Numerical Analysis of the Effect of Weld – Joints Preheating on Temperature Distributions In GMAW

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ABSTRUCT

In this research , medium carbon steel type (AISI 1045) sheets with 8 mm thickness were welded by Gas Metal Arc Welding Process (GMAW), this study included the application of numerical analyses by using control volume method (CVM) to obtain the effect of preheating process with different temperatures (75 ˚C , 125 ˚C and 225 ˚C) on temperature distribution of the welded joint in addition to determination of cooling rates which were achieved for 3-D heat transfer in the weldment. Results showed the analyses contributed effectively to predict the temperatures distribution for the welded joint and get mathematical models for the cooling rates at welding variables (welding speed was equal 2.5 mm / sec , and welding current was equal 180 Amp) with different preheating temperatures.

Keywords; GMAW process, Temperature distribution , CVM, Preheating process.

التحليلات العددية لتأثير التسخين الأولي لمنطقة الربط على التوزيع الحراري بعملية لحام القوس الكهربائي المعدني الغازي

الخلاصـه :

في هذا البحث تم لحام صفائح من الفولاذ متوسط الكربون نوع (AISI1045) بطريقة لحام القوس الكهربائي المعدني الغازي (GMAW) لصفيحة ذات سمك 8 ملم . تضمنت هذه الدراسة تطبيق التحليلات العددية باستخدام طريقة الحجوم المحدود(CVM) على تـأثير عمليـة التسخين الاولي باختلاف درجات حرارية هي (75 م°, 125م°, 225م°) على التوزيع الحراري لمنطقة الربط, فضلاً عن تحديد معدلات التبريد لانتقال الحراره الثلاثي الابعاد في الملحومة. نتائج التحليلات العدديـة تبين انها ساهمت بشكل فعال في التنبؤ عن التوزيع الحراري لمنطقة اللحام والحصـول علـى نمـاذج رياضية لمعدلات التبريد عند متغيرات ظروف اللحـام هـي (سرعة لحام2.5 ملم/ثانيـة وتيار لحام 180 أمبير وعند مختلف درجات الحرارة للتسخين الاولي).

INTRODUCTION

Gas Metal Arc welding (GMAW) process uses the filler metal as a consumable electrode through the center of the weldement**.** In this case, when the electrode becomes close to the workpiece, an arc is struck between the filler metal and the workpiece, and the filler metal melts and joins the two plates by filling

metal droplet simultaneously in V-groove of plates**.** In the present work, a three - dimensional model will be used with the application of control volume method (CVM) in the modelling of rapid solidification processes. This method is suitable for problems, where the phase change occurs and moves the interface at a high temperature. The high temperature phase in the fusion zone is quenched. In the same cases, the first heat input in a given situation slows down the cooling rate. Preheating, by warming the base material before welding, also slagishes the cooling rate, higher preheat leads to slow cooling rates.

Svensson et al [1] (1997) studiednumerically a three - dimensional heat transfer, and fluid flow in gas metal arc (GMA) fillet welding to examine the temperature profiles, weld pool shape and the solidified weld bead geometry. Murugan et al [2] (2001) investigated the residual stresses and temperature distribution of AISI 304stainless steel and low carbon steel welds. They used manual metal arc welding process to weld plate of thickness 6, 8 and 12 mm. They found that the temperature range (250 °C and 700 °C) is important with respect to formation of residual stresses in both of stainless steel and low carbon steel welds. Zhang et al [3] (2002) studiedthe simulation annealing inverse technique to estimate the temperature history in gas tungsten arc welding (GTAW) workpiece. The test plate was made of stainless steel AISI 304, with dimensions (0.2m × 0.05m × 0.004m). In this case, a two-dimensional model with moving heat source was used, the component of the heat flux input goes into the workpiece. The results indicate a good agreement between the predicted and the measured temperature. Gareth et al [4] (2005)studiedthe evaluation and simulation of angular distortion in welding joints. They used a shielded metal arc welding (SMAW) processtoweld plates of low carbon steel type (A-283-C).Temperature distributions were obtained using finite difference method. Where, the transient heat conduction equation is solved using finite Difference Method (FDM). The aims of this work is to study the effect of welded preheat temperatures on the cooling rates numerically by using finite volume method (FVM) to solve a three - dimensional conduction heat transfer model, and predict the temperatures distribution with cooling rate for the welded joint.

Numerical Method.

In the present work,the Gas –metal –arc welding (GMAW) is a complex process which is rapid solidification , and there is no clear boundary between the liquid and solid, for this case the control volume method (CVM) is more appropriate to used heat transfer and prediction of phase change with moving interface. This method is based on the cell-centered finite volume (FV) method and a3-D transient model was adapted and conservation principle, i.e., energy balance is expressed for the control volume method **[5].**

Material data.

The evaluation of the proposed model was made on butt welding of medium carbon steel plates type (AISI 1045), with dimension (30 mm half- length × 30 mm width × 8 mm thickness). Material properties often behave with non-linearity in high temperature regimes and should be properly dealt with in the governing equation. **Table 1**, shows the physical properties used in the simulation. It is known that the physical properties of the metal change with temperature. Then, the physical properties are usually be solid and liquid, specific heat, solid and liquid thermal conductivity, latent heat, etc.

