Numerical simulation of copper temperature field in Gas Tungsten Arc Welding (GTAW) process

A.MOARREFZADEH, M.A.SADEGHI
Mechanical Engineering Group Department
Mahshahr Islamic Azad University
Mahshahr
IRAN
a_moarrefzadeh@yahoo.com, sadeghi@aut.ac.ir

Abstract: Thermal effects of gas tungsten arc (GTA) and temperature field from it on workpiece(copper) and shielding gas type, is the main key of analysis and process optimization for GTAW, that main goal of this paper is defined about that. Energy source properties of GTA strongly depend on physical property of a shielding gas. In this paper, carbon dioxide (CO$_2$) was used as an alternative gas for its low cost. The basic energy source properties of CO$_2$ GTA were numerically predicted ignoring the oxidation of the electrodes. It was predicted that CO$_2$ GTA would have excellent energy source properties comparable to that of He, Ar GTA.

Key-Words: Numerical simulation, Copper, Shielding gas, Heat source, GTAW, SIMPLEC, ANSYS

1 Introduction

The necessary heat for Gas Tungsten Arc Welding (TIG) is produced by an electric arc maintained between a nonconsumable tungsten electrode and the part to be welded.

The heat-affected zone, the molten metal, and the tungsten electrode are all shielded from the atmosphere by a blanket of inert gas fed through the GTAW torch. Inert gas is that which is inactive, or deficient in active chemical properties. The shielding gas serves to blanket the weld and exclude the active properties in the surrounding air. It does not burn, and adds nothing to or takes anything from the metal. Inert gases such as Carbon dioxide and argon and helium do not chemically react or combine with other gases. They possess no odor and are transparent, permitting the welder maximum visibility of the arc. In some instances a small amount of reactive gas such as hydrogen can be added to enhance travel speeds.

The GTAW process can produce temperatures of up to 35,000°F/ 19,426°C. The torch contributes only heat to the workpiece. If filler metal is required to make the weld, it may be added manually in the same manner as it is added in the oxyacetylene welding process. There are also a number of filler metal feeding systems available to accomplish the task automatically. Fig.1. shows the essentials of the manual GTAW process.

Thermal effects of welding electrical arc and thermal field from it on workpiece(copper) and shielding gas type, is the main key of analysis and process optimization for GTAW, that main goal of this paper is defined about that.

Fig.1. Essentials of the GTAW process
(water cooled)[1]

Welding process numerical simulation and effective parameters on it with Ansys software finding the thermal field material, the effect of parameters variation on thermal field by considering shielding
gases Ar, He, CO$_2$ and finally discussion about this process to being optimization are the main parts of this paper.

In this paper, by adopting carbon dioxide (CO$_2$), the basic energy source properties of CO$_2$ GTA are predicted. The properties of arc plasma and heat input intensity to a water-cooled copper anode are numerically analyzed ignoring oxidation of electrodes. The results are compared with those of conventional argon (Ar) and He GTA.[1]

2 Numerical simulation

This process simulation using the thermal transient analysis in Ansys software by SIMPLE numerical method in a exact way and considering separated fields for cooper, as a workpiece and shielding gas in 3 cases, Ar, He, CO$_2$ and a field for air around them starts. The equations of these fields are derived and at the end by thermal loading, equations of different fields are solved. The derived answers of thermal fields, the effect of each welding parameters are thus we can receive the GTAW process optimization. All mention steps for all 3 shielding gases happen till the thermal effect of each of them are achieved completely for the process optimization.

As interface equations of fluid and solid are non linear, analytical solutions are almost useless, because with inputs and initial values that give to interface problems to solve them, the problem gets so complicated, and numerical techniques are the only ways that we have for finding complete solutions.[3]

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

Modeling special technics for a finite elements :

1- Finite elements modeling , types and properties for model different parts
2- The definition of material properties
3- parameter definition
4- Loading
5- Boundary and initial value definition
6- Common interfaces definition
7- Control parameter definition

2.1 Finite element modeling

In Fig.2, finite element model is shown For meshing of solid field (copper) by considering the study of thermal field, from the thermal elements set, we chose the PLANE55 type. Because as axisymmetric element with conduction property, this element has 4 node with one degree of freedom. This element has mesh moving property as well. For shielding gas in 3 mentioned steps use FLUID141 element. Because this element is so suitable for transient thermal modeling. Also this element has thermal energy transmitting property.

![Fig.2. Modeling and Meshing][2]

2.2 Arc-electrode model

The tungsten cathode, arc plasma and anode are described in a frame of cylindrical coordinate with axial symmetry around the arc axis. The calculation domain is shown in Fig. 3. The diameter of the tungsten cathode is 3.2mm with a 60° conical tip. The anode is a water-cooled copper. The arc current is set to be 150 A. Ar, He or CO$_2$ is introduced from the upper boundary of the calculation domain. The flow is assumed to be laminar, and the arc plasma is assumed to be under local thermodynamic equilibrium (LTE). Physical properties of shielding gases are calculated in the same manner as that in literature.

