

Influence Mechanism of Metal Vapor in Plasma Arc Lap Welding

Metal vapor decreases arc energy efficiency in conduction plasma arc lap welding

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Abstract

A three-dimensional coupled tungsten electrode–plasma arc–metal vapor–weld pool model was developed to investigate plasma arc and metal vapor characteristics, weld pool convection, and energy transfer in conduction plasma arc lap welding. The arc energy efficiency was also calculated. The numerical results showed that in conduction plasma arc lap welding, the constraint effects of the plasma arc by a small constricting nozzle, plasma gas, and electromagnetic force were strong, and no keyhole was formed inside the weld pool, so the heat flux on the weld pool surface was high as well as the weld pool temperature and mole fraction of Fe vapor above the weld pool surface. The high concentration of Fe vapor in the arc decreased the conduction energy from the plasma arc to the weld pool along with the arc energy efficiency. The calculated arc energy efficiency was only 50.2%. Without considering Fe vapor, the calculated weld pool had complete joint penetration. When considering Fe vapor, the calculated weld geometry agreed well with the experimental result.

Keywords

- Conduction Plasma Arc Lap Welding
- Numerical Simulation
- Fe Vapor
- Energy Transfer

Introduction

In the manufacturing of a liquefied natural gas carrier, plasma arc welding (PAW) was used to improve welding efficiency and reduce the welding distortion of SUS304 stainless steel corrugated plates (Ref. 1). Since the corrugated plates were thin, and the welding quality specification required an incomplete joint penetration weld, a relatively low welding current (< 100 A) was used in the plasma arc lap welding process. Our high-speed images suggested that the weld pool surface deformation was small, and a keyhole was not generated inside the weld pool in PAW of corrugated plates (Ref. 2).

A keyhole formation inside the weld pool has a great influence on arc characteristics, weld pool convection, and energy transfer in keyhole PAW (Ref. 3). With an open keyhole, the flow pattern of arc plasma is changed and the maximum plasma temperature decreases (Ref. 4). The weld pool convection becomes complicated and the maximum weld pool temperature decreases (Ref. 5). It should be noted that different from laser keyhole welding, a keyhole can't increase arc energy absorption in PAW. In laser welding, owing to multiple reflections and Fresnel absorption by the keyhole (Ref. 6), the total laser energy absorbed by the weld pool increases. Kawahito et al. measured the absorption of a 10-kW fiber laser beam and showed that the maximum absorption ratios of steel and aluminum were 89 and 93%, respectively (Ref. 7). However, in keyhole PAW, the arc energy efficiency is relatively lower than in gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). Previous studies showed the arc energy efficiency of GMAW was 67 ~ 82% (Refs. 8–10) and the arc energy efficiency of GTAW was 68 ~ 84% (Refs. 9, 11–13) while the arc energy efficiency of keyhole PAW was only 47 ~ 66% (Refs. 9, 14, 15). In GMAW, both the cathode (weld pool) and anode (welding wire) are melted by the arc; the anode melts into droplets and transfers to the weld pool

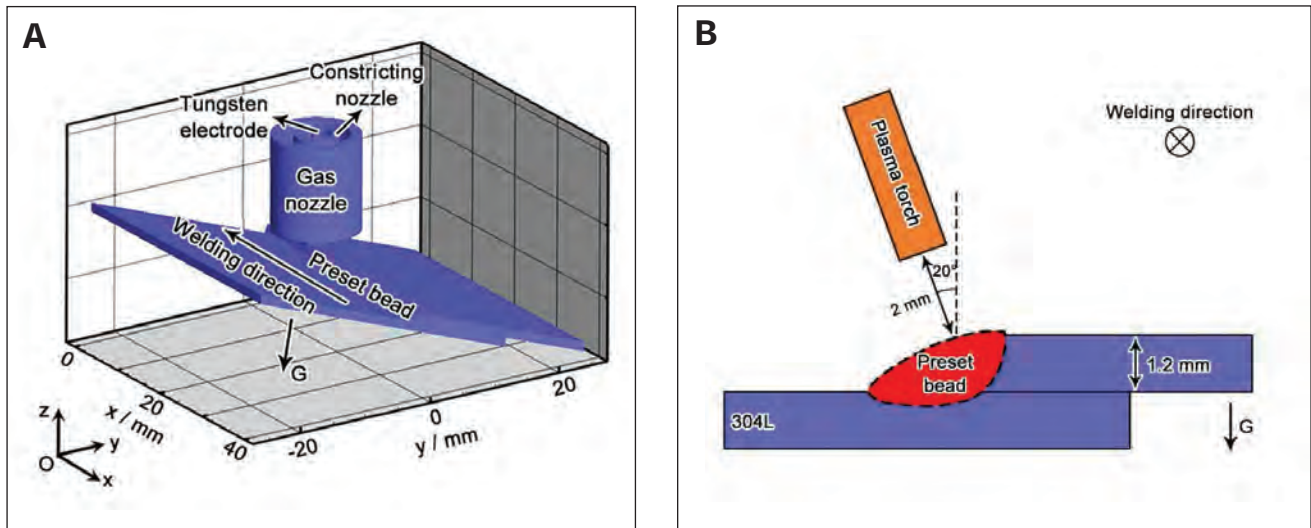


Fig. 1 — Schematic sketches of this model. A — Computation domain; B — conduction plasma arc lap welding.

(Ref. 16). As a result, the total energy absorbed by the weld pool increases, as does the arc energy efficiency (Ref. 10). In keyhole PAW, due to the formation of a keyhole, the plasma arc is expanded and the radiation loss and conduction loss of the plasma arc increase (Ref. 17); therefore, the arc energy efficiency of the keyhole PAW decreases.

