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Two-Dimensional Finite Element Modelling Of Transient Temperatures in Flash Butt Welded Bars

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Abstract-Flash butt welding is a resistance type metal joining process designed to produce butt welds between two materials of similar cross section. The primary objective of this study was to develop numerical simulation technique for prediction of temperature histories in flash butt welded bars. Welding process variables that affect temperature which were examined include; pre-heat, boundary convection severity, flash duration and material properties. Temperature profile plots were along the longitudinal and radial directions of the bar. The effect of nodal densities on temperature values at a point was examined. Finite element software ANSYS 16.0 was used to solve the quasi-linear thermal transient equation. Non-uniform plane77 mesh size was used in order to allow for higher concentration of nodes around the heat affected zone (HAZ). Applying a bar diameter of 25 mm, length 250 mm and flash duration of 4 seconds, indicated peak temperature values were 1400, 1238.9, 910.18 and 650.68 ^{0}C at distance 0, 1, 3 and 5 mm from the weld flash line. Peak temperatures generally increased with increased pre-heat condition and flash duration. Simulated peak temperatures were compared with weld temperature results of other related works and close correlations were observed.

Keywords-Flash Butt Welding, Finite Element Method, Flash Duration, Simulation, Temperature History, ANSYS 16.0

I. INTRODUCTION

Welding is one of the most efficient permanent metal joining processes in industry. It is applied in many endeavours such as; transportation, automobile, shipbuilding and aerospace. A localized fusion zone is generated in the weld joint because of high heat input from the arc and then non-uniform temperature distribution is induced due to heat conduction [i]. Flash-butt welding is a resistance welding process in which an electric potential is setup between two pieces of metal of the same cross section which are clamped side by side resulting in a current flow through the circuit. The heat generated is sufficient to produce a plastic state and the weld is completed by the application of an upset force [ii].

Although welding is an efficient and practical metal joining process, welding defects influence the mechanical properties of welded joints. Thermal cycles influence parameters such as residual stresses, weld microstructure, HAZ hardness and deformation. It is therefore important to control the thermal cycle as much as possible [ii]. The first critical step in predicting weld induced imperfections like residual stresses, deformations and weld solidification cracking is to accurately compute the transient temperature fields during welding process and subsequent cooling rate values [iv]. Other resulting properties can be correlated with temperature histories during welding and cooling.

There are three approaches to determination of temperature in welding namely analytical, numerical and experimental methods. Generally, analytical procedures give exact solution for temperature values. Although numerical methods give approximate solution, its flexibility and capacity to consider various factors that affects temperature profiles and histories has made it popular amongst researchers today. Due to the high costs of experimental procedures and its limitations in the area of capturing the effects of various parameters on temperature profile, it is mostly used to validate certain aspects of analytical and numerical models. The numerical model can then be expanded to determine the influence of other factors and parameters on the welding process.

The authors of [v] analyzed thermal histories at various points along the length of a circular section subjected to flash butt welding using the finite difference method. It was a one-dimensional nonlinear thermal numerical simulation and finite difference approach was used in the computational model. Simulated temperatures of the work-piece were found to increase as the preheating increased. A study was carried out on welding temperature distribution in thin welded plates through experimental measurements and finite element simulation. Three-dimensional finite element simulation was employed to predict the temperature distributions throughout the plate using

ABAQUS. The study showed that the peak temperature decreases as the distance from the weld melt line increases. The temperature decrease trend along the plates was nonlinear [iii].

The objective of [vi] was to illustrate thermal histories and longitudinal residual stress on two sides of the butting surfaces using advancing retreating factor. The uncoupled thermo-mechanical equations were solved using a nonlinear finite element code ABAQUS. Heat convection coefficient was found to predominantly affect temperature distribution. Finite element simulation of residual stresses in butt welding of AISI 304 stainless steel plates was discussed in [vii]. Using finite element based software ANSYS, coupled thermal-mechanical finite element model was developed and employed to evaluate the transient temperature and residual stress fields during welding. It was concluded that residual stresses are high in and around the weld zone because very high temperatures are attained around this zone [vii, viii].

