Interactive Phenomena in Hybrid KPAW–GMAW–P

The interaction of the arc, droplet, keyhole, and weld pool improves weld pool convection in a hybrid KPAW–GMAW–P technique

BY D. WU, S. TASHIRO, Z. WU, K. NOMURA, X. HUA, AND M. TANAKA

ABSTRACT

A hybrid welding technique formed by combining keyhole plasma arc welding (KPAW) and pulsed gas metal arc welding (GMAW–P) is characterized by the complex interactions of the arc, droplet, keyhole, and weld pool. With the help of a high-speed video camera, zirconia particles, and a thermal camera, the complex interactive phenomena of the hybrid KPAW–GMAW–P process was analyzed. Owing to the formation of a direct-current path between the KPAW cathode (tungsten electrode) and the GMAW anode (welding wire), the ionized plasma arc was extended to the GMA side, causing an expansion of the GMA. The current at the GMAW droplet was diverged; thus, the Lorentz force promoted a more stable one pulse one droplet metal transfer mode compared with that of GMAW–P. The strong backward flow from the keyhole was suppressed because of the pull-push flow pattern on the top surface of the weld pool between the two arcs. As the heat and molten metal in the weld pool were transported from the region near the GMA (high temperature) to the region near the plasma arc (low temperature), the weld pool temperature decreased.

KEYWORDS

- Hybrid Welding • Arc Interference
- One Pulse One Drop • Weld Pool Convection
- Pull-Push Flow Pattern

Introduction

To suppress weld defects and improve the weld bead formation of keyhole plasma arc welding (KPAW), the paraxial hybrid KPAW and gas metal arc welding (GMAW) capable of successfully welding 12-mm-thick carbon steel plates in one pass has been proposed by many researchers (Refs. 1, 2). In this welding technique, the plasma torch is located at the leading direction, and the tungsten electrode is the cathode. The GMAW gun is located at the rear direction, and the welding wire is the anode. Therefore, the hybrid KPAW–GMAW technique forms a direct-current path between the KPAW cathode (tungsten electrode) and the

GMAW anode (welding wire) through the plasma arc, and arc interference can be observed. A deeper understanding of the interactive phenomena of the hybrid KPAW–GMAW process can provide guidance to welding engineers in their development of welding procedures to obtain high-quality welds.

Both hybrid gas tungsten arc welding (GTAW) and GMAW and hybrid KPAW–GMAW are characterized by the formation of a direct-current path between the cathode (tungsten electrode) and the GMAW anode (welding wire) (Ref. 3). In the hybrid GTAW–GMAW technique, the cathode spots of the GMA become stable (Ref. 4). The temperature gradients on the top surface at the middle and rear parts of the hybrid weld pool are lower than that in the conventional GMA weld pool, while the heat input is increased (Ref. 5). Owing to the additional heat input and electromagnetic force generated by the GTA, the GMA length increases, and the droplet transfer is easy and stable (Refs. 4, 6). In the hybrid KPAW–GMAW technique, because of the strong impingement of the plasma arc (PA), a large keyhole forms (Ref. 2) that may have a significant influence on the arc and droplet behaviors and weld pool convection. Han et al. (Ref. 7) proposed the electrical conductivity of the GMA increased in the hybrid variable polarity plasma arc (VPPA)–GMAW technique because of the large number of metal ions and electrons provided by the keyhole. Furthermore, the VPPA had a compression effect on the GMA.

Both the hybrid laser-GMAW and hybrid KPAW–GMAW techniques are characterized by complex interactions of the arc, droplet, keyhole, and weld pool. In the hybrid laser-GMAW technique, the metal temperature increases, and intense evaporation occurs because of the irradiation of the laser beam on the base metal surface (Ref. 8). Under the influence of the vaporization-induced recoil pressure, a keyhole with a large depth-to-width ratio is generated (Ref. 9). Shinn et al. (Ref. 10) found a laser can stabilize the arc cathode spots in the hybrid laser-GMAW of a titanium alloy. Zhang et al. (Ref. 11) investigated the plasma and droplet behaviors of a hybrid CO₂ laser-GMAW and proposed the metal vapor jet from the keyhole acted as a resistance force on the droplet and suppressed droplet transfer. Liu et al. (Ref. 12) calculated the forces acting on a droplet in hybrid