Table 1 : Physical Properties of medium carbon steel (AISI 1045) [6].

Sample	Physical Property	Value
ρL	Liquid density	$7.833*10^3$ Kg/m^3
ρs	Solid density	6980 Kg/m^3
KL	Liquid thermal Conductivity	54.0 W/m.^{O}C
KS	Solid thermal Conductivity	51 W/m.^{O}C
CpL	Liquid specific heat	473.0 J/Kg.^{O}C
CpS	Solid specific heat	473.0 J/Kg. ^{O}C
TL	Liquid temperature	1538 ^{O}C
TS	Solid temperature	35 ^{O}C
H	Latent heat	272 kJ/kg
Tm	Melting temperature	1483 ^{O}C

Welding parameters.
Table 2 shows the welding parameters used in the simulation, V-single joint with 8 mm plate thickness, welding current (A), voltage (V), welding speed (S), welding efficiency (η), Heat input (H) and different welding preheat temperatures (To).

Table 2 Welding parameters used in numerical calculations.

Sample	I(Amp)	V(Volt)	S(mm/s)	η (%)	To(˚C)	H (KJ/mm)
1	180	26	2.5	80	75	1.49
2	180	26	2.5	80	125	1.49
3	180	26	2.5	80	225	1.48

Assumptions
    The following assumptions are made for the three - dimensional model used to simulate the welding process of the present work :
1- The convection and radiation heat transfer are neglected.
2- The fluid movement within the welding joint during the melting process is neglected.
3- The energy from the arc welding heat source is applied at a uniform rate.
4- The weld metal droplet (molten) is moving with a constant speed.
5- All the plate boundaries are insulated.
6- The heat transfer from the filler metal droplets is taken into account by using a time-volumetric heat source and filling it instantaneously.
7- The weld physical properties data used in this analysis are summarized in
Table 1, which are dependent on the material type.

Initial and Boundary Conditions

Initial conditions are required only when dealing with transient heat transfer (weld metal) problems, in which the temperature of material changes with time. The boundary conditions (**Figure 1**) used as welding boundary conditions are:-

1-Symmetry between right and left half of the welded plate was assumed.
2- Top surface; the weld top surface was assumed to be flat and insulated. The welding velocity component along the X, and Y directions is equal to zero, while the velocity of welding along Z is varied with the welding parameters.
3- Other surfaces; all other surfaces are insulated.
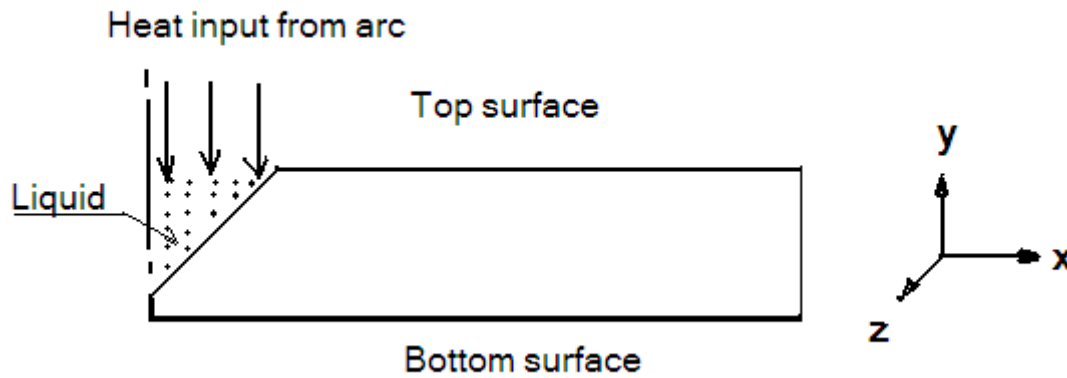4- The initial preheat temperatures before welding are respectively 75°C, 150°C and 225°C.

Figure (1) A schematic diagram of the boundary conditions used in the calculation.

Governing Equations
Control Volume Model (CVM).

For most of rapid solidification, there is no clear boundary between the liquid and solid; for this case the enthalpy is more appropriate **[7].** A three-dimensional volumetric heat source model is the conservation of energy equation in the enthalpy method is considered in term of enthalpy instead of temperature. The governing equations are based directly on the model of **Cao, Faghr, and Chang [6]:-**

$$\frac{\partial(\rho E)}{\partial t} = \frac{\partial^2(\Gamma E)}{\partial X^2} + \frac{\partial^2(\Gamma E)}{\partial Y^2} + \frac{\partial^2(\Gamma E)}{\partial Z^2} + P \qquad \text{.........} \quad (1)$$

