SUPPLEMENT TO THE *WELDING JOURNAL,* NOVEMBER 2011
Sponsored by the American Welding Society and the Welding Research Council

Laser-Enhanced Metal Transfer – Part II: Analysis and Influence Factors

Laser intensity and arc voltage were examined for their effects on metal transfer

BY Y. HUANG AND Y. M. ZHANG

ABSTRACT

Experiments were previously done to demonstrate that applying a relatively low-power laser to the liquid droplet could produce free flight transfers with welding currents below the transition one. In this paper, the effects of the laser intensity and arc voltage on metal transfer process in laser-enhanced GMAW were discussed and analyzed. The enhancement of the laser was found to increase as the laser intensity increased. The larger laser intensity tended to help reduce the size of the droplet detached. The arc voltage affected the metal transfer process through changing the current and changing the gap and possible time interval of the droplet development. A larger arc voltage helped reduce the size of the droplet detached through an increased electromagnetic force. It also tended to provide a longer time to grow the droplet. In both cases, the chance for short-circuiting or repelled drop globular was reduced.

Introduction

In the first part of this investigation (Ref. 1), it was shown that the laser affected the metal transfer process as an additional detaching force that tended to change a short-circuiting transfer to drop globular transfer (even drop spray), reduce the diameter of the droplet detached in drop globular transfer, or reduce the diameter of the droplet such that the metal transfer changes from drop globular to drop spray.

Metal transfer, which is referred to as the periodical metal melting and droplet forming, growing, detaching, and traveling process, is a key issue in gas metal arc welding (GMAW). As previously mentioned (Ref. 1), the American Welding Society classifies the metal transfer into three major types/modes: short circuiting, globular, and spray (Ref. 2). Metal transfer modes are affected by several operational factors, such as welding current, composition of shielding gas, wire extension, the ambient pressure, active elements in the electrode, polarity, and welding material (Refs. 3–6). Of all of these, welding current is the most important factor to determine the metal transfer mode. When a continuous waveform current is used and the current is small, the droplet may not be detached until it contacts the weld pool. This transfer mode is referred to as short-circuiting transfer. If the welding current increases or the arc length increases, the droplet will gradually grow until the gravitational force balances the surface tension, and then the droplet will detach. This transfer mode is globular transfer. When the current further increases, the electromagnetic force may become a sufficiently large enough detaching force to detach the droplets whose diameter is similar (drop spray) to or much smaller (streaming spray) than that of the electrode wire. The metal transfer modes were widely studied in the literature (Refs. 6–8). Metal transfer control was also a focus in the research community (Refs. 9–12). The International Institute of Welding (IIW) further classifies globular transfer into drop globular and spelled globular (Refs. 8, 13). The IIW classification for metal transfer is shown in Table 1.

In Part 1, welding current was preliminarily discussed as a major factor affecting the metal transfer. Laser recoil pressure force was found to be responsible for achieving free-flight transfer modes with welding currents below the transition current. However, there are other major factors that affect the metal transfer in laser-enhanced GMAW. This part of the paper is thus devoted to understanding how the laser intensity and arc voltage affect the metal transfer in laser-enhanced GMAW.

KEYWORDS

GMAW
Laser
Metal Transfer
Drop Globular
Drop Spray
Short Circuiting
Welding Current
Arc Length

Y. HUANG and Y. M. ZHANG (ymzhang@engr.uky.edu) are with Department of Electrical and Computer Engineering, University of Kentucky, Lexington, Ky.

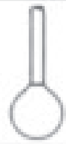
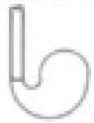
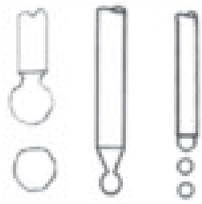
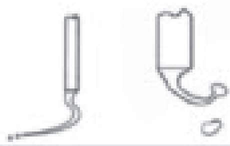
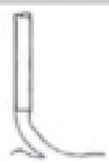
Effects of Laser Intensity

The major parameter of the laser in the laser-enhanced GMAW is the recoil pressure that is determined by the laser intensity and the cross section of the droplet that intercepts the laser. To study the effect of the laser intensity, three levels of laser power were used: 645, 754, and 862 watts (W). The laser beam used in this study is 1 × 14 mm. The corresponding intensity is thus 46, 54, and 62 W/mm^2. Because the laser is applied along the wire axis direction, if the diameter of the droplet is smaller than 1 mm, the interception area aforementioned increases quadratically with the droplet diameter; however, for the majority of the experiments studied in this investigation, the droplet detached has a diameter greater than 1 mm, and the interception area increases linearly with the diameter of the droplet.

