Y. M. Zhang
Mem. ASME

S. B. Zhang

M. Jiang

Welding Research Laboratory,
Center for Robotics and Manufacturing
Systems and
Department of Electrical and
Computer Engineering,
University of Kentucky, Lexington,
KY 40506

Sensing and Control of Double-Sided Arc Welding Process

The welding industry is driven to improve productivity without sacrificing quality. For thick material welding, the current practice is to use backing or multiple passes. The laser welding process, capable of achieving deep narrow penetration, can significantly improve welding productivity for such applications by reducing the number of passes. However, its competitiveness in comparison with traditional arc welding is weakened by its high cost, strict fit-up requirement, and difficulty in welding large structures. In this work, a different method, referred to as double-sided arc welding (DSAW) is developed to improve the arc concentration for arc welding. A sensing and control system is developed to achieve deep narrow penetration under variations in welding conditions. Experiments verified that the pulsed keyhole DSAW system developed is capable of achieving deep narrow penetration on a 1/2 inch thick square butt joint in a single pass. [DOI: 10.1115/1.1467603]

1 Introduction

Deep narrow penetration offers higher productivity, lower heat input, less distortion, and better robustness against variations in manufacturing conditions. Although the laser welding process is characterized by deep narrow penetration [1], its competitiveness in comparison with traditional arc welding is weakened by its high cost, strict fit-up requirement, and difficulty in welding large structures. Hence, arc welding is still the dominant joining method in heavy industry. If the energy density in arc welding can be improved to improve the penetration capability, the potential impact on the welding productivity will be significant.

Figure 1(*a*) shows a plasma arc welding (PAW) system, in which the workpiece and the power supply are electrically connected by the ground cable and the electric arc is established between the workpiece and the torch. A numerical analysis shows [2] that the majority of the current flows through the surface of the workpiece in PAW. As a result, the distribution of the current and the behavior of the arc depend to a significant degree on the geometrical shape of the workpiece surface, which defines an equal potential surface. For the cases of nonpenetrated and penetrated keyholes shown in Figs. 2(*a*) and 3(*a*), the shapes of the keyholes will define the equal potential surface. Because of the minimum voltage principle, the current distribution tends to reach the equal potential surface by the shortest paths. Hence, the shape of the keyhole will affect the distribution of the current flow. As a result, the current flow diverges before reaching the keyhole surface as illustrated in Figs. 2(*b*) and 3(*b*).

To improve arc energy density, the influence of the geometry of the workpiece surface should be eliminated. One way to realize this is to disconnect the workpiece from the power supply and place a second torch to complete the loop as shown in Fig. 1(*b*). As a result, the current flows through the workpiece approximately along the arc axis direction. The electric arc is established between the workpiece and each of the torches. The resultant process is referred to as double-sided arc welding (DSAW) [3]. In this study, both the development of the process and its control are addressed.

2 Arc Density Improvement

The DSAW system in Fig. 1(*b*) uses a PAW torch and a gas tungsten arc welding (GTAW) torch. The PAW torch has a constraining orifice so that electrons emitted from the tungsten electrode flow through the ionized plasma gas and form a highly con-

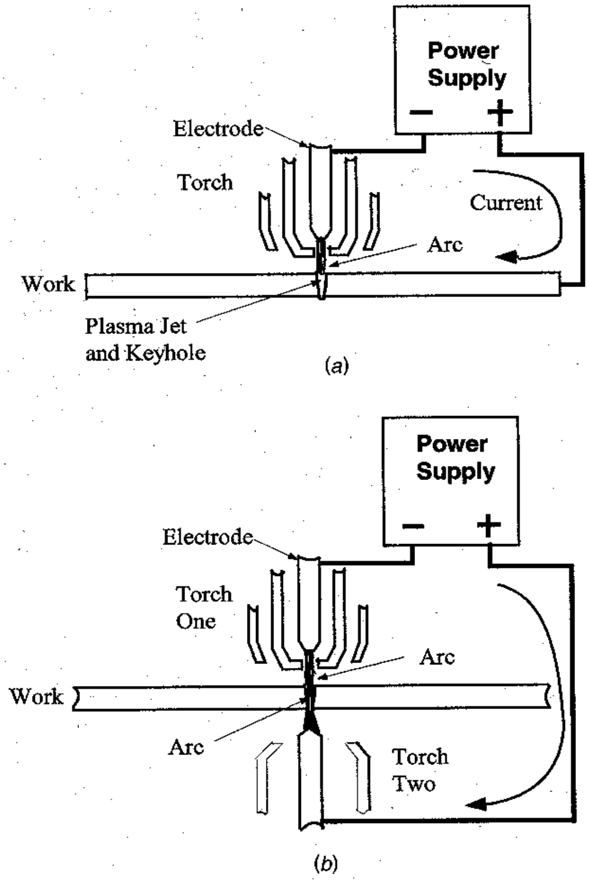


Fig. 1 Schematic diagrams of welding systems: (*a*) regular welding system (*b*) double-sided arc welding system

