Numerical analysis of hybrid plasma generated by Nd:YAG laser and gas tungsten arc

Y.T. Cho a,*, W.I. Cho b, S.J. Na b

a Mechatronics & Manufacturing Technology Center, Corporate Technology Operations, SAMSUNG Electronics Co., LTD, Suwon, Republic of Korea
b Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 373-1, Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

A R T I C L E   I N F O

Article history:
Received 20 December 2009
Received in revised form 16 September 2010
Accepted 22 September 2010

Keywords:
Laser arc hybrid welding plasma
Nd:YAG laser
Gas tungsten arc

A B S T R A C T

When the output from a high power Nd:YAG laser irradiates a metallic surface, metal vapor is generated and changes into the plasma state, which is called a laser-induced plasma plume. If the high power laser is combined with an arc plasma, they mutually attract and influence each other. In this study, several analytic steps are introduced to analyze the laser-arc hybrid welding plasma. A conduction equation is first solved to obtain the temperature distribution on the metallic surface. Next, an analysis of the metal vapor is conducted to investigate the Ar–Fe mixture using a numerical method. As a result of the analysis, it is revealed that the plasma is concentrated in the vicinity of the laser-irradiation position and that the local temperature of the plasma is increased. Plasma flow and current density profiles are also affected by the laser irradiation.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Laser arc hybrid welding, which simultaneously uses a high power laser and a conventional arc, has been developed to improve welding speed and quality. After the development of hybrid welding techniques, a considerable number of studies have been carried out on system configurations, parameter optimization and the characteristics of weld beads [1–7]. Although the hybrid welding plasma operates in a quite different way from the conventional plasma, little attention has been given to the new welding heat source. When the laser and arc plasma are used simultaneously, each heat source mutually assists and influences the other. The reason why the characteristics of hybrid plasma are improved is the generation of intense metal vapor over the laser irradiated position. When sufficient laser light energy irradiates the metal surface, it can cause metal vaporization and the metal vapor can be further developed to form a laser induced plasma (LIP) plume by continuous supply of more laser energy. Because LIP is generated inside the arc plasma in laser arc hybrid welding, the two kinds of plasma interact with and affect each other. In the coupling of the laser and plasma, previous studies [8–10] have shown that the absorption of the laser beam is an important phenomenon; simulations have been used to understand this interaction effect. For the absorption mechanism of laser beams in the plasma, inverse Bremsstrahlung, photoionization and Mie absorption have been considered [8,9]. In the case of Nd:YAG and CO 2 lasers, inverse Bremsstrahlung is dominant because of its relatively long wavelength [10], whereas it is known that for ultraviolet lasers the photoionization effect is dominant [9]. Additionally, the Mie absorption is dominant at low plasma temperature [11], when the effect of inverse Bremsstrahlung and photoionization is low. For CO 2 laser-TIG hybrid welding, Startsev et al. [12] conducted a numerical simulation for a co-axial axisymmetric hybrid configuration. They considered the absorption of laser beams in the Ar arc plasma. The results show a significant temperature rise in the core of the arc, but LIP is not considered. LIP has been considered in laser welding simulation [9] but it has not yet been considered with arc plasma in hybrid welding.

Thus, this paper is focused on an investigation of the interaction mechanism between laser and arc/LIP mixture plasma by the method of numerical analysis. In addition to this, the characteristics of hybrid plasma such as temperature distribution, current density distribution and flow pattern are explained. In numerical simulations, the other absorption mechanisms, except for inverse Bremsstrahlung, are neglected for Nd:YAG LIP and Ar arc plasma. First, the temperature distribution of the base metal due to laser irradiation is obtained by solving the corresponding heat conduction equations. By using this result as the boundary condition, the distribution of metal vapor induced by the laser can be obtained. The distribution of temperature in the base metal and metal vapor is set as the boundary condition and analysis domain, respectively, in order to conduct the analysis of the hybrid plasma. The analysis is completed after checking the absorption of laser light in the plasma by inverse Bremsstrahlung.

* Corresponding author. Tel.: +82 10 5228 8912.
E-mail address: yt11.cho@samsung.com (Y.T. Cho).

