−001	1.82827174e−002	1.17268946e+000	|78.65451|
176	7.07527154e−001	2.58796671e+000	2.57632934e−001	1.81074224e−002	1.17785197e+000	|78.69607|
177	6.97473170e−001	2.59079960e+000	2.56066267e−001	1.86552990e−002	1.18050454e+000	|78.67270|
178	7.00672183e−001	2.59944086e+000	2.56773386e−001	1.83050392e−002	1.17812077e+000	|78.77088|
179	7.11091865e−001	2.58662603e+000	2.60057451e−001	1.85473608e−002	1.17005761e+000	|78.65529|
180	7.03849846e−001	2.59203164e+000	2.57604099e−001	1.82675050e−002	1.17683512e+000	|78.65213|
181	7.00123278e−001	2.59361387e+000	2.56283146e−001	1.80853242e−002	1.18072462e+000	|78.68731|
182	7.12783245e−001	2.55899748e+000	2.56591285e−001	1.87561155e−002	1.17420382e+000	|78.68121|
183	7.10285563e−001	2.57258990e+000	2.57497117e−001	1.86117756e−002	1.17394242e+000	|78.65591|
184	6.97500243e−001	2.59926384e+000	2.57179512e−001	1.83615671e−002	1.18129335e+000	|78.63277|
185	6.88325457e−001	2.61241835e+000	2.56260257e−001	1.82502026e−002	1.18778086e+000	|78.63864|
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189	7.06652901e−001	2.58331413e+000	2.57777821e−001	1.84930269e−002	1.17554580e+000	|78.64179|
190	6.93173030e−001	2.60012595e+000	2.55147749e−001	1.81794622e−002	1.18643602e+000	|78.68683|
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192	6.91965171e−001	2.59885311e+000	2.55760742e−001	1.85131731e−002	1.18438926e+000	|78.63026|
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197	6.73435385e−001	2.62439271e+000	2.54460773e−001	1.84907246e−002	1.19605650e+000	|78.66083|
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199	6.70170677e−001	2.61913894e+000	2.52655983e−001	1.85431915e−002	1.20005860e+000	|78.64989|
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208	6.99688111e−001	2.58801590e+000	2.57338681e−001	1.87444598e−002	1.17901543e+000	|78.64015|
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210	6.89337493e−001	2.60086931e+000	2.55696663e−001	1.84726057e−002	1.18663618e+000	|78.61648|
211	6.85255346e−001	2.60266121e+000	2.54901738e−001	1.84702399e−002	1.18963986e+000	|78.61626|
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<tr><td>435</td><td>6.14852523e−001</td><td>2.62915805e+000</td><td>2.38828456e−001</td><td>1.86764198e−002</td><td>1.18321914e+000</td><td>|78.57397|</td></tr>
<tr><td>436</td><td>6.14457567e−001</td><td>2.62956161e+000</td><td>2.38773638e−001</td><td>1.86756788e−002</td><td>1.18315473e+000</td><td>|78.57398|</td></tr>
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<tr><td>438</td><td>6.14241773e−001</td><td>2.62939917e+000</td><td>2.38699650e−001</td><td>1.86793073e−002</td><td>1.18324073e+000</td><td>|78.57397|</td></tr>
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<tr><td>441</td><td>6.14584864e−001</td><td>2.62921718e+000</td><td>2.38772483e−001</td><td>1.86775941e−002</td><td>1.18322926e+000</td><td>|78.57397|</td></tr>
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90	1.02250184e+000	1.17424747e+000	1.96686364e−001	1.61972525e−002	9.74076492e−001	|185.14855|
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114	1.02206029e+000	1.18040086e+000	1.99359965e−001	1.47939877e−002	9.86353567e−001	|183.87897|
115	1.02540060e+000	1.18472096e+000	1.99681492e−001	1.45007969e−002	9.94025762e−001	|183.18502|
116	1.02926690e+000	1.18887463e+000	1.98678463e−001	1.36882648e−002	9.99899176e−001	|182.98945|
117	1.02389096e+000	1.18412323e+000	2.01736475e−001	1.53903812e−002	9.95369373e−001	|183.17262|
118	1.02531139e+000	1.18442624e+000	2.03003058e−001	1.57878029e−002	9.95584336e−001	|183.47255|
119	1.02718411e+000	1.17936996e+000	2.09504924e−001	1.57698198e−002	1.00197623e+000	|182.58723|
120	1.03012595e+000	1.17617111e+000	2.16459663e−001	1.61498664e−002	1.00988656e+000	|182.16280|
121	1.03907530e+000	1.18649358e+000	2.01010724e−001	1.43180009e−002	1.00507739e+000	|182.47221|
122	1.03165443e+000	1.19055304e+000	2.06646363e−001	1.44238034e−002	1.01357084e+000	|181.55642|
123	1.03377476e+000	1.19708833e+000	2.09115050e−001	1.37807436e−002	1.02597832e+000	|180.73536|
124	1.03714215e+000	1.18867411e+000	2.07797092e−001	1.35430999e−002	1.01889999e+000	|181.56853|
125	1.04386307e+000	1.19079746e+000	2.11487921e−001	1.32016090e−002	1.02852720e+000	|180.67968|
126	1.05384912e+000	1.19413458e+000	2.16363644e−001	1.21072229e−002	1.04510612e+000	|180.26707|
127	1.04832001e+000	1.18815005e+000	2.21620006e−001	1.42713087e−002	1.04208018e+000	|179.27018|
128	1.05784657e+000	1.18778776e+000	2.33090777e−001	1.45628306e−002	1.06317068e+000	|177.92219|
129	1.04602012e+000	1.19104877e+000	2.32119767e−001	1.37395045e−002	1.06013928e+000	|179.29303|
130	1.06132714e+000	1.20732231e+000	2.22934869e−001	1.09434942e−002	1.07543120e+000	|179.22355|
131	1.06398493e+000	1.20227859e+000	2.37652551e−001	1.25104184e−002	1.08903024e+000	|176.51145|
132	1.07740632e+000	1.20908083e+000	2.52580280e−001	1.19940777e−002	1.12409537e+000	|174.37362|
133	1.08480495e+000	1.19866138e+000	2.53720685e−001	1.15581084e−002	1.12119873e+000	|175.53680|
134	1.07711292e+000	1.20342584e+000	2.61414907e−001	1.30119833e−002	1.13250798e+000	|174.01115|
135	1.08874482e+000	1.20807147e+000	2.83940538e−001	1.34643634e−002	1.17620892e+000	|172.14802|
136	1.10203180e+000	1.21332073e+000	2.66387093e−001	1.12696452e−002	1.16390268e+000	|171.71837|
137	1.13003764e+000	1.22445670e+000	2.83520756e−001	1.00347156e−002	1.21578438e+000	|169.23197|
138	1.11420898e+000	1.20390095e+000	2.99806346e−001	1.37021441e−002	1.20475203e+000	|170.82600|
139	1.14023452e+000	1.22988077e+000	3.16336665e−001	9.73853309e−003	1.27364510e+000	|167.84435|
140	1.18142849e+000	1.25092728e+000	3.57959610e−001	7.32638432e−003	1.37888231e+000	|166.69731|
141	1.15192556e+000	1.23991352e+000	3.37402327e−001	1.10505657e−002	1.31869047e+000	|166.13086|
142	1.18548586e+000	1.26053959e+000	3.79243148e−001	1.07967944e−002	1.41743634e+000	|166.18321|
143	1.20255599e+000	1.25007757e+000	3.89207879e−001	1.01356830e−002	1.43313022e+000	|164.28507|
144	1.26513083e+000	1.27057593e+000	4.57521679e−001	9.20648568e−003	1.58764765e+000	|166.51185|
145	1.23674196e+000	1.26788936e+000	3.99954558e−001	7.33392516e−003	1.48378520e+000	|162.73267|
146	1.31074053e+000	1.29779831e+000	4.57961567e−001	4.26870604e−003	1.63757334e+000	|164.36235|
147	1.26029100e+000	1.29765525e+000	4.24148034e−001	4.54885686e−003	1.56685535e+000	|162.29194|
148	1.33333201e+000	1.34453241e+000	4.86318879e−001	−2.77867752e−005	1.74790700e+000	|167.61162|
149	1.29656368e+000	1.30637892e+000	4.96684535e−001	6.02194187e−003	1.69625139e+000	|162.95193|
150	1.29122691e+000	1.30208900e+000	4.77735652e−001	8.20849619e−003	1.66010109e+000	|173.09162|
151	1.20887810e+000	1.26371771e+000	3.87903620e−001	7.54691229e−003	1.44918700e+000	|162.78333|
152	1.29652643e+000	1.29374793e+000	4.59916302e−001	3.43813333e−003	1.63424732e+000	|163.63067|
153	1.31704447e+000	1.32167811e+000	4.78234941e−001	1.42022478e−003	1.69900028e+000	|165.99374|
154	1.23117811e+000	1.26797770e+000	4.11464645e−001	7.95681846e−003	1.49959774e+000	|162.31695|
155	1.19693471e+000	1.26769965e+000	3.88145855e−001	9.92524853e−003	1.44402335e+000	|164.92187|
156	1.27162850e+000	1.28723586e+000	4.41973690e−001	5.05991213e−003	1.58669133e+000	|162.06488|
157	1.18692338e+000	1.24741143e+000	3.29493284e−001	6.95662809e−003	1.33819526e+000	|165.63964|
158	1.26915361e+000	1.29163705e+000	4.54886722e−001	6.25561343e−003	1.60673736e+000	|161.88146|

159	1.29871918e+000	1.30124038e+000	4.65067439e−001	4.91513813e−003	1.64827978e+000	|163.20163|
160	1.23133837e+000	1.27309838e+000	4.07194575e−001	6.88896875e−003	1.49896020e+000	|162.01877|
161	1.26869387e+000	1.29915233e+000	4.55912509e−001	4.95014269e−003	1.61975159e+000	|162.40089|
162	1.26070590e+000	1.29133659e+000	4.41923021e−001	5.54608831e−003	1.58575999e+000	|161.89302|
163	1.28606883e+000	1.30840755e+000	4.56585773e−001	3.36295732e−003	1.63840395e+000	|163.31343|
164	1.24490079e+000	1.27808516e+000	4.22744927e−001	6.80835318e−003	1.53429929e+000	|161.83523|
165	1.25079987e+000	1.27090196e+000	4.33341140e−001	7.67471745e−003	1.55812392e+000	|161.82628|
166	1.24605430e+000	1.25752532e+000	4.52937693e−001	9.23764775e−003	1.55375820e+000	|162.48010|
167	1.23113091e+000	1.27478780e+000	4.26062464e−001	8.20958432e−003	1.52686097e+000	|162.23167|
168	1.26150410e+000	1.28412385e+000	4.37995884e−001	5.84733018e−003	1.57173374e+000	|161.77702|
169	1.28348734e+000	1.29333547e+000	4.73162102e−001	5.96387227e−003	1.64370152e+000	|162.02365|
170	1.24437561e+000	1.27815765e+000	4.23686457e−001	6.65769463e−003	1.53514553e+000	|161.78104|
171	1.24758770e+000	1.26982568e+000	4.31139031e−001	7.75139524e−003	1.53665594e+000	|162.11356|
172	1.25742635e+000	1.28595886e+000	4.39227024e−001	6.09741504e−003	1.57348398e+000	|161.73002|
173	1.23444908e+000	1.26725395e+000	4.11911450e−001	6.97859076e−003	1.50237723e+000	|162.08022|
174	1.26047748e+000	1.28554127e+000	4.44142904e−001	6.43635776e−003	1.58064732e+000	|161.73359|
175	1.26493257e+000	1.28378827e+000	4.52612437e−001	6.27705284e−003	1.59335450e+000	|161.70717|
176	1.27494846e+000	1.28663983e+000	4.67546192e−001	6.01140268e−003	1.62288211e+000	|161.85129|
177	1.26468657e+000	1.29612600e+000	4.35724742e−001	4.85162273e−003	1.58362211e+000	|162.07153|
178	1.25427154e+000	1.27720797e+000	4.41437040e−001	6.96894377e−003	1.56449847e+000	|161.70526|
179	1.27506921e+000	1.28849044e+000	4.62479659e−001	5.99314521e−003	1.61834168e+000	|161.78855|
180	1.25204901e+000	1.28074085e+000	4.33384757e−001	6.49155727e−003	1.55594457e+000	|161.71313|
