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Citation	Transactions of JWRI. 2005, 34(1), p. 19-23
Version Type	VoR
URL	https://doi.org/10.18910/9012
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Micro Welding of Thin Stainless Steel Foil with a Direct Diode Laser†

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Abstract

Recently, industrial product parts and components are being made smaller to reduce energy consumption and save space, creating a growing need for the micro-welding of thin foil less than 100μm thick. For this purpose, laser processing is expected to be the method of choice because it allows more precise heat control compared with arc and plasma processing. In this report, the practicability of welding thin stainless steel foil with a direct diode laser system was investigated. The elliptically shaped laser beam of the direct diode laser enabled successful butt-welding of thin stainless steel foil 100μm and less in thickness. At a output power of 100W, 100μm and 50μm thick foils could be welded at a high speed of 6.0m/min and 18.0m/min, respectively. They had narrow bead widths of 100μm which was narrower than the beam size of the laser. No spatter or plasma plume was observed when welding without an assist gas. The tensile strength of the weld bead was nearly the same as that of the base material.

KEY WORDS: (Diode Laser), (Micro Welding), (Thin Foil), (Butt Welding), (High Speed Welding)

1. INTRODUCTION

In the electronics and precision machining industries many parts, such as pressure sensors with diaphragms, bellows and steel belts, are manufactured by welding together thin metallic sheets. 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 foil 100μm or less in thickness. It is difficult to weld such thin foil using an ordinary processing method such as arc welding or plasma welding, as molten metal is likely to drop down before solidification due to the wide heated area. Thin foil welding requires a heat source that heats a smaller area. Laser heat sources heat a smaller area because of their ability to be finely focused. However, CO_2 lasers, Nd:YAG lasers and other commonly used laser systems have the drawback of low energy conversion efficiency.

Diode lasers offer many advantages including high conversion efficiency, small size, and a long lifetime. The authors previously applied a high power 2kW class diode laser to the welding of metallic sheets ranging in thickness from 150μm to 3mm[1, 2]. However, it was difficult to weld thin foil below 100μm in thickness, most probably due to the fact that high power diode lasers employing an optical fiber have a circular beam shape; at a low power density, the beam is too large to weld thin foil, while if a finely focused beam is used the power density becomes too high resulting in plasma formation and welding defects. Direct diode lasers without an optical fiber have an elliptical beam shape which is effective in the formation of a narrow bead with high heat input without plasma formation and welding defects. In this paper, a welding system for thin foils was manufactured consisting a 500W class diode laser without an optical fiber, and the practicability of an elliptical direct beam from it was investigated for welding thin stainless steel foil 100μm and 50μm in thickness.

2. EXPERIMENTAL APPARATUS

2.1 Direct diode laser micro-welding system

The micro-welding system used for test welding of thin foil is shown in **Fig. 1**. It consists of a micro-positioning stage, a micro-monitor system and a direct diode laser with a maximum output power of 500W and a wavelength of 808nm. The laser head is ϕ65mm x 300mm and weighs 2kg. The micro-positioning stage and micro-monitor system are used for precisely aligning the laser beam along a contact line of specimens. Specimens were directly irradiated at a normal angle without an optical fiber.

The output characteristics of the laser head were

† Received on July 1, 2005

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

measured with a power meter. The output power increased proportionally to the input current as shown in **Fig. 2** (a). The beam profile was measured using a beam profiler. **Figure 2** (b) shows the beam profile at the focal point. The shape of the beam was elliptical, and the beam size was 0.3 x 1.8mm. The mean power density at the maximum power of 500W was 92kW/cm^2. The work distance between specimen and the laser head was 47mm.

