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Laser-Enhanced GMAW

An innovative method to detach droplets at given arc variables is proposed

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ABSTRACT

A novel modification to conventional GMAW is introduced by applying a low-power laser to droplets to generate an auxiliary detaching force. The electromagnetic force needed to detach droplets, thus the current that determines this force, is reduced. The undesired dependence of the metal transfer on the current is decoupled such that the current may be freely chosen to control the weld penetration and weld pool without restrictions as in conventional GMAW due to the need for metal transfer. The resultant process is referred to as laser-enhanced gas metal arc welding. To prove the feasibility of this idea, a constant-power laser was applied to droplets from a 0.8-mm-diameter steel wire in GMAW. A number of experimental conditions that typically would result in short-circuiting transfer in conventional continuous waveform GMAW were designed to conduct laser-enhanced GMAW experiments. It was found that the metal transfer changed from short circuiting to spray in all these experimental conditions as can be seen from high-speed video images. The principles and fundamentals were analyzed to better understand the results and the process.

Introduction

Gas metal arc welding (GMAW) is currently one of the most widely used welding methods. It is operated as a semiautomatic or automatic arc process for joining metals. It is the most widely used process for robotic welding, in which a robot carries a welding gun along the weld joint or applies electrodes to join sheets (Refs. 1, 2).

In the GMAW process, as illustrated in Fig. 1, a welding wire is fed to the contact tube, which is typically connected to the positive terminal of the power supply. When the wire touches the negatively charged workpiece, an arc is ignited and the tip of the wire is rapidly melted forming a gap between the wire and the workpiece. The melted metal forms a droplet at the tip of the wire. After the droplet is detached, another droplet starts to form and a new cycle starts. This metal transfer process is subject to periodic changes in the arcing conditions and plays the most critical role in determining/controlling the weld quality in GMAW. To produce high-quality welds similar to gas tungsten arc welding (GTAW) where the arcing conditions are stationary, the metal transfer needs to be appropriately controlled.

The American Welding Society classifies metal transfer into three major types: short-circuiting transfer, globular transfer, and spray transfer (Ref. 3). When a continuous waveform current is used and the current is small, the droplet may not be detached until the droplet contacts the weld pool. In this case, the droplet is transferred into the weld pool by the surface tension at a short-circuiting condition and the transfer mode is short-circuiting. As a result of the low current, the heat input is relatively small and relatively thin materials can be welded with relatively low heat input, distortion, and residual stress. However, the process needs to be appropriately controlled to minimize spatter that otherwise may be severe. If the current increases, but not large enough to generate a sufficiently large electromagnetic force (Ref. 4) to detach the formed droplet, then the droplet may surpass the diameter of the electrode wire and be detached mainly by gravity. This transfer mode is globular metal transfer. If the current further increases such that the detaching electromagnetic force becomes sufficiently large, the transfer mode may change to projected spray transfer in which discrete droplets detached at diameters similar to that of the wire; or even streaming or rotating spray transfer resulting in a stream of small continuous droplets. With spray transfer, high productivity is obtained due to the high current but may be at the expenses of high heat input, distortion, and residual stress.

The metal transfer mode under a continuous waveform current without control is mainly determined by the amperage of the current as can be seen above. For short-circuiting or globular mode, spatter typically would be expected. The surface tension transfer (STT) that adjusts the current waveform reactively based on the particular stage during the short-circuiting transfer process can reduce spatter to a minimum but is not suitable for other transfer modes where higher heat inputs may be needed (Refs. 5–7). Spray is a transfer mode associated with a stable arc and is often preferred. For continuous waveform current, an amperage higher than the transition current (Ref. 3) is needed to produce a spray transfer. However, if a pulsed current is used, the desired spray transfer may be produced at a wide range of average amperage (thus heat input and distortion).

While pulsed GMAW has been widely adopted in industry, it does have certain limitations. The fundamental cause of these limitations is that a peak current higher than the transition current (Ref. 3) must be used in order to detach the droplet to complete the metal transfer. Vaporization occurs with high amperage and results in fumes. More critically, the arc pressure is proportional to the square of the amperage (Ref. 8). The high arc pressure may blow liquid metal away from the weld pool. For a complete-joint-penetration application where the workpiece has to be fully penetrated through the entire thickness, the high arc pressure

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KEYWORDS

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Laser
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Recoil Pressure

WELDING RESEARCH

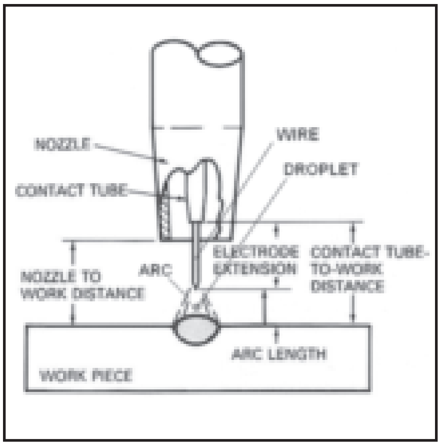


Fig. 1 — Illustration of the GMAW process (Ref. 3).

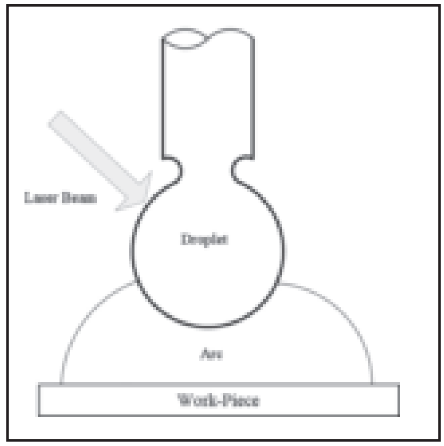


Fig. 2 — Principle of laser-enhanced GMAW.