---

Contributed by the Manufacturing Engineering Division for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received Nov. 2000; Revised Sept. 2001. Associate Editor: S. Jack Hu.

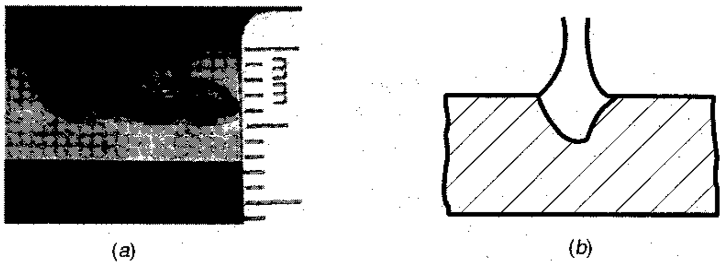


Fig. 2 Nonpenetrated keyhole and arc behavior: (*a*) nonpenetrated keyhole (*b*) arc divergence

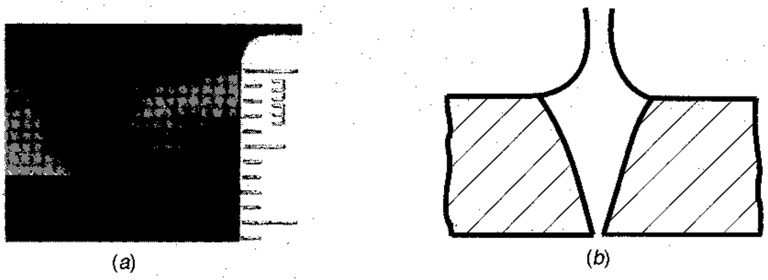


Fig. 3 Penetrated keyhole and arc behavior: (*a*) penetrated keyhole (*b*) arc divergence

strained plasma jet [1]. This plasma jet melts the workpiece and can displace the molten metal to form a nonpenetrated keyhole or penetrated keyhole as shown in Fig. 4. Therefore, the use of a PAW/GTAW torch combination may generate a keyhole, as can be observed in regular PAW, in DSAW.

In the nonpenetrated keyhole mode as shown in Fig. 4(*a*), the current has to flow through the workpiece. (The dashed lines in the figure indicate the outlines of the current.) That is, the electrons emitted from the tungsten electrode of the PAW torch must enter the workpiece from one surface at the (workpiece) anode and then re-emit from another surface of the workpiece at the

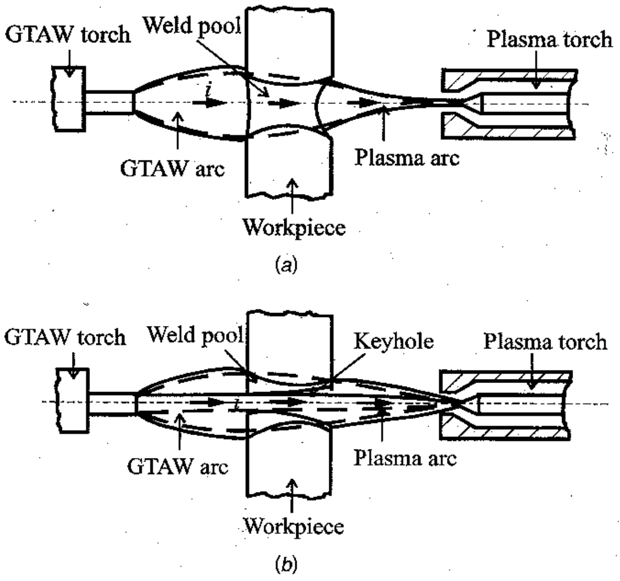


Fig. 4 Nonpenetrated and penetrated keyhole in DSAW: (*a*) nonpenetrated keyhole (*b*) penetrated keyhole