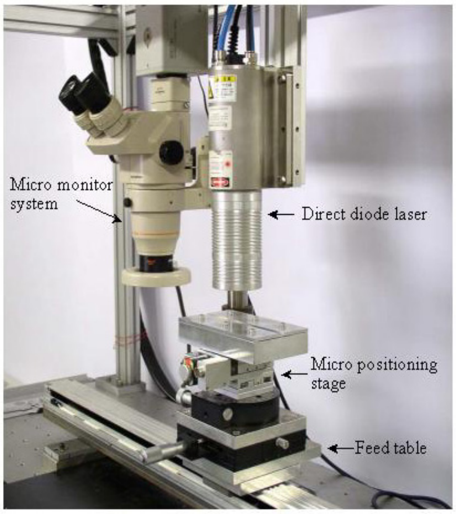
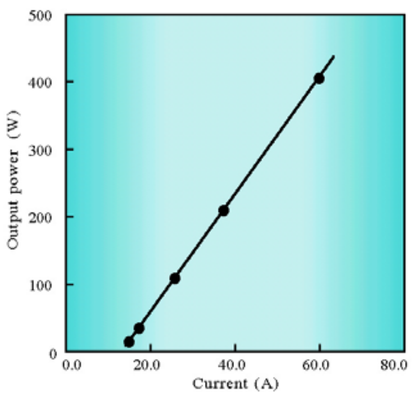
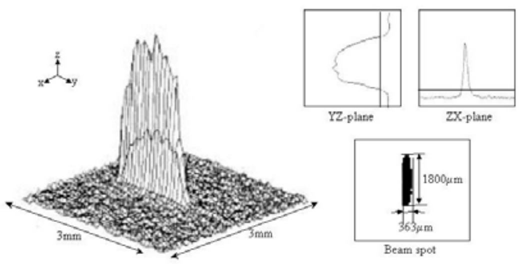


Figure 1 Micro-welding system with diode laser



(a) P-I characteristic



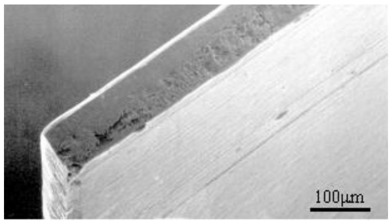
(b) Beam profile

Figure 2 P-I characteristic and beam profile at focal point

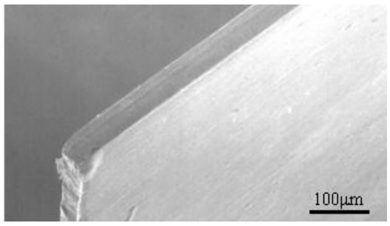
2.2 Specimen, welding conditions and evaluation method

The specimens used were stainless steel foil (SUS304H) 100μm and 50μm in thickness. The length and width were 70mm and 12.5mm, respectively. Their edges were finished by grinding as shown in **Fig. 3**, so that the two specimens made good contact with each other without a gap. The specimens were fixed on the micro-positioning stage using welding jigs. The contact line was precisely aligned with the irradiation point of the beam and positioned parallel to the long axis of the beam with the micro-monitor system. The micro-positioning stage traveled parallel to the long axis of the elliptical beam as shown in **Fig. 4**. The laser beam irradiated the surface of the specimens at the focal point under the welding conditions as shown in **Table 1**.

Cross sections of the weld beads were polished and electrochemically etched and observed using an optical microscope. The tensile strength of the weld beads was evaluated with a tensile strength tester.



(a) 100μm thick foil



(b) 50μm thick foil

Figure 3 SEM images of edges of 50μm and 100μm thick foils used for welding test.

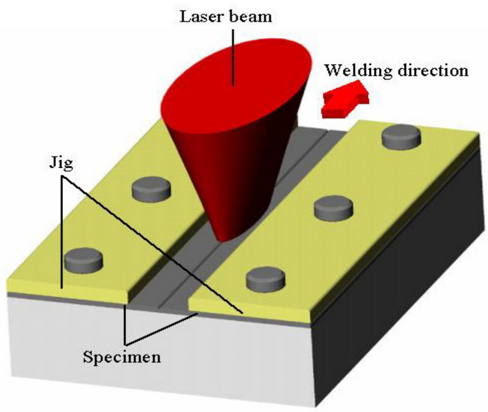


Figure 4 Schematic illustration of micro- welding with elliptical laser beam.

Table 1 Welding conditions

Thickness (μm)	Output power (W)	Weld speed (m/min)
50	50	4.5 – 9.0
	75	9.0 – 15.0
	100	13.5 – 19.5
100	100	2.1 – 7.5
	200	7.5 – 15.0
	300	12.0 – 22.5

3. RESULTS AND DISCUSSION

3.1 Appearance of weld bead

Figure 5 shows optical microscope photographs of front and rear appearance of the weld beads of 100μm thick foil specimens welded at various speeds at output powers 100W and 300W. At an output power of 100W, a sound bead was formed in the range from 3.0 to 6.0m/min. At welding speed faster than 7.5m/min, no weld bead could be observed on the rear face. In contrast, holes were observed in the weld bead at welding speeds slower than 2.1m/min. It is conceivable that the holes in the weld bead were caused by condensation of the molten metal due to surface tension. There are optimum weldable speed ranges for laser powers. At an output power of 300W, a sound bead was formed in the range from 13.5 to 21.0m/min. At welding speeds slower than 12.0m/min, holes were observed, and at welding speeds faster than 22.5m/min, no weld bead could be obtained on the rear face.

