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Welding of Thin Foils with Elliptical Beams†

ABE Nobuyuki*, FUNADA Yoshinori** and TSUKAMOTO Masahiro *

Abstract

Recently industrial products and components are being made smaller to reduce energy consumption and save space, and this trend needs to employ an advanced micro welding method for thin foils less than 100μm thick. In this report, in order to examine the applicability of a direct diode laser system with an elliptical beam, butt-, lap- and edge-welding were performed with thin metallic foils less than 100μm in thickness. It was found that the elliptical shape direct diode laser beam was effective to form a weld bead with the narrow width at high welding speed rather than with the ordinary circular laser beam. The direct diode laser with an elliptical beam enabled butt-welding of thin stainless steel foils with the thickness down to 40μm, lap-welding of thin stainless foils of 20μm in thickness onto a thick substrate and edge-welding of INCONEL718 thin foils of 100μm in thickness without crack.

KEY WORDS: (Direct Diode Laser) (Thin Foil) (Welding) (Beam Shape) (Elliptical Beam)

1. Introduction

In the electronics and precision machining industries, there are many products and parts manufactured by welding of thin metallic foils, such as pressure sensors with diaphragms, welded bellows and steel belts. Recently such parts and components are being made smaller to increase their energy efficiency and achieve greater compactness. This has created the need for an advanced welding method suitable for thin foils of 100μm or less in thickness.

It becomes difficult to weld thin foils using an ordinary processing method such as arc welding or plasma welding when its thickness is reduced to less than 100μm, since molten metal is likely to drop down before solidification due to the wide heated area. Laser heat sources can heat a smaller area because of their ability to be finely focused[1)], however, CO_2 lasers, Nd:YAG lasers and other commonly used laser systems have the drawback of high initial cost, complicated system and low energy conversion efficiency.

Diode lasers offer many advantages including high conversion efficiency, small size and a long lifetime[2)], but it is difficult to focus a laser beam to a circular shape, since the divergence angle of the beam differs with the emitting axis. In contrast, a laser beam from a diode laser can be focused with an elliptical shape easily even though the power density is lower than the conventional laser beam. For this reason, the principal applications for diode lasers are limited to surface treatment and plastic material joining[3, 4)]. It has been thought that a direct diode laser is not suitable for micro processing requiring a micro circular spot and high power density.

However, thin metallic foil welding which is a kind of micro welding requires a narrower weld bead. A laser beam from a diode laser can be focused elliptically with a narrow width, although its power density is low. It is expected that this feature is applicable to thin metallic foil welding because of the low heat capacity of thin foils.

In this paper, the applicability of an elliptical beam of direct diode laser on thin foil micro welding was estimated with thermal conduction analysis by the finite element method. Then, butt-, lap- and edge-welds for thin metallic foils whose thickness were less than 100μm were welded using the direct diode laser with an elliptical beam in order to examine its practical use.

2. Influence of Beam Shape on Temperature Distribution during Thin Foil Welding

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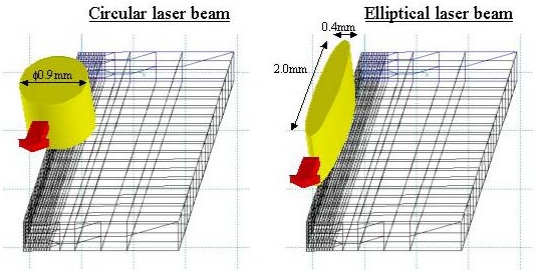

Figure 1 Symmetric models used for thermal conduction analysis by FEM.

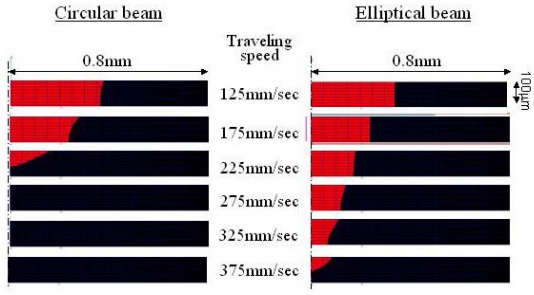

Figure 2 Comparison of temperature distributions over the melting point of stainless steel (1678K) at various welding speeds.

Thermal conduction analysis using a finite element method was performed in order to estimate the influence of beam shape on thin foil micro welding.

