WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, DECEMBER 2015
Sponsored by the American Welding Society and the Welding Research Council

Laser-Assisted GMAW Hardfacing

The welding wire was preheated with a laser to reduce the heat input into the substrate

BY Y. ALI, K. GUENTHER, A. BURT, AND J. P. BERGMANN

ABSTRACT

The influence of a laser preheated wire in gas metal arc welding (GMAW) on the process behavior and deposit characteristics during hardfacing was investigated. Thereby, the continuous and the pulsed waveform of globular transfer mode were investigated. Focusing the diode laser beam on the welding wire above the ignited arc enhances the wire melting. As a result, the welding current decreased proportionally to the increase of laser power, and thus the heat input in the workpiece was reduced. This had a positive effect on the hardfacing weld metal characteristics, especially the dilution, which is a very important factor. In this work the welding process was analyzed and evaluated by recordings of current and voltage waveforms and high-speed camera documentations of the metal transfer. It could be shown, under the same wire feeding rate and voltage, that an increase of the laser power resulted in a rise of the arc length and droplet size. In addition, the welding beads were metallographically analyzed and compared with the conventional GMAW process. The results showed that the dilution decreased by increasing the laser power.

KEYWORDS

• GMAW • Hardfacing • Cladding • Laser Preheating • Preheated Wire • Metal Transfer

Introduction

In the mining, oil, extrusion and other industries, many components are exposed to excessive tribological conditions (e.g., abrasion, erosion, corrosion), which lead to their quick breakdown. In this context, hardfacing of engineering components is of high economic importance in order to improve the tribological properties and thus service life. In other words, an appropriate alloy, which meets the desired tribological properties, is homogenously deposited on a substrate (usually low- or medium-carbon steel), maintaining the ductility and toughness of the component (Refs. 1, 2). In order to decrease the costs of wear in industrial applications (2 to 7% of the national product of industrial countries), many hardfacing processes have been developed in recent years (Ref. 3), whereas two processes are of high economic importance. Regarding the plasma transferred arc welding (PTAW) process, the deposited material is in powder form, which does not require a high heat input. The result is a high-deposition rate, up to 15 kg/h, with a low dilution into the substrate (< 10%) (Ref. 4). In contrast, gas metal arc welding (GMAW) has also become a well-known welding process for hardfacing applications. The popularity of this process comes from its simple operability because of the small number of process control variables compared to PTAW, the high productivity, the easiness for automation, and the simple and controlled feeding of the filler metal in the form of a wire electrode. This makes GMAW ideal for use on the construction site, where repair and welding works cannot be avoided in constrained positions. However, the main issue of GMAW is the correlation between the deposition rate and welding current, so that increasing the deposition rate will indeed result in an increase of the welding current and consequently lead to high dilutions between 15 and 30% (Ref. 5). This high degree of dilution decreases the efficiency for hardfacing applications, as the specified properties and thus wear protection will only be achieved after several layers. Furthermore, the high level of dilution leads to high internal stresses in the coated layer, so that distortion or cracking during cooling can occur.

For this reason, further developments in GMA welding are required in order to achieve high deposition rates and low dilutions at the same time. A method to control the heat input in the GMAW process by decoupling the base metal current from the gun current was investigated (Ref. 6). By adding a GTAW nonconsumable electrode to a GMAW consumable electrode, the welding current will partially flow through the GTAW electrode

Y. ALI, K. GUENTHER, and J. P. BERGMANN are with Department of Production Technology, Ilmenau Technical University, Germany. A. BURT is with EWM AG, Mündersbach, Germany.

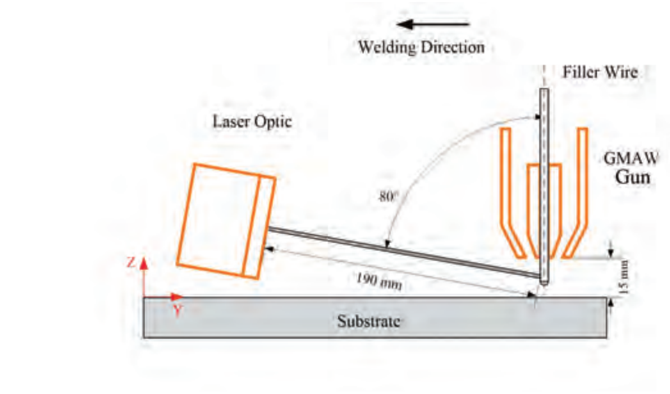

Fig. 1 — Schematic drawing of the laser-preheated GMAW process.

