Welding of Aluminum Alloy with High Power Direct Diode Laser†

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Abstract

Characterized by high conversion efficiency, small size, light weight and a long lifetime, high power diode lasers are currently being developed for application to various types of metal fabrication, such as welding. In this report, a 4kW high power direct diode laser was used to weld aluminum alloys, which are the focus of increasing attention in the automobile industry because of their light weight, high formability and easy recyclability. The applicability of a direct diode laser to aluminum alloy bead-on-plate, lap-fillet and butt welding was studied under various welding conditions. A sound bead without cracks was successfully obtained when 1mm thick aluminum alloy was welded by bead-on-plate welding at a speed of 5m/min. Moreover, the bead cross section was heat conduction welding type rather than the keyhole welding type of the conventional laser welding. Investigation of the welding phenomena with a high-speed video camera showed no spattering or laser plasma, so there was no problem with laser plasma damaging the focusing lens despite the diode laser's short focusing distance.

KEY WORDS: (High power direct diode laser) (Aluminum alloy) (Bead-on-plate welding) (Lap-fillet welding) (Butt welding) (High-speed video camera)

1. Introduction

Diode lasers are widely used as light sources for laser printers, audio systems and optical communication systems because of their many advantages that include high conversion efficiency, small size, light weight, and a long lifetime. Recent advances have boosted both the output power and brightness of diode lasers through improvements in the laser diode itself and stacking technology. This has led to the possibility of applying diode lasers for various types of materials processing including marking, soldering, surface hardening, cladding, and welding of metals.

Aluminum alloys are presently used for such varied applications as packing containers, cooking appliances, structural components, printing plates, and heat exchangers because of their light weight, high conductivity, easy formability and high corrosion resistance. Their light weight and easy recyclability in particular are attracting the attention of the automobile industry from the standpoint of environmental-friendliness as a substitute for steel. A great deal of research has been performed on welding aluminum alloys with high power CO_2 or Nd:YAG lasers, including the seam of the hood[1], the body frame and chassis[2], but there have been few reports on diodelaser welding of aluminum alloys[3]. In this report, the practicability of using a 4kW high power direct diode laser for welding aluminum alloy automotive body sheets was examined.

2. Beam characteristics of a 4kW direct diode laser

A high power direct diode laser with a maximum power of 4kW and a wavelength of 805nm (Nuvonyx Inc. ISL-4000) was used as the heat source. The laser head was 267mm x 186mm x 140mm and weighed 6.8kg. As shown in Fig.1, the specimen was directly irradiated without optical fiber.

The output characteristic was measured with a LabMaster (Coherent). Figure 2 shows the relationship between the diode current and output power. The output power increased proportionally to the input electric current, attaining a maximum output of 4.2kW at a beam current of 65A.

The beam profile was examined using a UFF100 beam profiler (Prometec Inc.). Figure 3 shows the beam size at various work distances from the laser head.

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The beam had a long and thin oval shape. The focal point was 40mm from the laser head. The beam profile at the focal point is shown in Fig.4. The $1/e^2$ beam size was 2mm x 10mm and the mean power density at the focal point was about $20kW/cm^2$, in a range slightly above an arc heat source.