0030-3992/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
2. Metal vapor generation by laser

When the output from a laser irradiates a metal surface, a laser-induced metal vapor is generated that contains electrons, ions and atoms. If the laser energy is absorbed through the material’s surface, it gives rise to high local temperatures in the material. Particles depart from the surface at temperatures beyond the vaporization temperature when the metal absorbs an amount of energy higher than the bonding energy of the atoms. The set of the evaporated atoms with a mixture of electrons and ions formed over the surface is called a plasma plume. The size and density of this plasma plume are dependent on several process variables, such as laser power, spot size of the laser beam, type of shielding gas used, and pressure of the surrounding atmosphere [13–15]. In our work, for simplification, the keyhole formation is not taken into consideration.

2.1. Temperature distribution of base metal

Because the concern of this paper is not the weld bead but the behavior of the hybrid plasma, a 3-dimensional heat conduction equation was used to obtain the temperature variation of the base metal. In order to simplify the problem, the conduction equation was solved analytically by the method of separating variables. Fig. 1 shows the coordinate system for the analytic solution. \((X,Y,Z)\) is the moving coordination according to position of the laser irradiation and \((X,Y,Z)\) is the absolute coordination fixed on the base plate.

In this coordination, the heat conduction equation can be expressed as follows:

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

where \(t\) is the time and \(T\) is the temperature,

With these boundary conditions, convection occurs over the upper surface and beneath the lower surface, which convection can be formulated as follows:

\[
-k \frac{\partial T(X,Y,0)}{\partial z} + h_1(T(X,Y,0) - T_0) = 0, \\
k \frac{\partial T(X,Y,d)}{\partial Z} + h_2(T(X,Y,d) - T_0) = 0
\]

where \(k\) is the thermal conductivity, \(h_1\) and \(h_2\) are the convection coefficients, \(T_0\) is the initial temperature and \(d\) is the workpiece thickness.

The initial temperature is room temperature and the position infinitely far from the origin also has room temperature. This condition can be expressed as follows:

\[
T(X,Y,Z,0) = T_0
\]

\[
\lim_{t \to \infty} T(X,Y,Z,t) = T_0
\]

Since the laser beam can be assumed to be a Gaussian distributed heat source in Gaussian shape, the heat source equation is expressed as follows:

\[
q_{\text{laser}} = \frac{3\pi Q}{\pi \lambda^2} \exp \left( - \frac{3\pi^2}{\lambda^2} \right)
\]

where \(\lambda\) is the effective radius of laser beam, \(Q\) is the laser power and \(\eta\) is the efficiency of laser beam. Under convection boundary conditions, the 3-dimensional transient solution of the heat conduction equation can be obtained by solving the eigenvalue problem and integrating it with time, as follows [16]:

\[
T = T_0 + \int_0^t \frac{\eta Q}{\pi \rho c d} \times \frac{6}{\lambda^2 + 12 \pi (t - \tau)} \\
\times \exp \left[ -3 \left( x + X(t) - X(\tau) \right)^2 + \left( y + Y(t) - Y(\tau) \right)^2 \right] \\
\times \sum_{n=0}^{\infty} A_n \exp \left( -\gamma_n(t - \tau) \right) \left( \cos \left( \frac{\gamma_n}{\gamma_n} \right) + \frac{\gamma_n}{\gamma_n} \sin \left( \frac{\gamma_n}{\gamma_n} \right) \right) \bigg|_{t}^{T} d\tau
\]

\[
A_n = \frac{2}{\gamma_n} \int_{y_1}^{y_2} \frac{\lambda_{1/2} d y}{\sqrt{\lambda_{1/2} d y}} \\
\gamma_1 = \frac{h_1}{k}, \quad \gamma_2 = \frac{h_2}{k}, \quad \tan \left( \frac{\gamma_n}{\gamma_n} \right) = \frac{\sqrt{\lambda_{1/2} d y}}{\lambda_{1/2} d y}
\]

where \(\rho\) is the density, \(c\) is the specific heat, \(z\) is the thermal diffusivity \((k/\rho c)\) and \(\xi_n\) is the eigenvalue. The result of the temperature distribution on the metal surface is shown in Fig. 2, when the welding velocity is 10 mm/s, the convection coefficient on the top surface \(h_1\) is 50 W/m² K that on the bottom surface \(h_2\) is 18 W/m² K, the effective radius of the laser beam is 0.6 mm, and the absorptivity of Nd:YAG laser on the steel is 0.3.

