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Combination Mechanism of High Speed Leading Path Laser-Arc Combination Welding†

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Abstract

In order to fully understand the causes of high speed welding defects in Leading Path Laser-Arc Combination (LPLAC) welding, the authors observed the welding process with a high speed video camera and a long distance microscope under a variety of conditions using various arc voltage and arc current settings, and also varied the distance between the laser and arc. These experiments revealed how the arc parameters affect the interaction between the laser plasma and the arc, the effects of various arc setting combinations on both the quantity and behavior of the molten metal produced by the arc, and the ways in which the interaction between the laser and molten metal can be affected. In LPLAC welding, the behavior of the molten metal produced by the arc, and the interaction between the laser and arc are both critical factors. As the distance between the laser and arc directly affects their interaction, it must be carefully considered for each welding speed.

KEY WORDS: (Laser-Arc Combination Welding) (High Speed Welding) (Welding Defect) (Laser Welding) (Arc Welding)

1. Introduction

LPLAC welding, as shown in **Fig.1**, is a very effective laser-arc combination welding method which makes it possible to weld at much higher speeds than conventional laser welding systems and to achieve significantly deeper penetration[1]. The LPLAC method is characterized by the following features[2]:

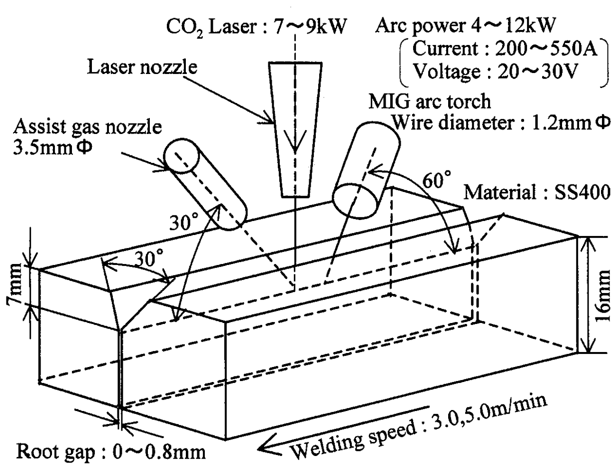

Fig.1 LPLAC welding method.

1. A leading path for the laser beam (**Fig.2**) allows for much deeper penetration than conventional laser welding.
2. The arc electrode supplies molten metal to both the gap and the groove.
3. The arc is stabilized by the laser plasma[3], a feature which is particularly important for high-speed welding in a narrow groove.

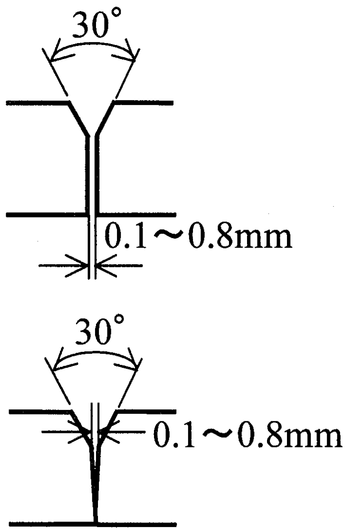

Fig.2 Leading path for laser beam.

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4. The laser plasma leads the electric pole of the arc to a deeper point in the groove in the base metal.

In addition, LPLAC welding offers the following advantages over laser welding:

1. When thick plates are welded by a laser beam, blow holes often occur. LPLAC welding, however, avoids this problem by reheating the metal melted by the laser with the arc. This effectively suppresses the creation of blow holes by the laser[2)].
2. One of the major problems with laser welding is that the deposited metal sometimes has a low impact strength. In LPLAC welding, molten metal is supplied by the wire used for arc welding, making possible improvement of the impact strength of the deposited metal.
3. When materials with a root gap are welded by a conventional laser, underfill is generated. LPLAC systems, however, can weld such workpieces without underfill because molten metal is supplied by the arc.

While the above-mentioned features of LPLAC systems are well documented[1, 2)], little is known about the phenomena which occur during the process of LPLAC welding. Up until now, the authors were able to successfully weld 12mm thick mild steel by LPLAC single pass full penetration welding at a speed 2 m/min[2)]. However, when carrying out welding at higher speeds, defects such as porosity and cracking often resulted. The authors thus decided to closely examine the mechanism of LPLAC welding in order to elucidate the welding phenomena. As a result, the authors were able to achieve high speed welding of 8mm thick mild steel at a speed of 3 m/min and 6 mm thick mild steel at a speed of single path 5 m/min without any defects using a 7kW CO_2 laser and 10kW MIG arc.

