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RESIDUAL STRESS AND DISTORTION IN SAMPLES OF COMPLEX GEOMETRY SUBJECTED TO SPRAY QUENCHING

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ABSTRACT

This paper discusses the residual deformation modelling of a complex shaped stainless steel AISI316L component heated to 900°C and quenched with a water spray subcooled to 80K. The paper shows that accurate deformation modelling of the problem necessitates not only an adequate mathematical formulation of the physical system but also the application of precise thermal and mechanical boundary conditions. Correlations of experimentally measured spatio-temporal heat transfer coefficients found valid for *spray* Reynolds numbers, $Re_s = Gd_d / \mu_f$, of $6\times10^{-2} < Re < 3$ and *spray* Weber numbers, $We_s = G^2 d_d / \rho_f \tilde{\sigma}$, of $4.6\times10^{-7} < We < 4.1\times10^{-2}$ used in the calculation are presented. These boundary conditions are used in a finite element model (FEM) to enable predictions of the deformation history of a complex geometry subjected to spray quenching. The results of the modelling are compared to the deformed shape of the processed component. The excellent agreement between the modelling and experiment suggest that the method used to analyse this problem is consistent and may be applied to determine the residual stress and strain formation of complex shaped components subjected to a spray quench with great accuracy. The results of this study provide the opportunity to do life assessments with reliable residual stress and strain predictions which may be applied to components such as electronic chips, aluminium extrusions or metal sheet rollers.

INTRODUCTION

The study of spray quenching has become a popular science recently for reasons that include relatively high heat fluxes during critical heat flux, increased processing controllability and potentially favourable residual stress formation after processing. However, despite of these advantages, complete benefit of the process is yet to be gained as many questions concerning the thermodynamics of this complex multiphase boiling process are still left unanswered. For instance, what is the effect of large spatial temperature gradients due to thermal mass variations on the local temporal heat flux and also residual stress and strain formation? In addition to this, it is not clear whether the spray quench boiling curve can be utilised efficiently during high temperature transient cooling operations as experienced during materials processing. Some reasons for these uncertainties may be in consequence of literature providing studies of heat transfer for either particular salient values on the boiling curve or only a selective region of the boiling curve (usually nucleate boiling) thus not presenting a complete description of the problem involved. This might provoke the perception that spray cooling is a highly effect cooling process. The evidence presented in this paper argues the contrary. The boiling correlations presented indicated ineffective cooling using this technique at temperature greater than the minimum flux condition of the spray. It is argued that in addition to speculating the high heat fluxes possible during the nucleate boiling regime, it must be mentioned that this regime is particularly narrow when considering a water spray quench at atmospheric conditions. This should be of particular interest to engineers working with cooling of high temperature systems because it can immediately be recognised that the only cooling regime that can be taken advantage of during high temperature transient cooling is the film boiling regime. This regime has a very stable but considerable lower heat transfer coefficient than during nucleate boiling and is the active mechanism of heat transfer above and beyond the rewetting temperature of the fluid which may be as low as 250°C for water. The same is true for temperature controlled heating processes in that the effective cooling regime at critical heat flux is but a peak on boiling curve, as supposed to a broad ‘plateau’ like regime during bath quenching. A small perturbation of temperature away from the critical heat flux temperature may therefore result in a remarkable change in heat flux for a spray in both the heating and cooling directions. Figure 1 shows an example of residually deformed aluminium extrusion after spray quenching.

Figure 1 Warped aluminium extrusions subsequent to a spray quenching.

This paper therefore addresses some of the key issues of spray cooling that might be misinterpreted. It furthermore focuses particularly on the development of thermo-mechanical finite element model of spray quenching with experimentally measured heat transfer boundary in the form of empirical correlations applied to it. This is done to emphasize the importance of recognising the full spatial dimensionality of this transport phenomenon to enable accurate residual stress and strain interpretation subsequent to processing. The validity of the heat transfer correlations presented is herein are tested by means of comparison of spatial temperature distributions and residual deformation of a processed component with complex shape.

