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# Numerical simulation for thermal and electrical optimization of Submerged Arc Welding (SAW) process

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**ABSTRACT**

In submerged arc welding (SAW), selecting appropriate values for process variables is essential in order to control heat-affected zone (HAZ) dimensions and get the required bead size and quality. Also, conditions must be selected that will ensure a predictable and reproducible weld bead, which is critical for obtaining high quality. In this investigation, mathematical models were developed to study the effects of process variables and heat input on various metallurgical aspects, namely, the widths of the HAZ, weld interface, and grain growth and grain refinement regions of the HAZ. The color metallography technique and response surface methodology were also used.The thermal effect of Submerged Arc that specially depends on the electrical arc, flux type and temperature field of it in workpiece, is the main key of analysis and optimization of this process, from which the main goal of this paper has been defined. Numerical simulation of welding process in SIMPELC method and by ANSYS software for gaining the temperature field of copper, the effect of parameter variation on temperature field and process optimization for different cases of Submerged Arc are done. The influence of the welding parameter for each mode on the dimensions and shape of the welds and on their ferrite contents is investigated.



## Introduction

Submerged Arc Welding (SAW) uses heat generated by an arc formed when an electric current passes between a welding wire and the workpiece. The tip of the welding wire, the arc, and the weld joint are covered by a layer of granular flux. The heat generated by the arc melts the wire, the base metal and the flux. The flux shields the molten pool from atmospheric contamination, cleans impurities from the weld metal, and shapes the weld bead. Depending on the design of the flux, it can also add alloying elements to the weld metal to alter the chemical and mechanical properties of the weld.

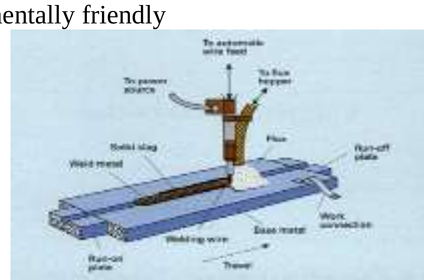
A wide range of flux compositions is used with submerged arc welding. Generally speaking, fluxes with the best welding characteristics give inferior weld metal mechanical properties. These fluxes are known as acid fluxes. Neutral fluxes generally give a good all round performance. While basic fluxes give the best metallurgical results, they possess inferior welding characteristics. The normal approach is to select the flux with the best running characteristics that will meet the metallurgical requirements comfortably.

SAW may be carried out using either DC or AC power sources. The best all round welding conditions are normally obtained with DC electrode positive. DC electrode negative will give higher deposition rates, but fusion characteristics are reduced so that this mode of transfer is mainly used on weld surfacing applications. AC welding may also be used, but arc control is not as good as on DC electrode positive. This means that many fluxes are developed primarily for DC operation and will not operate satisfactorily on AC. voltage controls the arc length and this has a major influence on the shape of the weld and its exterior appearance. Raising the arc voltage increases the arc length and this, in turn, increases the weld width. Lowering the arc voltage has the opposite effect. The travel speed controls the heat input into the joint area. Increasing travel speed reduces the heat input and supplies less filler metal per unit length of weld, resulting in less weld reinforcement.

Increasing travel speed reduces weld penetration but can cause undercut. Reducing travel speed provides time for the gases to escape from the molten metal and thus porosity may be reduced. Electrode “stick out”, the distance between the contact tube and the arc, has a major affect on weld penetration and deposition rate. Increasing the “stick out” increases deposition rate and reduces weld penetration. However, to maintain optimum process control, the electrode “stick out” is normally maintained between 25–35 mm unless special nozzle adapters are fitted. SAW Process shows in Fig.1.

