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Surface void suppression for pure copper by high-speed laser scanner welding

Masanori Miyagi[a,*], Xudong Zhang[a], Yousuke Kawahito[b], Seiji Katayama[b]

[a] Research & Development Group, Hitachi, Ltd. 1-1 Omika-cho 7 chome, Hitachi, Ibaraki, 319-1292, Japan
[b] Osaka University, Joining and Welding Research Institute, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

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ABSTRACT

Welding of copper was conducted using a single-mode fiber laser rotated at a high speed by a galvano scanner. The rotation diameter and frequency were changed to investigate the effect of the beam rotation on the welding quality. The rotation diameter changed from 0.3 to 1.0 mm and the rotation frequency changed from 77 to 285 Hz. The weld depth obtained with scanning is smaller than that obtained without scanning. The weld depth decreases as rotation frequency increases, regardless of the rotation diameter. The bead width obtained with scanning is larger than that obtained without scanning because of the larger laser radiation area. In the welding there is an unscanned area, based on the relationship between laser scanning conditions and welding speed, that makes the weld depth periodic. It was found that welding geometry can be controlled by adjusting scanning parameters. Spatter and surface voids decrease as rotation frequency and diameter increase. It was confirmed a scanning speed over 500 mm/s suppressed large spatter and surface voids.

1. Introduction

Copper is one of the materials most frequently used for the current-carrying components of batteries, power modules, industrial motors, etc. because of its high electrical performance and high formability. To take advantage of its great electrical performance, one needs welding technology that can produce metallurgical bonding over a large area. Copper's high thermal conductivity, however, makes it hard to obtain the high quality and highly effective welding needed for industrial use. Tungsten inert gas (TIG) welding is often used for welding small copper parts but does not provide enough heat to melt and join large ones. Friction Stir Welding (FSW), a solid-state welding method in which the material is stirred by the welding tool, can be used to weld large copper parts because it is a process without melting. Yufeng et al. (2012) investigated the relationship between FSW parameters and the microstructure and mechanical properties of welded copper plates. They reported that the microstructure and grain size in the welded area changed with different welding parameters, and as a result so did mechanical properties such as tensile strength and elongation. High performance of the welding portion can be obtained using FSW because it causes less deformation and fewer defects than other fusion joining processes do, but with some product structures there is some limitation to using FSW because of the huge force applied to during FSW. In addition, FSW is not suitable for structures that are complicated and compact because it is conducted by pressing a tool into the material. In case of resistance welding, it is difficult to achieve the bonding due to high electrical performance. Brazing is often used for copper welding because it can produce welds without defects, but the brazing process requires heat treatment and is therefore not a process suitable for use in mass-production. Furthermore, the brazing filler material changes the electrical properties of the welded portion. A highly effective high-quality process applicable in a small space is needed for welding current-carrying components, and a new welding process satisfying this demand is eagerly anticipated.

In recent years, during which remarkable progress in high-power and high-brightness lasers has been achieved, research and development efforts have been devoted to materials that, like copper, are hard to weld with a conventional laser. In laser welding of copper, it is difficult to form a melt pool because copper not only has high thermal conductivity but also shows high reflectivity at the 1-μm wavelength of the conventional laser light. Recently, however, many research works on the laser welding of copper with high-brightness and high-power lasers have been conducted.

* Corresponding author.
E-mail address: masanori.miyagi.dc@hitachi.com (M. Miyagi).

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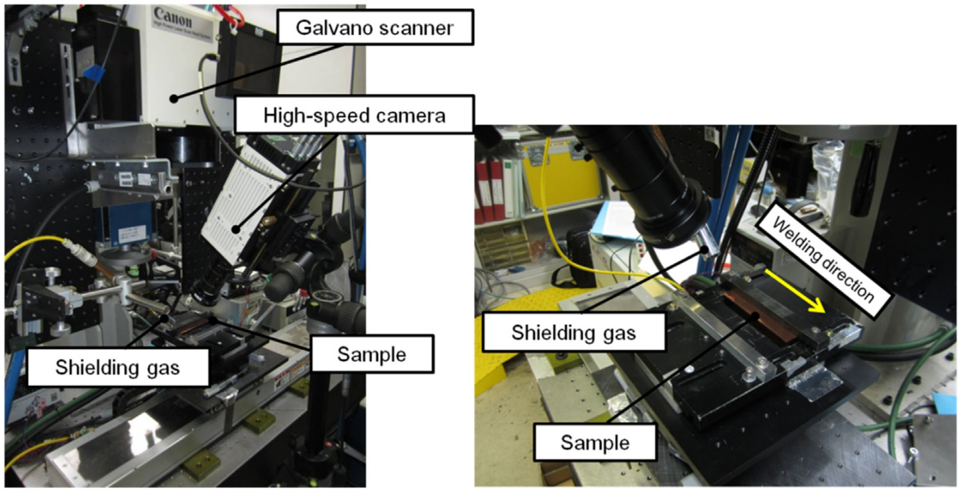

Fig. 1. Experimental setup for laser welding.