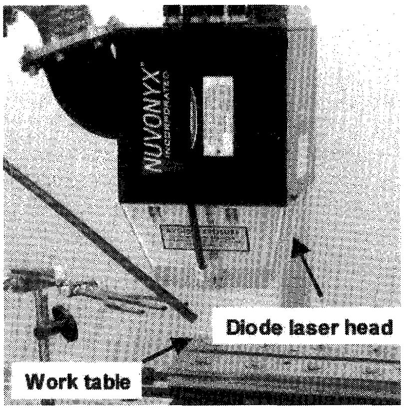


Fig.1 Diode laser head

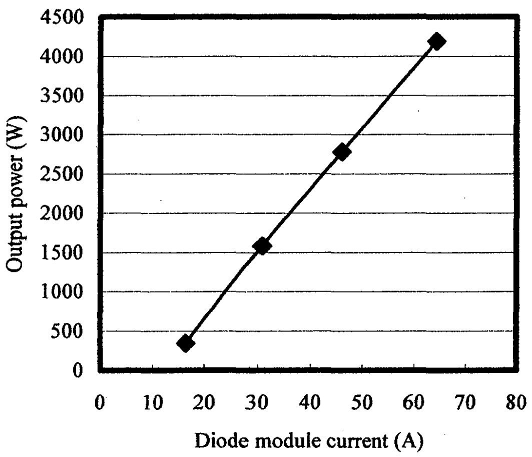


Fig.2 P-I characteristics

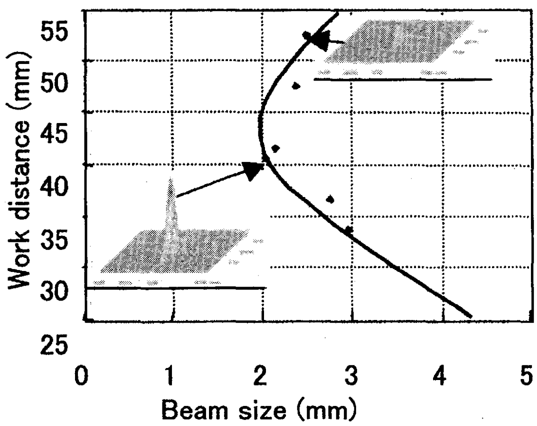


Fig.3 Beam characterristics

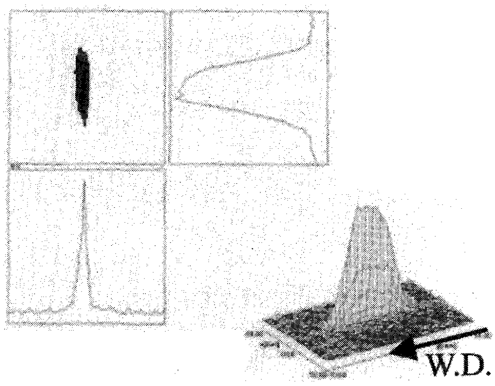


Fig.4 Beam profile at focal position

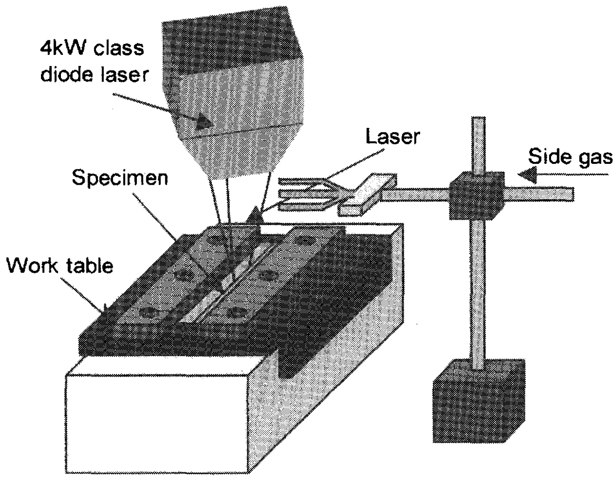


Fig.5 Experimental apparatus

3. Experimental apparatus

A schematic drawing of the experimental apparatus is shown in Fig.5. The following three types of aluminum alloys were used as specimens:

(1) AA5083-O, 8mmt (Al-4.5Mg-Mn)
(2) AA5022-O, 1mmt (Al-4.6Mg-0.35Cu)
(3) AA6016-T4, 1mmt (Al-1Si-0.45Mg)

The aluminum alloy AA5083 is a general purpose Al-Mg series alloy. The 5000 series AA5022 and 6000 series AA6016 aluminum alloys are used for automotive body sheets. Each specimen was fixed to a work table with a welding jig, and was traversed by the long axis of the laser beam. Argon was used as a shield gas, and air was blown from the side to protect the focusing lens from spatter and plume.

4. Results and discussion

4.1 Effect of work distance on weld

The effect of the work distance on the weld bead was examined to evaluate the work distance tolerance. Bead-on welding of AA5083 was performed at a welding speed of 1.2m/min at various work distances. The bead shape was a heat conduction welding type rather than the keyhole welding type characteristic of Nd:YAG and CO_2 laser welding. Figure 6 shows the bead width and bead depth at each working distance. There was no significant change in the bead width or bead depth within a work distance of from 37mm to 42mm.

