Numerical Modeling of Cooling Rate and Hardness Prediction in Axi-Symmetric Flash Butt-Welded C45 Steel Circular Long Bars

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Abstract. FE investigation into the effect of welding variables on the cooling rate, Δt₈/₅ (cooling time from 800 to 500 °C), around the weld and heat affected zone (HAZ) areas of C45 steel was carried out. Weldment material hardness property changes was examined using Brinell hardness test method, variation in hardness at known distances from the weld line in the HAZ arising from different cooling rates was the main focus. There exists in literature empirical correlations that relate cooling rates and hardness vis-a-vis welding variables, these were used for the computational evaluation of hardness. To establish the effects of welding variables on the cooling rate, a computer programme was written with Matlab. Generalized numerical prediction of temperature distribution, peak temperature, cooling rate and thermal cycles in solid bars joined by butt arc welding process was carried out and subsequently used to predict hardness of C45 steel. Increase in arc duration reduced the cooling rate, which consequently reduced the hardness by as much as 47%. The cooling rate decreased with increase in preheat, results in a significant decrease in hardness of the HAZ by as much as 49%. The results also indicated that the cooling rate increased slightly with an increase in coefficient of convection and caused an insignificant increase in hardness. It was discovered from the results that metal pre-heat temperature prior to welding has minimal effect on the cooling rate. Simulated weldment hardness obtained was in good agreement with the experimental value within 9 %.

Keywords: cooling rate; welding variable; arc duration; preheat temperature; hardness

1. Introduction

It is important to evaluate the cooling rate and hardness at particular locations of a weldment so that it can be controlled in a proper way for prevention of cracks. Cooling rate dictates the soundness of the weld metal in respect of porosity, inclusion and the weld bead geometry. Cooling rate also affects the mechanical properties such as hardening and embrittlement of the hardenable steel and the metallurgical structure [1,2]. In the heat-affected zone, the metallurgical structure can be controlled favorably in order to avoid such defects as embrittlement, cracks or excessive hardening of the metal. Typical materials such as stainless steels where the chromium carbide formation takes place in the heat affected zone under the slow cooling conditions within a sensitive temperature range lead to the loss of corrosion resistance of the stainless steel. Control is made in form of faster cooling through the sensitive temperature range where the chromium carbide precipitation takes place. The cooling rate in the heat affected zone affects the metallurgical structures that consequently influence the mechanical properties as well as the corrosion behavior.

Allied welding processes such as friction stir welding had witnessed extensive research works in the examination of temperature distribution [3,4]. In 2009, Martinson et al., stated that phase transformation due to different cooling rates is important when dealing with high strength or advanced high-strength steel, which are being used more frequently in the car industry [5]. In 2012, Dean obtained the transient temperature distributions, residual stress and deformation induced by electro-slag welding [6]. In 2014, Mato et al., examined numerical and experimental residual stresses and distortions...
induced in T-joint welding of two plates [7]. A simplified method of predicting stresses in surfaced steel rods was carried out by Jerzy Winczek [8]. In his research, the dependence of stresses and strains was assumed on the basis of tension curves considering temperature. In 2010, Hwa et al., examined the effect of temperature field on the sensitization of Alloy 690 welds fabricated using the gas tungsten arc welding method and the laser beam welding method respectively [9]. The welding thermal cycle of the two welding methods were based upon a moving heat source model. Finite element modeling of temperature cycles in axi-symmetric flash butt-welded thin steel rods and experimental validation was carried out by Olabamiji and Adedayo, 2016. Welding process variables examined include; effect of pre-heat temperature, flash temperature, flash duration, and material geometries on temperature profile at various points along the rod and length of the rod [10]. The present work modeled cooling rates in Arc-welded bars with experimental validation.

2. Heat Treatment Analysis

a. Geometrical Configuration

Figure 1 depicts the welding process of two relatively long circular bars whose lengthwise dimension is large compared with the diameter. (L>>d).

![Figure 1: Flash butt-welded bar](image)

With the application of flash as obtained in electrical resistance welding, sparks are produced which generate the necessary heat input for welding of materials. Conductive heat flow is principally along the rod length (L) while some are lost to convection and radiation at rod boundaries and circumferential surfaces.

b. Transient Temperature Distribution Modeling

The following assumptions are made in the modeling equations:

(i) Latent heat associated with phase transformation is not factored in the temperature modeling.
(ii) The heat transfer process is assumed to be symmetrical about the centre line of the welded joint.
(iii) Heat transfer by conduction is principally along the axial direction.
(iv) Effect of fixture and related clamping devices are neglected.
(v) Internal heat generation associated with metallurgical changes is assumed to be negligible.
(vi) Heat loss by convection is considered only at the circular end and circumferential curved surfaces of the rod [11].

