CHAPTER 5

FILLER METALS FOR WELDING 3CR12

SYNOPSIS

In the first part of this study the effect was studied of the base and weld metal mechanical properties on the susceptibility of defect-free bead-on-plate welds on 6 mm 3CR12 and 3CR12Ni plate, to brittle cleavage fracture in the HT HAZ. It is demonstrated that the recently developed E3CR12 weld metal has a detrimental effect on the fracture behaviour of defect-free welds.

In the second part of this study different filler metals (AISI 309L, 316L, 308L and E3CR12) were evaluated for welding of 3CR12 plate. The filler metals were compared on the basis of their relative effects on the fusion line notch fracture toughness of fillet welds on 12 mm 3CR12 plate. For this purpose a new test method was also developed for measuring the fusion line notch fracture toughness of fillet welds.

It is demonstrated that the fusion line fracture behaviour of welds on 3CR12 is critically dependent on the weld metal and base metal mechanical properties. A type AISI 309L filler metal is recommended for welding 3CR12. The E3CR12 filler metal is not recommended for welding 3CR12 due to its detrimental effect on the fusion line notch fracture toughness of welds.

FILLER METALS FOR WELDING 3CR12

1. INTRODUCTION

Two of the most important requirements for a filler metal for welding 3CR12 plate are the as-deposited properties that are to be both mechanically and electrochemically compatible with the base metal.

Gooch and Davey compared the suitability of different austenitic type AISI 309L, 309 and 310 filler metals for welding 3CR12(13). They found that all consumables gave crack-free welds with matched parent metal strength, adequate bend ductility and matched crossweld tensile properties. Although all filler metals gave satisfactory results a type AISI 309 was recommended due to the significant capacity for dilution without forming crack-sensitive microstructures. Hoffman recommended that any austenitic type filler metal may be used for welding 3CR12, but found the use of type AISI 308L, 309L and 309LMo to be preferable(8).

Both the abovementioned recommendations were based mainly on a weld metal with matching parent metal mechanical properties. Due to the cost of high alloy austenitic filler metals and the possibility of the occurrence of galvanic corrosion in the weld HAZ, Pagani has developed a lower alloy weld metal with as-deposited properties which, according to Pagani, are both electrochemically and mechanically compatible with the 3CR12 parent plate(15). In the present study the strength of this new weld metal, designated E3CR12, was found to be much higher than that of the parent metal. The hardness of the predominantly martensitic E3CR12 weld metal of both MIG and MMA welds ranged from 373 HV to 385 HV (50kg) in comparison with 170 to 190 HV for 12 mm 3CR12 plate. It appears that the main emphasis in Pagani's study was on the electrochemical and fatigue properties of the weld metal.

The mechanical tests which were mainly used in the abovementioned studies were the hardness test and the unnotched bend and crossweld tensile tests. It is of importance at this stage to consider the validity of the unnotched bend and crossweld tensile tests as criteria for evaluating the suitability of different filler metals in welding 3CR12.

The formation of the narrow, dual phase, coarse grained HT HAZ in the HAZ of 3CR12 is well documented. The very low fracture toughness of this zone was clearly demonstrated in the previous chapter. The bend and cross weld tensile tests, which were used by Gooch et al. and Hoffman, have not revealed any detrimental effect of this narrow coarse grained zone on the ductility and fracture behaviour of 3CR12, welded with different austenitic filler metals. The principal shortcoming of these mechanical tests is that they only evaluate the plane stress fracture behaviour of welds.

With an increasing degree of constraint, the narrow HT HAZ is expected to affect the fracture behaviour of welds significantly. In the case of fusion line type defects, this zone will be highly constrained and subjected to triaxial stresses in comparison with defect free bend and crossweld tensile tests. Due to the coarse grain size of the HT HAZ the fracture stress of this zone is expected to be much lower than that of the austenitic weld metal or that of the adjacent fine grained and low temperature HAZ. At increasing constraint and the development of a triaxial stress state, the fracture stress of the HT HAZ may be reached prematurely with subsequent brittle fracture. The level of constraint in this zone, and therefore the maximum stresses which may develop during loading, is not only dependent on the type, size and orientation of fusion line defects but also on the mechanical properties of the adjacent weld metal, fine grained HAZ, low temperature HAZ and base metal. The fusion line notch fracture toughness of welds on 3CR12 is thus expected to be critically dependent on, inter alia, both the weld metal fracture toughness and mechanical properties.

In the present study it was therefore decided to study and compare the suitability of some austenitic type AISI 309L, 316L and 308L and a dual phase martensitic-ferritic type E3CR12 filler metals for welding 3CR12 by comparing the effects of the different weld metals on the fusion line notch fracture toughness of welds. The fusion line notch fracture toughness is one of the crucial criteria in comparing different filler metals for welding 3CR12.

This study consists of two parts:

1. In the first part the influence of the base and weld metal

mechanical properties on the fracture behaviour of defect-free welds on 6 mm 3CR12 and 3CRNi plate were evaluated using a newly developed unnotched bead-on-plate face bend test.

2. In the second part a new test method was developed for measuring the fusion line notch fracture toughness (FLNFT) of fillet welds on 12 mm 3CR12 plate. The suitability of different filler metals (AISI 309L, 316L, 308 and E3CR12) for welding 3CR12 plate was also evaluated with the FLNFT test.

2. EXSPERIMENTAL RESULTS AND DISCUSSION

2.1 Bead-on-plate bend test

2.1.1 Introduction

The first part of the present study is mainly concerned with the effect of the base metal and weld metal mechanical properties on the fracture behaviour of defect-free bead-on-plate welds on 6.2 mm 3CR12 and 3CR12Ni plate. If the fracture stress of the coarse grained high temperature HAZ is less than the fracture stress of the austenitic weld metal, and the fine grained and low temperature HAZ, the plane stress fracture behaviour of defect-free welds is expected to be determined mainly by the fracture behaviour of the HT HAZ. The fracture behaviour of this coarse grained zone will again be determined by the maximum principal stress which will develop in this zone during, for example, bend or tensile loading. The satisfactory bend and crossweld tensile test results which were obtained by Gooch et al. and Hoffman can therefore be accounted for by the fact that the fracture stress of this zone was never reached during plane stress testing as a result of the low strength of both the austenitic weld metal and low temperature HAZ.

At increasing constraints and thus at an increase in stress triaxiality, the fracture toughness of this coarse grained HAZ decreases. The fracture stress increases with a decrease in fracture ductility as shown in figure 5.1. Figure 5.1 shows an increase of the flow stress curves with increasing constraint. The ductile (curve a) and brittle fracture (curve b) stress curves, according to Ludwik and Davidenkov(19), are also included in figure 5.1. Depending on the fracture toughness and the test temperature a fracture mode transition from ductile fracture to brittle cleavage fracture may occur at increasing constraints as shown by the intersection of the fracture stress curves in figure 5.1.

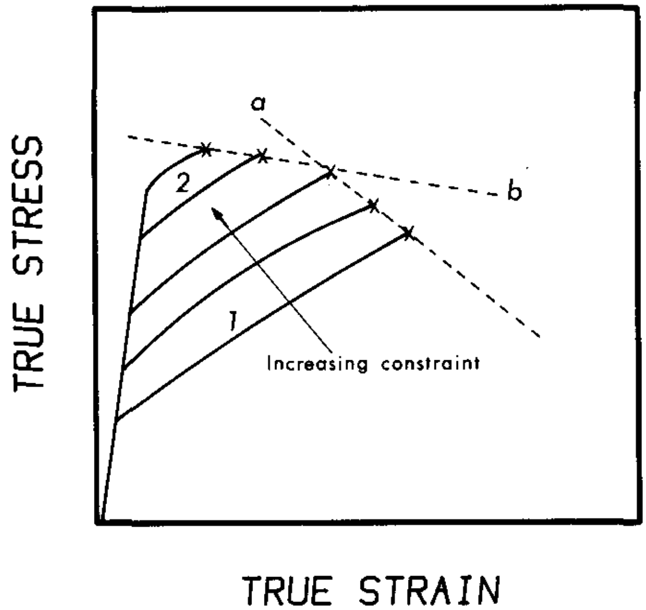


Figure 5.1: Flow stress curves for different constraint conditions.
Curve a. Ductile fracture stress curve
Curve b. Brittle cleavage fracture stress curve

The constraint in the narrow, coarse grained HAZ of a weld on 3CR12 depends not only on the size and notch tip radius (stress concentration factor) of fusion line defects, the section size and weld joint design, but also on the mechanical properties of the weld and parent metal. Consider the smooth composite tensile test specimen in figure 5.2 which is composed of two different materials (B and A), with mechanical properties similar to the HT HAZ of 3CR12, with 40 percent low carbon martensite, and an austenitic weld metal respectively. For similar mechanical properties for the composite materials of the composite tensile specimen in figure 5.2, the specimen will fracture by ductile fracture according to curve 1 in figure 5.1. By increasing the yield and tensile strength of the weld metal above that of the coarse grained HAZ, the centre part of the composite tensile specimen in figure 5.1 will be subjected to increasing constraints when the HAZ starts yielding. A triaxial stress field will develop in

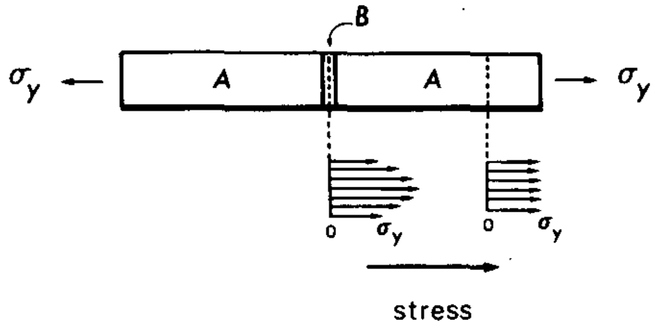


Figure 5.2: Composite tensile test specimen composed of two different materials. The narrow centre part (B) of the specimen has mechanical properties similar to the coarse grained HT HAZ in 3CR12 while both ends (A) have properties similar to that of an austenitic type weld metal. Note also the stress distribution in the different materials when the HAZ (B) starts yielding.

this narrow centre part of the test specimen during tensile loading as a result of local necking or deformation in this part and the high weld metal strength which plastically constrains it. At high constraints (higher weld metal mechanical properties) the composite tensile specimen may, therefore, fracture by brittle cleavage fracture in the centre part of the specimen as a result of the reduced fracture toughness of this part and the triaxial stress which reached the brittle fracture stress of this centre part according to curve 2 in figure 5.1.

2.1.2 Experimental Procedure

Bead-on-plate three point face bend specimens (fig. 5.3) were prepared from both hot rolled-and-tempered and hot rolled 6.2 mm 3CR12 plate and 3CR12Ni plate. The HT HAZ of welds on 3CR12Ni plate contains about 98 percent low carbon martensite (fig. 4.3) compared to the 15 to 35 percent martensite in this zone of welds on 3CR12 plate (fig. 4.2). The chemical compositions of 3CR12 and 3CR12Ni are shown in table 4.1.