2.2. Generation of metal vapor

When the metal is heated beyond the vaporization temperature, vaporized particles depart from the surface. The vaporization flux is determined by the Hertz–Langmuir equation, as follows [17–19]:

\[
J_v = \frac{\lambda P_v}{\sqrt{2 \pi M k_b T}}
\]

where \(M\) is the molecular weight of metal vapor, \(k_b\) is the Boltzmann constant and \(P_v\) is the pressure of vaporized particles. The symbol \(\lambda\) represents the compensation coefficient for condensation in the liquid–vapor interface, and it can be regarded as one for metals. The pressure of a metal vapor is dependent on its temperature, and is expressed by the integration of the Clausius–Clapeyron equation, as follows [20]:

\[
P_v = P_0 \exp \left( \frac{H_v}{RT_v} - \frac{1}{T} \right)
\]

where \(P_0\) is the atmospheric pressure, \(H_v\) is the latent heat of vaporization, \(R\) is the universal gas constant and \(T_v\) is the vaporization temperature.

The calculation results of vaporization flux for iron are shown in Fig. 3. Because high laser power yield high temperature of the surface, much vaporization flux for iron is generated from
the metallic surface. From these results, it can be concluded that the iron vapor flux steeply increases with the increase in the laser power.

2.3. Distribution of metal vapor

It can be assumed that the welding plasma reaches a steady state within a short time, because the laser moves continuously and the plasma absorption of the laser beam is negligible for the Nd:YAG laser. As aforementioned for the Nd:YAG laser (1.064 μm), which is an infrared laser, the inverse Bremsstrahlung is dominant, while the other mechanisms such as photoionization and Mie absorption are negligible. If the dominant mechanism only, inverse Bremsstrahlung, is considered, however, 99.98% of the laser beam is transmitted through the plasma in the present simulations. This means that the absorption of the laser beam in the plasma can be neglected in these welding conditions. Therefore, this process can be regarded as having a quasi-steady state. The flow of the vaporized metal from the surface can be described by the Navier–Stokes equation, and the governing equation can be expressed as follows:

\[ \nabla \cdot (\rho \mathbf{v}) = 0 \]  

\[ \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla P + \mu \nabla^2 \mathbf{v} \]  

\[ \rho c (\mathbf{v} \cdot \nabla) T = -P \nabla \cdot \mathbf{v} + \nabla \cdot (k \nabla T) \]  

where \( \mathbf{v} \) is the velocity vector, \( \mu \) is the viscosity and \( P \) is the pressure, and all of these physical properties are dependent on the temperature [21].

For the purpose of simplification of the numerical analysis, the electrode of the arc and the direction of the laser irradiation are assumed to be perpendicular to the base metal, as shown in Fig. 4. The geometry of numerical analysis is then axisymmetric. Boundary conditions and analytic domain are indicated in Fig. 5. Axisymmetric conditions are given on the boundary AB, and there is no change of temperature and velocity through the boundary CD because it is sufficiently far from the vaporized region. The shielding gas is supplied with a velocity of \( W_{\text{given}} \) on the boundary AD, and metal vapor is generated with a velocity of \( W_{\text{calculation}} \), which can be calculated from the vaporization flux and temperature on the boundary BC given by the Eq. (6).

In addition, the axial velocity given by the shielding gas flow and the pressure of the arc plasma are considered in laser-arc hybrid welding. The equation for arc pressure is expressed as
follows \[22\]:

\[
P_A = \frac{3\mu_0 I}{4\pi r_A^2} \exp\left(-\frac{3r^2}{r_A^2}\right)
\]

(12)

where \(\mu_0\) is the magnetic permeability in vacuum, \(I\) is the arc current and \(r_A\) is the effective radius of arc current.