The term “complex shape” in the context of this paper refers to geometry with distinct varying distributions of thermal mass. The authors of [1] have studied residual stress formation of axis-symmetric models while those of ref. [2] studied the thermal problem associated with a complex component. Neither of these however addressed the combination of residual deformation and exact temperature of complex shaped components. The contribution this research makes may be measured by i) the presentation of empirical heat transfer correlations of spray cooling over a wide range of droplet Reynolds and Weber numbers, ii) the validation of these correlations with respect to experimentally measured spatio-temporal temperature distributions and heat fluxes and iii) residual deformation prediction of a complex shaped component subjected to a spray quenching. The results proved may therefore be beneficial to scientists and engineers utilising sprays in high temperature cooling operations as those found in material processing applications or direct cooling operations of sheet metal rollers.

EXPERIMENTAL

Two sets of experiments are presented in this paper. In the first instance experiments were done to determine the heat transfer rate of a water spray followed by spray quench experiments of a complex shaped component. The majority of experiments found in the literature focused on spray heat transfer characterisation involve measuring the heat transfer from a cylindrical specimen or relatively small rectangular sections of aluminium, stainless-steel or platinum typically fully insulated from the environment. Almost all data in the spray cooling literature has been collected using heater areas smaller than 2 cm^2 for single nozzles or small nozzle arrays [3], and in all cases the heat transfer characterisation was done under steady state conditions by varying the electrical power input to the heater. Such experiments are usually accompanied by temperature measurements using thermocouples and heat transfer coefficients calculated by solving the one-dimensional Fourier heat conduction equation. However, a spray’s heat transfer coefficient is highly dependent on space and temperature. Nozzles with monotonically varying droplet flux fields as that of pressure atomised full or flat cone nozzles produces a maximum heat transfer coefficient at the position of maximum droplet flux. For these nozzles, the position of maximum droplet flux is at the geometrical centre of the spray and is therefore also the position where maximum heat transfer is achieved. In addition, ref. [4] illustrated that the spray heat transfer decays from this maximum, in space, towards areas of lower spray flux. Therefore, when considering small heater areas exposed to a spray, as discussed in the literature, the effects of the spatial degradation of the heat transfer coefficient is not considered. Mudawar (see for instance [5]) speculated this behaviour on numerous occasions but have yet to provide experimental evidence thereof. The experiments presented here were design to overcome this problem by enabling a more thorough examination of this phenomenon. The characterisation of the space and time dependence of the heat transfer of the sprays analysed in this study was done by in situ infrared (IR) measurement of temperature distributions of spray-quenched aluminium alloy (AA6082) specimens. The reduction of spatio-temporal heat transfer coefficients from infrared thermographs and the spray hydrodynamic parameter associated with these experiments are discussed elsewhere [4]. However, to summarise, thin aluminium alloy plates were heated to above 500°C and quenched with subcooled water of 80K under varying operating pressures. This set up was chosen because of the material’s particularly good thermal properties; to ensure low through thickness thermal gradients in the plate. Infrared thermographs were collected during the experiments and were analysed using a finite volume technique discussed in ref. [6] to compute spatio-temporal spray quench heat transfer coefficients by assuming negligible through (plate) thickness thermal gradient. The thin layer assumption is justified by making a quick calculation of the thermal gradient through the plate; for a plate of thickness 3mm heated to say 400°C having a thermal conductivity of 227W/mK and experiencing film boiling on its surface with a heat transfer coefficient in the order of 400W/m^{2}K, a temperature gradient of 0.95°C exists. It is recognised that the gradient will increase during critical heat flux conditions however, the nucleate boiling heat flux dome is particularly narrow [1] for spray quench processing and the time integrated error will therefore be negligible. The exact experimental set up associated with these experiments from which the correlations shown in Table 1 were computed is described in [4].

Conductive cooling of heat-generating volumes has been approached by other researchers as a volume- or area-to-point heat transfer problem [5]. Thermal tree theories have been developed to describe the distribution of low thermal resistant paths and heat transfer has been optimised for different thermal tree structures [6-8].