Finite element simulation of temperature profile during welding was done with COMSOL Multiphysics using Rosenthal's approach. The influence of variations in thermal conductivity and specific heat with temperature was considered and found to have a major effect on the temperature profile during welding [ix]. The authors of [iv] carried out numerical simulation of arc welding investigation of various process and heat source parameters by using author's written subroutines in ANSYS. The study combined numerical simulation and experimental validation to study the temperature distribution and prediction of fusion zone and heat affected zone in gas tungsten arc welding of low carbon steel. A sharp drop in temperature was observed after peak temperature was attained close to the weld line. The rise and fall of temperature becomes increasingly less steep the further the distance from weld line [iv, x].

Numerical investigation of heat transfer behaviour during tungsten inert gas welding of stainless steel pipes for various welding heat input conditions was carried out. The contour plots of various heat input values were presented. This shows increased peak temperatures as the welding heat input was increased [xi]. Authors of [xii] developed pseudo steady state condition solutions for moving heat source over semi-infinite solid made of ferrous metal. Mathematical expressions were constituted to describe temperature distribution in the welded material and temperature history at evaluated nodes. These mathematical expressions were then converted into MATLAB subroutine to produce graphs of temperature distribution and temperature histories for certain welding parameters. The steepness of the rise and fall of temperature was found to decrease as the distance from the center increases.

A one-dimensional finite element modeling of temperature profile in axi-symmetric flash butt-welded steel rods was carried out in[xiii]. It was observed that sharp drop in simulated temperature occurs immediately after peak temperature was attained. Peak temperature was found to also increase with increase in flash duration and plastic temperature of metal. Much is not available in literature on works done on flash butt welding process. One of the most recent works was carried out in [xiii]. However, it was done in one dimension using manual coding in MATLAB to solve related equations. This research work presents a two-dimensional analysis using a well-established finite element based software ANSYS.

Changing material properties with temperature have been factored into simulation in previous works and it was found to have remarkable effect on temperature histories and profiles [iii, x, xiv]. These properties were essentially gotten from elaborate experimentation done by other researchers. This can be factored into simulation depending on available means within the software being used.

It is advisable that before a typical flash butt welding process is carried out, the process parameters should be spelt out as concisely as possible. The first critical step in predicting weld induced imperfections like residual stresses, deformations and weld solidification is to accurately compute the transient temperature fields during welding process and subsequent cooling [iv]. Other resulting properties can be correlated with temperature histories during welding and cooling. In essence, three main methods are available for the determination of temperature profiles in welding. They are analytical, numerical and experimental methods.

In simple models, calculus, trigonometry and other mathematical techniques can be used to find a function which gives the exact solution of an equation. This is called analytic solution. In welding analysis, it involves the constitution of mathematical expressions to describe temperature distribution in the welded material and temperature history at evaluated nodes. These mathematical expressions can then be converted into a MATLAB subroutine to produce graphs of temperature distribution and temperature history for certain welding parameters [xii]. Rosenthal equation, Gaussian heat flux distribution and Goldak's approach are some of the analytic procedures that are used in determination of temperature history in welding.

There are problems for which there is no analytical solution or for which the analytical solution comes with so much challenges. This is the reason why numerical solutions are sought. Numerical solution entails inventing a mathematical model and finding the differential equation that embodies the physics. The next step is getting the computer to solve the equations, a process that is known by the name numerical analysis. Finite element methods (FEM) and finite difference methods (FDM) are common amongst the numerical methods.

In the FDM, the governing equation is discretized whereas in the FEM, the region or continuum of the system is discretized. In FEM, a typical element, e is the interval between two nodal points, i and j whereas in the FDM, the nodal point number is also used to name the region surrounding the nodal points. When more complex geometries are to be analyzed, FDM becomes harder to implement and its demands for computational power increase excessively. Technically, the nature of the problem and the solution technique adopted determines the advantages of one method over another in terms of the numerical properties such as convergence and stability [xv, xvi].

Numerical simulation methods applied to flash butt welding provides a good understanding of the process and can be utilized in the definition of optimum operating parameters and prediction of the final quality of the welds. Computer modeling is a cost and time saving option relative to experimental procedures [xvii].

II. THERMAL ANALYSIS AND MODELLING

Simulation process starts by defining correctly the initial and boundary conditions. These are fed into the software and property variation with temperature is applied through subroutines in the program. Differential equations defining the process are then used to calculate the variables after specified time step intervals. Two-dimensional Fourier equation is used to model the heat transfer state and temperature variation with time and then solved through finite element methods.