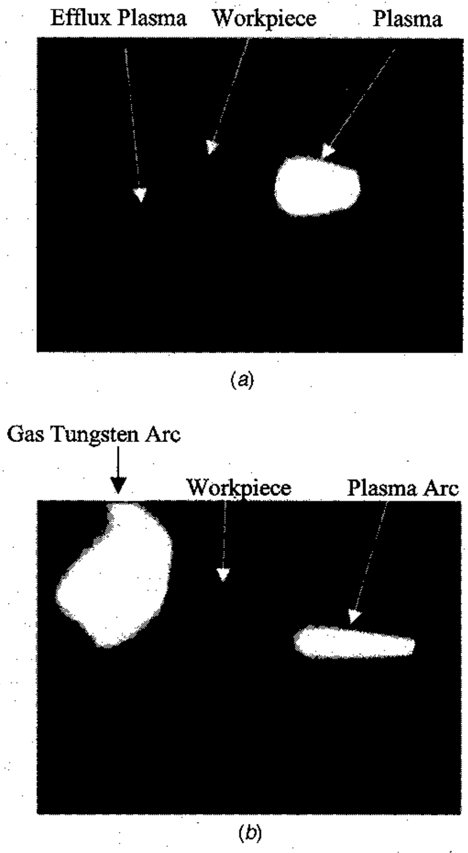
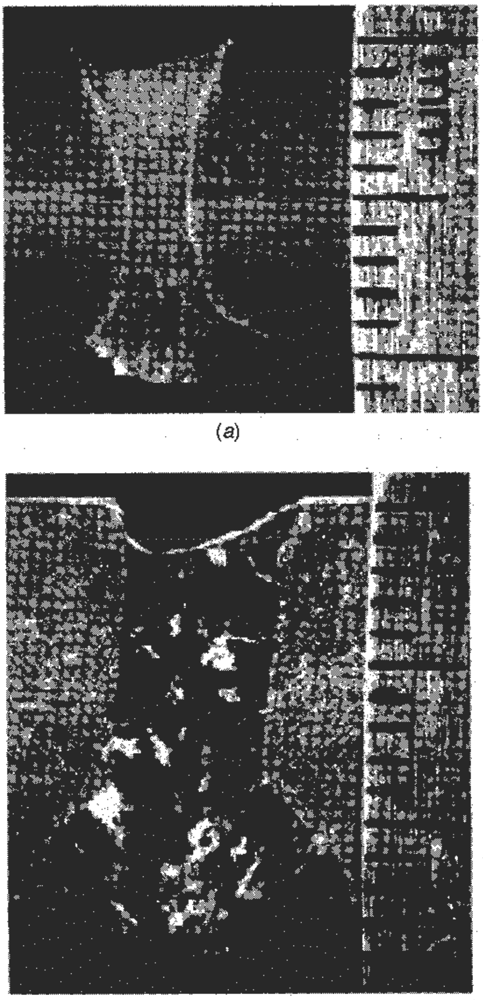


Fig. 5 Arc behaviors during keyhole welding. Welding current: 120 A, diameter of the orifice: 2.4 mm, flow rate of the orifice gas (argon): 1.8 L/min. (*a*) PAW (*b*) DSAW



(a)

(b)

Fig. 6 Welds made using DSAW process. Welding current: 70 A; Flow rate orifice gas (argon): 1.84 L/min; Diameter of orifice: 2.4 mm; Filler metal: none. (*a*) On 10 mm thick stainless steel plate at the flat position; Welding speed: 1.3 mm/s. (*b*) On 12.7 mm thick stainless steel plate at vertical-up position; welding speed: 0.83 mm/s.

(workpiece) cathode in order to travel to the tungsten electrode of the GTAW torch. Because of the good conductivity of the workpiece, the paths of the electrons are primarily determined by the shape of the workpiece cathode which is much larger in diameter than the workpiece anode [4]. Hence, the electrons diverge in the workpiece as schematically illustrated in Fig. 4(*a*), but at a small angle. Such a divergent angle is not sufficient to significantly affect the trajectory of the electrons before they reach the workpiece. Hence, in nonpenetration keyhole mode, the density of the plasma arc in DSAW is much higher than that in regular PAW; however, the density of the gas tungsten arc in DSAW should be similar to that in GTAW.