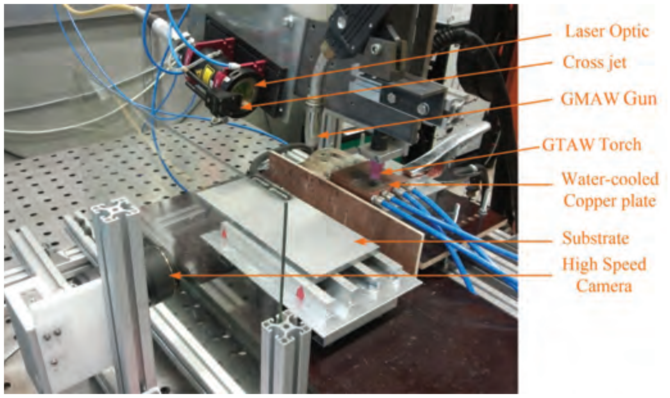

Fig. 2 — Installation of high-speed camera, GMAW gun, laser, and GTAW torch.

(bypass current) without going through the base metal (main current). Thereby, the bypass current controls the heat input into the base metal. A further development of the process where replacing the nonconsumable with a consumable electrode (thus, two GMA welding guns with two power supplies) showed that the deposition rate can be doubled (Refs. 7, 8). The increase in welding current compared to the process with a nonconsumable electrode was approximately 50 A, and the current flowing through the base metal was 65% less than the main current. However, there was no detailed information about the change in the dilution rate.

On the other hand, research showed that by inserting an additional resistive heating of the filler metal with a separate power supply, the additional preheating of the filler metal led to a reduced welding current of up to 25% and a reduced dilution from 33% (conventional GMAW) to 4.5% (Refs. 9, 10). Furthermore, the welding speed could be increased from 1.14 m/min to 2.28 m/min. Other studies showed that the resistive auxiliary preheating of the filler metal does not only positively affect the dilution, but also the melt-off loss of the alloying elements compared to conventional GMAW (Ref. 5). Preheating the filler metal with an additional GTAW torch instead of resistive heating was investigated (Refs. 11, 12). Thereby, the filler metal was preheated by a GTAW arc before entering the contact tip. The results showed that by increasing the GTAW current (preheating temperature), the welding current could be reduced to approximately 35% while both the arc length and droplet size increased (Ref. 12). The problem with these methods is that up to a certain preheating current, the wire melts partially, bends, and is thus rather difficult to feed through the contact tip.

In this paper the authors propose an alternative way to reduce the heat input by focusing a laser beam on the filler metal directly after leaving the contact tip. This preheating should reduce the welding current, which is necessary to melt the filler metal, so that the heat input and thus the dilution will be reduced. Compared to GTAW preheating, as described above, the laser-assisted preheating does not disturb wire feeding. Additionally, the laser-induced preheating of the consumable electrode did not cause any laser–arc interactions compared to hybrid-laser GMAW (Ref. 13), in which the laser is focused on the welding bead in order to reach a deep penetration and high travel speed. The study is also different from laser-enhanced GMAW (Refs. 14, 15), in which a low-power laser was directly focused on the molten wire tip. In this case, the induction of an auxiliary force made it easier to detach the droplet without any significant change in welding current and without preheating effect.

Experimental Procedures

Experimental Setup

Figure 1 shows a schematic drawing of the laser-preheated GMAW process. A laser beam is focused on the welding wire right below the gas nozzle. In addition to the resistance heating (joule heating), the heat transfer from the laser preheated the welding wire and helped reduce the arc energy necessary to melt the welding wire. The reduction of the arc energy — and the associated heat input into the substrate — positively affected the weld geometry, especially the dilution, which is an important factor for evaluating the wear resistance of cladding.

The experimental system contains a six-axis KUKA industrial robot, which provides an accurate and reproducible movement of the welding gun and laser optic. The welding power supply was a CV (constant voltage) power supply EWM alpha Q 552 with 4-roll drive system PHEONIX Drive 4. The laser source was a 1-kW diode laser LDM 1000 with a 300-μm fiber-optic cable. The laser beam was formed by a special focusing optic to the desired spot shape in order to achieve the preheating effect on a 1.2-mm flux-cored filler metal. For this study, an optic with a 600-μm focal beam diameter and a focal length of 200 mm were used. Both welding power supply and laser system were connected to the robot control unit controlling all functions.