Fig. 1 — Welding experiment setup of hybrid KPAW-GMAW-P.

laser-GMAW and found that the laser plasma compressed the arc and increased the electromagnetic resistance force of the droplet; thus, the droplet shape changed and the droplet transfer frequency decreased. Zhao et al. (Ref. 13) measured the fluid flow of the weld pool of a hybrid laser-GMAW by an advanced x-ray transmission imaging system and found that the arc shear stress and droplet momentum promoted an inward flow in the keyhole. However, in hybrid KPAW-GMAW, the molten-metal temperature near the keyhole was very low (Ref. 14), and the metal evaporation of the weld pool was very weak (Ref. 15); therefore, the metal vapor jet from the keyhole may have a minor influence on droplet transfer. Furthermore, the keyhole size is relatively large, and the action areas of the plasma arc pressure and plasma arc shear stress are very large (Ref. 16); thus, the droplet momentum may have a minor influence on the fluid flow near the keyhole. It can be concluded that the interactive phenomena of the arc, droplet, keyhole, and weld pool in hybrid KPAW-GMAW may differ significantly from those of hybrid laser-GMAW.

Pulsed GMAW (GMAW-P), especially the one pulse one drop (OPOD) metal transfer mode, is capable of reducing spatter and stabilizing the GMA (Ref. 17). However, the

welding parameter range for obtaining a stable OPOD mode is very narrow (Refs. 18, 19). In this study, the paraxial hybrid KPAW-GMAW-P technique was used, and a stable OPOD mode was obtained. During welding, the arc, droplet, keyhole, and weld pool behaviors were captured by a high-speed video camera. The measurement of the fluid flow of the weld pool was aided by zirconia particles. The weld pool temperature was measured with a thermal camera. Based on the observation of the complicated interactive phenomena of the arc, droplet, keyhole, and weld pool in hybrid KPAW-GMAW-P, the influences of arc interference and keyhole behaviors on the droplet transfer are discussed, and the convective patterns in the weld pool and their driving forces are revealed. Even though the heat input was much higher, the maximum temperature of the weld pool in hybrid KPAW-GMAW-P was lower than that of GMAW-P; this thermo-physical phenomenon is also explained.

Experiment Procedures

The welding experiment setup is shown in Fig. 1. A transfer-type plasma arc welding torch (100WH, Nippon

Table 1 — Detailed Welding Parameters

KPAW Torch Orifice Diameter	KPAW Electrode Diameter	KPAW Electrode Setback	KPAW Torch and GMAW Gun Distance	GMAW Gun Angle	Welding Wire Diameter	CTWD (KPAW)
4.0 mm	4.8 mm	3 mm	22 mm	70 deg	1.2 mm	5 mm
CTWD (GMAW)	Welding Speed	Plasma Gas Flow Rate (Ar)	KPAW Shielding Gas Flow Rate (Ar)	GMAW Shielding Gas Flow Rate (Ar)	KPAW Current	Wire Feed Rate
15 mm	3 mm/s	2.5 L/min	10 L/min	15 L/min	DC 280 A	5.8 m/min

Fig. 2 — Current waveform, arc, and droplet behaviors of hybrid KPAW-GMAW-P.

Fig. 3 — Current waveform, arc, and droplet behaviors of GMAW-P.

Steel Welding & Engineering Co. Ltd.), a KPAW power source (NW-300ASR, Nippon Steel Welding & Engineering Co. Ltd.), a GMAW power source (DP 350, Daihen Co. Ltd.), and a wire feeder (CM-7401, Daihen Co. Ltd.) were used as the welding equipment. Carbon steel plates with a thickness of 12 mm (SS400) were used as the base metal. A constant current was adopted for KPAW, and the pulsed mode was adopted for GMAW. Detailed welding parameters are listed in Table 1.

