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Suppression of spatter in deep penetration welding of pure copper plate using blue-IR superimposed laser

Shumpei Fujio[a,*], Mao Sudo[a], Keisuke Takenaka[b], Yuji Sato[b], Timotius Pasang[c], Masahiro Tsukamoto[b]

[a]*Graduate School of Engineering, Osaka University, 2-1 Yamadaoka Suita, Osaka 565-0871, Japan*
[b]*Joining and Welding Research Insitute, Osaka University, 11-1 Mihogaoka Ibaraki, Osaka 567-0047, Japan*
[c]*Department of Manufacturing & Mechanical Engineering & Technology, Oregon Institute of Technology, 3201 Campus Drive Klamath Falls, Oregon 97601, USA*

Abstract

In this research, a bead-on-plate welding of pure copper was conducted with a hybrid laser which superimposed an infrared (IR) laser and a high-intensity blue laser to achieve a deep-penetration and spatter-less welding of pure copper. In the hybrid laser welding, the blue laser was used for preheating to increase the absorptivity of pure copper for IR laser. To investigate an effect of the blue laser preheating, a welding with the hybrid laser was conducted varying the blue laser intensity. During welding, melt pool, keyhole, and spatter were observed. As the results, it was found that the IR laser was irradiated onto melted copper which has high absorptivity during the welding with the high-intensity blue laser preheating. This effect caused to ease a fluctuation of the absorptivity of copper and led to stabilize the melt pool and keyhole formation. Stabilization of them led to a reduction of spatters.

Keywords: Fiber laser; Blue diode laser; Welding, Copper; Spatter

1. Introduction

Pure copper is one of the key materials for the energy conservation and carbon neutrality based on its excellent heat and electric conductivity. Accompanying to the rapid growth of the demand for the pure copper, the high-quality welding process of pure copper has been needed as well.

Generally, tungsten inert gas arc (TIG) welding is used for copper welding in several industry (Ito et al., 2016). However, this process has some issues such as a low power density and a low processing speed.

On the other hands, laser is attracting attention as a heat source for the welding because of its advantages such as a high intensity, low heat input and high controllability. An IR (infrared) laser which has the wavelength of around 1000 nm is widely used to achieve a high-speed and deep penetration welding for steel (Chao et al., 2020), titanium (Ciazzo et al., 2013), and nickel (Ming et al., 2008). However, the welding of pure copper with an IR laser is challenging. This is due to the properties of pure copper. Pure copper has low light absorptivity for the IR region (lower than 10%). (Hummel et al., 2020) Also, the light absorptivity for IR increases with temperature and a jump of absorptivity occurs near the melting point. (Blom et al., 2003) This effect leads to unstable heat input during the deep penetration welding and results in unstable welding dynamics with spatters.

Recently, blue diode laser has been attracting attention for the pure copper welding. The blue diode laser has the wavelength of 450 nm and pure copper has high light absorptivity for this wavelength about 60%. (Hummel et al., 2020) Moreover, it is clarified that the temperature dependence of the light absorptivity for the blue laser is smaller than that of the IR region. (Morimoto et al., 2019) Because of these advantages, it has been clarified that the blue diode laser can supply an effective and stable heat input for pure copper. (Hara et al. 2020)

To realize a high-quality laser welding of pure copper, a blue-IR superimposed laser was developed. In the blue-IR superimposed laser, a blue diode laser is used as a preheating source to increase the light absorptivity of pure copper for IR laser. In our previous research, a welding of pure copper wire was conducted with a blue-IR superimposed laser using a 200 W class blue diode laser. It was found that the penetration depth of pure copper increased with the decrease of spatter by the blue diode laser preheating to about 1000 K. (Fujio et al. 2022)

In this research, to further increase the penetration depth and suppress the spatters, a 1.5 kW high power blue diode laser was used for preheating to increase the temperature of welding part locally. By using the 1.5 kW blue diode laser, it is expected that the pure copper in preheated area could be melted, and the light absorptivity of IR laser increased further.