An orthogonal coordinate system is used for the mesh generation, and the governing equation is discretized by means of FDM. The results of metal vapor analysis are shown in Fig. 6 for the case of a 300 W Nd:YAG laser with a 0.6 mm spot size, for which the arc pressure and shielding gas velocity are considered.

3. Analysis of laser-arc hybrid welding plasma

3.1. Basic assumptions

In order to avoid complexity, several assumptions are introduced. The assumptions on the arc are as follows: the arc plasma is circularly symmetric; the local thermodynamic equilibrium (LTE) state is conserved\[23,24\]; the flow is laminar\[25\]; the plasma is optically thin\[26,27\]; and anode deformation can be neglected. Using these assumptions, the temperature contours of the arc plasma can be calculated to show a good agreement with the experimental data in GTA welding\[28\]. The assumptions for the laser are as follows: the metal vapor satisfies the quasi-steady state; keyhole formation is not considered; and absorption of the Nd:YAG laser energy in plasma is neglected\[29\]. These assumptions will be verified in Section 3.4. The assumptions for properties are as follows: the partial pressure of the metal vapor is dependent on the temperature and the properties of the mixture are determined by the lever rule.

3.2. Governing equations and boundary conditions

The governing equations for the plasma in cylindrical coordinates are the conservation equations for mass, momentum and energy, and can be written as follows:

**Mass conservation**

\[
\frac{\partial}{\partial t}(\rho u) + r \frac{\partial}{\partial r}(\rho u r) + \frac{\partial}{\partial z}(\rho w) = 0
\]

(13)

where \(u\) and \(w\) are the radial and axial velocity, respectively.

**Momentum conservation**

\[
\frac{\partial}{\partial t}(\rho u) + r \frac{\partial}{\partial r}(\rho u r) + \frac{\partial}{\partial z}(\rho w) = -\frac{1}{\rho} \frac{\partial P}{\partial r} + r \frac{\partial}{\partial r}(r \mu \frac{\partial u}{\partial r}) - \frac{1}{\rho} \frac{\partial}{\partial z}(r \mu \frac{\partial u}{\partial z}) - j_r B_y
\]

(14)

**Energy conservation**

\[
\frac{\partial}{\partial t}(\rho e) + r \frac{\partial}{\partial r}(\rho e r) + \frac{\partial}{\partial z}(\rho e w) = \frac{1}{\rho} \frac{\partial}{\partial r}(r \mu \frac{\partial e}{\partial r}) + \frac{1}{\rho} \frac{\partial}{\partial z}(r \mu \frac{\partial e}{\partial z}) + j_r B_y
\]

(15)

where \(j_r\) and \(B_y\) are radial current density and self-induced azimuthal magnetic field that comes from the Lorentz force, respectively. The magnetic flux density is expressed as follows:

\[
B_y = \frac{\mu_0}{r} \int_0^r j_r \, \sigma \, d\delta
\]

(16)

**Current continuity**

\[
\frac{1}{r} \frac{\partial}{\partial r}(r \frac{\partial \phi}{\partial r}) + \frac{\partial}{\partial z}(\frac{\partial \phi}{\partial z}) = 0
\]

(17)

where \(\sigma\) is the electrical conductivity and \(\phi\) is the electric potential.
In particular, for the energy equation, the absorbed energy from the laser is considered as follows:

\[
\frac{\partial (\rho h)}{\partial t} + \frac{1}{\sigma} \left( \frac{\partial}{\partial r} \left( r \rho u h \right) - \frac{\partial}{\partial z} \left( \rho w h \right) \right) = \frac{\hat{J}_h^2 + \hat{J}_z^2}{\sigma} - S_h + \frac{5}{2} \frac{k_B}{e} \left( \frac{\partial h}{\partial r} + \frac{\partial j_e h}{\partial z} \right) + \hat{e}_{\text{abs}} \tag{18}
\]

where \( h \) is the enthalpy, \( S_h \) is the radiation loss per unit volume and \( \hat{e}_{\text{abs}} \) is the absorption of laser energy per unit volume. The left side of the equation includes the conduction and convection terms, while the right side includes the joule heating, radiation loss, transfer of enthalpy by electron motion and a novel energy absorption term.

