Nonlinear Modeling of Dynamic Metal Transfer in Laser-Enhanced GMAW

By estimating an improved laser recoil pressure force, along with other factors, a modified nonlinear model was developed for this welding process.

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ABSTRACT

In laser-enhanced gas metal arc welding (GMAW), which projects a lower-power laser onto the droplet, free flight metal transfer was obtained. Laser recoil pressure force is identified as the main reason to change the metal transfer process. However, control of laser-enhanced GMAW, this additional detaching force is estimated at a reasonable level. A nonlinear model of dynamic metal transfer is established based on the physics fundamental of this process. Laser recoil pressure force is combined into dynamic force balance theory to be as the reset criterion to detect the droplet detachment. It is found that the simulation results agree with the experimental results, which indicate that the model could be used for the further closed-loop control.

Introduction

Laser-enhanced gas metal arc welding (GMAW) is an innovative process recently proposed and developed at the University of Kentucky (Refs. 1–3), shown in Fig. 1. It adds a relatively low-power laser to conventional GMAW, and the objective is to provide an auxiliary force to help detach the droplet at a desired diameter with a desired welding current. In laser-enhanced GMAW, the droplet size is a critical parameter that determines the process stability and produces a desired appearance and quality of welds. Relatively large droplet sizes will lead to ripples in the welds and decrease the directional quality of the welds. In laser-enhanced GMAW, laser recoil pressure force is the additional detaching force compared to conventional GMAW. However, it is hard to directly calculating this force value precisely as many physical coefficients are unknown.

For the recoil pressure acting on a substrate during intense laser evaporation, Ref. 4 gave the following expression:

\[ P_r = A B_0 T_s \exp{\frac{1}{2} \left( -U/T_s \right)} \]  

where \( A \) is a numerical coefficient, \( B_0 \) is a vaporization constant, \( T_s \) is the surface temperature, and \( U = M_g L_v / (N_A k_b) \). Here, \( M_g \) is the atomic mass, \( L_v \) is the latent heat of vaporization, \( N_A \) is Avogadro’s number, and \( k_b \) is the Boltzmann’s constant. This equation is relatively complicated, and Ref. 5 gave a simpler expression as follows:

\[ P_r = (P/A) \exp{\frac{1}{2} \left( -U/T_s \right)} \]  

where \( P/A \) is the power density of the laser, \( p \) is density of the vapor, and \( E \) is the energy needed to evaporate 1 kg metal. However, all these equations give approximate estimation, and the estimating result may not be accurate enough. In some cases, they may not be suitable to be used, such as molten metal in the arc zone.

To fully control the GMAW process, many models were proposed and developed for the GMAW process. PI control strategy could be developed for maintaining the desired heat and mass by regulating the current (Ref. 6). A steady-state model for heat and mass transferred from the electrode to the workpiece was established (Ref. 7). In the later research, robustness is also taken into account (Ref. 8). An adaptive multi-input, multi-output (MIMO) scheme was developed to control both geometrical and thermal characteristics of a weld based on lumped parameter and distributed parameter modeling and identification (Refs. 8–10). However, GMAW is a complex process, and it has many parameters to be monitored and controlled. The relationship between them cannot be considered linearly. The nonlinearities of GMAW should be considered when establishing a model for this process.

The laser recoil pressure force was estimated in Ref. 1. However, it was estimated approximately, and it could only be used to illustrate the droplet detaching phenomenon in laser-enhanced GMAW. To further control laser-enhanced GMAW, an estimation of laser recoil pressure force with relatively less error is proposed and developed in this paper. Considering the nonlinearities of laser-enhanced GMAW, a nonlinear model should be established for future control. Based on the nonlinear model developed by Refs. 10 and 11, a modified nonlinear model for laser-enhanced GMAW is developed in this paper. The simulating results are compared to the experimental one to test the model validation.

Experimental System and Conditions

Experimental System Setup

The principle of the laser-enhanced GMAW proposed is shown in Fig. 1. A laser beam aims to the droplet. The intention is to detach the droplet using the laser recoil pressure as an auxiliary detaching force to compensate for the lack of the electromagnetic or gravitational force associated with a relatively small amperage...
that is needed for a particular application, rather than to provide an additional heat to speed the melting of the wire. The associated additional heat from the laser should be negligible in comparison with that of the arc used.