2. Experimental Method

The apparatus employed for observing the LPLAC welding process is shown in **Fig. 3**. Helium gas was employed both as the assist gas for the laser and as the shield gas for MIG arc welding. The specimens used were SS400 mild steel plates with a V groove and a narrow gap. A long distance microscope was used to observe the behavior of the molten metal, the laser plasma and the arc plasma. The welding portion was illuminated with a copper vapor laser, and both an ND filter and a band pass filter were used to suppress the intense light-noise from the laser and arc plasma. The occurrence of welding defects was investigated

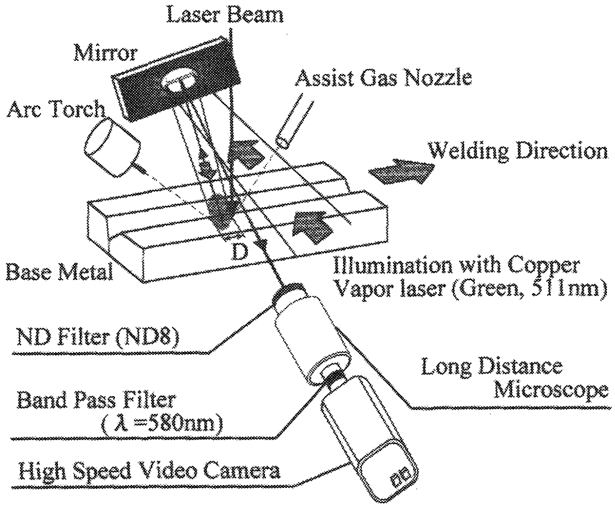

Fig.3 Experimental apparatus.

under various combinations of arc voltage and current in order to identify the arc conditions under which defect-free LPLAC welding can be consistently achieved. The ranges of experiments carried out are shown in Fig.1.

3. Results and Discussion

3.1 Effect on penetration depth of the distance between the laser and arc

Figure 4 shows cross sections of the LPLAC welds obtained with varying distances between the laser and arc. Judging from the shape of the bead cross-sections, as the distance between the laser and the arc increases, the molten metal from the arc does not mix as thoroughly with that produced by the laser. This indicates that the arc's electric pole moves up as the distance increases between the laser and arc. The cause of this change in the arc pole's position is apparently related to the interaction between the arc and laser. In other words, the laser leads the electric pole of the arc into deeper parts of the groove, but if the distance between the two increases, the interaction between the arc and laser weakens, causing the electric pole of the arc to move upward toward the top of the groove. The molten metal from the laser and the molten metal from the arc were found to separate completely when the distance between the two becomes too great.

In LPLAC welding, it is crucial that the two molten pools produced by the arc and laser mix properly. The success of this process is dependent on the interaction between the laser and arc, and that the laser leads the arc's electric pole to a point close to the molten pool produced by the laser. When the interaction between the laser and arc weakens as the

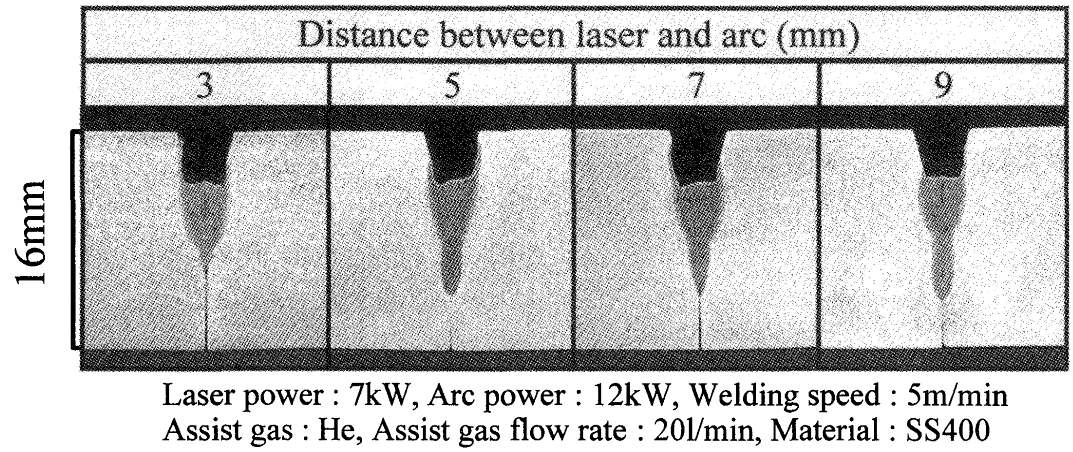

Fig.4 Cross-sections of welds obtained using LPLAC welding with varying distances between the laser and arc.

distance between the two increases, blow holes are more likely to result due to gas in the keyhole and the assist gas mixing with the molten metal.