Figure 6 shows optical microscope photographs of front and rear appearance of the weld beads of 50μm thick foil specimens welded at various speeds and output powers of 50W and 100W. At an output power of 100W, the foils could be welded in the range from15.0 to 18.0m/min. The welding speed range was shifted toward higher speed compared with 100μm thick foils. In the case of 50μm foil welding, a sound bead could be obtained in the range from 6.0 to 7.5m/min at an output power of 50W, that is, an extremely lower power density of 9.2kW/cm^2. These results confirmed that sound butt-welding of 100μm and 50μm thick foil was possible with a direct diode laser.

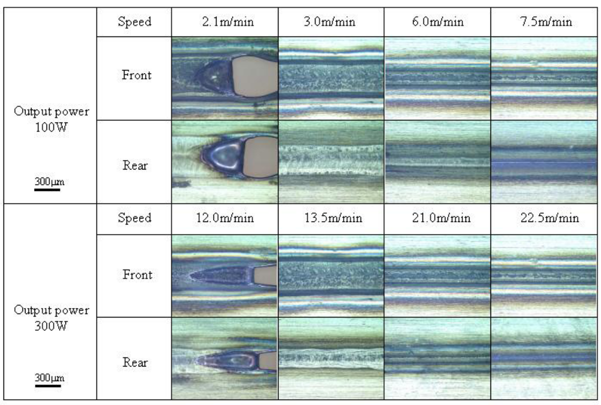


Figure 5 Microscope photographs of front and rear faces of weld beads of 100μm foil.

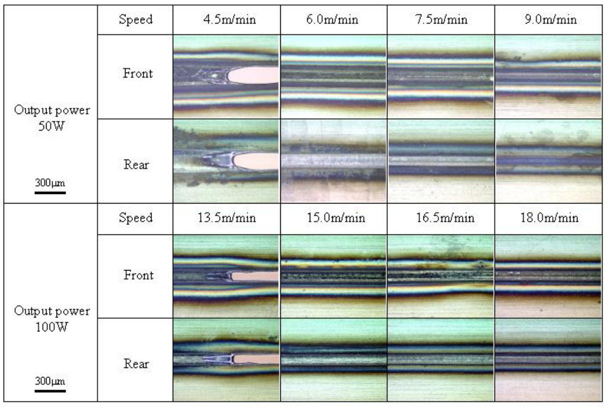


Figure 6 Microscope photographs of front and rear faces of weld beads of 50μm foil.

3.2 Weldable speed area for thin foils

Figure 7 shows the weldable speed areas of 100mm and 50mm thick foils against output power. At an output power of 300W, the weldable speed range for 100μm thick foil is 13.5 to 21.0m/min. However, it narrows to between 3.0 and 6.0m/min at a lower output power of 100W. In the case of 50μm thick foils, the weldabe speed range at an output power of 100W is 15.0 to 18.0m/min. However, it narrows to between 6.0 and 7.5m/min at a lower output power of 50W. The weldable speed range becomes narrower with decreasing output power.

100μm thick foils could be welded within a speed range of 13.5 to 21.0m/min at an output power of 300W. 50μm thick foils could be welded at a similarly high speed at an output power of 100W, but the weldable speed range was narrowed to between 15.0 and 18.0m/min. The weldable speed range further narrowed to between 6.0m/min and 7.5m/min at an output power of 50W. From these results it was concluded that decreasing output power and decreasing foil thickness narrow the weldable speed range. Therefore, more precise control of the welding conditions including both welding speed and output power will be required for thinner foils, such as the 20μm thickness used for a pressure sensor.