Figures 1 and 2 show the metal transfer at different laser intensity levels for 300 in./min, 30 V, 0–62 W/mm^2. (Figure 1 is the Fig. 6 in Part I, and is represented here to make analysis clear.) When the laser intensity was zero (Fig. 1A), the metal transfer was short circuiting. (For shorting-circuiting transfer, the diameter of the droplet such as that given in Fig. 3 is measured right before

WELDING RESEARCH

Table 1 — Classification of Metal Transfer in GMAW (Refs. 8, 14)

Metal Transfer Mode		Sketch	Examples
Free Flight Transfer	Globular drop		Low-current GMAW
	Repelled		CO_2 shielded GMAW
	Spray projected		Intermediate-current GMAW
	Streaming		Medium-current GMAW
	Rotating		High-current GMAW
	Explosive		SMA (covered electrode)
Bridging Transfer	Short circuiting		Short-circuiting GMAW
	Bridging without		Welding with filler metal

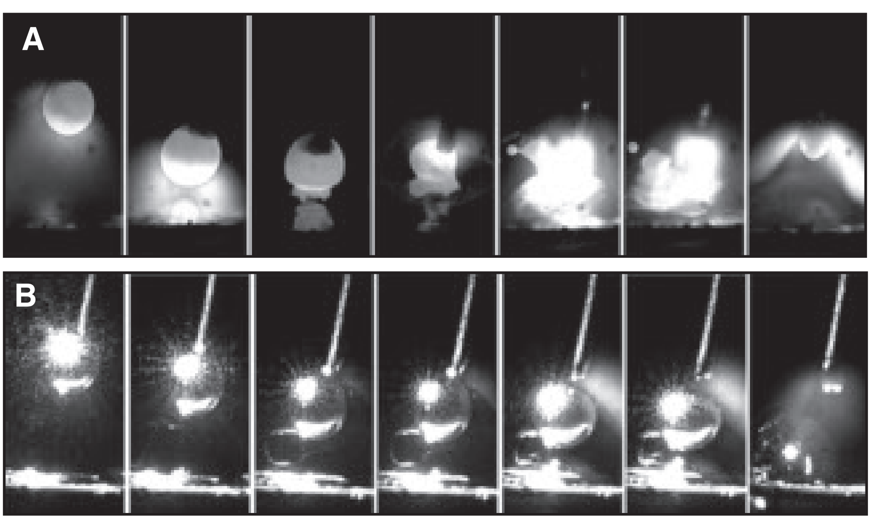


Fig. 1 — Typical metal transfer in comparative experiments with and without laser under 300 in./min, 30 V, 0 W/mm² and 300 in./min, 30 V, 62 W/mm².

the droplet touches the weld pool.) When it increased to 46 W/mm², the transfer was a mix of short circuiting and drop globular at approximately 50–50%, but the droplet was typically detached right before the droplet touched the weld pool. Hence, in Fig. 3, its droplet diameter is the same as that without the laser. (One should note that the diameter of the droplet detached under a short-circuiting condition differs from that under a drop globular transfer. Hence, the same droplet diameter observed in Fig. 3 for without a laser, reasonably equals a laser intensity of 46 W/mm².) When the laser intensity increased to 54 W/mm², the metal transfer became drop globular (Fig. 2); when the laser intensity further increased to 62 W/mm², the diameter of the detached droplet further reduced — Fig. 1B. As can be seen in Fig. 4B in Part 1, the current approximately remained unchanged. The increase in the laser intensity thus did not increase the electromagnetic force. Figure 3 clearly shows the tendency that the droplet diameter reduces as the laser intensity increases. The increased laser intensity decreased the need for a larger diameter for a larger interception area and large mass.

Metal transfer images in additional experiments at the different laser intensity levels for 250/350/400 in./min, 30 V, 0–62 W/mm² are shown in Figs. 4–6. To form a complete set of data to examine the effect of laser intensity at the 30 V setting, those previously presented images for laser intensity at zero (without laser) and 62 W/mm² in Part 1 are presented again. The complete set of data is illustrated in Fig. 7 to show tendency how the laser intensity affects the droplet diameter. However, there are details that deserve attention and are discussed below.

Let's first examine the experiment series associated with 250 in./min (250 in./min, 30 V, 0–62 W/mm²), as shown in Fig. 4. It is seen that the transfer with 46 W/mm² (Fig. 4B) is a mix of short circuiting and drop globular but the droplet diameter is almost the same as the one without a laser (Fig. 4A), as can be seen from Fig. 7. In these two cases, the laser recoil pressure (if any) is not large enough to compensate for the lack of gravitational force for a complete free flight transfer and a relatively large gravitational force is still needed to detach the droplet. In this mixed mode, short circuiting transfer dominated, but the drop globular transfer also occurred.