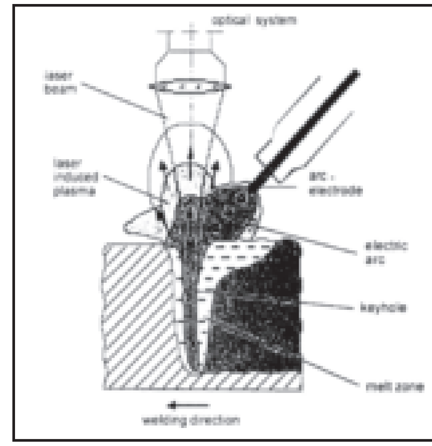


Fig. 3 — Laser-GMAW welding process (Ref. 17).

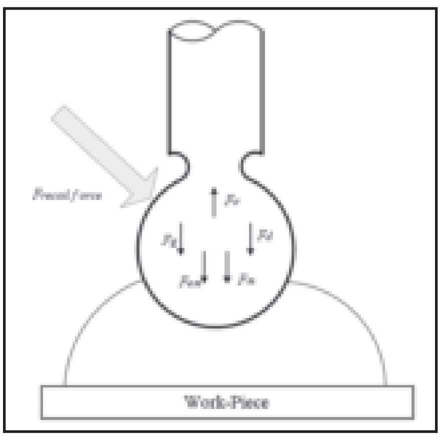


Fig. 4 — Major forces acting on the droplet in laser-enhanced GMAW.

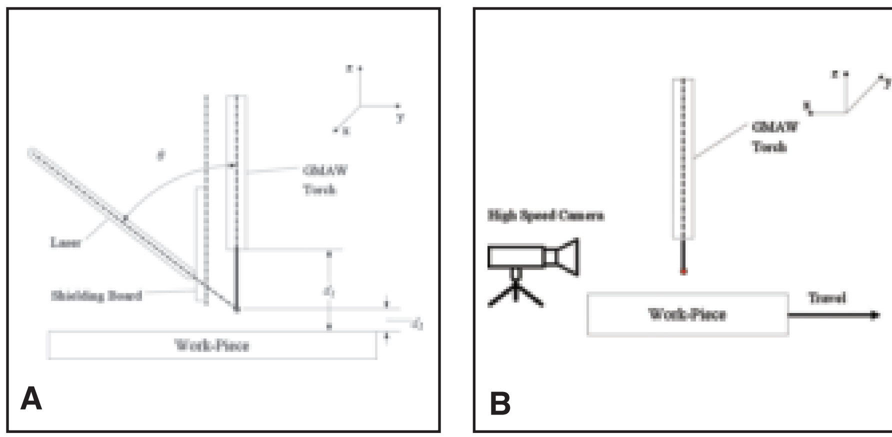


Fig. 5 — System installation parameters.

may easily cause melt-through. This is the major reason why the less productive GTAW process, the amperage for which can be set at whatever level needed, has to be used for the root pass in complete-penetration applications.

It is apparent that the major role of the high peak current in pulsed GMAW is to generate the electromagnetic force to detach the droplets. However, the high peak current produces undesirable side effects that affect GMAW's capability to be used in complete-penetration applications and to be a "clean" process to compete with the less-productive GTAW. In this paper, the authors propose an alternative way to apply a needed force to detach the droplets without producing undesirable side effects. The ultimate goal is to apply a pulsed laser of low power to the droplet to detach it whenever needed such that the droplet be detached at whatever amperage that best suits for the control of the weld pool. The resultant process is referred to as laser-enhanced GMAW. This study aimed to prove the concept and the feasibility of a laser-enhanced GMAW system, but it is subject to redesign and optimization in order to be developed into an industrial system.

Table 1 — Experimental Conditions and Welding Currents

Experimental Condition Number	Voltage (V)	Wire Feeding Speed (in./min)	Welding Current Measured in Conventional GMAW (A)
1	29	200	82.6 ± 21.0
2	30	250	98.8 ± 13.0
3	30	300	115.0 ± 8.1
4	30	350	125.0 ± 11.1
5	30.5	400	131.6 ± 9.6

Principle and Fundamentals

Figure 2 shows the principle of the proposed laser-enhanced GMAW. A laser beam aims at 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 force associated with a relatively small amperage that is needed for a particular application, rather than to provide additional heat to speed the melting of the wire. The associated additional heat from the laser should be insignificant in comparison with that of the arc used.

It should be mentioned, although the laser-enhanced GMAW system applies a laser beam into the GMAW process, it is different from the laser-GMAW hybrid process (Refs. 9–16) where a laser of significant power enhances the results of the arc in the weld pool. To this end, the laser in the hybrid process interacts with the GMAW process and is applied either at the arc or in the weld pool as shown in Fig. 3. Hence, the proposed laser-enhanced GMAW is different from the hybrid laser-GMAW process in both operation principle and objective.

Fig. 6 — Olympus i-speed high-speed camera.

Fig. 7 — Installation of GMAW and laser (the shielding board is not shown in the picture).

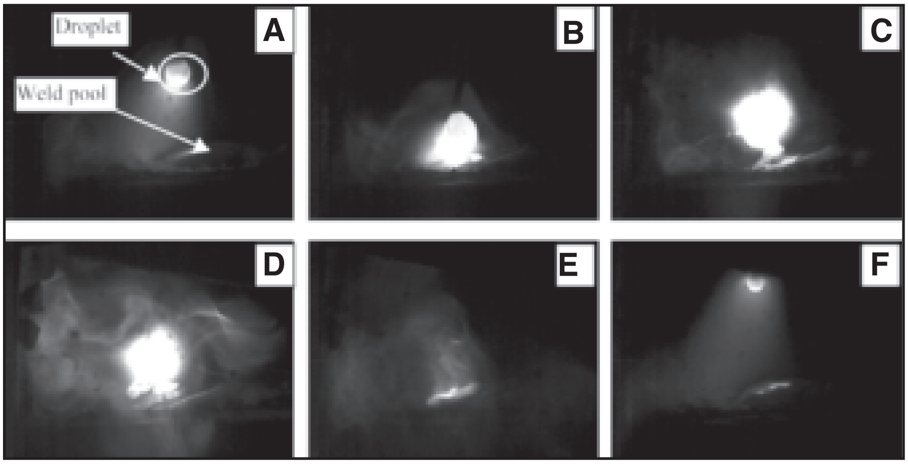


Fig. 8 — Metal transfer process during conventional GMAW under experimental condition No. 2 (without laser). Consecutive images in the figure were acquired at 3000 frames/s.