***Advantages of Submerged Arc Welding:***

- High productivity with true deposition rates as high as 100 pounds per hour
- Travel speeds up to 150 inches per minute single wire or as high as 220 inches per minute with multiple electrodes
- Operating factor approaching 100%
- Deepest penetration, up to 1 1/2 inches thick in a single pass
- High operator comfort, no visible arc or spatter
- High weld quality and repeatable results
- Usually fully automated process, exceptional control
- Environmentally friendly



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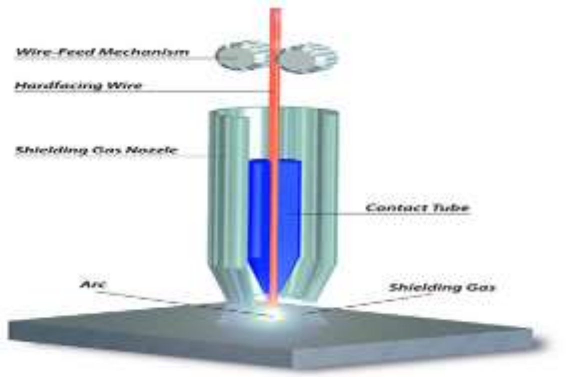



**Fig.1 Submerged Arc Welding (SAW) Process**

***Storage and Handling of Fluxes***

***Storage***

- Unopened flux bags must be stored in maintained storage conditions as follows:
- Temperature: 68°F, +/- 18°F (20°C, +/- 10°C) Relative humidity: As low as possible - not exceeding 60% max.
- Fluxes should not be stored longer than 3 years.
- The content of unheated flux hoppers must, after an 8 hours shift, be placed in a drying cabinet or heated flux hopper at a temperature of 300°F, +/- 45°F (150°C +/- 25°C).
- Remaining flux from unopened bags must be placed at a temperature of 300°F, +/- 45°F (150°C +/- 25°C).

***Re-Cycling***

- Moisture and oil must be removed from the compressed air used in the re-cycling system.
- Addition of new flux must be done with the proportion of at least one part new flux to one parts re-cycled flux.
- Foreign material, such as millscale and slag, must be removed by a suitable system, such as sieving or magnetic separator.

***Re-Drying***

- When handled and stored as above, the ESAB fluxes can normally be used straight away.
- In severe applications, stipulated by the applicable material specification, re-drying of the flux is recommended.
- Furthermore, if the flux has somehow picked up moisture, redrying can return the flux to its original moisture content.
- Re-drying shall be performed as follows: Agglomerated fluxes: 570°F, +/- 45°F (300°C +/- 25°C) for about 2-4 hours. Fused fluxes: 390°F, +/- 90°F (200°C +/- 50°C) for about 2-4 hours.
- Re-drying must be done either in equipment that turns the flux so that the moisture can evaporate easily or in an oven on shallow plates with a flux height not exceeding 2 in (5 cm).
- Re-dried flux, not immediately used, must be stored at 300°F, +/- 45°F (150°C +/- 25°C) before use.

***Disposal***

- Discard any product, residue, disposable container or liner in an environmentally acceptable manner, in full compliance with federal and local regulations.
- Please address your local disposal company for prescribed disposal.
- Information on product and residues are given in the Safety Data Sheets available through

**Governing equations**

In the common direct current electrode positive (DCEP) connection, the electrode is the anode and the workpiece is the cathode. A plasma arc is struck between the electrode and the workpiece. The electrode is continuously fed downward and melts at the tip by the high temperature arc. Droplets are then detached from the electrode and transferred to the workpiece.

The computational domain includes an anode zone (electrode), an arc zone, and a cathode zone (workpiece). The anode and cathode sheaths have been omitted and treated as special boundary conditions for computational simplifications. Assuming the arc is in local thermal equilibrium (LTE) and the plasma flow is laminar and incompressible, the differential equations governing the arc, the electrode, detached droplet, and the workpiece can be put into a single set.

The differential equations governing the conservations of mass, momentum, and energy based on continuum formulation given by Chiang and Tsai are modified and employed in this study. The derivation of the equations can be found in The idea of continuum formulation is to eliminate the need of explicitly tracking the solidifying or melting interface, and therefore the established conversation equations is valid for both solid and liquid phases[2].