In this series of experiments, an interesting phenomenon can be observed from Fig. 4A and B that the laser-enhanced short-circuiting transfer (Fig. 4B) still produced spatter but at a much reduced amount from conventional GMAW (Fig. 4A). Careful observation shows that the short-circuiting time was reduced approximately 20% by the laser at the intensity of

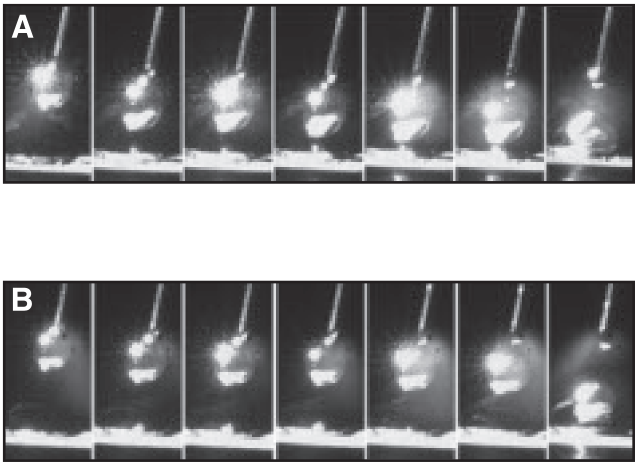


Fig. 2 — Typical metal transfer in comparative experiments with and without laser under 300 in./min, 30 V, 46 W/mm^2 and 300 in./min, 30 V, 54 W/mm^2.

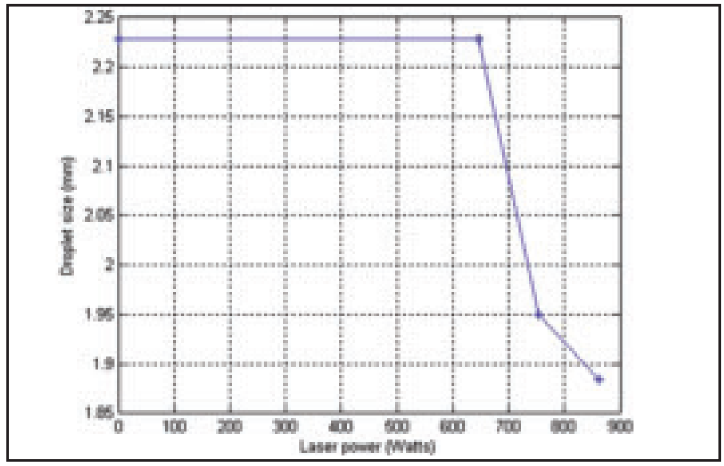
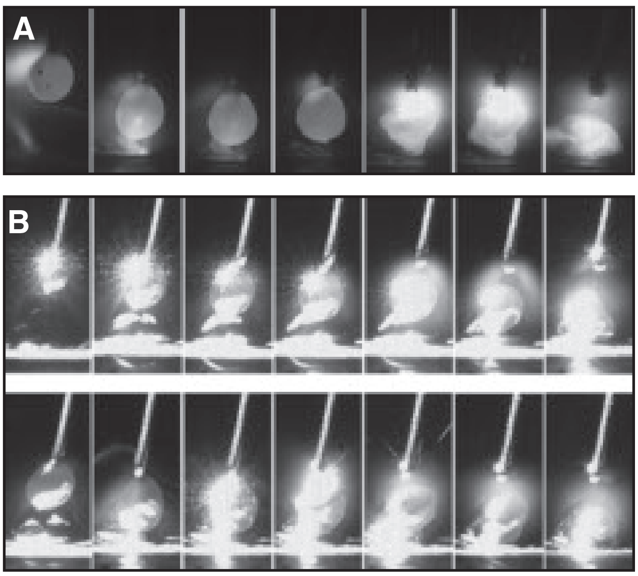


Fig. 3 — Droplet diameter with 30 V and 300 in./min under different laser power levels. The droplet diameter is the mean of the diameter of the droplet that is detached or touches the weld pool.