181	1.25415867e+000	1.28117105e+000	4.46325781e−001	7.06120050e−003	1.57543780e+000	|161.74033|
182	1.25599503e+000	1.28190925e+000	4.44243307e−001	6.75773292e−003	1.57451178e+000	|161.69645|
183	1.25339232e+000	1.27830081e+000	4.40218922e−001	6.60072298e−003	1.56407000e+000	|161.75145|
184	1.25870619e+000	1.28373116e+000	4.43161909e−001	6.47744906e−003	1.57650299e+000	|161.69634|
185	1.25695539e+000	1.27699214e+000	4.46708756e−001	7.09167931e−003	1.57244095e+000	|161.71242|
186	1.26429528e+000	1.28071067e+000	4.57880622e−001	6.93758589e−003	1.59657891e+000	|161.74290|
187	1.25511058e+000	1.28073330e+000	4.39508724e−001	6.60306443e−003	1.56610315e+000	|161.68781|
188	1.25865097e+000	1.28595584e+000	4.41676610e−001	6.14201790e−003	1.57754741e+000	|161.71817|
189	1.25737929e+000	1.27923306e+000	4.45450720e−001	6.85426396e−003	1.57371756e+000	|161.69001|
190	1.24765248e+000	1.27733762e+000	4.32908243e−001	7.18752881e−003	1.54877908e+000	|161.81602|
191	1.26061255e+000	1.28217561e+000	4.47686388e−001	6.50467184e−003	1.58221065e+000	|161.68107|
192	1.26084991e+000	1.28590498e+000	4.46583378e−001	6.30992911e−003	1.58471999e+000	|161.68611|
193	1.26106837e+000	1.28280200e+000	4.44713141e−001	6.34201844e−003	1.57878995e+000	|161.68217|
194	1.25930209e+000	1.28060843e+000	4.46415032e−001	6.56813004e−003	1.57771353e+000	|161.67521|
195	1.25960004e+000	1.27904706e+000	4.48041593e−001	6.61347053e−003	1.57831880e+000	|161.68445|
196	1.26139811e+000	1.28565666e+000	4.44511945e−001	6.07686159e−003	1.58209735e+000	|161.71285|
197	1.25838399e+000	1.28083896e+000	4.45216026e−001	6.65991336e−003	1.57581251e+000	|161.67876|
198	1.26497618e+000	1.28419869e+000	4.52736863e−001	6.35080069e−003	1.59359550e+000	|161.68824|
199	1.25757698e+000	1.28159965e+000	4.42815758e−001	6.53999849e−003	1.57297624e+000	|161.68012|
200	1.25792768e+000	1.27730488e+000	4.44155160e−001	6.73596376e−003	1.57028116e+000	|161.67393|
201	1.25646657e+000	1.27300483e+000	4.42941050e−001	6.94898109e−003	1.56306175e+000	|161.67900|
202	1.25645294e+000	1.27820901e+000	4.45802205e−001	6.86145256e−003	1.57280768e+000	|161.68617|
203	1.25991451e+000	1.28165375e+000	4.44985407e−001	6.47187697e−003	1.57729439e+000	|161.67690|
204	1.25662955e+000	1.27862666e+000	4.41748565e−001	6.68568122e−003	1.56742048e+000	|161.67399|
205	1.25928615e+000	1.27801342e+000	4.46192317e−001	6.70862765e−003	1.57443259e+000	|161.66838|
206	1.26014074e+000	1.27622031e+000	4.47880597e−001	6.79294223e−003	1.57516077e+000	|161.66489|
207	1.25918184e+000	1.27692665e+000	4.44857878e−001	6.64192432e−003	1.57133562e+000	|161.67164|
208	1.25735825e+000	1.27422101e+000	4.45037485e−001	6.89797966e−003	1.56747024e+000	|161.67266|
209	1.25719314e+000	1.27271138e+000	4.43056842e−001	6.93366643e−003	1.56295378e+000	|161.66854|
210	1.26009111e+000	1.27232703e+000	4.48246620e−001	6.91530934e−003	1.57146015e+000	|161.67148|
211	1.25965835e+000	1.27165767e+000	4.47476609e−001	6.93676503e−003	1.56907106e+000	|161.66518|
212	1.26114782e+000	1.27371620e+000	4.47569933e−001	6.79026328e−003	1.57252231e+000	|161.66087|
213	1.26304261e+000	1.27346379e+000	4.48836156e−001	6.73640509e−003	1.57504834e+000	|161.65800|
214	1.26086854e+000	1.26962543e+000	4.49340852e−001	7.08411093e−003	1.57014202e+000	|161.66025|
215	1.26027024e+000	1.27314440e+000	4.46389803e−001	6.87824654e−003	1.56949024e+000	|161.65439|
216	1.26035981e+000	1.27355308e+000	4.45461394e−001	6.85971514e−003	1.56850529e+000	|161.65346|
217	1.26443488e+000	1.27309674e+000	4.52541401e−001	6.83030894e−003	1.58021721e+000	|161.65346|
218	1.26805575e+000	1.27328942e+000	4.57283681e−001	6.77863019e−003	1.58884892e+000	|161.65922|
219	1.26388028e+000	1.27472607e+000	4.50147551e−001	6.78462790e−003	1.57855839e+000	|161.65786|
220	1.26489371e+000	1.26956573e+000	4.50650345e−001	6.92512497e−003	1.57382773e+000	|161.64084|
221	1.26727019e+000	1.26623844e+000	4.52035219e−001	6.99121635e−003	1.57316121e+000	|161.63067|
222	1.26672657e+000	1.27480582e+000	4.50267837e−001	6.59679844e−003	1.58005416e+000	|161.65299|
223	1.26602608e+000	1.27150427e+000	4.51345204e−001	6.88866161e−003	1.57715016e+000	|161.64671|
224	1.26604673e+000	1.26895327e+000	4.50512871e−001	6.88205229e−003	1.57307682e+000	|161.62850|
225	1.26712995e+000	1.26606688e+000	4.50695531e−001	6.93076449e−003	1.57033604e+000	|161.61541|
226	1.27227526e+000	1.26713178e+000	4.57292683e−001	6.83538479e−003	1.58386222e+000	|161.63151|
227	1.27133634e+000	1.26520214e+000	4.52113188e−001	6.86682134e−003	1.57360831e+000	|161.63308|
228	1.27088856e+000	1.25965158e+000	4.55124894e−001	7.20834099e−003	1.57119301e+000	|161.60504|
229	1.27296956e+000	1.25207446e+000	4.57553422e−001	7.51411226e−003	1.56676244e+000	|161.58817|
230	1.27436643e+000	1.25518121e+000	4.56530813e−001	7.16665808e−003	1.56994193e+000	|161.59161|
231	1.27026821e+000	1.25747497e+000	4.57529879e−001	7.30843305e−003	1.57201723e+000	|161.61526|
232	1.26852648e+000	1.25168261e+000	4.52445263e−001	7.52908890e−003	1.55702532e+000	|161.59310|
233	1.27403407e+000	1.24675360e+000	4.57866744e−001	7.58840637e−003	1.56127197e+000	|161.56403|
234	1.27741601e+000	1.23701118e+000	4.60782507e−001	7.88700137e−003	1.55532735e+000	|161.53802|
235	1.27828872e+000	1.23530290e+000	4.63241223e−001	8.03135298e−003	1.55809367e+000	|161.55567|
236	1.27835867e+000	1.23502597e+000	4.58691412e−001	7.94285238e−003	1.55084306e+000	|161.53581|
237	1.28240389e+000	1.22380147e+000	4.59272179e−001	8.26006205e−003	1.54025597e+000	|161.52048|
238	1.28565136e+000	1.22966588e+000	4.66506795e−001	8.01458580e−003	1.55912723e+000	|161.51557|

239	1.29421381e+000	1.21865752e+000	4.73537561e−001	8.25733424e−003	1.56017818e+000	|161.49706|
240	1.28775036e+000	1.21155780e+000	4.69223944e−001	8.81328709e−003	1.54230512e+000	|161.49096|
241	1.29444232e+000	1.18974610e+000	4.75570509e−001	9.63660159e−003	1.52848671e+000	|161.48133|
242	1.29773634e+000	1.18973321e+000	4.75408169e−001	9.31482863e−003	1.53017431e+000	|161.43804|
243	1.31011974e+000	1.15856258e+000	4.84335542e−001	1.02151868e−002	1.51188025e+000	|161.40746|
244	1.30514959e+000	1.17580865e+000	4.78158096e−001	9.67112145e−003	1.52035771e+000	|161.42252|
245	1.31711573e+000	1.14961935e+000	4.87567048e−001	1.05291211e−002	1.50913618e+000	|161.48021|
246	1.32601258e+000	1.13315620e+000	5.00395324e−001	1.10636840e−002	1.51175964e+000	|161.43033|
247	1.32692218e+000	1.10409963e+000	4.96873047e−001	1.21889517e−002	1.47247001e+000	|161.51084|
248	1.30239090e+000	1.19001805e+000	4.79371432e−001	9.24023862e−003	1.53825114e+000	|161.44096|
249	1.32987309e+000	1.13311984e+000	4.96360468e−001	1.06511392e−002	1.50806726e+000	|161.44957|
250	1.31230263e+000	1.16664678e+000	4.87881297e−001	9.80742696e−003	1.52699022e+000	|161.39106|
251	1.30989607e+000	1.17516050e+000	4.88038422e−001	9.44657990e−003	1.53591724e+000	|161.42805|
252	1.29251708e+000	1.19655707e+000	4.75696209e−001	9.34792394e−003	1.53562833e+000	|161.46828|
253	1.32053409e+000	1.14897914e+000	4.91194403e−001	1.03253354e−002	1.51495752e+000	|161.41050|
254	1.32725655e+000	1.12324330e+000	4.97414433e−001	1.11928632e−002	1.49612700e+000	|161.39894|
255	1.30413246e+000	1.17613998e+000	4.75198185e−001	9.42108952e−003	1.51636544e+000	|161.40989|
256	1.32458860e+000	1.13362007e+000	4.96251448e−001	1.07136393e−002	1.50617046e+000	|161.40138|
257	1.31082590e+000	1.15430594e+000	4.85237959e−001	1.02147469e−002	1.50805582e+000	|161.42238|
258	1.31810704e+000	1.15031084e+000	4.89705292e−001	1.02976883e−002	1.51323210e+000	|161.39278|
259	1.33281737e+000	1.11681345e+000	5.07037020e−001	1.14696323e−002	1.50539457e+000	|161.41524|
260	1.31130368e+000	1.16130835e+000	4.83157894e−001	9.93322522e−003	1.51362272e+000	|161.39342|
261	1.32730366e+000	1.13548915e+000	4.97428603e−001	1.05627504e−002	1.51057675e+000	|161.38537|
262	1.33589562e+000	1.12395243e+000	5.03975134e−001	1.07365322e−002	1.50992501e+000	|161.40652|
263	1.31392083e+000	1.16117930e+000	4.85983560e−001	1.00039423e−002	1.51804906e+000	|161.39024|
264	1.30591859e+000	1.18673047e+000	4.80248226e−001	9.04915003e−003	1.53686134e+000	|161.41434|
265	1.32192206e+000	1.13911509e+000	4.93122881e−001	1.06569349e−002	1.50631058e+000	|161.38501|
266	1.32611880e+000	1.13978812e+000	4.98490760e−001	1.05982719e−002	1.51644076e+000	|161.38888|
267	1.32252015e+000	1.14657653e+000	4.95457548e−001	1.03540423e−002	1.51811485e+000	|161.36976|
268	1.32472670e+000	1.14470938e+000	4.98333676e−001	1.03822194e−002	1.52055623e+000	|161.36171|
269	1.33329419e+000	1.12146563e+000	5.01462495e−001	1.10742206e−002	1.50178313e+000	|161.40082|
270	1.31755052e+000	1.15535149e+000	4.91276597e−001	1.01241254e−002	1.52068845e+000	|161.37928|
271	1.33312787e+000	1.12460199e+000	5.05477447e−001	1.09257785e−002	1.51178006e+000	|161.39113|
272	1.31872259e+000	1.15203497e+000	4.90857032e−001	1.02344014e−002	1.51648181e+000	|161.37919|
273	1.31797141e+000	1.15089191e+000	4.89916756e−001	1.01859006e−002	1.51340477e+000	|161.37383|
274	1.31305365e+000	1.16135199e+000	4.87974173e−001	1.00706823e−002	1.52039998e+000	|161.37474|
275	1.31488788e+000	1.16662081e+000	4.90220412e−001	9.74199667e−003	1.53030191e+000	|161.36817|
276	1.31819437e+000	1.15489213e+000	4.91644223e−001	1.01219547e−002	1.51976943e+000	|161.35453|
277	1.31851630e+000	1.15466245e+000	4.91828036e−001	1.01208694e−002	1.51930992e+000	|161.34221|
278	1.31693979e+000	1.15925965e+000	4.92452190e−001	9.96626599e−003	1.52510731e+000	|161.35233|
279	1.32416318e+000	1.14910569e+000	4.97126255e−001	1.00882186e−002	1.52307207e+000	|161.35851|
280	1.32172214e+000	1.15885128e+000	4.98067472e−001	9.93392737e−003	1.53393421e+000	|161.34297|