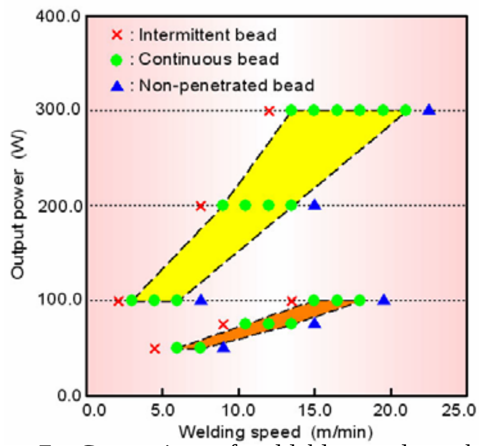


Figure 7 Comparison of weldable speed area between 100μm thick foil and 50μm thick foil

3.3 Cross section of weld bead

Figure 8 (a) and (b) show optical microscope photographs of cross sections of weld beads of 100µm and 50µm thick foil at an output power of 100W. The cross section has a heat conducting type bead shape rather than the keyhole type which is seen in CO_2 or Nd:YAG laser welding. It was found that the thin foil welding was possible with a direct diode laser which has lower power density than CO_2 or Nd:YAG laser welding. The lower power density results in very calm welding that forms smooth beads even without an assist gas. This strongly suggests that a direct diode laser is much more suitable for thin foil welding than CO_2 laser or Nd:YAG laser.

Figure 9 shows the overview of 50µm thick foils welded at an output power of 75W and a welding speed of 10.5m/min. The welded specimen has very smooth weld bead with little distortion. Welding of 50µm thick foils was possible using an elliptical beam produced by a direct diode laser with a power density of 13.7kW/cm^2, and contributed to a narrow weld bead width, and avoidance of thermal distortion.

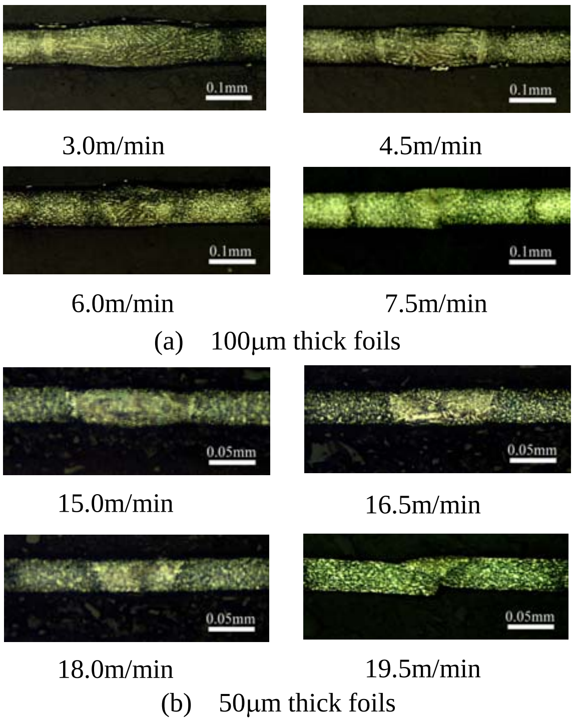


Figure 8 Cross-sections of weld beads of 100µm and 50µm in thickness at an output power of 100W .

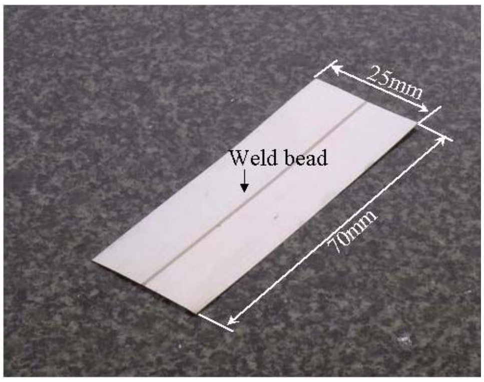


Figure 9 Overview of a welded foil of 50µm in thickness at an output power of 75W and a welding speed of 10.5m/min.

3.4 Observation of welding phenomena

The phenomena during thin foil welding were observed from the front of the welding direction using a CCD camera. **Figure 10** shows a typical photograph taken during welding at an output power of 75W and a welding speed of 10.5m/min.

The bright spot at the center of the photograph is the laser irradiation area. It shows the shape of the molten metal produced by irradiation with the laser beam, whose width is much narrower than 1mm. This is due to the elliptical beam shape of the direct diode laser which irradiates the contact line of the specimen with its long axis.

Neither spatter nor plasma plume were observed around this area, even though no assist gas nor shield gas was used. It was found that the welding phenomena with the direct diode laser were quite calm. The lower power density of diode lasers as compared to CO_2 lasers and Nd:YAG lasers contributes to the calm welding phenomena, with the result that there is no spatter or plasma plume.