In conduction plasma arc lap welding, the arc energy distribution is concentrated (Ref. 2); therefore, the overall energy input needed to join corrugated plates may actually be much smaller. It is of interest and worthwhile to investigate the arc energy efficiency of conduction plasma arc lap welding and what determines and controls it. It may even be speculated that in conduction plasma arc lap welding of corrugated plates, the arc energy efficiency is high owing to the high arc energy density and no keyhole formation inside the weld pool. In this study, a three-dimensional coupled tungsten electrode–plasma arc–metal vapor–weld pool model was developed to investigate plasma arc and metal vapor characteristics, weld pool convection, and energy transfer in conduction plasma arc lap welding of SUS304 stainless steel plates. The effects of metal vapor on energy transfer and arc energy efficiency were analyzed.

Mathematical Model

Computation Domain and Mesh Size

As shown in Fig. 1, the computation domain of conduction plasma arc lap welding included a constricting nozzle region, a gas nozzle region, a tungsten electrode region, an Ar-Fe plasma region, a base metal region, and a preset bead region. The size of the preset bead region was obtained by the metallographic experiment. The angle between the axis of the tungsten electrode and the normal of the base metal surface was 20 deg. The direction of gravity was perpendicular to the surface of the base metal downward.

The local thermodynamic equilibrium (LTE)-diffusion approximation method was used in the coupled model of conduction plasma arc lap welding, in which the mesh sizes adjacent to the cathode and anode were set larger than the diffusion length. The diffusion length of an electron is typically about 0.1 mm (Ref. 18). Based on a mesh convergence test, the mesh sizes near the cathode and anode surfaces were chosen to be 0.1 and 0.15 mm, respectively. Nonuniform hexahedral mesh grids were adopted for the computation domain: The mesh sizes of the tungsten electrode cylinder region and the tungsten electrode tip region were 0.15 and 0.1 mm, respectively; the mesh sizes of the gas nozzle region and Ar-Fe plasma region were 0.2 mm; the mesh size of the preset bead region was 0.15 mm; and the mesh sizes of other regions were 0.4 mm.

Governing Equations and Boundary Conditions

The governing equations of the three-dimensional coupled tungsten electrode–plasma arc–metal vapor–weld pool model mainly include mass, momentum, energy, current, and metal vapor conservation equations. In this section, only the effects of metal vapor and boundary conditions are discussed, and other equations are similar to our previous work (Ref. 17). The study of Block-Bolten and Eagar concluded if the mass fraction of Mn was below 1% in the material, Mn was not a dominant specie in the plasma (Ref. 19). The mass fraction of Mn in the SUS304 stainless steel used in the experiments was only about 0.9%. Therefore, the evaporation of Mn was ignored in this study, and the plasma in this model was considered as a mixture of Ar and Fe vapor. The metal vapor conservation equation (Ref. 20) is as follows:

$$\frac{\partial(\rho C)}{\partial t} + \nabla \cdot (\rho v C) = -\nabla \cdot (-\rho D \nabla C) + M_{vap} \quad (1)$$

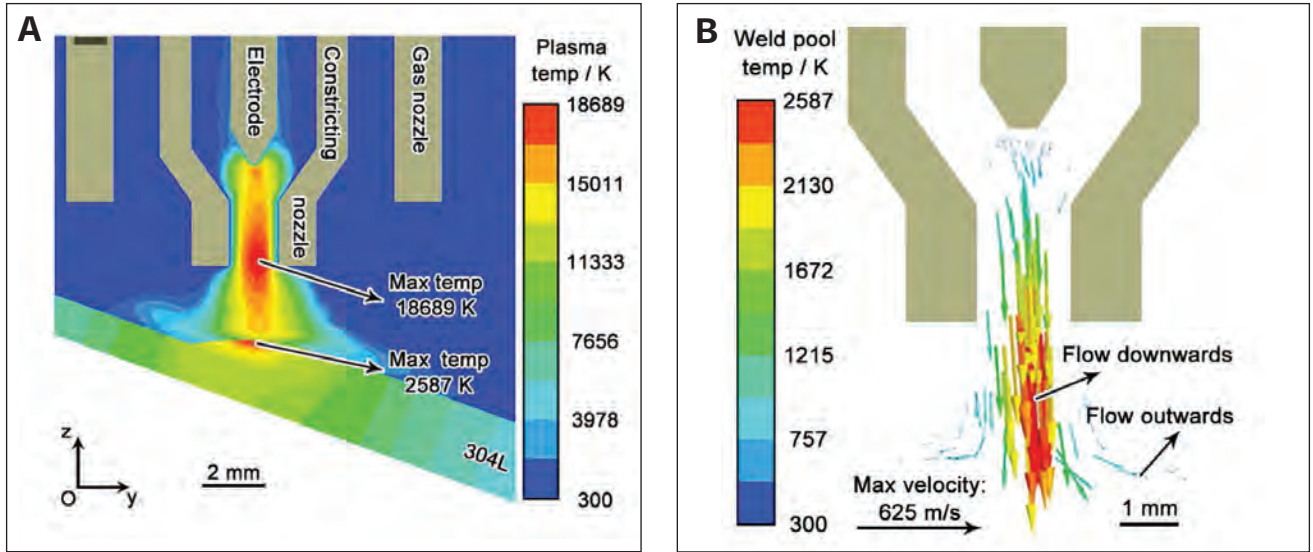


Fig. 2 — Plasma and weld pool characteristics at the $x = 0.015$ m cross section. A — Plasma and weld pool temperature distributions; B — plasma velocity distribution.