Even though thermal tree schemes present optimised heat transfer performance, it requires complex geometric layouts which at small dimensional scales can lead to high manufacturing costs. In passive power electronic modules, which typically have inductive, capacitive and transformative functions, restrictions imposed by the electromagnetic fields, dictates that only parallel-running internal embedded solid geometries can be considered. Such layouts, when placed in-line with magnetic field lines reduces the interference a cooling insert may have on magnetic and electric field distribution. Three-dimensional thermal path networks are thus not suitable for such applications

In a previous investigation [9], the thermal performance of a grid of discrete parallel-running rectangular solid inserts were studied and geometrically optimised in terms of fixed volume use. At the dimensional scale of interest in power electronics and electronics cooling, it was found that the geometric shape of embedded cooling inserts has a diminishing influence on thermal performance and that the fraction of volume occupied by the cooling system plays a much more dominant role [10]. With this in mind it may be appreciated that from an economic and manufacturing point of view, continuous cooling layers provides a more practical embedded conductive cooling configuration. This paper focuses on thermal characterisation of cooling layers and aims to provide some information on thermal cooling performance.

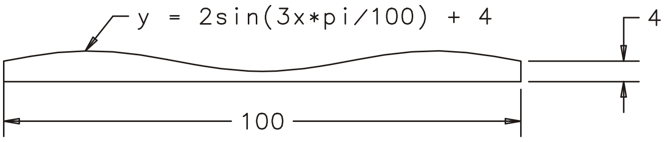

Figure 2 Illustration of specimen dimensions.

CORRELATIONS

The correlations shown below were determined in accordance with the optimisation procedure described in [4].

$$\vartheta_{min} = 62760\left(\rho_g H_{fg} Q\right)^{-0.409}\left(\frac{\tilde{\sigma}}{\rho_f Q^2 d_{32}}\right)^{-0.206}$$

$$h_{min} = 3\times10^{-6}\left(\rho_g H_{fg} Q\right)^{1.49}\left(\frac{\tilde{\sigma}}{\rho_f Q^2 d_{32}}\right)^{0.67}$$

$$\vartheta_{chf} = 388953.72\left(\rho_g H_{fg} Q\right)^{-0.558}\left(\frac{\tilde{\sigma}}{\rho_f Q^2 d_{32}}\right)^{-0.29}$$

$$\vartheta_{chf} = 9.5\left(v_d^{-0.271} d_{32}^{-0.460} Q^{0.107}\right)$$

$$h_{chf} = 3.34\times10^{-7}\left(\rho_g h_{fg} Q\right)^{1.89}\left(\frac{\sigma}{\rho_f Q^2 d_{32}}\right)^{0.82}$$

$$h_{chf} = 4544\left(v_d^{0.325} d_{32}^{-0.127} Q^{0.134}\right)$$

$$h_{local} = h_{max} - \left(1 - \frac{h_{chf,local}}{h_{chf,max}}\right)\left(h_{max} e^{-\left[\frac{\left(\vartheta - \vartheta_{chf}\right)^2}{\zeta\left(\frac{h_{min,max}}{h_{min,local}}\right)}\right]}\right)$$

The correlations above indicate that when operating a flat spray nozzle with water sub-cooled to 80K that the rewetting temperature at the geometric centre of the spray occurs around ϑ_{min} = 250°C, critical heat flux at ϑ_{chf} =130°C. The saturation temperature at atmospheric pressure is $\vartheta_{sat} \approx$ 100°C therefore indicating a that the high heat flux regime associated with this cooling process in confined to temperature range of $\Delta T \approx$150K. Furthermore, within this very narrow temperature domain the convective heat transfer coefficients varies between 400 W/m^{2}K at minimum heat flux and 16000 W/m^{2}K at critical heat flux indicating that small perturbations in temperature around the critical heat flux condition result in large flux differentials.

Following the latter experiments stainless steel AISI316L specimens were prepared to investigate if the correlations listed in Table 1 could be used to determine residual stress and strain formation due to spray quench processing. The specimen geometry, shown in Figure 2, was chosen to produce sections of variable thermal mass. The specimens were wire eroded from a 100mm by 100mm plate of 10mm thickness to reduce residual stress due to the manufacturing process. After preparation the specimen was heated to 900°C and the quenched with a 80K subcooled water spray operating under 5bar pressure using the JAQ1153 flat spray nozzle supplied by PNR nozzles UK. The specimen was quenched on its curved face.