Precise analysis of temperature fields in flash butt welding requires the use of finite element methods due to the complexity of the mathematics involved. A two-dimensional finite element model was developed in this work. Evaluation of temperature field is based on solving Fourier transient heat transfer equation while applying relevant boundary conditions. Material property dependency on temperature was factored into the computation while suitable time-steps towards fast convergence and grid spacing concentration at high temperature gradient points were applied. Fig. 1 is the schematic diagram of flash butt welding of two bars of circular cross section. Partial fusion takes place at the contact surface of the two bars achieved through application of heat and pressure [xviii]. Conductive heat transfer occurs in axial direction and in the radial directions. Heat loss by convection and radiation are principally at the bar boundaries and circumferential surface.

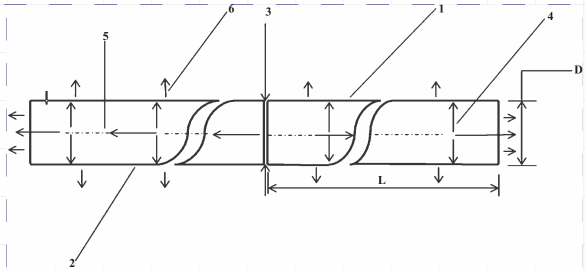

Fig. 1. Heat transfer mode in flash butt welding
1, 2 - Welded bars, 3 - Flash line, 4 - Conduction in radial direction, 5 - Conduction in axial direction, 6 – Convective heat, D - Bar diameter, L - Bar length

A. Governing Equations and Assumptions

After the electric power is activated and flash occurs at contact points of the bars, an interface temperature was assumed for all points located at the interface boundary. The generalized equation governing heat transfer is [xvi, xix]:

$$\frac{\partial}{\partial x}\left(k(T)\,\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\,\frac{\partial T}{\partial y}\right) + Q_o(T,t) = \rho(T)C_p(T)\,\frac{\partial T}{\partial t} + P\beta(T_s - T_\infty) \qquad (1)$$

where ρ is the density, C_p is the specific heat capacity of the material, k is the thermal conductivity, T is the temperature and t is the time, $P\beta\ (T_s - T_\infty)$ represents convective heat transfer where P is perimeter, β is coefficient of convection and Q_0 represents the internal heat generation term. Temperature dependent material properties are depicted in the equation.

The following assumptions were made:

- Heat losses by convection are considered only at the circular end and curved surfaces of the circular rod.
- Phase change effects are neglected.
- Heat transfer by conduction is along axial and radial directions only.
- Effects of work-piece support fixtures and current conductors are neglected.
- Internal heat generation is assumed to be zero.
- Perfect symmetry is assumed at weld interface.

B. Finite Element Modeling of Welding Process

Finite element software ANSYS 16.0 was used for the thermal analysis. A cylindrical bar having properties corresponding to low carbon steel was used in test running the program. The temperature-dependent material properties were factored into the program [xiv].

Cylindrical bar diameter was 25 mm and length was 250 mm. Around the HAZ region up to 25mm from the flash line, refined grid size of 0.5mm was used. Beyond that, a uniform grid size of 1.25mm was used, thus saving computational time. Boundary temperature at the flash line was taken as 1400°C being plastic state temperature of mild steel. It is customary to use combined heat loss boundary condition due to the difficulties associated with radiation modelling [iii]. Combined thermal radiation and convection coefficient between the work piece and the surrounding is therefore taken as 50 W/($m^{2\cdot 0}$C) [xiii]. Interface boundary is assumed to be adiabatic, with one-half of weld system modeled on assumption of symmetry. Ambient temperature and initial temperature of the work piece is taken as 35°C. The solution method used is Quasi-Linear Thermal Transient Solution in ANSYS. Element type is Plane77 (Total number of nodes - 29, 465, Total number of elements - 14, 466). Processor model is Intel(R) Core(TM) i5-3470 CPU @ 3.20GHz. Computational time for the test run was 249.5 seconds. Weld flash duration was 4 seconds.

Fig. 2 and 3 shows temperature field at the end of flash duration of 4 seconds and at the end of cooling time of 120 seconds respectively.