To better understand the principle of the proposed method, the forces affecting metal transfer are briefly reviewed and analyzed first. It is well known that in conventional GMAW, the major forces acting on the droplet include the gravitational force, electromagnetic force (Lorentz force), aerodynamic drag force, surface tension, and momentum force (Refs. 18–20). In laser-enhanced GMAW, a laser is applied and an additional force is introduced as shown in Fig. 4. To be simple, the dynamic-force balance theory (DFBM) (Ref. 21) is used in this paper to conduct preliminary analysis of the forces for laser-enhanced GMAW.

The force due to gravity can be expressed as

$$F_g = m_d g = \frac{4}{3}\pi r_d^3 pg \tag{1}$$

where m_d is the mass of the droplet, r_d is the droplet radius, ρ is the droplet density, and g is the acceleration of the gravity.

The surface tension is given as

$$F_\sigma = 2\pi R\sigma \tag{2}$$

where R is the electrode radius, while σ is the surface tension coefficient.

The aerodynamic drag force can be expressed as

$$F_d = \frac{1}{2} C_d A_d \rho_p \upsilon_p^2 \tag{3}$$

where C_d is the aerodynamic drag coefficient, A_d is the area of the drop seen from above, ρ_p and v_p are the density and fluid velocity of the plasma.

The momentum force can be expressed as

$$F_m = \upsilon_e \dot{m}_d \tag{4}$$

where v_e is the wire feed speed, $\dot{m}_d$ is the change of the droplet mass.

The electromagnetic force, F_{em}, is given by

$$F_{em} = \frac{\mu_0 I^2}{4\pi}\left(\frac{1}{2} + \ln\frac{r_i}{r_u}\right) \tag{5}$$

where μ_0 is the magnetic permittivity, I is the welding current, r_i is the exit radius of the current path, and r_u is the entry radius of the current path. r_i and r_u are related to the process of the droplet status. Before the droplet starts to be detached, r_u is the same as the radius of the wire and is thus a constant. However, once the droplet is being detached, r_u reduces. The increase of F_{em} thus accelerates and the detachment is completed rapidly. In the conventional GMAW process, the droplet is not detached when the retaining force F_σ is still sufficient to balance the detaching force F_T

$$F_T = F_g + F_d + F_m + F_{em} \tag{6}$$

During the metal transfer process, the major variables that change or can be changed to affect the detaching force are the droplet mass and the current as can be seen from Equations 1–5. Because the surface tension is the major retaining force and is fixed for the given wire, the droplet can only be detached by 1) waiting for the droplet to grow into a larger size such that the gravitational force is sufficient to break the balance, 2) waiting for the droplet to touch the weld pool such that an additional detaching force — surface tension between the droplet and weld pool — be added, or 3) increasing the current to increase the electromagnetic force. Since none of these is ideal, a laser was introduced in this project to increase the detaching force to a sufficient level. Because this laser force is controllable through laser intensity/power, droplets may be detached at a desired diameter at a desired amperage.

Experimental Setup and Conditions

System Setup Parameters

Figure 5 shows the important parameters needed to realize the laser-enhanced GMAW system developed in this project to prove the concept of detaching droplets. To conduct the laser-enhanced

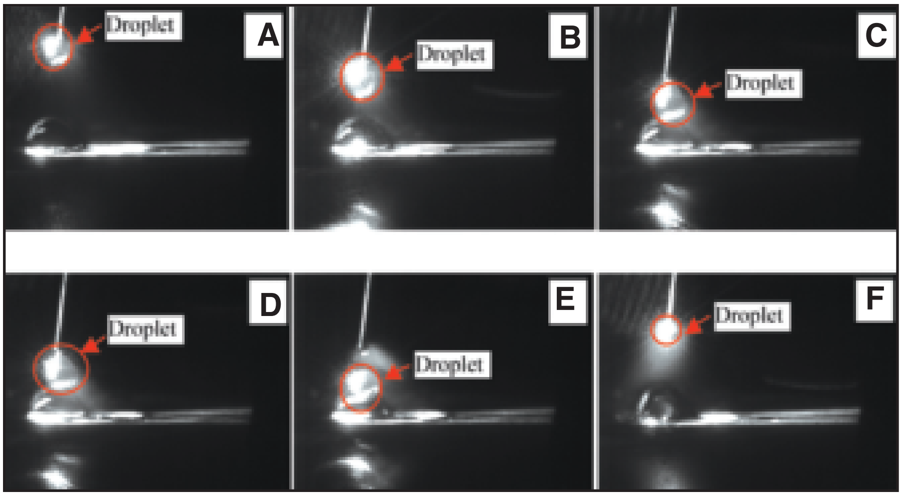


Fig. 9 — Metal transfer in laser-enhanced GMAW at experimental condition No. 1. Consecutive images in the figure were acquired at 3000 frames/s.

