# Investigation of Arc Welding Variables Influenced by Temperature Cycle Developed in High Carbon Steel Welded Butt Joints and its Effect on Distortion

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#### Abstract

The present work investigates the several welding variables developed due to transient temperature field during formation of butt joints by shielded metal arc (SMA) welding. Carslaw - Jaeger's mathematical model has been utilized to portray the variation of thermal conductivity with experimental peak temperature. To validate the temperature distribution experiment has been conducted for making butt joint of high carbon steel (AISI 1090). The cooling rate along the longitudinal direction from the fusion boundary has been derived by using Adam's two dimensional mathematical model. Effect of cooling rate is highlighted by results produced by Scanning Electron Microscope (SEM) images indicating the growth of crack. Distribution of surface heat flux has been estimated by implementation of Gaussian heat flux model. Effort has been made to correlate the distortion in welded structures due to highly variable thermal cycle with proper validation by implementation of temperature dependent transverse shrinkage model.

Key words: Shielded metal arc welding, butt joint, high carbon steel, thermal history, cooling rate, transverse shrinkage

# I. INTRODUCTION

Fusion welding processes are widely used for fabrications in many engineering applications such as automotive industries, nuclear reactor construction, periodic overhauling of boiler accessories, naval and shipbuilding industries. Shielded metal arc welding is one of the fusion welding process consisting heating, melting and solidification of parent metals by the movement of transient heating source to form a joint between two parent metals. Residual stresses have strong influence on weld deformation, fatigue strength, fracture toughness and bucking strength. It is very difficult to evaluate these stresses is emphasized by variation of temperature and non-linear heat loss.

#### II. LITERATURE REVIEW

Rosenthal (1, 2) provided one of the earliest approaches to the development of an analytical solution of heat flow during welding and it is based on conduction heat transfer to predict the shape of the weld pool for two dimensional (2D) and three dimensional (3D) welds. This model is very popular for studying the thermal history and its effect on residual stress in low temperature region. Friedman (3) has studied the weld puddle distortion to provide its relation with impact strength. Residual deformation and plasticity transformation in single pass welding of repair welds has been performed experimentally by Oddy et al. (4). Poorhavdari et al. (5) predicted cooling rate of arc welding with intermediate plate thickness. Mousavi and Miresmaeili (6) predicted the residual stress produced due to transient thermal cycle by experimental and numerical analyses in TIG welding of 304L stainless steel. Deng (7) investigated effects of solid state phase transformation on welding residual stress and distortion in low carbon and medium carbon steel based on ABAQUS code of simplified coupled thermal, metallurgical and mechanical 3-D finite element model. Gannon et al. (8) discussed the effect of four welding sequences on the magnitude of residual stress and distortion fields using element birth and death technique in both plate and stiffener in gas metal arc welding. Jiang et al. (9) presented estimation of residual stress and deformation in the repair weld stainless steel clad plate by FEM.

Estefen et al. (10) has represented welding relaxation effect of butt jointed steel plates, where welding was carried out by single and double electrode. Lee et al. (11) applied 3-D finite element method for applying residual stress in dissimilar welding from both technical and cost point of view. Sun et al. (12) has carried out a comparative study on welding temperature fields, residual stress distributions and deformations induced by laser beam welding and  $CO_2$  gas arc welding.



Fig. 1. Schematic diagram of moving point heat source

For investigation of surface heat flux, Gaussian heat source model has been adapted in this paper and it can be written as (13):

$$q(x, z, t) = \frac{3Q}{\pi r_b^2} \exp[-\frac{3\{x + vt\}}{r_b^2}] \exp(\frac{3z^2}{r_b^2}) (1)$$

Where,  $\mathbf{Q} = \eta \mathbf{V} \mathbf{I}$  is denoted as heat input (w) and 'r<sub>b</sub>' is radius (mm) of moving heat flux, 'x' and 'z' are space coordinates (refer fig. 1), 't' indicates the total time of welding, 'V' is voltage of welding transformer, 'l' is current provided to the arc torch (refer Table 4), '\eta' is heat transfer efficiency and 'v' is welding velocity (mm/s).