$$M_{vap} = J_{vap} \cdot \Delta A / \Delta V \quad (2)$$

where ρ is the density, C is the mass fraction of Fe vapor, v is the flow velocity of the plasma, D is the diffusion coefficient of Fe vapor in plasma, M_{vap} is the Fe vapor source term, and ΔA and ΔV are the area and volume of the cell of the plasma region on the weld pool surface, respectively. The evaporation mass flux J_{vap} is calculated using the Hertz-Knudsen-Langmuir equation, which considers weld pool evaporation and Fe vapor condensation (Ref. 21):

$$J_{vap} = \frac{16}{9} \left(\frac{m}{2\pi k_B} \right)^{1/2} \left(\frac{P_{vap}}{T_m^{1/2}} - \frac{P_{Fe}}{T_{Fe}^{1/2}} \right) \quad (3)$$

where m is the mass of an iron atom, k_B is the Boltzmann constant, T_m is the weld pool temperature on the surface, P_{Fe} is the Fe vapor partial pressure, and T_{Fe} is the Fe vapor temperature. The Fe vapor pressure P_{vap} is calculated using the Clausius-Clapeyron equation (Ref. 21):

$$P_{vap} = P_{atm} \exp \left[\frac{-H_{vap}}{R} \left(\frac{1}{T_m} - \frac{1}{T_b} \right) \right] \quad (4)$$

where P_{atm} is the atmospheric pressure, H_{vap} is the mole heat of evaporation, R is the ideal gas constant, and T_b is the boiling temperature.

The thermionic cooling by electrons, the radiation loss, the conduction energy from the plasma arc, and the ion heat should be considered in the energy boundary condition on the tungsten electrode surface, as shown in Equation 5 (Ref. 22):

$$H_t = -|j_e|\varphi_t + |j_i|V_i + k \frac{\partial T}{\partial z} - \epsilon_r \alpha T_t^4 \quad (5)$$

where j_e is the electron current density, j_i is the ion current density, φ_t is the work function of the tungsten electrode, V_i is the ionization potential of Ar, k is the thermal conductivity, T is the temperature, z is the displacement in the direction normal to the tungsten electrode surface, ϵ_r is the surface emissivity, α is the Stefan-Boltzmann constant, and T_t is the tungsten electrode temperature.

The thermionic heating by the electrons, the conduction energy from the arc plasma, the evaporation loss, and the radiation loss should be considered in the energy boundary condition on the weld pool surface, as shown in Equation 6 (Ref. 22):

$$H_b = |j|\varphi_b + k \frac{\partial T}{\partial n} - \epsilon_r \alpha T_m^4 - J_{vap} H_{vap} \quad (6)$$

where j is the total current density, φ_b is the work function of the base metal, and n is the displacement in the direction normal to the weld pool surface.

The tangential momentum boundary condition of the weld pool surface considers the arc shear stress and the Marangoni

Table 1 — Boundary Conditions of This Conduction Plasma Arc Lap Welding Model

Boundary Surface	Boundary Type	Velocity v	Temperature T/K	Electric Potential ϕ/V	Magnetic Potential $A/(T \cdot m)$
Top tungsten electrode surface	Wall	—	300	$j = \frac{I}{\pi r^2}$	$\frac{\partial A}{\partial n} = 0$
Top nozzle surface	Wall	—	300	$\frac{\partial \phi}{\partial n} = 0$	$\frac{\partial A}{\partial n} = 0$
Plasma gas inlet	Mass flow inlet	0.5 L/min	300	$\frac{\partial \phi}{\partial n} = 0$	$\frac{\partial A}{\partial n} = 0$
Shielding gas inlet	Mass flow inlet	12 L/min	300	$\frac{\partial \phi}{\partial n} = 0$	$\frac{\partial A}{\partial n} = 0$
Left base metal surface in yOz	Velocity inlet	0.2 m/min	300	$\frac{\partial \phi}{\partial n} = 0$	$\frac{\partial A}{\partial n} = 0$
Right base metal surface in yOz	Pressure outlet	—	—	$\frac{\partial \phi}{\partial n} = 0$	$\frac{\partial A}{\partial n} = 0$
Base metal side surface in xOz	Wall	—	$\frac{h_{con}(T_m - T_0)}{-\alpha \epsilon_r(T_m^4 - T_0^4)}$	0	0

stress caused by the surface tension gradient, as shown in Equation 7:

$$-\mu \frac{\partial v_t}{\partial n} = \frac{\partial \gamma}{\partial T_m} \frac{\partial T_m}{\partial S} - \mu_p \frac{\partial v_p}{\partial n} \quad (7)$$

where μ is the fluid viscosity, μ_p is the plasma viscosity, v_t is the tangential fluid velocity, v_p is the plasma velocity, and S is the tangential vector.

The boundary conditions of the computation domain are shown in Table 1. I is the welding current, r is the tungsten electrode radius, h_{con} is the convective heat transfer coefficient, and T_0 is the reference temperature. In this conduction plasma arc lap welding model, the welding torch was fixed. The solid metal flowed into the left side of the x-axis, and the high-temperature liquid metal flowed out of the right side of the x-axis. Thus, the movement of the base metal relative to the welding torch was realized.