VALIDATION OF THERMO-MECHANICAL MODELLING

When considering a general rectangular three-dimensional heat-generating solid, three main external boundary conditions types can be considered, namely heat transfer to the surroundings in a singular Cartesian direction with adiabatic conditions for other directional external surface sets, orthogonal bi-directional heat transfer to the surroundings with the other external direction being adiabatic, and a case with tri-directional heat transfer to the surroundings.

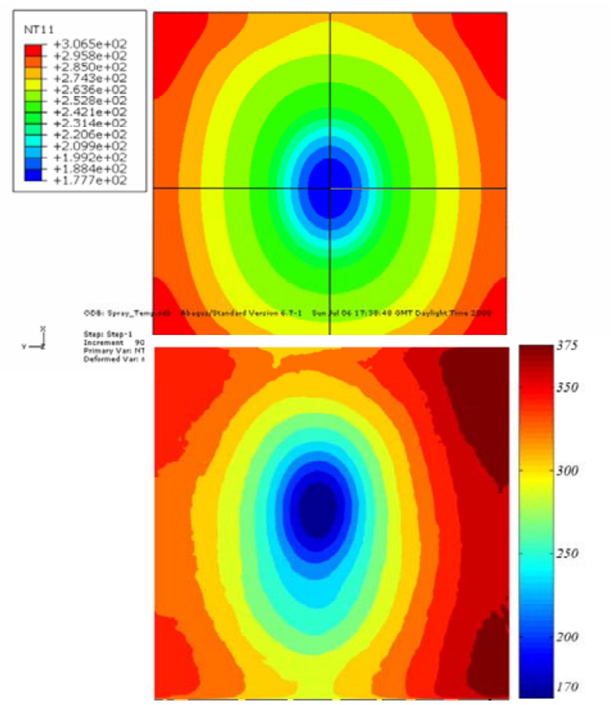

Figure 3 Illustrations of spatial temperature distributions a) modelled using FE and applying the heat transfer correlations in Table 1 as thermal boundary conditions and b) that measured experimentally using thermography.

On this basis it is speculated that an accurate description of the thermodynamics associated with the spray, or indeed the thermal strain evolution due to this cooling technique is provided and may be used to determine the residual deformation with great accuracy. Notice the particularly narrow nucleate boiling regime produced by the spray cooling. The rewetting condition associated with this process is evidently around 245°C.

The residual deformation of the component shown in Figure 2 was computed by applying the above correlations as thermal boundary conditions to a fully coupled thermo-mechanical analysis. The geometry was represented by parabolic tetrahedrons to enable capturing the nonlinear displacement gradients. The heat flux correlations were described in the DFLUX user flux routine provided by the Abaqus finite element software. The results of the analysis are shown in the following figures. Figure 5a shows a very crude measurement of the residual deformation of the specimen. The total deformation of specimen is seen to measure approximately 2□=8.5mm. The out of plane deformation of the specimen was measured using a coordinate measuring machine and was found to be negligible. Figure 5b shows the computed deformation of the specimen. The material constitutive model of this material is discussed in ref. [7]. The model predicts a displacement of 2□=8.34mm which is very similar to that measured in Figure 5a therefore providing evidence that the modelling of this thermo-mechanical process was well interpreted and implemented.

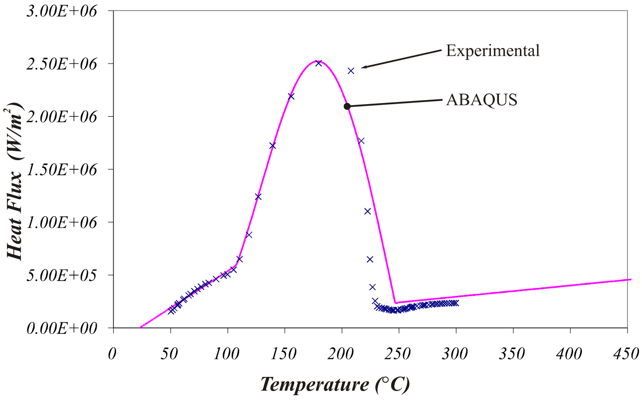

Figure 4 Comparison of measured and modelled heat flux at the centre of the spray nozzle.

