Laser Welding of Aluminum and Aluminum Alloys

Welds made with sharp bevel-groove weld preparation are larger and more uniform than welds made with either bead-on-plate or square-groove preparation

BY C. A. HUNTINGTON AND T. W. EAGAR

ABSTRACT. The effects of surface preparation and joint geometry on laser power absorption by pure aluminum and by aluminum alloy 5456 have been studied. The results indicate that initial absorption varies from a few percent to more than 25% depending upon the surface preparation. The fraction of absorbed power increases dramatically upon formation of a keyhole. As a result, welds made with sharp bevel-groove preparation are larger and more uniform than those made with either bead-on-plate or square-groove weld preparations.

Introduction

High energy density laser and electron beam welding characteristically produce a deep, narrow weld bead. This bead is formed by a keyhole mode of operation in which the keyhole cavity is produced by metal vaporization at power densities of 10^5 watts/cm^2 or greater. There are, however, significant differences between the two processes: lasers heat with photons of approximately 0.1 eV energy while electron beams use particles of 100,000 eV energy. This results in a beam of laser light which readily interacts with the free electrons found in the plasma. The plasma is formed by vaporization of the surface of the metal, and this interaction defocusses part of the incident beam producing a characteristic "nail-head" type of weld (Ref. 1).

The electrons of an electron beam, on the other hand, are too energetic to be deflected significantly by the plasma. As a result, it is possible to couple the energy much more efficiently using electron beam welding compared to laser welding.

One of the most dramatic illustrations of the differences in beam characteristics occurs when welding aluminum. Aluminum is one of the easiest metals to penetrate with an electron beam. On the other hand, it is one of the most difficult to melt with a laser. The poor coupling of the laser energy is due in part to the high density of free electrons in the solid, making aluminum one of the best reflectors of light. In addition, many aluminum alloys contain magnesium or zinc, which are easily vaporized and thereby form a plasma that blocks the incident beam.

Previous investigations have shown low power absorption (Ref. 2), alloy compositional differences (Ref. 3) and the importance of surface preparation (Ref. 3) when laser welding aluminum. The power absorption changes dramatically at times, producing an unstable process with poor penetration control and a rough bead surface. It is commonly believed that the difference in the fraction of absorbed power is caused by melting of the metal (Ref. 1,4).

It is well known that alloy composition and surface preparation of aluminum influence the absorption of laser light. Accordingly, the purpose of this study was to quantify these differences in order to determine the degree of control that can be achieved by modifications of either the material or of the process.

Experimental

Both pure aluminum (99.999%) and 5456 alloy (5.1% Mg with minor additions of Mn and Cr) were used for the absorption experiments. Actual welds were made on ¼ in. (6.4 mm) thick 1100 (99.0% Al) and 5456 alloy plate.

Four different surface preparations were studied. The as-received surface of 5456 was mill-finished, while the pure aluminum was machined on a lathe. Other samples were sandblasted with −300 mesh glass beads, anodized to one micron thickness, or electropolished in an alcohol-water-perchloric acid solution.

The absorption studies employed a 0.375 in. (9.5 mm) diameter sample machined as a cone on one end with the flat test surface on the opposite end. The cone was pressed into a holder as shown schematically in Fig. 1. The holder surrounded the conical end and absorbed all light beamed into this cavity. A thermistor was mounted on the holder which recorded the temperature rise of the sample and holder after each laser pulse. By beaming into the cavity, the total beam power was measured. By turning the entire assembly around, the absorbed power of the laser pulse on the flat surface could be measured. The ratio of the temperature rise on the flat surface to that produced by beaming into the

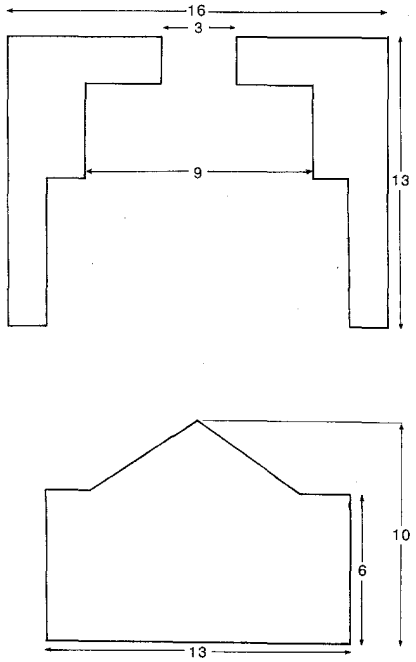

Fig. 1—Schematic of cone and holder assembly used for absorption studies. Dimensions are in millimeters (1 in. = 25.4 mm)

Paper presented during the 63rd AWS Annual Convention held in Kansas City, Missouri, during April 25-30, 1982.