After the keyhole is established, part of the electrons emitted from the PAW torch's electrode can directly go through the keyhole to reach the GTAW torch's electrode. If all the electrons can go through the keyhole, a continuous arc will be established between the two electrodes with no workpiece anode and cathode. The divergence caused by the workpiece cathode is eliminated. Further, the self-induced inward magnetic force concentrates the electron beam [5]. Hence, the energy density of the arc on both sides of the workpiece is significantly improved. Of course, some of the electrons may go through the workpiece metal as indicated by the outer dashed lines in Fig. 4(*b*). These electrons will re-emit from the bottom surface of the weld pool and then flow to the electrode of the GTAW torch. Hence, the arc on the GTAW torch side consists of two parts, the part determined by the re-emitted electrons with a lower energy density and larger diameter and the part determined by the electrons directly from the keyhole with a higher energy density and smaller diameter. The diameter of the arc on the GTAW torch side is determined by the one with the larger diameter but the penetration capability of the arc is primarily determined by the part with the smaller diameter. Therefore, despite the significant increase in the current and arc energy densities, the arc on the GTAW torch side still looks like a regular gas tungsten arc. For the significant increase in the plasma arc energy density over regular PAW, Fig. 5 gives a clear demonstration where the plasma arc in PAW shown in (*a*) is much broader than that in DSAW shown in (*b*) despite the fact that the current is the same in both cases.

Because of the improvement in the arc energy density, DSAW is capable of penetrating plates up to 1/2 inch thick in a single pass. As can be seen in Fig. 6, 10 mm (3/8 in.) and 12.7 mm (1/2 in.) thick stainless steel plates have been successfully DSAW welded. However, for 12.7 mm (1/2 in.) thick plate, the weld zone is much wider.

3 Controlled Pulse Keyhole

One method which appeared capable of reducing the weld pool size was to use a large welding current and higher travel speed. However, it was found that the high pressure associated with the high current blew the melt metal away from the workpiece. It became difficult to form a continuous weld.

To aid in the development of an effective method to dynamically minimize the weld pool, the pulsed keyhole method has been considered. Assume that the heat input and the plasma pressure are sufficiently large to establish a full penetration keyhole. Then the large plasma pressure will displace the liquid metal so that the plasma arc can directly heat the bottom of the nonpenetrated keyhole and that the radial heat transfer is reduced. Hence, if the welding current is large enough to provide a sufficiently large plasma pressure, which is proportional to the square of the current [6], and heat input, the penetrated keyhole mode may be quickly established at a minimized average width of the weld pool. If the current is then quickly decreased to a low level which cannot provide a sufficient heat input and plasma pressure to maintain a penetrated keyhole, the keyhole will close quickly and the molten pool will shrink as illustrated in Fig. 7. In this way, the weld metal can be prevented from being blown away from the workpiece. Hence, the penetrated keyhole can be periodically established and then closed to maintain the process at a dynamically stable mode which guarantees full penetration with minimized heat input. The resultant operating mode has been termed controlled pulse keyhole.

It can be seen that controlled pulse keyhole could be an effective mode for DSAW of thick materials. Moreover, experiments have shown that it provides the process a unique controllability. This controllability allows the process to be controlled to ensure the full penetration despite process uncertainties. It may also allow a control system to adaptively determine the welding parameters, primarily the duration of the peak current, in different applications with no trials or little trials if the peak current and the base current can be appropriately set such that the peak current can quickly establish the keyhole and the keyhole rapidly closes under the base current. Such controllability and robustness are needed for practical applications.