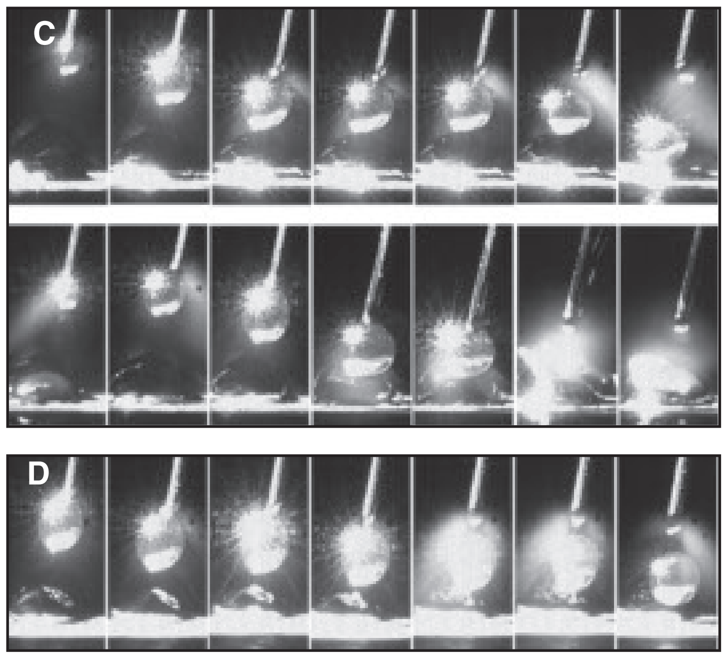


Fig. 4 — Typical metal transfer in comparative experiments with and without laser under 250 in./min, 30 V, 0 W/mm^2; 250 in./min, 30 V, 46 W/mm^2; 250 in./min, 30 V, 54 W/mm^2; and 250 in./min, 30 V, 62 W/mm^2.

46 W/mm^2. This may possibly be the cause that reduced the spatter.

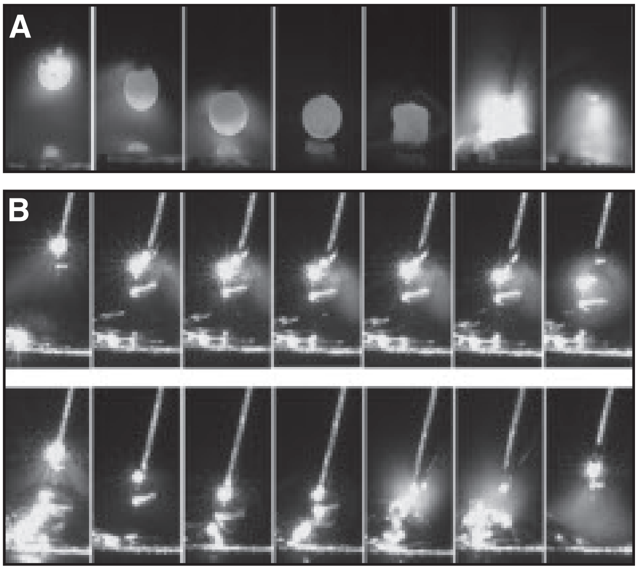
Examine the experiment series associated with 350 in./min (350 in./min, 30 V, 0-62 W/mm^2), as shown in Fig. 5. With a laser intensity of 46 W/mm^2 (Fig. 5B), the drop globular dominated and short-circuiting transfer seldom occurred. For 54 W/mm^2 (Fig. 5C), the transfer is a stable drop globular process, but the droplet diameter is larger than that with 62 W/mm^2 (Fig. 5D).

For the experiment series associated with 400 in./min (400 in./min, 30 V, 0–62 W/mm^2), as shown in Fig. 6, the metal transfer mode is different from the two aforementioned. As shown in Fig. 6B–D, the metal transfer mode is the drop spray transfer. Increasing the laser intensity will decrease the diameter of the droplet, though this change is not obvious.

As summarized in Fig. 7, for all the wire feed speeds, the diameter of droplet in each laser-enhanced GMAW experiment is smaller than its respective counterpart in conventional GMAW experiment. If the diameter for an increased laser intensity is the same with or very close to one for a lower laser intensity (or without laser), they both must be either short circuiting or very close to short circuiting (i.e., the droplet is detached right before it touches the weld pool). Of course, all these phenomena can be well explained based on force analysis as has been done in the Part 1.

Effects of Arc Length

The voltage setting on the metal transfer affects the metal transfer through its effect on the arc length, i.e., increasing/decreasing the voltage increases/decreases the arc length. The change in the arc length affects the metal transfer through 1) an increased arc length that reduces the wire extension such that the welding current increases when using a constant voltage power supply as in this study, and 2) an increased arc length provides a longer gap to allow a longer time for a new droplet to develop after a droplet detachment. (This gap, the distance from the bottom of the new droplet to the weld pool surface right after a droplet is detached, is referred to as the development gap hereafter in this study.) In laser-enhanced GMAW, an increased laser intensity does not increase the welding current, as shown in Fig. 4 in Part 1. (Instead, it reduces the current slightly.) However, when the voltage increased by 6 V, the welding current increased by 10 to 15 A (Fig. 4 in Part 1). Because the electromagnetic force as a de-