The good agreement of the model and experiment allows further investigating of parameters such as residual elastic strain and stresses subsequent to this processing shown in Figure 6a and Figure 6b and inelastic strain shown in Figure 6c. These distributions indicate that plastic flow is confined within the surface regions of the thin section. This result is to be expected as the combination of thermal stress and bending stress are most like to cause plastic flow at this location. Finally Figure 7a to Figure 7c illustrates the movement of the critical heat flux wave over the surface of the specimen indicating its initiation at the centre of the spray, in line with the geometric centre subsequently moving towards the edge of the specimen. It is important to match this exact behaviour because it is for this reason that the thermal strain in greatest at the centre where the critical heat flux initiates therefore resulting in the flow condition in this region to be initiated.

CONCLUSION

The conclusions that can be drawn from this analysis is that exact application of both mechanical and spatio-temporal thermal boundary conditions are necessary to accurately model the deformation and hence residual stress and strain distributions through the specimen. It may be concluded from the accuracy in the deformation predictions that the heat transfer correlations used in this analysis captures the thermodynamics of the process accurately. It can further be concluded that the particularly low rewetting conditions for a water spray makes the process inefficient for the purpose of microstructural modification processes. The stable film boiling regime may be exploited for even cooling processes. Residual stress and strain within the narrow nucleate boiling dome may be the result of premature failure of electronic chips or similarly brittle components operating at temperature comparable to that at critical heat flux.

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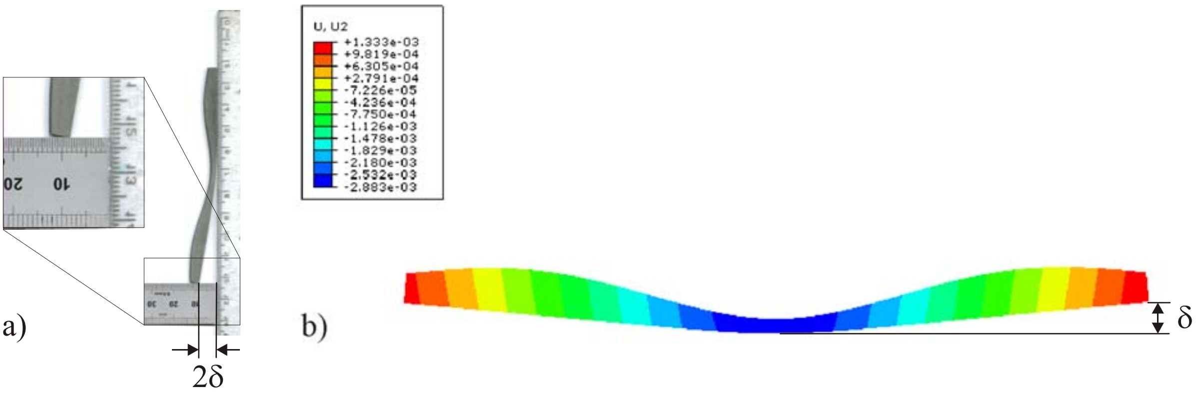

Figure 5 Comparison of the a) measured and b) modelled displacement of the specimen after processing.