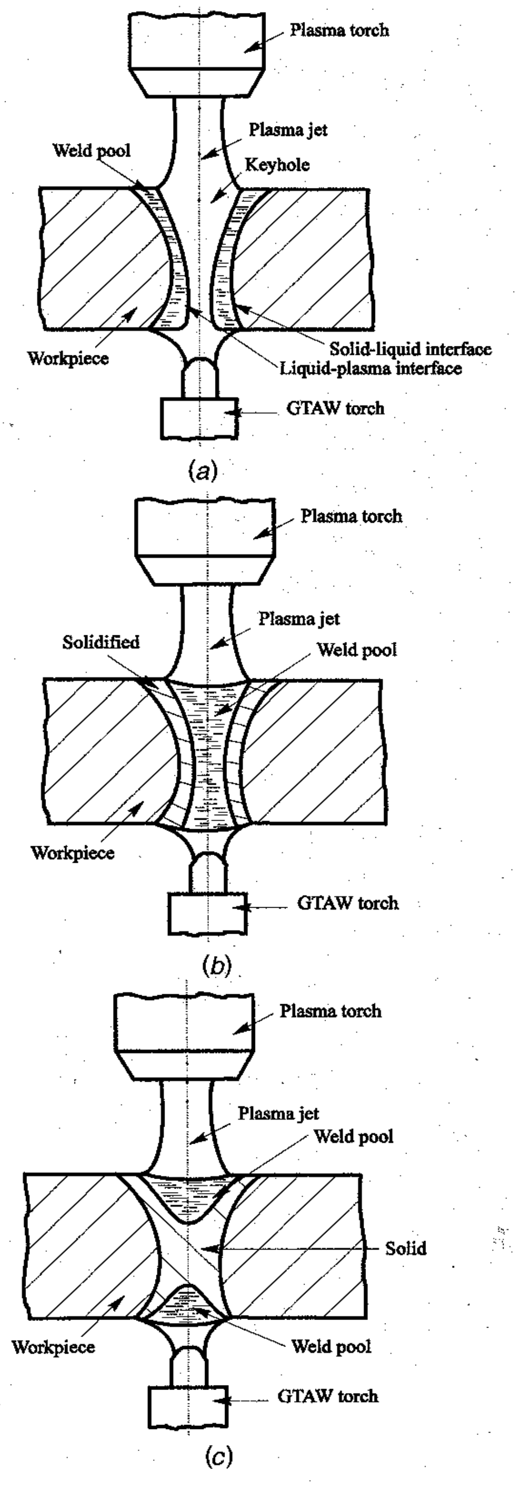


Fig. 7 Weld pool transition after current decrease: (*a*) transient state 1: keyhole (*b*) transient state 2: complete weld pools (*c*) incomplete weld pools

4 Keyhole Detection and Control

It is apparent that successful implementation of controlled pulse keyhole DSAW relies on reliable detection of the penetrated keyhole. After the penetrated keyhole is established, the efflux plasma jet may be observed at the GTAW torch side. Also, as discussed previously and experimentally observed, the establishment of the penetrated keyhole immediately changes the concentration of the plasma arc. Hence, various sensors may be developed to detect the establishment of the penetrated keyhole. However, it is preferred that the sensing and control system can be simple and reliable in the manufacturing environment.

Figure 8 illustrates the proposed sensing and control system. In this system, a controlled current shunt is used. When the system is ready to detect the establishment of the keyhole, the two switches are simultaneously closed. This causes the current to pass completely through switch 1 so that $I_{s1}=I$. The secondary arc on the GTAW torch side thus extinguishes immediately while the primary arc on the PAW torch side remains due to the alternative current path. Then switch 1 is opened. After switch 1 is opened, if the keyhole has been established, the efflux plasma jet provides a current path between the workpiece and the GTAW torch's tungsten electrode such that the secondary arc reignites immediately; as a result, a non-zero current is detected by the current sensor. However, if the keyhole is not present, the secondary arc will not be established and the current will only flow through switch 2 and the resistor; the output of the current sensor is thus zero. If this is the case, the control system immediately commands the high-frequency arc starter to re-ignite the secondary arc; the double-sided arcing process is reestablished. As a result, the controlled pulse keyhole DSAW can be realized by the proposed simple system.

Figure 9 illustrates current waveforms during the controlled keyhole DSAW. In this particular case, the peak current was 90 A and the base current was 50 A. In Fig. 9(*a*), the DSAW current I_{DSAW}, the current through the switches $I_s=I_{s1}+I_{s2}$, and the command signal of the DSAW current are shown. As can be seen in the figure, the DSAW current command is first switched to zero and then switched to the base current after a short period. During this period, the actual DSAW current I_{DSAW} rapidly reduces to zero and I_s, i.e., the current through the switches, quickly increases. In the case shown in Fig. 9(*a*), the keyhole was present. Hence, an efflux plasma existed between the workpiece and the electrode of the GTAW torch. As a result, after the command current is switched back to the non-zero base current level, the actual DSAW current I_{DSAW} quickly reaches to the command current. In Fig. 9(*b*), a typical waveform of the actual DSAW current is shown. In this particular case, the duty cycle of the actual DSAW current is approximately 25 percent and the pulse frequency is approximately 5 Hz.