The differential Equations (1) – (4) are solved iteratively by the SIMPLEC numerical procedure:

Mass continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho\upsilon_r)+\frac{\partial}{\partial z}(\rho\upsilon_z)=0 \qquad (1)$$

Radial momentum conservation equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho\upsilon_r^2)+\frac{\partial}{\partial z}(\rho\upsilon_r\upsilon_z)=-\frac{\partial\rho}{\partial r}-j_zB_\theta+ \frac{1}{r}\frac{\partial}{\partial r}(2r\eta\frac{\partial\upsilon_r}{\partial r})+\frac{\partial}{\partial z}(\eta\frac{\partial\upsilon_r}{\partial z}+\eta\frac{\partial\upsilon_z}{\partial r})-2\eta\frac{\upsilon_r}{r^2} \qquad (2)$$

Axial momentum conservation equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho\upsilon_r\upsilon_z)+\frac{\partial}{\partial z}(\rho\upsilon_z^2)=-\frac{\partial\rho}{\partial z}+j_rB_\theta+ \frac{\partial}{\partial z}(2\eta\frac{\partial\upsilon_z}{\partial z})+\frac{1}{r}\frac{\partial}{\partial r}(r\eta\frac{\partial\upsilon_r}{\partial z}+r\eta\frac{\partial\upsilon_z}{\partial r}). \qquad (3)$$

Energy conservation equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho\upsilon_r h)+\frac{\partial}{\partial z}(\rho\upsilon_z h)=\frac{1}{r}\frac{\partial}{\partial r}(\frac{rk}{c_p}\frac{\partial h}{\partial r})+ \frac{\partial}{\partial z}(\frac{k}{c_p}\frac{\partial h}{\partial z})+j_rE_r+j_zE_z-R, \qquad (4)$$

Where $\mu_0$ is the permeability of free space.

In the solution of Equation (1) – (4), special attention needs to be put on the energy effects on the electrode surface. At the cathode surface, additional energy flux terms should be included in Eq. (4) because of thermionic cooling due to the mission of electrons, ion heating, and radiation cooling [2].

**Numerical simulation**

Finite elements simulations are done in 3 steps with the main pieces:

1- Modeling by FEMB

2- The thermal study and processing

3- Post-Processing result of analysis by ANSYS software for results discussion

4. Elaboration of a mathematical model for melting rate

Influences of welding parameters on melting rate in single wire and twin wire submerged arc welding were studied during numerous experiments. Melting rate depends mostly on welding current intensity, polarity, the electrode diameter and the wire extension length. In multiple-wire electrode welding, it depends also on the number of wires applied and the distance between them. The other welding parameters, i.e. welding speed, arc voltage, kind of shielding medium, type of welding current source, chemical composition of the filler material (valid for low-alloy steels) etc., have little influence. The majority of these parameters have been studied, their influence is known and in our judgment, they may be neglected.

A study of the influence of current intensity on melting rate was carried out by means of practical experiments. The results obtained are shown in Figs. 2 and 3. Fig. 2 shows the influence of welding current on melting rate in welding with a single wire and a twin wire having a diameter of 3 mm. Welding was carried out also with wire diameters of 1.2, 1.6 and 2.0 mm. The results for the twin wire are shown in Fig. 2 (L is the wire extension length and b is the distance between the wires). Based on both diagrams (Figs. 2 and 3) similar conclusions may be drawn. In all cases the melting rate increases slightly exponentially with an increase in welding current intensity.

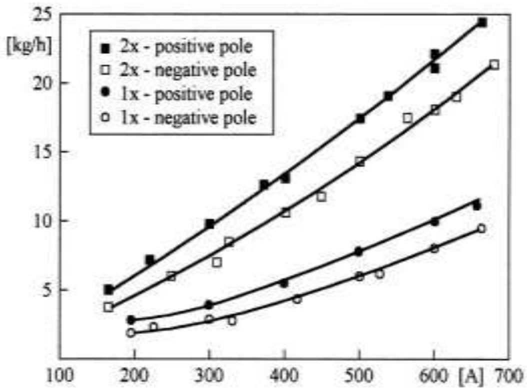



**Fig. 2. Melting rate depending on welding current intensity per wire and on polarity of a wire having a diameter of 3 mm; L.30 mm, b.8 mm**

**Numerical considerations**

For the metal domain, the method developed by Torrey et al. was used to solve p, u, v, and T. This method is Eulerian and allows for an arbitrary number of segments of free surface with any reasonable shape. The basic procedure for advancing the solution through one time step, Dt, consists of three steps. First, explicit approximations to the momentum Equations (2) – (4) are used to find provisional values of the new time velocities at the beginning of the time step. Second, an iterative procedure is used to solve for the advanced time pressure and velocity fields that satisfy Eq. (1) to within a convergence criterion at the new time. Third, the energy equation Eq. (5) is solved. Fig.3. shows A typical sequences of temperature, electrical potential, and pressure distributions on the symmetric plane for an axisymmetric stationary arc.