In order to evaluate the real process parameters, the real welding current and voltage were measured during the process by a Mephisto Scope UM 202 oscilloscope. The scanning rate was 2.5 kHz to obtain a detailed waveform for current and voltage. Additionally, a high-speed camera Optronis CamRecord CR3000x2 was used to record and characterize the metal transfer at 4000 frames per second. The camera, with appropriate filter, was placed perpendicular to the plane formed by laser beam and welding wire, as shown

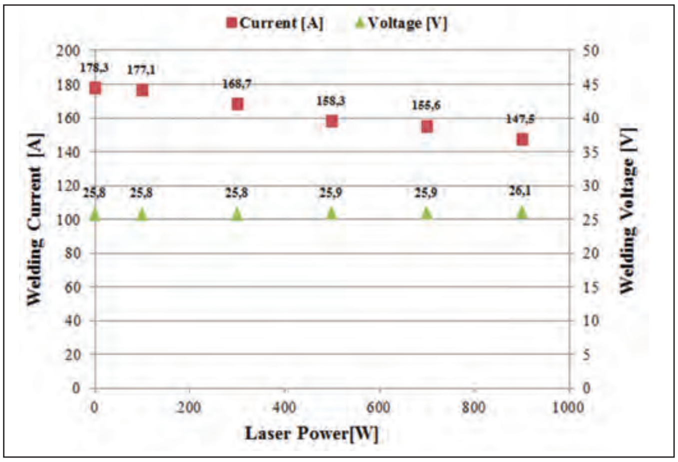

Fig. 3 — Influence of the laser power on the welding current and voltage for continuous waveform.

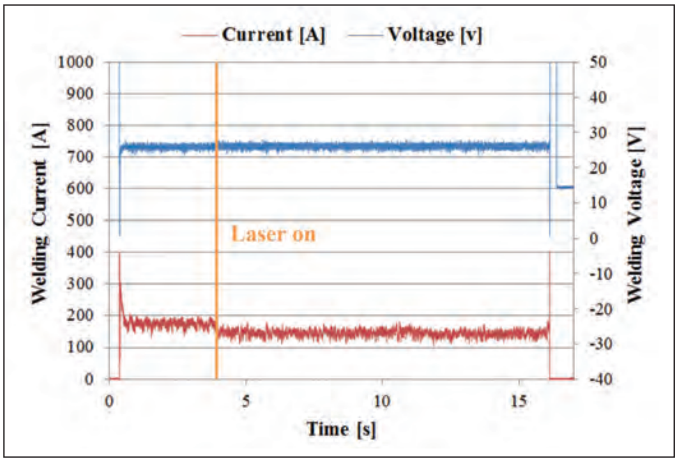

Fig. 4 — Effect of laser activation on the welding current and voltage for continuous waveform at 900-W laser power.

in Fig. 2.

S355 low-carbon steel plates with a dimension of 300 ¥ 130 ¥ 10 mm were employed as substrate material, whereas a nickel cored wire Thaloy® WSC-DUR Ni of 1.2-mm diameter with WC/W2C (fused tungsten carbides) particles was used to generate wear-resistant Ni–WC surfacing, i.e., fused tungsten carbides in a nickel-based alloy. All plates were cleaned by sand blasting and isopropanol in order to eliminate the oxide layer and impurities.

Experimental Conditions

The welding parameters used in this study are listed in Table 1. In this research, globular transfer with continuous and pulsed waveform (one droplet one pulse) was investigated, whereas 80-mm-long weld beads were generated and then evaluated metallographically. In all experiments, the laser was always activated 20 mm after the welding start point in order to demonstrate the difference in current and voltage waveform before and after the activation of the laser.

In order to achieve a preheat effect by laser, the laser spot was focused as high as possible. With an angle of 80 deg between the filler metal and the laser beam, the laser beam was focused 4 mm under the contact tip.

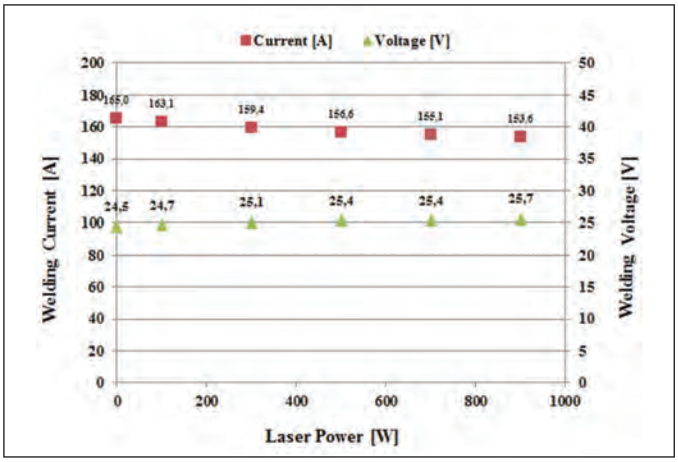

Fig. 5 — Influence of the laser power on the welding current and voltage pulsed waveform.