It should be pointed out that the most important characteristics of the proposed keyhole detection method are the reliability and simplicity. Except for the current sensor, installed in most commercial power supplies, no additional sensors are required. Furthermore, a mechanism is introduced to adjust the heat input balance on the two sides of the workpiece to further minimize thermal distortion. As can be seen in Fig. 6(*b*), because of the high penetration capability, the plasma arc side of the workpiece typically has narrower weld width. For the proposed keyhole detection method, the plasma arc remains unchanged during detection. This provides a mechanism to increase the heat input on the plasma arc side of the workpiece. The heat input balance thus becomes adjustable to control thermal distortion. If further heat input balance adjustment is needed, switch 2 can be opened with a delay after the keyhole is detected.

5 Experiments and Results

An experimental setup as shown in Fig. 8 was developed to implement the proposed control for the pulsed keyhole DASW process. A DC welding power supply was used to provide the welding current. Primary tests were done on stainless steel plates and additional tests on carbon steel plates were added to verify the robustness of the developed control system. Argon was used as shielding gas for both torches as well as the plasma gas. The

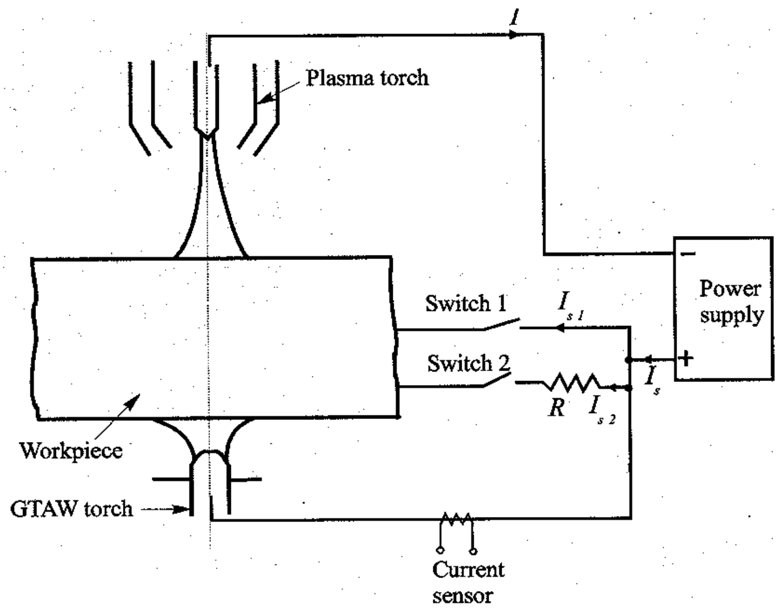
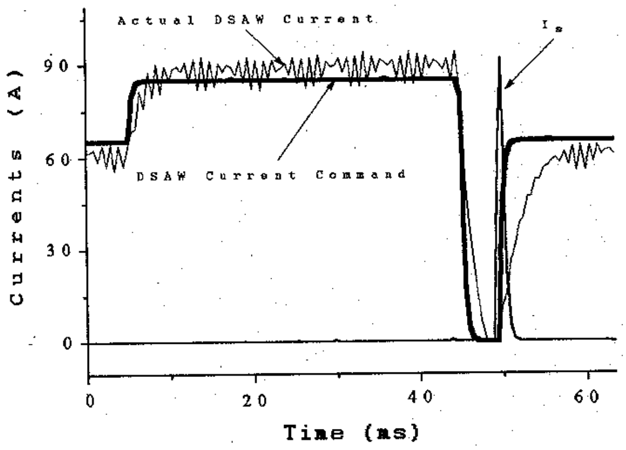
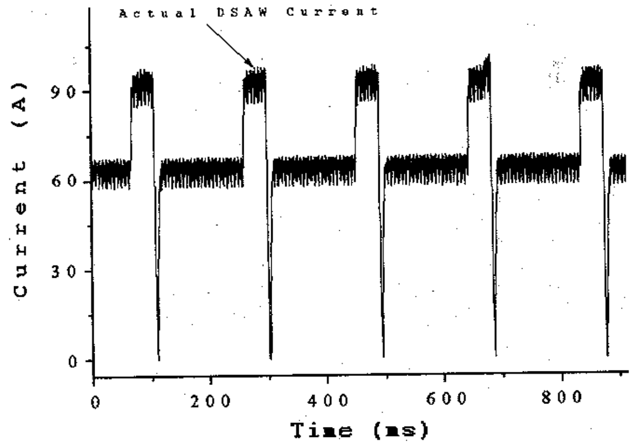


Fig. 8 Proposed sensing and control system



(a) Waveform of currents



(b) Waveform of DSAW current

Fig. 9 Illustration of current waveforms during controlled pulse keyhole DSAW: (a) waveform of currents (b) waveform of DSAW current

thickness of the materials included 10 mm (3/8 in.) and 12.7 mm (1/2 in.). Two current levels—peak and base current—were used. Wshielding gas for both torches as well as the plasma gas. The shielding gas for both torches as well as the plasma gas. The hile the duration of the base current was fixed at an experimentally determined value (150 ms), the duration of the peak current was automatically determined by the control system to control the pulsed keyhole mode. Table 1 lists the welding parameters used.