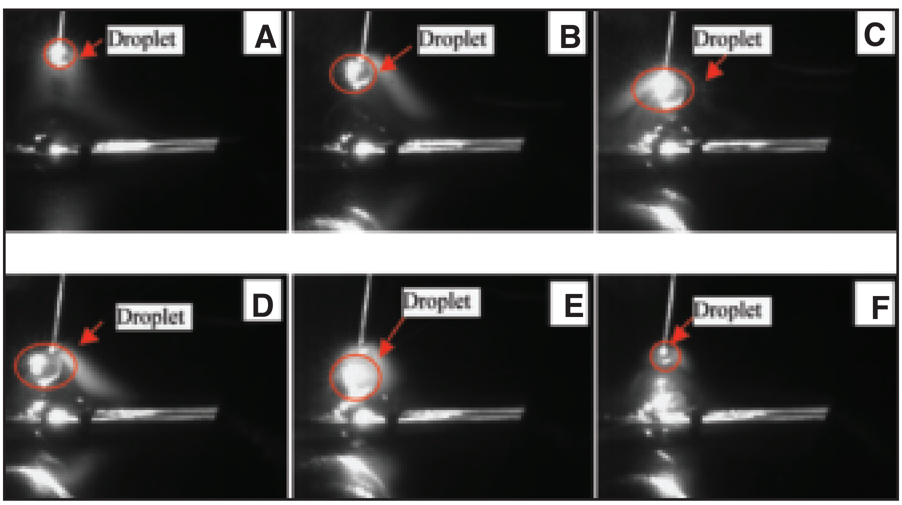


Fig. 10 — Metal transfer in laser-enhanced GMAW at experimental condition No. 2. Consecutive images in the figure were acquired at 3000 frames/s.

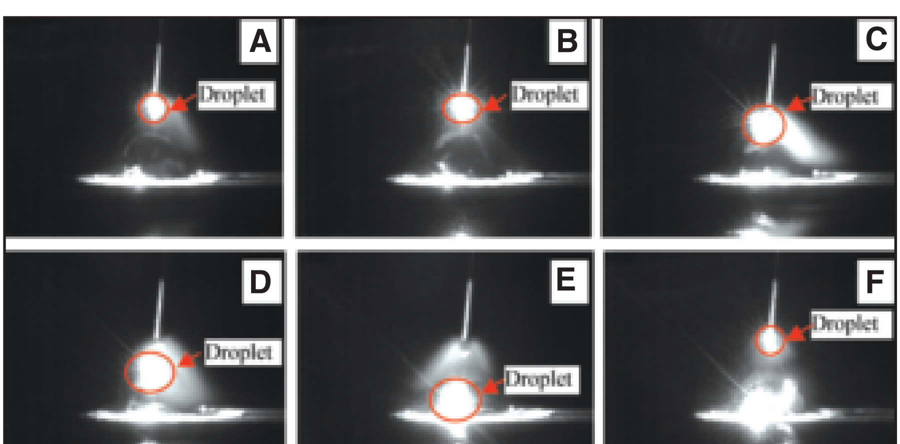


Fig. 11 — Metal transfer in laser-enhanced GMAW at experimental condition No. 3. Consecutive images in the figure were acquired at 3000 frames/s.

GMAW process as expected, parameters need to be set appropriately. 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 shown in Fig. 5A. The camera was also placed in this direction with a distance about 1.2 m from the gun.

Contact tube-to-workpiece distance. In conventional GMAW, this distance plays a role in determining the stability of the process. In laser-enhanced GMAW, a too small d_1 would make it difficult to install other components. Experimental results suggest that d_1 be set around 20 mm.

Angle between laser beam and GMAW gun. θ determines the orientation of the laser recoil force as a vector in relation to other forces and its component/projection as the effective detaching force. It also affects the compactness and realizability of possible future system for industry use. While a large angle would reduce the effective detaching force along the wire axis and affect the compactness of the system, a small angle would require the gas nozzle to be modified such that the laser can reach the droplet. In this feasibility study, the nozzle is not modified and the angle is selected to be around 60 deg for easy installation at the expense of reducing system compactness.

Another important parameter is the distance from the point where the laser intersects the wire axis and is denoted as (d_2) in Fig. 5. As the laser beam must be applied onto the droplet to detach, a high-speed camera was first used to record the conventional GMAW process and then the recorded video was analyzed. Figure 6 shows the high-speed camera used that is capable of recording the metal transfer at 33,000 frames per second. Analysis of videos showed that this distance should be set in the range from 3 to 7 mm.

Choice of laser. As the laser is supposed to point to the droplet rather than the weld pool, the focal zone of the laser should be not much larger than the diameter of the wire. In this study, the diameter of the wire was 0.8 mm and the diameter of the droplet was slightly greater. The laser should thus be selected accordingly. However, because this is a preliminary study that aims at proving the feasibility of the idea proposed, a laser with a much larger focal zone may also be used. The University of Kentucky Welding Research Laboratory possesses a Nuvonyx Diode laser ISL-1000L whose focal beam dimensions are 1 × 14 mm and 808 nm wavelength. When this laser is used, only less than ¼ of the laser beam can be applied onto the droplet to generate the recoil force to detach the droplet. However, for the preliminary study for idea verification presented in this paper, the efficiency of the laser is not a primary concern and the use of a laser of larger power and large focal zone should not affect the effectiveness of the experimental results. Figure 7 shows the arrangement of the laser in relation with the welding gun. In this experimental setup, the laser beam is aligned with the wire. In order to protect the end of the laser from possible contamination from fumes, a shielding board (not shown in Fig. 7) was added between the laser and welding gun, and the laser was projected through a hole on the shielding board to the wire.