Figure 1, the symmetric models (length: 10mm, width: 2mm, thickness: 100μm) were used for the FEM analysis. Temperature distributions along the depth of the models irradiated with circular or elliptical shape beams at various welding speeds were calculated. The size of the circular beam was ϕ0.9mm, and that of the elliptical beam was 2.0mm x 0.4mm. The elliptical beam moved along its long axis. The output power of the laser beam was the same at 300W. The heating areas of both lasers were the same, and the power densities were also the same at 47kW/cm^2. Absorption coefficient of stainless steel was assumed to be 35%.

Figure 2 shows the temperature distributions of the cross section at the center of the model. The area where the temperature exceeded melting point of stainless steel (1673K) was displayed. The elliptical laser beam enabled a melt deeper along the depth at higher welding speed rather than the circular laser beam. Furthermore, the elliptical laser beam formed a narrower melting area as compared with the circular laser beam. It is thought that these results were due to high heat input within the narrow bead width along a welding direction by the elliptical shape of the laser beam. The elliptical laser beam of direct diode laser is expected to be suitable for the micro thin foil welding, when they are used in long axis direction.

3. Butt-Welding of Thin Foils

In order to examine the results of thermal conduction analysis, butt-welding experiment was performed. A schematic diagram of butt-welding of thin foils is shown in **Fig.3**. A direct diode laser system (GTS500; SEPCTRA PHYSICS) was employed with an elliptical laser beam of 1.8mm x 0.4mm. For comparison, a fiber coupled diode laser system (LDL40-500; LASER LINE) was also employed with a circular laser beam of spot size ϕ0.9mm. Those spot areas were the same at 0.6mm^2. Stainless steel foils with a thickness of 100μm or less were used as specimens.

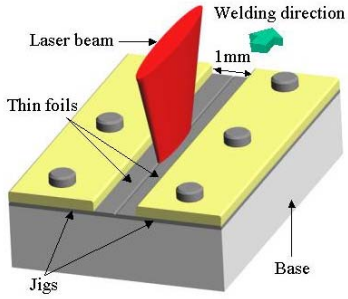

Figure 3 Schematic diagram of butt-welding of thin foils with direct diode lasers.

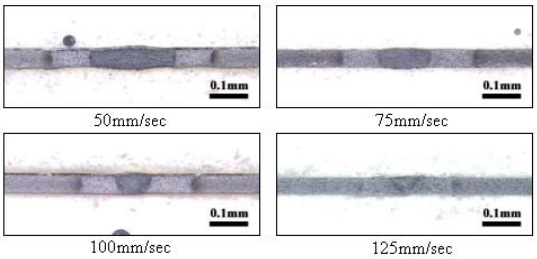

Figure 4 Cross sections of stainless steel thin foils of 100μm in thickness butt-welded with an output power of 100W.

Figure 4 shows the cross sections of weld bead for thin foils of 100μm in thickness welded at various welding speeds at an output power of 100W by direct diode laser with an elliptical laser beam. There were no defects such as porosity and cracks in the weld bead. **Figure 5** shows the comparison of weldable condition areas of thin stainless steel foils of 100μm in thickness between an elliptical laser beam and a circular laser beam. The weldable condition area with an elliptical laser beam shifted to the higher welding speed as compared with a circular laser beam. This means that the elliptical laser beam contributes to increase welding speed. This result agrees with the thermal conduction analysis.

Figure 6 shows the effect of foil thickness on the weldable condition area. With decreasing foil thickness, the required laser power decreased. However, the weldable condition area became extremely narrow. This means when the thickness of the foil becomes thinner, the output power of the laser has to be controlled more precisely. As shown in Fig.6, even a thin foils of 40μm in thickness could be welded, because the direct diode laser had superior controllability and stability of the output power.

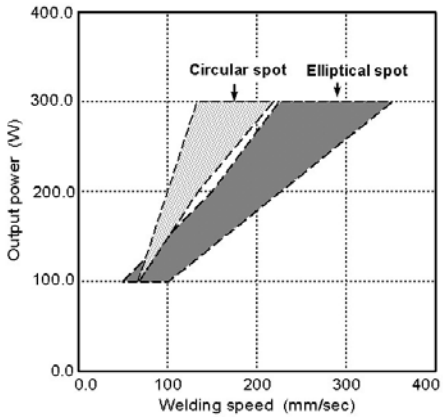

Figure 5 Comparison of beam shapes on butt-weldable conditions of thin foils of 100μm in thickness.