Figure 2 shows important parameters that specify a realization of the laser-enhanced GMAW system used in this paper. In this research, the GMAW gun and the laser head did not move. The workpiece moved at a constant speed. The direction of this movement was perpendicular to the plane as shown in Fig. 2. A high-speed camera was placed in this direction with a distance about 1.2 m from the gun to record the metal transfer process for later analysis. To conduct the laser-enhanced GMAW process in an expected way, parameters need to be set appropriately. As shown in Fig. 2, the three parameters used should be determined, and they are the contact tube to workpiece distance $d_1$, angle between laser beam to GMAW gun $\theta$, and the distance from the point where the laser interests the wire axis ($d_2$). In Ref. 1, standards have been found to set these parameters. Experimental results suggest that $d_1$ be set around 20 mm, $\theta$ be selected to be around 60 deg for easy installation at the expense of reducing system compactness, and $d_2$ be set at the range from 3 to 7 mm.

Figure 3 shows the arrangement of the laser in relation to the gun. In this experimental setup, the laser beam is aligned with the wire. In order to protect the end of the laser from contamination from possible fumes, a shielding board (not shown in Fig. 3) is added between the laser and gun, and the laser is projected through a hole on the shielding board to the wire.

**Experimental Conditions**

A constant voltage (CV) continuous waveform power supply was used to conduct experiments. Pure argon was used as the shielding gas, and the flow rate was 12 L/min (25.4 ft³/h). The workpiece was mild steel, and experiments were done as bead on plate at a travel speed of 6.6 mm/s (15.6 in./min). The wire used was ER70S-6 of 0.8 mm (0.03 in.) diameter. The distance from the contact tube to the workpiece was 20 mm as aforementioned. The welding voltage was set 30 V, and the laser power intensity was 62 W/mm². Four different wire feed speeds — 250, 300, 350, and 400 in./min — were used to produce different welding current levels. For convenience, the parameters are presented as a set (wire feed speed, voltage, laser intensity).

Figure 4 shows the mean current measured in all experiments. It can be seen that all the currents were lower than the transition current that is approximately 150 A (Ref. 12) for the wire material and diameter. The effect of the laser on the current is insignificant, no more than 5 A.

**Table 1 — Constants Used for Laser Recoil Pressure Estimation and Nonlinear Model**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$U_0$</td>
<td>15</td>
<td>V</td>
<td>Arc voltage constant</td>
</tr>
<tr>
<td>$L_s$</td>
<td>2.5e–5</td>
<td>H</td>
<td>Source inductance</td>
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<tr>
<td>$B_d$</td>
<td>0.0008</td>
<td>kg/s</td>
<td>Drop damping coefficient</td>
</tr>
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<td>$C_1$</td>
<td>2.885e–10</td>
<td>m³/(A s)</td>
<td>Melting rate constant</td>
</tr>
<tr>
<td>$C_2$</td>
<td>5.22e–10</td>
<td>m³/(A Ω s)</td>
<td>Melting rate constant</td>
</tr>
<tr>
<td>$E_a$</td>
<td>636</td>
<td>V/m</td>
<td>Arc length coefficient</td>
</tr>
<tr>
<td>$K_p$</td>
<td>3.5</td>
<td>N/m</td>
<td>Drop spring constant</td>
</tr>
<tr>
<td>$r_w$</td>
<td>0.0004</td>
<td>m</td>
<td>Wire radius</td>
</tr>
<tr>
<td>$R_w$</td>
<td>0.022</td>
<td>Ω</td>
<td>Arc resistance</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.004</td>
<td>Ω</td>
<td>Source resistance</td>
</tr>
<tr>
<td>$v_r$</td>
<td>10</td>
<td>m/s</td>
<td>Relative fluid to drop velocity</td>
</tr>
<tr>
<td>$C_d$</td>
<td>0.44</td>
<td></td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>1.6</td>
<td>kg/m³</td>
<td>Plasma density</td>
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<tr>
<td>$\sigma_r$</td>
<td>0.7836</td>
<td>Ω/m</td>
<td>Resistivity of the electrode</td>
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<tr>
<td>$\rho_e$</td>
<td>7860</td>
<td>kg/m³</td>
<td>Electrode density</td>
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<tr>
<td>$\sigma_0$</td>
<td>1.25664e–6</td>
<td>(kg m)/(A² s²)</td>
<td>Permeability of free space</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>1</td>
<td>N/m²</td>
<td>Surface tension coefficient</td>
</tr>
</tbody>
</table>
Metal Transfer in Laser-Enhanced GMAW

