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NUMERICAL SIMULATION OF TRANSIENT TEMPERATURE IN FLASH BUTT-WELDED AXI-SYMMETRIC CIRCULAR SECTIONS

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Abstract:

Thermal history along the length of a circular section subjected to flash-butt welding was analyzed by the finite difference method. A one–dimensional nonlinear thermal numerical simulation using a computational model based on the finite difference approach is formulated taking into consideration fusion zone (FZ) temperature as a measure of heat input, ambient and initial temperature of rod. Flexibility of physical characteristics such as bar length, diameter and temperature dependency of thermal properties and variation of boundary conditions were applied. Peak temperatures of 490°C and 410°C were computed for a 20 mm external diameter solid and hollow pipes respectively at distance 5 mm from weld line. Preheat temperatures of 200°C and 400°C resulted into a 41.1% and 89.3% increase respectively in peak temperature as compared with non preheat conditions. The predicted values from this model compared reasonably with experimentally obtained thermal histories.

Keywords: Flash butt welding, finite difference, boundary conditions, weld line, thermal histories.

A	area perpendicular to heat transfer
C_p	specific heat at constant pressure
d	inner diameter of weld rod
D	outer diameter of weld rod
h	coefficient of convective heat transfer
K	thermal conductivity
L	length of weld rod
m	mass of grid
Q	heat transfer rate
Q_{int}	internally generated heat source rate
r	radius of weld rod
T	temperature
T_a	atmospheric temperature
Δt	time step
ΔU	stored energy
Δz	grid spacing

Greek Letter

α	thermal diffusivity
ε	emissivity
σ	n-Boltzmann constant
ρ	density of the weld rod
θ	circumferential direction

Subscripts

a	ambient
c	surface of the rod within grid
cir	circumference of the rod within grid
cond	conduction
conv	convection
e	extreme node at HAZ temperature
i	internal node(s)
rad	radiation
x	x-direction
l	node at FZ

Superscripts

n	n^{th} time step
l	the FZ

Abbreviations

C	conduction
C^l	convection
FZ	Fusion zone
HAZ	Heat-affected zone
R	radiation

1. Introduction

Knowledge of temperature history in a welded material is vital to the correct prediction of micro-structural changes and consequently mechanical properties and residual stresses through knowledge of cooling rates and thermal gradients along the bar.

Metal joining by flash-butt welding is a form of resistance welding that evolved with advancements in metal joining technology. It had been used for many years in the automotive industry for joining component parts. It

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is particularly well suited for uncoated, low carbon steel. After the workpieces are properly positioned with the current, head speed and time selected, a cycle start button is actuated. This causes the moveable head (also called electrode cap) to approach the fixed head. As the highest asperities at the interface contact each other, large current flows through these small areas and instantly melts these projections (Carslaw and Jaeger, 1978). Thermal conditions at the two main interfaces; which is the workpiece / workpiece interfaces are particularly critical. It affects the size and quality of the weld.

Detailed thermal history within the fusion and heat-affected zones , including residual stresses distributions in flash-welding are still subjects of modern research. Knowledge of the thermal history will considerably help in controlling such characteristics as residual stresses and mechanical properties of metal around the HAZ. Allied welding processes such as friction stir welding had witnessed extensive research works in the examination of temperature distribution (Tang *et al*., 1998). Very limited works however exists on flash butt weld temperature simulation. There exist published research works on temperature distributions in welding presented in terms of the distributions of temperature around a moving point heat source (Rosenthal, 1941 and Adams, 1958) usually under a steady-state heat conduction formulation. Published works exist on thermal history at various points of a welded plate during and after welding (Adedayo and Adeyemi, 2000). Boo and Cho (1990) obtained the transient temperature distributions in a finite thickness plate during arc welding. Useful metallurgical property transformation and residual stresses are however obtainable if thermal history and strains at various locations along the pipe during steady state and unsteady state heat transfer processes are known precisely.

To further understand the fundamental mechanisms associated with the welding formation process and improve the weld quality of flash butt welded components, numerical modeling and simulations of transient temperature are valuable and necessary. To achieve this purpose a numerical computational model that can be applied to determine the temperature distributions with time along the rod or pipe length during and after flash butt welding operations at a given flash temperature under ambient and pre-heat conditions of the circular section is carried out using the explicit finite difference method. The computed transient temperature histories are hereby presented for different locations along the circular section and later compared with experimentally obtained values in order to validate the present simulation.

