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Welding and Forming of Steel Plates with Diode Laser†

Nobuyuki ABE*, Ritsuko HIGASHINO**, Naoki NAKAGAWA**, Masahiro TSUKAMOTO***, Shoji MIYAKE****, Shuichi NOGUCHI***** and Masakazu HAYASHI******

Abstract

Diode lasers offer the advantage of higher conversion efficiency than conventional CO₂ and YAG lasers, but their beam properties are very poor. Nevertheless, they can be focused into a spot 0.96mm in diameter at a laser power of 2kW. The feasibility was therefore examined of welding and forming steel plates using a diode laser with a high power of 2kW and a high power density of 236kW/cm². Steel plates ranging from 0.5mm to 10mm in thickness were successfully welded without porosities or cracks. The diode laser beam's top hat shape was found to be suitable for welding. Laser forming of thick steel plates with a high power diode laser was also investigated. A 5mm thick steel plate was bent at an angle of about 13.5° by scanning it 30 times with a 3.2mm diameter beam at a power of 1kW and a scanning speed of 1.5m/min. Even though the diode laser has a short focusing length, it was found to be suitable for laser forming because it does not require the melting of the specimen's surface.

KEY WRODS: (Diode laser)(High power)(High power density)(Welding)(Forming)

1. Introduction

Lasers are considered as ideal tools for the thermal processing of materials because of their ability to finely focus energy. The most commonly used devices in thermal processing are CO₂ and Nd:YAG lasers, which can generate high power levels. Due to their low conversion efficiency, however, such high power lasers must be quite large and waste quite large amounts of electric power. Diode lasers have very high efficiency, of over 40%, although they have the drawbacks of poor beam quality, low power and low brightness. Recently, however, there have been great improvements in the output power and beam quality. The authors believe that direct diode lasers will be the next generation of materials processing lasers, and thus have been developing high power density direct diode laser systems and studying their materials processing characteristics in a three-stage project.

In the first stage, a 15W class diode laser system was investigated which provided a maximum output power of 7.5W at a diode current of 35A, with a 1/e² beam diameter of 182μm and a mean power density of 25kW/cm². A penetration depth of 0.03mm was achieved for a specimen of 0.06mm thick mild steel plate at a welding speed of 0.3m/min, proving that the direct diode laser has the potential to be applied to welding.

In the second stage, a 50W class direct diode laser materials processing system was developed. In order to generate both higher power and a higher power density, the effectiveness of a combination method employing polarization coupling and wavelength coupling was examined using 4 diode arrays of 15W. At a diode current of 31.5A, a maximum output power of 38W was obtained with a 1/e² beam diameter of 264μm and a mean power density of 60kW/cm². This system welded 0.4mm thick SS400 mild steel with a penetration depth of 0.2mm at a welding speed of 0.06m/min. These second stage results showed that beams from 4 diode arrays could be effectively combined into a single beam using polarization coupling and wavelength coupling, and the increase in power density improved both the penetration depth and the bead shape.

In the third stage, a 2kW class direct diode laser materials processing system was developed using four

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1kW diode stack modules. At a diode current of 57A, an output power of 2kW was achieved with a \(1/e^2\) beam diameter of 966\(\mu\)m and a mean power density of 235kW/cm\(^2\). Although strong plasma formation was observed, full penetration single pass welding of 5mm thick SUS304 stainless steel plate was successfully achieved at a welding speed of 0.24m/min by suppressing the laser plasma with assist gas, obtaining a parallel bead shape with no welding defects. High speed welding of thin 1mm thick mild steel plate was also achieved at a welding speed of 4m/min, also with a parallel bead shape and no welding defects.

In this report, the 2kW diode laser system's welding characteristics for thick and thin steel plates are further described, as well as the new diode laser application of forming thick plates.

2. Welding of steel plates with diode laser

The welding characteristics of a high power density diode laser were examined by butt-welding SUS304 stainless steel plates with a thickness of 0.15, 0.3, 1, 2, 3, 5, and 10mm. Figure 1 shows a photographic overview of a 2kW class diode laser system, its specifications, the output power's dependency on the diode module current, and the beam profile at the focal point. The \(1/e^2\) beam diameter was 966\(\mu\)m, and a mean power density of 235kW/cm\(^2\) was achieved. Figure 2 shows the output power stability over a 30-minute period at output powers of 0.1kW, 0.5kW and 2.2kW. A good stability of 4.8% was obtained even at a low output power of 0.1kW.

![Diode laser head](image)

Diode laser head
- Wavelength: 807 and 940nm
- Size: 520 × 700 × 220mm
- Weight: 90kg

Power supply unit
- Output: 50V, 70A × 4
- Size: 535 × 600 × 970mm
- Weight: 160kg

Water cooling unit
- Size: 560 × 730 × 1650mm
- Weight: 100kg

Focusing unit
- Focusing distance: 50mm, 60mm
- Weight: 0.98 kg, 2kg

Fig.1 High power density direct diode laser system.

![Output power stability](image)

Fig.2 Output power stability of the diode laser system.

2.1 Thick plate welding

Figure 3 shows the penetration depth's dependency on the welding speed at an output power of 2kW when butt-welding of 1 to 5mm thick SUS304 stainless steel. With decreasing welding speed, the penetration depth increased and full penetration welding of 1mm thick SUS304 stainless steel was achieved at a welding speed of 4.5m/min. At a slower welding speed of 0.24m/min., full penetration butt-welding of 5mm thick SUS304 stainless steel was successfully achieved. For comparison purposes, the penetration depths of a conventional CO\(_2\) laser\(^4\) and Nd:YAG laser\(^5\) are shown.