Numerical Simulation

The thermodynamic and transport properties of Ar-Fe plasma, such as density, thermal conductivity, viscosity, radiative emission coefficient, and electrical conductivity, depend on both the temperature and mole fraction of Fe vapor. The plasma properties at the intermediate concentrations of Fe vapor were calculated using a linear approximation based on the properties at 0, 1, 5, 10, 20 mol% of Fe vapor mixture (Ref. 20). The computational fluid dynamics software Ansys Fluent was used to solve the governing equations and boundary conditions. The current conservation equation and magnetic vector equation were treated using the user-defined scalar equations. The pressure and velocity coupling was dealt with following the pressure-implicit with splitting of operators numerical procedure. Momentum conservation, energy conservation, and user-defined scalar equations all adapt the second order upwind discretization scheme. The convergence criteria for the residual of energy is 10^{-6} and the rest are 10^{-3} . When the calculated plasma temperature and velocity, weld pool temperature and velocity, welding voltage, Fe vapor fraction, and weld geometry do not sig-

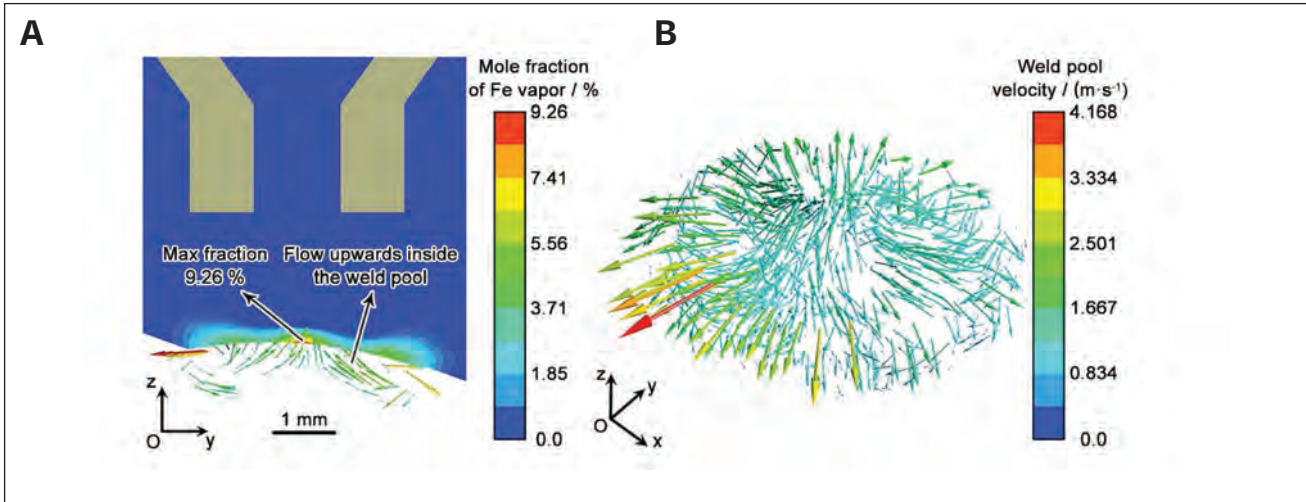


Fig. 3 — Fe vapor characteristics and weld pool convection. A — Weld pool convection and mole fraction of Fe vapor at the $x = 0.015$ m cross section; B — three-dimensional velocity field in the weld pool.

nificantly fluctuate with time, the welding process will reach a quasisteady state.

Experimental Procedures

The welding equipment mainly consisted of an LHM-315 plasma arc welding machine and a TP-3 plasma arc welding torch. In this study, a single conduction plasma arc lap welding process was measured as experimental validation,

and no fitting was done between the experimental and calculated results. Before welding, SiC particles with a diameter of 0.2 mm were placed on the base metal surface to track the weld pool convection. During welding, a Cavitux 640-nm diode laser and a Phantom VEO710S high-speed camera were used to observe the movement behaviors of particles on the weld pool surface. In the observation, the weld pool surface was specular while the base metal surface and SiC particles only diffusively reflected. Therefore, the directional specular reflection of the laser from the weld pool was not collected,

Table 2 — Thermophysical Properties of SUS304 Stainless Steel

Nomenclature	Value	Nomenclature	Value
Density/($\text{kg}\cdot\text{m}^{-3}$)	6900	Liquidus temperature/K	1727
Viscosity/($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$)	5.9×10^{-3}	Solidus temperature/K	1697
Specific heat (liquid state)/($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	720	Boiling temperature/K	3133
Specific heat (solid state)/($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	760	Heat transfer coefficient/($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$)	20
Latent heat of fusion/($\text{J}\cdot\text{kg}^{-1}$)	2.47×10^5	Coefficient of thermal expansion/ K^{-1}	$1.5 \times 10^{1.8}$
Thermal conductivity (liquid state)/($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	28.4	Surface tension/($\text{N}\cdot\text{m}^{-1}$)	1.8
Thermal conductivity (solid state)/($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	33.2	Surface tension gradient/($\text{N}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	-4.3×10^{-4}

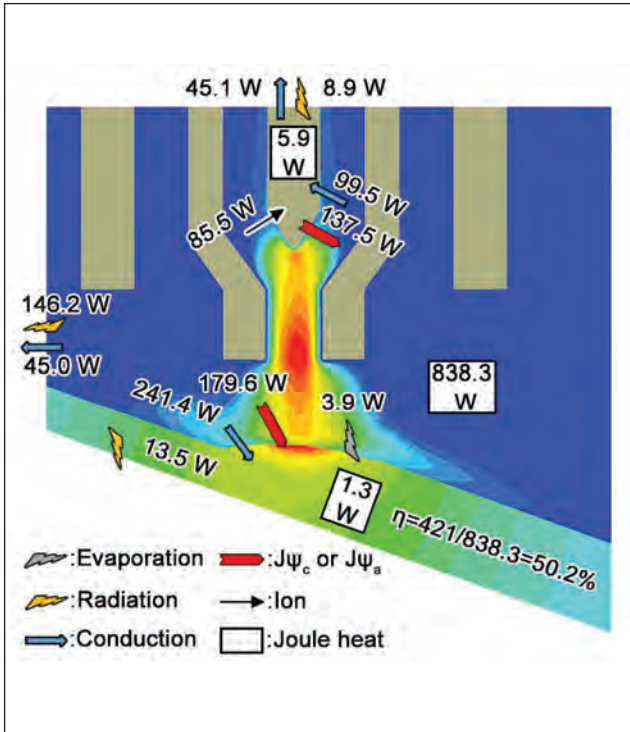


Fig. 4 — The energy transfer in the conduction plasma arc lap welding process.

while the nondirectional diffusive reflections from the base metal surface and SiC particles were collected (Ref. 23). In addition, a signal acquisition system with a sampling rate of 20 kHz was used to record the welding voltage signal.