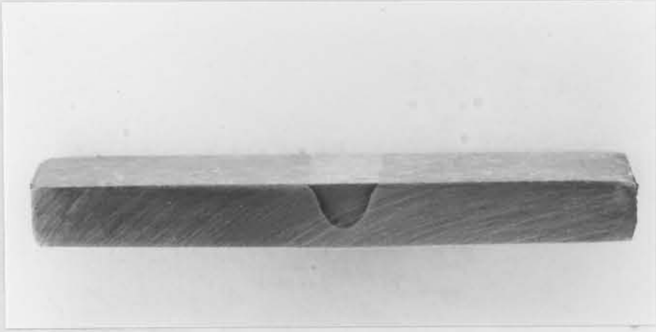


Figure 5.3: Bead-on-plate three point face bend specimen with the weld bead removed.

The bend specimens (6 mm x 10 mm x 60 mm) were machined from welded sections on which single beads were welded parallel to the rolling direction according to the following welding procedure:

Welding process	:	Gas metal-arc (MIG)
Welding wire	:	1.6 mm AISI 316L
	:	1.6 mm Flux cored E3CR12 (Philips)
Shielding gas	:	84%Ar, 13%CO_2, 3%O_2
Welding position	:	Flat
Current (amp)	:	360-380
Volts	:	20-21
Arc speed (cm/min.)	:	95 (316L)
	:	90 (E3CR12)

Bend specimens were prepared from both hot rolled and hot rolled-and-tempered 3CR12 and 3CR12Ni plate welded with a low strength austenitic type AISI 316L filler metal. Specimens which were welded with the high strength E3CR12 filler metal were only prepared from hot rolled 3CR12 and 3CR12Ni plate in which the customary tempering heat treatment was omitted. The weld bead was subsequently removed in order to eliminate any surface type defect.

The effect of the base metal strength on the fracture behaviour of the

HT HAZ was studied by comparing the bend test results of the hot rolled and the hot rolled-and-tempered specimens. The effect of weld metal strength was studied by comparing the bend test results of specimens welded respectively with AISI 316L and E3CR12 filler metals. The effect of the microstructure or phase composition of the HT HAZ on the fracture behaviour of the welds was studied by comparing the bend test results of 3CR12 and 3CR12Ni bent test specimens.

The deep penetrating welding variables were designed in order to obtain a fusion line and therefore a HT HAZ which ideally will be oriented normal to the plate surface. A very favourable orientation was obtained as shown in figure 5.3.

It is of some significance at this stage to consider the microstructure of the HAZ of MIG welded bead-on-plate welds on 6.2 mm 3CR12 and 3CR12Ni plate, as shown in figures 4.2 and 4.3, respectively. It has already been demonstrated in chapter 1 that the weld HAZ can be divided into three different zones:

1. A narrow coarse grained high temperature (HT) zone adjacent to the fusion line. The phase composition of this zone depends on the relative amounts of ferrite and austenite stabilizing elements in the steel, while the width depends on the heat input.

2. A much wider fine grained duplex zone, with ferrite and untempered martensite, right next to the coarse grained zone. The width of this zone, which was determined from the microhardness transverse of bead-on-plate welds on 3CR12 and 3CR12Ni in figures 5.4 and 5.5, respectively, ranges from 0.7 mm to 0.9 mm.

3. A third low temperature zone more distant from the fusion line. The width of this zone which was also determined from figures 5.4 and 5.5 ranges from 2.5 mm to 3 mm.

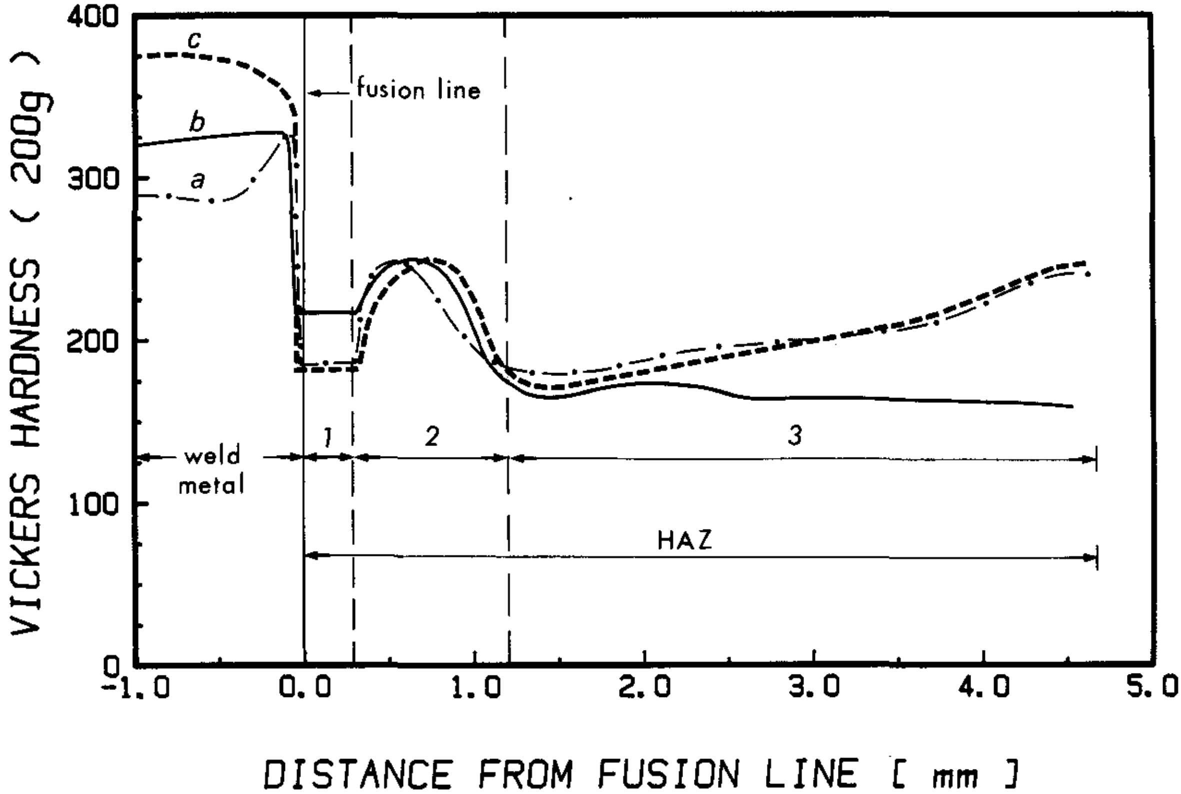


Figure 5.4: Microhardness transverse across the fusion line of bead-on-plate welds on 6.2 mm 3CR12 plate. The transverse was determined at a distance of 0.3 mm below the original plate surface.

Curve a: Hot rolled specimens welded with a 316L filler metal

Curve b: Hot rolled-and-tempered specimens welded with a 316L filler metal

Curve c: Hot rolled specimens welded with an E3CR12 filler metal

Zone 1: Narrow coarse grained HT HAZ. The weighed average hardness which is indicated in the figure was calculated from the microhardness of respectively the ferrite and martensite in this zone

Zone 2: Fine grained duplex HAZ

Zone 3: Low temperature HAZ

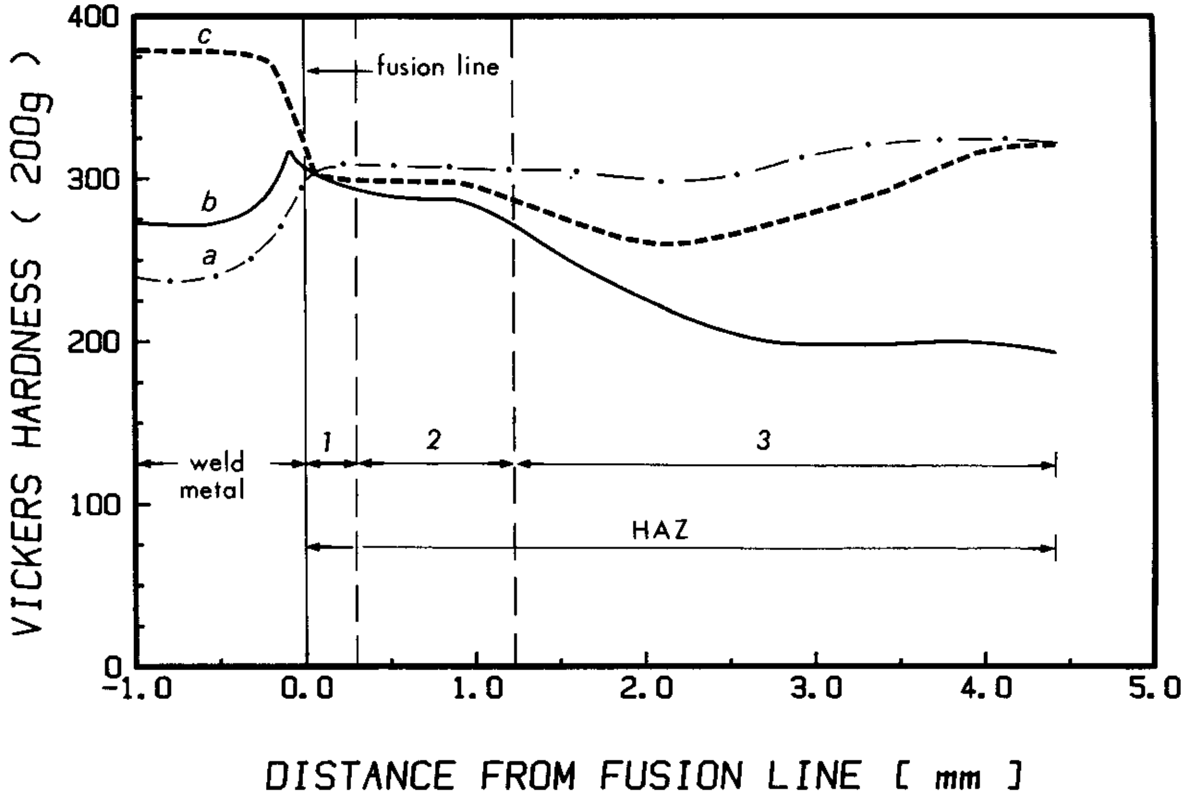


Figure 5.5: Microhardness transverse across the fusion line of bead-on-plate welds on 6.2 mm 3CR12Ni plate. This transverse was determined at a distance of 0.3 mm below the original plate surface.