The diameter of the detached droplet was obtained from a series of high-speed images in this study. All images presented as a series have the same dimension scale except for those presented individually. The time interval of consecutive images in the same series is constant. Figure 5 illustrates the scene in a typical metal transfer image.

Metal Transfer

A typical metal transfer cycle is shown in Fig. 6A with wire feed speed at 300 in./min and welding voltage at 30 V in conventional GMAW. From the images, it is found that this is a short-circuiting metal transfer process. Figure 6B is a typical metal transfer cycle from the comparative experiment with an application of the laser at an intensity of 62 W/mm². As can be seen, the large droplet did not touch the base metal before it detached, and there were no spatters produced. The reason to cause the difference is that laser recoil pressure force is added into laser-enhanced GMAW to be an additional detaching force. In this case, the lack of electromagnetic force to detach the droplet is compensated by the laser.

For these two comparative experiments, the laser did not change the mean welding current significantly as can be seen from Fig. 4. However, as the droplet did not touch the weld pool, the fluctuation of the welding current was reduced as can be seen in Fig. 7. The laser reduced the needed diameter (weight) of the droplet for detachment and changed the metal transfer type.

When the wire feed speed is 250, 350, and 400 in./min, similar experiment results will be achieved. The metal transfer type will be changed due to adding the laser. If it is short-circuiting transfer in conventional GMAW, laser-enhanced GMAW may change it to drop globular transfer. If conventional and laser-enhanced GMAW both produce drop globular, the latter reduces the diameter of the droplet. If it is short-circuit or drop globular transfer in conventional GMAW, laser-enhanced GMAW may become the drop spray. The established physics of metal transfer can explain all these changes by counting the additional detach force caused by the laser. All these experimental results and related physical fundamentals are detailed in Refs. 2 and 3.

As was observed previously, the application of the laser changed the metal transfer. In all cases, the diameter of the detached droplets was decreased as further shown in Fig. 8. The laser recoil pressure was identified as the major cause of these observed changes. The detailed discussion is shown in Refs. 2 and 3. The diameter change of droplet will be utilized to analyze the laser recoil pressure force in the later section.

Pulsed Laser-Enhanced GMAW

Adding a lower-power laser could change the metal transfer mode in laser-enhanced GMAW. In this case, spatters could be reduced or eliminated, and it will reduce the clean-up cost after welding and save much metal. In the aforementioned experimental results, a continuous laser was used to prove this proposal. A continuous power laser was not necessary for laser-enhanced GMAW. From the former analysis, the laser was only used to generate the recoil pressure as an additional detaching force, which was actually not needed before the detaching instant. To this end, the laser radiation could be activated onto the droplet only at the moment when the droplet grew to the desired size. The continuous laser will be replaced with a pulsed laser. Further smaller laser power energy will be adopted in laser-enhanced GMAW.

Figure 9 shows the experimental results with the welding voltage at 30 V and wire feed speed at 350 in./min. Different from the results shown in Ref. 2, the laser power was not continuous but pulsed instead. The frequency was 16 Hz with a duty cycle of 30%, and the peak laser power intensity was set as 62 W/mm² with
a base intensity of 0. In this case, when the droplet did not grow to the desired size, no laser was projected onto the droplet. The wire melts mainly due to resistance and arc heat. Because the detaching forces, mainly electromagnetic and gravitational, could not balance the retaining force, surface tension, the droplet would not detach. When it grew to a desired size, the laser pulse was introduced to generate an additional detaching force exerting onto the droplet to compensate the lack of detaching force. The droplet would be detached to realize a free flight transfer instead of short-circuiting transfer. No spatters were generated in this process. Less electric energy was used, and it also reduced the clean-up cost after welding. All these properties of laser-enhanced GMAW made it a sustainable future industrial process.