The response function representing any of the HAZ dimensions can be expressed as y = f (V, F, S, N). The relationship selected, being a second-degree response surface, is expressed as follows:

Y = b0 + b1V + b2F + b3S + b4N + b11V2 + b22F2 + b33S2 + b44N2 + b12VF + b13VS + b14VN + b23FS + b24FN + b34SN

For the arc plasma domain, a fully implicit formulation is used for the time-dependent terms, and the combined convection/ diffusion coefficients are evaluated using an upwind scheme. The SIMPLEC algorithm is applied to solve the momentum and continuity Equations (1) – (5) to obtain the velocity field. At each time step, the current continuity equation Eq. (6) is solved first, based on the updated parameters.

The new distributions of current density and electromagnetic force are then calculated for the momentum and energy equations. The momentum equations and the mass continuity equation are then solved in the iteration process to obtain pressure and velocity. The energy equation is solved to get the new temperature distribution. Next, the temperature-dependent parameters are updated, and the program goes back to the first step to calculate the current continuity equation. This process is repeated for each time step until the convergence criteria are satisfied[2].

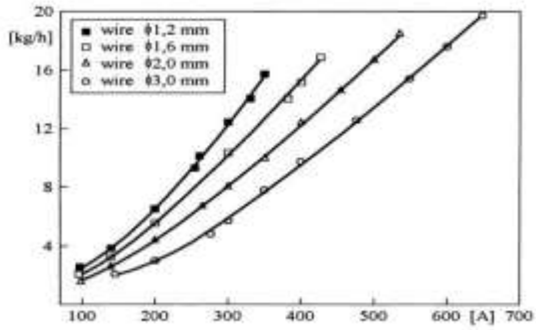


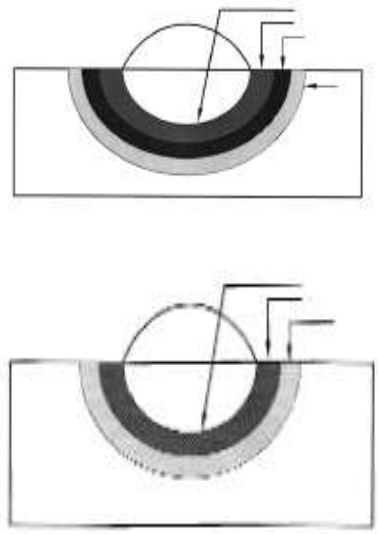

**Fig. 3. Influence of welding current intensity on the melting rate in twin electrode arc welding with the following wire diameters: 1.2, 1.6, 2.0 and 3.0 mm; L.25 mm, b.8 mm, U.30 V, electrode positive.**

**Results and discussion**

Conclusions for fluid temperature field copper temperature field, completely shown in Fig.4.

A complete 3D mathematical model for the SAW process is developed, the complete solution for a 3D case can be obtained if the numerical solution procedures proposed by Hu and Tsai are followed. The biggest challenge for such a 3D solution lies in the cost of numerical computation. Normally, the plasma flow can be computed with a relatively large grid size, but the metal flow requires a much smaller grid size in order to resolve various body forces within the tiny droplet.

a)



b)

**Fig.4. Conclusions for temperature field:**
**a) temperature field b)Copper temperature field**

Hu and Tsai used 0.1 mm grid size and $5*10^{-5}$ s time step in their computations [7]. It is almost impossible to use the same resolutions for the 3D model. For example, in this study, the grid size is 0.2 mm and the average time step is $5*10^{-5}$ s. The numerical computations showed that the 0.2 mm grid size was not small enough to accurately calculate the balance of the surface tension force and the strong electromagnetic force in the pendant droplet.

As it already takes hours to calculate one time step, it is impractical to further reduce grid size. Thus, simplifications must be made based on the interest of current study.