281	1.32753936e+000	1.14001457e+000	5.00902640e−001	1.04546036e−002	1.51848999e+000	|161.33412|
282	1.33386509e+000	1.12671144e+000	5.06243753e−001	1.08109071e−002	1.51258403e+000	|161.32872|
283	1.32135590e+000	1.15472682e+000	4.95953407e−001	9.98585602e−003	1.52504679e+000	|161.32129|
284	1.31967050e+000	1.15973555e+000	4.94763272e−001	9.78767434e−003	1.52729206e+000	|161.30929|
285	1.32012234e+000	1.15458246e+000	4.96215634e−001	1.01596391e−002	1.52421894e+000	|161.30390|
286	1.31810192e+000	1.15732084e+000	4.95760324e−001	1.01953494e−002	1.52479237e+000	|161.28713|
287	1.32781059e+000	1.14365298e+000	5.02212953e−001	1.03732251e−002	1.52205772e+000	|161.28129|
288	1.33324600e+000	1.13584965e+000	5.07093335e−001	1.05767046e−002	1.52053293e+000	|161.25887|
289	1.32763779e+000	1.13486070e+000	5.00208016e−001	1.06626746e−002	1.50787031e+000	|161.25398|
290	1.33059562e+000	1.12286541e+000	5.01278288e−001	1.10270482e−002	1.49483836e+000	|161.22351|
291	1.33567536e+000	1.12633070e+000	5.10227552e−001	1.08382040e−002	1.51270599e+000	|161.20970|
292	1.34425488e+000	1.11216483e+000	5.19427310e−001	1.11968713e−002	1.50940402e+000	|161.16595|
293	1.32448248e+000	1.14846306e+000	5.01085258e−001	1.03025521e−002	1.51815987e+000	|161.14401|
294	1.31979117e+000	1.15933887e+000	4.98506010e−001	1.00483746e−002	1.52094780e+000	|161.06528|
295	1.33872533e+000	1.11528029e+000	5.14062835e−001	1.14300649e−002	1.50091413e+000	|161.10676|
296	1.34854328e+000	1.10087877e+000	5.20386787e−001	1.15162760e−002	1.49386252e+000	|161.05188|
297	1.36376396e+000	1.07265774e+000	5.32700018e−001	1.21767393e−002	1.47839760e+000	|161.01329|
298	1.34560639e+000	1.09707321e+000	5.19296450e−001	1.17749347e−002	1.48126784e+000	|160.93139|
299	1.35178658e+000	1.07768499e+000	5.25398007e−001	1.23740498e−002	1.46163529e+000	|160.80638|
300	1.35673315e+000	1.09198528e+000	5.34759384e−001	1.18633918e−002	1.49368117e+000	|160.80279|
301	1.36980192e+000	1.07654522e+000	5.51499933e−001	1.22815635e−002	1.49310258e+000	|160.65990|
302	1.35329270e+000	1.08843802e+000	5.29439411e−001	1.21274455e−002	1.47259493e+000	|160.61044|
303	1.35781160e+000	1.07657461e+000	5.34445462e−001	1.25927326e−002	1.45419038e+000	|160.36312|
304	1.36645676e+000	1.06984029e+000	5.42956938e−001	1.23593190e−002	1.46239533e+000	|160.40205|
305	1.40405716e+000	9.89982267e−001	5.76294133e−001	1.46653871e−002	1.41894068e+000	|160.63626|
306	1.37620165e+000	1.04359321e+000	5.59537771e−001	1.35324815e−002	1.43770810e+000	|160.01754|
307	1.38242050e+000	1.02906094e+000	5.72956647e−001	1.42103526e−002	1.41736336e+000	|159.57721|
308	1.40043259e+000	1.01911634e+000	5.85863238e−001	1.40696922e−002	1.43676164e+000	|159.93471|
309	1.39466953e+000	9.97284561e−001	5.73506634e−001	1.48774299e−002	1.38275798e+000	|159.65466|
310	1.35665923e+000	1.08676843e+000	5.47597434e−001	1.25784233e−002	1.44244680e+000	|159.56041|
311	1.33296027e+000	1.13516151e+000	5.33249085e−001	1.15349414e−002	1.45419986e+000	|159.49330|
312	1.38086104e+000	1.03303890e+000	5.77051489e−001	1.45547404e−002	1.39571396e+000	|159.08352|
313	1.38806319e+000	1.01463821e+000	5.94098764e−001	1.56524512e−002	1.36237327e+000	|158.72143|
314	1.40160683e+000	1.00153001e+000	6.09424286e−001	1.55452143e−002	1.36719206e+000	|158.33001|
315	1.42350444e+000	9.64007711e−001	6.46913697e−001	1.70214551e−002	1.32369289e+000	|157.62654|
316	1.36821458e+000	1.03694483e+000	5.82426694e−001	1.52489599e−002	1.33939331e+000	|158.43812|
317	1.36339566e+000	1.07464072e+000	5.98351321e−001	1.45898342e−002	1.37605110e+000	|158.26438|
318	1.36803475e+000	1.06109625e+000	6.09059178e−001	1.54087042e−002	1.32492081e+000	|157.90522|

319	1.43152477e+000	9.25369582e−001	6.79090776e−001	1.96336204e−002	1.23637269e+000	|157.79359|
320	1.39380650e+000	1.01018543e+000	6.52237902e−001	1.71085784e−002	1.27779905e+000	|156.96263|
321	1.39667815e+000	1.00795904e+000	6.81307471e−001	1.78366420e−002	1.23551194e+000	|156.70770|
322	1.42504053e+000	9.76284490e−001	7.03462284e−001	1.85471424e−002	1.25922647e+000	|156.55581|
323	1.45345351e+000	9.45954318e−001	7.63980079e−001	2.01962337e−002	1.21914305e+000	|157.22281|
324	1.45451740e+000	8.99246109e−001	7.29582041e−001	2.07891914e−002	1.17583883e+000	|157.19630|
325	1.48447136e+000	8.48050521e−001	7.67083330e−001	2.21225164e−002	1.16733632e+000	|158.62937|
326	1.39714391e+000	1.00783482e+000	6.48565216e−001	1.70871572e−002	1.28552469e+000	|157.08972|
327	1.40722900e+000	1.01676329e+000	6.84841507e−001	1.68790149e−002	1.27554523e+000	|155.88353|
328	1.39508111e+000	1.06246014e+000	6.87716872e−001	1.55017121e−002	1.29513150e+000	|155.98909|
329	1.40388000e+000	1.01750613e+000	7.33339856e−001	1.88832829e−002	1.17680048e+000	|157.10627|
330	1.35261208e+000	1.12957174e+000	6.52174638e−001	1.43531833e−002	1.32503920e+000	|158.77431|
331	1.42904107e+000	9.56827517e−001	7.10230190e−001	1.91801894e−002	1.21313892e+000	|156.17775|
332	1.41331391e+000	9.87040275e−001	6.39172957e−001	1.63778543e−002	1.33861293e+000	|157.48036|
333	1.40623848e+000	1.00988967e+000	7.09798131e−001	1.82569258e−002	1.21725359e+000	|156.35917|
334	1.42368783e+000	9.97533523e−001	7.48440764e−001	1.86418875e−002	1.20258028e+000	|155.22565|
335	1.43695979e+000	9.92382874e−001	7.98378537e−001	1.94192526e−002	1.16110808e+000	|154.69279|
336	1.44026624e+000	9.91178832e−001	7.62526935e−001	1.85254470e−002	1.22283149e+000	|154.90115|
337	1.41799414e+000	1.02881112e+000	7.63997983e−001	1.78062683e−002	1.18455896e+000	|155.10572|
338	1.44149846e+000	1.00277453e+000	7.79342076e−001	1.79162220e−002	1.21345399e+000	|153.67672|
339	1.45912845e+000	9.99216960e−001	8.14114049e−001	1.77458700e−002	1.21155419e+000	|152.59653|
340	1.43073082e+000	1.07279245e+000	8.20463560e−001	1.64192306e−002	1.21693476e+000	|154.28216|
341	1.47895067e+000	9.71292756e−001	8.96075554e−001	2.04647153e−002	1.10366349e+000	|153.56575|
342	1.48042025e+000	9.81934428e−001	8.72625471e−001	1.92235379e−002	1.18187784e+000	|153.09906|
343	1.47420976e+000	1.01586896e+000	9.18135933e−001	1.87835956e−002	1.12722385e+000	|151.72130|
344	1.49118152e+000	1.02821402e+000	9.95940432e−001	1.89126699e−002	1.07942004e+000	|150.97649|
345	1.49920490e+000	1.02899737e+000	9.61309089e−001	1.76871569e−002	1.15627205e+000	|150.42158|
346	1.53032745e+000	1.04730462e+000	1.04277436e+000	1.68211091e−002	1.15385404e+000	|149.71184|
347	1.54527251e+000	9.38392660e−001	1.02814839e+000	2.08479303e−002	1.07521307e+000	|154.11630|
348	1.51663709e+000	9.71992608e−001	9.76227181e−001	1.97407554e−002	1.11064349e+000	|151.58012|
349	1.51212723e+000	1.04017230e+000	9.84597045e−001	1.65128617e−002	1.19127635e+000	|150.03836|
350	1.52334045e+000	1.05282577e+000	1.05283576e+000	1.66697685e−002	1.11682141e+000	|148.83823|
351	1.54480055e+000	1.08827145e+000	1.14294090e+000	1.53928838e−002	1.08429319e+000	|148.98438|
352	1.57890108e+000	1.07116504e+000	1.24287792e+000	1.72062419e−002	1.03624066e+000	|148.60172|
353	1.63878740e+000	1.10713908e+000	1.45725986e+000	1.69364279e−002	9.48583890e−001	|151.86687|
354	1.54629804e+000	1.13805836e+000	1.18742508e+000	1.41975512e−002	1.10739021e+000	|152.03586|
355	1.52405233e+000	1.01350905e+000	1.02902666e+000	1.83549543e−002	1.10983017e+000	|149.52485|
356	1.58490194e+000	1.07595496e+000	1.18094632e+000	1.48025504e−002	1.15077772e+000	|150.24694|
357	1.56147183e+000	1.06401973e+000	1.13469485e+000	1.58300803e−002	1.13293830e+000	|148.97942|
358	1.58369406e+000	1.07353565e+000	1.25232883e+000	1.69292461e−002	1.01558619e+000	|148.15952|
359	1.61947748e+000	1.09021733e+000	1.38619473e+000	1.71374384e−002	9.27741112e−001	|149.87956|
360	1.58684049e+000	1.07689574e+000	1.27797330e+000	1.66642535e−002	9.97701370e−001	|147.31997|
361	1.61509701e+000	1.09169130e+000	1.39557277e+000	1.65858257e−002	9.19625037e−001	|147.53920|
362	1.62953349e+000	1.14196422e+000	1.43833945e+000	1.44227568e−002	9.65643177e−001	|148.53577|
363	1.64267844e+000	1.08867893e+000	1.44258463e+000	1.69967765e−002	9.43720156e−001	|151.65394|
364	1.56927002e+000	1.08837332e+000	1.21785183e+000	1.57938570e−002	1.04914993e+000	|147.89297|
365	1.62912643e+000	1.12267209e+000	1.48409347e+000	1.65450907e−002	8.61559695e−001	|149.85839|
366	1.57838548e+000	1.07868282e+000	1.22204451e+000	1.60088329e−002	1.06509365e+000	|148.00668|
367	1.61149094e+000	1.11853389e+000	1.36757703e+000	1.46899655e−002	9.69798539e−001	|147.64223|
368	1.55364152e+000	1.03836257e+000	1.14381054e+000	1.75803341e−002	1.04205816e+000	|147.62864|
369	1.58745993e+000	1.09272191e+000	1.28641384e+000	1.53342799e−002	1.00270394e+000	|147.45403|
370	1.58934286e+000	1.10231503e+000	1.30345634e+000	1.45367968e−002	9.96262808e−001	|148.82468|
371	1.59639829e+000	1.09319038e+000	1.34244590e+000	1.59848720e−002	9.28240592e−001	|147.51943|
372	1.61636506e+000	1.08542670e+000	1.39647620e+000	1.62762539e−002	8.95820575e−001	|147.10748|
373	1.63991258e+000	1.08395339e+000	1.48578838e+000	1.65174523e−002	8.19155898e−001	|149.04662|
374	1.57609378e+000	1.04202326e+000	1.25831066e+000	1.80146607e−002	9.45580782e−001	|147.26868|
375	1.64292410e+000	1.12365885e+000	1.52787721e+000	1.52980228e−002	8.34730206e−001	|149.04489|
376	1.57596217e+000	1.05968664e+000	1.23982720e+000	1.70097563e−002	9.90226174e−001	|146.93625|
377	1.56581468e+000	1.05752825e+000	1.21381675e+000	1.64621034e−002	9.85403787e−001	|147.18503|
378	1.57227996e+000	1.04176432e+000	1.21549196e+000	1.72539497e−002	9.99653510e−001	|146.55616|
379	1.56022079e+000	1.01605129e+000	1.15201500e+000	1.78884886e−002	1.03535997e+000	|146.89262|