During welding, the current waveform of GMAW was measured by a clamp meter, and the measurement was sent to a datalogger at a frequency of 1 MHz. The arc and droplet behaviors were observed by the high-speed video camera, and the frame rate was 2000 frames/s. To measure the fluid flow of the weld pool before welding, the zirconia particles were placed into prefabricated holes in the base metal. During welding, the movement of the zirconia par-

ticles on the surface of the top weld pool was measured by the high-speed video camera with a frame rate of 2000 frames/s. A thermal camera (Miro Ex4 Phantom, Vision Research Inc.), including three color sensors composed of red (R), green (G), and blue (B) was adopted to obtain the weld pool surface images immediately after switching off the arcs. The weld pool temperatures can be calculated from the ratio of the R to the G sensor signal in the images based on the two-color pyrometry method. The arcs completely disappeared within 1.0 ms after switching off the arcs; therefore, the surface temperature decrease can be ignored (Ref. 20). Detailed descriptions of the observation and measurement methods can be found in our previous work (Ref. 14). For the GMAW-P and hybrid KPAW-GMAW-P, the temperatures of the weld pools were obtained after the droplet transfer in the base current stage.

Fig. 4 — Short-circuit transfer mode of GMAW-P.

Fig. 5 — Comparison of arcs of hybrid KPAW-GMAW-P and GMAW-P.

Fig. 6 — Comparison of droplet behaviors of hybrid KPAW-GMAW-P and GMAW-P.

Results

Arc and Droplet Behaviors in the Hybrid Technique

The current waveform, arc, and droplet behaviors of hybrid KPAW-GMAW-P are shown in Fig. 2. In the peak current stage, both the PA and GMA were very bright. The two arcs connected, and a direct-current path formed between the KPAW cathode (tungsten electrode) and the GMAW anode (welding wire) through the plasma arc as shown in Fig. 2A. In the decreasing current stage, the two arcs separated, and the arc interference became weak as shown in Fig. 2B. As shown in Fig. 2C, at the end of the decreasing current stage, the GMA was still bright near the wire axis but very weak and far from the axis. In the base current stage shown in Fig. 2D, the GMA was slightly weak, and a globular droplet detached from the tip of the welding wire. In Fig. 2E, the droplet almost reached the top surface of the weld pool. The average current of hybrid KPAW-GMAW-P was 170.1 A. In summary, the stable OPOD mode was obtained by the hybrid KPAW-GMAW-P technique. The arc interference was strong only during the peak current stage.

The current waveform, arc, and droplet behaviors of GMAW-P are shown in Figs. 3 and 4. Two droplet transfer

modes were observed: globular and short-circuit transfer mode.

As shown in Fig. 3, during the peak current stage, the GMA was very bright, and during the decreasing current stage, the arc length and width decreased. During the base current stage, a globular droplet was transferred. The average current of the GMAW-P was 157 A.

As shown in Fig. 4, the GMA length was short. When a globular droplet was almost detached from the tip of the welding wire, it contacted the weld-pool and extinguished GMA.

Here, the wire extension length (L_1) and arc length (L_2) are presented based on statistics of several pulse periods. As shown in Fig. 5, the wire extension lengths of the hybrid KPAW-GMAW-P and GMAW-P (globular transfer mode) were 5.4 and 7.1 mm, respectively. The arc lengths of the hybrid KPAW-GMAW-P and GMAW-P (globular transfer mode) were 7.1 and 6.4 mm, respectively. In summary, the wire extension length of the hybrid KPAW-GMAW-P technique was shorter, while the average arc length was larger.

The droplet diameter, velocity, and transfer frequency are shown in Fig. 6 based on the statistics of several pulse periods. The droplet diameters (D) of hybrid KPAW-GMAW-P and GMAW-P (globular transfer mode) were 1.14 and 1.22 mm, respectively. The droplet velocities (V) of hybrid

Fig. 7 — Convective patterns on the top surface near the PA.

KPAW–GMAW-P and GMAW-P (globular transfer mode) were 1.16 and 0.69 m/s, respectively. The transfer frequencies (f) of hybrid KPAW–GMAW-P and GMAW-P (globular transfer mode) were 119 and 107 Hz, respectively. In summary, the droplet velocity and transfer frequency of the hybrid KPAW–GMAW-P technique increased, while the droplet diameter decreased.

Convective Patterns of Hybrid KPAW–GMAW-P

As shown in Fig. 7A, in the base current stage, a particle cluster existed on the top surface of the weld pool near the PA, and the distance from the PA center was 7.28 mm. In the peak current stage shown in Fig. 7B, the two arcs connected. As shown in Fig. 7C, in the decreasing current stage, the particle cluster flowed away from the PA, and the distance from the PA center was 7.93 mm. With time, as shown in Fig. 7D–F, the distance between the particle cluster and the PA center increased. In summary, the molten metal on the top surface of the weld pool near the plasma arc flowed backwards in hybrid KPAW–GMAW-P.