Curve a. Hot rolled specimens welded with a 316L filler metal

Curve b. Hot rolled-and-tempered specimens welded with a 316L filter metal

Curve c. Hot rolled specimens welded with an E3CR12 filler metal

Zone 1. Narrow coarse grained HT HAZ

Zone 2. Fine grained duplex HAZ

Zone 3. Low temperature HAZ

The specimens were tested at room temperature in slow three point face bending with the bend radius equal to plate thickness. The weld bead was therefore subjected to tensile stresses during bending. The maximum bend angle for cleavage fracture initiation in the narrow coarse grained HT HAZ was determined.

2.1.3 Experimental results

180° bends were successfully achieved for the hot rolled-and-tempered 3CR12 specimens welded with 316L. Figure 5.6 shows a close view of the weld bead surface of such a bent specimen. The three zones which have previously been identified in the weld HAZ are cleary evident as a result of the different amounts of deformation which occurred in the different zones during bend testing.

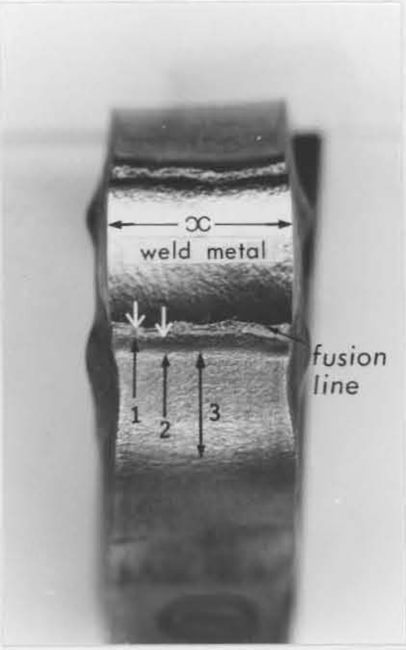


Figure 5.6: Surface view of a hot rolled-and-tempered 3CR12 bent specimen welded with AISI 316L. Note the different amounts of surface deformation which occurred in the coarse grained HT HAZ (zone 1), the fine grained HAZ (zone 2) and the low temperature HAZ (zone 3).

The bend test results are summarized in table 5.1. In each instance the average of three tests is reported. The relative surface transverse strain of the weld metal and the high (zone 1) and low (zone 3) temperature HAZ, which was achieved at the maximum bend angle, is also shown in table 5.1 together with the parent and weld metal hardness values. The transverse strains are expressed on a ten point scale. These values were obtained by measuring the total transverse deformation ((10-x)/10) of the weld metal and low temperature HAZ (zone 3) together with the width of the coarse grained HAZ (zone 1) in figure 5.6. These values are then expressed on a relative scale with the deformation in that zone which exhibited the largest deformation equal to ten units. The transverse strain is expressed on a relative scale since it depends on the width of the bend specimen.

180° bends were successfully achieved with the hot rolled-and-tempered 3CR12 specimens, welded with AISI 316L. This is primarily due to the large amount of deformation which occurred in the low temperature HAZ (zone 1) as shown in table 5.1 and figure 5.6. Considerable deformation also occurred in the coarse grained HT HAZ (zone 1 in fig. 5.6) with less deformation in the fine grained HAZ (zone 2).

With a large fraction of the total deformation occurring in the low temperature HAZ during bending, the actual bend angle of the weld metal and zone 1 is less than 180° as indicated schematically by the dotted line in figure 5.7.

Table 5.1: Bend test results of bead-on-plate face bend test.

Steel	Condition	Filler metal	Bend angle	Relative deformation expressed on a ten point scale			Vickers Hardness 2.5kg	
				Weld metal	Zone 1 (Fig. 5.6)	Zone 3 (Fig. 5.6)	Weld metal	Parent metal
3CR12	Tempered	316L	180°	3.9	4.8	10	311	165
3CR12	Hot rolled	316L	133°	4.3	10	7	277	246
3CR12	Hot rolled	E3CR12	9°	0	2.5	0.5	374	246
3CR12Ni	Tempered	316L	180°	5.5	1	10	282	196
3CR12Ni	Hot rolled	316L	59°	10	0.2	1.5	220	322
3CR23Ni	Hot rolled	E3CR12	42°	5.2	0.2	1.5	383	322

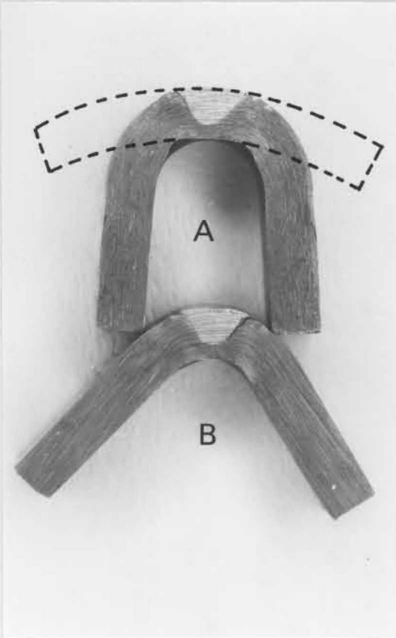


Figure 5.7: Hot rolled-and-tempered (A) and hot rolled (B) 3CR12 bead-on-plate bent specimens welded with 316L.

A maximum bend angle of 133° was obtained for the higher strength hot rolled bent specimens, welded with 316L (fig. 5.7B), before a cleavage fracture occurred in the narrow HT HAZ. A comparison of the surface appearance of such a bent specimen (fig. 5.8) with that of the annealed specimen in figure 5.6 shows that more deformation occurred in the HT HAZ with less deformation in zone 3 (table 5.1). This change in deformation mode in the hot rolled specimens, in comparison to the tempered specimens, occurred as a result of the higher strength of zone 3 with the strength of the HT HAZ unaffected. A brittle cleavage fracture occurred therefore in the narrow HT HAZ with the development of higher stresses during bend testing (the flow stress curve is raised in fig. 5.9) as a result of the higher degree of constraint which was imposed by the higher strength hot rolled low temperature HAZ and parent metal (fig. 5.4).

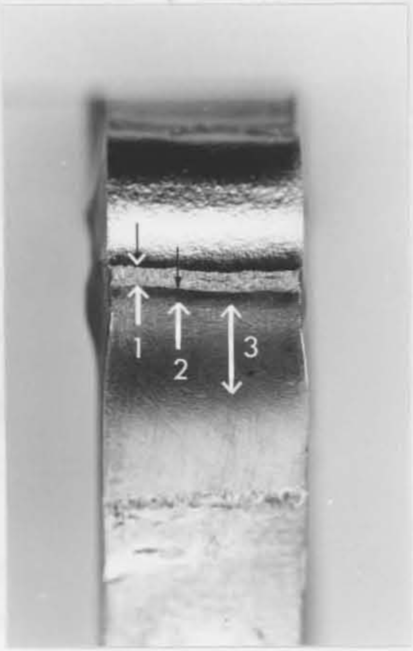


Figure 5.8: Surface view of a hot rolled 3CR12 bent specimen welded with 316L. A comparison with the bent specimen in figure 5.6 reveals that less deformation occurred in zone 3 with more deformation in the HT HAZ (zone 1).

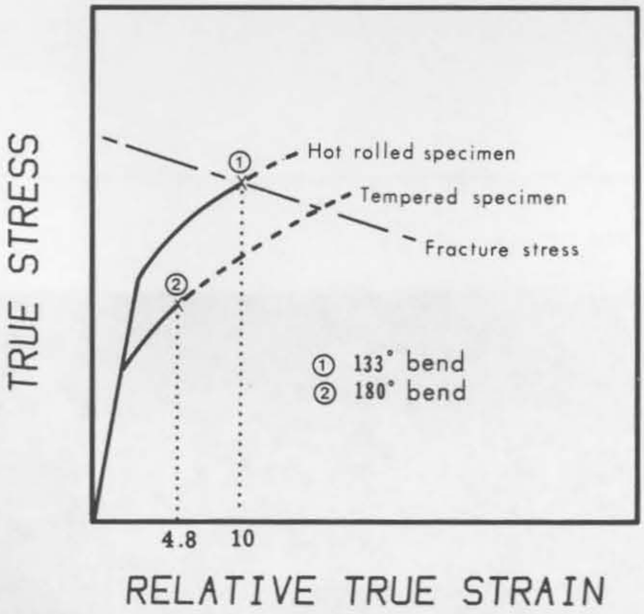


Figure 5.9: Flow stress curves for the HT HAZ (zone 1) of hot rolled and hot rolled-and-tempered 3CR12 bent specimens, respectively.

The unusual high hardness of the 316L weld metal in table 5.1 can be attributed to the high dilution of 40 to 45 percent which occurred during welding, with the subsequent formation of some low carbon martensite in the weld metal. At lower dilutions and consequently lower weld metal strengths, 180° bends may even be obtained with the higher strength hot rolled 3CR12 specimens.

A maximum bend angle of only 9° was achieved with hot rolled 3CR12 specimens welded with a high strength E3CR12 filler metal (fig. 5.4 and table 5.1). This very small bend angle in comparison with a bend angle of 133° for the specimens welded with a lower strength 316L filler metal (fig. 5.10) cleary demonstrates the detrimental effect of this high strength E3CR12 filler metal on the fracture behaviour of this very narrow coarse grained HT HAZ in 3CR12. The top view of a hot rolled 3CR12

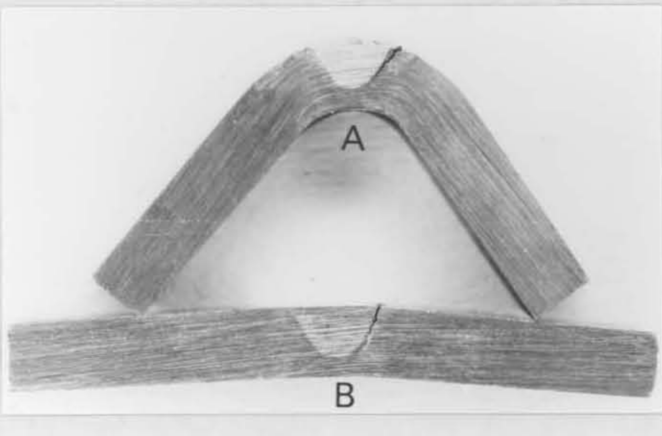


Figure 5.10: Hot rolled bead-on-plate 3CR12 bent specimens welded with a 316L (A) and E3CR12 (B) filler metal. Note the brittle cracks in the coarse grained HAZ adjacent to the fusion line.

bent specimen in figure 5.11 shows that most of the deformation occurred in the low strength HT HAZ. This is also indicated in table 5.1. The reduced fracture ductility of this zone, as a result of the large constraint imposed by the high strength E3CR12 weld metal (fig.5.1), is evident from a comparison of the amount of deformation in this zone shown in figures 5.8 and 5.11.