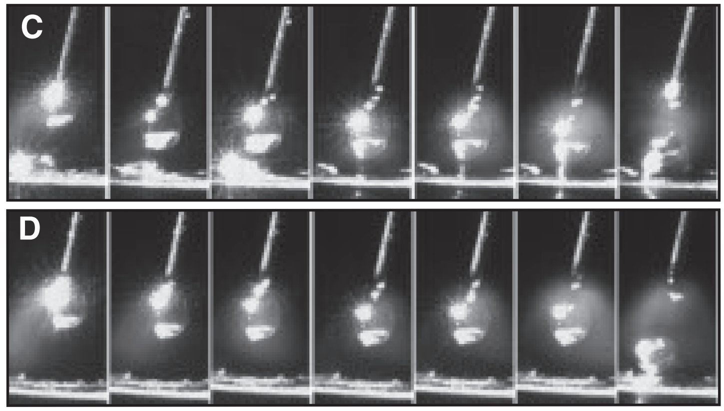
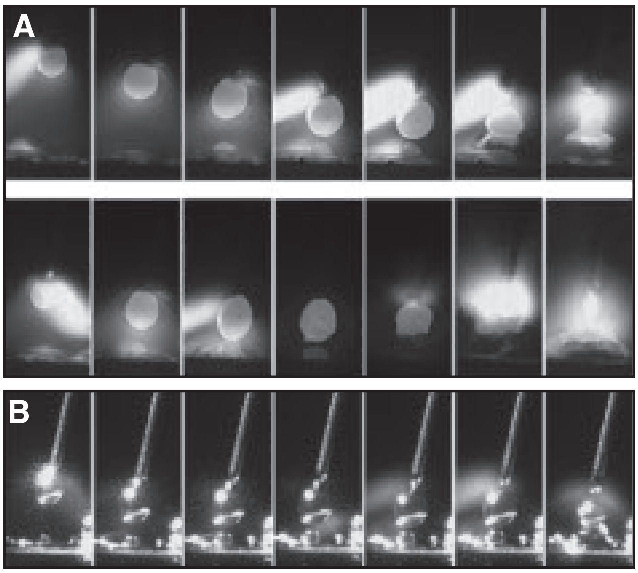


Fig. 5 — Typical metal transfer in comparative experiments with and without laser under 350 in./min, 30 V, 0 W/mm²; 350 in./min, 30 V, 46 W/mm²; 350 in./min, 30 V, 54 W/mm²; and 350 in./min, 30 V, 62 W/mm².



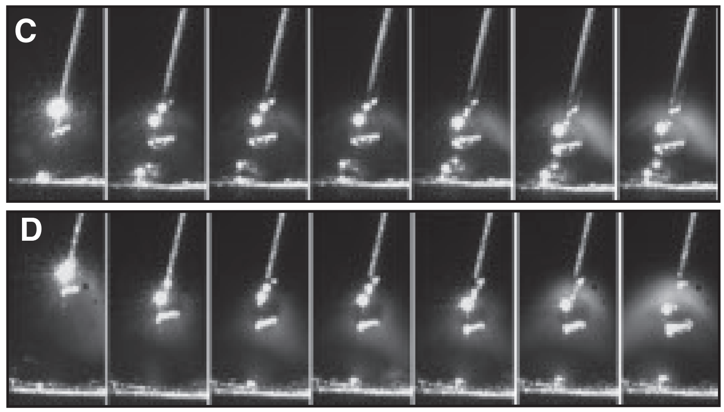


Fig. 6 — Typical metal transfer in comparative experiments with and without laser under 400 in./min, 30 V, 0 W/mm²; 400 in./min, 30 V, 46 W/mm², 400 in./min, 30 V, 54 W/mm²; and 400 in./min, 30 V, 62 W/mm².

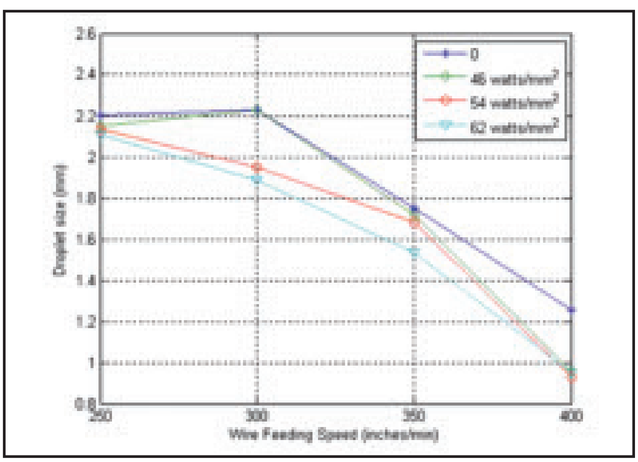


Fig. 7 — Droplet diameter with 30 V under different wire feed speed and laser power levels. The droplet diameter is the mean of the diameter of the droplet that is detached or touches the weld pool.