As shown in Fig. 8A, in the base current stage, a particle cluster existed on the top surface of the weld pool before the GMA, and the distance from the welding wire center was 5.38 mm. After the peak current stage (Fig. 8B), the particle cluster flowed forward, and the distance from the

welding wire center was 7.20 mm — Fig. 8C. In the base current stage shown in Fig. 8D, the particle cluster flowed backwards, and the distance from the welding wire center decreased. After the next two periods, the particle cluster flowed forward as shown in Fig. 8E–I, and the particle cluster finally stopped at the weld-pool side.

As shown in Fig. 9A, in the decreasing current stage, three particles existed on the top surface of the weld pool after the GMA. In the base current stage, the distance between the particles and the welding wire center increased as shown in Fig. 9B. In the next period, the particles flowed backwards as shown in Fig. 9C and D, and then reached the rear part of the weld pool. In conclusion, the molten metal after GMA flowed backwards in hybrid KPAW–GMAW-P.

The convective patterns on the top surface of the GMAW-P weld pool were similar to those shown in Fig. 9 (Ref. 21), and the convective patterns on the top surface of the KPAW weld pool were similar to those in Fig. 7 (Ref. 22).

Temperature Distribution and Weld-Bead Formation of Hybrid KPAW–GMAW-P

As shown in Fig. 10, in hybrid KPAW–GMAW-P, a high-temperature region existed near the GMA, and the maximum temperature was 2489 K. In the GMAW-P, the maxi-

Table 2 — Comparisons of Arc, Droplet, and Keyhole Behaviors between Hybrid Laser-GMAW-P and Hybrid KPAW–GMAW-P

	Keyhole Temperature	Metal Vapor	Metal Vapor Jet Force Effect	Arc Behavior	GMAW Current Density	Lorentz Force Effect
Hybrid laser-GMAW-P	High	Strong	Suppresses droplet transfer	Arc contraction	Converged	Suppresses droplet transfer
Hybrid KPAW-GMAW-P	Low	Weak	Minor influence	Arc expansion	Diverged	Promotes droplet transfer

Fig. 8 — Convective patterns on the top surface of the weld pool before the GMA.

imum temperature near the GMA was 2584 K, and high-temperature regions existed at the rear part of the weld pool. As shown in Fig. 10, even though the welding current of KPAW was very high, the maximum temperature of the weld pool was only 2259 K, which is much smaller than that of hybrid KPAW-GMAW-P and GMAW-P.

As shown in Fig. 11A, in hybrid KPAW-GMAW-P, a sound weld bead formation was obtained. In GMAW-P, the weld width was narrow and the reinforcement was high. In KPAW, an undercut formed at the weld toe.

Discussion

Influence of Arc Interference and Keyhole Behavior on Droplet Transfer

Even though both hybrid laser-GMAW-P and hybrid KPAW-GMAW-P are characterized by the complex interaction of the arc, droplet, keyhole, and weld pool, the influence of arc interference and the keyhole behavior on the droplet transfer of these two welding techniques were totally different. In hybrid laser-GMAW-P, the maximum weld pool temperature on the keyhole wall was higher than the boiling temperature of the material, and a large amount of metal vapor was produced. As shown in Fig. 12A, the metal vapor ejected from the keyhole produced a resistance force on the droplet (Ref. 11). Moreover, the current at the droplet converged because of the arc contraction caused by the strong laser plasma. Based on Equation 1 (Ref. 23), the electromagnetic resistance force of the droplet transfer increased (Ref. 12). All of these events contributed to the suppression of the droplet transfer in hybrid laser-GMAW-P.

$$F_{emz} = -\frac{\mu_0 I^2}{4\pi} \left[\frac{1}{4} - \ln \left(\frac{r_d \sin \theta}{r_w} \right) + \frac{1}{1 - \cos \theta} - \frac{2}{(1 - \cos \theta)^2} \ln \left(\frac{2}{1 + \cos \theta} \right) \right] \quad (1)$$

where I is the welding current, r_d is the droplet radius, r_w is the wire radius, θ is the arc hanging angle, and μ_0 is the permeability of free space.