Generalized governing differential equation (1) representing temperature distribution profile in one-dimension is depicted by the partial differential parabolic equation:
\[
\frac{\partial}{\partial x} \left( k A \frac{\partial T}{\partial x} \right) + A g = \rho C A \frac{\partial T}{\partial t} + P \beta (T_s - T_w), \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (1)
\]

3. Finite Element Modeling of Temperature and Hardness Prediction

3.1 Finite Element Equations

Application of the Galerkin’s Weighted Residual Method (GWRM) to the governing equation (1) neglecting internal heat generation gives the expression:

\[
\sum_{h=1}^{N} \int_{0}^{l} N^T \left[ w \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} \left( a_e \frac{\partial T}{\partial x} \right) + (c_e T) \right] dx = 0 \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (2)
\]

Where:

\( NT \) - transpose of the shape function,

\( we - \rho c A \)

\( he \) - element length

The second order term in eq. (2) need to be reduced to the first order equivalent using integration by parts;

\[
\sum_{h=1}^{N} \int_{0}^{l} N^T w_e \frac{\partial T}{\partial t} + a_e \frac{\partial N^T}{\partial x} \left( \frac{\partial T}{\partial x} \right) + c_e N^T T \] dx + \left[ a_e N^T \frac{\partial T}{\partial x} \right]_{0}^{l} = 0 \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (3)
\]

Evaluation of the term results in Neumann’s boundary condition. Its interior nodes vanish during element assembly except for the end nodes. Therefore, the term is dropped at this point because its contribution is incorporated in Neumann’s boundary specification [12,13].

The discretized function, \( T(x) = [N]T \) is substituted into eq. (3) to yield:

\[
\sum_{h=1}^{N} \int_{0}^{l} N^T w_e \frac{\partial T}{\partial t} \left( [N]T \right) + a_e \frac{\partial N^T}{\partial x} \left( [N] \right) \left( \frac{\partial T}{\partial x} \right) + c_e N^T ([N])T \] dx = 0 \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (4)
\]

The addition of the three component terms of eq. (4) and presentation in matrix form gives:

\[
\frac{\rho C A}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \left[ T_1 \right] + \frac{k A}{he} \begin{bmatrix} 1 \\ -1 \end{bmatrix} \left[ T_1 \right] + \frac{P \beta h_e}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \left[ T_2 \right] = 0 \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (5)
\]

The assembled global matrix equation can assume the following general form:

\[
[A][T] + [E][T] = 0 \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (6)
\]

\([A]= Because of the time assemblage of the first matrix

\([E]= Addition of the assemblage of the second and third matrices.
In derivation of \( \{ \mathbf{f} \} \) in equation (6), there is a need to carry out some form of approximation to the derivatives to reduce the equation to a system of algebraic equivalent before solution can be advanced.

3.2. Evaluation of Time Derivatives

The concept of extending the finite element to include the time domain is found in literature. The approach is to regard the approximation function as being dependent on time as well as the domain as given in equation (7).

\[
\frac{\partial T(x, t)}{\partial t} = \frac{\partial N_i(x, t)}{\partial t} T_i \quad \ldots \quad (7)
\]

Where,

- \( T(x, t) \) = dependent variable, \( T \), as a function of space, \( x \) and time, \( t \);
- \( N_i(x, t) \) = approximation function at node, \( i \), as a function of space and time.

When the time derivatives are approximated with finite differences, either a central in time (Crank-Nicholson) or a backward/forward in time (implicit) scheme can be used [13].

Forward difference,

\[
\hat{T} = \frac{T^{n+1} - T^n}{\Delta t} \quad \ldots \quad (8)
\]

Where: \( n \) is time level.

\( \Delta t = \) time step,

Substitution of eq. (8) into eq. (6) yields:

\[
[A]\left[\frac{T^{K+1} - T^K}{\Delta t}\right] + [E][T^K] = 0 \quad \ldots \quad (9)
\]

If \( \Theta \) is dimensionless time – weighting factor. A value of \( \Theta = 0.55 \) is chosen which minimizes distortion while conservatively ensuring theoretical stability [13].

The introduction of dimensionless time – weighting factor, \( \Theta \) into eq. (9) gives:

\[
[A + \Delta t\theta E]T^{K+1} = [A - \Delta t(1 - \theta)E][T^K] \quad \ldots \quad (10)
\]

3.3. Computational Procedure

After power activation, an interface plastic state temperature was assumed for all points located at this interface boundary. In the numerical simulation of the butt-arc welding it is assumed that the two bars are welded symmetrically. The arc point is the symmetric line and thus only half of the welded bar is modeled. With the assumption of symmetry, the weld line is modeled as an adiabatic boundary [6,9,10,14]. The weldment zones are divided into a number of elements.