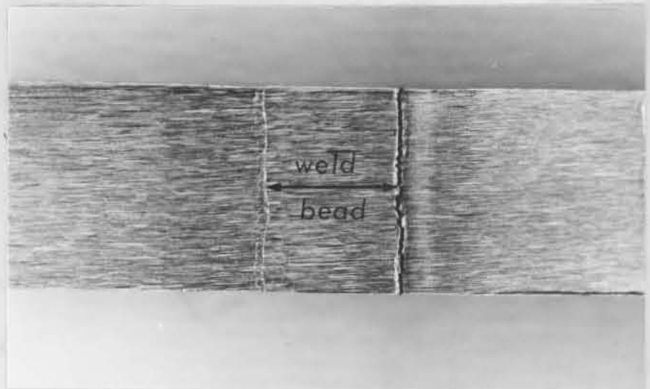


Figure 5.11: Top view of a hot rolled 3CR12 bent specimen welded with E3CR12. The brittle fracture which occurred in the HT HAZ is clearly evident together with the local plastic deformation in this zone on the left hand side of the weld bead.

With the strength of the fine grained HAZ (zone 2) higher than that of the adjacent HT HAZ (zone 1, fig. 5.4) this zone will also constrain the HT HAZ from plastic deformation during bend testing. This is also evident from figures 5.6 and 5.8 which show that less deformation occurred during bending in this zone in comparison with the HT HAZ and low temperature HAZ.

The microhardness transverse across the fusion line of bead-on-plate welds, welded respectively with 316L and E3CR12 filler metals, on 3CR12Ni plate, are compared in figure 5.5. The higher strength of the HT of 3CR12Ni in comparison with the same zone in 3CR12 (fig. 5.4) can be attributed to the finer grain size and higher content of low carbon martensite. This zone will therefore exhibit a higher fracture toughness as well as a higher fracture stress compared to the same zone in 3CR12. The higher toughness may also partly be attributed to the higher nickel content of 3CR12Ni. The fracture behaviour of this zone will also be determined by the mechanical properties of the adjacent weld metal, HAZ and parent metal. Figure 5.5 shows that the hardness of this zone is very similar to that of the adjacent fine grained HAZ (zone 2).

180° bends were successfully achieved with hot rolled-and-tempered 3CR12Ni specimens welded with a 316L filler metal (table 5.1). During bending most of the deformation occurred in the low strength low temperature HAZ (fig. 5.5) with some deformation in the weld metal. As a result of the relatively lower strength of the adjacent weld metal and low temperature HAZ, the fracture stress of the HT HAZ was therefore not exceeded during bending. The actual bend angle of this bend specimen is also, as shown in figure 5.7, less than 180°. This is due to the deformation which was concentrated mainly in the low temperature HAZ.

Figure 5.5 shows that for the hot rolled 3CR12Ni specimens, welded with a 316L filler metal, the hardness of the fine grained and low temperature HAZ is virtually similar to that of the HT HAZ with the hardness of the parent metal higher than that of this zone (table 5.1). A bend angle of only 59° was therefore obtained with this specimen before a cleavage fracture occurred in the HT HAZ. Most of the deformation occurred in the 316L weld metal (table 5.1). This smaller bend angle in comparison with that of the hot rolled-and-tempered specimen was obtained notwithstanding the lower weld metal hardness (220 HV against 282 HV, table 5.1). The weld metal and HT HAZ were subjected to higher stresses during bend testing as a result of the constraint imposed by the higher strength low temperature HAZ and that of the hot rolled parent plate. The flow stress of the austenitic weld metal increased, due to work hardening, to such an extent that at a bend angle of 59° the brittle fracture stress of the HT HAZ was exceeded. This indicates therefore that the fracture behaviour of the HT HAZ or the maximum bend angle is also dependent on the yield strength and work hardening rate of the weld metal. A larger bend angle may have been obtained with a ferritic weld metal with a similar yield stress but a lower rate of work hardening.

The hot rolled 3CR12Ni specimens which were welded with the high strength E3CR12 filler metal fractured by brittle cleavage fracture in the HT HAZ at a bend angle of 42° (table 5.1). The brittle behaviour of this zone in 3CR12Ni indicates that, although its fracture toughness is expected to be superior to that in 3CR12 as a result of its finer grain size and higher martensite and nickel content, the room temperature fracture toughness is still very low.

2.1.4 Discussion

One of the most important observations at this stage is the very low room temperature fracture toughness of the HT HAZ of defect free bead-on-plate welds on 6 mm 3CR12 and 3CR12Ni plate. Successfull 180° bends were achieved only when this zone was protected from high stresses by adjacent soft material (316L weld metal and tempered plate).

The results have clearly demonstrated the detrimental effect of the high strength E3CR12 weld metal on the fracture behaviour of defect-free bead-on-plate welded 3CR12 bend specimens. It has also been shown that the susceptibility of welds to brittle cleavage fracture in the HT HAZ increases with improved parent metal mechanical properties. The fracture behaviour of welds on 6 mm 3CR12 and 3CR12Ni plate is therefore critically dependent on the mechanical properties of the weld metal, base metal and that of the different zones in the weld HAZ.

In the developing filler metals for welding 3CR12 plate, the restrictions on the mechanical properties of the weld metal (yield stress, tensile stress, work-hardening rate) are as important as other requirements such as matching electrochemical, fatigue and fracture toughness properties. When the steel is considered for any high integrity structural type applications with highly restrained weld joints, the mechanical property requirements to insure fracture toughness are of even greater importance.

2.2 Fusion line notch-fracture toughness testing

2.2.1 Introduction

One disadvantage of the bead-on-plate face bend test is that although a qualitative indication is obtained of the effect of the weld and parent metal mechanical properties on the fracture behaviour of welds, the influence of typical 316L and E3CR12 weld metal compositions was not determined. This is due to the unusually high dilutions which occurred with the base metal during welding, with the formation of some low carbon martensite even in the 316L weld metal.

The combined effect of the base metal, HAZ and weld metal on the fracture behaviour of welds on 3CR12 and 3CR12Ni are determined with the bead-on-plate bend test. 180° bends were successfully achieved on annealed 6 mm 3CR12 plate, welded with a 316L filler metal. This is due to the fact that most of the deformation occurred in the low strength, low temperature HAZ during bending. With the presence of a notch type defect on the fusion line, the susceptibility of welds to brittle fracture in the HT HAZ, will be determined by the mechanical properties and fracture toughness of the weld metal rather than the properties of the low temperature HAZ and parent metal. The choice of the correct filler metal for welding 3CR12 therefore becomes even more important.

It was therefore decided that the fusion line notch fracture toughness is a better criterion for comparing different filler metals. In this second part of the present study the effect of different filler metals (AISI 309L, 316L, 308L and E3CR12) on the fusion line notch fracture toughness of welds on 12 mm hot rolled and annealed 3CR12 plate was studied with a newly developed fusion line notch fracture toughness (FLNFT) test.

2.2.2 Fusion line notch fracture toughness test specimen design and preparation

The introduction of a reproducible artificial notch type defect or crack on the weld fusion line has been one of the major design considerations in designing the FLNFT test specimen shown in figure 5.12. The specimen is machined from a welded cruciform test specimen shown in figure 5.13. The cruciform test specimen is prepared by welding 12 mm hot rolled-and-tempered 3CR12 plate sections (100 mm x 200 mm) to the machined top and bottom surfaces of a 200 mm x 200 mm x 12 mm 3CR12 plate section. The plates were tack welded prior to welding in order to prevent distortion during welding.

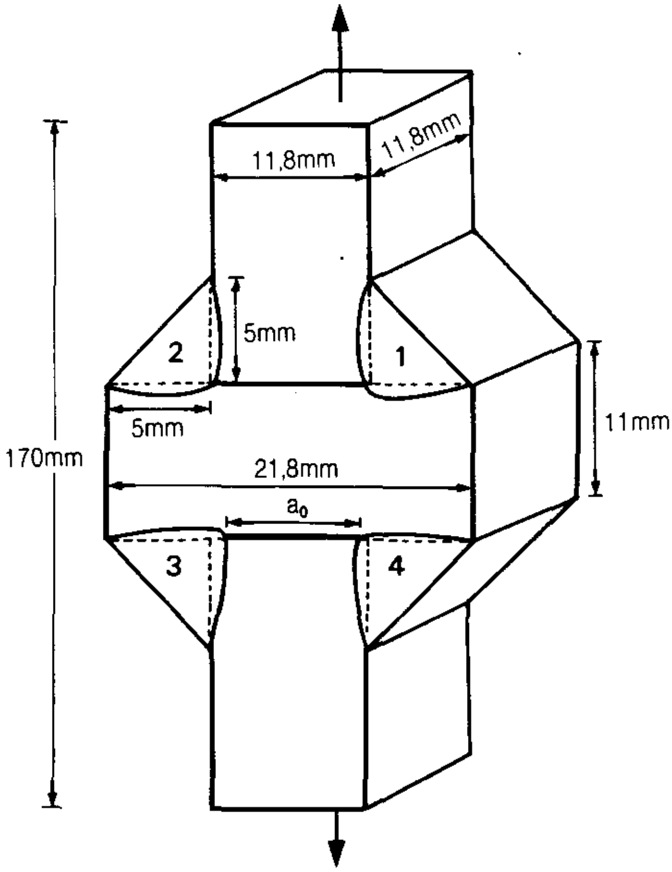


Figure 5.12: FLNFT test specimen design. a_o is the artificial through-thickness crack length. The sequence of welding of the single bead fillet welds is also indicated.