Detailed comparisons of the arc, droplet, and keyhole behaviors between hybrid laser-GMAW-P and hybrid KPAW-GMAW-P are provided in Table 2. In hybrid KPAW-GMAW-P, the maximum weld pool temperature was only 2259 K, which is much lower than the boiling temperature of the material (2900 K); therefore, the metal vapor ejected from the keyhole can be ignored, and the metal vapor jet force had a minor influence on the droplet transfer. The ionized PA was extended to the GMA side because of the formation of a direct-current path between the KPAW cathode (tungsten electrode) and the GMAW anode (welding wire). Based on the minimum voltage principle, an arc has an automatic dropping tendency to drive the electric field intensity E to a minimum value (Ref. 24). As the GMA is heated by the PA, it automatically expands, and the cross-sectional area of the GMA increases. Therefore, the current density decreases, and the electric field intensity E is reduced to a minimum. As shown in Fig. 12B, the current at the GMAW droplet was diverged, and the Lorentz force acted as a detachment force; therefore, the droplet velocity and droplet transfer frequency increased, and the droplet diameter of hybrid KPAW-GMAW-P decreased.

Fig. 9 — Convective patterns on the top surface of the weld pool after the GMA.

more than that of GMAW-P. As a result, the wire extension length was shorter, the arc length longer, and the arc width wider in hybrid KPAW-GMAW-P compared to that of GMAW-P. In summary, the coupled arcs improved the stability of the OPOD metal transfer mode of hybrid KPAW-GMAW-P.

Interaction of the Arc, Droplet, Keyhole, and Weld Pool

Based on the convective patterns of GMAW-P (Ref. 21) and KPAW (Ref. 22) of previous studies and our experimental results, the convective patterns on the weld pool surface and their driving forces in hybrid KPAW-GMAW-P are shown in Fig. 13. Convective pattern 1 (backward flow) on the top surface of the weld pool near the PA was caused by the Marangoni force and the PA shear stress. Convective pattern 2 (forward flow) on the top surface of the transition region was caused by the Marangoni force and the GMA shear stress. Convective pattern 3 (inward flow) on the top surface of the weld pool near the GMA was caused by the arc pressure, Lorentz force, and droplet impingement force. Convective pattern 4 (backward flow) on the

top surface of the weld pool after the GMA was caused by the Marangoni force and the GMA shear stress.

In the peak current stage shown in Fig. 13A, the GMA shear stress was large, and convective pattern 2 (forward flow) on the top surface of the weld pool was strong, while convective pattern 3 (inward flow) was relatively weak. If a particle P_1 is located in the action area of convective pattern 2, it will flow forward as shown in Fig. 8A-C. In the base-current stage shown in Fig. 13B, the GMA shear stress, arc pressure, and Lorentz force were all very small, and convective pattern 2 became weaker. However, the strong droplet impingement caused a strong inward flow, and convective pattern 3 became stronger. If a particle P_2 is located in the active area of convective pattern 3, it will flow inward as shown in Fig. 8C and D. If a particle P_3 is located in the action area of convective pattern 2, it will also flow forward as shown in Fig. 8H and I.

Here, convective pattern 1 (backward flow) is defined as a “pull” flow, and convective pattern 2 (forward flow) as a “push” flow. This pull-push flow pattern on the top surface of a weld pool between the two arcs of hybrid KPAW-GMAW-P is caused by the Marangoni force and the arc shear stress. This flow pattern was also found in tandem GMAW-P

Fig. 10 — Weld pool temperature distributions of hybrid KPAW-GMAW-P, GMAW-P, and KPAW.

(Ref. 25), which prevented the irregular backward flow of molten metal and facilitated sound weld bead formation. As revealed in a previous study, the strong backward flow is one of the most important factors for undercut formation in GTAW (Ref. 26). Owing to the pull-push flow pattern of hybrid KPAW-GMAW-P, the strong backward flow from the keyhole is suppressed and prevents undercut formation as shown in Fig. 11.

