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FINITE ELEMENT PREDICTION OF DROPLET TEMPERATURE IN GMAW PROCESS

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Abstract
In this study, fist the temperature distribution along the consumable wire was simulated using a two-dimensional finite element model and then, average temperature of melt droplet was calculated using temperature gradient and thermal balance equation in solid/liquid interface. Next, the results of finite element modeling were compared with the semi-empirical model and experimental data. The results showed that when welding current led to globular mode of metal transfer, the presented finite element model was in good agreement with experimental data.
Key words: Melt droplet temperature; GMAW; Finite element method; Semi-empirical model.

Introduction
Gas–metal arc welding (GMAW) is a process that melts and joins metals by heating them with an arc established between a continuously fed filler wire electrode and the metals Melt droplets, produced on consumable wire tip, are of crucial importance in heat transfer during GMAW process. These droplets fill the gap between work pieces and play an important role in heat transfer from filler metal (wire) to parent metal. Wire consists of solid and molten parts during welding process. Heat in solid part is mostly transferred through thermal conduction and in molten part through the plasma phase around the droplet. Considering the interrelation between these two parts, thorough and simultaneous description of heat transfer in these parts is quite difficult [1]. Moreover, the formed melt droplet's temperature exceeds the melting point [2]. The total energy input in welding processes with consumable electrode is categorized in two

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parts. One part is spent on melting the electrode and increasing the melt droplet's temperature over the melting point. The rest of the energy directly enters the weld pool through radiation [3]. Another important issue that has recently received lots of attention is the calculation of fume formation rate in GMAW process [2, 6].

The main parameter that controls both foregoing issues is the temperature of melt droplet produced in GMAW process. In the current research, first a mathematical model of heat transfer in GMAW process is presented and then, the results are compared to the analytical and semi-empirical models and experimental data.

Mathematical model of the process

The heat transferred to the work piece from arc can be calculated using Eq. 1:

$$q_{total} = \eta VI = q_{ind} + q_{dir} \tag{1}$$

where q_{ind} is the required heat for melting the filler metal and increasing its temperature to droplet temperature and q_{dir} is the part of the total heat that is directly transferred from arc to wire [3]. One of the difficulties in simulation of welding processes with filler metal, like GMAW, is to specify the two parts of the total energy input mentioned in earlier paragraphs [3]. If the melting wire is considered as shown in Fig.1 and heat flux from plasma phase to the droplet is Q_{pl}; first, this heat flux melts the wire tip and heats it up to T_d and the rest of it, Q_{ls}, is transferred to the solid part of the wire by thermal conduction [1].

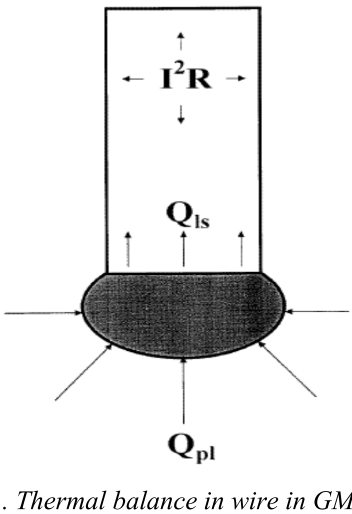

Fig. 1. Thermal balance in wire in GMAW [1].

Thermal balance equation can be considered as Eq. 2:

$$Q_{pl} = \rho SV[C(T_d - T_m) + \Delta H] + Q_{ls} \tag{2}$$

where, S, V, ρ, C, ΔH and T_d are wire cross-section area, wire feeding rate, density, specific heat, latent heat of fusion and average temperature of droplet, respectively. For calculating T_d, it is needed to have Q_{pl} and Q_{ls} [1]. Q_{pl} is obtained from the following Eq. 3[1]:

$$Q_{pl} = IV_{pl} = I(\Phi_e + \frac{3}{2}\frac{kT}{e} + V_a) \tag{3}$$

Where, Φ_e, $^3/_2\ kT/e$ and V_a represent work function, heat energy of electrons and reduction of potential in anode, respectively [2]. V_{pl} for Argon plasma arc is approximately 6 volts [1]. One-dimensional heat transfer for wire in GMAW is presented in Eq. 4. The wire diameter is constantly fed from the welding torch. It's presumed that the solid part of the wire (stickout value) stays unchanged and equals to L during the process. Numerical or analytical solving of the following equation results in the temperature distribution in wire [1].