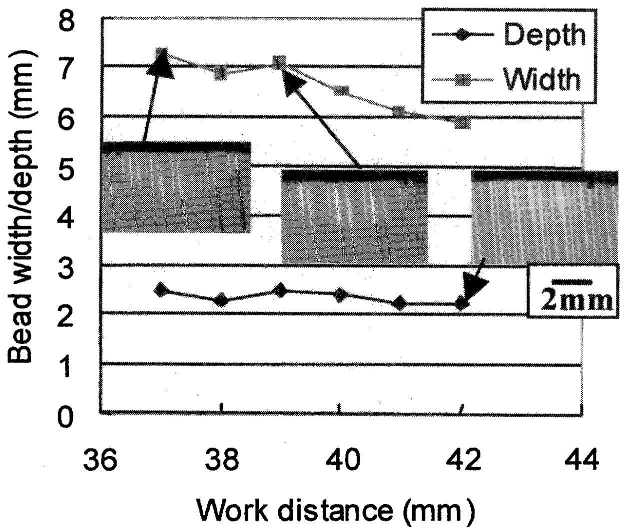


Fig.6 Effect of work distance on weld bead

4.2 Dynamic observation of welding phenomena

Welding phenomena were dynamically observed with a high-speed video camera during bead-on-plate welding of AA5022. A schematic illustration of the observation system is shown in Fig.7. The surface and bottom of the specimen were observed during welding using an HSV-1000 high-speed video system (Nac Inc.) at a frame speed of 500 frame/s with illumination from a 2kW Xe short arc lamp. Observation was from the side, parallel to the welding direction. A typical example of the high speed photographs obtained is shown in Fig.8. A long and narrow molten pool is seen in the center. At the center of the molten pool is a bright area denoting the area irradiated by the laser. Unlike conventional laser welding, no spattering or laser plasma formation was observed during diode laser welding of the aluminum alloys. Even at welding speed as slow as 6m/min, the width of the molten pool does not spread beyond 3mm, or 3 times the beam diameter. The surface of the molten pool is very calm, with periodical solidified ripple lines clearly visible. These quiet welding phenomena correspond to a heat conduction welding type bead shape and a very smooth and narrow bead width.

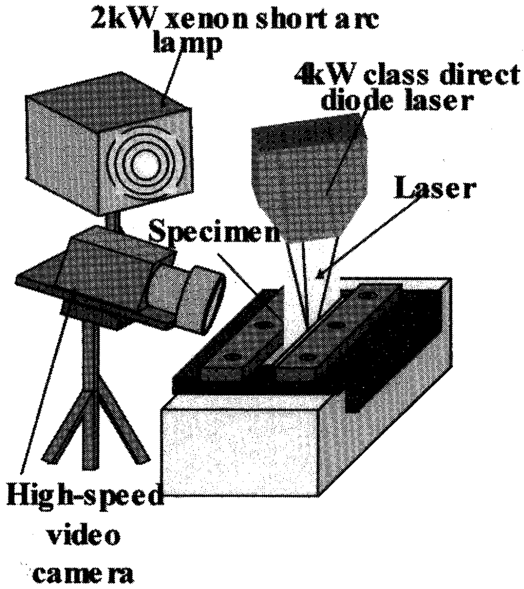


Fig.7 Observation system

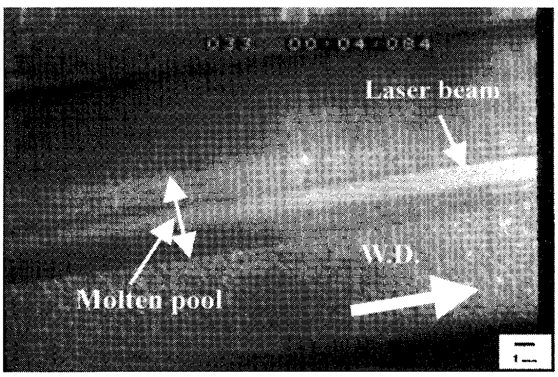
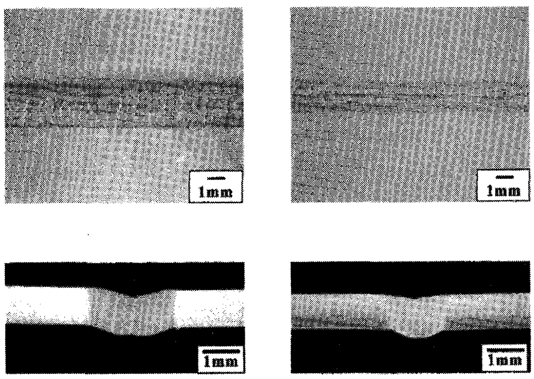
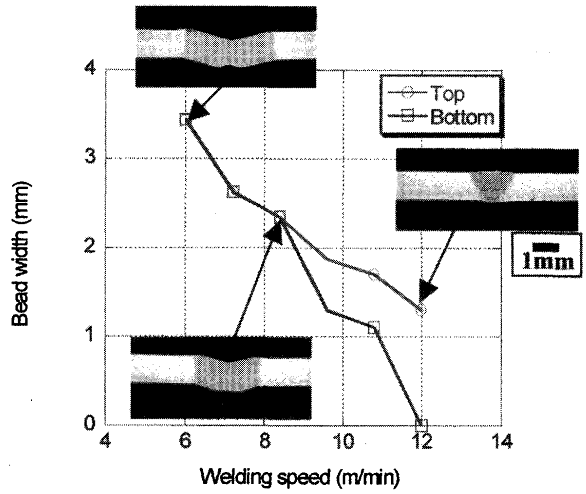