Evaluation Methods

The measured values of welding current and voltage were used in Equation 1 to calculate the arc power from the welding power supply.

$$P = \int_0^t \frac{UI}{dt} \quad (\mathrm{W}) \qquad (1)$$

Where U is the real welding voltage in (V), I is the real welding current in (A) and t is the welding time in (s). To calculate the heat input H in the substrate, taking into account the heat loss in the surroundings, the following equation was used:

$$H = \eta \frac{P}{\upsilon} \quad (\mathrm{J/mm}) \qquad (2)$$

Table 1 — Welding Parameters

Parameter	Voltage	Frequency	Wire Feed Rate	Welding Speed	Gun Angle	Stickout	Shielding Gas	Shielding Gas Flow
Continuous Waveform	26 (V)		5 (m/min)	0.3 (m/min)	90 deg	15 (mm)	Ar + 30% He	15 (L/min)
Pulsed Waveform	26 (V)	100 Hz						

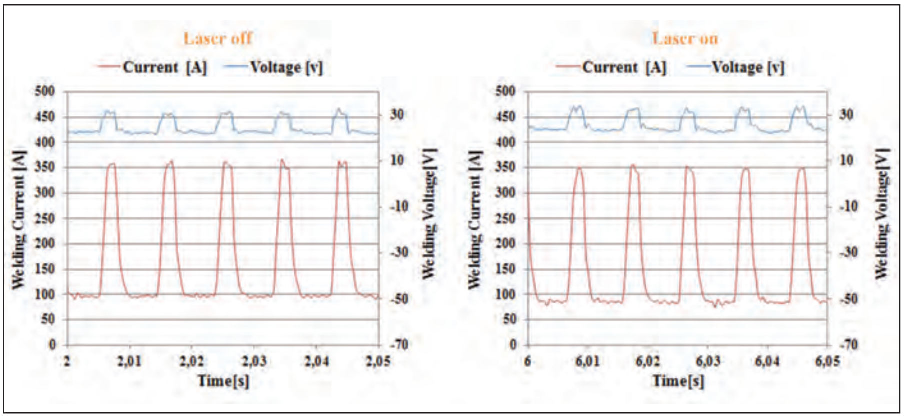

Fig. 6 — Current and voltage waveforms of pulsed waveform with and without laser (900 W).

Where η is the thermal efficiency of the process, which is related to the welding process. For GMAW and for the used transfer mode, the average thermal efficiency is approximately 73% (Ref. 16). v is the travel speed in mm/min. The amount of heat transfer into the plate is just for the welding arc and not for welding arc and laser. The explanation will come later during the discussion.

Metallurgical analyses of the weld beads were performed to study the effect of wire preheating on the bead geometry. For this purpose, three cross sections for each bead were extracted and metallographically prepared. The specimens were mounted, ground with SiC papers from P280 to P2500, and then polished with diamonds using grain sizes of 6 µ and 3 µ. After polishing, the required evaluation criteria of the weld were analyzed under the microscope, e.g., weld width and height, dilution, and wetting angle.

Experimental Results

Welding Current and Voltage

In order to evaluate the influence of the laser preheating on the welding current and voltage, the mean current and voltage values were calculated in dependence on the laser power. For a continuous waveform, Fig. 3 shows that the increase of laser power continuously reduces the welding current so that a decline of approximately 31 A was obtained with a laser power of 900 W. It has to be noted that activating the laser during the welding process leads to a quick decrease of the welding current — Fig. 4. At the same time, the welding voltage shows a slight growth by increasing the laser power.

Compared to the continuous waveform, the pulsed waveform shows a lower decrease in welding current by increasing the laser power (approximately 11 A at 900 W laser power) — Fig. 5. Thereby, just the background current is reduced while the peak current remains constant during the activation of the laser — Fig. 6.

Improving the cladding efficiency requires lower heat input in the base metal, which reduces the dilution and improves the welding quality. By applying a laser as a preheating source, it was thus possible to reduce the welding current without changing the wire feeding rate. This means that its additional use had an influence on the heat input during cladding. As Fig. 7 shows, the heat input decreases with increasing laser power and thus "preheating temperature" in the case of the continuous waveform. As a consequence, a 17% reduction of the heat input could be achieved by a laser power of 900 W. In contrast, the pulsed waveform does not show any substantial changes.

Arc Characteristics and Metal Transfer

In order to analyze the arc properties and metal transfer, the welding arc was observed by a high-speed camera for different laser powers. As shown in Fig. 8, the arc length rises with increasing laser power. The distance be-

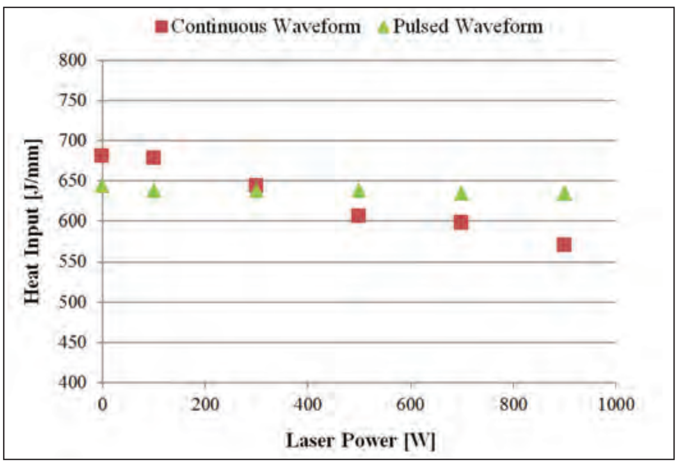

Fig. 7 — Influence of laser power on the heat input.