In the element discretization of the bar length, the specimen was divided into two parts based on element sizes. The first portion close to weld line around the HAZ has fine and even mesh sizes while the other coarse part
contains dispersed elements.
The preferred mesh size for the modeling within the refined mesh region was taken to be 0.5 mm. This spacing provides a good compromise between accuracy and computation time. The mesh in the remaining part was 10 mm.

Parameters used for the trial program are:
- Convection coefficient = 50 [W m\(^{-2}\) 0C\(^{-1}\)].
- Initial temperature at weld line = 1,600 0C.
- Initial temperature at other points on rod length = 35 0C.
- Diameter = 30 mm
- Length = 240 mm
- Number of elements = 39
- Number of nodes = 40
- Arc duration= 5 seconds
- Material type = 0.45% C Steel (\(k = 54\) M/m 0C , \(c = 465\) J/Kg 0C , \(\rho = 7833\) kg/m\(^3\)).

A computer program written in Matlab_Windows_R2012a on a microcomputer (Processor Speed = 1.6 GHz, RAM = 1.00 GB, Hard Disk Capacity = 148 GB) was used for the computational analysis.

### 3.4. Prediction of Hardness and Experimental Validation.

A major area of application of simulated temperature and cooling rates is in the prediction of some mechanical properties of materials. Hardness can be obtained from the relationship between Jominy-distance and Rockwell C scale Hardness (HRC) value [15,16]. The Jominy-distance is obtained from standard Jominy-distance versus cooling-time curve. Characteristic cooling that is critical for microstructural phase transformation in ferrous materials is the time of cooling from 800 0C to 500 0C often designated as \(\Delta t_{8/5}\). Tables 1 and 2 are cooling time (\(\Delta t_{8/5}\)) versus Jominy distance and Jominy distance versus hardness (HRC) for a typical (0.45 % C) carbon steel. Information from Tables 1 and 2 is used in obtaining the predicted hardness results.

#### Table 1 Cooling time versus Jominy distance (Source: Rose, 1958)

| Cooling time from 800 °C to 500 °C (s) | 0 | 20 | 40 | 80 | 120 | 140 | 160 |
|----------------------------------------|---|----|----|----|-----|-----|-----|
| Jominy distance (mm)                   | 0 | 10 | 15 | 28 | 42  | 50  | 60  |

#### Table 2: Jominy Test Results of C45 Carbon Steel (HRC) (Source: Rose, 1958)

| Jominy distance (mm) | 1.5 | 3  | 5  | 8  | 11 | 15 | 20 | 25 | 30 | 35 | 40 | 80 |
|----------------------|-----|----|----|----|----|----|----|----|----|----|----|----|
| Hardness (HRC)       | 56  | 55 | 55 | 53 | 52 | 45 | 38 | 35 | 32 | 31 | 30 | 22 |
A 240 mm length and 30mm diameter medium carbon steel bar of 0.45% carbon was used in the experiment. Current intensity and voltage were chosen as 80 A and 150 V. After welding, the specimen was air-cooled. Hardness test was carried out using a Brinell Hardness Tester model and Serial No (EEDB 0006/13). Hardness at 1 mm from the weld line was obtained. Applied force was 29.42KN and dwell time was 15 seconds.

4. Numerical Results and Discussions

4.1 Effect of distance from weld line on temperature variation

Figure 2 shows simulated thermal cycles at different distances from the weld line. Peak temperatures of 1,250.9, 965.4, 737.2 and 574.6 °C were attained at distances 0.5, 1.5, 2.5 and 3.5 mm respectively from weld line. Time to attain peak temperatures gradually increased with distances due to time taken at such points to experience the conductive heat wave propagation. The lower peak temperature at farther distances from weld line is due to continual heat losses between the interval surfaces. Also, at distance 0.5 mm from weld line, cooling was rapid immediately after the attainment of peak temperature and subsequently slow cooling obtains. Convection accounted largely for cooling in weldments and is dependent upon the temperature differential between the material and ambient. This differential is highest around peak temperature thus accounting for highest cooling rate around peak temperature.