Fig.8 High speed photograph during welding at a welding speed of 4.8m/min

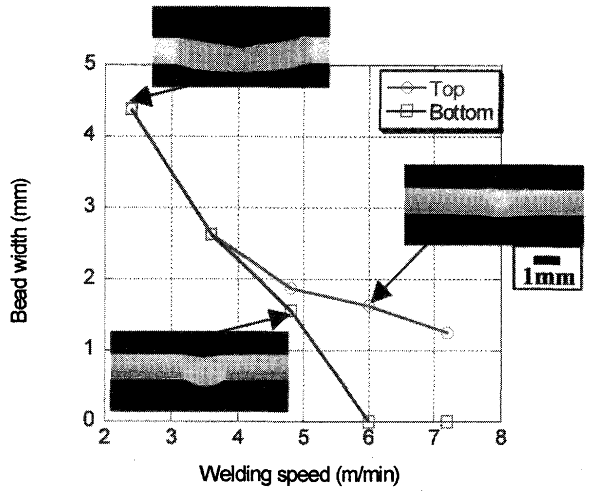


(a)AA5022 (b)AA6016

Fig.9 Typical bead surface and cross section in bead-on plate welding of AA5022 and AA6016 at a welding speed of 7.2m/min and 4.8m/min, respectively



(a)AA5022



(b)AA6016

Fig.10 Bead width and depth of bead-on plate welding of aluminum alloy of AA5022 and AA6016

4.3 Results of bead-on plate welding

The aluminum alloys AA5022 and AA6016 were used as specimens for bead-on-plate welding. The welding speed was varied from 2.4m/min to 12.0m/min. Typical examples of the weld beads obtained are shown in Fig. 9.

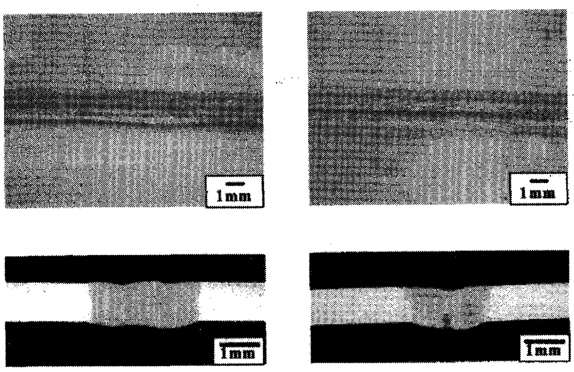
The bead surface was very flat and smooth compared to the weld bead produced by a Nd:YAG laser. No defects such as eutectic fusion or cracks were found in the weld metal. Figure 10 shows the relationship between the welding speed and bead width. With increasing welding speed, the bead width became narrower in both alloys. Full penetration welding was possible at a maximum welding speed of 12.0m/min for AA5022 and 6.0m/min for AA6016, similar to that for AA66016, similar to that for conventional laser welding. The maximum welding speed for full penetration welding differed between the two alloys because of their differing heat conductivity.

The aluminum alloys AA5022 and AA6016 were used as specimens for butt welding. The welding speed was varied from 4.2m/min to 12.0m/min. Typical examples of the weld beads obtained are shown in Fig.11. The bead surface was very flat and smooth compared to the weld bead produced by a Nd:YAG laser. Small porosities were observed in the bead cross section.

Figure 12 shows the relationship between the welding speed and bead width. With increasing welding speed, the bead width became narrower in both alloys. Full penetration welding was possible at a maximum welding speed of 12.0m/min for AA5022 and 6.0m/min for AA6016, similar to that for conventional laser welding. The maximum welding speed for full penetration welding differed between the two alloys because of their differing heat conductivity.