Increasing the distance between the laser and arc also, however, allows for deeper penetration as shown in **Fig.5**, which describes how penetration depths are affected by changes in the distance between the laser and arc (i.e. the laser's penetration depth becomes deeper as the distance between the laser and arc increases). When the laser-arc distance is short, the molten metal produced by the arc prevents the laser reaching the deeper parts of the root gap, thereby resulting in shallower penetration (**Fig.6**, D=3mm). In addition, the penetration depth almost always corresponds to the depth of the keyhole, but, if large amounts of molten metal produced by the arc are present under the laser beam, the laser beam will be unable to make a deep keyhole. As can be seen from Fig.6, when the distance reaches 9 mm, there is a boundary between the molten pool produced by the

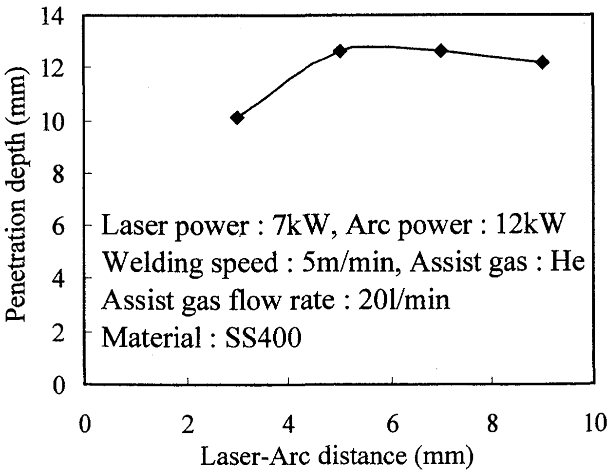

Fig.5 Penetration depth at various distances between the laser and arc.

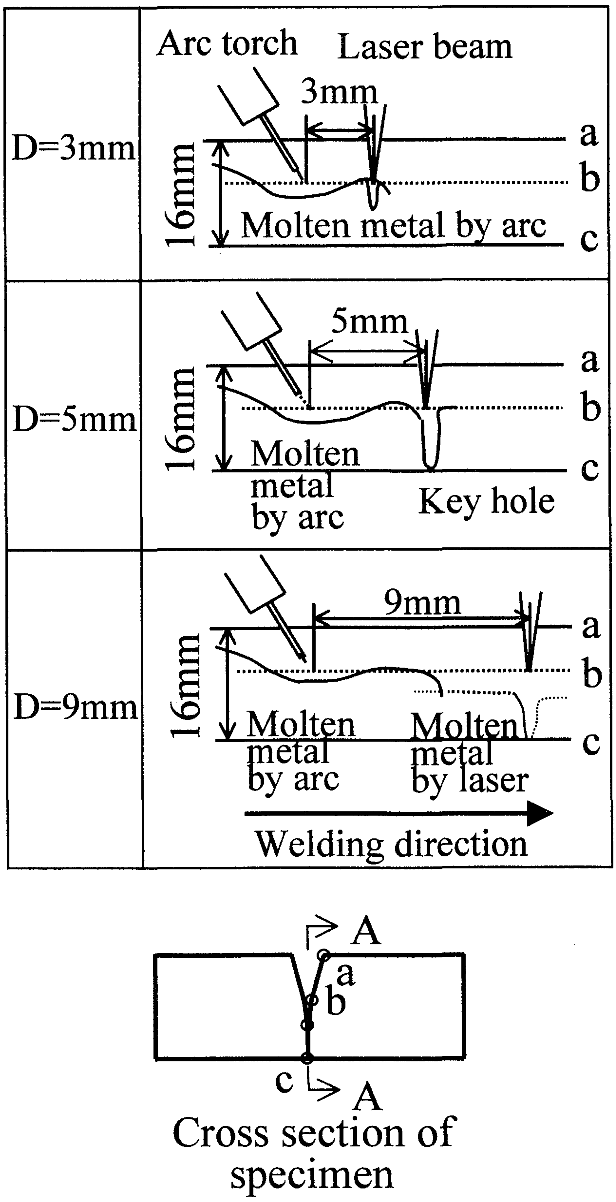

Fig.6 Behavior of molten metal in the groove as influ-enced by changes in distance between the laser and arc.

laser and the molten pool produced by the arc. The creation of this boundary is thought to be due to the distance being too great, as the molten pool produced by the laser starts cooling before it can mix with the molten pool from the arc.