Figure 10 shows two bead-on-plate welds on 10 mm (3/8 in.) thick stainless steel (type 304) made in the flat position and the vertical-down position, respectively. If a 10 KW laser beam is used, the weld width is approximately 2 mm [7]. As can be seen in the figure, deep narrow penetration has also been achieved by the controlled pulse keyhole DSAW for both positions. The width of the weld zone in the middle portion along the thickness direction is approximately 3 mm.

Table 1 Welding parameters

Welding Parameter	Value
Orifice diameter	2.4 mm
Electrode diameter: PAW	4.8 mm (3/16 inch)
Electrode diameter: GTAW	6.4 mm (1/4 inch)
Plasma gas	1.84 L/min (4 ft^3/h)
Shielding gas: PAW	13.8 L/min (30 ft^3/h)
Shielding gas: GTAW	23 L/min (50 ft^3/h)
Stand-off (PAW electrode)	6 mm (0.24 inch)
Stand-off (GTAW electrode)	10 mm (0.38 inch)
Peak current	120 A
Base current	60 A
Duration of peak current	Adaptive
Duration of base current	150 ms
Welding Speed	100 mm/min
Welding voltage	Approx. 45 V

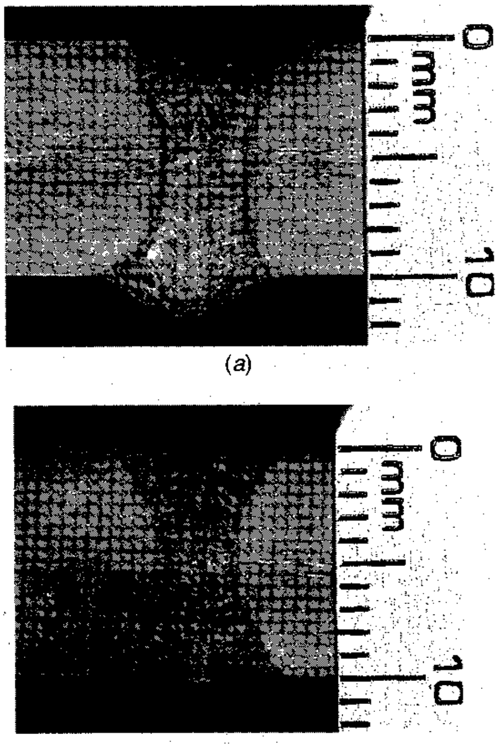


Fig. 10 Bead-on-plates welds made using controlled pulse keyhole DSAW process: thickness: 10 mm, material: stainless steel (type 304); filler metal: none. (*a*) flat position (*b*) vertical-down position

Figure 11 shows a butt weld made on a square butt joint on 13 mm (1/2 in.) stainless steel (type 304) plates at the vertical-down position. The root opening was 1 mm. As can be observed, the width of the weld zone in the middle portion is still approximately 3 mm. Thus, high depth-to-width (DTW) ratio was still achieved.

In the tests described above, adjustment of the duration of the peak current was automatically made by the control system when the thickness and the welding position changed. In addition, the automatic adjustment can also be done when the material change or mismatch occurs. For the weld shown in Fig. 12, the mismatch was approximately 2 mm and the root opening is negligible. The material was DH36 (carbon manganese steel). As can be seen, despite the large mismatch, basic geometrical characteristics of the weld zone remain unchanged as compared to the welds made under different conditions in Figs. 10 and 11.