The base metal used in the experiments was stainless SUS304 steel plate with a dimension of 150 × 50 × 1.2 mm. The thermophysical properties of SUS304 are shown in Table 2 (Refs. 24, 25). Both the plasma gas and the shielding gas were pure Ar. The detailed welding parameters are shown in Table 3.

Results

The Plasma Arc, Metal Vapor Characteristics, and Weld Pool Convection

As shown in Fig. 2A, even though the welding current was only 40 A, under the constraint effects of the constricting nozzle, plasma gas, and electromagnetic force, the plasma temperature near the constricting nozzle was as high as 18,689 K. The maximum weld pool temperature was 2587 K. As shown in Fig. 2B, under the driving of electromagnetic force, the arc plasma near the constricting nozzle flowed downward with a maximum velocity of 625 m/s. The arc plasma impinged on the weld pool surface and flowed toward the edge of the weld pool.

As shown in Fig. 3A, the highest mole fraction of Fe vapor appeared below the center of the plasma arc, which was 9.26%. The mole fraction of Fe vapor above the edge of the weld pool surface was relatively low. The liquid metal flowed downward at the edge of the weld pool and changed direction after reaching the bottom of the weld pool and flowed upward at the center of the weld pool. The three-dimensional velocity field in the weld pool is shown in Fig. 3B. Under the driving of Marangoni force and arc shear stress, the liquid metal on the weld pool surface flowed from the center to the edge with a maximum velocity of 4.168 m/s.

Energy Transfer of the Welding Process

The energy transfer in the conduction plasma arc lap welding process is shown in Fig. 4. The conduction energy from the plasma arc to the tungsten electrode, the ion heat, and the Joule heat were 99.5, 85.5, and 5.9 W, respectively. The thermionic cooling by electrons emitted from the tungsten electrode surface ($j\psi_c$), the conduction loss, and the radiation loss of the tungsten electrode were 137.5, 45.1, and 8.9 W, respectively.

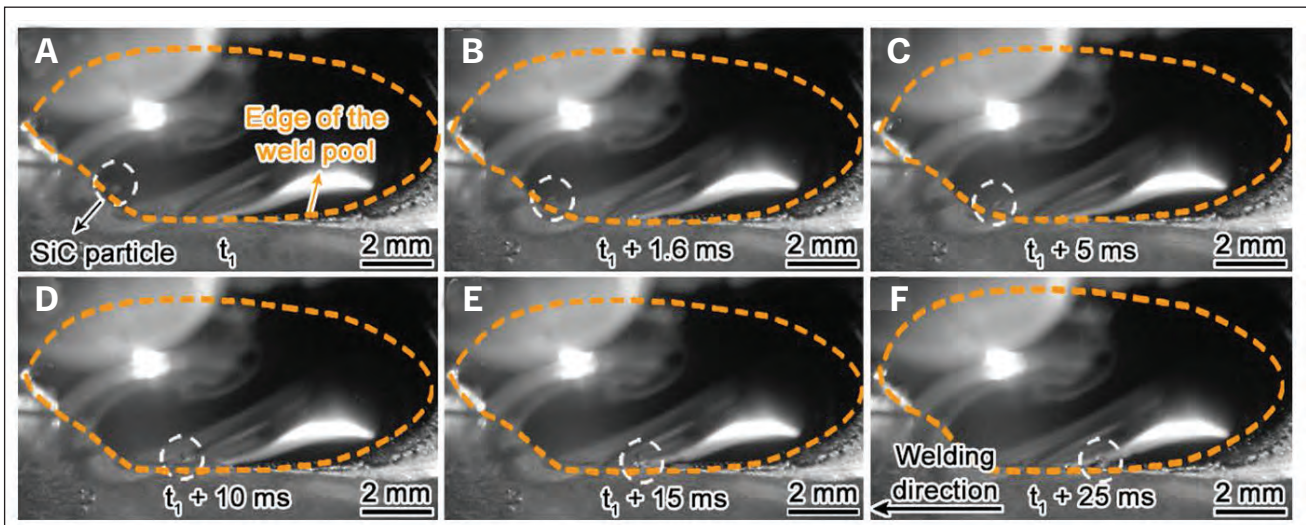


Fig. 5 — High-speed images of the movement of the SiC particle.

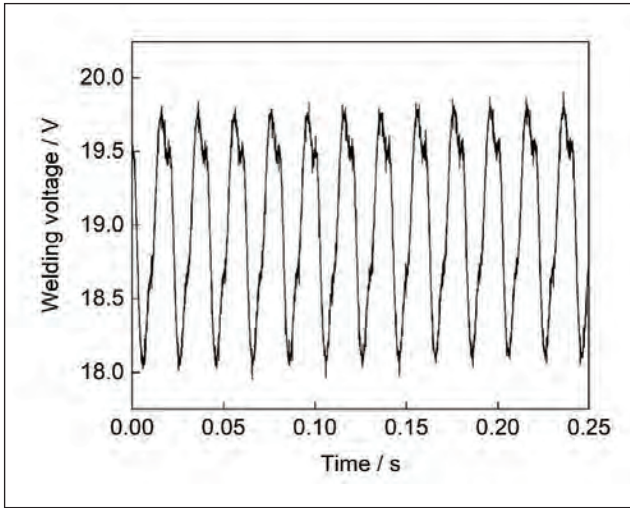


Fig. 6 – Welding voltage signal of conduction plasma arc lap welding.