2. Theoretical Analysis

2.1 Geometrical configuration

Consider the welding together of two relatively long circular rod or pipe whose dimensions along their length is large compared with diameter (i.e. L >> d) . Figure 1 shows a schematic diagram of a one-dimensional heat flow pattern in a flash butt-welded circular section.

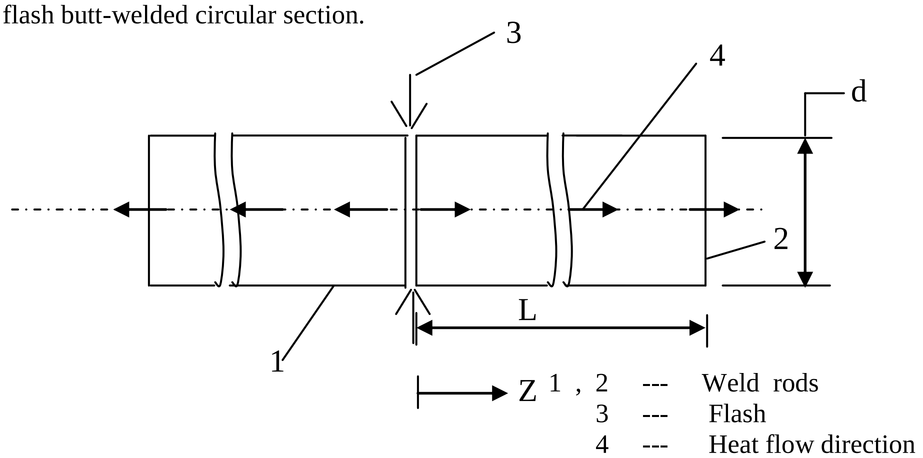

Fig. 1: Schematic diagram of a flash butt welding process

Upon contact of the components, a very thin layer at the interface is melted with simultaneous pressure application. Conductive heat flow is principally along the rod length (L) while some are lost to convection and radiation at pipe or rod boundaries and circumferential surfaces.

2.2 Theoretical formulation

Heat transfer equations used in this formulation are those that govern conduction, convection and radiation with energy balances at the interacting zones.

2.2.1 *Assumptions*

The following assumptions are made:-

(i) Effect of pressure application at start of flash cycle neglected,
(ii) Phase change effects neglected,
(iii) Thermal properties of the metal are assumed to be varying with temperature only.
(iv) The heat transfer process is assumed to be symmetrical about the centre line of the welded joint.
(v) Heat transfer mode along axial direction only.
(vi) Effect of fixture and related clamping devices are neglected.
(vii) Internal heat generation assumed to be negligible.

2.2.2 *Governing heat transfer equations*

After power activation and flash at contact points of the rod, an interface plastic temperature was assumed for all points located at this interface boundary.

The transient temperature field (T) is a function of time (t) and the polar coordinates (r , θ , z). This is determined by the three dimensional nonlinear heat transfer equation (Carslaw and Jaeger, 1978) as applicable to a cylindrical metal piece (Radaj, 1992):

$$\rho c \frac{\partial T}{\partial t} = K\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] + Q_{\text{int}} \qquad 1(a)$$

With an assumption of a 1- D heat transfer mode, Equation 1(a) becomes

$$\rho c \frac{\partial T}{\partial t} = K\left[\frac{\partial^2 T}{\partial z^2}\right] + Q_{\text{int}} \qquad 0 \le Z \le L \qquad 1(b)$$

The heat produced by the flash weld are propagated rapidly along the rod length by conduction as well as convection and radiation through the boundary.

The following boundary conditions are applicable;

Based on principle of symmetry of heat flow at the centre of weld:

$$Z = 0 \;;\quad \frac{\partial T}{\partial z} = 0 \qquad (2)$$

On the boundary or the surfaces of the workpiece; convection and radiation in heat transfer are responsible for heat loss to the ambient; to consider such heat loss at ends of the bar :

$$z = L \;;\quad K\frac{\partial T}{\partial z} = h_c(T_e - T_a) + \varepsilon\sigma[T_e^4 - T_a^4] \qquad (3)$$

In heat conduction analysis, conversion of electrical energy to heat energy due to current passage through resistance wire results in temperature increase. Islam *et al*. (2012) described internal heat generation as the ability to emit greater than normal heat from the body. Another source of internal heat generation associated with processes subjected to rapid heating and cooling is due to metallurgical phase transformations resulting into latent heat of transformation (Simsir and Gur, 2010). Due to the highly restricted portion of the weldment that constitutes the heat affected zone and minimal resistance to current flow along the rod, internal heat generation is assumed to be zero in subsequent expressions.