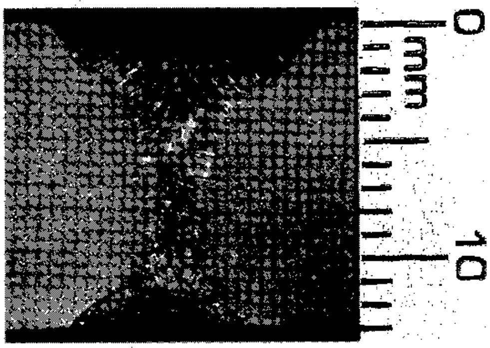


Fig. 11 Butt weld made using controlled pulse keyhole DSAW process: thickness: 13 mm, material: stainless steel (type 304), welding position: vertical-down, filler metal: none

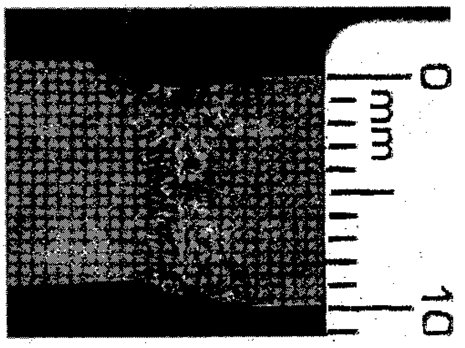


Fig. 12 Butt weld made using controlled pulse keyhole DSAW process: thickness: 10 mm, material: DH36, mismatch: 2 mm, welding position: vertical-down, filler metal: none.

Experimental results shown in Figs. 10–12 demonstrate the strong robustness and adaptiveness of the developed control system with respect to manufacturing condition variations and changes in thickness, welding position, material, and mismatch. In this system, the heat input is automatically adjusted by the duration of the peak to achieve full penetration by switching the peak current to the base current after the keyhole is detected. Further, as has been shown, basic characteristics of the weld, which include the symmetrical geometry, high DTW ratio, and narrow weld zone, remain unchanged despite variations in the welding conditions. Of course, the symmetrical heating, the concentrated arc, the pulsed keyhole mode, and the reliable sensing and control system are responsible for these observed attributes.

It should be pointed out that all the welds were made without filler metal. Hence, underfill can be observed in most of the welds. However, filler metal or a cover pass can be introduced to obtain the required reinforcement.

In addition to laboratory experiments, a shipyard's preliminary assessment, including material properties, has been done for the controlled pulse keyhole DSAW [8]. It was concluded that "The DSAW process can produce full penetration butt welds on various materials up to 1/2″ in thickness. The testing done by University of Kentucky demonstrates that this process has potential use in making butt welds. Further development of this process is warranted." [8] The research team is currently conducting a study on the feasibility of DSAW in ship structure manufacturing with shipyard industry.

6 Conclusions

- The DSAW system described in this paper provides a method to improve the arc energy density.
- The controlled pulse keyhole DSAW process is capable of achieving deep narrow penetration in a single pass on a square butt joint up to 1/2 in. thick.
- The controlled pulse keyhole DSAW process is robust with respect to various variations in the welding conditions including thickness, root-opening, mismatch, and material.
- The principle and design simplicity of the sensing and control system plays an important role in determining the system's reliability.
- Experiments verified the effectiveness of the controlled pulse keyhole DSAW process and the developed sensing and control system.

Acknowledgment

This work is funded by the National Science Foundation under Grant DMI-9812981 and the Center for Robotics and Manufacturing Systems at the University of Kentucky. The authors would like to also thank Electric Boat Corporation, Lincoln Electric Company, Thermal Arc, Inc., and NASA Marshall Space Flight Center for financial, equipment, and material support.

References

[1] *Welding Handbook*, 8th edition, Vol. 2, Welding Processes, AWS.
[2] Dowden, J., and Kapadia, P., 1994, "Plasma Arc Welding: A Mathematical Model of the Arc," J. Phys. D, **27**, pp. 902–910.
[3] Zhang, Y. M., and Zhang, S. B., 1999. "Method of Arc Welding using Dual Serial Opposed Torches," U. S. Patent, No. 5,990,446.
[4] Lancaster, J. F., 1986. *The Physics of Welding*, Pergamon Press, Oxford, New York.
[5] Lowke, J. J., 1979, "Simple Theory of Free-burning Arc," J. Phys. D, **12**, pp. 1873–1886.
[6] Rokhlin, S. I., and Guu, A. C., 1993, "A Study of Arc Force, Pool Depression, and Weld Penetration during Gas Tungsten Arc Welding," Weld. J. (Miami), **72**, pp. 381s–390s.
[7] Dawes, Christopher, 1992. *Laser Welding: A Practical Guide*, Abington Publishing, Cambridge, England.
[8] Mayott, W., 2000. "A Shipyard's Preliminary Assessment of the DASW Process," *Proceedings of the How To Competitively Weld The 21st Century Ship Conference*, pp. 279–289, Nov. 8–9, Norfolk, VA, American Welding Society.