Where;

$$P = \frac{\partial^2 S}{\partial X^2} + \frac{\partial^2 S}{\partial Y^2} + \frac{\partial^2 S}{\partial Z^2}$$

$$\Gamma = \Gamma(E), S = S(E)$$

The energy equation has been transformed into a non-linear equation with a single dependent variable E. The non-linearity of the phase –change problem is evident in the above equation. In the liquid region, equation (1) reduces to the normal linear energy equation.

$$\frac{\partial(\rho_L E)}{\partial t} = \frac{\partial}{\partial X}\left(k_L \frac{\partial T}{\partial X}\right) + \frac{\partial}{\partial Y}\left(k_L \frac{\partial T}{\partial Y}\right) + \frac{\partial}{\partial Z}\left(k_L \frac{\partial T}{\partial Z}\right) \qquad \ldots\ldots\ldots\ldots \text{(2)}$$

Also, in the solid region equation (1) reduces to

$$\frac{\partial(\rho_S E)}{\partial t} = \frac{\partial}{\partial X}\left(k_S \frac{\partial T}{\partial X}\right) + \frac{\partial}{\partial Y}\left(k_S \frac{\partial T}{\partial Y}\right) + \frac{\partial}{\partial Z}\left(k_S \frac{\partial T}{\partial Z}\right) \qquad \ldots\ldots\ldots\ldots \text{(3)}$$

Enthalpies of the liquid and solid phases are given by:

$$E_L = C_L T + E_{L0} \qquad\qquad\qquad \ldots\ldots\ldots\ldots \text{(4)}$$

$$E_S = C_S T \qquad\qquad\qquad \ldots\ldots\ldots\ldots \text{(5)}$$

The linear rule is used to calculate the solid mass fraction and is given by

$$f_s = 1 - \left(\frac{T - T_S}{T_L - T_S}\right) \qquad\qquad \ldots\ldots\ldots\ldots \text{(6)}$$

The numerical solution of equations (2), (3) for liquid and solid region is **[8]**:

$$\iiint\limits_{\Delta V} \rho \frac{\partial E}{\partial t} dV = \iiint\limits_{\Delta V} \left[\frac{\partial}{\partial X}k\frac{\partial T}{\partial X} + \frac{\partial}{\partial Y}k\frac{\partial T}{\partial Y} + \frac{\partial}{\partial Z}k\frac{\partial T}{\partial Z}\right] dV \quad \textbf{...........} \text{(7)}$$

$$\rho\Delta V \frac{E_P - E_P^o}{\Delta t} = \left[\frac{k_e A_x}{\delta X_e}(T_E - T_P) - \frac{k_w A_x}{\delta X_w}(T_P - T_W)\right] + \left[\frac{k_n A_y}{\delta Y_n}(T_N - T_P) - \frac{k_s A_y}{\delta Y_s}(T_P - T_S)\right]$$

$$+ \left[\frac{k_t A_z}{\delta Z_t}(T_T - T_P) - \frac{k_b A_z}{\delta Z_b}(T_P - T_B)\right]$$

$$E_P = E_P^o + \frac{\Delta t}{\rho\Delta V}\left[a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_T T_T + a_B T_B - a_P T_P\right] \quad \ldots\ldots \text{(8)}$$

Where:

$$a_E = \frac{k_e A_x}{\delta X_e} ; a_W = \frac{k_w A_x}{\delta X_w}$$

$$a_N = \frac{k_n A_y}{\delta Y_n} \; ; a_S = \frac{k_s A_y}{\delta Y_s}$$

$$a_T = \frac{k_t A_z}{\delta Z_t} \; ; a_B = \frac{k_b A_z}{\delta Z_b}$$

$$a_P = a_E + a_W + a_N + a_S + a_T + a_B$$

$$A_x = \Delta Y \Delta Z \; ; A_y = \Delta X \Delta Z \; ; A_z = \Delta X \Delta Y \text{ and } \quad \Delta V = \Delta X \Delta Y \Delta Z$$

To demonstrate the methodology, let us consider a phase change problem (solution of interface region) in one space dimension. In this case, equation (1) reduces to

$$\rho \frac{\partial E}{\partial t} = \frac{\partial^2 (\Gamma E)}{\partial X^2} + \frac{\partial^2 S}{\partial X^2} \qquad \text{………….. (9)}$$

With $\Gamma = \Gamma(E)$ and $S = S(E)$, explains the estimate of Γ and S coefficient. The discretization of the above equation employs the control-volume approach. In this methodology, the discretization equations are obtained by applying conservation laws over finite size control volumes surrounding the grid nodes and integration of the equation over the control volume, i. e. ,

$$\iiint_{\Delta V} \rho \frac{\partial E}{\partial t} dV = \iiint_{\Delta V} \left[\frac{\partial (\Gamma E)}{\partial X^2} + \frac{\partial^2 S}{\partial X^2} \right] dV \qquad \text{…………. (10)}$$

Using a fully implicit scheme thus:

$$\iiint_{\Delta V} \frac{\partial E}{\partial t} dV = \rho \Delta X \frac{E_P - E_P^o}{\Delta t} \qquad \text{…………. (11)}$$

Equation (11) is referring to the volume integral for one dimensional problem.