The analytic domain and boundary conditions are shown in Fig. 7. From the results of metal vapor analysis, the boundary conditions for the analysis of laser arc hybrid welding plasma can be rearranged. On the anode boundary, the equi-potential lines are changed from the laser is considered as follows:

\[
\phi - \phi_0 = \frac{1}{\sigma} \int J \, dA
\tag{20}
\]

### 3.3. Properties

The properties of the plasma are determined by the components of the plasma, in this study, Ar–Fe mixtures. The radiation loss term is expressed as follows:

\[
S_h = 4\pi \hat{e}_{\text{abs}}
\tag{21}
\]

where \( \hat{e}_{\text{abs}} \) is the net emission coefficient. For the Ar–Fe mixture, the net emission coefficient calculated by Gleizes [34] is used. In addition, the electrical conductivity, which is the most important property, can be obtained from the results of Gonzalez [35]. The thermal conductivity, viscosity and specific heat of iron can be obtained from Yoshida’s results [16]. The properties of Ar–Fe mixtures are assumed to be determined by the ratio of the mixture.

### 3.4. Absorption of laser light

In laser-arc hybrid welding, the laser light goes through the arc plasma, which has charged particles of high temperature. The energy of the laser is locally absorbed in the arc plasma, which can be described by the inverse Bremsstrahlung. Although there are several mechanisms to explain the absorption of laser light, it is assumed that inverse Bremsstrahlung is the main effect of absorption. The absorption coefficient is expressed in the following equation [36,37]:

\[
\beta = \frac{n_i n_e N_{c}^{2} e^{6} (1 - \exp(-h_{0}/k_{B} T_{e}))}{6\sqrt{3} \mu_{p} e_{0}^{3} c_{l} h_{0} \exp^{3} m_{e}^{2}} \left( \frac{m_{e}}{2 \pi k_{B} T_{e}} \right)^{1/2} g
\tag{22}
\]

where \( n_i \) and \( n_e \) are the ion and electron density, respectively, \( N_{c} \) is the charge number, \( \omega \) is the angular frequency of the laser beam, \( T_{e} \) is the electron temperature, \( m_{e} \) is the electron mass, \( h_{0} \) is Planck’s constant, \( e_{0} \) is the permittivity, \( e \) is the elementary electron charge, \( c_{l} \) is the velocity of light and \( g \) is the Gaunt factor.
In order to check the effect of absorption on the plasma calculation, we chose a normal value of electron temperature and density of plasma: $T_e = 15000 \text{ K}$ and $n_e = 2 \times 10^{23}$ are substituted and the absorption coefficient is calculated to be $0.13 \text{ m}^{-1}$ for the Nd:YAG laser. In other words, about $0.2\%$ of laser energy is absorbed while passing through the 1 cm plasma. From this result, it was concluded that light absorption can be neglected for the hybrid plasma of the Nd:YAG laser and gas tungsten arc.

**4. Results and discussions**

**4.1. Temperature distribution**

The temperature distribution of the laser-arc hybrid plasma is shown in Fig. 8 for the case in which a CW Nd:YAG laser with power of 200 W and spot radius of 0.6 mm, and a gas tungsten arc with 100 A current and 5 mm arc length, are combined. The case of arc plasma without laser is shown in Fig. 9 for comparison.
When the laser is used, although the whole shape of the plasma is almost the same, an increase in local temperature over the laser irradiation point occurs. The temperature is about 15000 K under the electrode and about 14000 K in the vicinity of the laser irradiation point, while it is far below 10,000 K in the case of arc plasma only.

The simulation results for temperature distribution for various laser powers are shown in Fig. 10. In the case of a laser with low power, the amount of evaporation is relatively small and the effect of current concentration decreases. Consequently, the local increase of plasma temperature gradually disappears. On the contrary, the local increase of plasma temperature in the vicinity of laser irradiation is extended and the absolute value of temperature also increases when the laser power is high.

