Character of Melting and Evaporation in Laser Beam Welding of Two Aluminum Alloys

The evaporation of magnesium, the main alloying element for A5052 and A5083 aluminum, influences weld penetration

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ABSTRACT. The phenomenon of evaporation within the keyhole during laser beam welding of aluminum Alloys A5052 and A5083 was investigated under different welding conditions. The character of the molten pool was compared and analyzed. It was found that the evaporation of the main alloying element for these alloys, magnesium, greatly influenced the reaction force induced between the metal vapor and thermal plasma, which in turn affected the degree of penetration. The results of these experiments also confirmed that increasing shielding gas flow rate, within a limit, and a slight increase in the entrance angle of the laser beam improved meltability and increased penetration depth. Surface preparation was also observed to improve beam absorption and increase penetration.

Introduction

During laser beam welding of aluminum alloys, some low-melting-point alloying elements, such as magnesium, zinc and lithium, evaporate. This may lead to a reduction in the mechanical properties of the weld joint (Ref. 1). Because different alloys contain varying levels of alloying elements, the degree of evaporation loss, as well as properties affected by evaporation, may be different for various alloys. In this paper, the phenomenon of evaporation within the keyhole during laser beam welding of Al Alloys A5052 and A5083 was investigated.

Experimental Conditions

The experiment was conducted through the use of a Nd:YAG laser operating in the continuous wave mode. Parameters utilized during the experiment are shown in Table 1. Nominal compositions for the Al alloys utilized during the experiment are shown in Table 2.

Autogenous laser beam welds were produced along the center of specimens that were approximately 100 x 100 mm (4 x 4 in.) in size and 6 mm (0.24 in.) in thickness. Prior to welding, the samples were polished using 320-grit emery paper to remove the oxide film and then degreased with acetone. Optical metallography and microprobe analysis were utilized to characterize selected specimens.

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Experimental Results and Discussion

Evaporation of Magnesium

Magnesium is the main alloying element in Alloys A5052 and A5083. Magnesium evaporates readily in the molten pool because of its low boiling point and high vapor pressure relative to pure Al. The boiling point of Mg is 1380 K (2024°F) and is compared to the boiling point of Al of 2727 K (4449°F). Electronic probe microanalysis (EPMA) was used to determine the amount of magnesium that had been evaporated from selected specimens. The areas of analysis representing the weld fusion zone and base metal of Alloys A5052 and A5083 are shown in Figs. 1 and 2, respectively. Tables 3 and 4 list the results of EPMA for the fusion zone and base metal for the two alloys welded using a beam diameter of 10 µm and identical welding parameters. The area ratio is the ratio of the region of the same Mg concentration shown in Figs. 1 and 2 as determined by EPMA. The dark shaded region shown in Figs. 1 and 2 is the fusion zone.

As shown in Table 3, Mg comprised less than 2.5% of the weld fusion zone of A5052. Evaporation loss of Mg during welding resulted in the lower Mg content found within the weld fusion zone. Evaporative loss of Mg was greatest in the upper and center regions of the weld fusion zone. As shown in Table 4, the Mg content was less than 4.25% in the weld fusion zone of A5083 and even less present in the upper portion of the fusion zone. If the extent of evaporative losses may be estimated by the average Mg content within the fusion zone, the loss of Mg due to laser beam welding of Alloys A5052 and A5083 was 0.48% and 0.74%, respectively. The results indicate that the level of alloying content within the base metal has a direct effect on the amount of evaporation within the weld, that is, the loss of Mg was related to the Mg content within the alloys. Alloy A5083, which contained a greater amount of Mg, displayed greater evaporative losses.