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Table 1—Percent Power Absorbed from a 200 Joule, Two Second Pulse

Surface preparation	5456 aluminum alloy	99.999% pure aluminum
Anodized	27	22
Sandblasted	22	20
As-received	5–12[a]	7
Electropolished	4	5

[a]Mill finished samples exhibited considerably more scatter than laboratory prepared surfaces.

cavity gives a direct measurement of the absorbed power.

The entire holder and sample weighed 6.5 grams (0.014 lb). This allowed accurate measurements of absorbed power as small as two joules (J). For lower power absorption a smaller holder and sample was employed which weighed 0.8 g (0.0018 lb) total.

The power absorption studies were performed with both a 200 watt (W) and a 1300 W Coherent radiation CO_2 laser. The higher power laser was operated in the gaussian mode. Welds were produced on a Spectra Physics 5 kW laser operating in the unstable resonator mode.

Results and Discussion

Table 1 illustrates the effect of surface preparation on power absorption for a 200 J, 2 second(s) pulse. It will be noted that sandblasting and anodizing significantly increase the absorbed power, while electropolishing decreases the absorption somewhat. The increased absorption of the anodized sample is no doubt due to the decreased free electron concentration at the surface. The one micron anodized layer is, in principle, too thin to interact directly with the 10.6 micron radiation, but the decrease in charge carriers near the surface still has an influence.

Scanning electron microscopy revealed that the high absorption of the sandblasted samples was most likely due to light absorption by glass beads embedded in the surface. The as-received samples produced considerably more scatter in the measurements, presumably due to local differences in oxide thickness in 5456 alloy and surface roughness variations in the pure aluminum. The smooth electropolished samples have the highest reflectivity of all.

Although it is not immediately apparent from the data in Table 1, the 5456 alloy usually had a slightly higher absorption than the pure aluminum of similar surface preparation. This was confirmed by more than 100 measurements; the alloy has an absorption coefficient which is approximately 20 to 25% larger than the pure aluminum. The differences at low absorption powers were less pronounced due to greater experimental error, but the trend was consistent throughout this study. The most likely explanation is the lower free electron concentration in the alloy material. It will be noted that the differences in absorption due to alloy composition are much less than those due to surface preparation.

At higher beam power, melting will occur as shown in Fig. 2. The melting was confirmed by inspection in the scanning electron microscope as shown in Fig. 3. It will be noted from Fig. 2 that the absorption increases dramatically in some instances at the higher powers. SEM study confirmed that the high absorption coefficient is due to the formation of the keyhole rather than the onset of melting as commonly believed (Ref. 1, 4). This is seen even more clearly in Fig. 4, which indicates low absorption power over a range of power inputs even when surface melting occurs. If high absorption coefficients are to be achieved, a keyhole must be formed.

Table 2—Absorption in Drilled Keyhole, 0.5 Second Pulse, %

Watts	5456 aluminum alloy	99.999% pure aluminum
400	3	100
500	23	66
1200	17	35

As a further test of whether a keyhole or melting is responsible for high power absorption, flat bottomed holes 2.4 mm (0.094 in.) in diameter by 6.2 mm (0.24 in.) deep were milled in each alloy. The absorption in each of these "keyholes" was measured with the results as shown in Table 2.

It will be noted that the absorption coefficient is generally much greater in the artificial keyhole than would be expected on a flat surface. In this case, the keyhole acts like a cavity, reradiating the power between the walls until most of it is absorbed. It will further be noted that the absorption of the pure aluminum is greater than the 5456 alloy in the keyhole. This is believed to be due to generation of a magnesium vapor plasma in the 5456 alloy keyhole. This plasma absorbs the incident light, thereby reducing the effective depth of the keyhole.