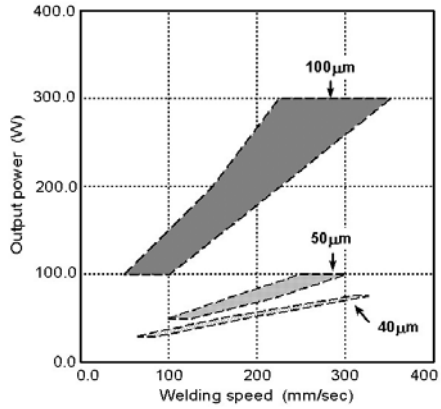

Figure 6 Comparison of thickness of thin foils on butt-weldable conditions using a direct diode laser with an elliptical laser beam.

The power density of the direct diode laser used in this experiment was 47kW/cm^2. It is much lower than the conventional pulsed laser with high power density which is usually used for micro welding. Therefore, welding type of this direct diode laser processing is heat conduction type[5]. The reason why the direct diode laser was applicable to thin foil welding in spite of heat conduction type welding, is due to the thickness of the foils and the formation of narrow weld beads by the irradiation with an elliptical narrow laser beam.

Furthermore, sputter and plasma plume which caused welding defects in the keyhole welding were not observed during welding owing to the heat conduction type welding. From these results, it was found that the direct diode laser was applicable to the micro thin foil butt-welding.

4. Lap-Welding of Thin Foil onto Thick Substrate

Electronics parts such as pressure sensors or electric cells requires lap-welding of thin foil onto thick substrate for their manufacture. In the case of lap-welding, a weld bead is required to penetrate the upper material, and reach into the lower substrate. Therefore, a keyhole type welding with a high power density is generally used.

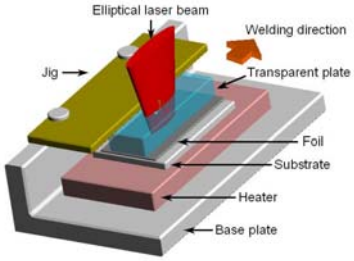

Figure 7 Schematic diagram of lap-welding of thin foils onto thick substrate with a direct diode laser.

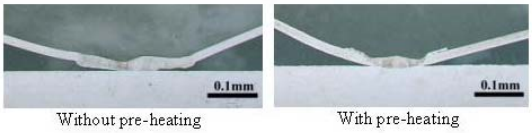

Figure 8 Comparison of cross sections of the lap-welded beads with and without preheating.

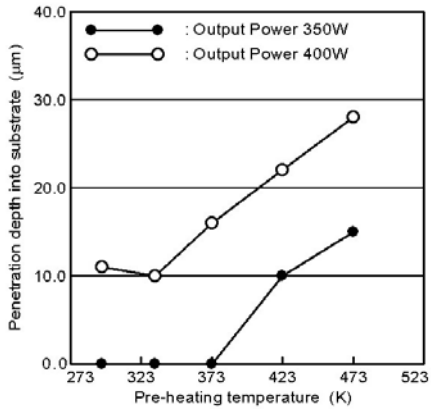

Figure 9 Effect of pre-heating temperature on penetration depth into substrate at a welding speed of 500mm/sec.

However, a direct diode laser with an elliptical beam can be expected to be applied to lap-welding when the lapped upper foil is extremely thin. So, lap-welding of thin foils on thick substrates was examined using a direct diode laser with an elliptical laser beam.

The samples used were stainless steel foil of 20μm in thickness onto the same material plates of 2mm in thickness as the substrate. The thin foil was lapped and fixed onto the thick substrate with a transparent plate, so that the lapped foil could make enough contact with the substrate for heat conduction. The lapped thin foil was welded with an elliptical laser beam from a direct diode laser through the transparent plate as shown in **Fig.7**. The substrate was mounted on a heater and pre-heated at a temperature up to 473K.

