Weldability of Aluminum with the YAG Laser and an Estimation of Weld Strength by Numerical Analysis*

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Lapped spot welding of aluminum plates is examined using a normal pulsed YAG laser, and the influence of experimental conditions on the weldability is discussed. The weld strength is investigated in relation to the irradiating conditions of the pulsed YAG laser, and an empirical formula of weld strength is presented. Heat conduction is analyzed by a finite difference method in which the dependency of the thermal constants of a test piece on temperature and the characteristics of the used laser beams are considered. Molten configurations under various conditions of laser irradiation are obtained by the numerical analysis. The weld strength is determined by using the molten configuration and the empirical formula.

Key Words: Nontraditional Processing, Numerical Analysis, Pulsed YAG Laser, Laser Spot Welding, Welding of Aluminum, Weld Strength, Finite Difference Method, High-Energy-Rate Beam Machining

1. Introduction

Laser beams are used widely in drilling, cutting, welding and heat treatment⁽¹⁾. In the field utilizing welding, especially, small parts have been welded automatically⁽²⁾, and titanium alloy⁽³⁾ and aluminum alloy⁽⁴⁾, which have been evaluated as difficult-to-weld materials, have been welded by making the best use of the excellent characteristics of laser beams. The melting point of aluminum is low. However, a large amount of heat is needed to melt it, since the specific heat and the latent heat for melting aluminum are larger than those of general-purpose metals. Furthermore, partial heating of aluminum is difficult because of the high thermal conductivity. Therefore, electron beams⁽⁵⁾ and laser beams, by which high power density is easily obtained, are useful for welding of aluminum. Laser beam welding is more useful than electron beam welding, since the former is possible in arbitrary atmospheres.

In this study, the strength of lapped spot welding of aluminum was investigated in relation to the irradiating conditions of normal pulsed YAG lasers, such as irradiation energy, pulse duration and defocused value, and combination of welded plate thickness. Molten configurations were analyzed by means of the finite difference method, with the consideration of temperature dependencies of thermal constants, laser waveforms, spatial distribution of laser intensity and complicated phenomena such as the reflection change at the surface of a test piece, and generation of a beam hole. The weld strength was estimated using the molten configurations and the empirical formula.

2. Experimental Apparatus and Procedure

In the laser machining system used in this study, it is possible to arbitrarily change irradiation energy (E), pulse duration (τ) and defocused length (D_{ef}). The laser beam was defocused at positions over the surface of a workpiece. The focal length of the lens (f) was 50 mm. The test piece material was pure aluminum (A 1050 P-H 14). The surface was polished chemically and washed by acetone in a supersonic

* Received 22nd March, 1990. Paper No. 88-0870A

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bath. As shown in Fig. 1, a lower plate is lapped by an upper one and pressed by one pair of springs. Welding of three spots is carried out in the center of the lapped area. The weld strength was evaluated by the average value of strengths in nine spots.

3. Experimental Results and Discussions

3.1 Relationship of power density to weld strength

Figure 2 shows the relationship between the weld strength and power density at the surface of a test piece. The power density is determined by E and τ , since f and D_{ef} are constant, and the relationship between E and τ is shown in the upper part of each figure. The thickness of the upper plate is 0.2 mm, and those of the lower plates are 0.2, 1.0 and 1.5 mm, respectively, in each figure of Fig. 2. It was found independent of the combination of E and τ from the figures that welding is possible from the power density of about 0.7 MW/cm² and that the weld strength is maximum in the power density from 1.0 to 2.0 MW/cm². When the power density is more than 2.0 MW/cm², the weld strength decreases with increasing power density, since the removed portion is at the upper part of an upper plate. The larger the thickness of the lower plate, the greater the tendency toward

decreasing strength.