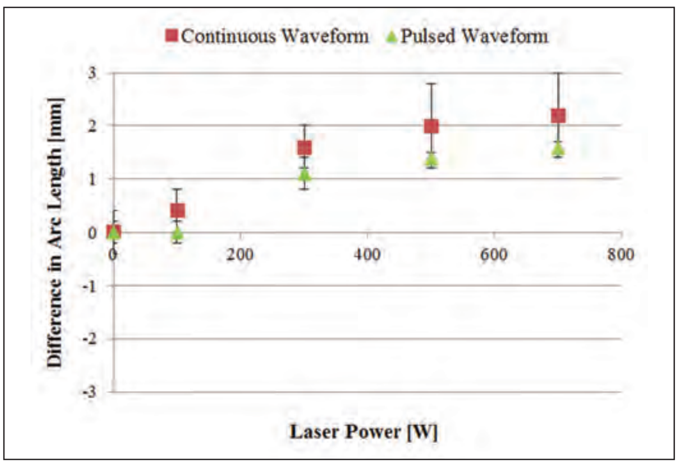

Fig. 8 — Influence of laser power on arc length.

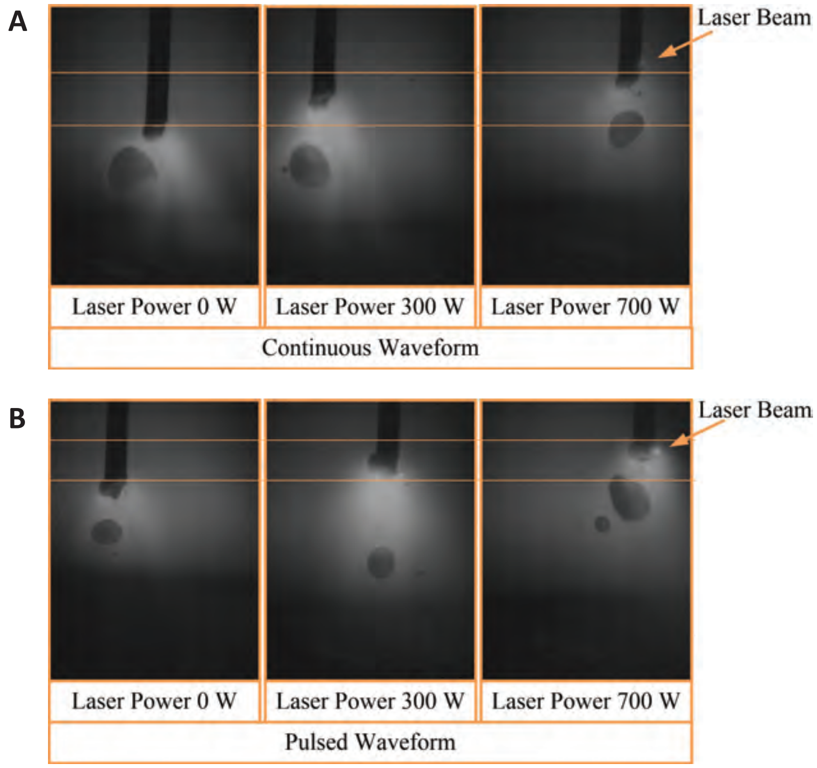

Fig. 9 — Influence of laser power on the arc length. A — Continuous; B — pulsed waveform.

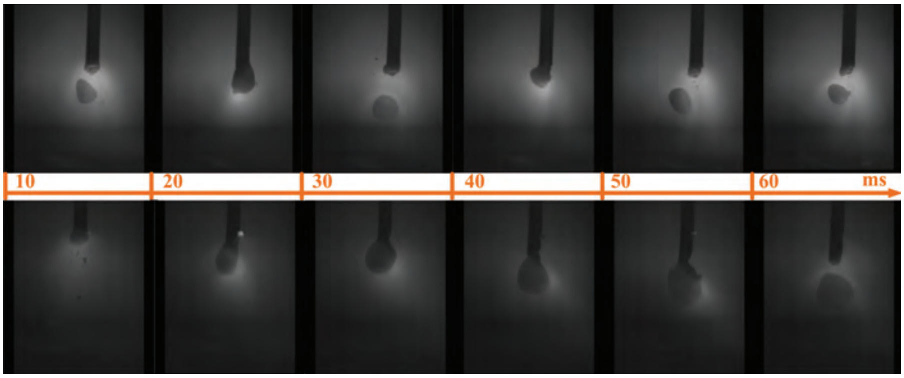

Fig. 10 — Metal transfer of continuous waveform, conventional (top), with 700-W laser power (bottom).