380	1.57032266e+000	1.01156455e+000	1.21776449e+000	1.89262252e−002	9.38252579e−001	|147.79421|
381	1.58317561e+000	1.07243257e+000	1.26925150e+000	1.62322662e−002	9.86591097e−001	|146.79032|
382	1.58452154e+000	1.07442692e+000	1.25024400e+000	1.55328866e−002	1.01177986e+000	|146.80334|
383	1.60228339e+000	1.06568140e+000	1.30930881e+000	1.67137572e−002	9.82507282e−001	|146.96547|
384	1.54610035e+000	1.02988483e+000	1.09178241e+000	1.70746081e−002	1.10676518e+000	|148.00333|
385	1.59879888e+000	1.07154123e+000	1.32030275e+000	1.64758424e−002	9.48556726e−001	|146.54820|
386	1.55878821e+000	1.05197406e+000	1.18334737e+000	1.65419388e−002	1.00649825e+000	|147.19846|
387	1.59140960e+000	1.06225457e+000	1.27781845e+000	1.66708026e−002	9.88505023e−001	|146.61120|
388	1.59128840e+000	1.05899599e+000	1.26802547e+000	1.61103583e−002	9.98090895e−001	|146.19966|
389	1.59895152e+000	1.05865067e+000	1.28212461e+000	1.56606594e−002	1.00202326e+000	|146.11242|
390	1.62252207e+000	1.11967109e+000	1.40788153e+000	1.43404943e−002	9.39622415e−001	|147.61702|
391	1.57579611e+000	1.04195624e+000	1.21598163e+000	1.70014900e−002	1.01142558e+000	|146.42365|
392	1.59473114e+000	1.04830719e+000	1.29594757e+000	1.72835376e−002	9.63060815e−001	|146.39280|
393	1.60069929e+000	1.04065139e+000	1.28761850e+000	1.70046666e−002	9.78837464e−001	|146.14253|
394	1.59618118e+000	1.04218812e+000	1.28297158e+000	1.66996758e−002	9.73056513e−001	|145.70978|
395	1.59856697e+000	1.03215490e+000	1.28554814e+000	1.67141124e−002	9.65332258e−001	|145.38061|
396	1.58869913e+000	1.01714693e+000	1.22658543e+000	1.69899440e−002	1.01971502e+000	|145.77208|
397	1.61686311e+000	1.03680819e+000	1.33514807e+000	1.64596780e−002	9.60161946e−001	|145.31085|
398	1.63739661e+000	1.03423416e+000	1.39473130e+000	1.61887720e−002	9.34530129e−001	|145.10478|

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401 1.62280892e+000 9.95156733e-001 1.32084180e+000 1.67974088e-002 9.60112914e-001 |144.60122|
402 1.63473761e+000 9.63409764e-001 1.34020040e+000 1.73657836e-002 9.39157743e-001 |144.44937|
403 1.65147669e+000 1.01516561e+000 1.42182697e+000 1.56184601e-002 9.10198234e-001 |144.51840|
404 1.64012475e+000 1.00176251e+000 1.38894543e+000 1.71381227e-002 9.09884542e-001 |145.07744|
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406 1.67967000e+000 9.74442837e-001 1.50383072e+000 1.72272243e-002 8.44802533e-001 |146.22410|
407 1.63116320e+000 1.01223173e+000 1.34697939e+000 1.61115991e-002 9.59036461e-001 |144.77701|
408 1.60503455e+000 1.02711638e+000 1.30646165e+000 1.68628624e-002 9.50101067e-001 |145.19207|
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410 1.63440716e+000 9.69289112e-001 1.34144925e+000 1.69742962e-002 9.28913161e-001 |144.19582|
411 1.63291244e+000 9.36816588e-001 1.31480822e+000 1.73670583e-002 9.26104677e-001 |144.21696|
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414 1.63963040e+000 9.19984293e-001 1.34819021e+000 1.76617177e-002 8.87430298e-001 |144.45331|
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1.10367823e+000 1.99182344e+000 4.33752324e-001 3.77559374e-001 1.16228345e+000 |202.07622|
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81	1.08484951e+000	2.20236327e+000	3.12456681e−001	3.89441331e−001	8.74629176e−001	|140.13676|
82	1.08743902e+000	2.19755374e+000	3.13435075e−001	3.81377475e−001	8.82314306e−001	|140.02742|
83	1.08506692e+000	2.22991226e+000	3.11768464e−001	3.62125140e−001	8.69834347e−001	|140.10039|
84	1.07093731e+000	2.22780850e+000	3.03299518e−001	4.16492701e−001	8.54444591e−001	|140.45134|
85	1.09326418e+000	2.19711556e+000	3.16467495e−001	3.58100949e−001	8.91574084e−001	|139.99384|
86	1.08985576e+000	2.17166214e+000	3.14267488e−001	3.91394917e−001	8.97256721e−001	|140.06726|
87	1.09656384e+000	2.21703859e+000	3.21826240e−001	3.94232477e−001	8.86843928e−001	|140.02279|
88	1.09103498e+000	2.24438465e+000	3.17665615e−001	3.72433689e−001	8.70529110e−001	|140.05486|
89	1.09074018e+000	2.22620402e+000	3.16816083e−001	3.77173996e−001	8.77211013e−001	|139.99753|
90	1.09477219e+000	2.22995317e+000	3.19850431e−001	3.80769738e−001	8.83430207e−001	|139.92374|
91	1.09843877e+000	2.24615288e+000	3.23058110e−001	3.80465870e−001	8.83988158e−001	|139.88033|
92	1.08639735e+000	2.22211402e+000	3.11952014e−001	3.62408094e−001	8.77758278e−001	|140.03488|
93	1.09402221e+000	2.21830745e+000	3.19357684e−001	3.86276381e−001	8.84572515e−001	|139.97086|
94	1.08702065e+000	2.22314618e+000	3.16002906e−001	3.68029355e−001	8.82983085e−001	|139.88440|
95	1.09018510e+000	2.21238289e+000	3.17088995e−001	3.75141623e−001	8.90543849e−001	|139.88757|
96	1.08642947e+000	2.24757829e+000	3.17686183e−001	4.01030939e−001	8.75768684e−001	|139.89565|
97	1.10287110e+000	2.24728186e+000	3.27401048e−001	3.76461175e−001	8.90873205e−001	|139.86774|
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109	1.10618689e+000	2.38529223e+000	3.40924223e−001	3.59843616e−001	8.84337365e−001	|139.45736|
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124	1.09283738e+000	2.72860851e+000	3.72211577e−001	2.70836791e−001	8.94090530e−001	|138.95595|
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127	1.08063736e+000	2.69910852e+000	3.66697226e−001	2.34420913e−001	9.03641258e−001	|138.86197|
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129	1.06854198e+000	2.65375292e+000	3.56060671e−001	2.28731748e−001	9.06057333e−001	|138.75612|
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132	1.06114198e+000	2.76195885e+000	3.63981037e−001	1.97883664e−001	9.07264491e−001	|138.83740|
133	1.06654759e+000	2.60045631e+000	3.48205104e−001	2.36501523e−001	8.97679356e−001	|138.75996|
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138	1.04650876e+000	2.68607814e+000	3.51280926e−001	1.77917917e−001	9.12906167e−001	|138.71552|
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148	1.04532286e+000	2.50224506e+000	3.30894397e−001	2.32603972e−001	9.05425538e−001	|138.68067|
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152	1.04881965e+000	2.58800744e+000	3.38669509e−001	2.51032210e−001	8.87279351e−001	|138.76321|
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157	1.00732419e+000	2.45797505e+000	3.13380963e−001	1.83013152e−001	9.06942579e−001	|138.48541|
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425	−4.56073907e−002	2.88796500e+000	1.22825734e−001	−1.08964677e+000	9.12743938e−001	|137.16655|
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443	−1.56086539e−001	2.97284137e+000	1.15476930e−001	−1.26707530e+000	9.23933851e−001	|137.15458|
444	−2.07276480e−001	3.01293505e+000	1.11545620e−001	−1.31956391e+000	9.20762843e−001	|137.17758|
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448	−8.95022058e−002	2.93390028e+000	1.21747178e−001	−1.17945918e+000	9.22084516e−001	|137.16961|
449	−1.14734676e−001	2.93714423e+000	1.17852641e−001	−1.18867816e+000	9.16565584e−001	|137.13790|
450	−1.34639911e−001	2.94704381e+000	1.15922531e−001	−1.20623576e+000	9.14715334e−001	|137.13949|
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458	−1.19623194e−001	2.95687075e+000	1.19037628e−001	−1.21061730e+000	9.20369829e−001	|137.13738|
459	−1.48491637e−001	2.97007503e+000	1.16127801e−001	−1.23490584e+000	9.17402514e−001	|137.12419|
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461	−1.71673209e−001	2.98929174e+000	1.14519660e−001	−1.26813740e+000	9.18562213e−001	|137.12634|
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465	−2.16735277e−001	3.02873696e+000	1.11853117e−001	−1.32485796e+000	9.18494183e−001	|137.11456|
466	−2.62788532e−001	3.06630790e+000	1.08780044e−001	−1.38270854e+000	9.18498777e−001	|137.13340|
467	−1.87715662e−001	3.00881842e+000	1.14266102e−001	−1.28856557e+000	9.18389757e−001	|137.11251|
468	−1.95736888e−001	3.01858175e+000	1.14139322e−001	−1.29877965e+000	9.18303529e−001	|137.11493|
469	−1.99321131e−001	3.00617189e+000	1.12199955e−001	−1.28924119e+000	9.14994799e−001	|137.11797|
470	−1.91813264e−001	3.00455466e+000	1.13481137e−001	−1.29128861e+000	9.18019616e−001	|137.11580|
471	−2.18270735e−001	3.03129723e+000	1.11847571e−001	−1.32192978e+000	9.17040176e−001	|137.10787|
472	−2.44350379e−001	3.05562998e+000	1.10282003e−001	−1.35346496e+000	9.16536485e−001	|137.11337|
473	−2.40172309e−001	3.04529123e+000	1.10193772e−001	−1.34833356e+000	9.16954434e−001	|137.10485|
474	−2.77573405e−001	3.07466663e+000	1.07657967e−001	−1.39349050e+000	9.16521162e−001	|137.11279|
475	−2.22561768e−001	3.04130751e+000	1.12456724e−001	−1.34074900e+000	9.20564467e−001	|137.10781|
476	−2.42369036e−001	3.05762588e+000	1.10765777e−001	−1.35848574e+000	9.18557591e−001	|137.11784|
477	−2.04452207e−001	3.01782246e+000	1.12802297e−001	−1.30808789e+000	9.18154110e−001	|137.10870|
478	−2.12533795e−001	3.02907777e+000	1.12773469e−001	−1.31820836e+000	9.17946994e−001	|137.10803|

479	−2.51480664e−001	3.05710006e+000	1.09763432e−001	−1.36635787e+000	9.17874315e−001	|137.10091|
480	−2.83363165e−001	3.08124089e+000	1.07512096e−001	−1.40525401e+000	9.17616595e−001	|137.11089|
481	−2.53555501e−001	3.06380706e+000	1.10011690e−001	−1.37014353e+000	9.17998045e−001	|137.09963|
482	−2.78107148e−001	3.08679935e+000	1.08616386e−001	−1.40117136e+000	9.17920012e−001	|137.10472|
483	−2.61882595e−001	3.06644346e+000	1.08935806e−001	−1.38079713e+000	9.18225581e−001	|137.12557|
484	−2.24870995e−001	3.03841919e+000	1.11814053e−001	−1.33385555e+000	9.18016641e−001	|137.10192|
485	−2.58785760e−001	3.06707279e+000	1.09848298e−001	−1.38184602e+000	9.19522985e−001	|137.09607|
486	−2.79043273e−001	3.08496058e+000	1.08848662e−001	−1.41180415e+000	9.20764389e−001	|137.09382|