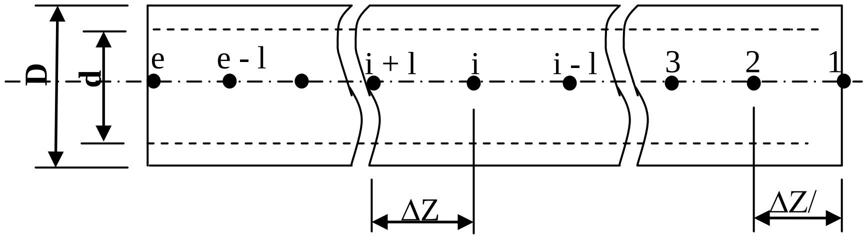

Fig. 2: Weld cylindrical bar nodal numbering

2.3 Numerical solution techniques

In the numerical simulation of the flash weld it is assumed that the two rods are welded symmetrically during and after welding. The flash point is the symmetric line and thus only half of the welded rod is modeled. This approach to modeling is adopted by other researchers on simulation of welded plates (Adedayo and Adeyemi, 2000 and Rong-Hua *et al.,* 2003 and Zhu et al., 2004). The weldment zones are divided into fixed number of grid points. Fig. 2 shows the weld circular section grid numbering.

The length of pipe or rod (L) is divided into (e - l) parts. All internal nodes have grid spacing, ΔZ, while the boundary nodes have spacing, ΔZ/2 on one side only. In the grid layout discritization, $\Delta Z = L/(e-1)$.

(a) **Boundary node (Fusion zone):** This corresponds to node 1 in Fig. 2. It is analysed as an insulated boundary (i.e., heat does not flow across the weld interface). By employing the principle of energy conservation, the equations for all the nodal points are set up. During a small interval of time, Δt , the net flow of heat into an element is set equal to the change of internal energy of that element, thus incorporating both present and future temperatures at the node. Equations (4 - 6) were derived based on this principle (Chapra and Raymond, 1985)

Solid circular section

$$T_1^{n+1} = \frac{2\propto_1 \Delta t T_2^n}{\Delta Z^2} + \left(1 - \frac{2\propto_1 \Delta t}{\Delta Z^2} - \frac{4h\propto_1 \Delta t}{K_1 D}\right) T_1^n + \frac{4h\propto_1 \Delta t}{K_1 D} T_a + 2\varepsilon\sigma\alpha_1 \Delta t (T_a^4 - T_l^4) \quad (4a)$$

i = l

Hollow circular section

$$T_1^{n+1} = A_1 T_2^n + B_1 T_1^n + C_1 T_\alpha + D_1 (T_\alpha^4 - T_l^4) \quad (4b)$$

where:

$$A_1 = \frac{2\Delta t \alpha_1}{\Delta Z^2};\ B_1 = \left[1 - \frac{2\Delta t \alpha_1}{\Delta Z^2} - \frac{4hD\alpha_1 \Delta t}{K_1 (D^2 - d^2)} - \frac{4hd\alpha_1 \Delta t}{K_1 (D^2 - d^2)}\right];\ C_1 = \left[\frac{4h\alpha_1 \Delta t D}{K_1 (D^2 - d^2)} + \frac{4h\alpha_1 \Delta t d}{K_1 (D^2 - d^2)}\right] \ \&\ D_1 = \frac{4\alpha_1 \Delta t \varepsilon\sigma\, (D+d)}{K_1 (D^2 - d^2)}$$

(b) Internal nodes

Solid circular section

$$T_i^{n+1} = \frac{\alpha_1 \Delta t}{\Delta z^2}(T_{i+1}^n + T_{i-1}^n) + \left(1 - \frac{2\alpha_i \Delta t}{\Delta z^2} - \frac{2h\alpha_i \Delta t}{k_i r}\right) T_i^n + \frac{2h\Delta t T_a}{k_i r} + \frac{2\varepsilon\sigma\, \alpha_i \Delta t}{k_i r}(T_a^4 - T_i^{n4}) \quad (5a)$$

