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Monitoring and Adaptive Control of Laser Spot Welding[†]

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Abstract

Recently the use of lead solder has been one of the important problems from the environmental viewpoint. Laser micro spot welding is thought to have a great potential as one process to replace the mounting of electronic components with lead solder. However, copper, one of the conductive materials for electronic products, has such a high thermal conductivity and such a high reflectivity that it is extremely difficult to produce stable high quality welds with a YAG laser beam of 1,064 nm in wavelength. Nevertheless, the constant production of sound welds is always required In this research, therefore, we developed an adaptive control system in micro welding of 0.2mm thick copper sheet with a fundamental YAG laser combined with an AO Q-switched second harmonic YAG laser. Then, the number of the second harmonic YAG laser pulses was controlled at 1 ms interval, according to a neural network judgment on the basis of the data of a reflected beam of the fundamental YAG laser and vibration of the specimen relating to the melting behavior.

KEY WORDS: (Laser Spot Welding), (In-Process Monitoring), (Adaptive Control), (Copper),
(Pulsed YAG Laser), (Q-Switched YAG Laser)

1. Introduction

Recently the reduction in environmental burden has been one of the important problems. For example, the use of solder containing lead should be restricted and many trials have been made to mount electric components with lead-free solder. However, since the melting point of lead-free solder (Sn-Ag) is 40 K higher, as compared with 456K, that of conventional solder (Sn-Pb), it is difficult to apply lead-free solder for mounting electric components which do not have heat resistance at 496K. In such cases, laser micro spot welding is thought to have a great potential instead. But pure copper, one of the common conductive materials for electronic products, has such a high thermal conductivity and such a high reflectivity that it is extremely difficult to produce stable high-quality welds with a YAG laser beam of 1,064 nm in wavelength. Thus the laser welding result of copper is strongly influenced by slight irregularities in its surface condition. It is necessary to develop a technology for the production of high-quality laser welds in pure copper.

In this research, we developed an adaptive control system for micro welding of copper sheet of 0.2mm in thickness by means of a fundamental YAG laser combined with an AO Q-switched second harmonic YAG laser. The objective of this study is to confirm the feasibility of this adaptive control system for producing sound spot welds by controlling the number of the second harmonic YAG laser pulses at 1ms intervals, according to the neural network judgment on the basis of a reflected beam of the fundamental YAG laser and the vibration of the specimen during welding.

2. Material and Experimental Procedures

The experimental specimen was 99.9% pure copper sheet 50^{w} x 40^{l} x 0.2^{t}mm. Combined beams of a fundamental YAG laser and an AO Q-switched second harmonic YAG laser (SHG-YAG laser) were irradiated perpendicularly to the specimen in the atmosphere

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without any shielding gas. The laser monitoring head and welding situation are shown in **Fig. 1**. The conditions of the laser beams are listed in **Table 1**. The start of the SHG-YAG laser irradiation was synchronized with the initiation of the fundamental YAG laser irradiation. A reflected laser beam of the fundamental YAG laser was measured by a silicon pin-photo diode was measured. The vertical vibration velocity of a specimen was measured at a point of 0.75 mm away from the center of the laser spot by a Doppler velocity meter. The velocity was considered to be the main signal depending upon the drilling process due to the shot of the AO Q-switched SHG-YAG laser [2].

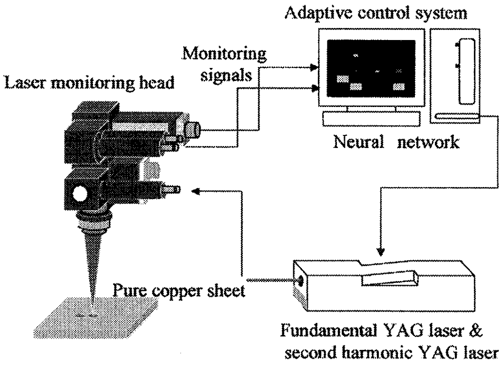


Fig. 1 Schematic experimental setup.