tween the two lines in Fig. 9A, B represents the growth of the arc length, but also the reduction of the free wire end. This change in arc length is, for the pulsed waveform, lower than for the continuous one as shown in Fig. 8.

It can also be noticed that the preheating of the welding wire for continuous waveform leads to an instability of the droplet size and the droplet detachment time compared to the conventional process. Figure 10 depicts that the detachment time for one droplet almost increased three times due to the laser application (700-W laser power) compared to the conventional GMAW process. Since the formation of a large droplet during laser-preheated GMAW happens irregularly, it was noticed that the transfer rate decreased to one half due to laser preheating. This effect was also observed for pulsed waveform, where the detachment of the droplet needs sometimes five pulses to take place.

Metallurgical Results and Weld Formation

In all cladding processes, high-quality welds require a low-dilution rate to reduce the mixing between the filler metal and the base metal. In this case, it was aimed to decrease the heat input in the substrate so that a lower volume of the workpiece melted and a smaller ratio of the Ni/WC alloy mixed with the base metal.

As previously stated, the use of laser-preheated GMAW reduces the heat input into the base metal, which should be positively reflected in the dilution rate. Figure 11A, B displays the metallurgical results of the laser-preheated GMAW. It can be observed that the dilution reduces with increasing laser power. The optimal value for the continuous waveform is a laser power of 500 W, leading to a reduced dilution of more than one-half compared to the conventional process. However, a further increase of laser power does not lead to a continuing effect on the weld dimensions. For the pulsed waveform, no significant change in the dilution rate could be observed, since the heat input was not substantially affected by the laser.

The metallurgical investigation showed that the laser-preheated GMAW has no significant effects on the bead width, the height of the bead, and the wetting angle.

Comparison with Other Wire Preheated GMAW Methods

Compared to the results of arc-preheated GMAW (Refs. 11, 12), lower reduction in welding current and irregular metal transfer were obtained with laser-induced preheating. The reason for this is that the diffraction and reflection of the laser beam on the cylindrical form of the welding wire play an important role, so that just a small amount of laser power was absorbed from the welding wire. This means a welding wire with a larger diameter or a laser optic with smaller spot diameter will obtain better results. The metallurgical results in Refs. 11 and 12 showed a reduced dilution rate, but without giving any information about the difference. The results in Ref. 5 with auxiliary preheating show a re-