Experimental Conditions

A CV (constant voltage) continuous waveform power supply was used to conduct experiments. The wire used was ER70S-6 of 0.8 mm (0.03 in.) diameter. Pure argon was used as the shield gas and the flow rate was 12 L/min (25.42 ft^3/h). The workpiece was mild steel and experiments were done as bead-on-plate at a travel speed 10 mm/s (24 in./min). In the experiments, the power of the laser was set at 862 W and applied to the wire continuously. For the wire diameter and material, the transition current for the spray transfer is approximately 150 A (see Table 4.1 in Ref. 3). Table 1 shows a number of experimental conditions designed to conduct laser-enhanced GMAW and comparative conventional GMAW whenever needed. The current shown in the table is the actual measurements from the conventional GMAW experiments. It is apparent that in all experiments, the currents were lower than the transition current that is approximately 150 A (Ref. 3), and a short-circuit should be expected in conventional GMAW.

Experimental Results and Analysis

Metal Transfer

In the designed experiments shown in Table 1, the voltage was set approximately the same and the wire feed speed was altered. When conventional GMAW experiments were conducted without the application of the laser, short-circuiting transfer and spatter were observed for all conditions in Table 1.

A band-pass filter centered at the laser waveform 808 nm was used to observe the process and record the images. All images presented in this study were recorded using the high-speed camera shown in Fig. 6 with this band-pass filter. Figure 8 is an image series, at 3000 frames/s, that demonstrates the metal transfer process under experimental condition No. 2 without the laser. In this series, Fig. 8C clearly shows that the droplet does touch the weld pool. From Fig. 8D, spatter is seen clearly. Hence, the metal transfer is in the short-circuiting mode. This was because F_T is smaller than the maximum retaining force that can be provided by F_σ in the whole process before the droplet touches the weld pool. It is apparent that the current smaller than the transition current is the cause.

Figures 9–13 show the metal transfer processes when the laser-enhanced GMAW process was performed using the experimental conditions given in Table 1.

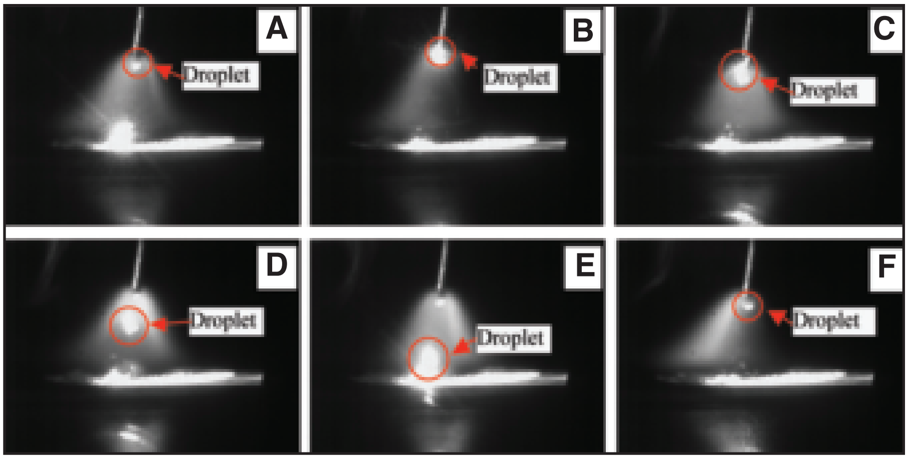


Fig. 12 — Metal transfer in laser-enhanced GMAW at experimental condition No. 4. Consecutive images in the figure were acquired at 3000 frames/s.

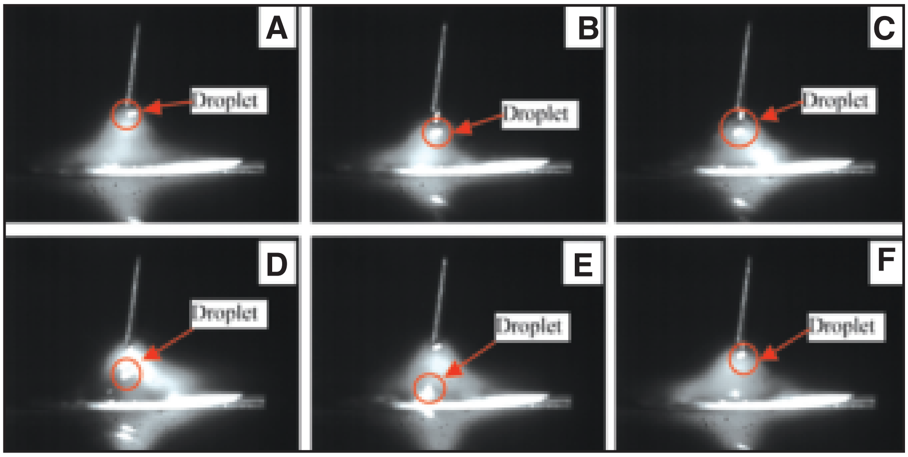
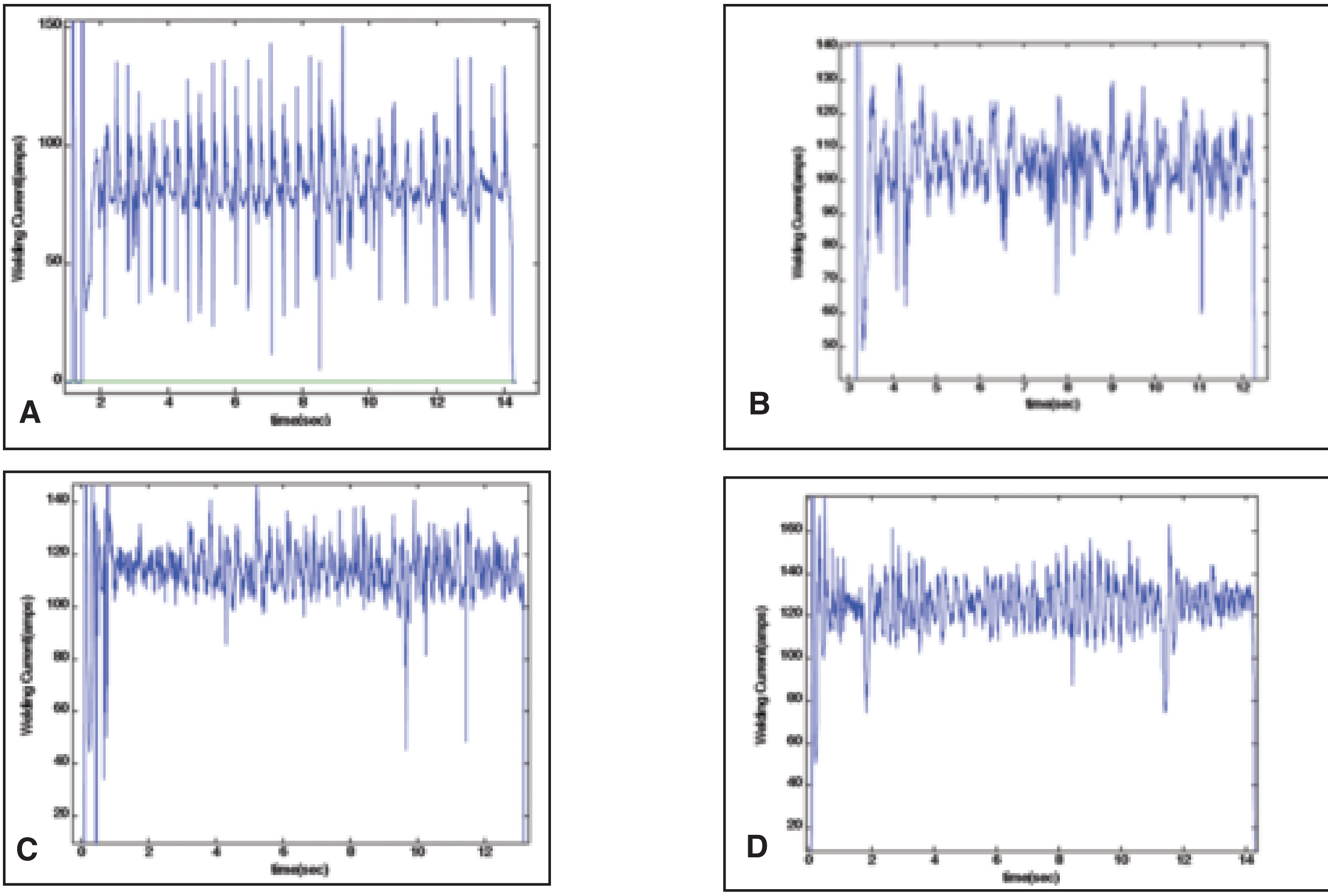