Table 1 Condition of laser beams used

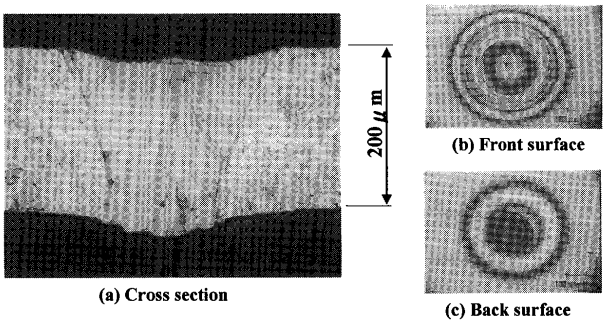
Laser parameter	Fundamental YAG laser beam	Second harmonic YAG laser beam
Laser power	10.4 J	0.8 mJ
Pulse duration	10 ms	78 ns
Number of laser shots	1 shot	1- 10shots
Frequency of laser pulse	—	1kHz
Laser focus	@focus	@focus
Spot diameter	0.4mm	0.05mm

3. Experimental Results and Discussion

3.1 Laser micro-spot weld in pure copper

In welding with combined beams of a fundamental YAG laser and an SHG-YAG laser, the formation of a fusion zone in the laser spot weld of pure copper was improved drastically by confining the fundamental laser beam inside the hole formed by the Q-switched SHG one [3]. The 0.2mm full penetration of pure copper sheet was made by 10 shots of the SHG-YAG laser pulse under the conditions of Table 1, as shown in **Fig. 2**. Figure 2 (a) shows a desirable penetration shape in the cross section of pure copper sheet. (b) shows the surface fusion zone of about 0.32mm in diameter. (c) shows the fusion zone of about 0.18mm in diameter on the back surface.

The desirable shape of full penetration suggests that the combined YAG laser beams were effective for the welding of pure copper.



(a) Cross section (b) Front surface (c) Back surface

Fig. 2 Cross-sectional and surface photos of lasers micro-spot weld in pure copper sheet.

3.2 In-process monitoring in laser micro spot welding for pure copper

3.2.1 Spot welding results with SHG-YAG laser

In a partially penetrated spot weld made by 7 pulse shots of the SHG-YAG laser under the conditions of Table 1, the power of the reflected beam of the fundamental YAG laser and the vertical vibration velocity of the specimen were measured during the irradiation of a fundamental YAG laser beam. **Figure 3** shows the surfaces subjected to laser irradiation. In the case of a sound spot weld, the average diameter of spot fusion zones was 0.184 mm as shown in 3 (a). The 5 concave surfaces, as shown in 3 (b), occurred at 7 pulse shots of SHG-YAG laser in 100 samples. As the number of SHG-YAG laser pulses increased, the ratio of the underfilled spot welds to the sound ones increased.

Fig. 3 Surface of spot weld fusion zones in copper sheets after laser welding, showing sound and underfilled welds.

3.2.2 Monitoring result of reflected beam of fundamental YAG laser during welding

Figure 4 shows the measured powers of the reflected beams of fundamental YAG lasers as a function of time, 0 ms represents the initiation time of the fundamental YAG laser pulse.

In the case of a sound spot weld as shown in Fig. 3 (a), the power of the reflected beam decreased slowly with an increase in the shot number of the second harmonic YAG laser. After irradiation termination of the SHG-YAG laser, the power of the reflected beam increased rapidly. On the other hand, in the case of an underfilled spot weld, as shown in Fig. 3 (b), the power of the reflected laser beam showed a similar tendency during the repetition of irradiation of the SHG-YAG laser. But, after termination of the repetition of laser irradiation, the power of the reflected beam decreased gradually. The formation of an underfilled spot weld was attributed to the phenomenon that molten copper was blown away as spatter, the reflected beam decreased, and thereafter the concave surface was formed.

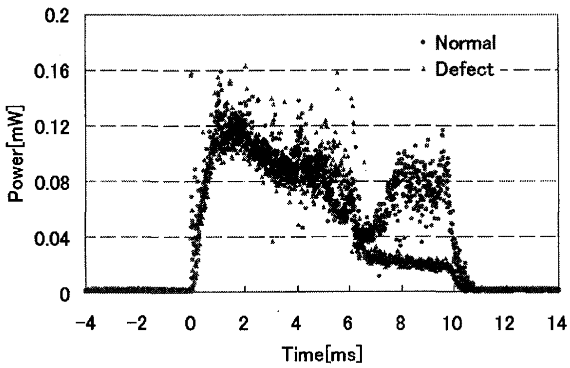


Fig. 4 Monitored reflected beam of fundamental YAG laser.

3.2.3 Monitoring result of vertical vibration velocity of specimen during laser welding

Figure 5 shows the measured results of the vertical vibration velocity of specimens during laser welding. The plus value of the velocity means that the specimen left the stage vertically.