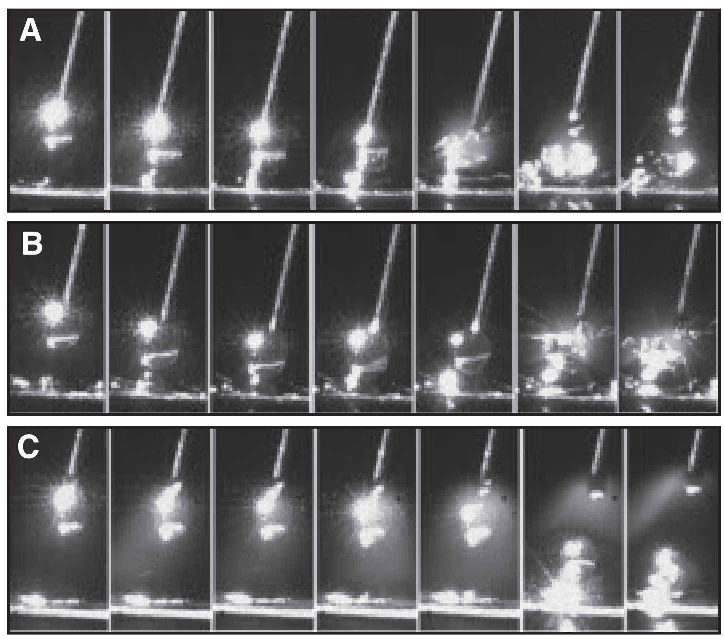


Fig. 8 — Typical metal transfer in comparative experiments with a laser under 350 in./min, 26 V, 62 W/mm²; 350 in./min, 28 V, 62 W/mm²; and 350 in./min, 32 V, 62 W/mm².

taching force increases faster than a quadratic speed as the current increases, the increase in the detaching force would be significant. Let's take the experiment series with 350 in./min wire feed speed (Figs. 5 and 8) as an example to illustrate how the voltage setting affects the metal transfer. When the voltage was 26 V, as shown in Fig. 8A, even if the laser power was 62 W/mm^2, the metal transfer was still short circuiting. This is because the development gap was short such that there was not

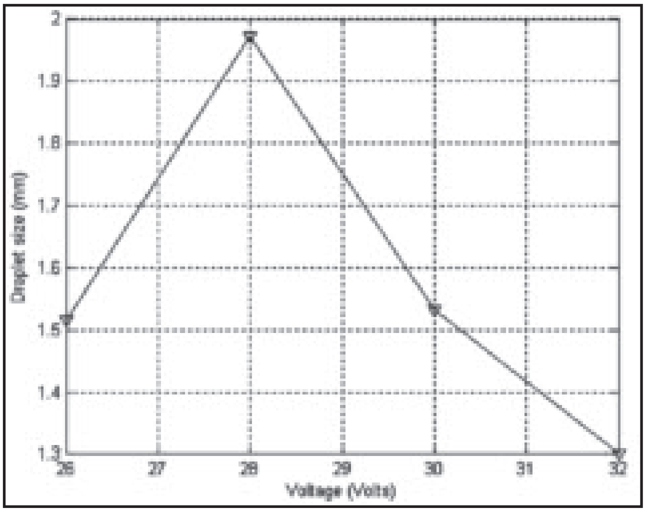


Fig. 9 — Droplet sizes with welding feed speed 350 in./min under different voltages.