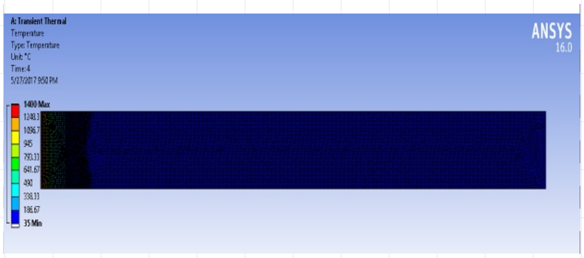

Fig. 2. Temperature field along the bar at 4 seconds

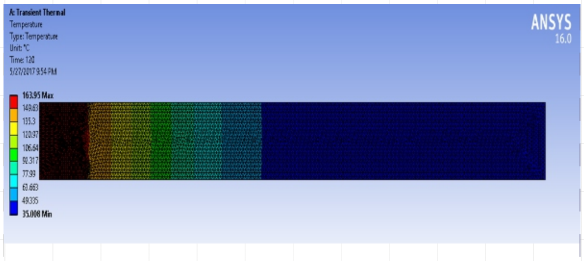

Fig. 3. Temperature field along the bar at 120 seconds

II. Results and Discussion

A. *Temperature Profiles at Selected Points*

Fig. 4 shows temperature profiles at 4 seconds flash duration within the HAZ. Peak temperatures of 1238.9, 1073.5, 910.18, 760.62 and 650.62 °C were attained at distance 1, 2, 3, 4 and 5 mm respectively from the weld flash line. Flash peak temperature at bar center was pre-fixed at 1400 °C. Slight differences in peak temperature attainment time were due to time-dependent heat flux from the flash line to the respective points by conduction.

The rate of heat convection to ambient is directly proportional to surface nodal temperature. Therefore, convective heat transfer is more rapid during the initial 20 seconds when temperature was relatively high in the heat affected zone and becomes increasingly less rapid as the bar approaches equilibrium temperature [iii, v, xx].

Simulated peak temperature at 5 mm distance was 650.68°C which compares favourably with findings of [xii] in arc welding using the Rosenthal's approach for semi-infinite solid. He obtained a peak temperature of 710°C at distance 5 mm giving a disparity of 59.32°C (*8.35 %)*. At a distance of 4 mm, peak temperature of 760.62 °C was observed in this model while 800 °C was obtained at the same distance in [xii] indicating a disparity of 39.38 °C (*4.92 %*).

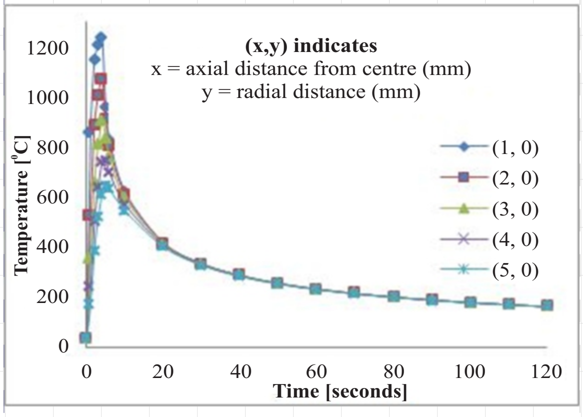

Fig. 4. Temperature histories around HAZ

B. *Peak Temperatures Variation Against Distances from Weld Flash Line*

Fig. 5 shows the variation of peak temperatures with axial distances from weld flash line at a flash duration of 4 seconds. The trend of temperature decrease with distance is non-linear. This is likely to be due to convective heat losses at the interface with the surrounding and the variation of material properties with temperature. Beyond 100 mm, the difference between successive peak temperatures becomes very small. Therefore length of the bar has little effect on thermal profile along the bar beyond this distance.

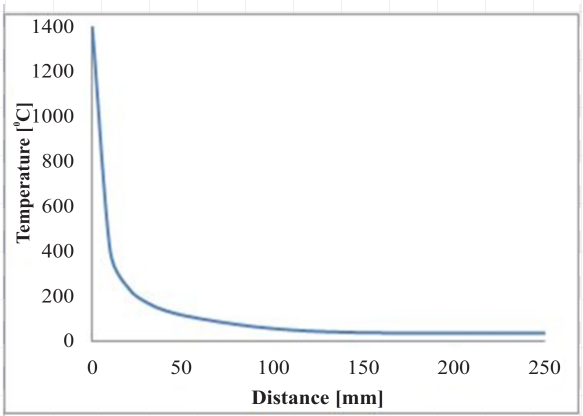

Fig. 5. Peak temperatures variations with axial distance

Fig. 6 shows the variation of peak temperatures with radial distances during cooling. Maximum temperature occurs at radial distance of 0 mm and decreases towards the surface of the bar. The trend of temperature decrease with distance is non-linear. This is likely to be due to convective heat losses at the interface with the atmosphere and the variation of material properties with temperature.