It appears from these results that the keyhole geometry is more important than surface preparation in determining the power absorption characteristics of pure aluminum. The effect of joint geometry may be less important in the high magnesium alloy, since the vapor reduces the effective depth of the cavity.

As a further test of the importance of keyhole geometry in laser welding of

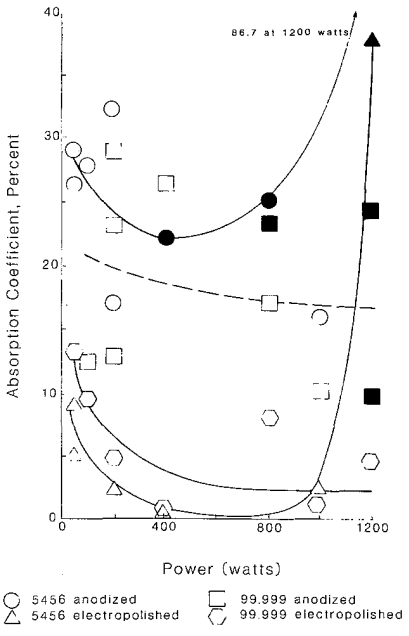


Fig. 2—Absorption vs. power for a 1 s pulse. The open symbols represent samples without surface melting, while the dark symbols represent samples that exhibited surface melting as viewed in the scanning electron microscope

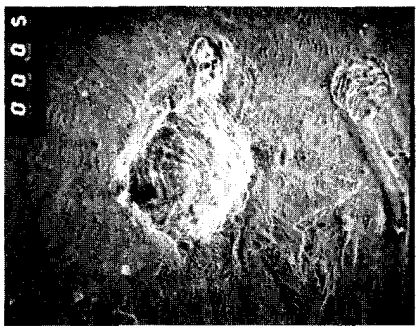


Fig. 3—Example of surface melting as seen in the scanning electron microscope. The specimen is 5456 alloy, anodized, 200 W, 1 s pulse. X200 (reduced 49% on reproduction)

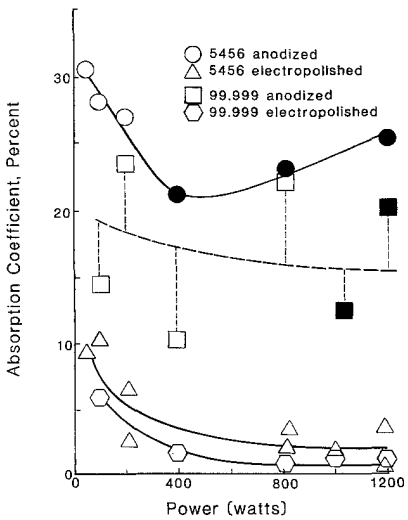
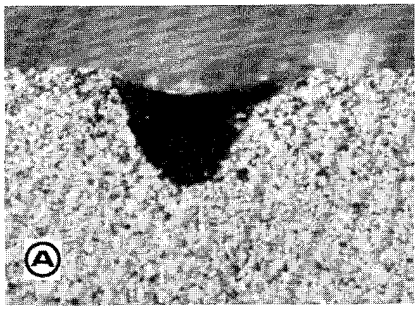
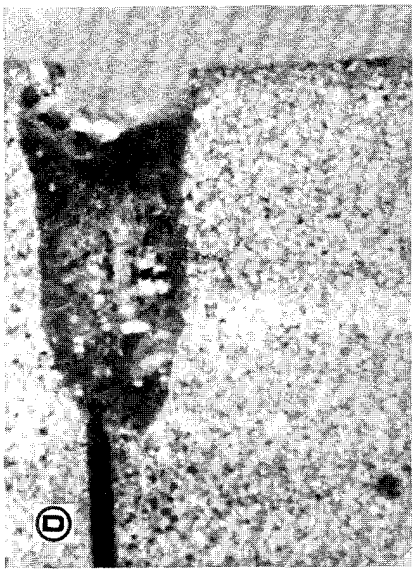
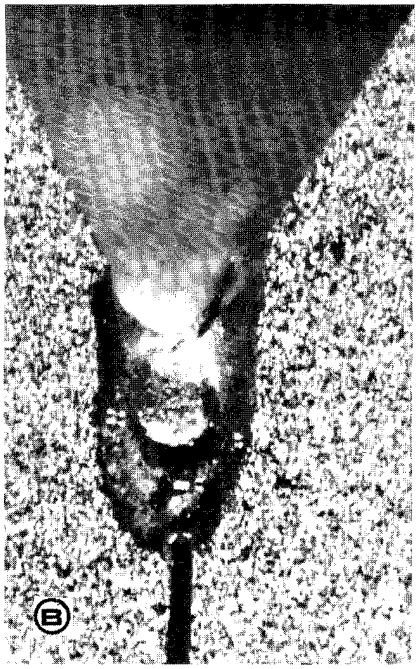
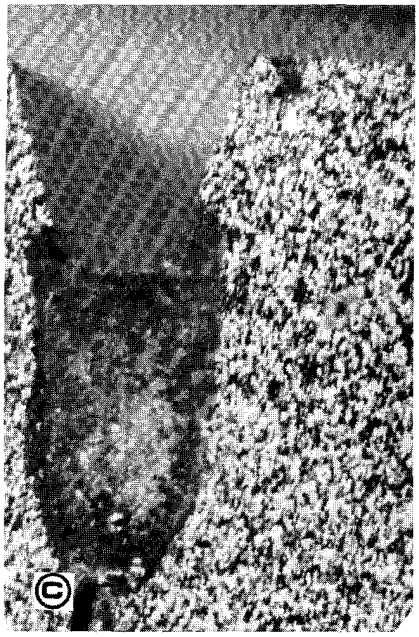