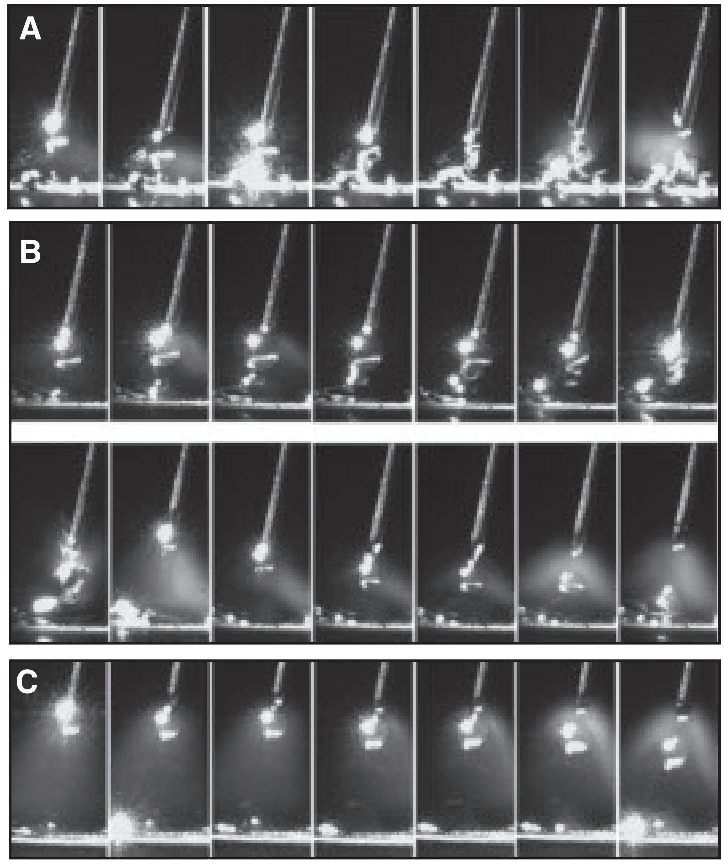


Fig. 10 — Typical metal transfer in comparative experiments with laser under 400 in./min, 26 V, 62 W/mm²; 400 in./min, 28 V, 62 W/mm²; and 400 in./min, 32 V, 62 W/mm².

enough time to grow the droplet. As a result, its small gravitational force together with the detaching electromagnetic force and laser recoil pressure force was not still sufficient to balance out the surface tension before the droplet touched the weld pool. When the voltage increased to 28 V (Fig. 8B), the development gap increased for the droplet to grow longer. In addition, the electromagnetic force increased. However, those increases were still not sufficient, and the metal transfer was still short circuiting. When the voltage increased to 30 V (Fig. 5D), the metal transfer changed to drop globular. When it further increased to 32 V, the droplet diameter is further reduced to a level comparable with that of the wire (Fig. 8C) due to the increased current/electromagnetic detaching force.

Figure 9 plots how the droplet size changed with the voltage setting for the experiment series analyzed above. The observed droplet size increase from 26 to 28 V was due to the increased development gap that provided a longer time for the droplet to grow. The increased electromagnetic force should have tended to help detach the droplet. However, since the droplet was not detached (still short-circuiting transfer), the electromagnetic force played no role in determining the droplet size. Hence, it was the increased development gap that contributed to increasing the droplet size before short circuiting. The droplet size decreases when increasing from 28 to 30 V and from 30 to 32 V were due to the respective increase in the current/electromagnetic force. The increased development gap played no role in this decrease. The laser may only help reduce the droplet size further or help the transfer to change from short circuiting to drop globular or drop spray.

Similar analysis can be done to understand how the voltage affects the metal transfer process for other wire feed speeds such as for 400 in./min — Fig. 10. Despite the change in the current that directly affects the electromagnetic force, the voltage setting still affects the metal transfer through its associated current change and development gap change.

In summary, a higher voltage setting increases the current and development gap. The increased development gap may help change the metal transfer from short circuiting to drop globular or even drop spray, but it plays neither role in affecting the size of the droplet detached under free-flight transfers nor a role in changing the transfer from drop globular to drop spray. The increased current affects the metal transfer by increasing the electromagnetic detaching force.

Conclusions

- Laser intensity and arc voltage are major factors affecting the metal transfer in laser-enhanced GMAW.
- The enhancement of the laser increases as the laser intensity increases and the droplet size could be effectively controlled by changing the laser intensity in an appropriate range.
- An increased arc voltage increases the current and can affect the metal transfer through an increased electromagnetic force.
- An increased arc voltage also increases the arc gap and possible time interval for the droplet to develop to reduce the chances for short-circuiting transfer or repelled drop globular transfer.
- Droplets can be detached at a given/desired diameter in a reasonable range by applying an appropriate laser intensity under a given current (arc variable) in a reasonable range, and the needed laser intensity is determined by the desired droplet diameter and the welding current used (arc variable).

Acknowledgment

This work was funded by the National Science Foundation under grant CMMI-0825956 titled *Control of Metal Transfer at Given Arc Variables*.

References

1. Huang, Y., and Zhang, Y. M. 2011. Laser enhanced metal transfer — Part 1: System and observations. *Welding Journal* 90(10): 183-s to 190-s.

2. O'Brien, R. L. 1991. *Welding Handbook* Vol. 2: Welding Processes. 8th edition, Miami, Fla. American Welding Society.

3. Kim, Y. S., and Eagar, T. W. 1993. Analysis of metal transfer in gas metal arc welding. *Welding Journal* 72(6): 269-s to 278-s.

4. Kim, Y. S. 1989. Metal transfer in gas metal arc welding. PhD dissertation, Massachusetts Institute of Technology.

5. Kim, Y. S., and Eagar, T. W. 1993. Metal transfer in pulsed current gas metal arc welding. *Welding Journal* 72(7): 279-s to 287-s.

6. Lesnewich, A. 1958. Control of melting rate and metal transfer in gas shielded metal arc welding: Part II control of metal transfer. *Welding Journal* 37(9): 418-s to 425-s.