487	−2.77087329e−001	3.07452374e+000	1.07795919e−001	−1.39144887e+000	9.16078663e−001	|137.10203|
488	−2.74242796e−001	3.08223302e+000	1.09099730e−001	−1.40111043e+000	9.19338387e−001	|137.09160|
489	−2.91278039e−001	3.10070392e+000	1.08552709e−001	−1.42749886e+000	9.20530364e−001	|137.09048|
490	−2.43004060e−001	3.06347258e+000	1.11800299e−001	−1.37241512e+000	9.21994839e−001	|137.11107|
491	−2.68566512e−001	3.07176095e+000	1.08797014e−001	−1.38669043e+000	9.17557707e−001	|137.09529|
492	−3.12698601e−001	3.11291383e+000	1.06575349e−001	−1.45114238e+000	9.19873287e−001	|137.09685|
493	−3.10576107e−001	3.11655847e+000	1.07350738e−001	−1.45255387e+000	9.20815201e−001	|137.08765|
494	−3.40123828e−001	3.14628768e+000	1.06144391e−001	−1.49565188e+000	9.22285644e−001	|137.08748|
495	−3.43128600e−001	3.14284373e+000	1.05555560e−001	−1.49897154e+000	9.22406512e−001	|137.08509|
496	−3.87915149e−001	3.18236207e+000	1.03327496e−001	−1.56338555e+000	9.24610746e−001	|137.08746|
497	−3.14072120e−001	3.12151624e+000	1.07692760e−001	−1.46286997e+000	9.22426252e−001	|137.09939|
498	−3.13041980e−001	3.11506444e+000	1.06854702e−001	−1.45407428e+000	9.20511529e−001	|137.08897|
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515	−3.86759478e−001	3.17754768e+000	1.02974724e−001	−1.55224341e+000	9.21905665e−001	|137.07587|
516	−4.16864616e−001	3.20179622e+000	1.01251216e−001	−1.59140109e+000	9.22253268e−001	|137.07698|
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524	−3.64467487e−001	3.15509895e+000	1.03946264e−001	−1.52145874e+000	9.21284523e−001	|137.07679|
525	−3.85591643e−001	3.17432146e+000	1.02786469e−001	−1.54491226e+000	9.20240636e−001	|137.07196|
526	−3.86071302e−001	3.17401674e+000	1.02632622e−001	−1.54063335e+000	9.18811459e−001	|137.06966|
527	−3.87289543e−001	3.18038931e+000	1.03225853e−001	−1.55264775e+000	9.21681516e−001	|137.07175|
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532	−3.98595436e−001	3.18504451e+000	1.02083634e−001	−1.55562956e+000	9.18499103e−001	|137.06348|
533	−3.91839739e−001	3.17829852e+000	1.02301638e−001	−1.53937587e+000	9.16247199e−001	|137.06346|
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539	−4.15053568e−001	3.20064189e+000	1.01226871e−001	−1.56697123e+000	9.15552045e−001	|137.05823|
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609 −8.25530931e−001 3.58848704e+000 8.53720934e−002 −2.08516793e+000 9.12163055e−001 |137.00809|
610 −7.75224052e−001 3.53944870e+000 8.71859485e−002 −2.02461753e+000 9.13557546e−001 |137.00153|
611 −7.69934694e−001 3.53205854e+000 8.72727496e−002 −2.01611240e+000 9.13143128e−001 |137.00335|
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613 −7.97462546e−001 3.56202010e+000 8.64256861e−002 −2.05223974e+000 9.13165517e−001 |137.00316|
614 −8.23004599e−001 3.58277119e+000 8.53515755e−002 −2.08677794e+000 9.13759806e−001 |136.99903|
615 −8.64946634e−001 3.61946281e+000 8.36783431e−002 −2.13990224e+000 9.13553153e−001 |137.00604|
616 −7.59176060e−001 3.52289139e+000 8.77827889e−002 −2.00866489e+000 9.15030455e−001 |137.00247|
617 −8.27384651e−001 3.58321484e+000 8.48673956e−002 −2.08816092e+000 9.12628833e−001 |137.00367|
618 −8.07363696e−001 3.56567406e+000 8.58553976e−002 −2.06086960e+000 9.12115735e−001 |137.00017|
619 −7.55391987e−001 3.52295127e+000 8.82078835e−002 −2.00170491e+000 9.14257024e−001 |137.01160|
620 −8.09386485e−001 3.56814895e+000 8.57025175e−002 −2.06654692e+000 9.13035881e−001 |136.99837|
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622 −8.13558854e−001 3.56919163e+000 8.55210004e−002 −2.07447489e+000 9.13891166e−001 |136.99359|
623 −8.21607008e−001 3.57277740e+000 8.50686576e−002 −2.08559246e+000 9.14253991e−001 |136.99307|
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627 −8.19306157e−001 3.57813275e+000 8.54456984e−002 −2.08131269e+000 9.13586631e−001 |136.99619|
628 −8.17392593e−001 3.57475295e+000 8.54146432e−002 −2.08470395e+000 9.15419489e−001 |136.99737|
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631 −8.09066502e−001 3.56131140e+000 8.56825716e−002 −2.07887356e+000 9.17068931e−001 |136.99627|
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636 −8.25999071e−001 3.57131103e+000 8.46662392e−002 −2.09794910e+000 9.16470981e−001 |136.99254|
637 −8.56395212e−001 3.60174027e+000 8.36572640e−002 −2.13728902e+000 9.16430998e−001 |136.98640|
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639	−8.59588038e−001	3.60445488e+000	8.35104556e−002	−2.14620579e+000	9.17885442e−001	|136.99055|
640	−8.92187833e−001	3.62998742e+000	8.20183871e−002	−2.18561002e+000	9.17279196e−001	|136.99933|
641	−8.29926831e−001	3.58018979e+000	8.47715120e−002	−2.10247601e+000	9.16113235e−001	|136.98875|
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643	−8.38732560e−001	3.58493789e+000	8.42705487e−002	−2.11452092e+000	9.16450660e−001	|136.98812|
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645	−8.63212748e−001	3.60526545e+000	8.32822172e−002	−2.14333349e+000	9.15705430e−001	|136.98633|
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647	−8.59859934e−001	3.60098091e+000	8.34521819e−002	−2.14639805e+000	9.17961803e−001	|136.98778|
648	−8.20143915e−001	3.57266393e+000	8.52144735e−002	−2.08676701e+000	9.15127644e−001	|136.99148|
649	−8.72899476e−001	3.61269609e+000	8.28799162e−002	−2.16172019e+000	9.17533572e−001	|136.98636|
650	−8.97890806e−001	3.63151680e+000	8.17880535e−002	−2.19469325e+000	9.17918091e−001	|136.98758|
651	−9.12748375e−001	3.64540027e+000	8.12960187e−002	−2.21471728e+000	9.18167638e−001	|136.98771|
652	−8.77805162e−001	3.61295766e+000	8.25653053e−002	−2.16739439e+000	9.17487763e−001	|136.98931|
653	−8.83080821e−001	3.62227902e+000	8.25268636e−002	−2.17456149e+000	9.17442079e−001	|136.98604|
654	−9.12072956e−001	3.64588215e+000	8.12570457e−002	−2.20921223e+000	9.16744921e−001	|136.99278|
655	−8.72913190e−001	3.61220622e+000	8.29033979e−002	−2.16210159e+000	9.17657583e−001	|136.98587|
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657	−8.95373891e−001	3.63109649e+000	8.19860542e−002	−2.19099964e+000	9.17709495e−001	|136.98603|
658	−8.57101244e−001	3.60190051e+000	8.36433261e−002	−2.13839331e+000	9.16501172e−001	|136.98578|
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670	−8.99951721e−001	3.63904586e+000	8.20118762e−002	−2.19036237e+000	9.15604199e−001	|136.98280|
671	−9.12736494e−001	3.65121037e+000	8.15496832e−002	−2.20449348e+000	9.14886100e−001	|136.98393|
672	−9.01286802e−001	3.63876163e+000	8.19099984e−002	−2.19927114e+000	9.17821147e−001	|136.98531|
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676	−9.13268155e−001	3.65170627e+000	8.15980823e−002	−2.20823987e+000	9.15797878e−001	|136.98150|
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678	−9.15564382e−001	3.65411408e+000	8.15319313e−002	−2.21198199e+000	9.16023094e−001	|136.98186|
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680	−9.05091456e−001	3.64278121e+000	8.18254378e−002	−2.19981173e+000	9.16485762e−001	|136.98200|
681	−9.27526966e−001	3.66269244e+000	8.09922690e−002	−2.22577178e+000	9.15623521e−001	|136.98174|
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683	−9.35428085e−001	3.67187297e+000	8.08853011e−002	−2.23755930e+000	9.16024894e−001	|136.97898|
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685	−9.08405365e−001	3.64764028e+000	8.18003198e−002	−2.20067048e+000	9.15391464e−001	|136.98111|
686	−9.34985725e−001	3.67242920e+000	8.08977237e−002	−2.23387764e+000	9.15058578e−001	|136.98062|
687	−9.32281337e−001	3.66842239e+000	8.09375470e−002	−2.23046564e+000	9.15135440e−001	|136.97969|
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689	−9.40060250e−001	3.67729407e+000	8.07924025e−002	−2.24021071e+000	9.14982185e−001	|136.97809|
690	−9.53456297e−001	3.69008797e+000	8.03895626e−002	−2.25619613e+000	9.14574339e−001	|136.97681|
691	−9.62943413e−001	3.69833914e+000	8.00258622e−002	−2.26999036e+000	9.15061749e−001	|136.97784|
692	−9.47546128e−001	3.68391419e+000	8.05797138e−002	−2.25122828e+000	9.15395903e−001	|136.97634|
693	−9.53826329e−001	3.68965668e+000	8.04207088e−002	−2.25990360e+000	9.15564565e−001	|136.97521|
694	−9.58868513e−001	3.69641472e+000	8.03331551e−002	−2.26641547e+000	9.15490690e−001	|136.97477|
695	−9.72162101e−001	3.71041088e+000	8.00309592e−002	−2.28439038e+000	9.15668316e−001	|136.97290|
696	−9.88905989e−001	3.72201105e+000	7.92456370e−002	−2.30466251e+000	9.15417764e−001	|136.97367|
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698	−1.02792031e+000	3.76255749e+000	7.82970357e−002	−2.34996719e+000	9.13722252e−001	|136.97008|
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700	−1.01187579e+000	3.74815616e+000	7.89786175e−002	−2.33309118e+000	9.14844844e−001	|136.96900|
701	−1.02841991e+000	3.76302894e+000	7.83996206e−002	−2.35660982e+000	9.15512758e−001	|136.96587|
702	−1.06590171e+000	3.79949942e+000	7.74046497e−002	−2.40681667e+000	9.15981967e−001	|136.96206|
703	−1.07288003e+000	3.80739732e+000	7.71620508e−002	−2.41166757e+000	9.14689492e−001	|136.96721|
704	−1.07138999e+000	3.80919746e+000	7.75036882e−002	−2.40971069e+000	9.14544984e−001	|136.96295|
705	−1.12782503e+000	3.86031226e+000	7.57074576e−002	−2.48011094e+000	9.13845100e−001	|136.96266|
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707	−1.15408292e+000	3.88962261e+000	7.54598068e−002	−2.52490384e+000	9.16899329e−001	|136.95573|
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709	−1.05514586e+000	3.79068099e+000	7.78130741e−002	−2.38986656e+000	9.15018509e−001	|136.96320|