3.2 Effect of arc voltage and current on welding defects

An investigation was also carried out of the conditions under which welding defects occur in high speed LPLAC welding. Various combinations of arc voltage and current were tested in order to identify the circumstances in which such defects can be avoided. **Figure 7** shows the various arc current and voltage combinations which produced either porosity, cracks, or no defects. When porosity and cracks occurred in the same specimen, the result was plotted as a crack rather than as porosity. Figure 7 shows three distinct areas of cracking, porosity, and no defects. These areas correspond to particular arc voltage and current setting combinations. When the arc voltage was too high, porosity occurred. When the current was too high, cracks occurred. These observations were analyzed by investigating the welding process in detail.

Figure 8 shows the arc plasmas at different arc voltages but at a constant arc current of 450A. As the arc voltage became higher, the metal transfer phenomena changed from stream transfer to globular transfer and then to fine spray transfer. **Figure 9** shows the arc plasmas and molten metals at different currents but at a constant arc voltage of 26V. It shows that as the arc current increases, the amount of molten metal produced also increases. It was also observed that higher arc currents appear to produce shallower penetration depths **(Fig.10)**. We believe

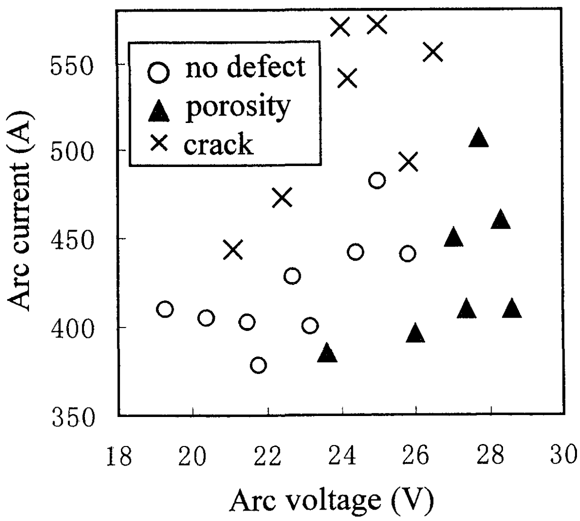

Fig.7 Welding defect dependency on arc settings.

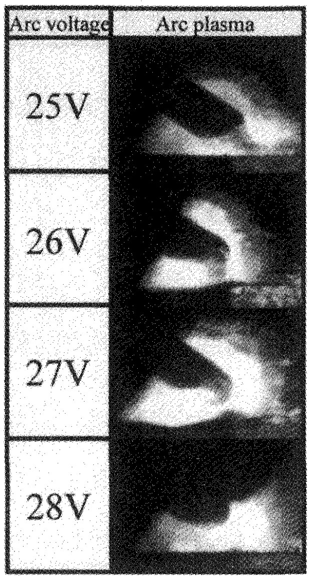

Fig.8 High speed photographs of LPLAC welding at various arc voltages.

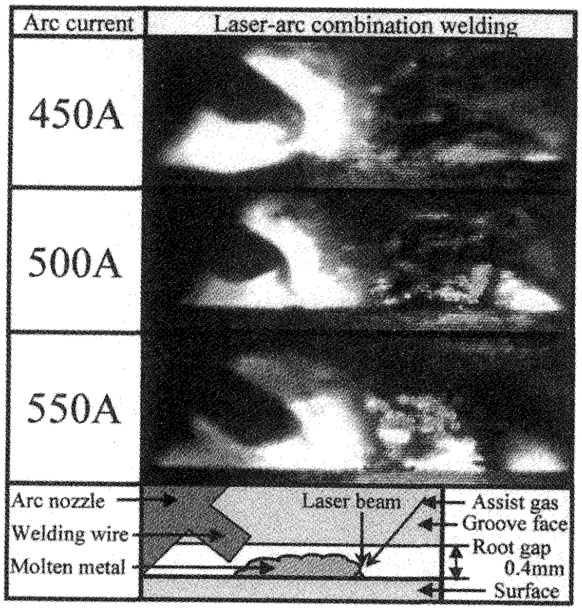

Fig.9 High speed photographs of LPLAC welding at various arc current settings.