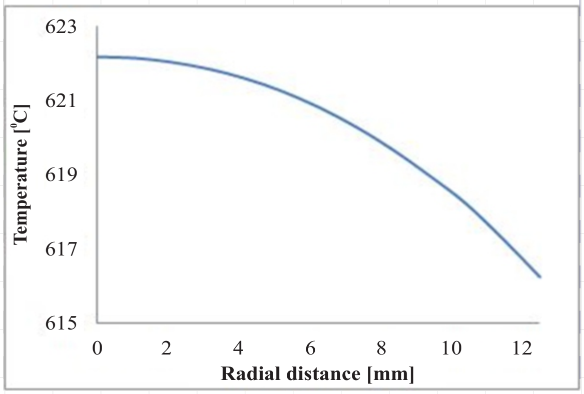

Fig. 6. Peak temperatures variations with radial distance

C. *Temperature Profile under Different Preheat Temperatures*

Fig. 7 shows temperature profiles at different preheat conditions at an axial distance of 2 mm from the weld flash line. Peak temperatures of 1086.90, 1109.60 and 1132.80^{0}C were attained under preheat conditions of 100, 200 and 300 ^{0}C respectively. These correspond to14.7, 37.4 and 60.6^{0}C (*1.37, 3.49 and 5.65 %)* increase in peak temperatures respectively relative to a non-preheat condition of 35^{0}C. At a distance of 10 mm from the flash line under a similar set of conditions, 37.21, 95.29 and 154.68^{0}C (*9.36, 23.97 and 38.91 %*) increase in peak temperatures respectively was recorded at pre-heat temperatures of 100, 200 and 300 ^{0}C respectively relative to the non-preheat condition of 35^{0}C. Metal preheat effect is more pronounced the further the distance is from the flash line.

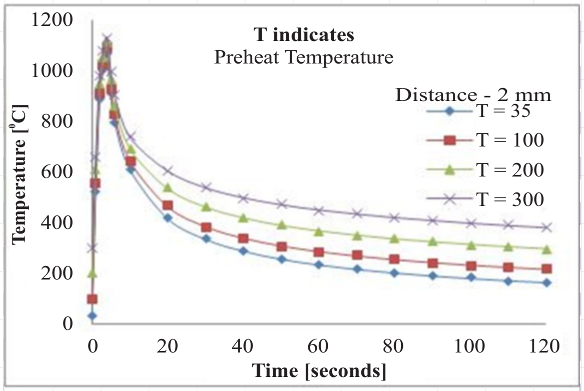

Fig. 7. Effect of metal preheat on temperature profiles

D. *Effect of Flash Line Temperature on Thermal History*

Interface flash temperature is a function of energy supplied and welded material properties. Fig. 8 shows the effect of flash temperature on temperature profile in a cylindrical bar at an axial distance of 1 mm. Flash point temperature of 1200, 1400 and 1500^{0}C resulted in peak temperatures of 1081.7, 1238.9 and 1340.6^{0}C respectively. The higher the flash temperature, the higher the peak temperatures attained. This is due to an increased energy input which leads to higher heat flow from the flash line through the bar.