i = 2 , 3, . . . e - l

Hollow circular section

$$T_i^{n+1} = A_2 [T_{i+1}^n - T_{i-1}^n] + B_2 + C_1 [T_a^4 - T_i^{n4}] + D_1 T_a \qquad i = 2, 3, \ldots e - 1 \quad (5b)$$

$$A_2 = \frac{\alpha_i \Delta t}{\Delta z^2};\ B_2 = \left[1 - \frac{2\alpha_i \Delta t}{\Delta z} - \frac{4\alpha_i \Delta t h D}{k_i (D^2 - d^2)} - \frac{4\alpha_i \Delta t h d}{k_i (D^2 - d^2)}\right];\ C_2 = \frac{4\alpha_i \Delta t \varepsilon\sigma\, (T_a^4 - T_i^{n4})(D+d)}{k_i (D^2 - d^2)} \ \&\ D_2 = \frac{4\alpha_i \Delta t h T_\alpha (D+d)}{k_i (D^2 - d^2)}$$

(c) Boundary Node (Parent metal boundary)

Energy balance on this node taking cognizance of convection and radiation give:

Solid circular section

$$T_e^{n+1} = \frac{2\alpha_e \Delta t}{\Delta Z^2} T_{e-l}^n + \left[1 - \frac{2h\alpha_e \Delta t (r + \Delta Z)}{k_e r \Delta Z} - \frac{2\alpha_e \Delta t}{\Delta Z^2}\right] T_e^n + \frac{2h\alpha_e \Delta t (r + \Delta Z) T_a}{k_e r \Delta Z} \frac{2\varepsilon\sigma\alpha_e \Delta t (r + \Delta Z)(T_a^4 - T_e^{n4})}{Ke\ r\ \Delta Z}$$

i = e (6a)

Hollow circular sections

$$T_e^{n+1} = A_3 T_{e-l}^n + B_3 T_e^n + C_3 T_a + D_3 (T_a^n - T_e^{n4}) \quad (6b)$$

$$A_3 = \frac{2\alpha_e \Delta t}{\Delta z^2};\ B_3 = \left[1 - \frac{2\alpha_e \Delta t}{\Delta z^2} - \frac{2\alpha_e h \Delta t}{k_e (D^2 - d^2)} - \frac{4\alpha_e h D \Delta t}{k_e (D^2 - d^2)}\right];\ C_3 = \frac{2\alpha_e h \Delta t}{k_e \Delta z} - \frac{4\alpha_e h \Delta t d}{k_e (D^2 - d^2)} + \frac{4\alpha_e h D \Delta t}{k_e (D^2 - d^2)} \ \&$$

$$D_3 = \frac{2\alpha_e \varepsilon\sigma\Delta t}{k_e \Delta z} + \frac{4\alpha_e \varepsilon\sigma\Delta t d}{k_e (D^2 - d^2)} + \frac{4\alpha_e \varepsilon\sigma\Delta t D}{k_e (D^2 - d^2)}$$

2.4 Stability and convergence criterion

For avoidance of irregular fluctuations in temperature values, the physical parameters are selected such that the nodal temperature equations will always give positive values. From the coefficient of T_i^n in equations 4(b), 5(b) and 6(b) for hollow sections;

$$\Delta t \le \frac{1}{\frac{2\alpha_i}{\Delta z^2}+\frac{4h\alpha_i D}{k_i(D^2-d^2)}+\frac{4h\alpha_i d}{k_i(D^2-d^2)}} \quad (7a)$$

$i = 1$

$$\Delta t \le \frac{1}{\frac{2\alpha_i}{\Delta z^2}+\frac{4h\alpha_i D}{k_i(D^2-d^2)}+\frac{4h\alpha_i d}{k_i(D^2-d^2)}} \quad (7b)$$

i = 2, 3, . . . e – 1

$$\Delta t \le \frac{1}{\frac{2\alpha_i}{\Delta z^2}+\frac{4h\alpha_i(d+D)}{k_i(D^2-d^2)}+\frac{2\alpha_e h}{k_e\Delta z}} \quad (7c)$$

i = e

The chosen value of Δt must satisfy Equations 7(a) to 7(c). Similar expressions are obtained for solid circular section by making d = 0 in Equations 7(a) to 7(c). A computer program was written in order to make a choice of the least time step, Δt.