As an example, molten configurations are shown in Fig. 3, where the combination of plate thicknesses is 0.2 and 1.0 mm, and irradiation energy is 10 J. When the pulse duration was large, i.e., the power density was small, the weld strength showed a low value since the welded area was small. When the pulse duration decreased, i.e., the power density increased, the weld strength increased since the welded area increased. When the duration decreased further, the strength decreased rapidly, since the removed area increased near the surface of the upper plate.

As verified through the observation of the laser beam at the back surface of the test piece using a silicon photosensor⁽⁶⁾, when the melt zone reaches the back surface, as for pulse durations less than 3.9 ms, some of irradiation energy passes through the melt zone. Therefore, the energy which is actually absorbed by a test piece decreases. By this reason, when the total thickness of both plates is small, as

Fig. 1 Welded specimen and shearing direction

Fig. 3 Effect of pulse duration upon sectional melt feature

Fig. 2 Relationship of power density to shearing force under various irradiating conditions and several pairs of plates

shown in the combination of (0.2+0.2) mm, the weld strength does not decrease with increasing power density.

It was clarified that the most suitable molten configuration must be created at the welded part for obtaining the high weld strength. Therefore, aluminum plates must be welded in the region of appropriate power density.

3.2 Welded area and shearing stress of welded part

3.2.1 Effects of pulse duration (τ) and defocused value (D_{ef}) Figure 4 shows shearing force (weld strength), welded area and shearing stress which is defined by the shearing force divided by the welded area, when the irradiation energy (E) is 10 J and the power density changes according to changes of the pulse duration or the defocused length. When the power density is larger than about 1.8 MW/cm², the effect of τ or D_{ef} on the force and the area is similar. However, when the power density is less than 1.8 MW/cm², D_{ef} affects the force and the area more markedly than does τ . The reasons for this are as follows. As the beam diameter at the surface of the test piece increases with increasing D_{ef} , energy losses due to reflection from the surface of the aluminum plate and to heat conduction in the radial direction increase, while the melt depth and the welded area decrease.

On the other hand, when τ increases, overall power density decreases. However, the welded area

Fig. 4 Effects of pulse duration and defocused value upon weldability

increases because the test piece is irradiated by the laser beam for long time.

3.2.2 Effects of combination of both upper and lower plates upon the weldability Figure 5 shows the relationships of power density to shearing force, welded area and shearing stress, when the upper plate is 0.2 mm in thickness and the lower plates are 0.2, 0.6 and 1.0 mm in thickness. The effect of the lower-plate thickness on the force and the area is small when the power density is low. When the power density is about 1.5 MW/cm², the force and the area decrease together with the lower-plate thickness.

Figure 6 shows the molten configurations when the upper plates are from 0.2 to 1.0 mm in thickness. In Fig. 6(a), the melt zone reached 1.7 mm in depth, and in Fig. 6(b), the melt zone reached the back surface of the lower plate. However, both the molten configurations were similar from the top surface to 0.8 mm in depth. The melt width increased in the region from 0.8 mm in depth to the back surface of the lower

Fig. 5 Effect of lower-plate thickness upon weldability

Fig. 6 Relationship between total thickness of both plates and molten configuration

plate, since heat conduction was impeded and heat was accumulated near the back surface. In Fig. 6(c), all of the molten configurations are shown in pile when the upper plates are 0.2, 0.4, 0.6 and 1.0 mm in thickness.

When the increased melt zones shown by dotted lines are neglected, the molten configurations are united in one solid line. This united molten configuration is defined as the standard molten configuration in this paper.

Figure 7 shows the standard molten configurations under the conditions where E is 10J and τ are values from 2.8 to 7.0 ms. Thus, it was found that the standard molten configurations were affected significantly by the pulse duration.

Figure 8 shows an example of a microphotograph of the melt zone. The bulk structure shows aggregation generated by a rolling operation. It is recognized that the columnar structure grows from the outskirts to the central-upper part of the melt zone.