**Laser Recoil Pressure Force Estimation**

In laser-enhanced GMAW, estimating the laser recoil pressure is a key issue for the further feedback control of this process. To better understand the physics fundamentals of the method, the forces affecting metal transfer are analyzed first. It is well known that in conventional GMAW, the major forces acting on the droplet include the gravitational, electromagnetic (Lorentz), aerodynamic drag, and momentum forces, plus surface tension (Refs. 13–15). In laser-enhanced GMAW, a laser is applied and an additional force is introduced as shown in Fig. 10. To be simple, the dynamic-force balance theory (DFBM) (Ref. 16) is used in this paper to conduct preliminary analysis of the forces for the laser-enhanced GMAW.

The force due to gravity can be expressed as

\[ F_g = m_d g = \frac{\pi}{4} r_d^4 \rho g \]  
(3)

where \( m_d \) is the mass of the droplet, \( r_d \) is the droplet radius, \( \rho \) is the droplet density, and \( g \) is the acceleration of the gravity.

The surface tension is given as

\[ F_s = 2 \pi r_w \sigma \]  
(4)

where \( r_w \) is the electrode radius, while \( \sigma \) is the surface tension coefficient.

The aerodynamic drag force can be expressed as

\[ F_d = \frac{1}{2} C_d A_d \rho v^2 \]  
(5)

where \( C_d \) is the aerodynamic drag coefficient, \( A_d \) is the area of the drop seen from above, and \( \rho \) and \( v \) are the density and fluid velocity of the plasma.

The electromagnetic force can be expressed as

\[ F_{em} = v_c m_d \dot{m}_d \]  
(6)

where \( v_c \) is the wire feed speed, and \( \dot{m}_d \) is the change of the droplet mass.

The electromagnetic force, \( F_{em} \), is given by

\[ F_{em} = \frac{\mu_0}{4\pi} \left( \ln \frac{r_w}{r_d} \sin \theta - \frac{1}{4} \left( 1 - \cos \theta \right) \right) \]  
(7)

where \( \mu_0 \) is the magnetic permittivity, \( I \) is the welding current, and \( \theta \) is the half-angle subtended by the arc root at the center of the droplet. In the conventional GMAW process, the droplet is not detached when the retaining force \( F_t \) is still sufficient to balance the detaching force \( F_i \).

\[ F_i = F_g + F_d + F_m + F_{em} \]  
(8)

In laser-enhanced GMAW, the total detaching force \( F_T \) will be expressed by

\[ F_T = F_g + F_d + F_m + F_{em} + F_{laser\ recoil\ force} \]  
(9)

When the total detaching force \( F_T \) could balance the surface tension, the droplet will be detached. However, the laser recoil pressure force \( F_{laser\ recoil\ force} \) is unknown because there is less accurate calculating theory to achieve this value. In this case, the author proposes a calculating method to estimate this force.

As the radius of welding wire and surface tension coefficient are constant, the surface tension is fixed, and it indicates that the retaining force keeps constant. To calculate aerodynamic drag force, the area of the drop seen from above \( A_d \) should be calculated first. \( A_d \) can be given by

\[ A_d = \pi (r_w^2 - r_d^2) \]  
(10)

Take the case of wire feed speed at 300 in./min, laser power intensity at 62 W/mm², and welding voltage at 30 V as an example to analyze this force. The experiment results (shown in Fig. 8) show that the largest radius of droplet with these welding parameters is about 0.95 mm. In this case, the largest aerodynamic drag force is about \( 8 \times 10^{-5} \) N. It could be neglected when estimating the laser recoil pressure. The calculating constants used are shown in Table 1 (Refs. 11, 17, 18).