Petring and Goneghany (2011) investigated the effect of welding parameters such as laser power and welding speed on penetration depth and showed that it is necessary to select the beam size, laser power, and welding speed depending on the kind of Cu alloy and the weld geometry. Liebl et al. (2014) conducted welding experiments using multi-mode fiber lasers and pure copper, and they reported that the occurrence of melt pool ejection depended on laser power and welding speed: at laser powers over 3 kW, melt pool ejection was suppressed with welding speeds over 8–9 m/min. They also evaluated effect of shielding gas and reported that melt pool ejection was less likely to occur with helium gas than without it because of changes in the surface tension and convection of the melt pool. Hess et al. (2011) reported that using a combination of 1030-nm and 515-nm wavelength lasers for copper alloy welding enables a deeper penetration depth to be achieved than can be achieved using the 1030-nm wavelength laser separately. The combined laser process also reduced the occurrence of melt pool ejection. Combining laser welding of different wavelengths is effective for avoiding dramatic changes of laser absorption based on the difference of 1-μm laser absorption in liquid and solid copper. Heider et al. (2011a,b) examined the stabilization of the quality laser welding of copper by laser power modulation and reported that melt pool ejection for Cu-ETP and CuSn6 can be reduced drastically by modulating laser power with around 200 Hz. They also examined a welding process combining laser power modulation with a 515-nm laser and found that it can drastically reduce the melt pool ejection. Heider et al. (2014) evaluated the effect of laser power on the melt pool ejection with a 16-kW disk laser and reported that in case of high laser power, the welding speed range avoiding melt pool ejection is wider at lower speeds than it is with lower laser powers such as 2 or 5 kW. Heider et al. (2013) used high-speed X-ray imaging to observe melt pool dynamics related to melt pool ejection and reported that the bottom of the keyhole expanded momentarily and the pressure inside the keyhole became high, expelling the weld pool and resulting in the ejected molten metal becoming spatter. Miyagi and Zhang (2015) used high-speed X-ray imaging to observe the weld pool dynamics of laser welding of pure copper under several welding conditions and found the same mechanism of melt pool ejection reported by Heider et al. (2013). They also found that a large melt pool is not expelled by the pressure of keyhole expansion and, as a result, is less likely to cause a welding defect such as surface void. Thus it is reported that at welding speeds over 10 m/min, keyhole expansion doesn't occur, keyholes can be kept stable, and high-quality welding can be obtained.

One infers from the information provided above that in laser welding of copper, suppression of melt pool ejection is necessary to obtain high-quality welding. This inference is based on the results of studies examining laser power modulation, combined use of lasers with different wavelengths, and high-power laser welding. In the research discussed so far, we have focused on high-speed welding of high quality. Because the welding bead in high-speed welding is narrow, however, the accuracy of laser position alignment is an issue. On the other hand, a galvano scanner head that can enable high-power laser scanning has been developed recently. With this scanner head it is possible to weld with a rotating laser at a very high speed. Therefore it is assumed that the welding bead width can be increased while keeping high-speed laser movement. The objective of the research reported here was to obtain high-quality welding without melt pool ejection by using high-speed laser scanning.

2. Experimental procedures

A single-mode fiber laser with a maximum output power of 2 kW was used in order to avoid melt pool ejection. The laser beam was delivered by a 14-μm fiber, and the beam spot size at the focal point was 54 μm. The laser beam was irradiated at an angle of 10° to avoid reflecting off the copper. Sample movement was generated with a tool slide, and Ar gas was used as the shielding gas. Fig. 1 shows a photograph of the laser welding system with the galvano scanner.

The high-speed camera was used to better understand the welding phenomena. Since an illumination laser with a 940-nm wavelength was used in this setup, a band pass filter needed to be placed in front of the high-speed video camera. The image was captured by a high-speed video camera at a frame rate of 5 kHz. The welding was conducted using a laser rotated at a high speed by the galvano scanner. The rotation diameter and frequency were changed to investigate the effect of the beam rotation on the welding quality. Table 1 lists the welding conditions.

Copper welding using the galvano scanner was conducted for several rotation diameters and frequencies with two different welding speeds. Pure copper (C1100) was used for the experiments, and the copper plate dimensions were 100 × 20 × 2.5 mm. The joint configuration was a bead on the plate, and the welding length was 80 mm. The cross sections for macroscopic examination were prepared by etching with $FeCl_3 \bullet 6H_2O$ at room temperature for 10–60 s.