KEY WORDS

Laser Beam Welding
Evaporation
Aluminum Alloy
Absorptivity
Meltability
Fusion Zone
Metal Vapor
Plasma

Influence of Plasma on Penetration

As the metal surface is irradiated by the laser beam, the high energy density at the focal point caused the temperature to approach the boiling point of aluminum. If low-boiling-point alloying elements are contained within the metal, it is likely that evaporation of these elements will occur. Thermal electrons are easily emitted from a metal vapor and liquid metal at temperatures within the molten pool. These electrons move at high speed from the internal to external portions of the molten pool. Ono (Ref. 2) has shown that a blast wave will be produced due to an accumulation of electrons within the molten pool, which results in further ionization and a filling of the keyhole with thermal plasma. The thermal plasma will jet from the molten pool at a certain frequency, which has been observed by Ono to be 200 Hz for carbon steel.

The plasma and metal vapor contact the shielding gas over the surface of the molten pool, while the shielding gas, in part, is aroused and ionized. Finally, the plasma will disappear by energy exchange. In the course of a plasma being generated from the keyhole, it absorbs laser energy and reduces the available energy for melting. Hence, the plasma may become a barrier to the irradiation of the laser beam. Conversely, the plasma and metal vapor jet from the molten pool at higher pressures, and the surrounding liquid metal is expelled, which allows direct irradiation by the laser beam at the bottom of the vapor cavity resulting in improved penetration. Figure 3 shows the longitudinal section of the fusion zone for laser beam welds of Alloys A5052 and A5083, produced under identical conditions (P_0 = 1.5 kW, V = 0.6 m/min, f = 100 mm, f_d = 0, R_g = 30 L/min). Within the molten pool each jet of plasma and metal vapor results in increased penetration depth and movement of the liquid metals by the reaction described above. Every impact and movement produce a waviness or spiking within the weld bead. The frequency of the spiking was determined using the welding velocity and the longitudinal sections represented in Fig. 3. These frequencies were found to be 180 Hz for Alloy A5052 and 70 Hz for Alloy A5083, which are somewhat less than those reported for carbon steel (Ref. 2). Although the spiking frequency of A5083 was less than that of A5052, the jet pressure of the plasma and metal vapor was believed to be higher due to the higher Mg content in this alloy, the large amount of evaporative loss and the larger amount of metal vapor generated.

Table 1 — Parameters Utilized during Laser Beam Welding Experiments

P_0kW	V (m/min)	f (mm)	f_d (mm)	R_g (L/min)
0.9–1.6	0.3–3.0	100	−2–2	15

Table 2 — Nominal Composition of Aluminum Alloys A5083 and A5052

Element	Mn	Mg	Zn	Cu	Si
A5083	0.5	4.5	0.25	0.1	0.4
A6062	0.1	2.5	0.25	0.1	0.46

Influence of Gas Flow Rate on Shape of Fusion Zone

Figure 4 shows the change in penetration and weld width with varying gas flow rates. In the limit of 30 L/min, the penetration and weld width of the A5083 weld head increased with increasing gas flow rate; the penetration was maximum at a gas flow rate of 30 L/min.

As mentioned above, plasma and metal vapor generation are beneficial from a penetration standpoint; however, the generation of the plasma and periodic collapse of the vapor cavity may lead to defects within the weld. In order to overcome the formation of defects, all or part of the plasma must be removed. Increasing the shielding gas flow rate results in an increase in the stiffness of the gas column and provides an efficient exchange of energy between the shielding gas and plasma in a short distance over the surface of the workpiece. Therefore, the energy of the laser beam is reduced only a small amount and results in greater energy to the workpiece. As the gas flow rate was increased to more than 30 L/min, the state of the gas flow was altered and its stiffness was reduced, which resulted in reduced penetration.

In the case of Alloy A5052, the amount of plasma generated within the pool was less than that of A5083 because of its lower Mg content, and hence, the effect of shielding gas on suppression of the plasma was not obvious.

Influence of Focus Position

The energy of the laser beam absorbed by the workpiece was observed to change with a variation in the focus position. As the focus position was changed from positive to negative (focus position above the surface of the workpiece is positive), penetration increased and the shape of the fusion zone changed from a hemisphere to nailhead — Fig. 5. The change in weld profile for the two Al alloys was similar, but the degree of penetration in Alloy A5052 was less than that of A5083 for the same welding conditions. The difference in degree of penetration between the two alloys is believed

Fig. 1 — Results of the EPMA of Mg in the weld fusion zone and base metal for Alloy A5052.