Even though the heat input was much higher, the maximum weld pool temperatures of hybrid KPAW-GMAW-P (2489 K) and KPAW (2259 K) were lower than that of GMAW-P (2584 K). As revealed in our previous studies, the heat convection of KPAW caused by the fluid flow was the dominant mechanism for heat propagation in the weld pool. Owing to the much higher PA pressure and PA shear

Fig. 11 — Weld bead formation: A — Hybrid KPAW-GMAW-P; B — GMAW-P; C — KPAW.

stress, the fluid flow and heat propagation in the weld pool were strong. Heat does not accumulate in a keyhole but is transported to the entire weld pool together with the molten metal, causing a relatively low-temperature distribution near the PA (Refs. 14, 16). As shown in Fig. 14, in hybrid KPAW-GMAW-P, the weld pool temperature was lower in the region near the PA and higher in the region near the GMA. The molten metal in the region near the GMA was transported to the region near the PA because of the pull-push flow pattern on the top surface of the weld pool between the two arcs. As the heat in the weld pool was transported from the high-temperature region to the low-temperature region, the molten metal temperature near the GMA decreased. Moreover, the GMA expanded and the current density decreased because of the forma-

Fig. 14 — A — Convective patterns and energy propagation on the top surface of the weld pool between two arcs; B — main mechanism responsible for low weld pool distribution of hybrid KPAW-GMAW-P.

tion of the direct-current path between the KPAW cathode and the GMAW anode. Therefore, the GMA heat transported to the weld pool decreased. All of these mechanisms contributed to a lower weld pool temperature in hybrid KPAW-GMAW-P compared to that of GMAW-P, and the weld pool convection mechanism was especially important because the arc interference was strong only in the peak current stage.

Usually, multilayer and multipass GMAW with grooves should be adopted to join thick plates, and the welding efficiency is low (Ref. 27). Compared with GMAW, hybrid KPAW-GMAW-P has a higher energy density, deeper weld penetration, and higher welding efficiency. KPAW can be used to join thick plates with only one pass. However, undercut weld defects can easily form with a low welding current and low welding speed (Ref. 22). Compared with KPAW, hybrid KPAW-GMAW has a wider range of process parameters and better weld quality. Hybrid laser-GMAW can join thick plates with high efficiency and quality, but the laser equipment cost is high, and the joint tolerance is relatively low because the laser focus radius is small. Compared with hybrid laser-GMAW, hybrid KPAW-GMAW has lower equipment costs and higher joint tolerance. In summary, hybrid KPAW-GMAW has a promising future in the welding of thick plates.

Conclusion

In this study, the complex interactive phenomena of the arc, droplet, keyhole, and weld pool in a hybrid KPAW-GMAW-P were analyzed with the help of a high-speed video camera, zirconia particles, and a thermal camera. The conclusions are summarized as follows:

1) An ionized PA was extended to the GMA side by the formation of a direct-current path between the KPAW cathode (tungsten electrode) and GMAW anode (welding wire)

in the peak current stage. The wire extension length of hybrid KPAW-GMAW-P was shorter, and the arc length longer than that of GMAW-P.

2) The metal vapor from a keyhole had a minor influence on the droplet transfer, while the Lorentz force promoted the droplet transfer. The hybrid KPAW-GMAW-P process obtained a stable OPOD mode.

3) The pull-push flow pattern on the top surface of a weld pool between two arcs caused by the Marangoni force and arc shear stress suppressed the strong backward flow from the keyhole.

4) The interaction of the arc, droplet, keyhole, and weld pool in hybrid KPAW-GMAW-P promoted the fluid flow and heat transfer in a weld pool and decreased the weld pool temperature.

Acknowledgment

The authors thank the China Scholarship Council for providing a scholarship.