Adams cooling rate for 2-dimensional heat flow can be written as (14):

$$\frac{dT}{dt} = 2\pi k\rho C_{p} (\frac{d}{H_{net}})^{2} (T_{P} - T_{0})^{3}$$
(2)

Where, k is thermal conductivity, d is plate thickness, H<sub>net</sub> is net heat input to the joint ( $H_{net} = \frac{\eta VI}{v}$  J/mm, 'v' is welding velocity (mm/s)), T<sub>P</sub> is peak temperature of thermal cycle and T<sub>0</sub> is ambient temperature.

Determination of thermal conductivity is important due to its strong influence on cooling rate at different specified locations. By using experimental temperatures cycle data acquired from data acquisition system, the variation of thermal conductivity has been predicted by Carslaw-Jaeger's mathematical model for moving point heat source and mathematically it yields (15):

$$\theta = \frac{Q_{pt}}{4\pi kR} \exp[-\frac{v}{2\alpha}(x+R)]$$
(3)

Where,  $\theta$  is temperature difference,  $\alpha$  is thermal diffusivity, R is radial distance considered from the fusion boundary ( $R = \sqrt{x^2 + y^2 + z^2}$ ) mm and 'v' is welding velocity (mm/s).

Mandal and sundar (16) have suggested a model for prediction of transverse shrinkage, based on the assumption that the plates undergoing welding are made up of thermoelasto-plastic zone and fully elastic zone. The shrinkage was found to be dependent on the peak temperature attained and can be expressed as:

$$\mathbf{S} = \left[\frac{\beta \mathbf{T}_{\mathrm{m}} \mathbf{T}_{\mathrm{p}}}{2\mathbf{T}_{\mathrm{m}} - \mathbf{T}_{\mathrm{p}}} - \frac{\sigma_{\mathrm{y}}}{\mathbf{E}}\right] \mathbf{L}$$
(4)

 $\beta$  is thermal expansion coefficient, T<sub>m</sub> is melting temperature of base metal, T<sub>P</sub> is peak temperature,  $\sigma_Y$  is yield strength of metal, E is Young's modulus and L is length of near field zone.

# **IV. EXPERIMENTAL WORK**



Fig. 2. Mounting of thermocouples on base metal plate

As referred from figure 2, five k-type thermocouples are mounted on the specimen along the longitudinal direction from weld bead maintaining equal distance each. The rear end of the thermocouple wires are inserted to the channels of Data Acquisition System (DAQ) as shown in figure 3 and figure 4.

Density ρ (kg/m <sup>3</sup> )	7790
Thermal expansion coefficient β (/°C)	13.6×10 <sup>-6</sup>
Thermal conductivity k (w/m-K)	49.8
Specific heat C <sub>p</sub> (kJ/kg-K)	0.465
Melting point Tm (°C)	1485
Thermal diffusivity $\alpha$ (m <sup>2</sup> /s)	13.74
Emissivity ε	0.8
Young Modulus E (GPa)	200
Yield strength $\sigma_Y$ (MPa)	460



Fig. 3. Connection of thermocouples with data acquisition system



Fig. 4. Broad view of experimental set-up

# Table 2: Specification of experimental apparatus

Base metal specimen	Size: 180×60×6 mm,
	Material: AISI 1040,
	Shape: Rectangular
Data acquisition system	NI 9213, 16 channel,
(DAQ)	24-bit thermocouple
	unit, CAT II, Ch. to
	Earth isolation.
Electrode	Coating: Medium
	coated rutile type for
	mild steel structure
Welding	Oil cooled, 12KVA,
Transformer	3φ, Primary-40V,
	20/20/40 Amps,
	Secondary- 20/20/40
	Amps, Secondary-
	20/40-8620/40-86
Thermocouple	K-type, 15m long

**Table 3: Experimental process parameters** 

Input current I (A)	150
Input voltage V (v)	40
Time of completing single	70
pass t (s)	
Welding velocity v (mm/s)	0.857
Heat input H <sub>net</sub> (J/mm)	1632
Heat transfer efficiency η (%)	85

### V. RESULTS AND DISCUSSION



Fig. 5. Experimental temperature cycle developed due to moving point heat source

Fig. 5 denotes the experimental temperature distribution measured through data acquisition system which has acquired data from the starting of moving point heat source to till end point for heat input of 1632w. The total time of welding is 70s. It has been observed that higher temperature sensed by thermocouples is in the region of 36mm and 72mm. The reason is that these locations are very near to the heat affected zone (HAZ) and the inter-molecular energy exchange near the fusion line is in rapid manner. This result can be easily justified by the work carried out by Deng (7).