The dependences of specific heat, thermal conductivity and electrical conductivity of the gases on the temperature are shown in Fig. 4.

The differential Eqs. (1)–(8) are solved iteratively by the SIMPLEC numerical procedure:

\[ \frac{1}{r} \frac{\partial}{\partial r} (rp_u) + \frac{\partial}{\partial z} (\rho u_z) = 0 \]  

(1)
Radial momentum conservation equation:
\[
\frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r^2) + \frac{\partial}{\partial z} (\rho v_r v_z) = -\frac{\partial \rho}{\partial r} - j_z B_0 + \frac{1}{r} \frac{\partial}{\partial r} (2 \eta \frac{\partial v_r}{\partial r}) + \frac{\partial}{\partial z} (\eta \frac{\partial v_r}{\partial z} + \eta \frac{\partial v_z}{\partial r}) - 2 \eta \frac{v_r}{r^2}.
\]  
(2)

Axial momentum conservation equation:
\[
\frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r v_z) + \frac{\partial}{\partial z} (\rho v_z^2) = -\frac{\partial \rho}{\partial r} + j_z B_0 \frac{\partial}{\partial z} (2 \eta \frac{\partial v_r}{\partial r}) + 1 \frac{\partial}{\partial r} (r \eta \frac{\partial v_r}{\partial z} + r \eta \frac{\partial v_z}{\partial r}).
\]  
(3)

Energy conservation equation:
\[
\frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r h) + \frac{\partial}{\partial z} (\rho v_z h) = \frac{1}{r} \frac{\partial}{\partial r} (r k \frac{\partial h}{\partial r}) + \frac{\partial}{\partial z} (k \frac{\partial h}{\partial z}) + j_z E_r + j_z E_z - R,
\]  
(4)

Conservation of thermal energy:
\[
\frac{\partial}{\partial t} (\rho C_p T) + \frac{u}{r} \frac{\partial}{\partial r} (\rho C_p r T) + \frac{w}{\partial z} (\rho C_p T) = \frac{1}{r} \frac{\partial}{\partial r} (k r \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) - \frac{\Delta H}{C_p} \frac{\partial F_L}{\partial t}.
\]  
(5)

Conservation of electrical charge:
\[
\frac{1}{r} \frac{\partial}{\partial r} (\sigma r j_r) + \frac{\partial}{\partial z} (\sigma j_z) = 0
\]  
(6)

Current continuity equation:
\[
\frac{1}{r} \frac{\partial}{\partial r} (r j_r) + \frac{\partial}{\partial z} (j_z) = 0
\]  
(7)

Ohm's law:
\[
f_r = -\sigma E_r, j_z = -\sigma E_z
\]  
(8)

For boundary condition of fluid field:
\[
\int_\Omega \frac{1}{C^2} P + (V)^T \nabla P d\Omega + \int_\Omega \frac{1}{r} P dT = 0
\]  
(9)

For boundary condition of solid field:
\[
\int_\Omega \frac{1}{r} P dT = 0
\]  
(10)

Heat transfer equation:
For conduction:
\[
q_x = -k_x \frac{dT}{dx}
\]  
(11)

For convection:
\[
q_h = h (T - T_\infty)
\]  
(13)

Potential of heat transfer equation:
\[
\Pi p = u + \Pi_v + \Pi_q + \Pi_h
\]  
(15)

where \( t \) is the time, \( h \) the enthalpy, \( P \) the pressure, \( v_x \) and \( v_y \) the axial and radial components of velocity respectively, \( j_x \) and \( j_y \) the axial and radial component of the current density respectively, \( g \) the acceleration due to gravity, \( k \) the thermal conductivity, \( C_p \) the specific heat, \( \rho \) the density, \( \eta \) the viscosity, \( s \) the electrical conductivity, \( \sigma \) the radiation emission power, \( E_r \) and \( E_z \) the radial and
axial components of the electric field defined by $E_r = -\frac{\partial V}{\partial r}$ and $E_z = -\frac{\partial V}{\partial z}$ and $V$ is electric potential.

\[ |j_k| = AT^2 \exp\left(-\frac{e\phi_e}{k_B T}\right) \tag{17} \]

where $A$ is the thermionic emission constant of the cathode surface, $\phi_e$ the effective work function for thermionic emission of the surface at the surface temperature and $K_B$ the Boltzmann’s constant. The ion-current density $j_i$ is then assumed to be $|j_i|\leq|j_k|$ if $|j_i|$ is greater than $|j_k|$, where $|j| = |j_e|+|j_i|$ is the total current density at the cathode surface obtained from Eq. (5).