Fig. 7 Influence of pulse duration upon molten configuration

Fig. 8 An example of microstructure at melt area

As shown in Fig. 4 and Fig. 5, when the power density decreased, the shearing strength and the welded area also decreased, but the shearing stress increased gradually. Therefore, the shearing stress was investigated in relation to the ratio (R) of the upper-plate thickness to the depth of the standard molten configuration, and the obtained result is shown in Fig. 9.

A large value of R shows that the welded plane is located in the lower part of the standard molten configuration. The shearing stress increased linearly with R . Namely, it was recognized from Fig. 9 that the lower the welded plane in the depth of the standard configuration, the larger the shearing stress. The reason for this is that, as shown in the microphotograph in Fig. 8, the slip stress which acts along the grain boundaries is the main stress at the upper part of the standard molten configuration, and the shearing stress which acts to cut across the grains is the main stress at the lower part of the configuration.

The following empirical formula was obtained from the relationship of the shearing force to R shown in Fig. 9:

$$\sigma = 50 + 72.7R \quad (1)$$

When the standard molten configuration is approximated by an ellipsoid which is created by rotating the equation $x^2/a^2 + y^2/b^2 = 1$ around the center axis, the area of the cross section perpendicular to the center axis at the depth of y ($y/b = R$) is given by the following equation:

$$A = \pi x^2 = \pi a^2(1 - R^2) \quad (2)$$

where $2a$ is the melt diameter at the surface of the test piece and b is the melt depth. Therefore, when the upper plate is y in thickness, the shearing force at the depth of y is obtained from Eqs. (1) and (2):

Fig. 9 Relationship between location of sheared plane and shearing stress

$$F = A \cdot \sigma = \pi a^2 (1 - R^2) \cdot (50 + 72.7R) \quad (3)$$

When $2a$ is assumed to be constant, F is determined only by R and is maximum at $R = 0.39$. Namely, the shearing force is maximum when the welded plane is located at approximately 40 percent of the depth of the standard molten configuration.

4. Numerical Analysis of Standard Molten Configurations

4.1 A method of numerical analysis

The weld strength of aluminum is determined by the standard molten configurations and the location of the welded plane. When the configurations are obtained through numerical analysis, the weld strength at each welded plane can be calculated using Eq. (3).

Phenomena generated during laser machining differ with the magnitude of laser power density. An analysis of shapes machined with a high-power laser beam is very complicated because of phase changes, reflectivity changes of the laser beam, generation of a beam hole or laser plume, and changes of thermal properties of the test piece due to changing temperature.

Therefore, in this section, an analysis of heat conduction is carried out using an explicit finite difference method in order to obtain molten configurations. The thermal field is divided into small doughnut-type elements, as shown in Fig. 10. Here, heat loss from the surface of the test piece to the surrounding atmosphere is neglected in the calculation. The temperature gradient in the θ -direction can be neglected since the heat source and the test piece are axisymmetric. Therefore, the equation of heat conduction of a four-variable system (r - θ - z - t) was simplified into a three-variable system (r - z - t).

The fundamental equation of temperature $T(r, z, t)$, an initial condition and a boundary condition are shown as follows:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left(\chi \frac{\partial T}{\partial r} \right) + \frac{\chi}{r} \cdot \frac{\partial T}{\partial r} + \frac{\partial}{\partial z} \left(\chi \frac{\partial T}{\partial z} \right) \quad (4)$$

$$T(r, z, t) = 0 \quad : t = 0 \quad (5)$$

Fig. 10 Method of dividing a semi-infinite body into elements

$$-\lambda \frac{\partial T}{\partial z} = F(r), \quad : z = 0 \quad (6)$$

Here, r : radius, z : depth, t : time, χ : thermal diffusivity, λ : thermal conductivity, $F(r)$: spatial distribution of laser intensity.