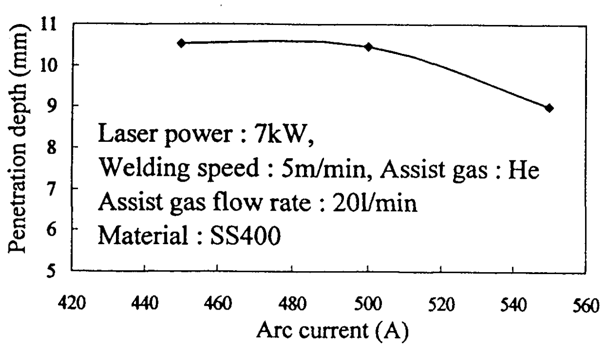

Fig.10 Variation in penetration depth according to arc current.

that laser beam irradiation into deeper parts of the groove, a critical factor for deep penetration, is suppressed by the larger amount of molten metal produced by high arc currents. This in turn causes excess heat input in the upper part of the bead, inducing cracking as shown in **Fig.11**. When the heat input is low, the shape of the bead cross-section is wedge-shaped. But when the heat input is high, the bead's cross-section becomes wider, making cracking more likely. It is therefore important to carefully consider the interaction between the laser and the molten metal, the distance between the laser and the arc, and the arc settings in order to successfully avoid welding defects.

Figure 12 shows photographs of the full penetration welding bead achieved with LPLAC welding of 6 and 8mm mild steel plates. Defect-free welding was achieved at speeds of 3m/min for 6mm plate and 5m/min for 8mm plate— a very fast welding speed for such thick plates compared to conventional 7kW CO_2 laser welding and a clear indication of the LPLAC system's effectiveness and capabilities.

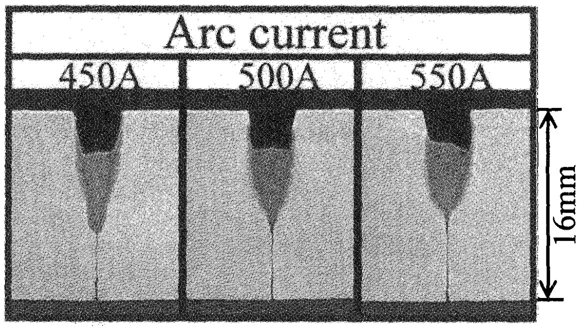

Fig.11 Cross-sections of welds performed using LPLAC welding at different currents and at a constant arc voltage of 26V.

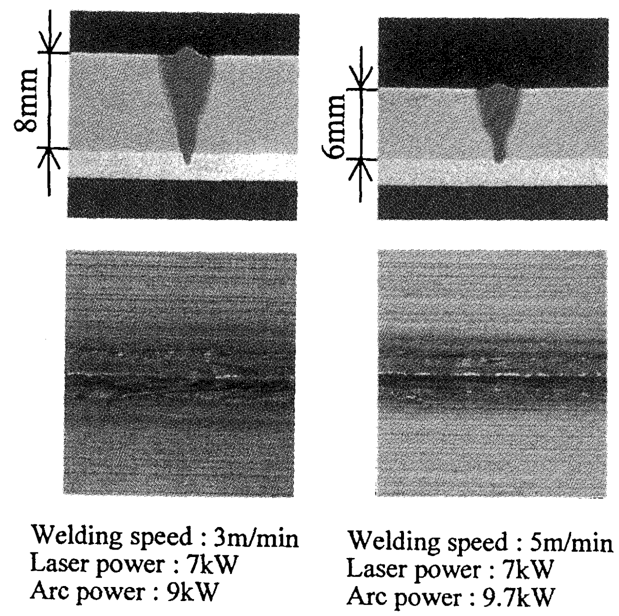

Fig.12 Full penetration LPLAC welding of mild steel plates.

4. Conclusion

The LPLAC system is a very effective welding method well suited to high speed welding of thick plates. By observing the LPLAC welding process in detail with a high speed video camera, the authors were able to elucidate some of the complex processes that occur during deep penetration and high speed welding. The conclusions are as follows:

(1) The penetration depth in LPLAC welding depends not only on the leading path and assist gas used, but also on the depth the laser beam reaches along the leading path. Interference with the laser beam by molten metal produced by the arc also results in shallower penetration by the laser.

(2) It is very important to ensure that the molten metal from the laser and from the arc mix properly, and that gas in the keyhole and the assist gas do not mix with the molten pools. The distance between the laser and arc plays an important role for mixing phenomena, because increasing distance reduces the amount of laser-arc interaction.

(3) The arc settings are an important factor in the avoidance of welding defects. Defects such as cracking and blow holes occur with certain arc voltage and current combinations: a high arc voltage leads to porosity defects, while a high arc current causes cracking.

(4) The authors were able to successfully weld 6 mm steel plates at a welding speed of 5m/min and 8mm steel plates at a welding speed of 3 m/min by single pass full-penetration LPLAC welding with a 7kW CO_2 laser and 10kW MIG arc without welding defects such as blow holes or cracks which can sometimes occur with high speed welding.

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