$$\rho CV\frac{dT}{dx} = \frac{d}{dx}(K\frac{dT}{dx}) + \beta(\frac{4i}{\pi d^2})^2 \tag{4}$$

where ρ, C, K, d, β and I are density, solid state heat capacity, thermal conductivity, wire diameter, electrical resistance and electric current intensity, respectively. Boundary conditions for solving Eq. 4 are as represented in Equations 5, 6 and 7 [1].

Where wire contacts the tube [1]:

$$T(x=0) = T_0 \tag{5}$$

In the solid-liquid interface:

$$T(x=L) = T_m \tag{6}$$

$$K(T_m)\frac{dT}{dx}_{(x=L)} = \frac{Q_{ls}}{S} \tag{7}$$

Therefore, the calculation of thermal gradient at x=L is necessary to solve Eq. 4. For calculating this gradient, both analytical and numerical methods can be used. If physical parameters stay unchanged, analytical solution of Eq. 4 by MAPLE software will be as following:

$$T(x) = -\frac{e^{\frac{\rho CVx}{K}}\left(T_o\rho CV\pi^2 d^4 - T_m\rho CV\pi^2 d^4 + 16i^2\beta L\right)}{\rho CV\pi^2 d^4\left(-1+e^{\frac{\rho CVL}{K}}\right)} + \frac{16i^2\beta x}{\rho CV\pi^2 d^4} + \frac{-T_m\rho CV\pi^2 d^4 + 16i^2\beta x + e^{\frac{\rho CVL}{K}}T_o\rho CV\pi^2 d^4}{\rho CV\pi^2 d^4\left(-1+e^{\frac{\rho CVL}{K}}\right)} \tag{8}$$

Despite the strong dependency of physical parameters on temperature, they were considered constant in Eq. 8, so the results of analytical solution could not match available experimental data. Accordingly, the finite element method and ANSYS software were employed to solve Eq. 4. In finite element model, axi-symmetric thermoelectric element PLANE67 was used as illustrated in Fig. 2.

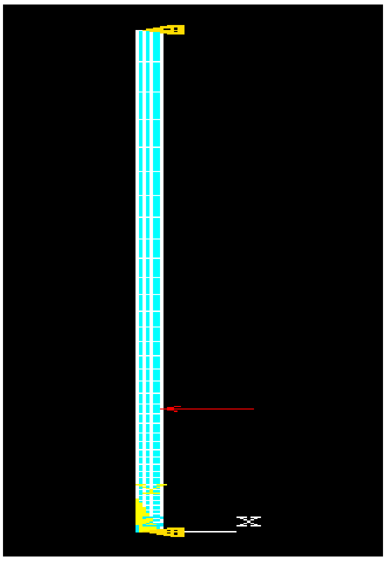

Fig. 2. The used mesh system and applied boundary conditions.

Moreover, temperature-dependent physical parameters were utilized. The applied material (mild steel) properties were normalized to the room temperature properties and the results as illustrated in Fig. 3. Thermal and electrical properties at room temperature were as following [1]: ρ=7600 kg/m^3, β=10 μΩcm, C=790 J/K.kg and k=73 W/mK.