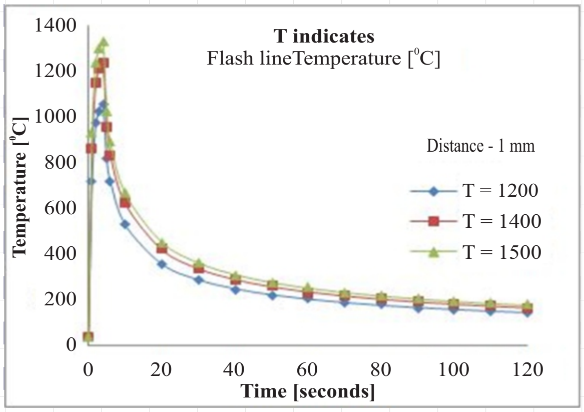

Fig. 8. Effect of flash temperature on temperature profiles

E. *Temperature profiles along radial directions*

Fig. 9 shows temperature profile at axial distance of 1, 2 and 3 mm. The maximum temperature occurred at the center of the bar; which is 622.17, 611.33 and 594.01^{0}C at axial distances of 1, 2 and 3 mm from the flash line respectively. At axial distance of 1 mm, temperature values were 622.17, 622.03, 621.33, 619.88 and 616.26^{0}C at radial distance of 0, 2, 5, 8 and 12.5 mm respectively. The temperature decreases towards the surface of the bar and this is due to convective heat transfer from the surface to the ambient. The difference in temperature between points at the center and points at the surface are 5.91, 5.67 and 5.38^{0}C for axial distance of 1, 2 and 3 mm respectively. This shows that there is temperature gradient also in radial directions of the bar owing to conductive and convective heat transfer at the surface.

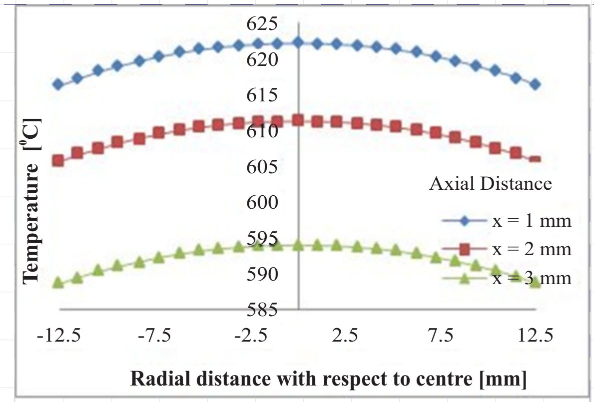

Fig. 9. Temperature profile across bar diameter at various axial distances from center

F. Cooling Rate and Temperature Relationship

Fig. 10 shows the relationship between cooling rates and convective boundaries at distance 1 mm from the flash line and at the depicted temperatures. At high temperature, there is high temperature gradient between the bar and ambient; therefore heat transfer rate to ambient is higher which is the reason for the higher cooling rate. However, as the bar approaches equilibrium temperature with the surroundings, cooling rate becomes increasingly lower. Cooling rates generally decreases with decreasing temperature at the same convection coefficient. For the same cooling temperature, the higher the convection coefficient, the higher the cooling rate.

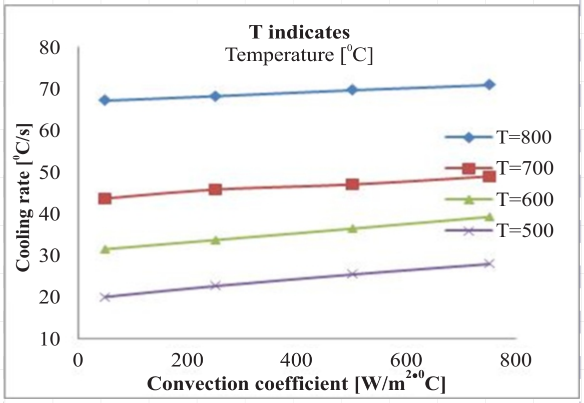

Fig. 10. Cooling rates at different convective boundaries

IV. CONCLUSION

A two-dimensional finite element model was developed capable of predicting temperature profile in a cylindrical bar subjected to flash butt welding. The following conclusions have been made:

- The model presented here can effectively predict temperature profiles at all locations during welding.
- Simulated temperature values increases as the work-piece preheat temperature increases.
- The relationship between peak temperatures and distance from weld flash line is non-linear.
- Peak temperature decrease with distance along radial direction has a non-linear trend.
- Peak temperatures under any set of conditions occur at the center of the bar because heat flow from the bar center is through conduction and convection occurs at the surface nodes.
- The higher the flash temperature and flash duration, the higher the temperatures attainable in the bar. The effect of flash temperature and flash duration on temperature histories become more pronounced as cooling progresses.

RECOMMENDATIONS

The following are the recommendations made for further research in the area of interest of this work.

- Effect of interface metal pressure on temperature profile and history may be taken into considerations in future works.
- Effects of internal heat generation may be considered in future works

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