The Joule heat of the plasma arc was 838.3 W. The conduction loss from the plasma arc was 45.0 W, and the radiation loss from the plasma arc was 146.2 W.

The conduction energy from the plasma arc to the base metal was 241.4 W, and the thermionic heating by electrons absorbed on the base metal surface ($j\phi_p$) was 179.6 W. The Ohmic heating in the base metal was 1.3 W. The radiation loss and the evaporation loss of the base metal were 13.5 and 3.9 W, respectively.

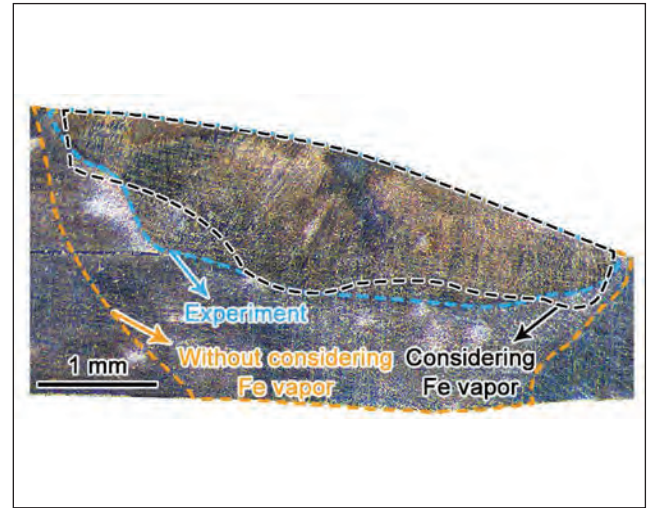


Fig. 7 – Comparison of calculated and experimental weld geometries.

Experimental Validation

As shown in Fig. 5, the SiC particle flowed from the middle of the weld pool toward the tail of the weld pool, which is consistent with the calculated result. The convection on the weld pool surface of conduction plasma arc lap welding was similar to that of GTAW (Ref. 26).

Yamamoto et al. (Ref. 27) developed a numerical model for a GTAW process with a current of 150 A. The maximum weld pool temperature was 2500 K, and the maximum mole fraction of Fe vapor was 10%. In this work, the maximum weld pool

Table 3 – Welding Parameters of Conduction Plasma Arc Lap Welding

Parameter	Value	Parameter	Value
Welding current/A	40	Welding voltage/V	19
Torch angle/deg	20	Welding speed/(m·min ⁻¹)	0.2
Diameter of tungsten electrode/mm	1.5	Tungsten electrode setback/mm	3
Diameter of constricting nozzle/mm	1.6	Distance between nozzle and base metal/mm	2
Plasma gas flow rate/(L·min ⁻¹)	0.5	Shielding gas flow rate/(L·min ⁻¹)	12

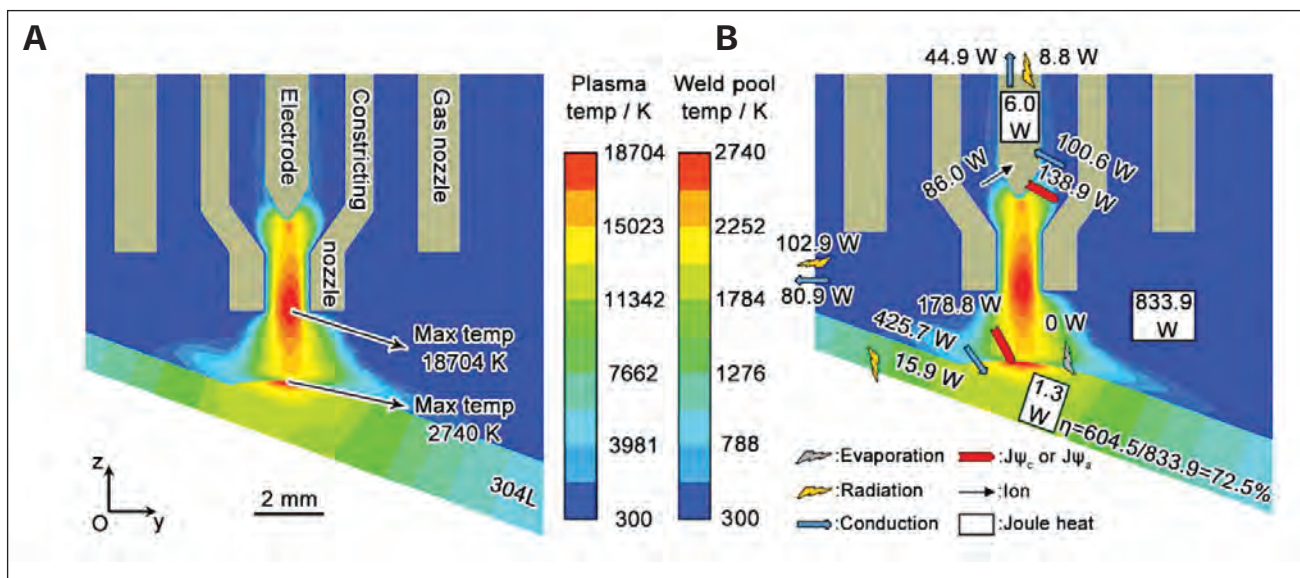


Fig. 8 — Temperature distributions and energy transfer without considering Fe vapor. A — Plasma arc and weld pool temperature distributions at the $x = 0.015$ m cross section; B — energy transfer in conduction plasma arc lap welding.

temperature of conduction plasma arc lap welding was 2587 K, and the maximum mole fraction of Fe vapor was 9.26%.