Figure 8 shows the comparison of cross sections of weld beads formed at an output power of 350W and a welding speed of 500mm/sec with and without pre-heating of the substrate. Without pre-heating, the weld bead did not penetrated the thin foil. In contrast, the weld bead penetrated the thin foil and reached to the

substrate at the pre-heating temperature of 473K. **Figure 9** shows the penetration depth of the weld beads into the substrate at various pre-heating temperatures. In the case of an output power of 350W, the pre-heating of 473K increased the penetration depth into the substrate up to 15μm. In the case of 400W, the penetration depth of the weld bead with the pre-heating of 473K was 28μm into the substrate. The penetration depth of the weld bead into the substrate was deeper with increasing pre-heating temperature. It is supposed that pre-heating assists the rise of the temperature of the substrate, having much heat capacity, and assists the melting of the surface of the substrate at low input laser power. It is confirmed that the pre-heating can overcome the drawback of the heat conducting type welding, and is effective to the lap-welding of the thin foil onto the thick substrate.

As the heat conduction of the upper foil to the lower substrate is thought to be affected by the surface roughness, a lap-welding experiment was performed using the as-rolled, polished and grounded substrates. **Figure 10** shows the cross sections of weld beads formed at an output power of 400W, a welding speed of 500mm/sec and a pre-heating temperature of 473K. In the case of lap-welding onto the polished substrate with roughness of Ra: 0.06μm, the penetration depth into the substrate was the deepest of the three kinds of substrates and reached to 28μm. In the case of lap-welding onto the as-rolled substrate with roughness of Ra: 0.13μm, the penetration depth was 20μm. Furthermore, in the case of lap-welding onto the grounded substrate with roughness of Ra: 0.22μm, the depth was 12μm. In this case, the upper thin foil melted widely. With increasing roughness of the surface of the substrate, the micro gap between the upper thin foil and the substrate increased. It was thought that heat conduction from the upper thin foil to the substrate was prevented. It can be confirmed that a direct diode laser can be applied to thin foil lap-welding when the roughness of the surface is enough small to keep the heat conduction to the substrate.

5. Edge-Welding of Thin Foils of INCONEL718

In semiconductor manufacturing plants, many welded bellows are used as flexible piping joints.

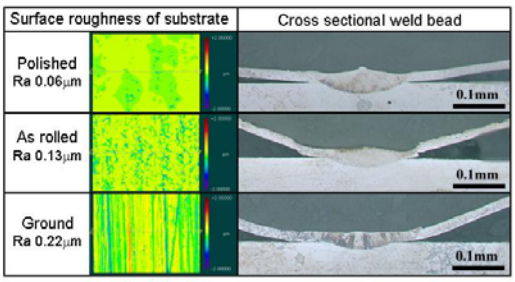

Figure 10 Influence of surface roughness of the substrates on the penetration depth of weld bead (laser power: 400W, welding speed: 500mm/sec, pre-heating temperature: 473K).

They are manufactured by edge-welding of thin foils with thicknesses under 100μm. Recently, Ni-based alloy is required to be used as a material for welded bellows because of its superior corrosion resistance and high strength at high temperature. They are generally produced by laser welding using a pulsed Nd:YAG laser. However, this process has two drawbacks: low productivity due to the low welding speed and generation of defects in the weld bead. Therefore, in order to examine whether a direct diode laser was applicable to manufacturing of welded bellows, edge-welding of INCONEL718 thin foils with a thickness of 100μm was examined using a direct diode laser.

A direct diode laser system used for thin foil edge-welding has a maximum output power of 200W with an elliptical laser beam of 2.0mm x 0.1mm. The laser head was equipped with a diachronic mirror that enables monitoring of the irradiated point from the direction of the laser beam. Two thin foils were lapped with no space using a jig as shown in **Fig.11**. Edge-welding was performed by moving the specimens parallel to the long axis of the elliptical laser beam. The output power was changed from 50 to 150W, and the welding speed was changed from 20 to 190mm/sec.

Figure 12 shows the weldable condition area of thin foil edge-welding, determined by welding speed and output power. When a welding speed was too fast, at low power, a sound appearance of the weld bead was not

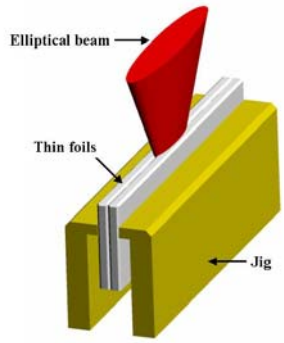

Figure 11 Schematic diagram of edge-welding of thin foils with a direct diode laser.