4.4 Results of butt welding

The aluminum alloys AA5022 and AA6016 were used as specimens for butt welding. The welding speed was varied from 4.2m/min to 12.0m/min. Typical examples of the weld beads obtained are shown in Fig. 11. The bead surface was very flat and smooth compared to the weld bead produced by a Nd:YAG laser. Small porosities were observed in the bead cross section.



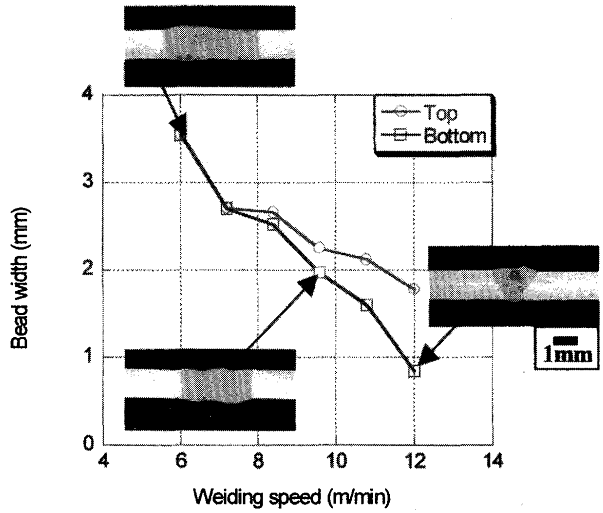
(a)AA5022 (b)AA6016

Fig.11 Typical bead surface and cross section in butt welding of AA5022 and AA6016 at a welding speed of 9.6m/min and 4.8m/min, respectively

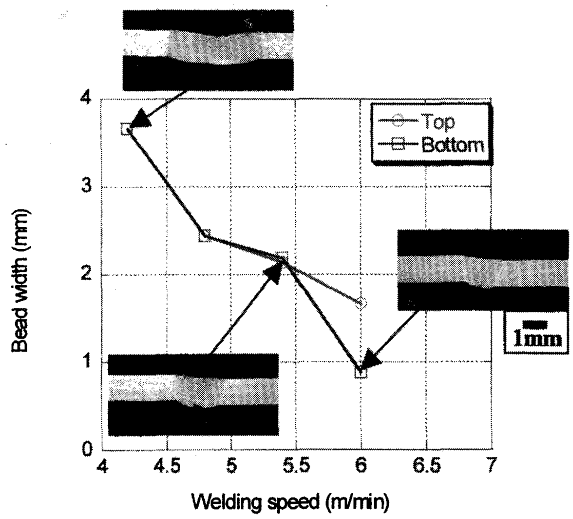
Figure 12 shows the relationship between the welding speed and bead width. With increasing welding speed, the bead width became narrower in both alloys. Full penetration welding was possible at a maximum welding speed of 12.0m/min for AA5022 and 6.0m/min for AA6016, similar to that for conventional laser welding. The maximum welding speed for full penetration welding differed between the two alloys because of their differing heat conductivity.

4.5 Results of lap-fillet welding

Lap-fillet welding of 1.0mm-thick sheets of AA5022 alloy was performed. Figure 13 shows the relationship between the welding speed and bead shape. The laser beam irradiated the edge of the upper plate, that is, the offset distance was zero. The focal point of the laser beam is on the surface of the upper plate. A sound bead was achieved at a welding speed of 0.6m/min with no porosities orcracks as shown in Fig.14. The maximum full penetration welding speed was less than 2m/min. Crack defects caused by a lack of fusion, similar to those which occur in arc welding, were occasionally found in the high speed region at the boundary between the two plates