Fig. 13 — Metal transfer in laser-enhanced GMAW at experimental condition No. 5. Consecutive images in the figure were acquired at 3000 frames/s.

In all images, the weld pool surface illuminated by the laser beam was clearly shown as a bright line. As can be seen, the metal transfer in all experimental conditions changed to the spray transfer and the droplet detached from the wire before it touched the weld pool. In particular, a direct comparison can be made between Fig. 10 and Fig. 8, which were both conducted using experimental conditions No. 2 in Table 1. Because of use of the laser, the metal transfer changed from short-circuiting transfer in Fig. 8 to spray transfer in Fig. 10.

Each image series in Figs. 9–13 represents a complete transfer cycle under the respective conditions. Each first image represents the beginning of a metal transfer cycle. As the droplet grows, the gravitational force increases. The cross section of the laser beam intercepted by the droplet increases as the droplet thus grows. Because the intensity of the laser on the cross section is independent from the droplet, the recoil pressure of the laser acting on the droplet increases. As a result, the auxiliary force applied by the laser on the droplet and the gravitational force both increase. On the other hand, the surface tension as can be seen in Equation 2 is approximately constant when the droplet grows. Hence, as the droplet grows, the detaching force increases but the retaining force remains approximately constant. As a result, once the sum of the detaching force becomes larger than the sum of the retaining force, the droplet is detached. Because the droplet is detached in all conditions listed in Table 1 before it may touch the weld pool, the auxiliary detaching force introduced by the laser is sufficient to implement the laser-enhanced GMAW for the conditions listed in Table 1. Because the laser is applied continuously, the detachment of the droplet appears to be the natural result of the balance of the forces. Because of possible variation in other forces, the diameter of the droplet being detached is not accurately controlled. To control the droplet diameter, the laser can be pulsed and applied when the droplet needs to be detached. The control of the droplet diameter exceeds the scope of this present work.



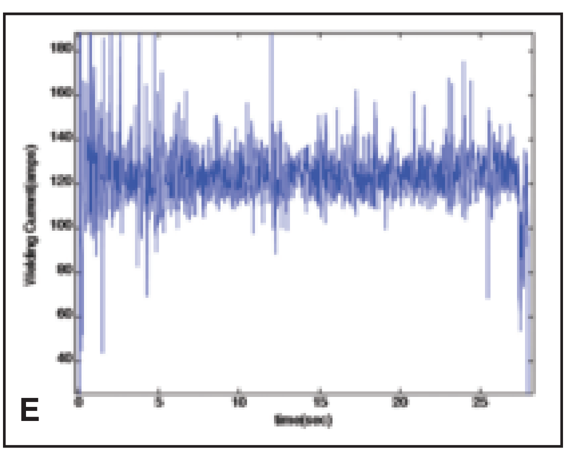


Fig. 14 — Current waveforms in laser-enhanced GMAW experiments. A — Experiment No. 1; B — Experiment No. 2; C — Experiment No. 3; D — Experiment No. 4; E — Experiment No. 5.