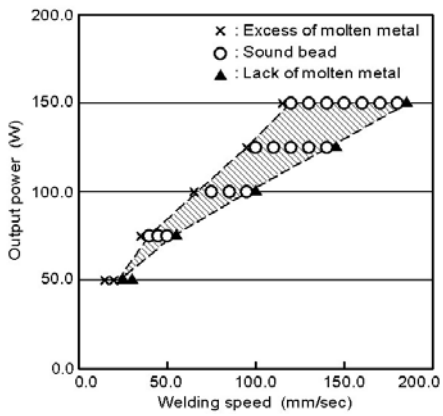

Figure 12 Weldable condition area of thin foils of INCONEL718 with a direct diode laser.

obtained because of lack of molten metal. A continuous weld bead was obtained at high power and high speed because of excess of molten metal. There were weldable speed ranges at each output power. Weldable speed reached 185mm/sec at an output power of 150W. This welding speed range was considerably faster than the 10mm/sec for the pulsed Nd:YAG laser conventionally used for manufacturing welding bellows. At a lower output power, the weldable speed was slower and the weldable area was narrower. In other words, edge-welding with the direct diode laser was possible at low output power even though the weldable speed range was quite narrow. This was due to the superior repeatability and controllability of the direct diode laser's output power.

Figure 13 shows the cross sections of weld beads formed at various welding conditions. They show a round shape resulting from surface tension. There was no porosity in the weld bead, however a crack was formed which thought to be a solidification crack, often generated in weld beads formed not only by conventional laser welding but also by arc welding for INCONEL718. **Figure 14** shows the relationship between a crack length and welding speed. The crack length increased significantly at welding speeds under 100mm/sec. In contrast, a crack length could be suppressed to less than 20μm, and edge-welding was possible with no defect when the welding speed exceeded 100mm/sec. It was found that a direct diode laser was applicable to edge-welding of thin foils at high speed area.

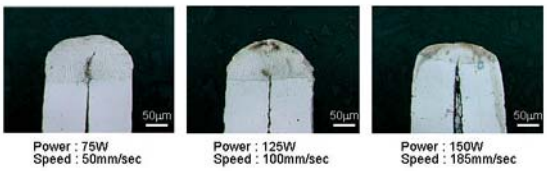

Figure 13 Cross sections of weld bead of thin INCONEL718 foils at edge-welding with a direct diode laser.

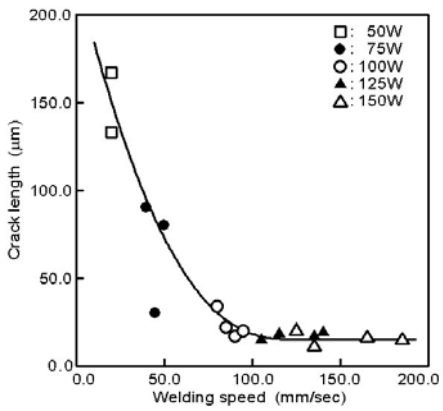

Figure 14 Influence of welding speed on crack length in weld bead formed with a direct diode laser.

6. Conclusion

In order to estimate the applicability of a direct diode laser with an elliptical beam to the micro thin foil welding, heat conduction analysis with FEM was performed. And in order to examine the results from analysis, butt-, lap- and edge-welding of thin foils were performed. The results obtained were as follows:

(1) An elliptical laser beam from a direct diode laser was effective in increasing welding speed and narrowing the width of the weld bead rather than a circular laser beam with the same power and power density.

(2) A direct diode laser with an output power of 300W enabled the butt-welding of stainless steel thin foils with a thickness of 100μm at high welding speeds over 300mm/sec. Also, it is possible to weld thin foils with a thickness down to 40μm.

(3) Lap-welding of stainless thin foils with thickness of 20μm onto a thick substrate of 2mm was possible at a high welding speed over 500mm/sec at an output power of 400W. Pre-heating and fixing using transparent plates were effective in increasing the penetration depth of weld beads into the substrate. Furthermore, the penetration depth increased when the surface roughness became smoother.

(4) Edge-welding of INCONEL718 thin foils with a thickness of 100μm was possible at a high welding speed of 185mm/sec and an output power of 150W. Although a crack was formed in the weld bead, the crack length was suppressed under 20μm at a welding speed of over 100mm/sec.

(5) From these results, it was concluded that a direct diode laser processing with an elliptical beam was applicable to micro thin foil welding.

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