3. Computational Method

A computer program written in QB 45 and run on a Pentium IV microcomputer was used for the computational analysis (Processor speed = 1.5 GHz, RAM = 512 MB). The iteration process continued until the following convergence criterion was satisfied.

$$\left|\frac{T_{new}-T_{old}}{T_{old}}\right|_{max.} \le 0.001$$

Some parameters were varied in order to obtain results for different conditions. These parameters are;

1. Inner diameter and external diameter (d, D)
2. Convection (h)
3. Radiation component
4. Distance from weld line
5. Pipe length (L)
6. Metal temperature at flash point.

Relevant data used in testing the program are;

(a) Material – 304L Stainless steel
  - (i) Density – 7800 kg/m^3
  - (ii) Nominal dimensions
    - Internal diameter – 15 mm
    - External diameter – 20 mm
    - Pipe length - 100 mm

(b) Thermal Properties

Material properties such as specific heat capacity and thermal conductivity variation with temperature was taken from the Metals handbook (Brown *et al*., 1993), while the density was assumed constant.

(c) Nodal Points

Maximum nodal point designated as "e" of 11 were used in the computation. For grid independency check the program was run with increased maximum nodes of 21 and 31.

4. Experimental Verification

To ascertain the reliability of computer simulated temperatures, experimental temperature measurement was carried out with stainless steel material having identical physical and thermal properties as that used in the numerical calculation. A pair of solid rods of length 100 mm, and diameter 20 mm were welded together. The temperature history at distance 20 mm from centerline was measured using a type K thermocouple and a chart plotter.

5. Results and Discussion

With a maximum node of 11, computational time was observed to be 130 secs and computational results of smaller grid sizes of 21 and 31 did not alter output temperature results at the examined points but computational time was increased to 195 and 270 secs respectively.

Fig. 3 shows the effect of metal temperature at flash point on thermal history of a solid rod. For a ferrous material of melting point 1600^{o}C superheat has a relatively low effect on peak temperatures. At a distance 10 mm from weld line superheat of 200^{0}C increase peak temperature by 32^{0}C (11.85%).

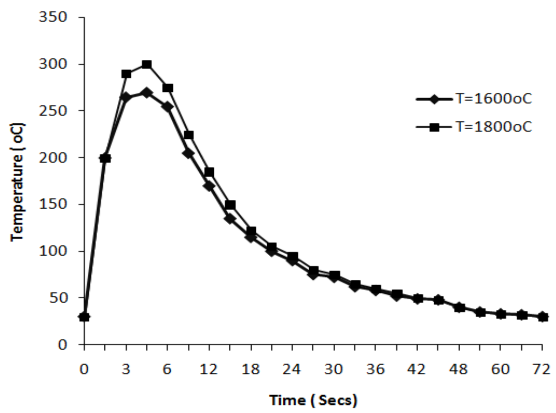

Fig. 3: Effect of superheat on bar temperature at distance 10 mm

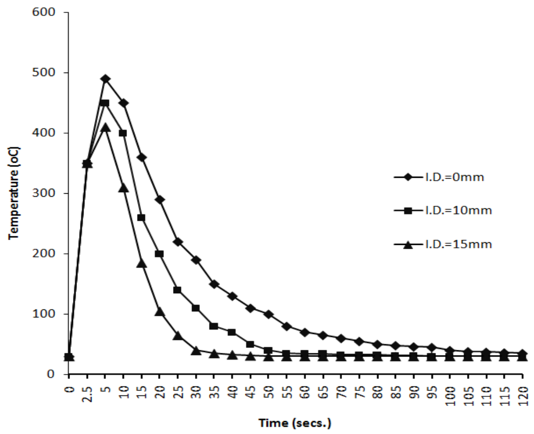

Fig. 4: Effect of inner diameter on temperature at distance 5 mm

Fig. 4 shows the effect of inner diameter on thermal history of an hollow pipe. Temperature comparison was made with that of a solid rod of 20 mm external diameter rod. A solid rod attained higher peak temperatures compared with hollow pipe. A 15 mm inner diameter pipe had a reduction in peak temperature of 80 ^{0}C at 5 mm from the weld line.

Fig. 5 shows the effect of external diameter on thermal history of a solid rod at 10 mm from the weld line. Peak temperatures increase with diameter. Diameters 10, 20 and 40 mm attained peak temperatures 235^{0}C, 270^{0}C and 295^{0}C respectively at 4 secs., 5 secs., and 6 secs. after weld flash. Peak temperatures are attained at a faster rate with smaller sized rods. This indicates higher heat transmission rate for the smaller rod. The greater mass associated with larger diameter with attendant higher heat content resulted in the higher peak temperatures associated with the bigger sized rods.