To estimate the momentum force, as the wire feed speed is a constant, the change of the droplet mass \( \dot{m}_d \) should be estimated first. \( \dot{m}_d \) can be expressed by

\[ \dot{m}_d = \pi r_w^2 (C_1 + C_2) \rho \frac{I^2}{r_w^2} \]  
(11)

By calculating, it is found that the maximum momentum force is around \( 5 \times 10^{-5} \) N. It could also be neglected when estimating the laser recoil pressure force.

To estimate the electromagnetic force, similar to the definition in Ref. 14, \( f_z \) is defined as

\[ f_z = \ln \sin \theta - \frac{1}{4} \left( 1 - \cos \theta \right) \]  
(12)

and

\[ f_z = \frac{2}{(1 - \cos \theta)^2} \ln \frac{1 + \cos \theta}{2} \]  
(13)

In this case, the electromagnetic force...
In laser-enhanced GMAW, the half-angle subtended by the arc root at the center of the droplet is in the range from 90 to 150 deg (Refs. 2, 3, 14). As shown in Fig. 11, the value of $f_2$ does not change significantly when the half-angle varies from 90 to 150 deg. The selection of the half-angle will not influence the estimating results. Let's recall the example case to analyze. As the mean welding current is a constant, the electromagnetic force will not change significantly in a certain time interval between the moments with and without a laser.

As Fig. 8 shows, the radius of the droplet reduces when the laser is adopted in GMAW. As the other main detaching force almost keeps the same, the change should be mainly due to the existence of the laser pulse. In this case, the gravitational force value difference could be considered as the estimating laser recoil pressure force. The gravitational forces in conventional and laser-enhanced GMAW are shown in Fig. 12. When the wire feed speed is at 300 in./min, laser power intensity is at 62 W/mm$^2$, and welding voltage is at 30 V, the value difference in the gravitational force is about $1.75 \times 10^{-4}$ N. Considering the estimating errors and other force value changes, the maximum laser recoil pressure force could be about $2.5 \times 10^{-4}$ N.

For further control consideration, the laser recoil pressure force estimating equation could be expressed as

$$ F_{\text{laser recoil force}} = \eta \times r_d $$

where $\eta$ is the laser recoil pressure force coefficient, and it is about 0.15 to 0.30 N/m.

**Nonlinear Model of Laser-Enhanced GMAW**

**Nonlinear Model Setup**

Modeling of the GMAW process is important for process control. Based on the physical fundamental analysis of the GMAW process, a nonlinear model has been set up (Refs. 10, 11, 17) for traditional GMAW. In laser-enhanced GMAW, all the properties are the same as the ones in conventional GMAW except laser pulse, which will be taken into account for the referred modified nonlinear model for the laser-enhanced GMAW.

First, a numbers of inputs, outputs, and states for the model should be defined. These are given as below.

**States:**

$x_1 = I$, welding current
$x_2 = l_r$, wire extension
$x_3 = x_d$, droplet displacement
$x_4 = v_d$, droplet velocity
$x_5 = m_d$, droplet mass

**Outputs:**

$y_1 = I$, welding current
$y_2 = r_d$, droplet radius

**Inputs:**

$u_1 = U_c$, welding voltage
$u_2 = WFS$, wire feed speed
$u_3 = r_d \text{ desired}$, desired droplet radius

Now, laser-enhanced GMAW can be described by the following nonlinear system.

$$ \dot{x} = f(x) + g(x)u $$

$$ y = h(x) $$

$$ x = t(x), \text{ if } L(x, u) \geq 0 $$

Now, let's examine the electric circuit of the GMAW, as shown in Fig. 13. The electric relationship of the welding current with other parameters could be ex-
pressed by

\[ I = \frac{U_i - R_I - U_{arc} - R_I}{I_s} \]  

Where \( U_{arc} = U_0 + R_I J + E_a (L - l_s) \) and \( R_I = \rho_r (l_s + \frac{1}{2} (r_d + x)) \). \( L \) is the distance from the contact tube to workpiece. As discussed in the former section, it is selected as 20 mm in this paper.