![Fig. 2 Temperature variations with distances from weld line.](image)

4.2 Effect of Arc Duration on Cooling Rate at point 1mm

Figure 3 shows the effect of weld duration on cooling rate at 1 mm from weld line. It is observed that cooling rate decreases with increase in weld duration as a result of increase in energy input and distribution across the weldment. This is in accordance with the findings of Martinson et al., 2009 and Suresh, 2014 [5,16]. At 5 seconds weld duration and 800 °C, cooling rate was 76 °C/s, while at 15 second weld duration, cooling rate was from 33.4 °C/s. A similar trend was observed in cooling rate obtained at lower metal temperature values. With further increase in arc duration, the HAZ tends towards equilibrium temperature within its vicinity thereby reducing the
4.3 Effect of Metal Peak Fusion Temperature on Cooling Rate at Distance 1mm

Figure 4 shows the effect of metal fusion temperature on cooling rate at 1 mm from weld line. It is observed that cooling rate decreases with increase in metal fusion temperature. At 1800, 1600 and 1400 °C, peak temperatures cooling rate at temperature 800 °C was 24.3 °C/s, 33.2 °C/s and 47.7 °C/s respectively. Cooling rate increased with decreasing peak fusion temperature. Similar trend of cooling rate were obtained at HAZ within 800 °C and 500 °C cooling temperature. Higher cooling rate at lower metal peak fusion temperature was as a result of higher rate of heat loss through conduction to the neighboring region near the HAZ as a result of high temperature gradient between them. With the increase in metal temperature, the HAZ attains equilibrium temperature within its vicinity thereby making the cooling rate slower.

Fig. 4 Effect of Cooling Temperature on Cooling Rate at different fusion temperatures
4.4 Effect of Boundary Convection on Cooling Rate.

Figure 5 shows the effect of boundary convection on cooling rate at distance 1mm from weld line. It is observed that cooling rate increases with the increase in convection coefficient. At 50, 1,000 and 2,000 W/(m² °C), cooling rate at temperature 800 °C was 33.4, 36.5 and 39.5 °C/s respectively. Cooling rate increased with increasing convection coefficient. Similar trend of cooling rate obtains at lower cooling temperatures. At higher convective coefficient faster heat removal from the HAZ occurs.

![Graph showing effect of cooling rate on different convective boundary conditions.](image)

Fig. 5 Effect of Cooling Temperature on Cooling Rate at different Convective Boundary.

4.5 Effects of Preheat Temperature on cooling rate at 1mm from weld line.

Figure 6 shows the effects of preheat temperature on cooling rate at distance 1 mm from weld line. It is observed that cooling rate decreases with increase in preheat temperature. At 35, 200 and 300 °C pre-heat temperatures, peak temperature cooling rate at temperature 800 °C was, 44.5 and 29 °C/s respectively. Cooling rate decreased with increasing preheat temperature. Similar trend of cooling rate obtains at other lower cooling temperatures. This is in accordance with the findings of [17].

![Graph showing effect of cooling rate on different pre-heat conditions.](image)

Fig. 6 Effect of Pre-Heat on Cooling Rate under Cooling Temperature Conditions.
5. Hardness Prediction

The validity of simulated hardness value was made by comparing with experimentally obtained result. At distance 1 mm from weld line, simulated hardness value of 29.1 (HRC) was obtained as shown in Table 3. Experimentally obtained hardness value of 32 (HRC) at the same distance was observed under the same welding condition as stated in the computational procedure with a discrepancy of 9%. This agrees with the findings [18,19]. The disparity is accounted for based on some assumptions made and heat losses not accounted for in the one-dimensional simulation.

Table 3: Predicted Hardness for Various Welding Parameters at Distance 1 mm.

| S/n | Welding variable          | 5   | 10  | 15  |
|-----|---------------------------|-----|-----|-----|
| 1   | Arc duration (Sec)        | 55  | 49.5| 29.1|
|     | Hardness (HRC)            |     |     |     |
| 2   | Metal temperature (°C)    | 1400| 1600| 1800|
|     | Hardness (HRC)            | 55.3| 55  | 53.5|
| 3   | Boundary Convection (W/m²°C) | 50 | 1000| 2000|
|     | Hardness (HRC)            | 55  | 55.2| 55.5|
| 4   | Preheat Temperature (°C)  | 35  | 200 | 300 |
|     | Hardness (HRC)            | 55  | 50.5| 28  |

6. Conclusion

The following conclusions can be drawn:

- Cooling rate decreases with increase in arc duration, which leads to a significant decrease in hardness of the HAZ. There is a 47% reduction in hardness when the arc duration is increased from 5 to 15 seconds.
- Cooling rate decreases with increase in metal temperature, which leads to a slight decrease in hardness of the HAZ. A slight reduction in hardness of 3.3% was archived with the increase in metal temperature from 1,400 to 1,800°C.
- Cooling rate increases negligibly with increase in boundary convection, which leads to a slight increase in hardness of the HAZ.
- Cooling rate decreases appreciably with increase in preheat temperature, which leads to a considerable reduction in hardness of the HAZ. A 49% reduction in hardness was achieved when the preheat temperature was increased from 35 to 300 °C.

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