Hereby, a bead-on-plate welding test of pure copper was conducted with a blue-IR superimposed laser using the 1.5 kW blue diode laser preheating. Through the experiment, an effect of blue diode laser intensity on the penetration depth and spatter formation was investigated.

2. Experimental setup

Fig. 1 shows a schematic diagram of experimental setup. A 1.5 kW single-mode fiber laser was employed as a welding source. A 1.5 kW class blue diode laser was used as a preheating source. Table. 1 shows experimental conditions of this research. The single-mode fiber laser was irradiated vertically onto the pure copper sample and the blue diode laser was irradiated from 45 degree from the vertical direction. Each laser spot was set at x:55 µm, y:54 µm for the single-mode fiber laser and x:424 µm, y:300 µm for the blue diode laser respectively. Both laser spots were centered and superimposed at the processing point. Each laser spot was scanned for 25 mm on the 2 mm thick pure copper plate fixed on the stage at the scanning speed of 100 mm/s. During scanning the stage, the single-mode fiber laser and the blue diode laser were irradiated simultaneously by controlling the laser irradiation time with a pulse generator (DG535. Stanford Research Systems). The output power of the single-mode fiber laser was set at 4.21×10^{7} W/cm^{2} and that of the blue diode laser was varied from 0 to 0.85×10^{6} W/cm^{2}.

During the laser irradiation, the spatters and the melt pool were observed with high-speed video cameras.

Observation conditions of cameras are listed in Table. 2.

From the image of high-speed video camera, the number of spatter generated per scanning length was measured and it was defined as spatter rate [/mm].

After the welding, the cross-section of the sample was observed with a microscope.

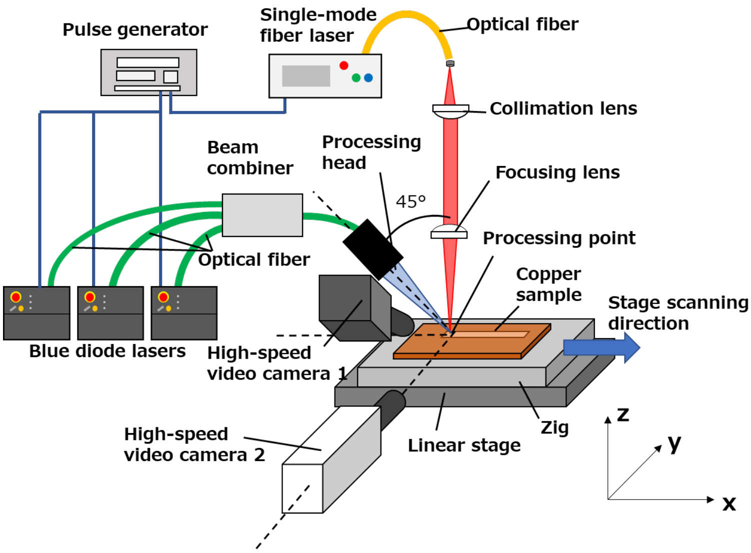

Fig. 1. Schematic diagram of experimental setup

Table 1. An example of a table

	Blue diode laser	Single-mode fiber laser
Wavelength	450 nm	1070 nm
Output power	0 ~ 850 W	1000 W
Spot size	x:424 µm, y:300 µm	x: 55 µm, y:54 µm
Intensity	0 ~ 0.85×10^{6} W/cm^2	4.21×10^{7} W/cm^2
Incident angle	45 °	0 °
Scanning speed	100 mm/s	
Sample	Oxygen-Free-Copper (>99.96%)	
Sample size	10 mm^w×30 mm^l×2 mm^t	
Shielding gas	Ar	
Gas flow rate	40 L/min	