The single bead fillet welds on the cruciform specimen were welded in the sequence shown in figure 5.12 according to the following welding procedure:

Welding process	:	Shielded metal arc
Filler metal	:	AISI 309L (3.25 mm dia.)
	:	AISI 316L (3.25 mm dia.)
	:	AISI 308L (3.25 mm dia.)
	:	E3CR12 (3.25 mm dia.)
Welding position	:	Flat
Heat input	:	1.4 kJ/mm (160amp, 23 volts)
	:	1.2 kJ/mm (110amp, 28 volts)

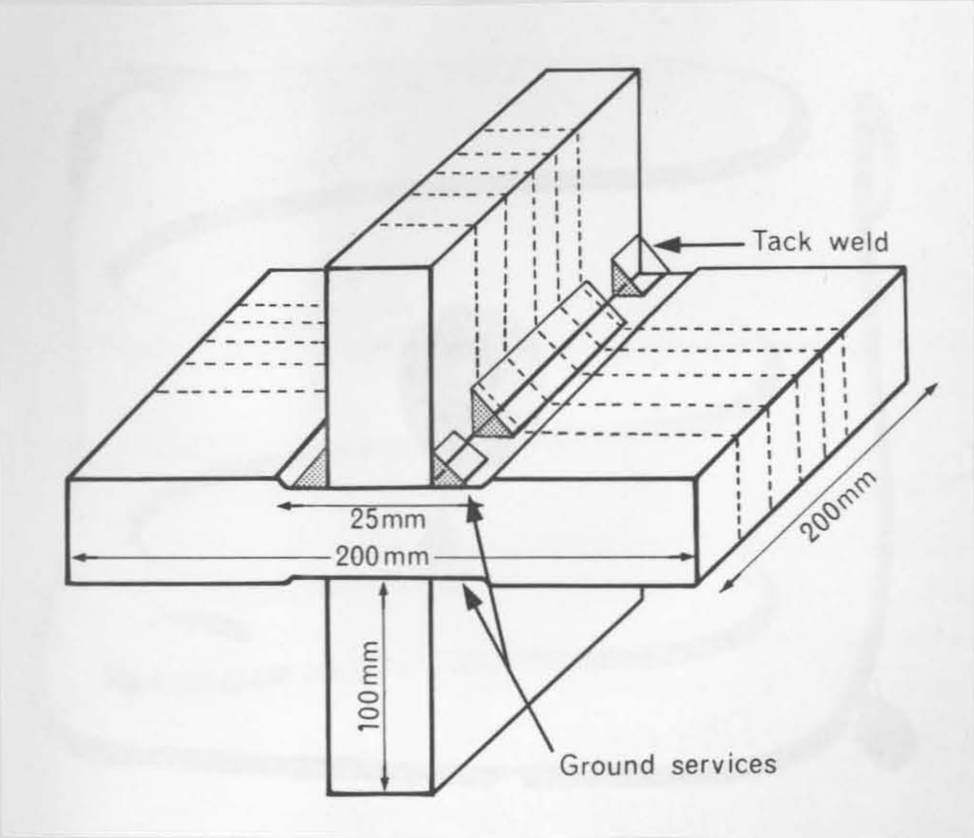


Figure 5.13: Cruciform test specimen.

Both high weld heat input (1.4 kJ/mm) and low weld heat input (1.2 kJ/mm) cruciform specimens were prepared with AISI 309L, 316L, 308L and E3CR12 filler metals, respectively. The cruciform specimens were allowed to cool to room temperature prior to welding subsequent fillet welds. Each subsequent fillet weld is subjected to a higher degree of constraint during cooling than the previous one, and if cracking occurred it was usually restricted to the fourth weld.

Four FLNFT test specimens were machined from the centre part of a cruciform specimen. One specimen was polished, etched and examined to establish whether any cracking has occurred in the weld or base metal.

Figure 5.14 shows a polished and etched section of a FLNFT test specimen which was welded with an E3CR12 filler metal at a heat input of 1.4 kJ/mm. The HT HAZ of each fillet weld together with the two artificial through-thickness cracks are clearly evident.

Figure 5.14: Polished and etched section of an FLNFT test specimen with the HT HAZ and two through-thickness cracks clearly evident. A clip gauge was attached to the specimen at the two small drilled holes during testing.

2.2.3 Experimental results and discussion

The FLNFT specimens were tested at room temperature by tensile testing. The load versus crack-opening-displacement (COD) curves were determined at a crosshead speed of 20 mm/min. The total crack-opening-displacement (δ) of the two through-thickness cracks were measured during testing with a clip gauge attached to the specimen at the small drilled holes shown in figure 5.14. The maximum load Pm together with the total crack-opening-displacement (δ_m) at maximum load were determined from the load-displacement curves as shown in figure 5.15. For the particular design of the FLNFT specimen (fig. 5.14) the measured crack-opening-displacement is equal to the crack-tip-opening displacement (δ =2CTOD) (17).

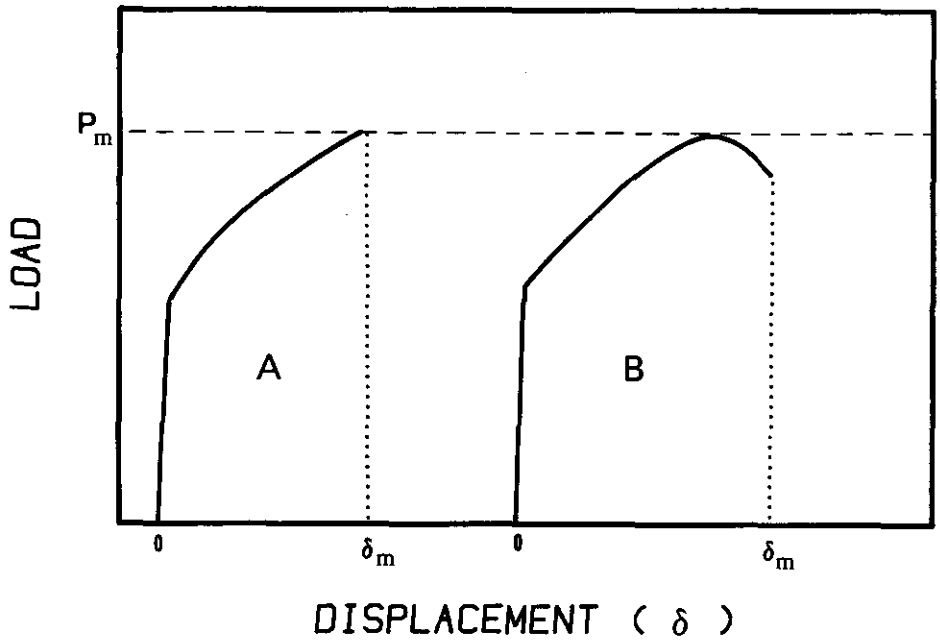
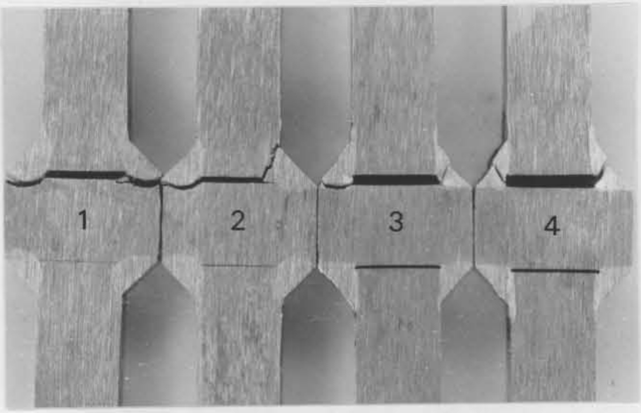


Figure 5.15: Typical load versus crack-opening displacement (δ) curves for the FLNFT test specimen.

Depending on the weld metal mechanical properties and the weld heat input, the FLNFT test specimens fractured in four possible different modes. The different failure modes are shown in figure 5.16. The load-displacement curves of specimens which fractured with modes 1 and 2 corresponded with curve A in figure 5.15 while specimens which fractured with modes 3 and 4 had load-displacement curves similar to curve B in figure 5.15.

The fusion line notch-toughness test results is summarized in table 5.2. In each instance the average result of three similar tests is reported.



Fracture mode : 1. Cleavage fracture in HT HAZ of both fillet welds
2. Cleavage fracture in HT HAZ of both fillet welds
3. Cleavage fracture in HT HAZ of one fillet weld and ductile tearing in the weld metal of the second fillet weld
4. Ductile tearing in the weld metal of both fillet welds

Figure 5.16: Different fracture modes of FLNFT specimens. Note the increase in the COD with fracture mode transitions from mode 1 to 4.

Table 5.2: Fusion line notch fracture toughness test results.

Filler metal	Heat input (kJ/mm)	Hardness (HV) weld metal*	Crack length a_0 (Fig. 5.12)	Max. load (MPa)	Displacement m(mm) (Fig. 5.15)	Fracture mode (Fig. 5.16)
Nicromax 309L	1.40	200	10.90	322	1.02	4
	1.21	184	11.90	291	1.45	3 and 4
Transarc 316L	1.40	207	11.35	315	0.76	4
	1.21	186	12.00	292	1.15	3 and 4
Transarc 308L	1.40	280	11.26	337	0.42	1
	1.21	185	11.94	295	0.98	3
Transarc E3CR12	1.40	373	8.90	456	0.15	1 and 2
	1.25	372	10.80	386	0.30	1 and 2

* The parent metal hardness of the hot rolled and tempered 3CR12 plate is 160HV.

2.2.3a High heat input (1.4 kJ/mm) test results

At a weld heat input of 1.4 kJ/mm, complete joint penetration of the fillet welds was achieved with each of the four filler metals (AISI 309L, 316L, 308L and E3CR12). Figure 5.14 shows an example of such a specimen welded with an E3CR12 filler metal. The crack tips of the through-thickness cracks were therefore successfully positioned on the weld fusion line of the fillet welds as shown for example in figures 5.17 and 5.18 for FLNFT specimens welded with E3CR12 and 316L filler metals, respectively. Figure 5.17 shows a smaller through-thickness crack tip radius for the specimen welded with an E3CR12 filler metal compared to the crack tip radius of the specimen in figure 5.18. This resulted from the higher constraint in the HAZ of the high strength E3CR12 fillet welds compared to the constraint in the HAZ of the lower strength austenitic fillet welds (table 5.2).

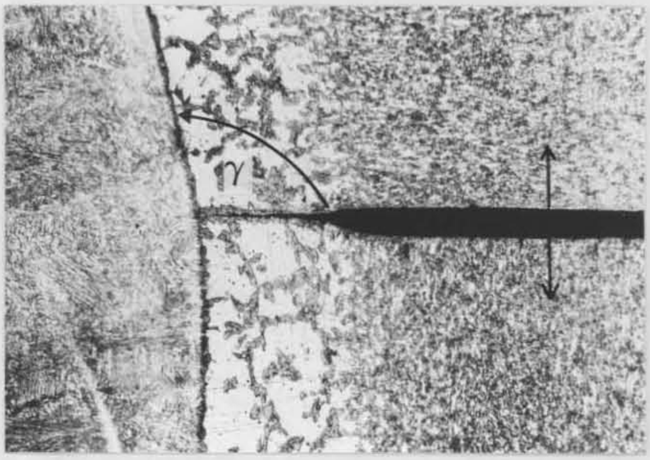


Figure 5.17: Through-thickness crack in a FLNFT test specimen with the crack tip on the fusion line of the E3CR12 weld metal. The direction of the principal load during tensile testing is indicated (35X).