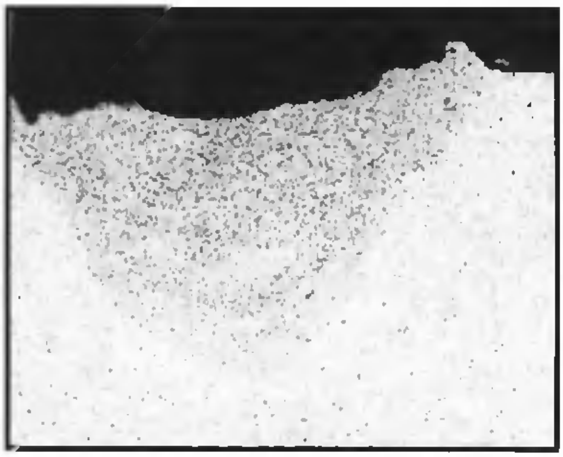

Fig. 2 — Results of the EPMA of Mg in the weld fusion zone and base metal for Alloy A5083.

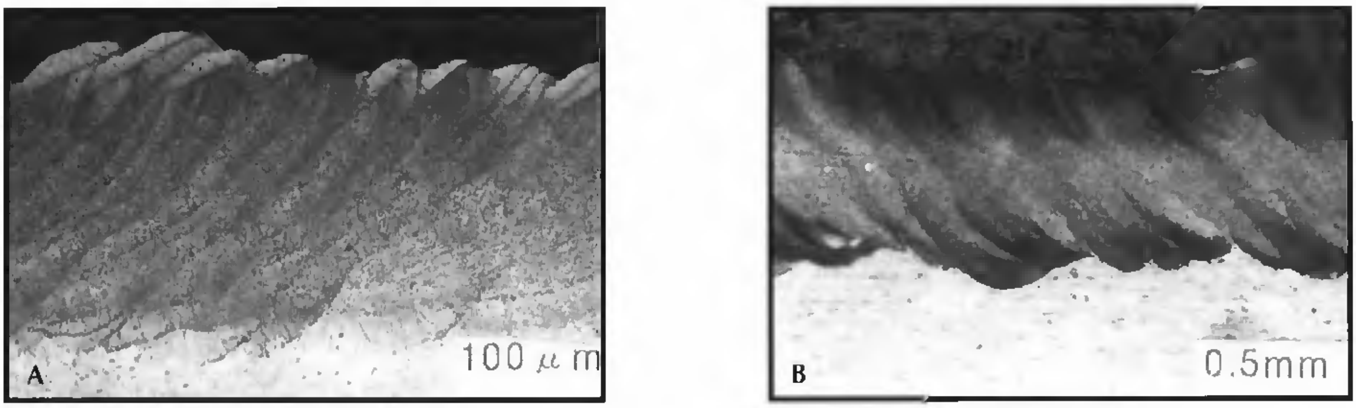

Fig. 3 — A longitudinal section of weld bead. A — Alloy A5052 and B — Alloy A5083.

to be due to the difference in physical properties, *i.e.*, thermal conductivity, surface tension and viscosity (Ref. 3).

Preparation of Workpiece Surface

The absorptivity of Al alloys under laser beam irradiation is very low. In order to increase absorptivity, the surface of the workpiece is usually treated or polished with emery paper before welding (Ref. 4). Three workpieces were polished with three types of emery paper (80, 320 and 400 grit). The results of the experiments for penetration and weld profile are shown in Fig. 6. Penetration was greatest for the alloys prepared with 400-grit paper, *i.e.*, the surface being beneficial in absorbing the laser beam (Ref. 5). As expected, the laser beam exhibited greater absorptivity when utilizing a square butt joint configuration due to secondary reflection at the sidewall of the root opening.