7. Lesnewich, A. 1997. Letters to the Editor: Metal transfer modes made correct. *Welding Journal* 76(7): 21, 22.

8. Lancaster, J. F. 1984. *The Physics of Welding*. Pergamon Press, Oxford, UK.

9. Zhang, Y. M., and Liguo, E. 1999. Method and system for gas metal arc welding. U.S. Patent, #6,008,470.

10. Zhang, Y. M., Liguo, E., and Kovacevic, R. 1998. Active metal transfer control by monitoring excited droplet oscillation. *Welding Journal* 77(9): 388-s to 395-s.

11. Zhang, Y. M., and Li, P. J. 2001. Modified active control of metal transfer and pulsed GMAW of titanium. *Welding Journal* 80(2): 54-s to 61-s.

12. Lin, Q., Li, X. S., and Simpson, W. 2001. Metal transfer measurements in gas metal arc welding. *J. Phys. D: Appl. Phys.* 34: 347–353.

13. Ponomarev, V., Scotti, A., Silvinskiy, A., and Al-Erhayem, O. 2003. Atlas of MIG/MAG welding metal transfer modes. IIW Doc. XII-1771 to 1775-03. Bucharest.

14. Iordachescua, D., and Quintinob, L. 2008. Steps toward a new classification of metal transfer in gas metal arc welding. *Journal of Materials Processing Technology* 202: 391–397.

Statement of Ownership, Management and Circulation for U.S. Postal Service (Required by U.S.C. 3685)

1. TITLE OF PUBLICATION: Welding Journal — 2. PUBLICATION NO.: ISSN 0043-2296
3 DATE OF FILING: September 23, 2009 — 4. FREQUENCY OF ISSUE: Monthly
5. NO. OF ISSUES PUBLISHED ANNUALLY: 12 — 6. ANNUAL SUBSCRIPTION: $120.00
7. MAILING ADDRESS OF KNOWN OFFICE OF PUBLICATION: 550 N.W. LeJeune Rd., Miami, Dade County, Florida 33126
8. MAILING ADDRESS OF THE HEADQUARTERS OR GENERAL BUSINESS OFFICES OF THE PUBLISHERS:
550 NW LeJeune Rd., Miami, Dade County, Florida 33126
9. NAMES AND COMPLETE ADDRESS OF PUBLISHER, EDITOR AND MANAGING EDITOR:
PUBLISHER: Andrew Cullison, AWS, 550 NW LeJeune Rd., Miami, Florida 33126
EDITOR: Andrew Cullison, AWS, 550 NW LeJeune Rd., Miami, Florida 33126
EDITOR: Mary Ruth Johnsen
10. OWNER: NAME: American Welding Society,Inc. ADDRESS: 550 NW LeJeune Rd., Miami, Florida 33126
11. KNOWN BONDHOLDERS, MORTGAGEES, AND OTHER SECURITY HOLDERS OWNING OR HOLDING 1 PERCENT OR MORE OF TOTAL AMOUNT OF BONDS, MORTGAGES OR OTHER SECURITIES: None
12. The purpose, function, and nonprofit status of this organization and the exempt status for Federal income tax purposes: Has not changed during preceding 12 months
13. Publication Title: Welding Journal — 14. Issue date for Circulation Data Below: October 2009
15. EXTENT AND NATURE OF CIRCULATION:

	Average No. Copies Each Issue During Preceding 12 Months	Actual No.Copies of Single Issue Published Nearest to Filing Date
A. Total No. Copies Printed (Net Press Run)	55,088	52,400
B. Paid and/or Requested Circulation		
1. Paid / Requested Outside-County Mail Subscriptions Stated on Form 3541	52,928	50,451
2. Paid In-County Subscriptions Stated on Form 3541	None	None
3. Sales Through Dealers and Carriers, Street Vendor, Counter Sales, and other Non-USPS Paid Distribution	None	None
4. Other Classes Mailed Through the USPS	None	None
C. Total Paid / Requested Circulation	52,928	50,451
D. Free Distribution by Mail (Samples, complimentary and other free)		
1. Outside-County as State on Form 3541	454	449
2. In-County as Stated on Form 3541	None	None
3. Other Classes Mailed Through the USPS	None	None
4. Free Distribution Outside the Mail (Carriers or other means)	None	None
E. Total Free Distribution	454	449
F. Total Distribution	53,382	50,900
G. Copies not Distributed	1,706	1,500
H. Total	55,088	52,400
I. Percent Paid and / or Requested Circulation	99.1%	99.1%

16. Statement of Ownership will be printed in the November 2009 issue of this publication.
I certify that the statements made by above are correct and complete:
Andrew Cullison, Publisher