710	−1.11685817e+000	3.85232778e+000	7.63934197e−002	−2.47289591e+000	9.15826464e−001	|136.95810|
711	−1.15927727e+000	3.89370282e+000	7.51745347e−002	−2.52790866e+000	9.15820628e−001	|136.95812|
712	−1.17818805e+000	3.90898849e+000	7.45522592e−002	−2.55534372e+000	9.16804411e−001	|136.95573|
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714	−1.23422014e+000	3.96929493e+000	7.35819228e−002	−2.63161881e+000	9.17633573e−001	|136.95668|
715	−1.17082173e+000	3.90532838e+000	7.51749929e−002	−2.55201088e+000	9.18520091e−001	|136.95519|
716	−1.17659397e+000	3.91114115e+000	7.51752220e−002	−2.56406200e+000	9.19869822e−001	|136.96201|
717	−1.23482625e+000	3.96790366e+000	7.34687372e−002	−2.63866963e+000	9.19591706e−001	|136.96243|
718	−1.14635019e+000	3.88122175e+000	7.56622491e−002	−2.51433934e+000	9.16767774e−001	|136.95486|

719	−1.21156699e+000	3.94443827e+000	7.38860818e−002	−2.59625006e+000	9.15962052e−001	|136.95583|
720	−1.11018382e+000	3.84254487e+000	7.63122332e−002	−2.46552032e+000	9.16347889e−001	|136.95671|
721	−1.20321106e+000	3.93760741e+000	7.42645004e−002	−2.59009419e+000	9.17312152e−001	|136.95375|
722	−1.12949459e+000	3.86466918e+000	7.61594416e−002	−2.49842673e+000	9.18559451e−001	|136.95754|
723	−1.19104889e+000	3.92449600e+000	7.44544218e−002	−2.57179423e+000	9.16611402e−001	|136.95349|
724	−1.16801786e+000	3.90632197e+000	7.54541292e−002	−2.54591328e+000	9.17639888e−001	|136.95870|
725	−1.17564551e+000	3.90832186e+000	7.47777267e−002	−2.55298611e+000	9.17013280e−001	|136.95361|
726	−1.20074804e+000	3.93316755e+000	7.42737495e−002	−2.58758605e+000	9.17590551e−001	|136.95055|
727	−1.22408059e+000	3.95494002e+000	7.36807209e−002	−2.61892716e+000	9.17936162e−001	|136.94846|
728	−1.20531276e+000	3.93730644e+000	7.39608546e−002	−2.58724552e+000	9.15736217e−001	|136.95610|
729	−1.17944449e+000	3.91332289e+000	7.48714584e−002	−2.56081954e+000	9.17824122e−001	|136.95278|
730	−1.24302202e+000	3.97425353e+000	7.31572821e−002	−2.64350915e+000	9.17911073e−001	|136.95443|
731	−1.21885407e+000	3.95099558e+000	7.37835239e−002	−2.61121670e+000	9.17625248e−001	|136.95201|
732	−1.19241836e+000	3.92322313e+000	7.43626403e−002	−2.57620330e+000	9.17491933e−001	|136.94997|
733	−1.22669306e+000	3.95846919e+000	7.36833793e−002	−2.62259827e+000	9.17982267e−001	|136.94906|
734	−1.22554734e+000	3.95588433e+000	7.36982673e−002	−2.62411176e+000	9.18932492e−001	|136.94950|
735	−1.25559288e+000	3.98408201e+000	7.28119543e−002	−2.66040333e+000	9.18163118e−001	|136.94664|
736	−1.29366707e+000	4.01946157e+000	7.17822023e−002	−2.71019523e+000	9.18332616e−001	|136.94748|
737	−1.24610850e+000	3.97379571e+000	7.30993601e−002	−2.64959759e+000	9.18644939e−001	|136.94679|
738	−1.25973572e+000	3.98519578e+000	7.27572783e−002	−2.66878804e+000	9.19154785e−001	|136.94922|
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740	−1.34482121e+000	4.07108423e+000	7.08410774e−002	−2.78285140e+000	9.20113219e−001	|136.94585|
741	−1.30860084e+000	4.03521596e+000	7.15364287e−002	−2.72955609e+000	9.18271190e−001	|136.94540|
742	−1.35012759e+000	4.07488178e+000	7.04555094e−002	−2.78227826e+000	9.17940539e−001	|136.95397|
743	−1.34021823e+000	4.06332981e+000	7.06925364e−002	−2.77385272e+000	9.19336984e−001	|136.94497|
744	−1.39698081e+000	4.11576012e+000	6.91971150e−002	−2.84947995e+000	9.20014342e−001	|136.95972|
745	−1.38928574e+000	4.11021489e+000	6.94999211e−002	−2.83949405e+000	9.19943417e−001	|136.95538|
746	−1.26538188e+000	3.99375874e+000	7.26355209e−002	−2.67406888e+000	9.18437976e−001	|136.94538|
747	−1.30838519e+000	4.03541222e+000	7.17397672e−002	−2.73377545e+000	9.19589106e−001	|136.94418|
748	−1.31574426e+000	4.04338754e+000	7.17185496e−002	−2.74556555e+000	9.20217351e−001	|136.94928|
749	−1.38085444e+000	4.10572467e+000	6.98787721e−002	−2.82804423e+000	9.19654450e−001	|136.95868|
750	−1.27979498e+000	4.00677795e+000	7.22942131e−002	−2.69420925e+000	9.18897317e−001	|136.94399|
751	−1.25613124e+000	3.98271364e+000	7.27183091e−002	−2.65933356e+000	9.17699810e−001	|136.94397|
752	−1.21178626e+000	3.93852834e+000	7.36569250e−002	−2.59757464e+000	9.16493106e−001	|136.94694|
753	−1.27136377e+000	3.99758098e+000	7.24957100e−002	−2.68453985e+000	9.19313288e−001	|136.94559|
754	−1.29929157e+000	4.02580722e+000	7.17762490e−002	−2.71830203e+000	9.18531714e−001	|136.94360|
755	−1.32814660e+000	4.05185759e+000	7.10529090e−002	−2.75772032e+000	9.19183997e−001	|136.94051|
756	−1.35952897e+000	4.08090702e+000	7.02616031e−002	−2.79954604e+000	9.19557008e−001	|136.93933|
757	−1.26103456e+000	3.98931741e+000	7.28235202e−002	−2.66821381e+000	9.18372999e−001	|136.94706|
758	−1.32042231e+000	4.04482671e+000	7.12252824e−002	−2.74744299e+000	9.19095987e−001	|136.94221|
759	−1.29768243e+000	4.02100080e+000	7.15704955e−002	−2.71375810e+000	9.17923628e−001	|136.94332|
760	−1.33342762e+000	4.05532420e+000	7.07265625e−002	−2.76114384e+000	9.18225942e−001	|136.94317|
761	−1.38800992e+000	4.10843274e+000	6.95057679e−002	−2.83674364e+000	9.19633902e−001	|136.95140|
762	−1.28910091e+000	4.01414341e+000	7.19151738e−002	−2.70368608e+000	9.18183333e−001	|136.94209|
763	−1.34077333e+000	4.06067364e+000	7.05033979e−002	−2.77192879e+000	9.18662645e−001	|136.94018|
764	−1.35961882e+000	4.08134919e+000	7.02823124e−002	−2.79974099e+000	9.19566338e−001	|136.93944|
765	−1.33435011e+000	4.05743579e+000	7.09485453e−002	−2.76779412e+000	9.19800183e−001	|136.94015|
766	−1.35292654e+000	4.07297691e+000	7.03391306e−002	−2.78963542e+000	9.19211815e−001	|136.93717|
767	−1.36917866e+000	4.08705201e+000	6.98960547e−002	−2.81073163e+000	9.19269729e−001	|136.93522|
768	−1.41627904e+000	4.13282365e+000	6.88415915e−002	−2.87621055e+000	9.20559028e−001	|136.93965|
769	−1.39480891e+000	4.11515343e+000	6.95886449e−002	−2.84968054e+000	9.20838269e−001	|136.93789|
770	−1.42541565e+000	4.14147833e+000	6.85995373e−002	−2.88656978e+000	9.20115966e−001	|136.94037|
771	−1.35711650e+000	4.07844642e+000	7.03612933e−002	−2.79748803e+000	9.19879129e−001	|136.93837|
772	−1.31982170e+000	4.04433958e+000	7.13143718e−002	−2.74666435e+000	9.19085161e−001	|136.94061|
773	−1.39216471e+000	4.11070263e+000	6.94597866e−002	−2.84382400e+000	9.20190561e−001	|136.93770|
774	−1.38950028e+000	4.10755541e+000	6.95446407e−002	−2.84076710e+000	9.20327540e−001	|136.93567|
775	−1.40157866e+000	4.11865695e+000	6.92785650e−002	−2.85745048e+000	9.20645084e−001	|136.93500|
776	−1.42260350e+000	4.13753191e+000	6.87870459e−002	−2.88640270e+000	9.21189122e−001	|136.93425|
777	−1.43018593e+000	4.14475173e+000	6.85491758e−002	−2.89507435e+000	9.20846960e−001	|136.93350|
778	−1.46672065e+000	4.17790439e+000	6.76431171e−002	−2.94386751e+000	9.21330876e−001	|136.93310|
779	−1.42125821e+000	4.13314512e+000	6.85436131e−002	−2.88055663e+000	9.20084862e−001	|136.93222|
780	−1.43448285e+000	4.14214096e+000	6.80210972e−002	−2.89599468e+000	9.19708159e−001	|136.93202|
781	−1.44082967e+000	4.15017124e+000	6.80969957e−002	−2.90728145e+000	9.20539609e−001	|136.93064|
782	−1.46516215e+000	4.16990555e+000	6.74156002e−002	−2.93901017e+000	9.20714133e−001	|136.93059|
783	−1.47375885e+000	4.17825852e+000	6.71605254e−002	−2.94963558e+000	9.20557267e−001	|136.92947|
784	−1.51588813e+000	4.21361007e+000	6.59684677e−002	−3.00406981e+000	9.20672131e−001	|136.93174|
785	−1.53591254e+000	4.23524452e+000	6.57148996e−002	−3.03523263e+000	9.22130093e−001	|136.93350|
786	−1.52781131e+000	4.22384966e+000	6.55950499e−002	−3.01909353e+000	9.20587090e−001	|136.93754|
787	−1.44890545e+000	4.15911135e+000	6.79890469e−002	−2.91957540e+000	9.21038614e−001	|136.93106|
788	−1.37969944e+000	4.09568379e+000	6.95768551e−002	−2.82400071e+000	9.19209526e−001	|136.93394|
789	−1.49685926e+000	4.20035433e+000	6.66803885e−002	−2.98242465e+000	9.21399952e−001	|136.93028|
790	−1.46094678e+000	4.16200389e+000	6.72635462e−002	−2.93078868e+000	9.20036374e−001	|136.93203|
791	−1.46239025e+000	4.16597902e+000	6.73584389e−002	−2.93405839e+000	9.20360000e−001	|136.93020|
792	−1.50434753e+000	4.20730255e+000	6.66205027e−002	−2.99388700e+000	9.21919827e−001	|136.93031|
793	−1.51210176e+000	4.20960864e+000	6.61051354e−002	−3.00003091e+000	9.20941858e−001	|136.93028|
794	−1.51462091e+000	4.21469567e+000	6.61543962e−002	−3.00500443e+000	9.21357428e−001	|136.93071|
795	−1.47752684e+000	4.18110308e+000	6.71002992e−002	−2.95550874e+000	9.20874957e−001	|136.92972|
796	−1.46470725e+000	4.16681889e+000	6.71414122e−002	−2.93477631e+000	9.19733786e−001	|136.93177|
797	−1.49443746e+000	4.19718163e+000	6.67507301e−002	−2.97910933e+000	9.21373317e−001	|136.92950|
798	−1.44988730e+000	4.15954200e+000	6.79150175e−002	−2.92026376e+000	9.20884339e−001	|136.93093|

799	−1.49654815e+000	4.19709198e+000	6.65576059e−002	−2.98008912e+000	9.20927478e−001	|136.92957|
800	−1.46500535e+000	4.16749135e+000	6.72906513e−002	−2.93693581e+000	9.20237256e−001	|136.93141|
801	−1.48889579e+000	4.19213859e+000	6.68329542e−002	−2.97105244e+000	9.21109278e−001	|136.92951|
802	−1.51007659e+000	4.21233050e+000	6.64024070e−002	−3.00009969e+000	9.21576919e−001	|136.92899|
803	−1.53391976e+000	4.23550624e+000	6.59243910e−002	−3.03312034e+000	9.22185379e−001	|136.92953|
804	−1.50795989e+000	4.20969741e+000	6.63813898e−002	−2.99648572e+000	9.21342747e−001	|136.92968|
805	−1.50035163e+000	4.20254882e+000	6.65611172e−002	−2.98624148e+000	9.21225799e−001	|136.92929|
806	−1.49045998e+000	4.19589125e+000	6.69254876e−002	−2.97436628e+000	9.21409554e−001	|136.92954|
807	−1.49198202e+000	4.19619143e+000	6.68335172e−002	−2.97579699e+000	9.21289035e−001	|136.92926|