$$\grave{} \iiint_{\Delta V} \frac{\partial^2}{\partial X^2} (\Gamma E) dV = \left(\frac{\partial (\Gamma E)}{\partial X} \right)_e - \left(\frac{\partial (\Gamma E)}{\partial X} \right)_w = \frac{\Gamma_E E_E - \Gamma_P E_P}{(\delta X)_e} - \frac{\Gamma_P E_P - \Gamma_W E_W}{(\delta X)_w} \qquad \text{………... (12)}$$

Thus:

$$a_P E_P = a_E E_E + a_W E_W + b \qquad \text{…………. (13)}$$

With E°_{ρ} denoting the old value of E at grid point p

$$a_E = \frac{\Gamma_E}{(\delta X)_e} \; ; a_W = \frac{\Gamma_W}{(\delta X)_w}$$

$$b = \frac{\rho \Delta X E_P^o}{\Delta t} + \frac{S_E - S_P}{(\delta_X)_e} + \frac{S_P - S_W}{(\delta_X)_w}$$

$$a_P = \frac{\Gamma_P}{(\delta X)_e} + \frac{\Gamma_P}{(\delta X)_w} + \frac{\rho \Delta X}{\Delta t}$$

Arc Heat Input

In this case, the energy of the heat source moves with a constant speed (S) along the z-axis of affixed rectangular co-ordinate system. The heat input (q) can be defined by [9];

$$Q = (\eta.V.I) / S*1000 \quad (KJ/mm) \quad\quad\quad …………... (14)$$

Where;

V and I represent the arc voltage and welding current, respectively. The variable η is the thermal efficient of the gas metal arc welding, equals (80%), and S is the welding speed.

Preheat Temperature Model

The following function shows relationship between preheat temperature, heat input, and cooling rate **[10]:-**

$$R \; \alpha \; 1/To \; H \quad\quad\quad ……………. (15)$$

Where;

R = Cooling rate (ºC/sec)
To = Preheat temperature (ºC)
H = Heat input (kJ/mm)

Results and discussion

The mechanical properties of weld metal zone depend upon the cooling curves. This curve is influenced by preheat temperatures before welding. The cooling curves are assumed to be independent of the position within the fusion zone of a given weld bead. There is no reliable method for determining the cooling curves as a function of welding current, welding speed, preheats temperature and plate thickness. However, it can be measured experimentally in each case; this clearly limits the usefulness of the model, the aim of which was to enable the theoretical controls of cooling curves with various welding parameters, Numerical analyses by Control Volume Method program was helped to predicate the:-