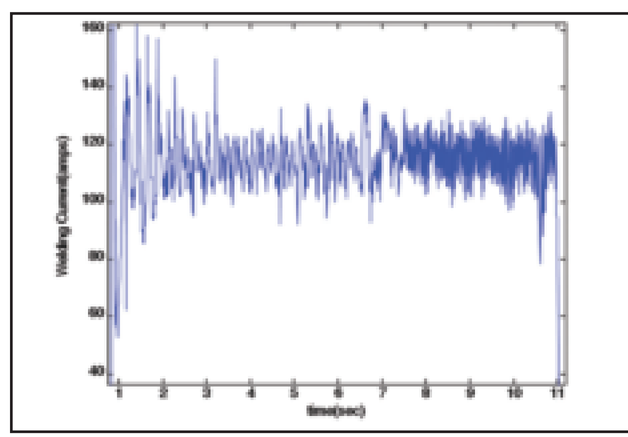


Fig. 15 — Comparative conventional and laser-enhanced GMAW using condition No. 4. The average current does not change significantly. This implies that the heat applied by the laser to the wire is insignificant for wire melting.

Current Waveforms

Figure 14 is the measured current waveforms for laser-enhanced GMAW experiments conducted using the conditions in Table 1. Observation of these current waveforms shows that the current waveforms become less fluctuating when the wire feed speed or the current increases. This can also be seen from the right column in Table 1. As analyzed above, the detachment of the droplet under a continuous laser application is a natural result of the balance of the force. When the current increases, the electromagnetic force increases at least quadratically with the current as initially suggested by Equation 5

$$F_{em} = \frac{\mu_0 I^2}{4\pi}\left(\frac{1}{2} + \ln\frac{r_i}{r_u}\right).$$

Further, the exit radius of the current path, i.e., r_i also increases as the current increases as the arc climbs toward the neck of the droplet. Hence, the electromagnetic force increases rapidly as the current increases. On the other hand, the surface tension does not change and the vapor jet force at most increases proportionally. Hence, the detaching force increases much faster than the retaining force as the current increases. The gravitational force needed to break the balance reduces. Hence, the droplet is detached at smaller diameters when the current increases in

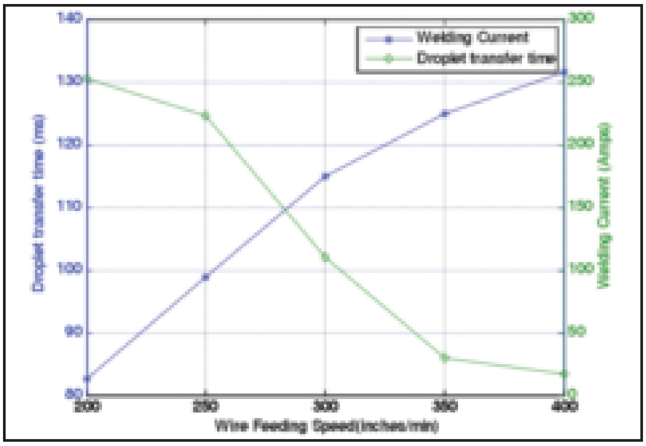


Fig. 16 — Effect of wire feed speed on current and droplet transfer time in laser-enhanced GMAW.

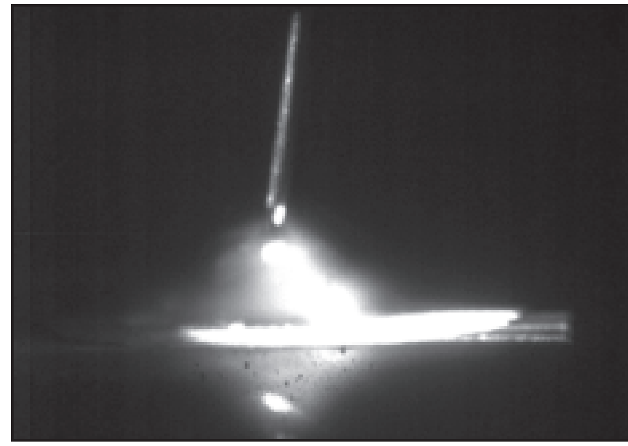


Fig. 17 — Pinch effect in the laser-enhanced GMAW process.

continuous laser-enhanced GMAW. Further, the melting speed also increases such that the period of metal transfer is quickly reduced. As a result, the arc length and wire extension are subject to smaller fluctuations and variations. The current waveform thus becomes less fluctuating. To control the transfer period, droplet diameter, and current fluctuation, laser pulses can be applied whenever the detachment is needed.

Figure 15 is the recorded current waveform in an experiment conducted using condition No. 4 in Table 1. From t = 1 s to t = 7 s, no laser was applied, and the process was conventional GMAW. After t = 7 s, the laser was applied and the process was the continuous laser-enhanced GMAW. As can be seen, the current fluctuation was significantly reduced after the laser was applied due to a change in transfer from short-circuiting to spray. The variance of welding current before 7 s was 369.21 A^2, and dramatically reduced to 91.22 A^2 after t = 7 s. The standard deviation reduced from 19.21 to 9.55 A after t = 7 s.

Process Parameters

Welding voltage and wire feed speed are two important process parameters in addition to the laser used and the wire diameter and material.

When others parameters are the same, increasing the voltage would increase the arc length and thus allow the droplet to grow for a longer time into a larger volume. Also, when the contact-tube-to-work distance is given, the wire extension will be reduced due to the increased arc length. As the wire extension reduces, the resistive heat will reduce. For small-diameter wires, such a reduction could be significant. As a result, for the same wire feed speed, the current will increase. Because the electromagnetic force as a detaching force increases faster than a quadratic speed as the current increases, the increase in the detaching force would be significant. The increased gravitational force and electromagnetic detaching force would reduce the transition current. For experimental condition No. 4 in Table 1, if the voltage is changed to 34 V, the metal transfer will become spray mode without the application of a laser. Similarly, for the laser-enhanced GMAW process, the voltage setting would also affect the metal transfer in a similar way. For the same laser, when the voltage is reduced, the transfer could be changed from spray to short circuiting. However, in principle, it may typically be possible for laser-enhanced GMAW to ensure a spray transfer by increasing laser power. A pulsed laser of relatively high peak power is thus appropriate for laser-enhanced GMAW.