![Penetration depth dependency](image)

Fig.3 Penetration depth dependency on the welding speed when welding various thicknesses of SUS304 stainless steel.
in the same figure. Although the 5kW CO₂ laser's penetration depth is about 1.5 times greater than the diode laser's, it is approximately equal to that of the diode laser if the CO₂ laser's power is proportionately reduced to 2kW, since the beam diameters are nearly equal. The equivalent penetration depth was obtained with a 1.8kW Nd:YAG laser. Figure 4 shows the welding bead section and beam profile of a Nd:YAG laser⁶ and diode laser. Both shapes are quite similar, showing that the diode laser maybe used for the same type of welding applications if a sufficiently high power and high power density are achieved, because the diode laser has competitive capital and running costs compared with conventional Nd:YAG lasers⁷.

Figure 5 shows cross sections of the butt-welded beads of 1 to 5mm thick SUS304 stainless steel at an output power of 2kW. The bead cross sections show a parallel bead shape without any welding defects. Strong plasma formation was observed during high power density beam welding of thick plates without an assist gas, resulting in serious damage to the protective glass. The use of assist gas together with side gas, however, effectively suppressed the laser plasma. Figure 6 shows the penetration depth's dependency on the assist gas flow rate at a welding speed of 0.023m/min when butt-welding of 10mm thick SUS304 stainless steel. As the assist gas flow rate increased, the penetration depth also increased. Figure 7 shows the laser plasma and cross sections of the weld bead with side gas only and with both assist gas and side gas. The laser plasma was completely suppressed at a He assist gas flow rate of 70l/min with a side gas flow rate of 100l/min. The results clearly showed that a high power density diode laser can be used for welding thick plates. The penetration depth is not inferior to other lasers, such as CO₂ and Nd:YAG lasers, which are currently used for materials processing.
2.2 Thin plate welding

For deep penetration welding of thick plates, a high power density is required but results in strong plasma formation. The application of diode lasers to the welding of thick plates is thus restricted because of the diode lasers' short focal distance. On the other hand, a low power density is sufficient for thin plate welding. The authors therefore examined butt-welding of thin SUS304 stainless steel plates ranging in thickness from 0.15 to 0.5mm as a possible application for diode lasers.

Figure 8 shows the butt-welded beads at various powers and plate thicknesses at a welding speed of 3m/min. Although there were burn-through defects in regions of high heat input, such as when welding 0.5mm plate at a power of 1.5kW, a good bead was obtained when the proper power was chosen, in this case 0.5kW. A sound bead was also obtained for 0.15mm thick plate by decreasing the laser power to 0.1kW.

Figure 9 shows the results of butt-welding 0.15mm thick SUS304 stainless steel at an output power of 100W. Although burn-through defects were observed at welding speeds of 1 and 1.5m/min, a good weld bead was obtained at a welding speed of 2m/min. Figure 9 also shows the laser plasma formed while welding 0.15mm thick SUS304 stainless steel at a laser power of 0.1kW.

Compared with the strong plasma formation during high power density welding, no laser plasma was observed when welding at low power such as 0.1kW. It was thus concluded that welding of thin plates is another very suitable application for diode lasers.

3. Forming of thick steel plates with diode laser

In order to examine the diode laser's feasibility for another materials processing application, laser forming
was performed using SUS304 stainless steel. The experimental apparatus is shown in Fig. 10. The SUS304 stainless steel specimens measured 100mm x 125mm with thicknesses of 2, 3, 4 and 5mm. The working distance was 40mm, the beam diameter was 3.2mm, and the mean power density was 10kW/cm². Figure 11 shows the relationship between the number of laser scans and the bending angle of various thickness SUS304 stainless steel plates at an output power of 1kW and laser scanning speed of 1.5m/min. The specimens were cooled to room temperature between each laser scan. The amount of bending was proportional to the number of laser scans. A 2mm thick specimen of SUS304 stainless steel was bent about 16° after 10 laser scans. However, the bending angle per laser scan cycle decreased with increasing plate thickness because the input power was not enough to sufficiently raise the temperature of the thicker plates.

So the authors measured the specimens' temperature of 5mm thick plate. Figure 12 shows the specimens' temperature history at a distance of 7mm from the laser heating line and the change in bending angle. In this case, the specimen was cooled to 360K after laser scanning of 10 times, and this cycle repeated 3 times. It was enough to sufficiently raise the temperature of the specimen. As shown in Fig. 12, the bending angle increased proportionally with increased heating cycle. The rise in temperature is thought to determine the bending angle and be the most important parameter for laser forming of thick plates. Figure 13 shows laser forming of 5mm thick SUS304 stainless steel at an output power of 1kW with 30 laser scans at a scanning speed of 1.5m/min. By ensuring a sufficient temperature rise, a forming angle of 13.5° was achieved with only 30 laser scans. This 5mm thick plate was formed U-shape when this 30 laser scan heating cycle was repeated on 18 lines separated by 5mm as shown in Fig. 14. The process of laser forming does not require
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Fig.14 U-shaped forming of 5mm thick SUS 304 stainless steel plate.

a high power density because it is not necessary to melt the surface. It was thus concluded that laser forming is another very suitable application for diode lasers.

4. Conclusions

In order to examine the feasibility of using a 2kW high power density diode laser system for welding tests were performed on SUS304 stainless steel plates ranging in thickness from 0.15 to 10mm. Even at a small working distance of 30mm, the high power density diode laser system successfully performed deep penetration welding when the proper assist gas flow and side gas flow were used.

In order to examine the diode laser’s possible application to a new type of materials processing, laser forming of SUS304 stainless steel was performed. A forming angle of 13.5° was achieved for 5mm thick SUS304 stainless steel with 30 laser scans. Laser forming is another very promising application for diode lasers because it does not require a high power density.

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