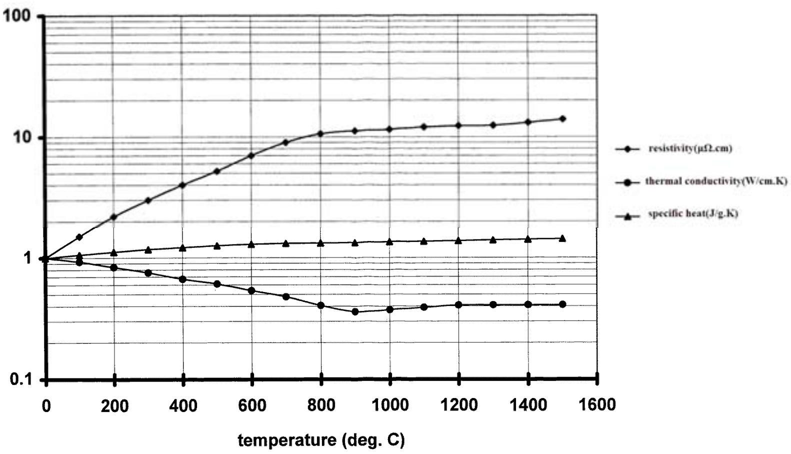

Fig. 3. The thermal properties of mild steel [1].

The stickout length was considered constant and equal to 38 mm, wire diameter was 1.2 mm and calculations were carried out for four different welding current: I=89,113,142 and 195 A.

Semi-empirical model was also used in this research work. In the model proposed by Deam *et al*. [4], droplet superheat temperature is calculated. As expected, it was also assumed that the total heat input from plasma phase to the droplet followed Eq. 9 and ignored liquid to solid heat input (Q_{ls}).

$$Q = \rho SV\left[C\overline{\Delta T} + \Delta H\right] \tag{9}$$

where. $\overline{\Delta T}$ was the average droplet superheat. They also suggested Eq. 10 for calculating Q_{pl}:

$$Q_{pl} = SN_u \frac{K}{d}\Delta T \tag{10}$$

In which, S, d_e, ΔT, K and N_u were cross section area of the wire, the efficient final droplet diameter, the maximum droplet superheat, thermal conductivity and the Nusselt number, respectively. By equating the two equations mentioned above, having $\overline{\Delta T} = 0.5\Delta T$ and given the Nusselt number dependance on wire diameter and feeding rate, Eq. 11 is obtained [4,5]:

$$\Delta T = \frac{(Vd)^{0..5} D}{1 - (Vd)^{0.5}\frac{E}{2}} \tag{11}$$

where, V is the wire feeding rate, d is the wire diameter in millimeters and E and D are given in following equations:

$$E = \frac{\rho C \times 10^{-3}}{208K} \tag{12}$$

$$D = \frac{\rho \Delta H \times 10^{-3}}{208K} \tag{13}$$

Assuming the chemical composition of wire close to that of pure iron, D and E will get the values below:

$$E = 0.7884 \quad و \quad D = 1256 \tag{14}$$

Therefore, for pure iron the magnitude of superheat will be as Eq.15:

$$\Delta T = \frac{(Vd)^{0.5} 1256}{1 - (Vd)^{0.5} . \frac{0.7884}{2}} \tag{15}$$

Results and discussion

In figures 4 and 5, the temperature distribution and thermal gradient for sample 2 are illustrated.

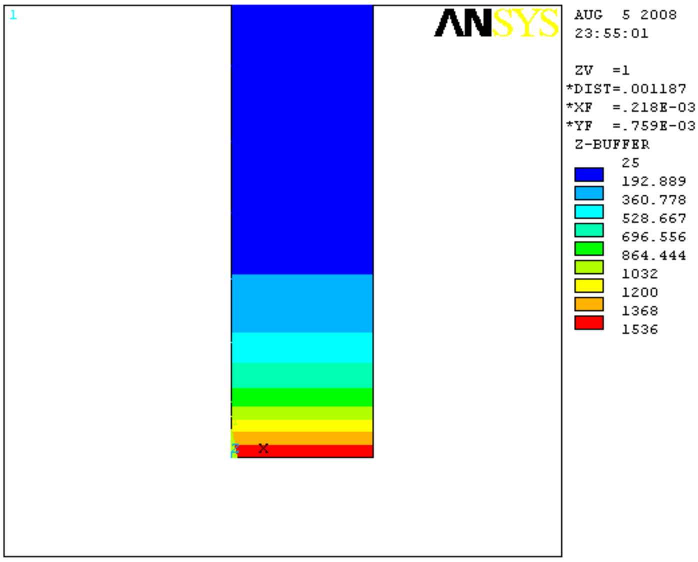

Fig. 4. The temperature distribution in sample 2.