The direction of the principal applied load during tensile testing is indicated in figure 5.17. A difference in the relative orientation (γ) between the through-thickness cracks and the fusion line of some of the E3CR12 welds (fig. 5.17) in comparison with the austenitic welds (fig. 5.18) was observed. The smaller angle (γ) in figure 5.17 is due to the

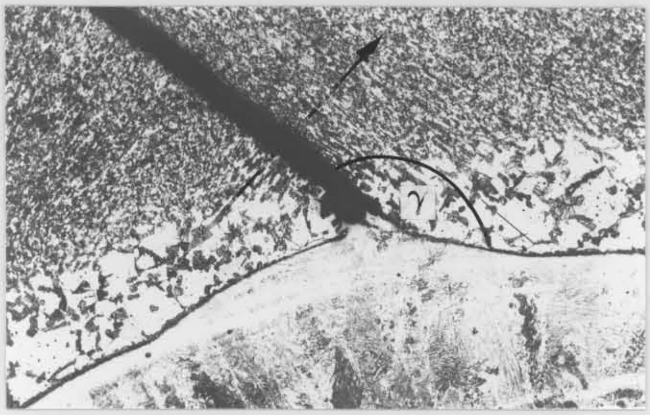


Figure 5.18: Through-thickness crack in an FLNFT test specimen with the crack tip on the fusion line of the 308L weld metal. The direction of the principal load during tensile testing is indicated (35X).

deeper penetration during welding with the thinner 3.15 mm diameter E3CR12 electrode (table 5.2). Although the angle (γ) is determined by the amount of weld bead penetration, roughly similar values were achieved for most of the fillet welds of the different austenitic filler metals.

A microscopic investigation of the FLNFT specimens, after welding and machining revealed that weld cracking occurred only in some fillet welds of the specimens welded with the E3CR12 filler metal. The cracking occurred in the fourth welded segment which was subjected to the highest degree of constraint. Figure 5.19 shows such a crack in the predominantly martensitic crack sensitive E3CR12 weld metal. The cracked specimens were not used for fracture toughness testing. These cracks are most probably hydrogen-induced cold cracks which developed as a result of inadequate drying of the welding electrodes. The electrodes were dried at 350°C for one hour prior to welding.

The bead-on-plate bend test results have shown that the cleavage fracture stress of the HT HAZ in 3CR12 is much lower than the ductile fracture stress of the predominantly austenitic 316L weld metal. The fracture stress, which also depends on the test temperature, usually increases with a decrease in grain size. With the crack tip on the fusion line (figs 5.17

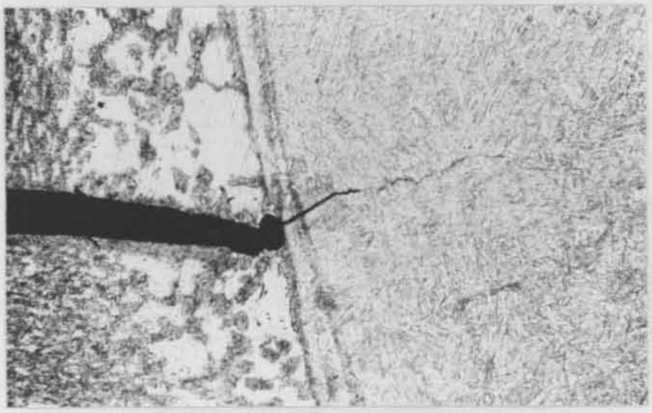


Figure 5.19: Weld metal crack in the fillet weld of a FLNFT test specimen welded with an E3CR12 filler metal. The crack initiated after some crack tip blunting of the through-thickness crack (35X).

and 5.18) the weld metal at the crack tip will be subjected to the maximum tensile stress during tensile loading. Since a smaller component of the principal stress is expected to result in fracture in the HT HAZ, a ductile fracture or tear may occur in the weld metal even with the fracture stress of the weld metal much higher than the fracture stress of the HT HAZ. A brittle fracture will therefore occur in the HT HAZ only when the component of the principal stress, which acts perpendicularly to the fusion line, exceeds the fracture stress of this zone before the principal stress exceeds the fracture stress of the weld metal.

The FLNFT specimens, which were welded with a heat input of 1.4kJ/mm and with AISI 309L and 316L filler metals respectively, fractured by ductile tearing in the weld metal (mode 4 in fig. 5.16). Sections through the two fillet welds on the side of fractured FLNFT specimens which did not fracture during testing, showed the crack tip state prior to fracture. Figure 5.20 shows crack tip blunting of a through-thickness crack in one of the fillet welds of a 309L welded and tested FLNFT specimen. Small voids have already developed at the crack tip indicating incipient tearing. Figure 5.21 shows that stable crack extension has occurred in the 309L weld metal of the second fillet weld prior to primary fracture. The results indicate that some stable crack extension occurred during tensile testing when the maximum applied load was reached.

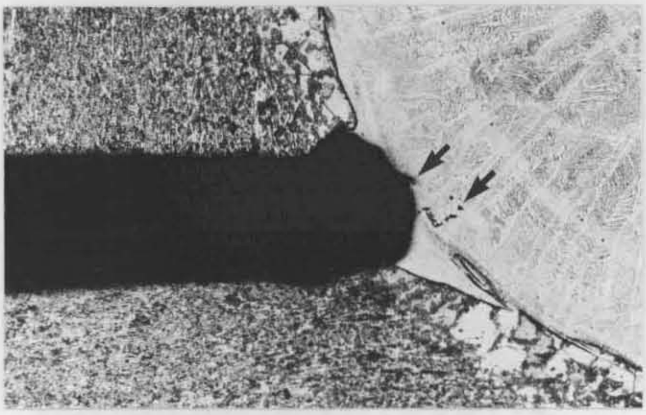


Figure 5.20: Crack tip blunting in the 309L weld metal of a fractured FLNFT specimens. Small voids have already initiated at the crack tip which shows incipient tearing (arrows) (35X).

Although the 309L and 316L welded FLNFT specimens have similar weld metal strengths and although similar maximum loads were applied during tensile testing, a larger total crack-opening-displacement (δm = 1.02 mm) was obtained for the 309L welded specimen than the δm value of 0.76 mm for the 316L welded specimen.

Figure 5.21: Stable crack extension in the 309L weld metal of a through-thickness crack in a fractured FLNFT specimen (35X).

Assuming that the δm value is a qualitative indication of the crack tip plastic zone size prior to fracture, a larger plastic zone developed in the 309L weld metal in comparison with that of the 316L weld metal. The larger plastic zone probably developed as a result of a lower yield stress which in turn can be attributed to a lower ferrite content. The weld metal hardness of different weld metals indicate the relative weld metal tensile strengths but does not necessarily indicate the relative yield stress values of the weld metal.

The FLNFT test specimens, welded with a 308L filler metal, fractured at an δm value of 0.42 mm by cleavage fracture in the coarse grained HT HAZ of both fillet welds (mode 1, fig. 5.16). Less crack tip blunting occurred and therefore a smaller crack tip plastic zone developed. This is due to the higher weld metal yield and tensile strength (table 5.2) in comparison with the plastic zone in for example the 316L welded specimen. The higher strength weld metal induces some plastic constraint at the crack tip, reducing plastic deformation or crack tip blunting. This results in the development of higher stresses in the HT HAZ. After a certain amount of crack tip blunting, transgranular cleavage cracks initiated in the HT HAZ prior to unstable brittle cleavage fracture in this zone (fig. 5.22).

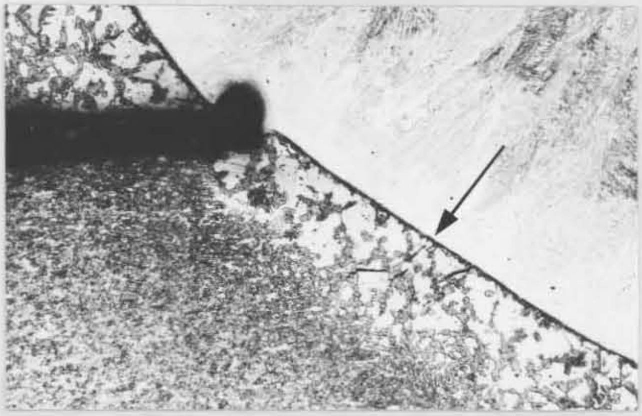


Figure 5.22: Crack tip blunting in the 308L weld metal of a FLNFT specimen during tensile loading. Small transgranular cleavage cracks have already initiated in the coarse grained HAZ. Compare crack tip blunting and δm value of this specimen with that of the 309L welded specimen in figure 5.20 (35X).

The FLNFT test specimens, welded with an E3CR12 weld metal, also fractured by cleavage in the HT HAZ of both fillet welds (modes 1 and 2, fig. 5.16). The high strength E3CR12 weld metal plastically constrained the crack tip from plastic deformation to a much greater extent in comparison with the 308L and 316L weld metals. Most of the crack tip blunting occurred in the lower strength, HT HAZ (fig. 5.12) before a cleavage fracture occurred. Table 5.2 shows that the δm value in this zone was only 0.15 mm.

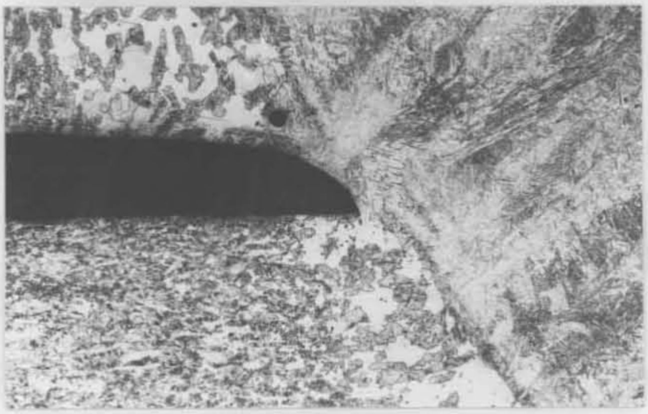


Figure 5.23: Crack tip blunting in an E3CR12 welded FLNFT test specimen during tensile loading. Incipient tearing has already occurred at the crack tip (270X).

Much higher maximum loads were reached with the E3CR12 welded specimens in comparison with the other specimens (table 5.2). This can be attributed partly to the shorter initial crack length of these specimens.

2.2.3b Low heat input (1.2 kJ/mm) test results

Complete joint penetration was not achieved at a weld heat input of 1.2 kJ/mm. A much larger initial crack tip radius resulted as shown in figure 5.24. Larger δm values were therefore measured for the FLNFT specimens welded at a low weld heat input (table 5.2). The largest δm value was again obtained with a 309L filler metal while the smallest δm value was again measured on the E3CR12 welded specimen.

Two of the three test specimens of both the 309L welded and 316L welded

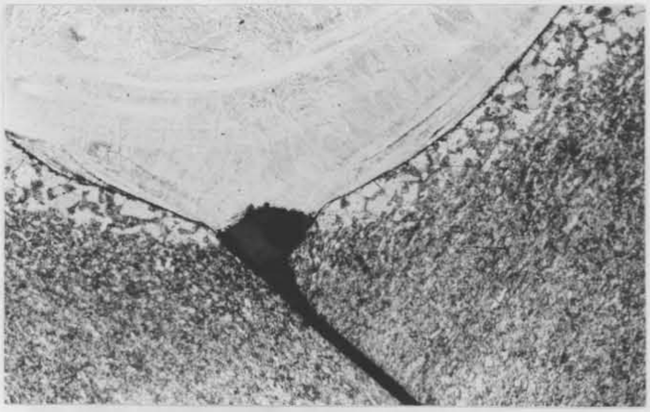


Figure 5.24: Through-thickness crack tip in an FLNFT test specimen welded with a 308L filler metal with a heat input of 1.2 kJ/mm. Note the incomplete joint penetration of the fillet weld (35X).