Table 2. Observation conditions of high-speed video cameras

	Melt pool observation	Spatter observation
Flame rate	5000 fps	10000 fps
Shatter speed	50k	500k
Filming angle from the x-y surface	45°	0°

3. Results & Discussion

3.1. Analysis of spatter rate

During the welding of pure copper, spatters generated from the melt pool were observed with a high-speed video camera, and the spatter rate for each blue diode laser intensity was measured. Fig. 2 shows a correlation between spatter rate and the blue diode laser intensity. It was found that the spatter rate decreased with the increase of the blue diode laser intensity. With the 0.21×10^6 W/cm^2 blue diode laser, the spatter rate decreased by 32% from the single-mode fiber laser only. On the other hand, with the 0.85×10^6 W/cm^2 blue diode laser, the spatter rate decreased by 90% compared to the single-mode fiber laser only.

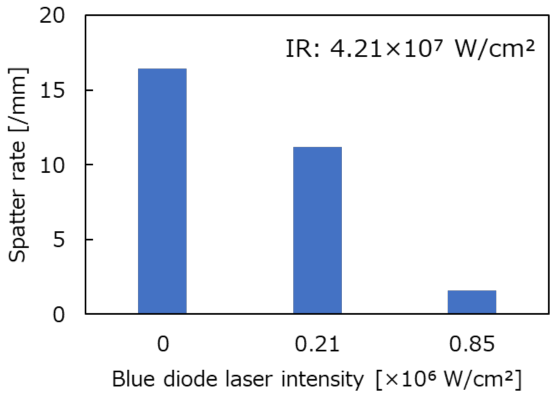

Fig. 2. Correlation between spatter rate and blue diode laser intensity in the blue-IR superimposed laser

3.2. Observation of cross-section

Fig. 3 shows the cross-sectional images of welding bead at the center. (a) is the single-mode fiber laser only and (b) is the single-mode fiber laser with the 0.85×10^6 W/cm^2 blue diode laser preheating. It was found that each cross-section showed a narrow and sharp form of deep penetration welding.

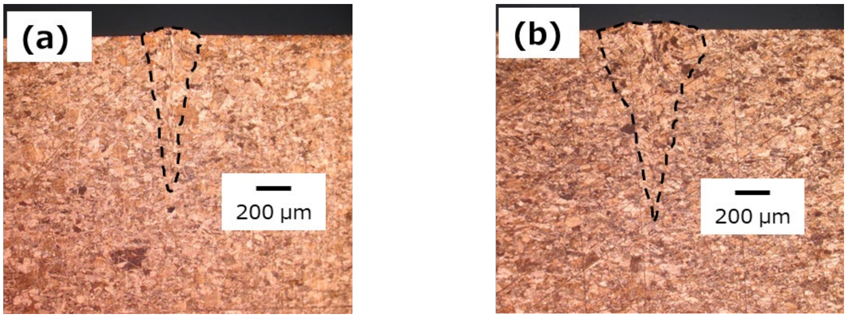

Fig. 3. Cross-sectional image of pure copper sample after irradiation of (a) single-mode fiber laser and (b) single-mode fiber laser with 0.85×10^6 W/cm^2 blue diode laser

Fig. 4 shows a correlation between the penetration depth and the superimposed blue diode laser intensity. It was found that the penetration depth of pure copper increased with the increase of blue diode laser intensity. The penetration depth of pure copper with 0.21×10^6 W/cm^2 blue diode laser preheating was 1.13 times higher than that of the single-mode fiber laser only. On the other hand, with 0.85×10^6 W/cm^2 blue diode laser, the penetration depth increased 1.35 times higher compared to the single-mode fiber laser only.