Fig. 4—Absorption vs. power for a 0.5 s pulse. The dark symbols represent samples which exhibit surface melting









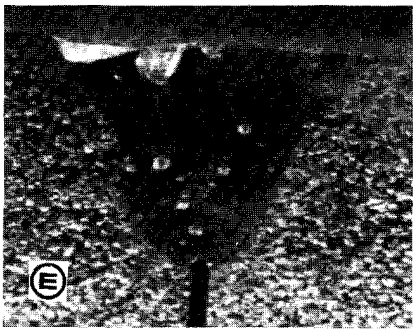


Fig. 5 — Welds made on 1100 aluminum with the following preparations: A — bead-on-plate; B — 30 deg angle V-groove; C — 20 deg angle V-groove; D — square groove; E — square groove. All welds were made with equal power

aluminum, a series of welds were made on 1100 and 5456 alloy at 152 mm/s (359 ipm) travel speed and 3 kW beam power with helium shielding gas. Figure 5 shows a bead-on-plate weld, a 30 deg included angle V-groove weld, a 20 deg included angle V-groove weld and two welded square butt joints in 1100 alloy, respectively.

The very small amount of melting of the bead on plate geometry is increased with the V-groove weld preparation, which simulates a keyhole. The smaller weld cross section in Fig. 5D and 5E is due to the welded square butt joint acting as an average between a bead-on-plate and a near perfect keyhole. The difference in melting between Fig. 5D and 5E is probably due to small variations in either root gap or beam alignment in the gap.

It appears that a square butt joint (i.e., square-groove weld) preparation is very sensitive to geometric changes, which can significantly alter the percent of beam power absorption. The V-groove weld preparation appears to be the best geometry for both weld consistency and efficient use of beam power. Similar results were observed with the 5456 alloy.

Conclusions

A study of laser light absorption on pure aluminum and 5456 alloy has shown the following:

1. Joint geometry has the greatest influence on beam absorption, while surface preparation also has a significant influence. Alloy composition is of lesser importance with bead-on-plate welds but could produce significant differences in the keyhole mode if volatile alloy additions are present.

2. Increased power absorption does not occur with the onset of melting but rather with the beginning of keyhole formation.

Acknowledgments

The authors are grateful for the financial support of the Office of Naval Research under Contract N00014-80-C-0384. They are also indebted to Mr. Greg Dunn for assistance with many of the absorption studies and Mr. E. Prescott, of the Alcoa Technical Center, for production of the welded samples.

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