In this nonlinear system, the nonlinear state equations are listed below.

\[ \dot{x}_1 = \frac{1}{I_s} [x_1 - (R_0 + R_I) x_1 - U_0 - E_a (L - x_2)] \]

\[ - \rho_r (x_2 + \frac{1}{2} (r_d + x))^3] x_1 \]  

\[ \dot{x}_2 = u_2 - MR (\pi r_o^2) \]  

\[ \dot{x}_3 = x_4 \]  

\[ \dot{x}_4 = \frac{1}{x_5} (-K_d x_2 - B_d x_4 + F_f) \]  

\[ \dot{x}_5 = (C_1 x_1 + C_2 \rho_r x_2 x_1^2) \rho_w \]  

Based on the physics fundamentals of laser-enhanced GMAW, a few equations used are stated below.

\[ r_d = \left( \frac{3x_5}{4\pi \rho_w} \right)^{1/3} \]  

\[ MR = C_1 x_1 + C_2 \rho_r x_2 x_1^2 \]  

\[ FL_{laser recoil force} = \eta r_d \]  

\[ F_m = MR * \rho_w * WFS = \rho_w u_2 \]  

\[ (C_1 x_1 + C_2 \rho_r x_2 x_1^2) \]  

\[ F_g = g x_5 \]  

\[ F_d = \frac{1}{2} C_d \pi (r_d^2 - r_o^2) \rho w^2 \]  

\[ F_{em} = \frac{\mu_0}{4\pi} \left( \ln \frac{L}{r_w} + f_2 \right) \]  

Combined with Equations 4 and 9, these equations could be used to calculate the states equations.

In laser-enhanced GMAW, laser recoil pressure force plays a significant role in determining the detachment of the droplet. In this case, modified dynamic force balance theory was used to decide whether the droplet is detached. The reset condition can be expressed by

\[ F_i = F_g + F_d + F_m + F_{em} + F_{laser recoil force} > F_o \]  

If the detachment criterion is fulfilled, then

\[ x_1 = x_1 \]  

\[ x_2 = x_2 \]  

\[ x_3 = (3x_5/4\pi \rho_w)^{1/3} \]  

\[ x_4 = 0 \]  

\[ x_5 = x_5 (1/(1 + \exp (-100x_4))) + 1 \]  

Otherwise,

\[ x_1 = x_1 \]  

\[ x_2 = x_2 \]  

\[ x_3 = x_3 \]  

\[ x_4 = x_4 \]  

\[ x_5 = x_5 \]  

Simulation Results

A simulation program for laser-enhanced GMAW was developed in Simulink. It was based on the model described in the former section. To validate the proposed model, the simulating results should be compared to the experimental results.

Let’s recall the example case again. Wire feed speed \( u_2 \) will be set at 300 in./min (0.127 m/s), laser power intensity at 62 W/mm², and welding voltage \( u_1 \) at 30 V. To simulate the practical experiment environment, a Gaussian noise will be added to the welding voltage. The noise is with noise power at 0.00001, and the sampling time was selected at 0.0001. Other constants used in this model were listed in Table 1.

Choose 1 s as the time interval to analyze. Continuous laser power was adopted. The welding current and wire extension were shown in Figs. 14 and 15. From Fig. 14, it was found that the mean welding current was about 110 A. This result agreed with the results shown in Figs. 4 and 7. The arc length will be about 8 mm. By carefully analyzing the images shown in Fig. 6B, it was found that the arc length was about 6 mm, and the wire extension was about 10 mm in the experiments. There are several reasons that could cause this simulation...
error. In this nonlinear model, some conditions that restricted the laser-enhanced GMAW were neglected. The weld pool height above the workpiece was also not considered.

The most important simulation result is the droplet mass and size. Figures 16 and 17 show the simulating droplet radius and droplet mass. In conventional GMAW, as the welding current is lower than the transition current, the droplet needs to grow to a relatively large size to achieve enough gravitational force to compensate for the lack of detaching force. Short-circuiting metal transfer always occurs.

When the laser was adopted, the droplet does not need to grow to such a large size. As shown in Fig. 16, the radius of the droplet is about 0.95 mm. Although it is slightly larger than the radius of the welding wire, free flight transfer was obtained. From Fig. 8, it was found that the radius of the droplet in the experiment was about 0.97 mm. The simulation result agrees well with the experimental results.