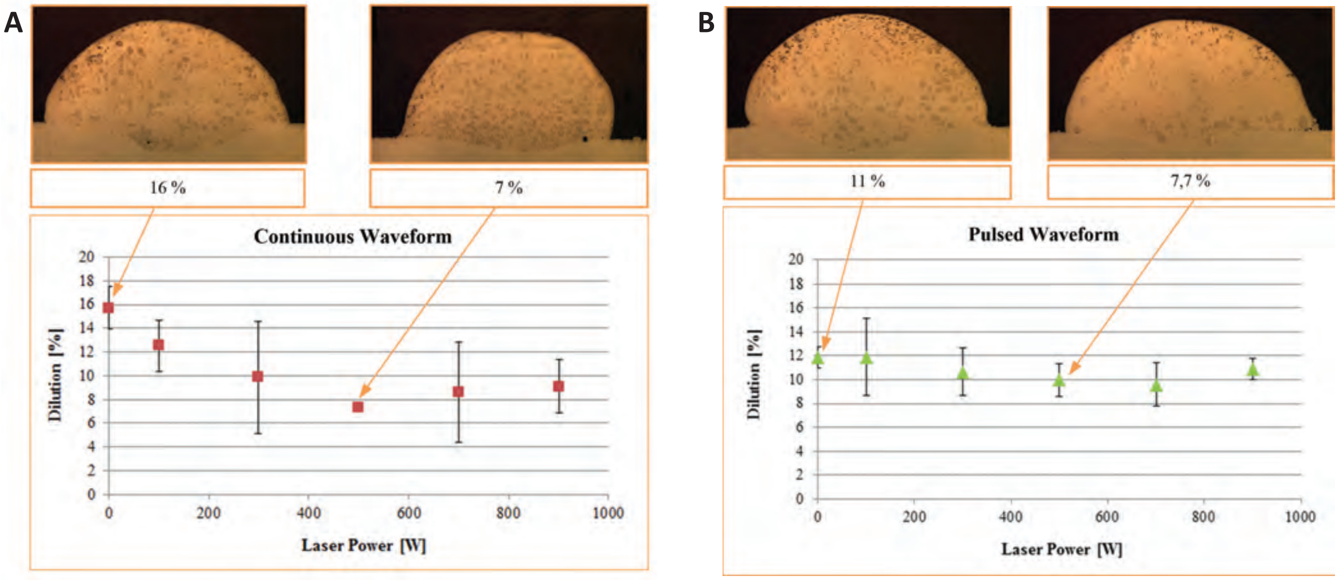

Fig. 11 — Effect of laser power on the dilution. A — Continuous; B — pulsed waveform.

duction in dilution of up to 44% (20.3 to 11.3%), which is lower than the value achieved by laser preheating (54%, Fig. 11A). However, the welding current and the metal transfer were not investigated (Ref. 5).

Discussion

In order to understand the effect of laser preheating on the GMAW process, it should first be known that the welding power source with constant voltage characteristics used in this study controls its voltage and amperage output. Figure 12 shows the behavior between the voltage and the current for a constant voltage power source. The welding current is determined by the wire feed rate, so that a spontaneous change in feed speed will change the arc length due to the reduced melting rate, which in turn changes the welding current.

Back to the studied case, the laser beam is focused onto the filler metal, which eases the melting of the wire and decreases the energy portion of the arc, which is used to melt the filler metal. The result was an increase in arc length and decrease in welding current. According to the controlling process of the power source, an increase of the arc length, for example due to geometrical changes, should lead to a decrease of the welding current — Fig. 12. This reduction in welding current by a constant wire feed rate should decrease the wire melting rate so the arc length returns to its normal position. Due to the laser preheating of the GMAW filler metal, this controlling process is disrupted.

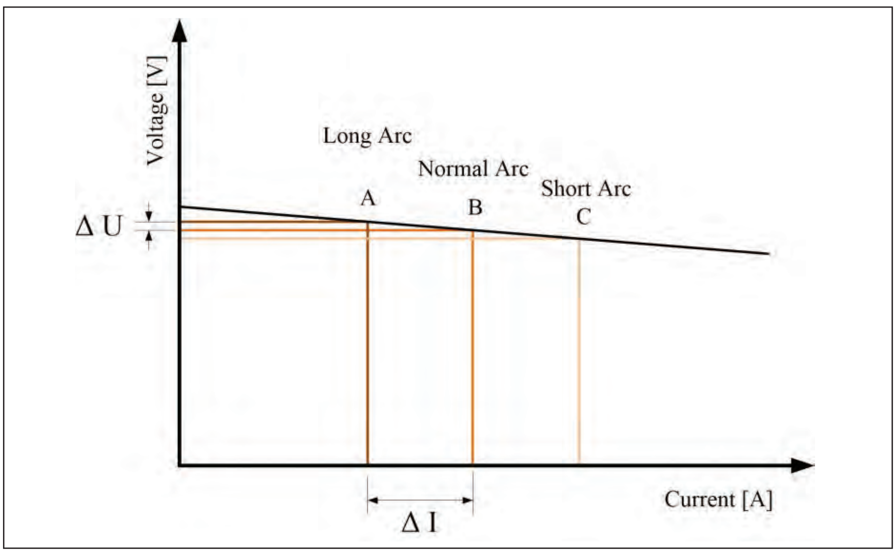

Fig. 12 — Constant voltage welding power supply characteristic.

Regarding the laser-preheated wire for GMAW, the arc length cannot return to its original position despite the reduction in welding current and the constant feeding of the welding wire. The point is that focusing the laser beam onto the welding wire increases the melting rate of the filler metal due to the laser-induced preheating effect. Furthermore, high-laser power melts the affected area of the wire. This rise in melting rate increases the arc length and decreases the free end of the wire. As a result, the total heat input in the base metal decreases (Fig. 8), which leads to a reduction of the dilution compared to conventional GMAW — Fig. 11A. This reduction in dilution did not affect the weld width as expected, which might be explained by the increase of the arc length, widening the arc distribution, and consequently the weld bead.

As already shown, the reduction in welding current for the pulsed waveform is lower compared to the continuous waveform. The reason is that the ratio between the background current and the peak current (amplitude) remains almost constant because of the controlling method of the power source. The slight increase of the voltage in Figs. 3 and 5 is a normal result for the increase of the arc length — Fig. 11.