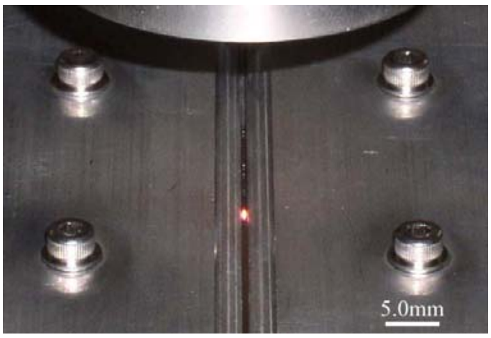


Figure 10 Laser irradiation speed situation during welding of foil 50µm in thickness at the output power of 75W and the welding speed of 10.5m/min.

3.5 Tensile strength of welded foil

In order to evaluate the tensile strength of the welded foil, tensile fracture tests were carried out. The results are shown in **Table 2** for welded thin foils of 50μm in thickness at typical combinations of output power and welding speed which produced sound beads. The mean tensile strength was more than 1200MPa, which is nearly equal to the nominal strength of SUS304H.

Figure 11 shows a typical cross section of a fractured sample. The fracture occurred not in the bead, but rather in the heat affected zone due to the fact that direct diode laser welding produces a smooth bead with no defects produced by the welding.

3.6 Critical width of weld bead

Figure 12 (a) and (b) show the relationship between the bead width and welding speed at several output powers when welding 100μm and 50μm thick foil, respectively. The bead width drastically decreased with increasing welding speed. In the case of 100μm thick foil, a full penetration continuous bead was obtained at 100W when the bead width was less than 300μm. When the bead width was more than 300μm, an intermittent bead was formed due to condensation of the molten metal. In the case of 50μm thick foil, a bead width below 150μm was required for obtaining a continuous bead. These widths can be thought as the critical widths below which a continuous bead was obtained. The critical widths were three to four times larger than the foil's thickness.

Table 2 Tensile strength of weld beads of 50μm thick foil

Output power (W)	Welding speed (m/min)	Strength (MPa)
50	7.5	1223
75	10.5	1287
100	16.5	1241

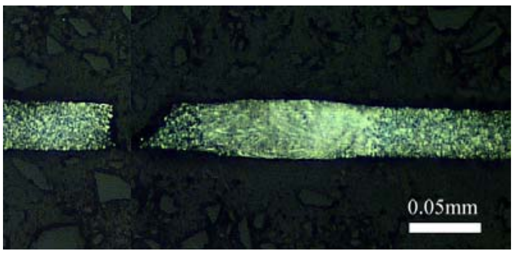


Figure 11 Microscope photograph of cross-section of fractured 50μm thick foil welded at an output power of 75W and welding speed of 10.5m/min.

Formation of an intermittent weld bead is caused by condensation of the molten metal due to surface tension. The change in welding phenomena from a continuous bead to an intermittent bead occurs when the surface area of the rectangular molten pool becomes larger than that of spherically condensed molten metal as shown in the upper illustration in Figure (a). If it is assumed that the width of the rectangular molten pool produced by the elliptical beam is equal to the diameter of the spherically condensed molten metal, the rectangular molten pool's surface area will become larger than that of the spherically condensed molten metal when the rectangular molten pool's width exceeds three times its thickness. It is thought that an intermittent bead is formed when the bead width exceeds three times the foil's thickness as shown in **Fig. 12**. Therefore, in order to weld thin foil with a full-penetrated weld bead, its width must be below the three or four times of the thickness.

4. CONCLUSION

Butt-welding of 100μm and 50μm thick stainless steel foil (SUS304H) was investigated using a 500W class direct diode laser with a beam size of 0.3 x 1.8mm and a maximum power density of 91kW/cm^2. The following results were obtained.

(1) The direct diode laser was able to weld 50μm thick foil at a high speed of 18.0m/min with an output power of 100W.
(2) The bead shape was heat conduction welding type.
(3) The welding phenomena with a direct diode laser were very calm, and no spatter or plasma plume generation was observed even without an assist gas.
(4) The tensile strength of the welded foil was nearly equal to the nominal value of the base material.
(5) In order to weld thin foil, the bead width must be narrower than three times the foil thickness. A direct diode laser was able to form such a narrow bead through precision control of the output power and welding speed.

5. ACKNOWLEDGMENTS

The authors would like to express many thanks to Mr. H. Mamezuka for his invaluable contribution in conducting the experiments

6. REFERENCES

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