References

- Guo, Y. Y., Pan, H. H., Ren, L. B., and Quan, G. F. 2018. An investigation on plasma-MIG hybrid welding of 5083 aluminum alloy. *The International Journal of Advanced Manufacturing Technology* 98(5-8): 1433–1440. DOI: 10.1007/s00170-018-2206-4
- Nguyen, V. A., Tashiro, S., Hanh, B. V., and Tanaka, M. 2017. Development of plasma-MIG hybrid welding process. *Quarterly Journal of JWS* 35(2): 132–136. DOI: 10.2207/qjws.35.132s
- Kanemaru, S., Sasaki, T., Sato, T., Era, T., and Tanaka, M. 2015. Study for the mechanism of TIG-MIG hybrid welding process. *Welding in the World* 59(2): 261–268. DOI: 10.1007/s40194-014-0205-0
- Kanemaru, S., Sasaki, T., Sato, T., Mishima, H., Tashiro, S., and Tanaka, M. 2014. Study for TIG-MIG hybrid welding process. *Welding in the World* 58(1): 11–18. DOI: 10.1007/s40194-013-0090-y
- Chen, J., Zong, R., Wu, C. S., Padhy, G. K., and Hu, Q. X. 2017. Influence of low current auxiliary TIG arc on high speed TIG-MIG hybrid welding. *Journal of Materials Processing Technology* 243: 131–142. DOI: 10.1016/j.jmatprotec.2016.12.012
- Zong, R., Chen, J., and Wu, C. S. 2019. A comparison of TIG-MIG hybrid welding with conventional MIG welding in the behaviors of arc, droplet and weld pool. *Journal of Materials Processing Technology* 270: 345–355. DOI: 10.1016/j.jmatprotec.2019.03.003
- Han, Y. Q., Tong, J. H., Hong, H. T., and Sun, Z. B. 2018. The influence of hybrid arc coupling mechanism on GMAW arc in VPPA-GMAW hybrid welding of aluminum alloys. *The International Journal of Advanced Manufacturing Technology* 101(1-4): 989–994. DOI: 10.1007/s00170-018-3007-5
- Panwisawas, C., Perumal, B., Ward, R. M., Turner, N., Turner, R. P., Brooks, J. W., and Basoalto, H. C. 2017. Keyhole formation and thermal fluid flow-induced porosity during laser fusion welding in titanium alloys: Experimental and modelling. *Acta Materialia* 126: 251–263. DOI: 10.1016/j.actamat.2016.12.062
- Kawahito, Y., and Wang, H. Z. 2018. In-situ observation of gap filling in laser butt welding. *Scripta Materialia* 154: 73–77. DOI: 10.1016/j.scriptamat.2018.05.033
- Shinn, B. W., Farson, D. F., and Denney, P. E. 2005. Laser stabilization of arc cathode spots in titanium welding. *Science and*

Technology of Welding and Joining 10(4): 475–481. DOI: 10.1179/174329305X46673

11. Zhang, W., Hua, X. M., Liao, W., Li, F., and Wang, M. 2014. Behavior of the plasma characteristic and droplet transfer in CO₂ laser-GMAW-P hybrid welding. *The International Journal of Advanced Manufacturing Technology* 72(5–8): 935–942. DOI: 10.1007/s00170-014-5731-9

12. Liu, S. Y., Zhang, F. L., Dong, S. N., Zhang, H., and Liu, F. D. 2018. Characteristics analysis of droplet transfer in laser-MAG hybrid welding process. *International Journal of Heat and Mass Transfer* 121: 805–811. DOI: 10.1016/j.jheatmasstransfer.2018.01.047

13. Zhao, L., Sugino, T., Arakane, G., and Tsukamoto, S. 2009. Influence of welding parameters on distribution of wire feeding elements in CO₂ laser GMA hybrid welding. *Science and Technology of Welding and Joining* 14(5): 457–467. DOI: 10.1179/136217109X434252

14. Wu, D. S., Nguyen, V. A., Tashiro, S., Hua, X. M., and Tanaka, M. 2019. Elucidation of the weld pool convection and keyhole formation mechanism in the keyhole plasma arc welding. *International Journal of Heat and Mass Transfer* 131: 920–931. DOI: 10.1016/j.jheatmasstransfer.2018.11.108

15. Jian, X. X., and Wu, C. S. 2016. Influence of Fe vapor on weld pool behavior of plasma arc welding. *Acta Metallurgica Sinica* 52(11): 1467–1476. DOI: 10.11900/0412.1961.2016.00008

16. Wu, D. S., Tashiro, S., Hua, X. M., and Tanaka, M. 2019. A novel electrode-arc-weld pool model for studying the keyhole formation in the keyhole plasma arc welding process. *Journal of Physics D: Applied Physics* 52(16): 165203. DOI: 10.1088/1361-6463/aafeb0

17. Wu, C. S., Chen, M. A., and Lu, Y. F. 2005. Effect of current waveforms on metal transfer in pulsed gas metal arc welding. *Measurement Science and Technology* 16(12): 2459. DOI: 10.1088/0957-0233/16/12/009

18. Ueguri, S., Hara, K., and Komura, H. 1985. Study of metal transfer in pulsed GMA welding. *Welding Journal* 64(8): 242-s to 250-s.