FLNFT test specimens fractured by tearing or ductile fracture in both fillet welds (mode 4, fig. 5.16). The third specimen fractured by ductile fracture in the one fillet weld and by cleavage fracture in the coarse grained HT HAZ of the second fillet weld (mode 3, fig. 5.16). The δm values for these specimens were smaller (0.91 mm for the 309L and 1.1 mm for the 316L welded specimen) than the average values reported in table 5.2. Sections of the fractured specimens (fig. 5.25) revealed that brittle

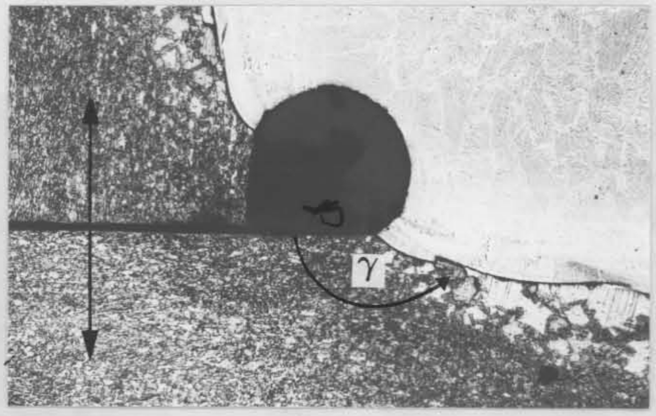


Figure 5.25: Incomplete joint penetration of a fillet weld in a FLNFT test specimen welded with a 309L filler metal. The direction of the principal stress during tensile loading is indicated (35X).

fracture occurred in the HT HAZ of fillet welds with even less joint penetration in comparison with the average joint penetration shown in figure 5.24.

In the case of incomplete weld joint penetration the relative orientation between the through-thickness crack and the fusion line (γ in fig. 5.25) is such that the coarse grained HAZ is subjected to a larger tensile stress than the same zone in a full penetration joint shown in figure 5.18. Since the fracture stress of the austenitic weld metal is higher that that of the HT HAZ, the incompletely penetrated fillet weld will be more susceptible to brittle cleavage fracture in the HT HAZ.

Sections through both the 309L and 316L welded and fractured FLNFT specimens which fractured by cleavage fracture in the HT HAZ of one of the fillet welds (mode 3, fig. 5.16), revealed that a ductile crack has also initiated and propagated in the weld metal of this fillet weld. Some stable crack extension therefore occurred probably in the weld metal prior to cleavage fracture in the HT HAZ. The detection of stable crack growth prior to fracture is extremely difficult with a conventional COD bend test specimen(17). With two through-thickness cracks in the FLNFT test specimen, stable crack extension prior to fracture has been positively identified (figs. 5.21 and 5.26). The δm values reported were therefore determined at maximum load (fig. 5.15).

Figure 5.26: Section through the fillet weld of a 309L welded and fractured FLNFT specimen which fractured by cleavage fracture in the HT HAZ of one fillet weld. The direction of propagation of the cleavage crack is indicated by an arrow.
Note also the ductile tearing in the weld metal (35X).

Table 5.2 shows that different δm values were obtained for the specimens welded with 309L, 316L and 308L filler metals, respectively in spite of similar maximum loads during testing and although the weld metal hardness is the same for the different weld metal compositions. The different plastic zone sizes (δm) may be attributed to different weld metal yield strength and different weld metal work hardening rates. A larger crack tip plastic zone will result with a lower weld metal yield strength and a lower weld metal work hardening rate.

The FLNFT specimens, welded with an E3CR12 filler metal, fractured by brittle cleavage fracture in the coarse grained HT HAZ of two fillet welds. A larger δm value (0.3 mm) was obtained for the specimen welded with a low heat input (1.2 kJ/mm) than the value of 0.15 mm for the specimen welded with a heat input of 1.4 kJ/mm. The larger δm value may be attributed to the low heat input and the incomplete penetration.

Table 5.2 shows, apart from the incomplete penetration effect, significant differences, between the low and high weld heat input test results of 308L welded specimens. At the lower weld heat input a much lower weld metal strength was obtained and the maximum applied load dropped. A fracture mode transition occurred and δm increased with 0.56 mm. These differences can be attributed to the formation of some low carbon martensite in the weld metal of the high heat input welds. This is due to a large dilution with the base metal (fig. 5.27). The low heat input weld metal exhibited only austenite and some interdendritic δ-ferrite structures (fig. 5.28).

Figure 5.27: Weld metal microstructure of a FLNFT test specimen welded with a 308L filler metal with a heat input of 1.4 kJ/mm. The microstructure consists of austenite, martensite and interdentritic ferrite (250X).

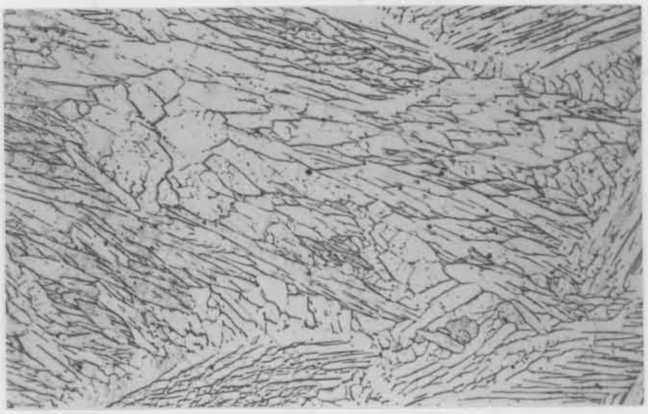


Figure 5.28: Weld metal microstructure of a FLNFT test specimen welded with a 308L filler metal with a heat input of 1.2 kJ/mm. The microstructure consists only of austenite and interdendritic δ-ferrite (250X).

The Schaeffler diagram in figure 5.29 was used to determine graphically the minimum percentage dilution which is required for the formation of martensite in 309L, 316L and 308L weld metals, respectively, during welding of 3CR12 (table 5.3). The chemical compositions of the different filler metals which were used to calculate the chromium and nickel equivalents are also shown in table 5.3.

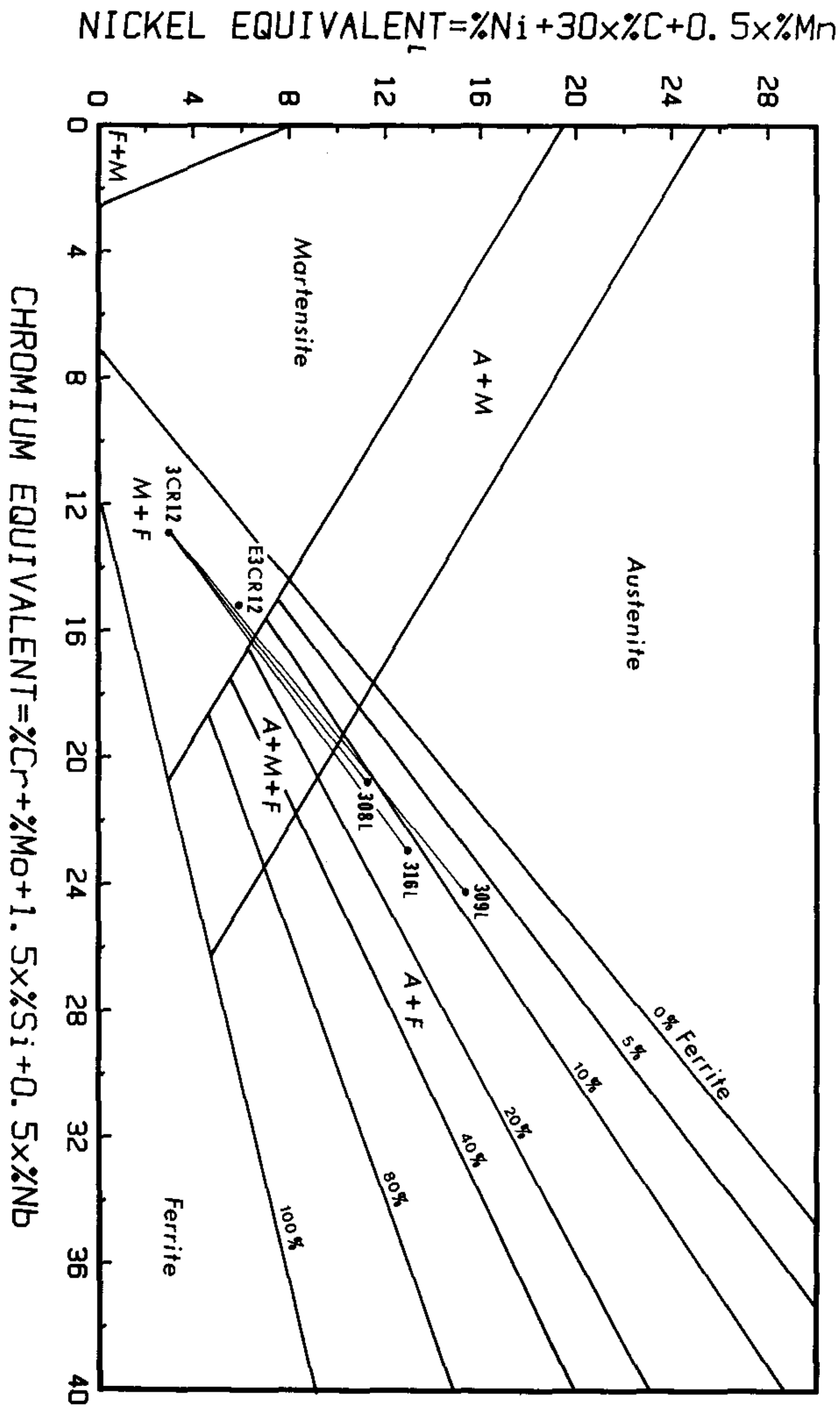


Figure 5.29: Schaeffler diagram. Superimposed on the diagram are the dilution lines for welding 3CR12 with 309L, 316L and 308L filler metals, respectively.

Table 5.3: Typical chemical compositions of AISI 309L, 316L and 308L filler metals. The critical dilution with 3CR12 base metal for martensite formation is also included.

Filler metal	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	% dilution
309L	0.02	0.40	2.20	0.015	0.015	23.5	13.5	-	43
316L	0.02	0.40	1.80	0.015	0.015	19.0	11.5	2.2	27
308L	0.02	0.40	1.80	0.015	0.015	20.0	10.0	-	16
E3CR12*	0.03	0.67	0.87	0.013	0.012	13.6	4.9	0.5	0

*Chemical composition obtained by chemical analysis of an MIG welded multilayer cladded 3CR12 plate.