808	−1.49934683e+000	4.20246577e+000	6.66503645e−002	−2.98530078e+000	9.21299657e−001	|136.92876|
809	−1.50457235e+000	4.20762936e+000	6.65590697e−002	−2.99242496e+000	9.21394847e−001	|136.92845|
810	−1.49785911e+000	4.20160182e+000	6.66559245e−002	−2.98257015e+000	9.21044230e−001	|136.92967|
811	−1.49529287e+000	4.19828668e+000	6.67270287e−002	−2.97997453e+000	9.21291045e−001	|136.92909|
812	−1.52715134e+000	4.22853620e+000	6.60727305e−002	−3.02417948e+000	9.22153791e−001	|136.92907|
813	−1.51127844e+000	4.21464084e+000	6.64767841e−002	−3.00274878e+000	9.21856456e−001	|136.92886|
814	−1.52736662e+000	4.22837800e+000	6.60616908e−002	−3.02397399e+000	9.22020188e−001	|136.92873|
815	−1.53688526e+000	4.23831929e+000	6.59020442e−002	−3.03739623e+000	9.22309835e−001	|136.92862|
816	−1.50892037e+000	4.21198300e+000	6.64880678e−002	−2.99847798e+000	9.21509507e−001	|136.92829|
817	−1.49980488e+000	4.20370639e+000	6.66957364e−002	−2.98562722e+000	9.21187365e−001	|136.92805|
818	−1.52188644e+000	4.22473906e+000	6.62757231e−002	−3.01676878e+000	9.21930558e−001	|136.92841|
819	−1.52492778e+000	4.22646800e+000	6.61209216e−002	−3.01972769e+000	9.21680662e−001	|136.92782|
820	−1.53175245e+000	4.23238157e+000	6.59429903e−002	−3.02821714e+000	9.21592765e−001	|136.92738|
821	−1.51059393e+000	4.21433226e+000	6.64885347e−002	−3.00019974e+000	9.21345960e−001	|136.92752|
822	−1.49055876e+000	4.19479617e+000	6.68827775e−002	−2.97189891e+000	9.20670763e−001	|136.92773|
823	−1.51726623e+000	4.22035282e+000	6.63552351e−002	−3.00865976e+000	9.21296117e−001	|136.92716|
824	−1.52361316e+000	4.22671455e+000	6.62533177e−002	−3.01677716e+000	9.21246752e−001	|136.92681|
825	−1.50064284e+000	4.20403333e+000	6.66296196e−002	−2.98431929e+000	9.20486884e−001	|136.92671|
826	−1.49002104e+000	4.19368046e+000	6.68065678e−002	−2.96809454e+000	9.19765047e−001	|136.92651|
827	−1.51881086e+000	4.22105562e+000	6.62539388e−002	−3.00844777e+000	9.20661149e−001	|136.92587|
828	−1.52831384e+000	4.22973023e+000	6.60330401e−002	−3.01985805e+000	9.20398041e−001	|136.92493|
829	−1.54315901e+000	4.24393946e+000	6.57270027e−002	−3.04135975e+000	9.21068663e−001	|136.92500|
830	−1.53614987e+000	4.23624625e+000	6.58166328e−002	−3.02952291e+000	9.20282548e−001	|136.92468|
831	−1.54892784e+000	4.24720324e+000	6.54806819e−002	−3.04418450e+000	9.19750841e−001	|136.92398|
832	−1.52186151e+000	4.22412561e+000	6.61772538e−002	−3.00789246e+000	9.19298973e−001	|136.92392|
833	−1.51691604e+000	4.21999762e+000	6.62943855e−002	−2.99773012e+000	9.18152077e−001	|136.92384|
834	−1.52732195e+000	4.22710585e+000	6.58833535e−002	−3.01171362e+000	9.18407116e−001	|136.92364|
835	−1.52917634e+000	4.22730150e+000	6.56983713e−002	−3.00918185e+000	9.16987299e−001	|136.92488|
836	−1.57583443e+000	4.27351010e+000	6.49608176e−002	−3.07784387e+000	9.19345648e−001	|136.92128|
837	−1.61874113e+000	4.31342491e+000	6.40379425e−002	−3.13271854e+000	9.19135949e−001	|136.91870|
838	−1.55292931e+000	4.25104528e+000	6.53647586e−002	−3.04112218e+000	9.17268947e−001	|136.92429|
839	−1.57762066e+000	4.27378053e+000	6.47914087e−002	−3.07112953e+000	9.16687931e−001	|136.92292|
840	−1.56288174e+000	4.26155958e+000	6.52303502e−002	−3.06186834e+000	9.19584620e−001	|136.92177|
841	−1.57246477e+000	4.27114416e+000	6.50142943e−002	−3.06587957e+000	9.17036236e−001	|136.92063|
842	−1.62669606e+000	4.31880839e+000	6.36885542e−002	−3.13959371e+000	9.18188664e−001	|136.91964|
843	−1.65603980e+000	4.34838118e+000	6.32216665e−002	−3.17676226e+000	9.17846243e−001	|136.91602|
844	−1.72039873e+000	4.40901885e+000	6.18908230e−002	−3.25928658e+000	9.17565807e−001	|136.91437|
845	−1.66285231e+000	4.35580182e+000	6.31533769e−002	−3.19260916e+000	9.19916579e−001	|136.91692|
846	−1.71757946e+000	4.40571967e+000	6.18836462e−002	−3.25416668e+000	9.17152674e−001	|136.91627|
847	−1.76604230e+000	4.44996530e+000	6.08474429e−002	−3.32547030e+000	9.19747633e−001	|136.93161|
848	−1.62085915e+000	4.31584945e+000	6.39725814e−002	−3.13077725e+000	9.17714085e−001	|136.91764|
849	−1.70947625e+000	4.40111749e+000	6.22867938e−002	−3.24822957e+000	9.18405374e−001	|136.91156|
850	−1.75086635e+000	4.44227204e+000	6.15859137e−002	−3.30254749e+000	9.18513729e−001	|136.90871|
851	−1.77028127e+000	4.45803982e+000	6.09565940e−002	−3.32303633e+000	9.17209201e−001	|136.91784|
852	−1.73239623e+000	4.42188609e+000	6.17269311e−002	−3.27545688e+000	9.17690888e−001	|136.91346|
853	−1.81277808e+000	4.49802994e+000	6.01236949e−002	−3.38284946e+000	9.18621786e−001	|136.93087|
854	−1.66883888e+000	4.36139457e+000	6.30103598e−002	−3.19379530e+000	9.17941010e−001	|136.91450|
855	−1.77317955e+000	4.46031466e+000	6.08856926e−002	−3.32149201e+000	9.15629065e−001	|136.91402|
856	−1.74069244e+000	4.43223481e+000	6.17562419e−002	−3.28686462e+000	9.17783526e−001	|136.90867|
857	−1.75224893e+000	4.44549238e+000	6.16925398e−002	−3.30321359e+000	9.18098951e−001	|136.90667|
858	−1.82279703e+000	4.51019904e+000	6.01024002e−002	−3.39100332e+000	9.17058366e−001	|136.91557|
859	−1.70732842e+000	4.39859569e+000	6.22833699e−002	−3.24309731e+000	9.17720349e−001	|136.91192|
860	−1.76600907e+000	4.45840549e+000	6.13789558e−002	−3.31903634e+000	9.17495386e−001	|136.90629|
861	−1.78881424e+000	4.48309882e+000	6.11230222e−002	−3.34891122e+000	9.17460176e−001	|136.90381|
862	−1.71948212e+000	4.41622334e+000	6.24790181e−002	−3.26779858e+000	9.20164572e−001	|136.91032|
863	−1.75509979e+000	4.45238681e+000	6.19386143e−002	−3.31077040e+000	9.19092223e−001	|136.90788|
864	−1.79927615e+000	4.49719367e+000	6.12442733e−002	−3.37019921e+000	9.19611511e−001	|136.90480|
865	−1.81904007e+000	4.51195414e+000	6.05547272e−002	−3.38645818e+000	9.16946064e−001	|136.90249|
866	−1.86881905e+000	4.55981954e+000	5.95925818e−002	−3.44578798e+000	9.15336810e−001	|136.90492|
867	−1.81492533e+000	4.51377829e+000	6.10353571e−002	−3.38527355e+000	9.17969841e−001	|136.90379|
868	−1.83462210e+000	4.52822011e+000	6.03213535e−002	−3.40685190e+000	9.16942394e−001	|136.90269|
869	−1.87042223e+000	4.56820563e+000	6.00189536e−002	−3.45586403e+000	9.17473043e−001	|136.90071|
870	−1.92950887e+000	4.62956226e+000	5.91821605e−002	−3.53218925e+000	9.17160089e−001	|136.90533|
871	−1.85185343e+000	4.54490913e+000	5.99770921e−002	−3.42314434e+000	9.15105095e−001	|136.90344|
872	−1.88753102e+000	4.58372810e+000	5.96399712e−002	−3.47412558e+000	9.16314399e−001	|136.90004|
873	−1.93688940e+000	4.63404275e+000	5.88984456e−002	−3.53673277e+000	9.15741511e−001	|136.90256|
874	−1.89046221e+000	4.58102856e+000	5.91694819e−002	−3.47330407e+000	9.15142558e−001	|136.91358|
875	−1.83380955e+000	4.53059086e+000	6.05688883e−002	−3.40728118e+000	9.17263020e−001	|136.90089|
876	−1.84631655e+000	4.54417041e+000	6.04644654e−002	−3.42908800e+000	9.18870473e−001	|136.90160|
877	−1.86822567e+000	4.56723955e+000	6.01774488e−002	−3.45427489e+000	9.17804406e−001	|136.90043|
878	−1.90348193e+000	4.60561968e+000	5.97931636e−002	−3.50179529e+000	9.18144072e−001	|136.90236|

879	−1.88237147e+000	4.58220329e+000	5.99835545e−002	−3.47296101e+000	9.17844570e−001	|136.90063|
880	−1.89062742e+000	4.58861657e+000	5.96910611e−002	−3.47671467e+000	9.15809303e−001	|136.89993|
881	−1.91278285e+000	4.61083965e+000	5.93043590e−002	−3.50052801e+000	9.14278718e−001	|136.90185|
882	−1.92586157e+000	4.62540640e+000	5.92355074e−002	−3.52629490e+000	9.16835268e−001	|136.90169|
883	−1.85682255e+000	4.55429474e+000	6.02355431e−002	−3.43703461e+000	9.17156082e−001	|136.90005|
884	−1.88380902e+000	4.58222727e+000	5.98720779e−002	−3.47018028e+000	9.16498461e−001	|136.89942|
885	−1.89050242e+000	4.58923809e+000	5.97986401e−002	−3.47733840e+000	9.16011170e−001	|136.90000|
886	−1.87243480e+000	4.56823920e+000	5.98628863e−002	−3.45197100e+000	9.15588490e−001	|136.89979|
887	−1.88826426e+000	4.58360280e+000	5.95431670e−002	−3.46973557e+000	9.14742288e−001	|136.90132|
888	−1.87323532e+000	4.57133036e+000	6.00188783e−002	−3.45814006e+000	9.17038876e−001	|136.89959|
889	−1.90623248e+000	4.60336186e+000	5.93984069e−002	−3.49541803e+000	9.15343730e−001	|136.89953|
890	−1.88300460e+000	4.58178200e+000	5.98973530e−002	−3.46684403e+000	9.15797144e−001	|136.90021|
891	−1.88639941e+000	4.58324158e+000	5.97043166e−002	−3.47230520e+000	9.16185086e−001	|136.89947|
892	−1.87821700e+000	4.57474354e+000	5.98515653e−002	−3.46249115e+000	9.16452554e−001	|136.89887|
893	−1.87201178e+000	4.56780703e+000	5.99318174e−002	−3.45537939e+000	9.16774180e−001	|136.89888|
894	−1.89624040e+000	4.59494804e+000	5.97073126e−002	−3.48859818e+000	9.17147643e−001	|136.89911|
895	−1.90464192e+000	4.60130395e+000	5.94266942e−002	−3.49461237e+000	9.15740763e−001	|136.89849|
896	−1.92034523e+000	4.61629074e+000	5.91306021e−002	−3.51284853e+000	9.15091707e−001	|136.89855|
897	−1.87728986e+000	4.57444400e+000	5.99400438e−002	−3.46430660e+000	9.17335101e−001	|136.89907|
898	−1.89347911e+000	4.59104525e+000	5.97284249e−002	−3.48422000e+000	9.16953751e−001	|136.89913|
899	−1.89993753e+000	4.59558675e+000	5.95032024e−002	−3.49196080e+000	9.16822492e−001	|136.89750|
900	−1.90800178e+000	4.60226649e+000	5.93187646e−002	−3.50285106e+000	9.16984507e−001	|136.89672|
901	−1.89607652e+000	4.59125727e+000	5.94829913e−002	−3.48537351e+000	9.16379504e−001	|136.89840|
902	−1.89324967e+000	4.58587817e+000	5.94143751e−002	−3.47970545e+000	9.15878357e−001	|136.89798|
903	−1.91858413e+000	4.61095588e+000	5.89713764e−002	−3.51015657e+000	9.15108201e−001	|136.89826|
904	−1.94249114e+000	4.63485239e+000	5.85954264e−002	−3.54099466e+000	9.15002730e−001	|136.89844|
905	−1.90301607e+000	4.59379334e+000	5.91825714e−002	−3.49478397e+000	9.16649613e−001	|136.89727|