The welding voltage signal of conduction plasma arc lap welding is shown in Fig. 6. The average welding voltage was 19 V, and the standard deviation of welding voltage was 0.6 V. The calculated welding voltage was given by the electric potential at the top of the cathode with respect to the electric potential at the bottom of the anode, and the value was 21.3 V. Since the LTE-diffusion approximation method was used in our study, the sheath voltage that influenced the energy transfer between the arc and weld pool was ignored. Benilov et al. showed the LTE model overestimated the resistance of the bulk of the arc column and part of the column that was adjacent to the cathode; this overestimation, to a certain extent, compensated for the neglect of the sheath voltage (Ref. 28). Trelles et al. also showed that the total arc voltage drops obtained with the LTE model were higher than those obtained with the non-LTE model (Ref. 29). In our study, even though the sheath voltage was ignored, the calculated welding voltage was slightly higher than the experimental result.

As shown in Fig. 7, the calculated weld geometry was complete joint penetrated without Fe vapor, which is significantly different from the experimental weld geometry. When considering Fe vapor, the calculated weld geometry was in agreement with the experimental result.

Discussion

The arc energy efficiency is defined as the ratio of the total arc energy absorbed by the weld pool to the arc Joule heat. By calculation, the arc energy efficiency of conduction plasma arc lap welding is only 50.2%, which is significantly lower than those of GMAW and GTAW (Refs. 8–13) and agrees well with the measurements of PAW (Refs. 9, 14, 15).

Without considering Fe vapor, the maximum plasma temperature was 18,704 K, and the maximum weld pool temperature was 2740 K, as shown in Fig. 8A. Uhrandt (Ref. 30) and Murphy (Ref. 31) found that in GMAW, the metal vapor ejected from droplets would cool the arc plasma, resulting in the formation of a lower plasma temperature region at axial positions near the wire. By means of spectral analysis and numerical simulation, Mu et al. (Ref. 32) found that in laser-GTAW hybrid welding, the metal vapor ejected from the keyhole would cool the arc plasma, resulting in the formation of a lower plasma temperature region near the keyhole. However, in conduction plasma arc lap welding, owing to the strong downward and outward plasma flow, Fe vapor is mainly concentrated above the weld pool surface; therefore, it has little effect on the radiation loss and maximum plasma temperature near the constricting nozzle.

Nguyen et al. (Ref. 33) investigated the weld pool temperature using a thermal camera in a keyhole PAW process with a welding current of 120 A and a welding speed of 0.18 m/min; the maximum weld pool temperature was only 1870 K. Li et al. (Ref. 2) used numerical simulation and an infrared camera to obtain the weld pool temperature of a conduction PAW process with a current of 44 A and a welding speed of 0.31 m/min; the maximum weld pool temperature was about 2382 K. In this work, by developing a coupled numerical model, the weld pool temperatures of conduction plasma arc lap welding were calculated when the current was 40 A and the welding speed was 0.2 m/min with and without considering Fe vapor; the maximum value was 2587 K when Fe vapor was considered and was 2740 K when Fe vapor was not considered. It can be concluded that even though the current of conduction plasma arc lap welding is relatively lower, the weld pool temperature is higher than those of low-current keyhole PAW (< 200 A). The Fe vapor above the weld pool surface decreases the weld pool temperature.

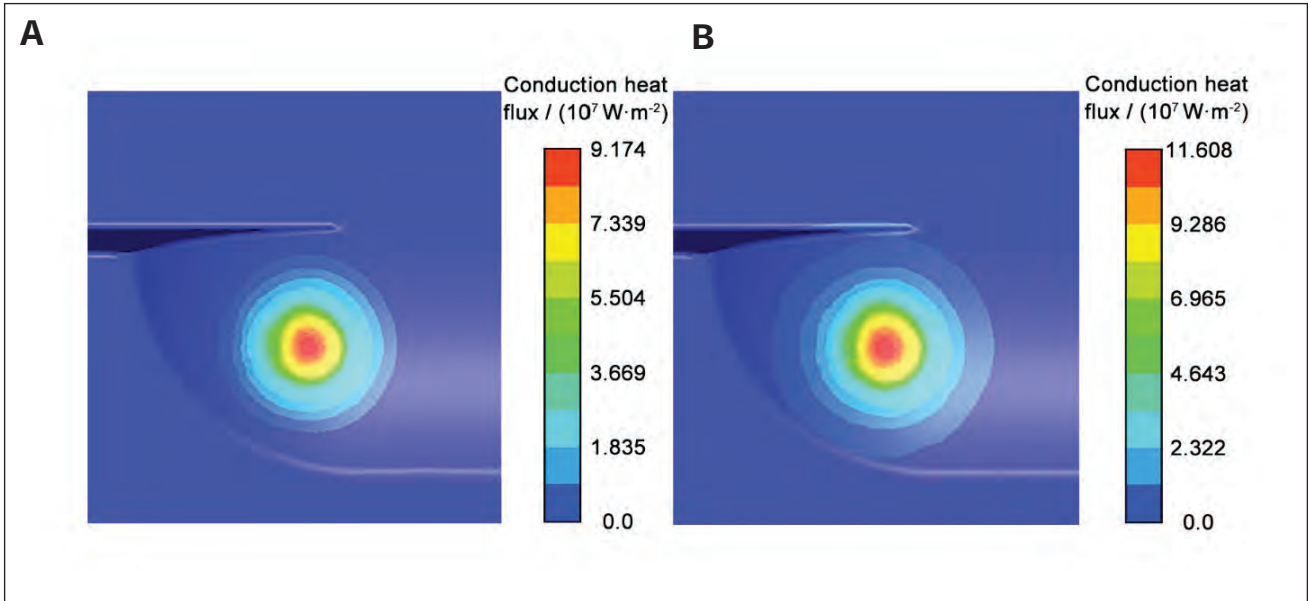


Fig. 9 — Arc conduction heat flux on the weld pool surface. A — Considering Fe vapor; B — without considering Fe vapor.