Temperature $T(r, z, t)$ of an element (m, n) in time t is defined as follows:

$$T(r, z, t) = T_{m,n}^p \quad \begin{matrix} r = m \cdot \Delta r, z = n \cdot \Delta z \\ t = p \cdot \Delta t \end{matrix} \quad (7)$$

The difference equation of temperature for elements on the surface is

$$\begin{aligned} T_{m,0}^{p+1} = & \frac{2\Delta t \cdot \chi}{\Delta z \cdot \lambda} F(m\Delta r) + (1 - 2\zeta_z - 2\zeta_r) \cdot T_{m,0}^p \\ & + 2\zeta_z \cdot T_{m,1}^p + \zeta_r \left(1 - \frac{1}{2m} \right) \cdot T_{m-1,0}^p \\ & + \zeta_r \left(1 + \frac{1}{2m} \right) \cdot T_{m+1,0}^p \end{aligned} \quad (8)$$

Likewise, the difference equation of temperature for inner elements is given by

$$\begin{aligned} T_{m,n}^{p+1} = & (1 - 2\zeta_r - 2\zeta_z) \cdot T_{m,n}^p \\ & + \zeta_r \left(1 + \frac{1}{2m} \right) \cdot T_{m+1,n}^p \\ & + \zeta_r \left(1 - \frac{1}{2m} \right) \cdot T_{m-1,n}^p + \zeta_z (T_{m,n+1}^p + T_{m,n-1}^p) \end{aligned} \quad (9)$$

Here, ζ_r and ζ_z are given by the following equations:

$$\zeta_r = \frac{\chi \cdot \Delta t}{(\Delta r)^2}, \quad \zeta_z = \frac{\chi \cdot \Delta t}{(\Delta z)^2} \quad (10)$$

χ and λ are obtained from the temperature dependency, as shown in the next section, and introduced into each equation.

4.2 Temperature dependencies of thermal constants

Exact thermal constants of the test piece must be used in order to analyze temperature distribution accurately or to precisely simulate shapes machined by laser beams. Figure 11 shows the temperature dependencies of λ and χ , which are necessary for the analysis of heat conduction. The marks $\bullet$ and $\circ$ show the values found in the literature⁽⁷⁾. The dependencies are approximated by the solid and dotted lines as shown in Fig. 11, and introduced into the calculation.

4.3 Quantifications of laser waveforms and spatial distribution of laser intensity

In general, normal pulsed laser beams have very complicated and different waveforms according to each oscillator. Therefore, the actual waveforms used in the experiments, must be introduced into the calculations to analyze the heat conduction precisely.

In this paper, the forms were quantified as the change in power density with each short interval of time. Figure 12 shows an example of waveforms used in this study. The forms are approximated as a series

of rectangular waveforms in 5 μ s.

Likewise, the spatial distribution of laser intensity must also be quantified and introduced into the calculations, since it greatly affects analyzed results of heat conduction. Figure 13 shows the spatial distribution used in this study. The dotted and the solid lines are the measured and the approximated results, respectively.

Figure 14 shows the method of approximating the measured result. The following equation was obtained by developing equations using the assumption that the volume of the body rotated around the center axis corresponds to the laser energy E irradiated during the pulse duration τ :

$$\begin{cases} F(r) = \frac{n \cdot E}{\pi r_0^2 (1 - e^{-n}) \cdot \tau} \exp\left(-\frac{n \cdot r^2}{r_0^2}\right) & r \leq r_0 \\ F(r) = 0 & r > r_0 \end{cases} \quad (11)$$

4.4 Method of introducing a beam hole into the calculation

In laser machining processes, a beam hole is generated in the melt zone by the vapor pressure, and

the laser beam is introduced deep into the melt zone through the beam hole. Therefore, when a laser beam of high power density is irradiated onto the surface of a test piece and a deep melt zone is generated, the beam hole must be considered in the calculation. The generation process of a beam hole is assumed to be as shown in Fig. 15⁽⁸⁾. When the top element (A) on the center axis absorbs a certain amount of the latent heat necessary for vaporization and is removed, the melt near the center axis is pushed down and out by the vapor pressure. Thus, a beam hole is generated in the melt zone, as shown in Fig. 15(b). These processes are introduced into the calculation.