Influence of Welding Position on Meltability

Experiments were also conducted to determine the influence of inclination of the workpiece on penetration and bead geometry — Fig. 7. When the welding bead was perpendicular to the workpiece surface, that is, the workpiece was horizontal, plasma jetting from the molten pool was in the opposite direction of the laser beam. Under this condition, the energy absorbed by the plasma was greater and the resultant laser absorption of the workpiece was low. As the workpiece was inclined (the angle between the workpiece and horizontal was 5 deg), the depth of penetration and weld width increased. Laser beam welding under the inclined condition produced a plasma generation out of path with the laser beam and led to increased absorptivity.

Conclusions

An investigation was conducted to illustrate the phenomenon of plasma formation during laser beam welding of Al alloys. The results of this investigation are shown below.

1) Evaporative loss of the alloy element Mg in Al Alloys A5052 and A5083

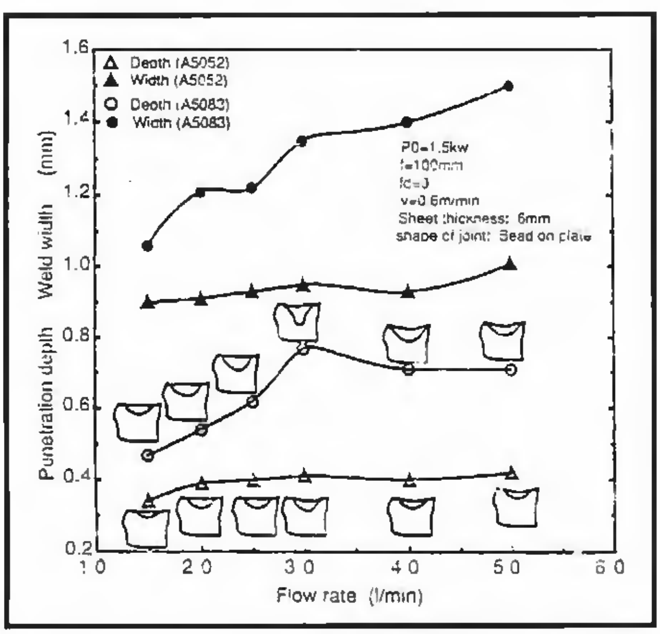

Fig. 4 — The influence of Ar gas flow rate on penetration depth and weld width.

Table 3 — EPMA Results of Mg Concentration and Area Ratios in Laser Weld Metal (A5052)

Mass (%)	Area (%)
3.5–	0.45
3–3.5	6.39
2.5–3	31.34
2–2.5	34.69
0–2	12.97

Table 4 — EPMA Results of Mg Concentrations and Area Ratios in Laser Weld Metal (A5083)

Mass (%)	Area (%)
6–	0.63
5.5–(6)	0.65
5–(5.5)	3.08
4.5–(5)	16.61
4.25–(4.5)	11.27
4–(4.25)	13.37
3.5–(4)	20.76
3–(3.5)	11.52
0–(3)	21.3

was exhibited in the fusion zone, but was greatest in the upper and center portions of the fusion zone.

2) Evaporative loss of the alloying element Mg was related to the Mg content of the base metal. Greater alloying content resulted in greater evaporative loss.

3) Increasing the shielding gas flow rate was found to be effective in reducing the plasma and increasing laser absorption.

4) Slight increases in the entrance angle appeared to improve absorption of the laser beam and resulted in increased penetration.

References

1. Moon, D. W., and Metzbower, E. A. 1983. Laser beam welding of aluminum alloy 5456. *Welding Journal* 62(2): 53-S.

2. Ono, M. 1991. Effect of ambient pressure and gas on penetration depth and laser-induced plasma behavior. *Essays of Japan Welding Society* 10(2): 9–14.