Table 4 — Comparison of Energy Transfer between Considering/without Considering Fe Vapor

	Considering Fe Vapor	Without Considering Fe Vapor
Joule heat of the plasma arc/W	838.3	833.9
Conduction loss of the plasma arc/W	45.0	80.9
Radiation loss of the plasma arc/W	146.2	102.9
Conduction energy from the plasma arc to the weld pool/W	241.4	425.7
Thermionic heating by electrons absorbed on the weld pool surface/W	179.6	178.8
Evaporation loss of the weld pool/W	3.9	0

Without considering Fe vapor, the energy transfer in conduction plasma arc lap welding is shown in Fig. 8B. By calculation, the arc energy efficiency was as high as 72.5%. The Fe vapor significantly decreased the arc energy efficiency.

The energy transfer in the plasma arc and weld pool, considering Fe vapor and without considering Fe vapor, is shown in Table 4. The Joule heat values of the plasma arc in the two cases were close. When considering Fe vapor, due to the high

net radiation coefficient of Fe vapor (Ref. 31), the radiation loss of the plasma arc increased. The conduction loss of the plasma arc and the conduction energy from the plasma arc to the weld pool decreased by 44.4 and 43.3%, respectively. The current flowing into the weld pool was 40 A, so the values of the thermionic heating by electrons absorbed on the weld pool surface were close in the two cases. When considering Fe vapor, the evaporation loss of the weld pool was 3.9 W,

which was only 0.93% of the total energy absorbed by the weld pool.

The conduction heat flux distributions on the weld pool surface in the two cases are shown in Fig. 9. Without considering Fe vapor, the maximum plasma temperature on the weld pool surface was 12,731 K; the conduction heat flux had a wider distribution range, and the maximum value was $11.608 \times 10^7 \text{ W}\cdot\text{m}^{-2}$. When considering Fe vapor, the maximum plasma temperature on the weld pool surface was 10,484 K; the conduction heat flux was concentrated below the center of the plasma arc with a maximum value of $9.174 \times 10^7 \text{ W}\cdot\text{m}^{-2}$. Li et al. (Ref. 34) established a unified model of a keyhole PAW process when the current was 169 A and the voltage was 24 V and calculated the conduction heat flux distribution, which had a maximum value of only about $4.3 \times 10^7 \text{ W}\cdot\text{m}^{-2}$. Wu et al. (Ref. 17) developed a fully coupled keyhole PAW model with a preset keyhole to calculate the conduction heat flux distribution when the current was 90 A and the voltage was 33 V, and the maximum conduction heat flux was only about $2.7 \times 10^7 \text{ W}\cdot\text{m}^{-2}$. Compared with low-current keyhole PAW, even though the current of conduction plasma arc lap welding is relatively lower, the maximum conduction heat flux is significantly higher.

The thermal conductivity of Ar plasma at a temperature range of 300 ~ 13,000 K was $0.0177 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1} \sim 1.89 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the thermal conductivity of Ar-10% Fe at a temperature range of 300 ~ 11,000 K was $0.0178 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1} \sim 0.896 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. It can be seen from Fig. 3A that Fe vapor with a high mole fraction and a high radiation coefficient concentrated above the weld pool surface, which caused the increase of radiation loss of arc plasma above the weld pool surface; the plasma temperature and thermal gradient above the weld pool surface decreased, as did the thermal conductivity of the arc plasma; therefore, the distribution range and maximum value of the heat flux on the weld pool surface decreased; and furthermore, the conduction energy from the plasma arc to the weld pool decreased.

Even though both the arc energy efficiency of keyhole PAW and conduction plasma arc lap welding are relatively low, the mechanisms of these two cases are different. The current of the keyhole PAW is higher than that of conduction plasma arc lap welding, but the weld pool temperature and the mole fraction of Fe vapor are lower (Refs. 33, 34). Jian et al. (Ref. 35) calculated the mass fraction of Fe vapor distribution of the keyhole PAW with a current of 190 A, and the maximum value was only 0.24%. The arc energy efficiency of the keyhole PAW was only about 47 ~ 66% (Refs. 9, 14, 15), which is mainly because the formation of a keyhole expands the plasma arc and increases the energy loss of the plasma arc (Ref. 17). The current of conduction plasma arc lap welding is relatively low, but the constraint effects of the plasma arc by the small constricting nozzle, plasma gas, and electromagnetic force are strong. Because no keyhole is formed, the heat flux on the weld pool surface and the weld pool temperature are high, which results in a high mole fraction of Fe vapor above the weld pool surface. The main reason for the relatively low arc energy efficiency of conduction plasma arc lap welding is that Fe vapor with a high radiation coefficient concentrates above the weld pool surface and decreases the conduction energy from the plasma arc to the weld pool.

Conclusions

1) Even though the current of conduction plasma arc lap welding is relatively low, the mole fraction of Fe vapor above the weld pool surface is still high.

2) When considering Fe vapor, Fe vapor with a high radiation coefficient increases the radiation loss of arc plasma above the weld pool surface; the plasma temperature and thermal gradient above the weld pool surface decrease, as does the arc plasma thermal conductivity. Therefore, the conduction energy from the plasma arc to the weld pool is lower than that in the case without considering Fe vapor.

3) When considering Fe vapor, the arc energy efficiency of conduction plasma arc lap welding is lower than that in the case without considering Fe vapor. The calculated arc energy efficiency is only 50.2%.

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