Table 5.3 shows that more than 16 percent dilution occurred during welding with a 308L filler metal at a heat input of 1.4 kJ/mm, while less than 16 percent dilution occurred during low heat input welding. The absence of any martensite in both the 309L and 316L weld metals indicates that less than 27 percent dilution (table 5.3) occurred with the base metal during welding at a high heat input.

The microstructure of the high strength E3CR12 weld metal consists of low carbon martensite with some interdendritic δ-ferrite (fig. 5.30). Superimposed on the Schaeffler diagram is also the composition of the E3CR12 filler metal which is situated in the martensite-ferrite dual phase field.

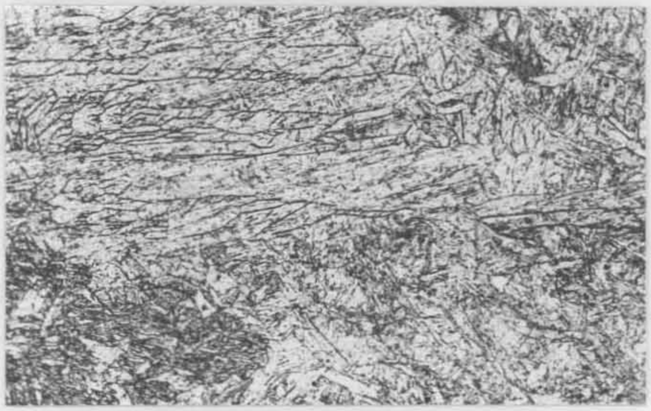


Figure 5.30: Weld metal microstructure of an FLNFT test specimens welded with an E3CR12 filler metal at a heat input of 1.2 kJ/mm. The microstructure consists of martensite and interdendritic δ-ferrite (250X).

3. GENERAL DISCUSSION

3.1 Filler metals for welding 3CR12

The bead-on-plate bend test results have clearly illustrated the cumulative effect of the base metal, weld metal and low temperature HAZ mechanical properties on the plane stress fracture behaviour of the narrow HT HAZ of welds on 3CR12 plate. In welds subjected to a high degree of restraint, the susceptibility of these welds to brittle cleavage fracture in the HT HAZ is primarily determined by the fracture toughness and mechanical properties of the weld metal. This fact was successfully confirmed with the FLNFT test. The susceptibility of welds to brittle fracture in the HT HAZ increased with higher weld metal yield-, tensile strength and work hardening rate.

The test results in table 5.2 indicate that the FLNFT test is a reliable test to compare different filler metals for welding 3CR12 plate. The choice of a certain filler metal will therefore determine the fusion line notch fracture toughness of welds on 3CR12. Although the E3CR12 weld metal meets the requirements on the electrochemical, fatigue and fracture toughness properties, this high strength weld metal has a detrimental effect on the fusion line fracture toughness of welds on 3CR12(15). It is therefore not recommended for welding 3CR12 in any critical structural type application.

Both the low and high weld heat input FLNFT test results in table 5.2 show that the highest fusion line fracture toughness (δm) for fillet welds on 12 mm 3CR12 plate was obtained with a 309L weld metal. Due to the high dilution capacity of this filler metal (table 5.3), satisfactory results are expected for dilutions up to 43%. At higher dilutions the fusion line fracture toughness will be reduced with the formation of some weld metal martensite. This filler metal is therefore recommended for welding 3CR12 for high integrity structural applications.

Satisfactory results were also obtained with both the low and high weld heat input specimens, welded with a 316L filler metal, although the fusion line fracture toughness of these welds are lower than the toughness values of the 309L welds (table 5.2). The mechanical properties of the 316L weld metal shown in table 5.2 indicate that the maximum dilution with the base metal did not exceed 27% during welding (table 5.3). At dilutions higher than 27% the fusion line fracture toughness will also be reduced as a result of the formation of martensite in the weld metal. In practice dilutions higher than 27% are common, depending on the weld joint design, the welding process and the weld heat input during welding. The following dilutions can occur with manual metal-arc welding:

a. Root run or square butt with gap : 30-40%
b. Single run fillet or normal cladding : 20-30%

TIG dilution varies from 20-35% for butt and fillet welds. MIG welds usually give 20-45% dilution, while submerged arc gives 30-50%. Fill passes of multirun welds can range from 0-45% depending upon the process and the exact position of the run. Careful control should therefore be exercised when welding 3CR12 with a 316L filler metal in order to limit the dilution during welding.

A type 308L filler metal is not recommended for welding 3CR12 due to the formation of martensite in the weld metal at dilutions exceeding 16%. The results in table 5.2 clearly show the detrimental effect of martensite formation in the 308L weld metal on the fusion line fracture toughness.

At this stage 309L filler metal appears to be the best filler metal for welding 3CR12. The major disadvantages of this filler metal is its high cost and the possibility of galvanic corrosion in certain environments. Neither the E3CR12 nor 309L filler metals, therefore meet both the mechanical (fusion line notch fracture toughness) and electrochemical requirements as a filler metal for welding 3CR12. In practice the specific application will dictate the choice of one of these filler metals.

The higher mechanical properties of the E3CR12 weld metal compared to those of annealed 3CR12 plate may be predicted from the Schaeffler diagram. The composition of any weld metal with matching electrochemical properties with the 3CR12 base metal will probably be situated in the martensite-ferrite dual phase field of the Scheffler diagram (fig. 5.29). Superimposed on the Schaeffler diagram in figure 5.29 is the composition of E3CR12. The mechanical properties of such an as-deposited weld metal will always be higher than that of the tempered 3CR12 base metal as a result of the relatively large amount of untempered martensite in such a weld metal.

3.2 Fusion line-defect orientation

It has been shown that the fusion line fracture toughness of the fillet welds of the FLNFT specimen is not only dependent on the weld metal mechanical properties but that it is also dependent on the relative orientation (γ in fig. 5.25) between the through-thickness crack (simulated fusion line defect) and the fusion line or HT HAZ. The relative orientation between a through-thickness crack and the fusion line is determined by the weld joint penetration and the welding process. Figure 5.31 shows a section through the fillet welds of an FLNFT specimen which was welded with the MIG process with a 1.6 mm diameter 316L filler metal and a heat input of 0.41 kJ/mm. The two simulated through-thickness cracks are indicated with arrows. The angle γ for the MIG welds in figure 5.31 is much smaller than that of MMA welds in figure 5.14. For similar weld metal mechanical properties the MIG fillet welds will be less susceptible (larger δm value) to brittle cleavage fracture in the HT HAZ than MMA fillet welds.

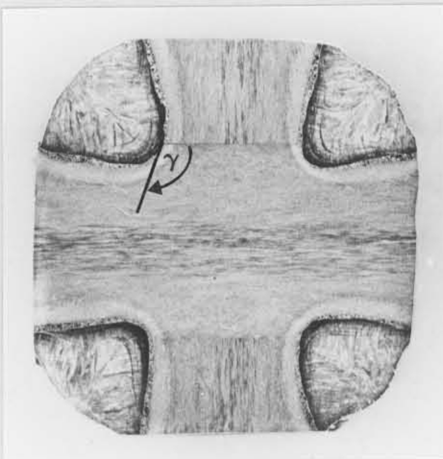


Figure 5.31: Section through the fillet welds of a MIG welded FLNFT test specimen.

The HT HAZ will be subjected to the maximum tensile stresses which develop at the through-thickness crack tip during tensile loading of the FLNFT specimen when the angle γ is equal to 180°. In practice this condition may occur with some fusion line defects such as incomplete joint and root penetration, lack of side-wall fusion, undercutting, slag inclusions, etc. A brittle cleavage fracture in the HT HAZ will then be inevitable during tensile loading since the fracture stress of the HT HAZ with 40% martensite is lower than the fracture stress of the austenitic weld metal. The weld metal mechanical properties will again determine whether a cleavage fracture will initiate from such a fusion line defect at the maximum design stress of the joint. The amount of crack tip blunting (δm value) which may occur at a certain design stress and which thus limits the maximum stress at the crack tip, is mainly determined by the weld metal yield strength and work hardening rate. For a particular design stress the susceptibility of a weld to cleavage fracture in the HT HAZ, with γ equal to 180° is increased by a higher weld metal yield strength.

As a result of the much finer grain size, the fracture stress of an austenitic weld metal, e.g. AISI 316L, with a yield stress similar to that of tempered 3CR12 plate, is much higher than the fracture stress of the coarse grained HT HAZ which contains for example 40% martensite. It therefore appears impossible to develop a weld metal with a yield stress matching that of 3CR12 base metal but with a fracture stress which is lower than that of the HT HAZ. This is only possible if the yield and fracture stress of the HT HAZ is increased by increasing the martensite content of this zone with the resultant reduction in grain size. The fusion line notch fracture toughness of a 316L weld on 3CR12Ni plate will thus be higher than that on 3CR12 plate due to the higher martensite content and fracture stress of the HT HAZ in 3CR12Ni.

3.3 Conclusion

It can be concluded that the FLNFT test is a more reliable test than the conventional bend and crossweld tensile tests for evaluating different filler metals for welding 3CR12. Although a 309L weld metal on 3CR12 greatly enhances the fusion line fracture toughness of welds, the very low fracture toughness of the HT HAZ is evident from the test results. It is therefore doubtful whether 3CR12 steel should be specified for any critical structural applications.

4. SUMMARY

a. The room temperature fracture toughness of the high temperature coarse grained HAZ of welds on both 3CR12 and 3CR12Ni steels is relatively low.

b. The fracture behaviour of the HT HAZ of defect-free bead-on-plate welds on 3CR12 and 3CR12Ni plate is dependent on the degree of restraint in this zone. The susceptibility of welds to brittle fracture in this zone increases at a higher constraint which is associated with a higher base metal and weld metal yield strength and work hardening rate.

c. A new test method has been developed for measuring the fusion line notch fracture toughness of fillet welds on 3CR12. Different filler metals for welding 3CR12 were characterised by evaluating the fusion line notch fracture toughness of welds. The susceptibility of welds to brittle cleavage fracture initiation, in the HT HAZ, from fusion line defects increases with a higher weld metal yield stress and work hardening rate.

d. A type AISI 309L weld metal is recommended for welding 3CR12 plate, especially for high integrity structural applications.

e. The maximum dilution should be limited when welding 3CR12 with a type AISI 316L weld metal.

f. Types E3CR12 and AISI 308L filler metals are not recommended for welding 3CR12 for any structural type applications.

g. The reliability and integrity of as-welded 3CR12 structures welded with even a 309L filler metal is questioned due to the very low fracture toughness of the HT HAZ adjacent to the fusion line.