4.2. Current density distribution

Fig. 11 shows the resultant electric field distribution in the laser-arc hybrid plasma. Over the laser irradiation point, the electric field distribution differs slightly from the arc without laser because of the evaporation of the metal. The change of electric field distribution becomes the reason for the variation of current density distribution, as indicated in Fig. 12. As can be seen in the figures, the current is concentrated on the laser irradiated position because of the laser-induced metal vapor. The local temperature increase in the vicinity of the laser irradiation point can also be explained by the concentration of current density.

4.3. Plasma flow pattern

Fig. 13 shows the results of the simulation of the plasma flow for various laser powers. The flow pattern varies with the laser power because of the high magnetic force induced by the concentration of current. Precisely, the pattern formed in the vicinity of the laser irradiated point is changed not only in magnitude but also in direction. Beyond a laser power of 400 W, a vortex caused by the metal vaporization can be observed. The resultant flow patterns will affect the shear stress formed on the surface of the weld pool.

The shear stress on the weld pool is shown in Fig. 14. According to the increase in laser power, the magnitude of shear stress decreases; this decrease shows a different direction for the laser power of 400 W. This is very interesting, because the weld pool shape is influenced by its surface shear stress.
4.4. Heat transfer to the anode

The total heat input to the anode is also changed by the laser irradiation, as shown in Fig. 15. It is also highly concentrated on the center position, because a high current density region is induced by laser irradiation. The heat transfer by conduction and convection remains almost unchanged, while that by electron flow is highly affected by current variation. It can be concluded that the heat transfer by electron flow is the dominant mechanism in laser-arc hybrid welding.

4.5. Comparison with experiment

To examine the validity of the models that are used in the simulation, a numerical result is compared with that of the experiment.
experiment for the specific condition of 50A TIG arc and 300 W Nd:YAG laser. First, the emissivity of the laser arc hybrid plasma is measured by CCD camera and temperature distribution is calculated using the Abel inversion method suggested by Cho and Na [38]. Then, a numerical simulation is conducted using the same conditions as those of the experiment; a comparison of results is shown in Fig. 16. In general, the temperature distribution is predicted fairly well but there is a discrepancy in the vicinity of the laser irradiated point. This discrepancy can be explained as follows; first, the assumptions used in the simulation might cause some computational error; especially, the assumption that LTE state is maintained for plasmas in mixtures of gases with metallic vapor might be the main reason for the discrepancy. Second, measurement error might lead to the discrepancy in the experiment. To measure the plasma emissivity, a CCD camera is used with a filter that helps show the characteristic line of Ar. In the vicinity of the laser irradiated point, however, the amount of metallic vapor is much higher than that of Ar gas and this can put a false color on the actual state. In addition, there is also a chance of a breaking of LTE state, because the experiment is conducted at low arc current to reduce metallic vapor generation.

5. Conclusion
Laser-arc hybrid welding plasma was simulated by dividing the analysis into steps. The first step is the analysis of the temperature distribution of the metal surface for laser irradiation. The second step is the analysis of the distribution of metal vapor induced by surface heating by laser. It can be seen that there is no need to consider the absorption of the Nd:YAG laser beam in the plasma by calculating the absorption rate related to the inverse Bremsstrahlung. Then, the plasma analysis for the Ar–Fe mixture is conducted and simulation results are obtained. The characteristics of the laser-arc hybrid plasma are found to be quite different from those in the case of argon plasma only. The simulation results confirm that the current density is concentrated in the vicinity of the laser irradiated point and, consequently, the temperature increases locally at that point. These results also show that the characteristics of shear stress on weld pool surface are considerably changed and that the heat flux is concentrated on the laser irradiated point. Finally, the numerical results are compared with the experimental ones to examine the validity of the models used in the simulation. As a result, it is shown that the numerical simulation using the suggested models can predict the considerably similar temperature contours of the Nd:YAG laser and the GTA arc hybrid plasma, while some discrepancy is observed near the laser irradiated point.

Acknowledgments
Support by the Brain Korea 21 project, and Mid-career Researcher Program through NRF grant funded by the MEST (No. 2010-0027749) is gratefully acknowledged.

References