3. Van Horn, K. R. 1978. *Aluminum*, American Society for Metals, New York, N.Y., pp.167–177

4. Katayama, S., and Matsunawa, A. 1991.Laser welding of commercial aluminum alloys. *Journal of Light Metal & Construction* 29(8): 8–10.

5. Katayama, S., and Matsunawa, A. 1991. Laser welding of aluminum alloy 5456. *Journal of Light Metal & Construction* 29(7): 1–13.

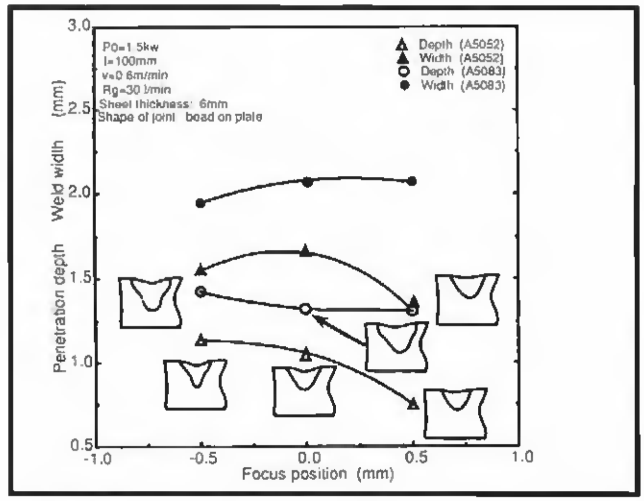

Fig. 5 — The influence of the focus position on penetration depth and weld width.

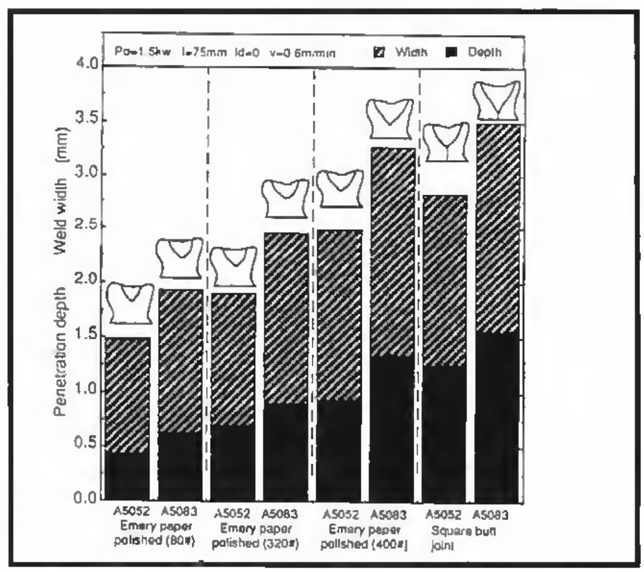

Fig. 6 — The influence of preparation of the workpiece surface and shape of the joint.

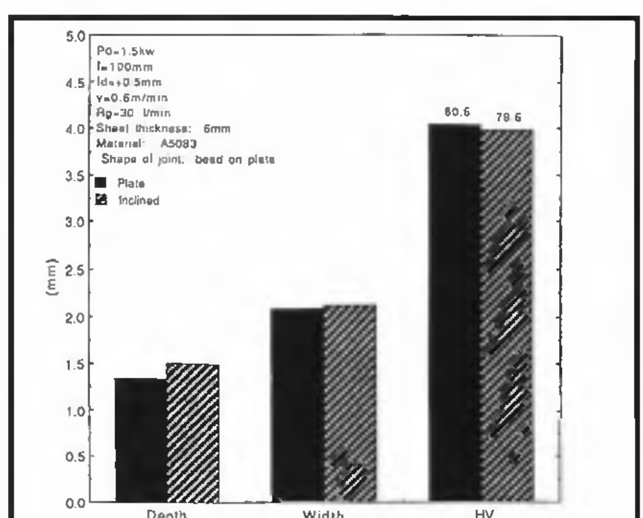

Fig. 7 — Comparison of the inclined workpiece with the plate workpiece.