Heat transfer analysis

Preheat temperatures before welding has effects on the heat transfer and cooling rates. Figures 2 and3, shows the influence of weldment preheat temperature on temperature distribution in fusion zone at X = 0 plane , welding current 180 Amp, voltage 26 V, welding speed 2.5 mm/s, for different welding preheats at time (1 and 2 sec), respectively. Regarding the effects of the welding preheat temperatures at constant welding current on the temperature distribution, increasesing the preheat temperatures decreases the cooling rate. These results are found in agreement with the results behavior of temperature distribution (Muna,et al[9], a comparisons shown in Figure 4.
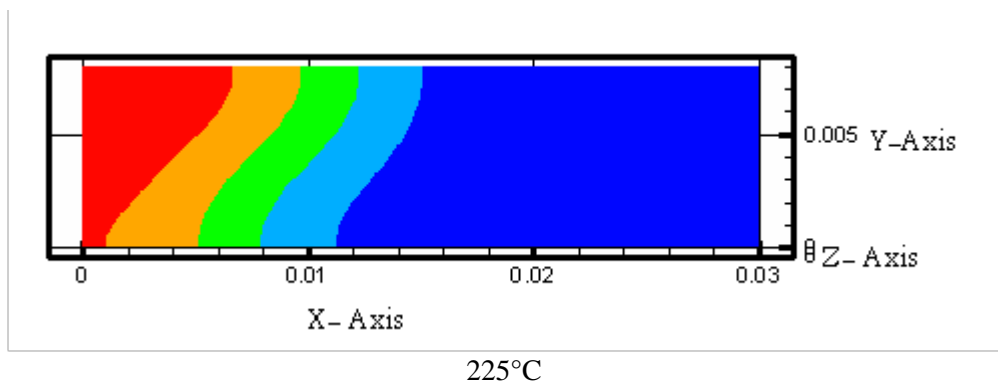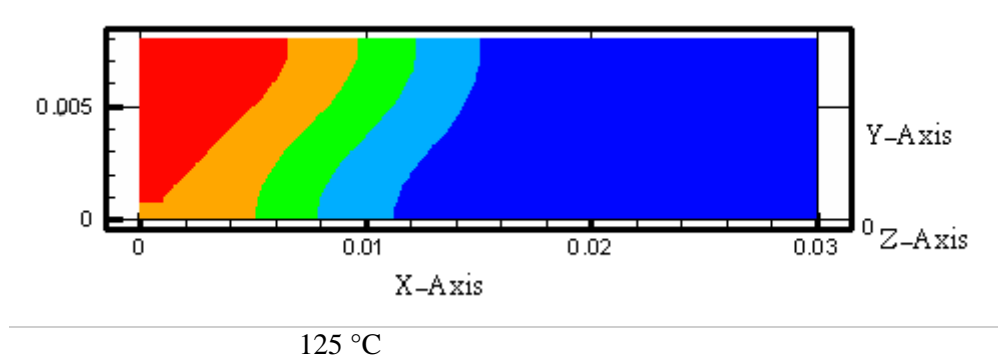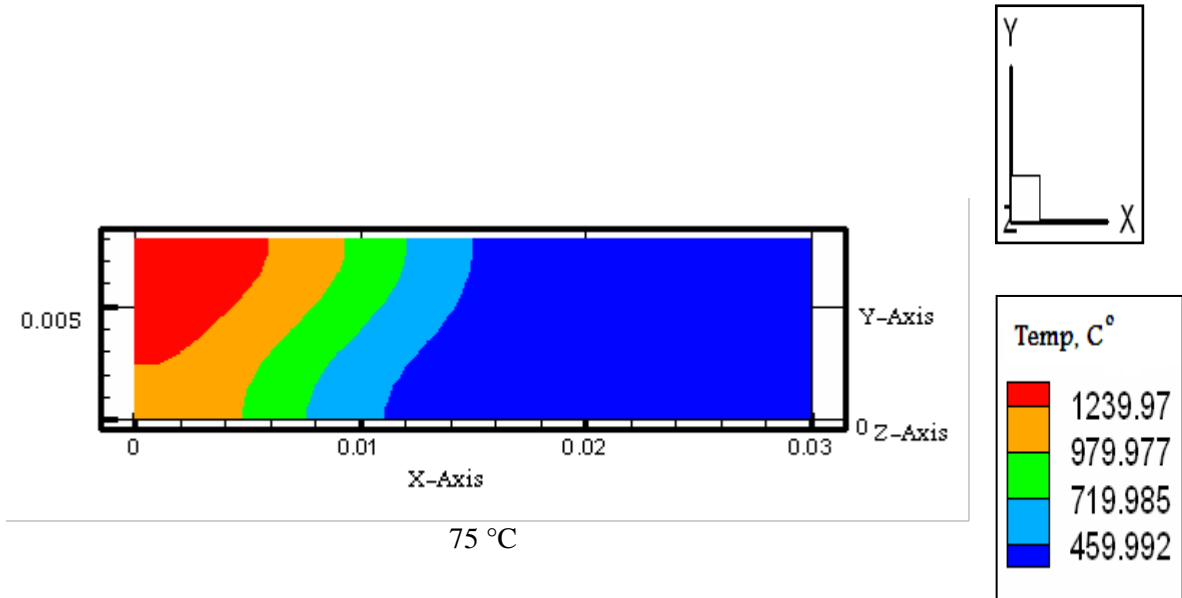
75 °C

125 °C

225°C

Figure (2) Contours of temperatures distributions showing the moving interface with time (1 Sec.) for weld (8 mm) thick, welding current 180A, voltage 26V, welding speed 2.5mm/s, and with different preheat temperatures(75°C, 125°C and 225°C).
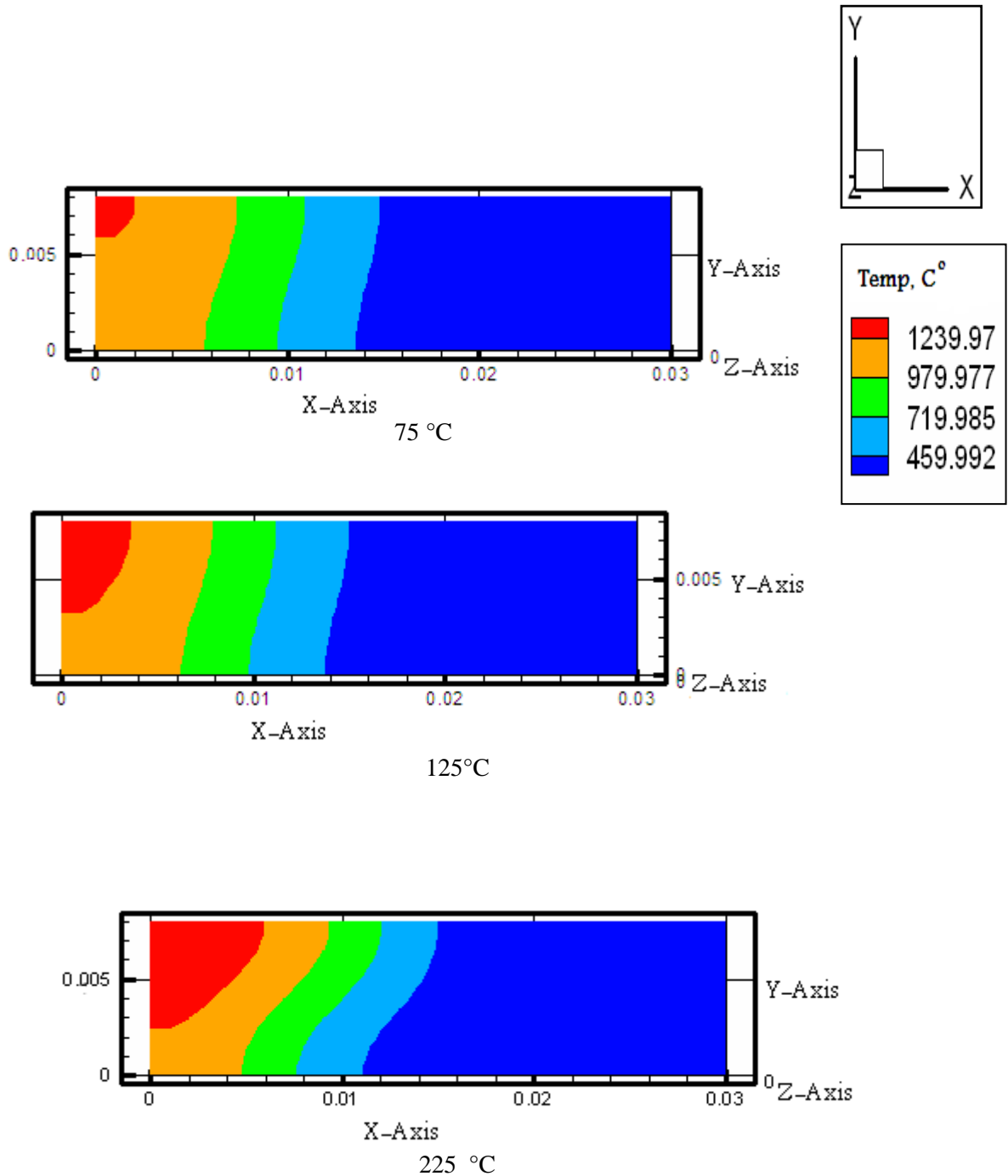