**Conclusions**

A more elaborate mathematical model than the one existing before was developed for calculation of melting rate in single-wire arc welding. Additionally a mathematical model for calculation of melting rate in twin-wire arc welding not known from the literature before was developed. On the basis of variation of validity of the mathematical models developed for single-wire and twin-wire arc welding it can be stated that the models are quite a true representation of the experimental results and that they are applicable to practical cases as well as to further research work. The use of the grey-based Taguchi method to determine the SAW process parameters with consideration of multiple performance characteristics has been reported in this paper.

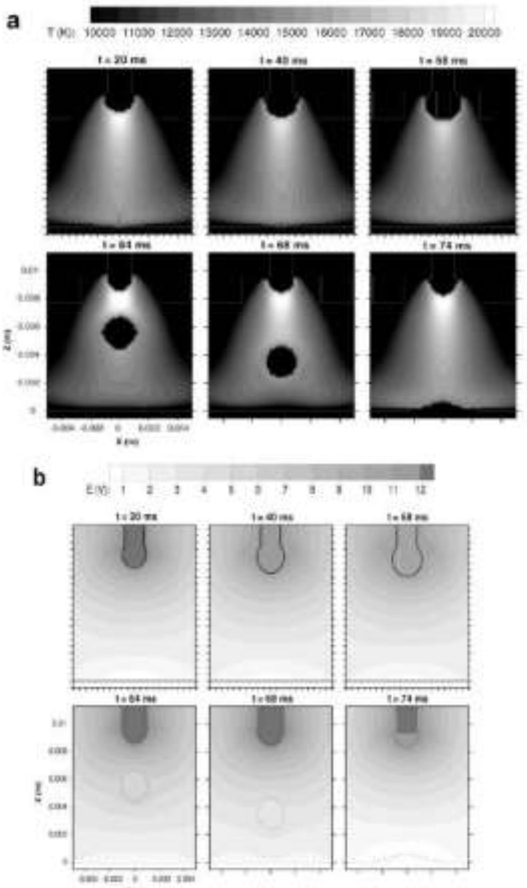
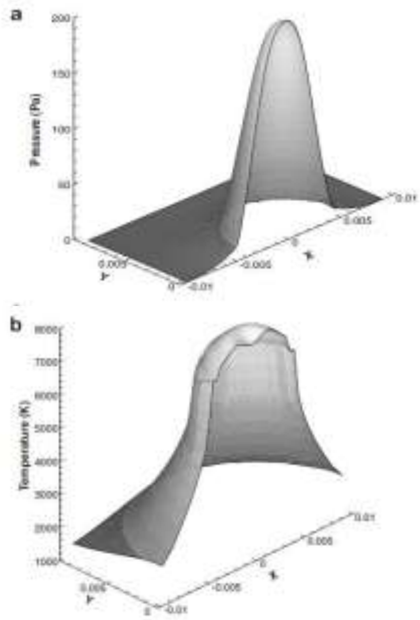



**Fig. 5. A typical sequences of temperature, electrical potential, and pressure distributions on the symmetric plane (y = 0) for an axisymmetric stationary arc: (a) temperature,(b) electrical potential**



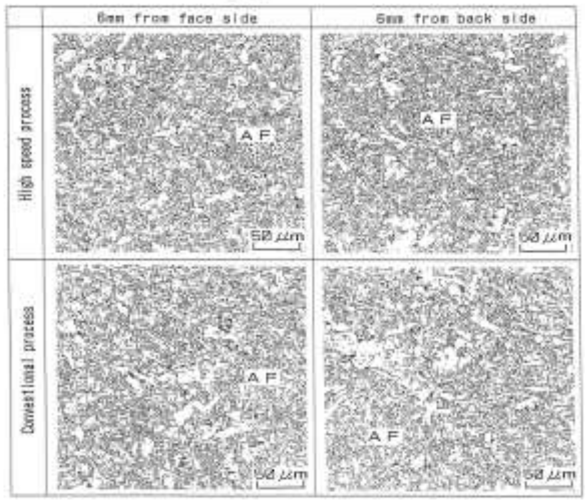




**Fig 6. Distributions at the workpiece surface at t = 64 ms: (a) pressure, (b) temperature**

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