(a)AA5022



(b)AA6016

Fig.12 Bead width and depth of butt welding of aluminum alloy AA5022 and AA6016

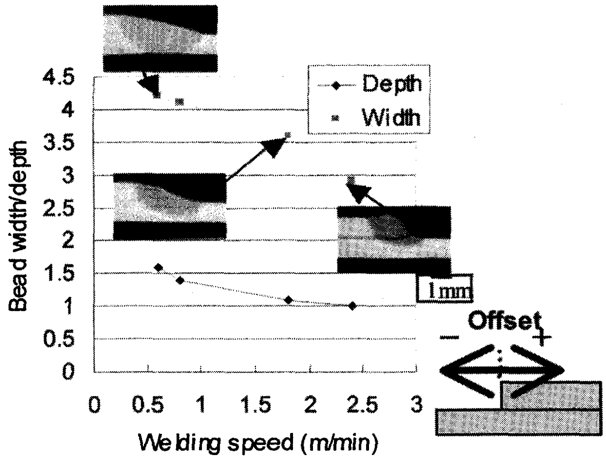


Fig.13 Bead width and depth of lap-fillet welding of aluminum alloy AA5022

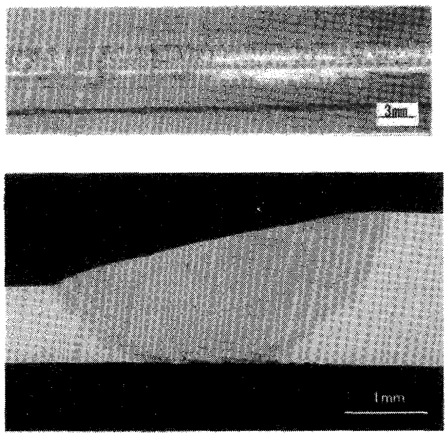


Fig.14 Typical example of lap-fillet welding bead of AA5022

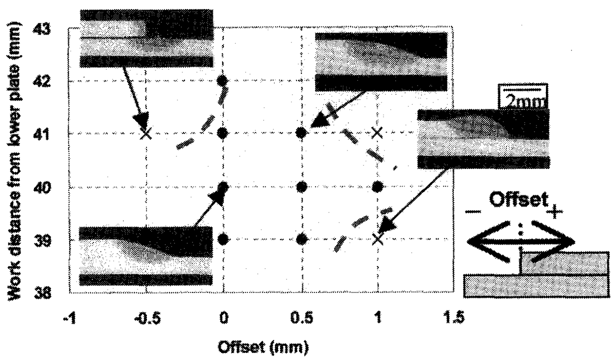


Fig.15 Effect of offset distance on weld bead of AA5022 lap-fillet welding

In order to improve the welding results for lap-fillet welding, the relationship between the work distance and the offset distance of the focal point from the edge of the upper plate was examined. Figure 15 shows the results and typical weld beads. When the focal point was set at the surface of the lower plate and the offset distance was on the slightly plus side, with the laser irradiating the area where the two sheets overlapped, a wider area of full penetration was obtained. When the focal point was set at the surface of the lower plate, the offset distance tolerance was about 1mm. This means that direct diode laser welding provides tolerance with regard to specimen size and setting position. At the optimum conditions, the maximum welding speed of 3m/min was achieved at the output laser power of 4kW.

4.6 Dynamic observation of lap-fillet welding phenomena

Lap-fillet welding phenomena on the optimum conditions were also observed with a high speed video camera. Figure 16 is a typical photograph of the surface of AA5022 aluminum alloy during lap-fillet welding. The bright band indicates the area irradiated by the laser beam. The brightest part at the left half indicates the molten metal of the upper plate. First, the front edge of the laser beam preheats the upper plate. Then, the upper plate is melted by the main part of the beam.

The molten metal of the upper plate heats up the lower plate. The small bright area under the molten pool of the upper plate is the molten metal of the lower plate.

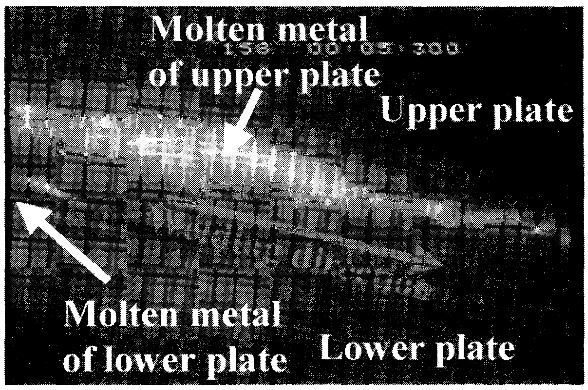


Fig.16 High speed photograph during lap-fillet welding at a welding speed of 3.0m/min

5. Conclusions

The following results were obtained when aluminum alloys were welded with a 4kW direct diode laser at a focal distance of 40mm, beam size of 2mm x 10mm, and a mean power density of $20kW/cm^2$.

(1) The welding phenomena were very quiet, with no spattering or laser plasma formation.

(2) A heat conduction welding type bead shape was produced, with a very smooth bead surface.

(3) Full penetration bead-on welding was possible up to a welding speed of 12.0m/min for AA5022 and 6.0m/min for AA6016.

(4) A sound bead was obtained when lap-fillet welding was performed on AA5022 alloy plates at a welding speed of 3m/min.

Acknowledgments

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