The analysis of the process recordings shows laser preheating leads to the formation of large droplets. The droplet detaching process is influenced by the pinch effect, in which an electromagnetic force is applied radially on the liquid end of the welding wire and causes it to form the droplet. This force is proportional to the square of the welding current, so that the decreasing of the welding current by using laser preheating weakens this force and thus the droplet detachment. In the case of the pulsed waveform, large droplets are sometimes formed, although the peak current and the resulting electromagnetic force, which are responsible for detaching the droplet, are not significantly reduced (approximately 11 A at 900-W laser power, Fig. 5). As already mentioned, the laser preheating treatment increases the wire melting rate, so that the reduction in the free end of the wire with constant wire feeding increases the amount of molten metal per unit of time. This means that more metal is molten per pulse than before (without laser) and the pulse time is not long enough to detach the increased molten volume. The result for this irregular metal transfer is the high standard deviation of dilution as shown in Fig. 10. The solution could be the adjustment of the pulse frequency, correlating with the melting rate "laser power" to achieve a regular droplet transfer, which wasn't investigated.

Conclusions and Future Work

In this paper, the effects of laser preheating of the welding wire in the GMAW process, and its influences on the weld characteristics, were investigated. The results showed that the correlation between the wire feed rate and the welding current can be uncoupled using laser preheating, so that increasing the laser power leads to a decrease of the welding current. This means that higher feeding rates can be used with lower heat input compared to the conventional GMAW process. The decrease in welding current goes along with an increase in welding voltage, which appeared as an increase in arc length. As a result, the heat input in the substrate decreased and led to a reduced dilution. These effects were clearer for the continuous waveform compared to the the pulsed waveform. It was also noticed that the decrease in welding current (electromagnetic force) for the continuous waveform and the increase of molten volume per pulse in the pulsed waveform led to larger droplets, and the droplets were detached irregularly by gravitational forces. For further work, the effect of the variation of pulse parameters, wire diameter, and stickout on the laser-induced welding process should be studied.

References

1. Chotěborský, R., Hrabě, P., Müller, M., Savková, J., and Jirka, M. 2008. Abrasive wear of high chromium Fe-Cr-C hardfacing alloys. *Research Agriculture Engineering* 54: 192–198.
2. Gautam, K., and Sachit Vardhan, O. P. 2012. Hardfacing by welding to increase wear resistance properties of EN31 by MR 3LH electrode. *International Journal of Emerging Technology and Advanced Engineering* 2(2): 4.
3. Mendez, P. F., Barnes, N., Bell, K., Borle, S. D., Gajapathi, S. S., Guest, S. D., Izadi, H., Gol, A. K., and Wood, G. 2014. Welding processes for wear resistant overlays. *Journal of Manufacturing Processes* 16(1): 4–25.
4. Cheng, J., Liang, X., Wang, Z., and Xu, B. 2013. Formation and mechanical properties of CoNiCuFeCr high-entropy alloys coatings prepared by plasma transferred arc cladding process. *Plasma Chemistry and Plasma Processing* 33(5): 979–992.
5. Shahi, A. S., and Pandey, S. 2008. Effect of auxiliary preheating of the filler wire on quality of gas metal arc stainless steel claddings. *Journal of Materials Engineering and Performance* 17(1): 30–36.
6. Zhang, Y., Jiang, M., and Lu, W. 2004. Double electrodes improve GMAW heat input control. *Welding Journal* 83(11): 39–41.
7. Li, K., and Zhang, Y. 2008. Consumable double-electrode GMAW — Part 1: the process. *Welding Journal* 87(1): 11.
8. Li, K., and Zhang, Y. 2008. Consumable double-electrode GMAW — Part 2: Monitoring, modeling, and control. Welding Journal 87(2): 44.
9. Stol, I. 1987. *Advanced Gas Metal Arc Welding Process (AGMAW)*. The Welding Institute, pp. 493–511.
10. Stol, I. 1984. *Method and Apparatus for Arc Welding*, Google Patents.
11. Ni, J., and Gao, H. M. 2013. Effect of the Wire Temperature on the Weld Formation in GMAW. *Advanced Materials Research*. 652: 2289–2292.
12. Ni, J., and Gao, H. M. 2013. Influence of preheated wire on GMAW process. *Advanced Materials Research* 668: 538–542.
13. Bagger, C., and Olsen, F. O. 2005. Review of laser hybrid welding. *Journal of Laser Applications* 17(1): 2–14.
14. Huang, Y., and Zhang, Y. 2011. Laser enhanced metal transfer — Part 1: system and observations. *Welding Journal* 90(10): 83–90.
15. Huang, Y., and Zhang, Y. 2010. Laser enhanced GMAW. *Welding Journal* 89(9): 181–188.
16. Hsu, C., and Soltis, P. 2002. Heat input comparison of STT vs. short-circuiting and pulsed GMAW vs. CV processes. *6th International Conference: Trends in Welding Research.*