Fig. 3. Schematic illustration of calculated domain.\[2\]

The azimuthal magnetic field $B_\theta$ induced by the arc current is evaluated by Maxwell’s equation:

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r B_\theta \right) = \mu_0 j_z, \]

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

In the solution of Eqs. (1)–(6), 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.

The additional energy flux for the cathode $H_K$ is:

\[ H_K = -\varepsilon \alpha T^4 - |j_e| \phi_K + |j_i| V_i, \tag{16} \]

where $\varepsilon$ is the surface emissivity, $\alpha$ the Stefan-Boltzmann constant, $\phi_K$ the work function of the tungsten cathode, $V_i$ the ionization potential of argon, $j_e$ the electron current density and $j_i$ the ion current density. At the cathode surface, thermionic emission current of electron, $j_e$, cannot exceed the Richardson current density $J_R$ [17] given by:

Fig. 4. Dependences of specific heat, thermal conductivity and electrical conductivity of gases on temperature. (a) Specific heat, (b) thermal conductivity and (c) electrical conductivity.\[3\]
Similarly, for the anode surface, Eq. (4) needs additional energy flux terms for thermionic heating and radiation cooling. The additional energy flux for the anode $H_A$ is:

$$H_A = -e\alpha T^4 + |j|\phi_A,$$

where $\phi_A$ is the work function of the anode and $|j|$ the current density at the anode surface obtained from Eq. (5).

The term including $\phi_A$ accounts for the electron heating on the anode because electrons deliver energy equal to the work function when being absorbed at the anode. The term is analogous to the cooling effect that occurs at the cathode when electrons are emitted.[4]

3. Results and discussion

Fig.5. shows two-dimensional distributions of the temperature and flow velocity in Ar, He and CO$_2$ GTA at 150A arc current. The peak temperatures on the anode surface are 600, 1000 and 1200K, respectively for Ar, He and CO$_2$ GTA. The peak plasma temperatures and the flow velocities are 17000, 19000 and 25000 K, and 217, 298 and 748 m/s, respectively, while the arc voltages are 10.8, 19.9 and 17.3 V, correspondingly.

Fig.6. shows the radial distribution of heat input intensity onto the anode surface consisting of the heat transportation from electrons (enthalpy and condensation) and the heat conduction. The peak heat input intensities are 5000, 16 000 and 17 600 W/cm$^2$, respectively.

For He GTA, the peak temperature on the anode surface reaches 1000 K, which is approximately two times higher than that of Ar GTA, mainly due to the higher peak of heat input intensity caused by the current constriction. As shown in Fig.4, the lower electrical conductivity of He than that of Ar reduces the diameter of the current channel and leads to the current constriction. The heat transportation from electrons is, therefore, concentrated near the arc axis. On the other hand, the plasma temperature and the flow velocity near the cathode are slightly higher than those of Ar GTA because of the highest thermal conductivity of He.

Since the expansion of high-temperature region on the cathode surface leads to the arc root expansion, the increase in current density is suppressed and resultantly the temperature and flow velocity are relatively low due to the low pinch force.

Now, turn to the results for CO$_2$ GTA. The peak temperature on the anode surface reaches 1200K that is slightly higher than that of He GTA. The heat transportation from electrons is comparable to that of He GTA, but the peak heat input intensity is higher than that of He GTA because the heat conduction in CO$_2$ GTA is higher due to the higher plasma temperature near the anode surface.
Fig. 6. Radial distributions of heat intensity onto the surface of watercooled copper anode for argon, helium and carbon dioxide gas tungsten arc at 150A arc current. (a) Ar, (b) He, (c) CO$_2$[3]

Cooper temperature field is according to Fig.7. if the shielding gas be a mixture of Ar, He in which the transmission of produced heat to copper is shown completely.

4. Conclusions

(1) A molecular gas with high mole specific heat such as CO$_2$ has the ability to constrict arc plasma and hence increases current density near the arc axis. The peak current density of CO$_2$ GTA on the anode surface and the arc voltage are respectively 1875 A/ and 17 cm$^2$.3 V, comparable to those of He GTA.

(2) The peak plasma temperature and flow velocity near the cathode are respectively 25 000K and 748 m/s, which are much higher than those of Ar and He GTA and lead to high arc pressure.

(3) The peak heat input intensity onto the anode surface is 17 600W/cm$^2$, which is higher than those of Ar and He GTA. The intensity due to the heat transportation from electrons is 8400W/cm$^2$, which is comparable to that of He GTA. However the intensity due to the heat conduction is 9200 W/cm$^2$, which is higher than that of He GTA due to the high temperature of the CO$_2$ plasma near the anode surface.

(4)According to achieved results from numerical solution for all tree cases of shielding gas it is obvious GTAW process is suitable for cooper, because of the depth of weld diffusion compared with width and melting deficiency, is so high.

References