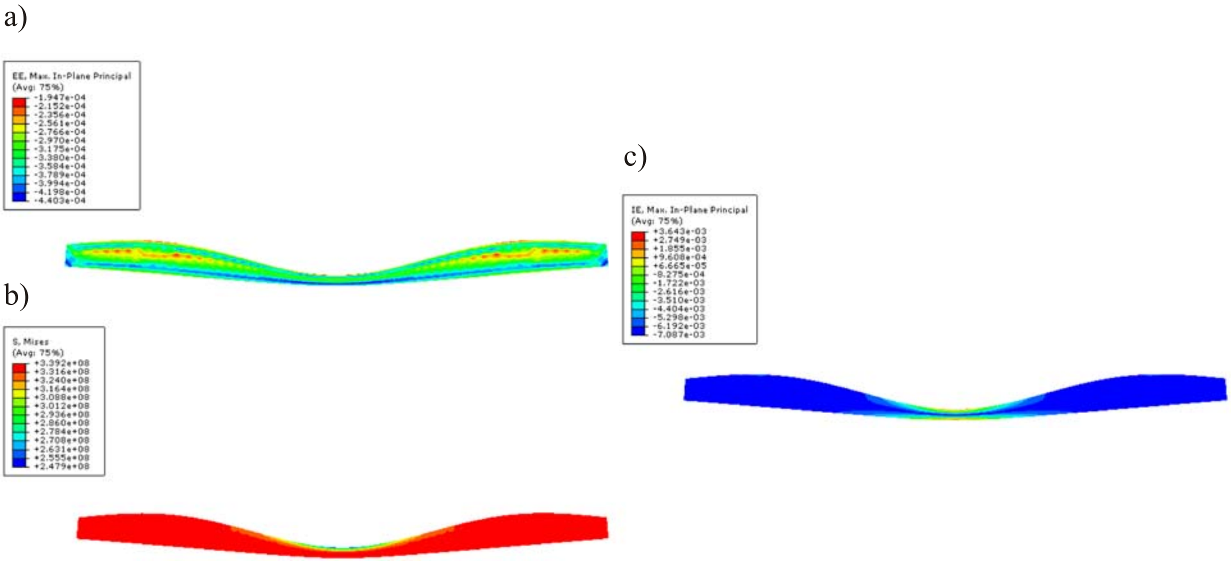

Figure 6. Figure showing a) the residual elastic strain, b) residual stress and c) inelastic strain.

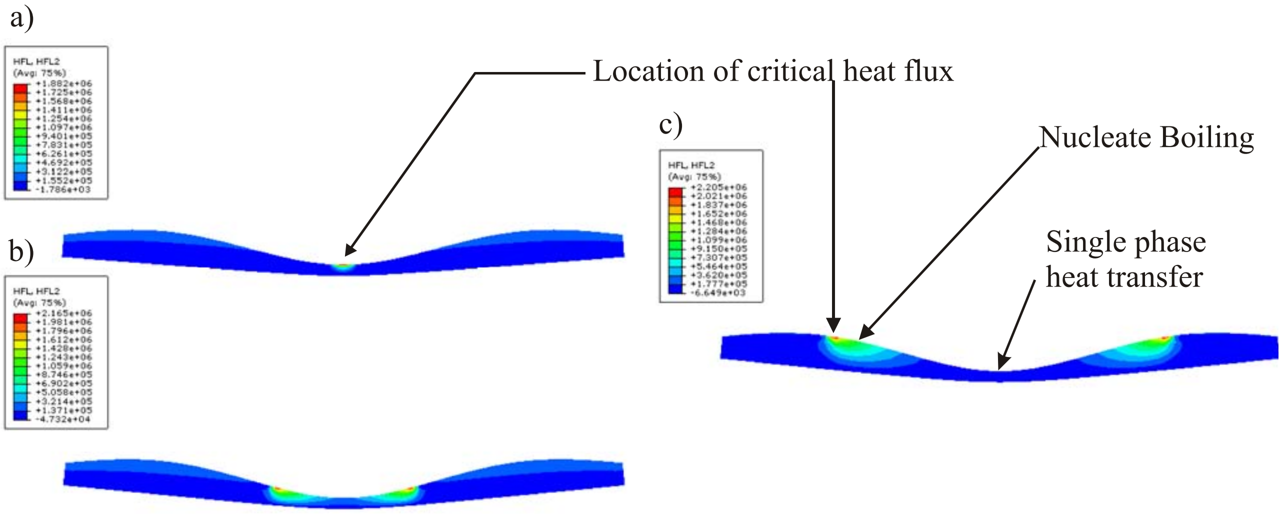

Figure 7 Illustration of a) the initiation of critical heat flux, b) the movement of the critical heat flux to the specimen edges in time and c) a snapshot showing critical heat flux, nucleate boiling and single phase heat transfer existing simultaneously