Because the wire feed speed is the major parameter to determine the current and thus the electromagnetic force, it plays a critical role in determining the laser power/intensity needed to ensure spray transfer. When the laser power/intensity and other welding parameters, including the wire diameter/material and arc voltage setting, are given, the droplet diameter and transfer frequency in the continuous laser-enhanced GMAW are primarily determined by the wire feed speed. As shown in Fig. 16, when increasing the wire feed speed from 200 to 400 in./min, the welding current increases approximately linearly from 82.6 to 131.6 A. However, because the electromagnetic force as a detaching force increases faster than a quadratic speed, the needed gradational force to break the force balance decreases rapidly. As a result, the time needed in each cycle to detach the droplet (i.e., the metal transfer time) decreases rapidly.

There is another important change when wire feed speed increases. When the wire feed speed is 350 or 400 in./min, as shown in Figs. 12 and 13, the pinch effect could be observed between the droplet and the solid wire. This pinch effect is also demonstrated in Fig. 17. However, as can be observed from Figs. 9–11, when the wire feed speed is lower than 300 in./min, the pinch effect was not obvious.

Analysis of Laser Effect

The first question that needs to be answered through analysis is how the laser affects the metal transfer. To this end, the actual laser power applied on the droplet was estimated first. Because the laser beam dimension is 1 × 14 mm and the diameter of the droplet can be assumed to be no greater than 1.2 mm, the actual incident power of the laser applied on the droplet should be less than 70 W. Then taking experimental condition No. 4 in the Table 1 as an example, one may extend an analysis as follows:

When the voltage was set at 30 V, the metal transfer without an application of the laser was short circuiting and the current was 125 A approximately. When the laser was applied, the current was still 125 A approximately, but the metal transfer changed to spray mode. Because the heat applied onto the droplet by the laser is insignificant in comparison with that of the arc, the change of the metal transfer must be primarily due to the force rather than the heat generated by the laser spot. In fact, in comparison with the anode arc power that melts the wire, the laser power is approximately 4.6% (70 W over 125 A of current multiplied by 12 V of estimated anode voltage). Due to the specular reflection of the droplet surface, no more than 50% of the incident laser power should be absorbed. That is, the application of the laser should only increase the heat by 2.3%. Unfortunately, even when the current (thus anode heat) increases 15% from 120 to 138 A, the metal transfer would still not be spray transfer. Hence, it is the force rather than the heat that effectively changed the metal transfer from short circuiting to spray during laser-enhanced GMAW.

Secondly, how the laser force is produced needs to be understood. Basically, the pressure imposed by the laser on the droplet can be considered to have two major components: radiation pressure and recoil pressure. For the laser radiation pressure, previous studies have obtained clear results/conclusions. The radiation pressure (P) of a normally incident continuous wave (cw) light imposed on a macro-object with a plane surface can be expressed as (Ref. 22)

$$P = I(1+R)/c \qquad (7)$$

where c is the speed of the light, R is the reflectivity of the illuminated surface, and I is the intensity of the light. However, the radiation pressure on the object (droplet in our case) is very insignificant in comparison with the recoil pressure. For example, for a 100-W laser with 1-mm spot and $R = 0.8$, the radiation force calculated from Equation 7 is in the order of 10^7N, while the surface tension needed to be overcome to detach the droplet is in the order of 4×10^{-3}N (Ref. 23).

For the recoil pressure acting on a substrate during intense laser evaporation, Ref. 24 gave

$$P_r = AB_0 T_s^{-1/2} \exp(-U/T_s) \qquad (8)$$

where A is a numerical coefficient, B_0 is a vaporization constant, T_s is the surface temperature, and $U = M_a L_v/(N_a k_b)$. Here M_a is the atomic mass, L_v is the latent heat of evaporation, N_a is Avogadro's number, and k_b is the Boltzmann's constant. This equation is relatively complicated and Ref. 25 gave a simpler expression

$$P_r = (P/A)^2/\rho E \qquad (9)$$

where P/A is the power density of the laser, ρ is density of the vapor, and E is the energy needed to evaporate 1 kg of metal. As its authors indicated (Ref. 25), when the laser intensity is about 3×10^6 W/cm^2, the recoil pressure will be about 10^7 Pa.

In the laser-enhanced GMAW process, as $F_T = F_g + F_d + F_m + F_{em} + F_{recoil\ force}$, a higher F_T could be produced by adding a laser beam. The power intensity of the laser used is about 6.17×10^3 W/cm^2 (864 W over the laser dimension 1 × 14 mm), the recoil pressure is at least on the order of 10^3 Pa. The surface of the droplet intercepting the laser beam could be estimated on the order of 10^{-6} m^2. In this case, the force generated by laser recoil pressure will be on the order of 10^{-3} N. It is at the same order of force to detach a droplet as aforementioned.

Conclusion and Future Work

- An experimental system has been established and the feasibility of the novel laser-enhanced GMAW process was experimentally demonstrated.
- The laser aiming at the droplet in laser-enhanced GMAW can apply an auxiliary detaching force without significant additional heat.
- Spray transfer was successfully produced at continuous currents in the range from 80 to 130 A for 0.8-mm-diameter steel wire that would produce short-circuiting transfers in conventional GMAW;
- Phenomena observed in laser-enhanced GMAW were satisfactorily analyzed by applying established theories and fundamentals.

The future fundamental research will focus on larger-diameter wires and the application of a pulse laser to detach the droplet at desired diameter and amperage with continuous waveform current.

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