19. Ghosh, P. K., Dorn, L., Kulkarni, S., and Hofmann, F. 2009. Arc characteristics and behaviour of metal transfer in pulsed current GMA welding of stainless steel. *Journal of Materials Processing Technology* 209(3): 1262–1274. DOI: 10.1016/j.jmatprotec.2008.03.049

20. Yamazaki, K., Yamamoto, E., Suzuki, K., Koshiishi, F., Tashiro, S., Tanaka, M., and Nakata, K. 2010. Measurement of surface temperature of weld pools by infrared two colour pyrometry.

Science and Technology of Welding and Joining 15(1): 40–47. DOI: 10.1179/136217109X12537145658814

21. Cho, M. H., Lim, Y. C., and Farson, D. F. 2006. Simulation of weld pool dynamics in the stationary pulsed gas metal arc welding process and final weld shape. *Welding Journal* 85(12): 271-s to 283-s.

22. Nguyen, V. A., Wu, D. S., Tashiro, S., Hua, X. M., and Tanaka, M. 2019. Undercut formation mechanism in the keyhole plasma arc welding. *Welding Journal* 98(12): 204-s to 212-s. DOI: 10.29391/2019.98.018

23. Liu, S. Y., Liu, F. D., Zhang, H., and Shi, Y. 2012. Analysis of droplet transfer mode and forming process of weld bead in CO₂ laser-MAG hybrid welding process. *Optics & Laser Technology* 44(4): 1019–1025. DOI: 10.1016/j.optlastec.2011.10.016

24. Lancaster, J. F. 1987. The physics of fusion welding. Part 1: The electric arc in welding. *IEE Proceedings B — Electric Power Applications* 134(5): 233–254. DOI: 10.1049/ip-b.1987.0040

25. Ueyama, T., Ohnawa, T., Tanaka, M., and Nakata, K. 2005. Effects of torch configuration and welding current on weld bead formation in high speed tandem pulsed gas metal arc welding of steel sheets. *Science and Technology of Welding and Joining* 10(6): 750–759. DOI: 10.1179/174329305X68750

26. Meng, X. M., Qin, G. L., and Zou, Z. D. 2016. Investigation of humping defect in high speed gas tungsten arc welding by numerical modelling. *Materials & Design* 94: 69–78. DOI: 10.1016/j.matdes.2016.01.019

27. Jiang, Z., Hua, X. M., Huang, L. J., Wu, D. S., and Li, F. 2017. Effect of multiple thermal cycles on metallurgical and mechanical properties during multi-pass gas metal arc welding of Al 5083 alloy. *The International Journal of Advanced Manufacturing Technology* 93(9–12): 3799–3811. DOI: 10.1007/s00170-017-0771-6

DONGSHENG WU, SHINICHI TASHIRO (tashiro@jwri.osaka-u.ac.jp), ZIANG WU, and MANABU TANAKA are from the Joining and Welding Research Institute, Osaka University, Osaka, Japan. KAZUFUMI NOMURA is from the Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, Osaka, Japan. D. WU and XUEMING HUA are also with Shanghai Key Laboratory of Material Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai, China.

American Welding Society

Authors: Submit Research Papers Online

Peer review of research papers is now managed through an online system using Editorial Manager software. Papers can be submitted into the system directly from the *Welding Journal* page on the AWS website (aws.org) by clicking on “submit papers.” You can also access the new site directly at editorialmanager.com/wj/. Follow the instructions to register or log in. This online system streamlines the review process, and makes it easier to submit papers and track their progress. By publishing in the *Welding Journal*, more than 70,000 members will receive the results of your research.

Additionally, your full paper is posted on the American Welding Society website for FREE access around the globe. There are no page charges, and articles are published in full color. By far, the most people, at the least cost, will recognize your research when you publish in the world-respected *Welding Journal*.