75 °C

125°C

225 °C

Figure (3) Contours of temperatures distributions showing the moving interface with time (2 Sec.) for weld (8mm) thick, welding current 180A, voltage 26V,

welding speed 2.5mm/s, and with different preheat temperatures(75°C, 125 °C and225 °C).
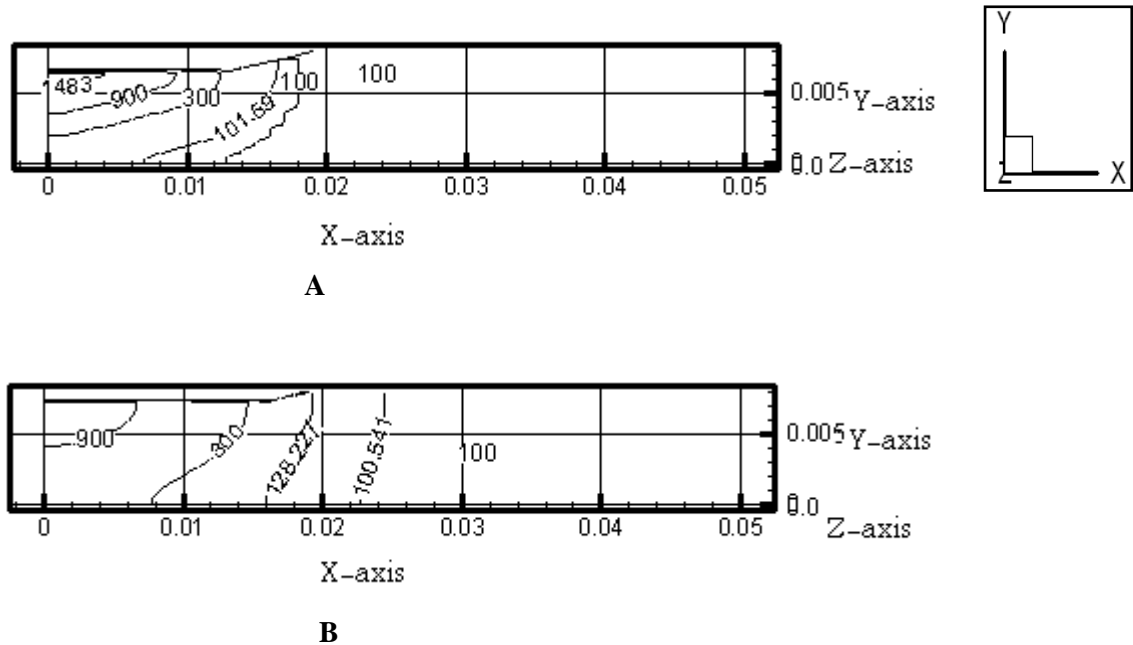

A

B

Figure (4) Comparison with Figure2and3. Temperatures distributions showing in Program temperature history at x=0 plane (welding speed 3.2mm/s, time A=0.5 Second, and B = 1.5 Second at with different preheat temperatures [9].