Figure 16 shows a configuration of a beam hole and the spatial distribution of laser power at the surface of a test piece. It was assumed in the calculation that the spatial distribution of laser power in the beam hole is similar to the distribution at the surface, since the diameter of the laser beam is small as compared with that of the melt zone, and the laser

Fig. 11 Dependencies of thermal conductivity and thermal diffusivity of aluminum on temperature

Fig. 12 An example of laser waveform oscillated from the system used in this study

Fig. 13 Measured result and approximate curve of the laser beam profile used in this study

Fig. 14 A method for quantifying the approximate curve of the laser beam profile

Fig. 15 A model for introducing a beam hole into the calculation

Fig. 16 Power distribution of laser beam at the surface and assumed configuration of a beam hole in the melt zone

beam is irradiated as an almost-parallel beam.

4.5 Comparison between experimental and calculated results of standard molten configurations

Figure 17 shows the configurations in each pulse duration when the irradiation energy is 10 J and the defocused value is 2 mm. The dotted and the solid lines show the experimental and the calculated results, respectively. Both results agreed well in each pulse duration. However, a slight difference between both results was recognized near the surface of the test piece and the lower part of the melt zone. Therefore, when the welded plane is located near the top or the bottom of the standard molten configuration, although such a case is unusual, some errors may appear in the calculated weld strength. The weld strength can be obtained using the calculated results

of standard molten configurations and Eq. (3). Namely, the strength can be obtained using the ratio R of the upper-plate thickness to the maximum melt depth of the configuration. For example, when the pulse duration is 2.8 ms, the irradiation energy is 10 J and the upper-plate thickness is 0.4 mm, the weld strength is calculated to be 31.8 N using the relations of $2a=0.8$ and $R=0.4/1.7$. This calculated value agrees well with the experimental value: 32.3 N.

Figure 18 shows the relationship between the results of weld strength obtained by the above-mentioned method and experimental results. On the whole, the calculated values are slightly larger than the experimental ones, but the calculation errors are less than 25%. It has been proven that the weld strength can be estimated using the molten configuration obtained by the numerical calculation, and conversely, necessary irradiating conditions of laser beams to obtain a certain weld strength can be determined easily by this calculation method.

Fig. 18 Comparison of weld strength between experimental results and calculated results

5. Conclusions

It was said that aluminum is difficult to weld since it has high thermal conductivity and reflectivity. Therefore, the relationship between the welding conditions and the weld strength of aluminum was investigated. The molten configurations were obtained by means of numerical analysis, and the weld strength was investigated using the obtained configurations. The results obtained were as follows:

(1) The weld strength showed the maximum value at the optimum power density (P_0). When the power density was less than P_0 , the weld strength decreased with decreasing power density because the welded area was not sufficient. When the power density was more than P_0 , the weld strength decreased due to the growth of the removed zone.

(2) The strength of the lapped spot welding of aluminum was shown by the empirical formula. It was clarified by the analysis of this formula that the weld strength was maximum when the welded plane was located at 40% of the depth of the standard molten configuration.

(3) The molten configurations can be obtained by means of numerical analysis employed with the temperature dependencies of thermal constants. The weld strength obtained using the configurations and the empirical formula agreed well with the experimental

one. From the above-mentioned results, it has been proven that the weld strength can be estimated and that the necessary irradiating conditions of laser beams to obtain a certain weld strength can be determined easily.

Acknowledgements

The authors wish to express their gratitude to Prof. Hisayoshi SATO of I.I.S. in Tokyo Univ. and Prof. Masayuki IKEDA of Hokkaido Univ. for their valuable advice. The authors also would like to thank Yoshinori ONODERA, Teruyuki MURAKAMI, Hiroshi ITO, Minoru OWADA and Akihiro YAMAUCHI for cooperation in the experimentation, programming and data processing.

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