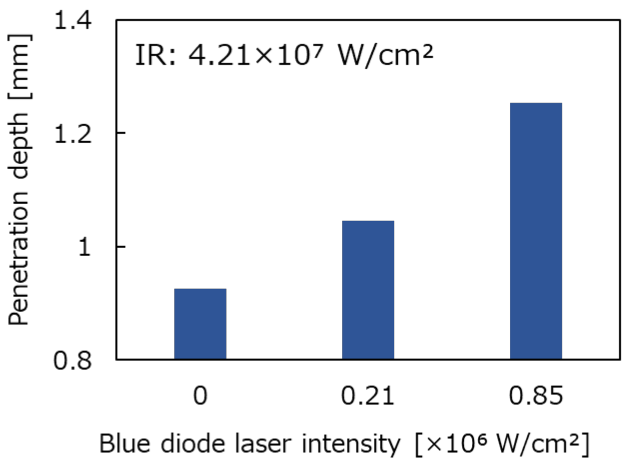

Fig. 4. Correlation between penetration depth and blue diode laser intensity

3.3. Observation of melt pool

To investigate the effect of blue diode laser intensity for the preheating, only the blue diode laser was irradiated onto pure copper sample, and the preheating process was observed with a high-speed video camera. Fig. 5 shows a surface of the copper sample while irradiating (a)0.21×10^6 W/cm^2 and (b)0.85×10^6 W/cm^2 blue diode laser respectively. With 0.21×10^6 W/cm^2 blue diode laser, the pure copper sample didn't melt and it was found that the pure copper was preheated within solid state. On the other hand, sample was melted with 0.85×10^6 W/cm^2 blue diode laser. From the results, it was found that the IR laser was irradiated onto melted copper in the welding with blue-IR superimposed laser using 0.85×10^6 W/cm^2 blue diode laser preheating. The light absorptivity of pure copper increases with the temperature and the jump of absorptivity is avoided by increasing the temperature of preheated area over melting point. This effect is considered to cause a suppression of spatter and increase of penetration depth with the increase of the blue diode laser intensity.

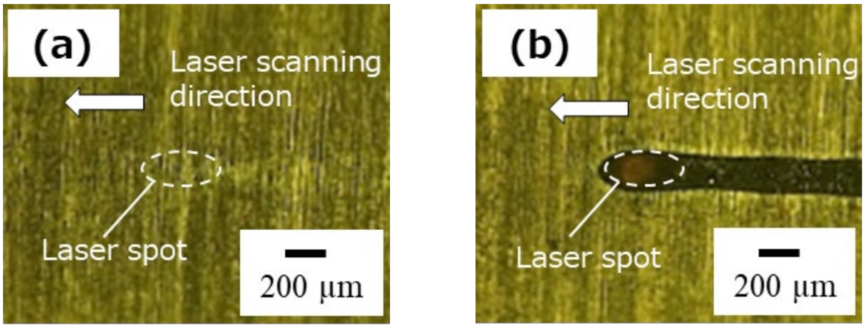

Fig. 5. View of copper sample during irradiation of (a) 0.21×10^6 W/cm^2 and (b) 0.85×10^6 W/cm^2 blue diode laser

4. Summary

In this research, a bead-on plate welding test of pure copper plate was conducted with the blue-IR superimposed laser. To realize a further spatter suppression and penetration depth increase, a high-power and high-intensity blue diode laser was employed as a preheating source. Through the experiment, the effect of blue diode laser intensity on the welding of pure copper with the single-mode fiber laser was investigated.

As the results, the spatter rate with the single-mode fiber laser decreased by 32% with the 0.21×10^6 W/cm^2 blue diode laser and 90% with the 0.85×10^6 W/cm^2 blue diode laser respectively. Also, the penetration depth of pure copper increased with the increase of superimposed blue diode laser intensity and the deep penetration welding of pure copper was acquired.

Moreover, it was found that the pure copper melted by preheating with the 0.85×10^6 W/cm^2 blue diode laser. This effect considered to cause a suppression of spatter and increase of the penetration depth with the increase of the blue diode laser intensity.

It was concluded that the spatter suppression was achieved in deep penetration welding of pure cooper with the single-mode fiber laser by using high-intensity blue diode laser preheating.

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