In Fig. 5, the velocity of the specimen changed as if it synchronized with laser irradiation during repetition of laser irradiation. But, in the case of an underfilled spot weld, just after the termination of the repetition of laser irradiation the velocity changed more rapidly in the minus direction. The difference between a sound and an underfilled spot weld was considered to indicate that, in the case of underfilled spot weld, the large minus value of the vertical velocity of specimen was caused by the power of evaporation when part of the molten pool was blown away

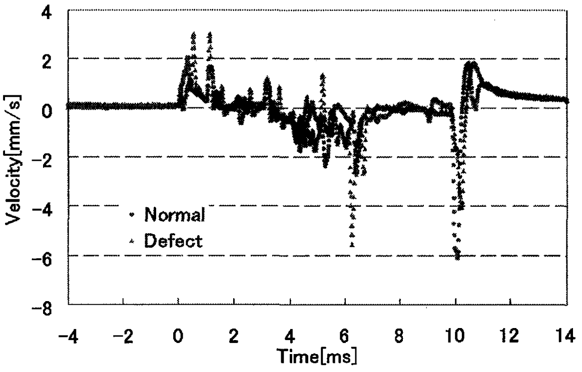


Fig. 5 Monitoring results of vertical vibration velocity of specimen during laser welding.

3.3 Adaptive control in laser micro-spot welding of pure copper

The conditions for the formation of an underfilled spot weld should be judged by the neural network model before the formation of concave surface due to spattering. The neural network deals with a nonlinear system and is suitable for multi input signals [4]. A neural network model is the typical back-propagation network as shown in **Fig. 6**. The neural network model had an input layer, an output layer, and two hidden layers. The input layer consists of 5 processing elements, both the hidden and output layer have one element respectively. The neural network was instructed by the experimental data of reflected beams of the fundamental YAG laser and the vertical vibration velocity of the specimen for both sound and underfilled spot welds.

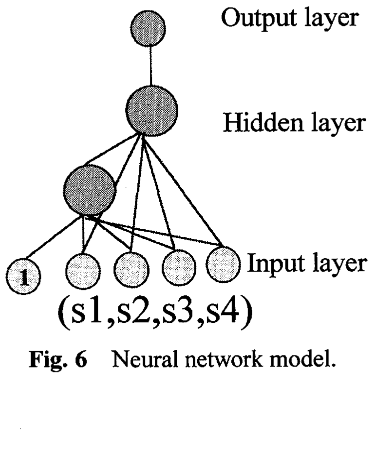


Fig. 6 Neural network model.

According to the judgment of the adaptive control system from the neural network on the basis of the above monitoring signals, the shooting number of the SHG-YAG laser was controlled at 1ms interval to produce a sound spot weld by preventing the generation of underfilled surface. **Table 2** gives the experimental results obtained by using the adaptive control. **Figure 7** shows the top surfaces of the spot welds made under adaptive control. It is found that the formation of an underfilled spot weld was prevented by the neural network judgment before the generation of a concave surface. However, the diameters of weld fusion zones ranged from 0.094mm to 0.23mm although their average diameter was 0.23mm. The shot number of the SHG-YAG laser was from 3 to 5 shots, and the average number was 4.3 shots

Table 2 Conditions of laser beams used and welding results

	Average	Maximun value	Minimum value
Diameter of molten part [μm]	184	230	94
Number of SHG-YAG Laser pulses	4.3	5	3
Underfill (Defect)	no existence		

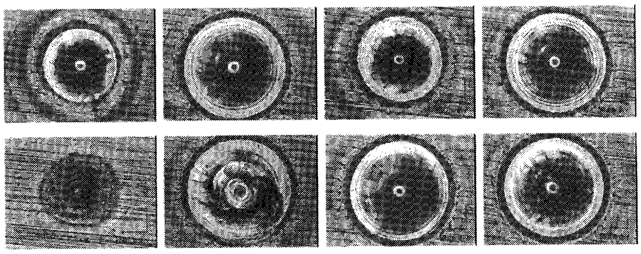


Fig. 7 Surface photos of spot weld fusion zones in Cu sheets produced under adaptive control.

4. Conclusions

The results obtained in this research can be summarized as follows.

(1) A reflected beam of the fundamental YAG laser and the vibration velocity of a specimen were measured during laser irradiation as input signals for intelligent laser process control. The shot number of SHG-YAG laser pulses was controlled at 1ms interval through a neural network instructed by experimental data. It was found that the intelligent laser process control could prevent the underfilled spot weld in micro welding of copper.

(2) The 0.2 mm full penetration welding of copper thin sheet was produced by means of combined laser beams with the fundamental laser and the AO Q-switched second harmonic YAG laser. The desirable shape of full penetration suggested that the combined YAG laser beams were effective for the welding of copper.

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