To better understand the metal transfer process, the forces acting on the droplet will be analyzed. Figures 18–22 show the simulation results of detaching...
forces. As shown in Figs. 18 and 19, the aerodynamic drag and momentum forces acting on the droplet were small. For the momentum force, it was almost a constant during the welding process. The electromagnetic force was still the main detaching force in the laser-enhanced GMAW, and it will compensate for most of the surface tension. The gravitational force increases with the increase of droplet mass, and the simulating result shows that it is an important detaching force.

Laser recoil pressure force was an additional detaching force in laser-enhanced GMAW compared to conventional GMAW. Compared to the results shown in Figs. 21 and 22, it was found that the magnitude of laser recoil pressure force is closed to the gravitational force. It indicates that the laser recoil pressure force was another main detaching force to determine the droplet detaching process. Figure 23 shows the total detaching force.

As discussed in the former section, to better utilize the laser power, a pulsed laser will be used. In this nonlinear model, the pulsed laser recoil pressure force was controlled by the droplet radius. When the desired droplet radius was fulfilled, the laser will exert an additional detaching force on the droplet. The laser recoil pressure force did not affect the welding current (Refs. 1–3), so the welding current will be kept the same with and without laser pulse. As shown in Fig. 24, the droplet radius was also the same as the one with a constant laser shown in Fig. 16. Examining the wire extension (seen in Figs. 25 and 15), the same result was obtained. It indicated that the laser did not influence the wire melting, but only exerted an auxiliary detaching force onto the droplet.

As the welding current and droplet radius were not changed, and all the other welding parameters were also not altered, the aerodynamic drag, momentum, electromagnetic, and gravitational forces were not changed. Before the droplet grew to the desired size, there was not a laser recoil pressure force on the droplet. When the criterion was fulfilled, the laser pulse would be exerted on the droplet. Figure 26 shows the laser recoil pressure force when a pulsed laser was adopted in the laser-enhanced GMAW.
enhanced GMAW.

As shown in Fig. 27, the sudden increase in the total detaching force $F_t$ was caused by adding the laser recoil pressure detaching force.

From the analysis above, it is found that this nonlinear model is suitable for forecasting the droplet growing process, and for further process control. For the future closed-loop control, the input welding voltage will be replaced by the real welding voltage, which will be obtained from the voltage sensor. In this case, all the states calculating will be based on the practical values. The results will be much more accurate. If this model can be combined with sensing technology, such as image processing or spectrum sensing, the droplet in laser-enhanced GMAW will be controlled at any desired size under any desired welding current.

Conclusions

- The experimental system was set up, and a series of experiments was conducted. Free flight metal transfer was obtained with a welding current under a transition current.
- The dynamic balance force theory could be used to explain the detaching phenomenon in laser-enhanced GMAW. The gravitational force difference due to the mass change when the laser was adopted could be used to estimate the laser recoil pressure force, and the result had a reasonable accuracy.
- A nonlinear model was set up for laser-enhanced GMAW. Laser recoil pressure force was combined into the detachment criterion to determine the droplet detaching.
- The simulation results have enough accuracy, and they agree with the experiment results. It indicates that this nonlinear model could be used for process control.

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References


Call for Papers

You are invited to submit papers for the 17th JOM International Conference on the Joining of Materials to be held May 5–8, 2013, at Konventum Lo Skolen, Helsingør, Denmark.

The conference program will cover all aspects of developments in joining and material technology but papers are especially invited on the following topics:

- Recent developments in joining technology: welding, soldering, brazing,
- Advances in materials, metallurgy, and weldability
- Mathematical modeling and simulation
- Process monitoring, sensors, control.
- Structural integrity and inspection
- Applications with relevance to industry needs, automotive, oil & gas, power generation,
- New developments in conservation, energy efficiency, and alternative energy resources
- Weld quality, structural properties, and environmental considerations
- Education, training, Qualification and Certification of welding personnel

Submit your name, address, and title of your presentation, along with a short abstract by November 2, 2012, to Osama Al-Erhayem, JOM, Gilleleje Strandvej 28, DK-3250 Gilleleje, Denmark, or e-mail to jom_aws@post10.tele.dk.