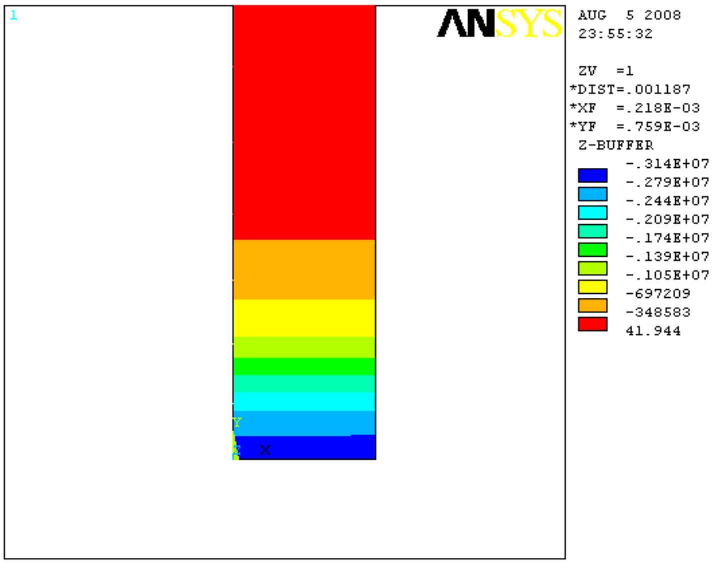

Fig.5. The temperature gradient in sample 2.

Maximum thermal gradients along the interface for all samples are presented in Table 1. These results show that there were sharp gradients in *y* direction (longitudinal direction of wire) for all four samples. As it can be seen in Table 1, higher welding current resulted in lower thermal gradient. The increase in the used welding current increased the Joule heating effect and the produced heat in different parts of wire, but temperature gradient at wire tip was decreased. It can be due to the strong effect of wire feeding rate on thermal gradient. Using this value of thermal gradient and the presented mathematical model, the temperature would be as given in Table.2.

Table.1. The maximum thermal gradients along the interface

Sample number	Welding current(A)	Wire feeding rate (cm/s)	Thermal gradient
1	89	3.5	0.317E7
2	113	4.8	0.314E7
3	142	6.6	0.308E7
4	195	11	0.292E7

Table.2. Comparing the results of finite element and semi-empirical models with experimental data

Welding current	Droplet transfer mode	Wire feeding rate (cm/s)	T_d (FEM)	T_d(semiempirical) [4]	T_d (experimental) [7]
89	globular	3.5	2570	1816	-
113	globular	4.8	2530	1868	2400
142	globular	6.6	2462	1933	2390
195	globular	11	2295	2068	2370

It can be clearly seen that the results of FEM analyses were in good agreement with experimental data, but the semi-empirical model failed to predict the real droplet temperature. This shows that just having wire feeding rate and wire diameter did not suffice for predicting the droplet temperature. In fact, one of the main parameters needed for achieving this goal was the transferred heat from liquid to solid metal (Q_{ls}). Moreover, temperature-dependent material properties should not be ignored. It should also be taken into account that the globular mode was regarded as the default mode in the current research. However, if droplets in GMAW process turned out to be transferred through other modes, like spray mode, the models for predicting droplet temperature might have been different. Finally, wire feeding rate and welding current were the main parameters that affected the final temperature of melt droplet.

Conclusions

1. The presented finite element model can predict the melt droplet temperature in GMAW process based on heat transfer between droplet, its surrounding plasma and solid part of wire and the results were in good agreement with experimental data.
2. The semi-empirical model's predictions were markedly different from experimental data, mainly due to ignoring the heat exchange between droplet and its surrounding plasma (Q_{ls}).

3. The main controlling parameters of the melt droplet temperature in GMAW process were wire diameter, feed rate and Q_{ls}.
4. For the range of welding current that caused globular mode of metal transfer, the results from the presented finite element model were in good agreement with experimental data.

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