Fig. 6 represents the heat flux variation based on Gaussian model towards the longitudinal direction of from fusion boundary (refer fig. 1). The distance (z = 1, 2, 3...) kept as small as possible due to exponential terms involved in the expression of Gaussian heat flux distribution and its inability to calculate the higher order terms. Traidia and Roger (18) have estimated the anodic heat flux along the weld pool

as well as along the longitudinal direction and Fig. 6 has shown good agreement with their results.



Fig. 7.Variation of thermal conductivity along with time duration of moving point heat source

By incorporating experimental temperature distribution (as shown in figure 5) in equation (3), in a specified time span of 60s, change in thermal conductivity has been studied. Figure 7 indicates that initially thermal conductivity is linear and due to rapid increase in heating cycle (refer figure 6), thermal conductivity suddenly drops in a high rate and very gradually increases with the slow cooling rate along the longitudinal direction from the weld pool. This analysis shows well agreement with Poorhaydari et al (5).





Fig. 8. (a), (b) and (c). Propagation of cooling rate wave front from fusion line to longitudinal direction

Cooling rate prediction is one of most important subject as the strength of the joint is dependent on it and it is the deciding factor for any weld joints for structural application. By application of experimental temperatures in Adams cooling rate as mentioned in equation (2), keeping other thermophysical properties (refer Table 1) as constant, rate of cooling has been analyzed in three different locations from fusion line (z =36mm, 72mm and 108mm) as depicted in Fig. 8. The higher temperature zone indicates the melting region. The width of HAZ zone is higher for z = 36mm due to nearest domain of liquid-solid interface. Also temperature of HAZ at z = 36mm is high ( $\approx$ 1200°C) compared to z = 72mm and z = 108mm due to random heat loss and propagation of solidification wavefront. Thus gradual cooling rate is similar to the temperature cycle as denoted in Fig. 8. The information containing in Fig. 8 shows good agreement with the research article as depicted in [19].





Figure 9 portrays the variation of transverse shrinkage with experimental peak temperature based equation 4 at different location from fusion line (a) z = 36mm, (b) z

= 72mm and (c) z = 108mm. As temperature cycle is directly proportional to stress, near the fusion boundary at z = 36mm, transverse stress is more (refer figure 8(a)) compared to z = 72mm and z = 108mm. As per the empirical formula provided by Mandal and Sundar (15), which is based on theory of thermoelasto-plastics, the effect of plasticity is clearly visible near the HAZ in fig. (9) (a), (b) and (c) due to solid-fluid interface at boundary of HAZ and fusion line of butt joint.



Fig. 10. Scanning electron micrograph depicting uniform cooling rate

Fig. 10 indicates the band of fine pearlite formation on the base metal of ferrtite surface. Fine pearlite takes place below the temperature of 600°C. It is greatly affected by cooling rate. Fig. 11 shows small crack propagation (blow holes) on the surface. These results have been well established and can be compared with the results obtained by S. Unfried et al. [20].



Fig. 11. Crack propagation due to uneven cooling rate

# **VI. CONCLUSION**

From the current study following remarks can be concluded:

 Experimental temperature cycle for SMA welding of high carbon steel is maximum near the heat affected zone (z = 36mm and z = 72mm). At same time interval other locations (z = 108, 144, 180mm) maximum temperature attained is very less due to rapid heat loss in movement of SMA electrode.

- At z = 36mm, a vigorous decrement of thermal conductivity (from 5.655 w/m-deg. C to 0.125w/mdeg) has been observed due to formation of transient temperature field and it also reveals the suitability of application of Carslaw-Jaeger's mathematical model for moving point heat source.
- Cooling rate along the longitudinal direction from the weld pool has followed the experimental temperature profile. It is maximum at z = 72mm as estimated from the weld pool. at z = 108mm temperature falls gradually and slow cooling rate has been observed compared with two other locations.
- Temperature dependent transverse shrinkage in welded joints is higher in heat affected zone and goes on decreasing in the region away from the fusion line.

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