Study on the Arcs Interaction in Plasma-GMAW Hybrid Welding

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Abstract. A 3D model was established to study the arcs interaction behaviors in a plasma-GMAW hybrid welding process using Computational Fluid Dynamics (CFD) method. The temperature field and electromagnetic force distribution were obtained. The effects of Lorentz force on the hybrid arcs were analyzed. Results show that the Lorentz force density in plasma arc zone is much larger than that of the GMAW arc zone. It moves the GMAW arc backward in the welding direction but makes the plasma arc move forward and enhance its stiffness.

1. Introduction
Plasma-gas metal arc welding (GMAW) Hybrid welding is a type of welding process that combines of the two normal welding processes, plasma arc and GMAW arc, into one hybrid process [1]. In the conventional hybrid welding process [2,3], the welding wire in GMAW and tungsten electrode in plasma welding are always have the same polarity, and the GMAW arc is surrounded by the hot plasma arc. Admittedly, this conventional hybrid welding process has various advantages, such as greater welding speeds than standard GMAW. However, if the current through the welding wire is too large, rotating jet transition is supposed to occur. As a result, the arc becomes un-stable.

Recently, a new innovative hybrid welding technology was developed [4]. Through the introduction of a plasma electrode within the GMAW process which establishes an arc at the leading position of the welding process. In this type hybrid welding process, the plasma arc leads the GMAW arc. A "keyhole" is created within the parent material resulting in deeper penetration and increased speed. However, in this hybrid process, the arcs interaction mechanisms are not very clearly. During the hybrid welding process, the plasma arc and the GMAW arc are not independent, they establish a complex coupling relationship by shared electromagnetic space and conductive ionized gas [5, 6]. In order to further understand the hybrid welding process and improve the application of this welding method, it is of great important to investigate the arc interaction mechanisms in the hybrid welding process.

2. Experiments and Models

2.1. Welding Experiment
Plasma-GMAW hybrid welding experiment was carried out on a 12mm thickness low-carbon steel plate. The welding parameters are listed in table 1. High-speed camera was used to capture the arcs shape during the welding process.
Table 1. Welding parameters

| Plasma Current (A) | Plasma Voltage (V) | GMAW current (A) | GMAW voltage (V) | Speed (cm min⁻¹) | Shielding gas flow rate (L·min⁻¹) |
|-------------------|--------------------|------------------|------------------|-----------------|----------------------------------|
| 100               | 23                 | 270              | 27.7             | 40              | 28                               |

2.2. Modeling
The simulation of the hybrid process was conducted in Computational fluid dynamics (CFD) framework. Due to symmetry, only half of the calculation domain is modeled as illustrated in figure 1.

![3D model of plasma-GMAW hybrid welding](image)

Figure 1. 3D model of plasma-GMAW hybrid welding

2.3. Governing Equations
The fluid in the calculation must obey the mass, momentum and energy conservation equations, which are given in equations (1)-(3), respectively.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}
\]

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = \nabla P + \nabla \cdot \mathbf{\tau} + \mathbf{F} \tag{2}
\]

\[
\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p T \mathbf{v}) = \nabla \cdot (\kappa \nabla T) + S \tag{3}
\]

Where, \( \rho \) is the density, \( t \) is time, \( \mathbf{v} \) is the velocity vector, \( P \) is the pressure, \( \mathbf{\tau} \) is the viscous sheartensor, \( \mu \) is the viscosity, \( T \) is the temperature, \( C_p \) is the specific heat, \( \kappa \) is the thermal conductivity. \( \mathbf{F} \) and \( S \) are the source terms in momentum and energy conservation equations, respectively, and are defined in equation (4) and (5).

\[
\mathbf{F} = \rho \mathbf{g} + \mathbf{j} \times \mathbf{B} \tag{4}
\]

\[
S = \frac{j^2}{\sigma_e} + \frac{5k_B}{2e} \mathbf{j} \cdot \nabla T - S_R \tag{5}
\]

Where, \( \mathbf{j} \) is the current density vector, \( \mathbf{B} \) is the magnetic flux density, \( \sigma_e \) is the electrical conductivity, \( e \) is elementary charge and \( S_R \) is the radiation heat loss. The relationship between \( \mathbf{j} \) and \( \mathbf{B} \) is defined by

\[
\nabla^2 A = -\mu \mathbf{j} \tag{6}
\]

\[
\mathbf{B} = \nabla \times \mathbf{A} \tag{7}
\]
Where, \( A \) is the magnetic vector potential and \( \mu_0 \) is the vacuum magnetic permeability.

2.4. Boundary Conditions
The boundary conditions applied in the calculation are listed in table 2.

### Table 2. Boundary conditions

| Zone                  | Type         | Voltage (V) | Temperature (K) | Electric potential (V) | Magnetic vector potential (wbm\(^{-1}\)) |
|-----------------------|--------------|-------------|-----------------|------------------------|-----------------------------------------|
| Tungsten electrode    | wall         | -           | 5000            | \( \sigma \frac{\partial \phi}{\partial n} = \frac{l_2}{\pi r_p} \) | \( \frac{\partial A}{\partial n} = 0 \) \(^a\) |
| Welding wire          | wall         | -           | 5000            | \( \sigma \frac{\partial \phi}{\partial n} = \frac{l_2}{\pi r_e} \) | \( \frac{\partial A}{\partial n} = 0 \) |
| Plasma gas inlet      | velocity- inlet | 23       | 1000            | \( \frac{\partial \phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| Shielding gas inlet   | velocity- inlet | 27.7    | 1000            | \( \frac{\partial \phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| Outflow               | pressure- out | -           | 1000            | \( \frac{\partial \phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| Workpiece bottom      | wall         | -           | -               | \( \frac{\partial \phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |

\(^a\) \( r_p \) is the radius of the tungsten electrode.
\(^b\) \( n \) is the unit vector normal to the surface.
\(^c\) \( r_w \) is the radius of the welding wire.

3. Results and Discussion

3.1. Temperature Field and Arches’ Shape
The temperature field contours under the given welding parameters is show in figure 2. The maximum value of the temperature in plasma arc zone is above 29000K, which is far larger than that of the GMAW arc zone (around 20000K). It is because that the strong compression effect by the plasma nozzle. Compared with the high-speed photography of the hybrid welding arcs (see figure 3), the shape of the arcs are in good agreement with the experimental ones.

![Figure 2. Temperature field in simulation](image1)

![Figure 3. High-speed photograph of the hybrid arcs](image2)
vectors in the hybrid arcs zone is shown in figure 4. Its horizontal component force along the path AB is illustrated in figure 5.

Figure 4. Lorentz force vectors in the hybrid arcs zone

Figure 5. Lorentz force density along path AB

It can be seen from figure 4 and figure 5 that the Lorentz force density in the plasma arc zone is obviously larger than that of the GMAW arc zone. Moreover, the Lorentz forces in the plasma arc zone are almost symmetrically distributed which makes the plasma arc have a higher stiffness. On the other hand, the Lorentz forces in the GMAW arc zone are all negative. That means the Lorentz force pushes the GMAW arc backward which is helpful to decrease its temperature and make the GMAW operate in the "conduction" mode to fill the pool.

4. Conclusions
The arcs interaction in a plasma-GMAW hybrid welding process have been studied using CFD method. The following conclusions can be obtained.
1. The maximum temperature of the plasma arc are far higher than that of GMAW arc.
2. The Lorentz force density in the plasma arc zone is larger than that of the GMAW arc zone.
3. Lorentz force makes the plasma arc move forward while makes the GMAW arc backward the welding direction.

5. References
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