906	−1.86508012e+000	4.55880807e+000	5.99526051e−002	−3.44815357e+000	9.17397343e−001	|136.89895|
907	−1.92313839e+000	4.61584131e+000	5.89347211e−002	−3.51778439e+000	9.15601383e−001	|136.89743|
908	−1.92231950e+000	4.61223681e+000	5.88457321e−002	−3.51673907e+000	9.15709321e−001	|136.89677|
909	−1.90130603e+000	4.59305057e+000	5.93070893e−002	−3.49458900e+000	9.17221071e−001	|136.89692|
910	−1.92986304e+000	4.62099724e+000	5.88211763e−002	−3.53099354e+000	9.16988002e−001	|136.89541|
911	−1.94816972e+000	4.63855677e+000	5.85245770e−002	−3.55663759e+000	9.17542824e−001	|136.89457|
912	−1.90998685e+000	4.60012029e+000	5.91367727e−002	−3.50845589e+000	9.18041551e−001	|136.89698|
913	−1.93289749e+000	4.62469903e+000	5.88706029e−002	−3.53692507e+000	9.17550097e−001	|136.89551|
914	−1.93509096e+000	4.62820359e+000	5.88099337e−002	−3.53464082e+000	9.15961577e−001	|136.89591|
915	−1.95728575e+000	4.64933450e+000	5.84407548e−002	−3.56452844e+000	9.16278259e−001	|136.89454|
916	−1.98527561e+000	4.67747647e+000	5.80075875e−002	−3.59949817e+000	9.15806852e−001	|136.89477|
917	−1.95025878e+000	4.64498735e+000	5.87401210e−002	−3.56149413e+000	9.18017585e−001	|136.89529|
918	−1.98147930e+000	4.67204600e+000	5.80356311e−002	−3.59883936e+000	9.17155629e−001	|136.89316|
919	−2.01821806e+000	4.70693576e+000	5.73940644e−002	−3.64683352e+000	9.17241190e−001	|136.89330|
920	−1.98764096e+000	4.67760178e+000	5.79781143e−002	−3.61192668e+000	9.18690405e−001	|136.89284|
921	−2.01391597e+000	4.70230088e+000	5.75622046e−002	−3.65056960e+000	9.20054819e−001	|136.89319|
922	−2.02224182e+000	4.71214707e+000	5.73940859e−002	−3.65510024e+000	9.18103774e−001	|136.89584|
923	−1.95523357e+000	4.64656104e+000	5.85014736e−002	−3.56646886e+000	9.17688516e−001	|136.89392|
924	−2.00687044e+000	4.69248824e+000	5.74291087e−002	−3.63252108e+000	9.17504658e−001	|136.89285|
925	−2.03517628e+000	4.71623868e+000	5.67736026e−002	−3.66803456e+000	9.17248195e−001	|136.89554|
926	−2.03243979e+000	4.72049140e+000	5.72064655e−002	−3.66773101e+000	9.17964153e−001	|136.89115|
927	−2.07457482e+000	4.76145871e+000	5.65474098e−002	−3.72327772e+000	9.18174817e−001	|136.89140|
928	−2.07023940e+000	4.75456335e+000	5.65329497e−002	−3.72333987e+000	9.19987341e−001	|136.89319|
929	−2.11829390e+000	4.80053773e+000	5.56848213e−002	−3.78414785e+000	9.19496614e−001	|136.90322|
930	−1.99599865e+000	4.68505521e+000	5.77973105e−002	−3.62088861e+000	9.18140541e−001	|136.89205|
931	−2.04642166e+000	4.73141079e+000	5.69535289e−002	−3.69340524e+000	9.20303680e−001	|136.89188|
932	−2.06372603e+000	4.74768964e+000	5.65419184e−002	−3.70680341e+000	9.17589596e−001	|136.89164|
933	−2.00479724e+000	4.69267769e+000	5.75747609e−002	−3.62741855e+000	9.16697976e−001	|136.89166|
934	−2.06733692e+000	4.75482858e+000	5.67368627e−002	−3.71619633e+000	9.18857986e−001	|136.88942|
935	−2.09757015e+000	4.78599875e+000	5.63907396e−002	−3.75803396e+000	9.19534649e−001	|136.88927|
936	−2.11883731e+000	4.80263902e+000	5.58060325e−002	−3.78268694e+000	9.18779747e−001	|136.89125|
937	−2.09738056e+000	4.78477473e+000	5.61908155e−002	−3.74588300e+000	9.16007034e−001	|136.89238|
938	−2.05916138e+000	4.74475178e+000	5.67628506e−002	−3.70652468e+000	9.19229519e−001	|136.89024|
939	−2.16075063e+000	4.84433747e+000	5.52448195e−002	−3.84351213e+000	9.20625356e−001	|136.89901|
940	−2.04378559e+000	4.73059264e+000	5.69922755e−002	−3.68144195e+000	9.17679821e−001	|136.88997|
941	−2.09384568e+000	4.78248672e+000	5.64578048e−002	−3.75398269e+000	9.19769825e−001	|136.88982|
942	−2.09070522e+000	4.77712885e+000	5.64164715e−002	−3.74979036e+000	9.19822607e−001	|136.88874|
943	−2.09877042e+000	4.78496393e+000	5.63510023e−002	−3.76304668e+000	9.20646502e−001	|136.88985|
944	−2.03518991e+000	4.72574447e+000	5.74020243e−002	−3.67722251e+000	9.19634821e−001	|136.89204|
945	−2.09792546e+000	4.78341538e+000	5.62050305e−002	−3.75632083e+000	9.18993516e−001	|136.88938|
946	−2.11037146e+000	4.79909716e+000	5.62220782e−002	−3.77330324e+000	9.19090648e−001	|136.88836|
947	−2.13597649e+000	4.82626985e+000	5.59516919e−002	−3.80669252e+000	9.19021213e−001	|136.88858|
948	−2.16262361e+000	4.85152719e+000	5.55764198e−002	−3.84848620e+000	9.21176903e−001	|136.89187|
949	−2.07349510e+000	4.76082627e+000	5.66383116e−002	−3.72320301e+000	9.18554091e−001	|136.88882|
950	−2.10442329e+000	4.79096893e+000	5.61830933e−002	−3.76363358e+000	9.18600606e−001	|136.88745|
951	−2.10971210e+000	4.79521003e+000	5.60457375e−002	−3.76845903e+000	9.18015996e−001	|136.88679|
952	−2.10505817e+000	4.79475812e+000	5.63721504e−002	−3.76615072e+000	9.18985907e−001	|136.88815|
953	−2.10840868e+000	4.79567850e+000	5.61790055e−002	−3.76768430e+000	9.18225277e−001	|136.88650|
954	−2.11382794e+000	4.80051837e+000	5.60731385e−002	−3.77250947e+000	9.17570590e−001	|136.88581|
955	−2.14861687e+000	4.83672782e+000	5.57053643e−002	−3.82223783e+000	9.18812434e−001	|136.88580|
956	−2.18617776e+000	4.87467859e+000	5.52388907e−002	−3.87175525e+000	9.18941606e−001	|136.88511|
957	−2.16959576e+000	4.85944513e+000	5.54561721e−002	−3.84443643e+000	9.17191518e−001	|136.88572|
958	−2.13777220e+000	4.82357425e+000	5.57227437e−002	−3.80263184e+000	9.17261034e−001	|136.88476|

959	−2.13867005e+000	4.82222645e+000	5.56082696e−002	−3.80060149e+000	9.16380944e−001	|136.88593|
960	−2.18177613e+000	4.86661243e+000	5.50425226e−002	−3.85776609e+000	9.16606390e−001	|136.88331|
961	−2.22013511e+000	4.90253959e+000	5.43777087e−002	−3.90357377e+000	9.15416631e−001	|136.88423|
962	−2.22129141e+000	4.90909234e+000	5.47017240e−002	−3.90950367e+000	9.16536555e−001	|136.88275|
963	−2.27708107e+000	4.96603349e+000	5.40297172e−002	−3.98002599e+000	9.15796835e−001	|136.88299|
964	−2.28247682e+000	4.96999005e+000	5.38569545e−002	−3.98845984e+000	9.16272459e−001	|136.88396|
965	−2.27186142e+000	4.95528126e+000	5.38342338e−002	−3.97414224e+000	9.16283908e−001	|136.87978|
966	−2.32299426e+000	5.00319932e+000	5.30232646e−002	−4.03899514e+000	9.15830103e−001	|136.87930|
967	−2.31000602e+000	4.99145609e+000	5.31652648e−002	−4.01371939e+000	9.13289219e−001	|136.88510|
968	−2.27904896e+000	4.96226172e+000	5.36836713e−002	−3.97822835e+000	9.14702316e−001	|136.88185|
969	−2.41492229e+000	5.09803542e+000	5.18657828e−002	−4.15308140e+000	9.13946304e−001	|136.91136|
970	−2.20705972e+000	4.89218954e+000	5.47585035e−002	−3.89024423e+000	9.16432351e−001	|136.88197|
971	−2.32732921e+000	5.01493006e+000	5.33631357e−002	−4.04680765e+000	9.16196995e−001	|136.88074|
972	−2.28292847e+000	4.96545560e+000	5.36863624e−002	−3.98526071e+000	9.15310981e−001	|136.87991|
973	−2.29066318e+000	4.96918100e+000	5.33762578e−002	−3.99578844e+000	9.15592263e−001	|136.87882|
974	−2.29745423e+000	4.97075476e+000	5.30495281e−002	−4.00366966e+000	9.15489977e−001	|136.88090|
975	−2.39412591e+000	5.07382154e+000	5.20945733e−002	−4.12778789e+000	9.14620712e−001	|136.88210|
976	−2.25382627e+000	4.93759754e+000	5.40925209e−002	−3.94963014e+000	9.15979441e−001	|136.88020|
977	−2.31204760e+000	4.99388369e+000	5.33329453e−002	−4.02836448e+000	9.16861597e−001	|136.87723|
978	−2.32854691e+000	5.00969468e+000	5.31575824e−002	−4.05343255e+000	9.17941238e−001	|136.87757|
979	−2.26425442e+000	4.93912120e+000	5.35712595e−002	−3.96243514e+000	9.16064616e−001	|136.88119|
980	−2.31156052e+000	4.99597785e+000	5.34151667e−002	−4.02571452e+000	9.16163900e−001	|136.87856|
981	−2.36085106e+000	5.03980584e+000	5.25709326e−002	−4.09004640e+000	9.16355953e−001	|136.87511|
982	−2.41436346e+000	5.09090999e+000	5.18101385e−002	−4.16025453e+000	9.16544209e−001	|136.87432|
983	−2.38432286e+000	5.06212953e+000	5.22266015e−002	−4.12441337e+000	9.17517704e−001	|136.87622|
984	−2.36878852e+000	5.04795790e+000	5.25710341e−002	−4.10484622e+000	9.17673623e−001	|136.87496|
985	−2.43236973e+000	5.11348698e+000	5.18959515e−002	−4.19167603e+000	9.18744006e−001	|136.87419|
986	−2.50322301e+000	5.18563997e+000	5.11557983e−002	−4.28961983e+000	9.20319878e−001	|136.87860|
987	−2.45979608e+000	5.13369379e+000	5.12493565e−002	−4.22813455e+000	9.19204412e−001	|136.87234|
988	−2.53391386e+000	5.20255176e+000	5.01664515e−002	−4.32934457e+000	9.20724668e−001	|136.87950|
989	−2.49530935e+000	5.16957659e+000	5.07436505e−002	−4.27029733e+000	9.17932343e−001	|136.88250|
990	−2.37023752e+000	5.04966516e+000	5.25540994e−002	−4.10764874e+000	9.17939015e−001	|136.87447|
991	−2.43389926e+000	5.11215600e+000	5.18056305e−002	−4.19261067e+000	9.18524401e−001	|136.87336|
992	−2.47547791e+000	5.15200686e+000	5.11550364e−002	−4.24728359e+000	9.18708794e−001	|136.87357|
993	−2.51612506e+000	5.19123629e+000	5.06123460e−002	−4.30033501e+000	9.18751314e−001	|136.87551|
994	−2.40670941e+000	5.08505794e+000	5.20686610e−002	−4.15582031e+000	9.18142090e−001	|136.87288|
995	−2.46893749e+000	5.14765064e+000	5.14597159e−002	−4.24595553e+000	9.20785273e−001	|136.87492|
996	−2.42800697e+000	5.10509515e+000	5.17225328e−002	−4.18167978e+000	9.17604475e−001	|136.87251|
997	−2.44918612e+000	5.12171692e+000	5.13045354e−002	−4.21053553e+000	9.18129662e−001	|136.87129|
998	−2.45759431e+000	5.12583189e+000	5.10088274e−002	−4.21996527e+000	9.17822491e−001	|136.87287|
999	−2.39556123e+000	5.07108106e+000	5.21052501e−002	−4.14022874e+000	9.17933221e−001	|136.87390|
1000	−2.45549874e+000	5.13177541e+000	5.13925898e−002	−4.22051988e+000	9.18514901e−001	|136.87189|
1001	−2.44918612e+000	5.12171692e+000	5.13045354e−002	−4.21053553e+000	9.18129662e−001	|136.87129|
1002	−2.44918612e+000	5.12171692e+000	5.13045354e−002	−4.21053553e+000	9.18129662e−001	|136.87129|