Analysis of Cooling Rates

Control Volume Method (CVM), helps of this new model to develop the cooling curve (Temperature-time) (T-t). Equations 16, 17 and 18 represent the model of cooling rate at welding speed (2.5 mm/s), welding current 180Amp, and preheat temperatures 75 °C, 150 °C and 225 °C, respectively. The influence of weldment preheat on the cooling rates was simulated as the preheat temperature increase; the cooling curve goes to decrease gradually to lower values**Figure5.**These results are found in agreement with the results of**Chol, and J.Mazumder [10]** as shown in **Figure 6.**

$$dT/dt = 70.61 * t^{(-1.11)} \qquad\qquad …………..\ (16)$$

$$dT/dt = 65.42 * t^{(-1.1)} \qquad\qquad …………..(17)$$

$$dT/dt = 60.23 * t^{(-1.09)} \qquad\qquad …………\ (18)$$

Where;   dT/dt is cooling rate and (t) is the time (second)

The preheat temperature has no effect on the heat input when the latter has a value of 1.49 kJ/mm, as shown in Figure, 7.The result is in agreement with the results of Fassani and Trevisan [11] as shown in Figure 8.
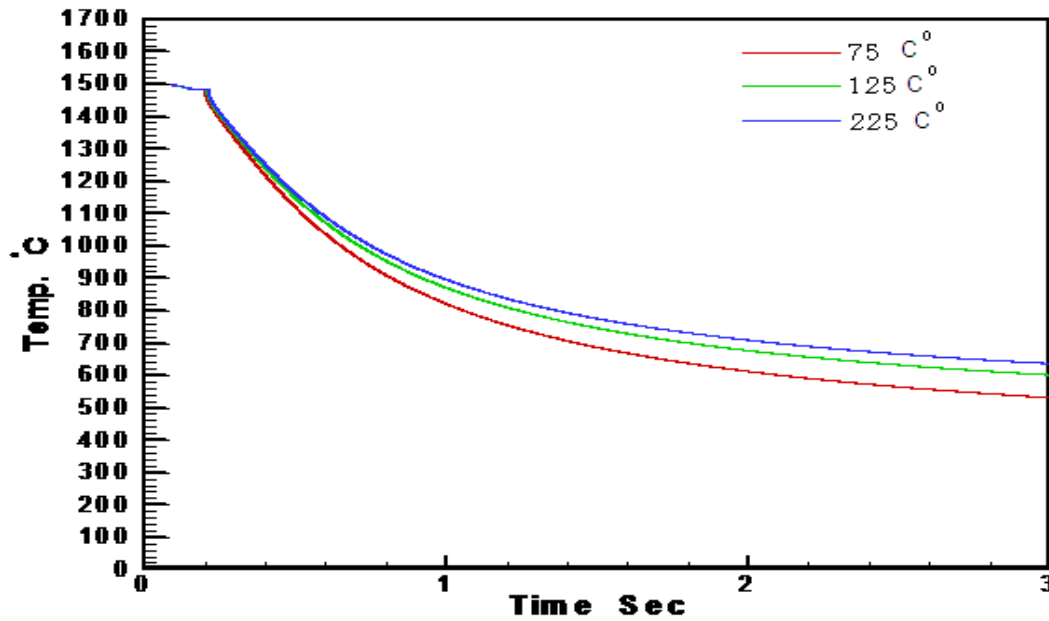

Figure (5) Computational cooling curves of fusion zone, with welding speed 2.5 mm/s, welding current 180Amp, voltage 26 V and different preheats temperatures
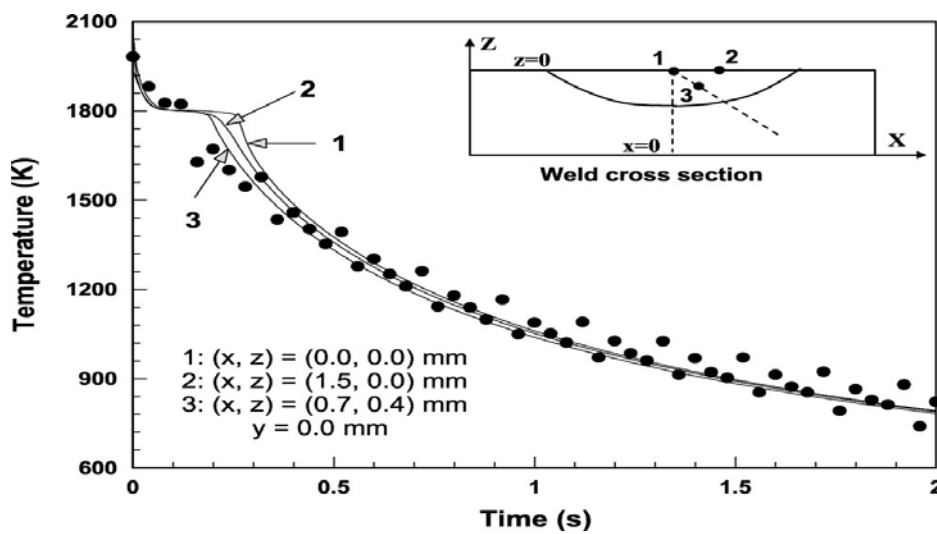
Figure (6) Comparison with Figure 5, the numerical cooling curves welding location in   (1) fusion zone and (2) heat affect zone, with conditions are current =108 A, arc voltage =18V, and different preheats [10].
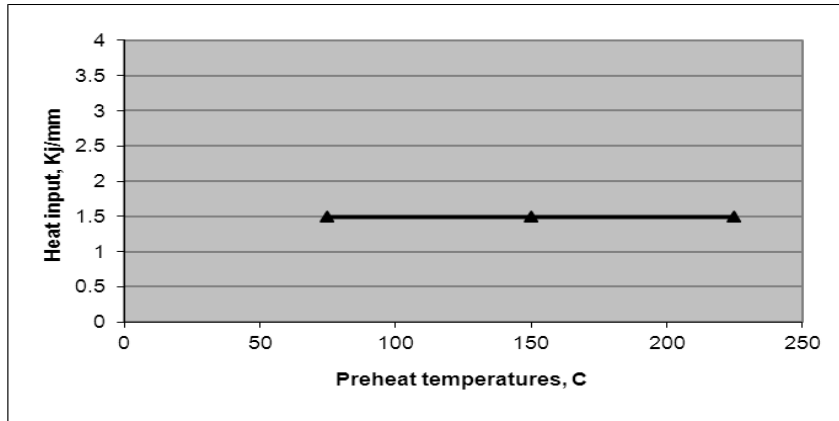