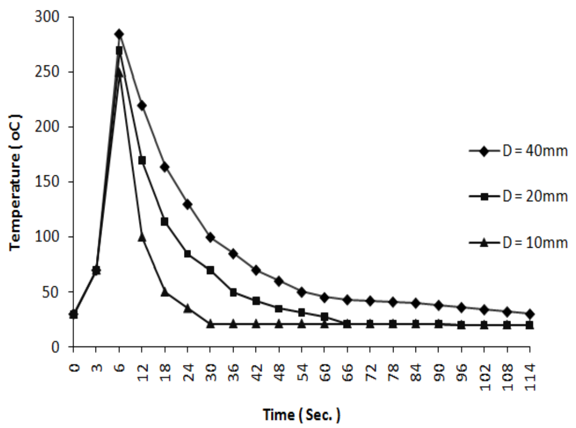

Fig. 5: Effect of solid bar diameter on temperature at distance 10 mm

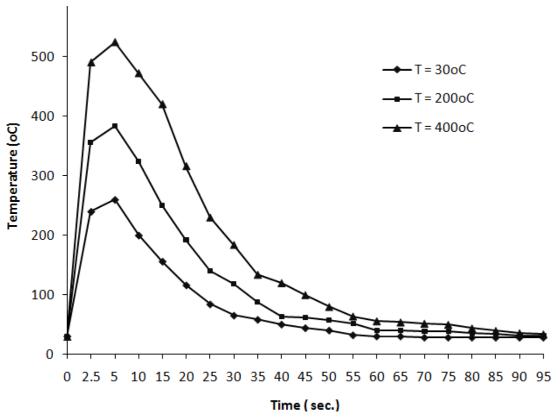

Fig. 6: Effect of preheat temperature on the solid bar temperatre at 10 mm from the flash centre

In practice, the rapid heating and cooling associated with welding process will result in brittleness, hardness or crack; therefore it is sometimes advisable to preheat the workpieces. Fig. 6 is the thermal history at 10 mm from weld line under preheat conditions. Peak temperatures of 514.97^{0}C and 383.9^{0}C were attained under 400^{0}C and 200^{0}C preheat temperatures respectively indicating 89.3 % and 41.1 % increase in peak temperatures compared with a non-preheat situation.

The validity of simulated results is made by comparison with experimentally obtained results as shown in Fig. 7. At distance 20 mm from weld line simulated and experimentally attained peak temperatures of 123^{0}C and 101^{0}C were observed, indicating a disparity of 17.88%. This disparity is accounted for based on some assumptions made in the simulation and limited experimental error.

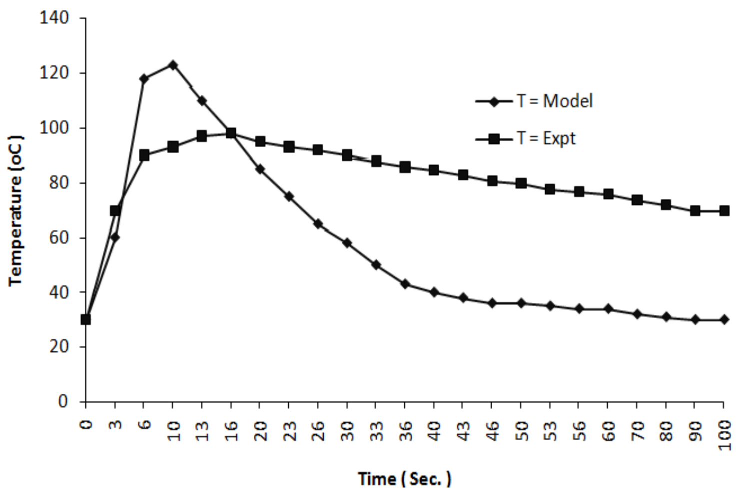

Fig. 7: Comparison of computer modeling and experimental values of temperature at 20 mm from flash centre

5. Conclusion

Thermal history along the length of a circular section subjected to flash-butt welding was analyzed by the finite difference method. From the above study, following conclusions can be drawn:

- Both outer and inner sizes of pipe affect transient temperatures in flash butt welding.
- Simulated temperatures of the work-piece increase as the preheating increases.
- Increase in nodal points did not change obtained temperature values however computational time was slightly increased.
- There is a modest agreement between the simulation and experimental temperature values in the welded circular section.

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