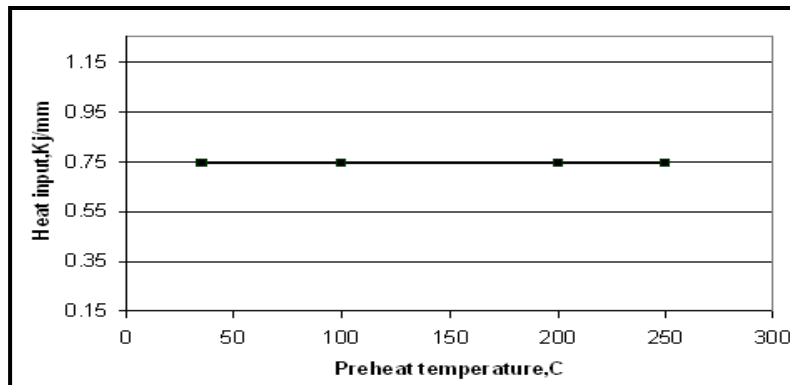**Figure (7) The relationship between preheats temperatures and heat input.**

Figure (8) Comparison with Figure7, relationship between heat input and preheat temperatures [11].

Conclusions

1- The computational solution obtained help to estimate the thermal cycles produced by one pass welding process in fusion zone (FZ). The most interesting regions for heat transfer analysis are the fusion zone (FZ), where high temperatures are reached and decreased to the base metal zone (BM). The temperature distribution was affected by preheat temperatures, increasing the preheat temperatures leads to decrease the cooling rates.

2- The following model derived from the cooling curves can be safely used to the cooling rates from the fusion zone (FZ),with different preheat temperatures 75 °C, 125°C and 225 °C, respectively:

$(dT/dt = 70.61 * t^{(-1.11)})$, $(dT/dt = 65.42 * t^{(-1.1)})$ and $(dT/dt = 60.23 * t^{(-1.09)})$

3- Preheat temperatures have no effects on the heat inputs, but they showed great effects on the cooling rates.

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NOMENCLATURE
a   Coefficient
Tm Melting temperature**,** °C
T1 Liquids temperature, °C
Ts Soldidus temperature**,** °C
ρl Liquid density, Kg/m³
ρs Solid density, Kg/m³
R Cooling rate, °C/S
Cρ Specific heat**,** J/kg.K
Kl Liquid Thermal conductivity**,** W/m.°K
H   Latent heat**,** J/kg
E Enthalpy**,** kJ/kg
 H Heat input, J/Kg
M   mass, Kg
V° Weld metal volume deposit per second**,** mm^3/s
ν Travel welding speed, mm/s
f_L liquid fraction
ΔT temperature difference, T_L- T_S(K)
 t   time, s
 x, y, z   coordinate directions
δx x- direction distance between two adjacent grid points
$\Delta y, \delta y$ similar to Δx, δx
Δz, δz similar to Δx, δx

SUBSCRIPTS

S   south neighbor of grid P
 s   control- volume face between P and S
T   top neighbor of grid P
t   control -volume face between P and T
N   north neighbor of grid P
n   control- volume face between P and N
 p   grid point
B bottom neighbor of grid   P
b   control- volume face between P and B
east neighbor of grid PEE
econtrol- volume face between P and E
W   west neighbor of grid P
w   control- volume face between P and W

GREEK SYMBOLS

ρ   Density, kg/m^3
η   efficiency of arc welding , %
Γ and S Coefficients in equation (1)