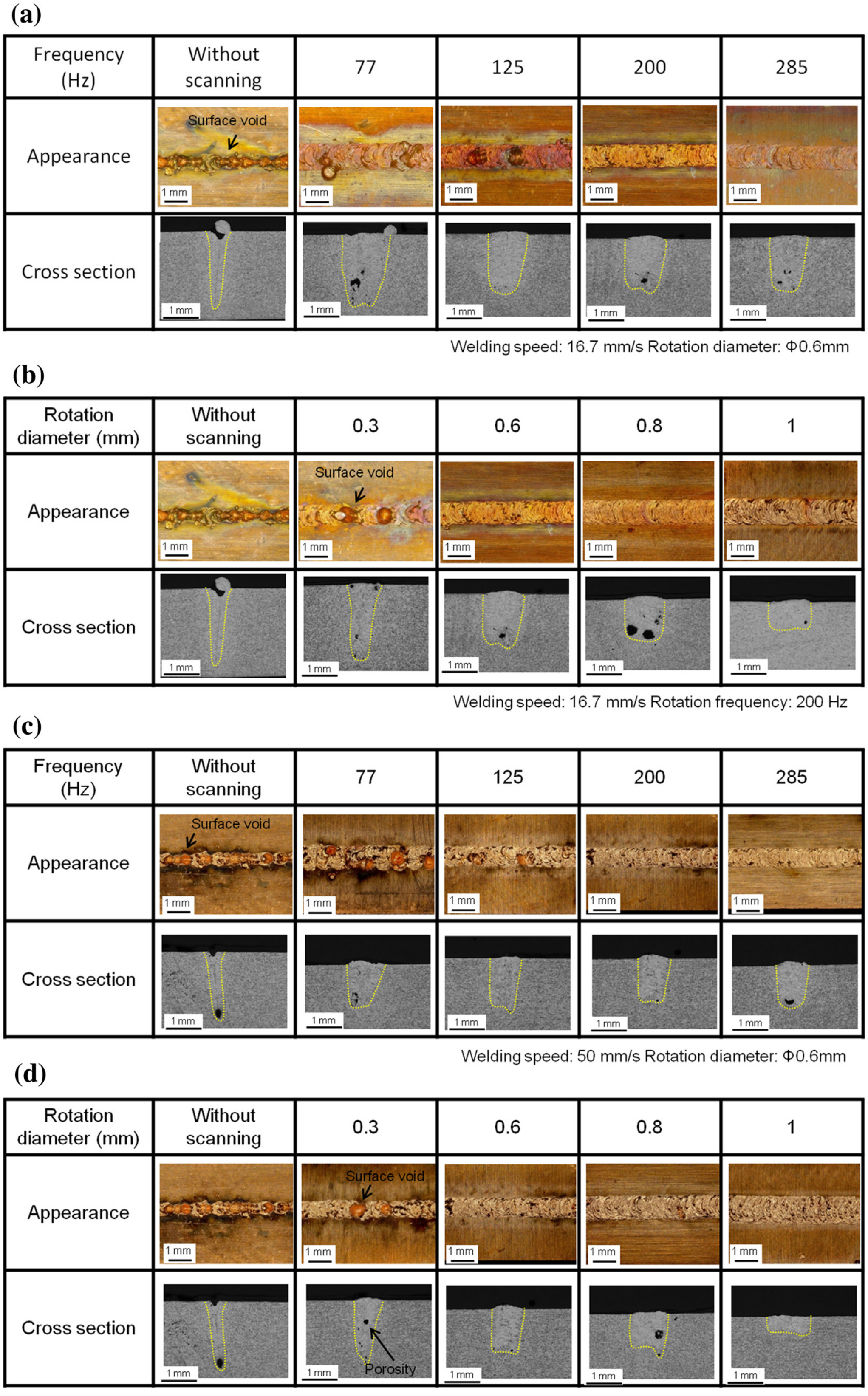

Fig. 2. (a). Appearance and cross section obtained with welding speed = 16.7 mm/s and rotation diameter φ = 0.6 mm (laser power = 1500 W, Df = 0 mm).
(b). Appearance and cross-section obtained with welding speed = 16.7 mm/s and rotation frequency = 200 Hz (laser power = 1500 W, Df = 0 mm).
(c). Appearance and cross-section obtained with welding speed = 50 mm/s and rotation diameter φ = 0.6 mm (laser power = 1500 W, Df = 0 mm).
(d). Appearance and cross-section obtained with welding speed = 50 mm/s and rotation frequency = 200 Hz (laser power = 1500 W, Df = 0 mm).

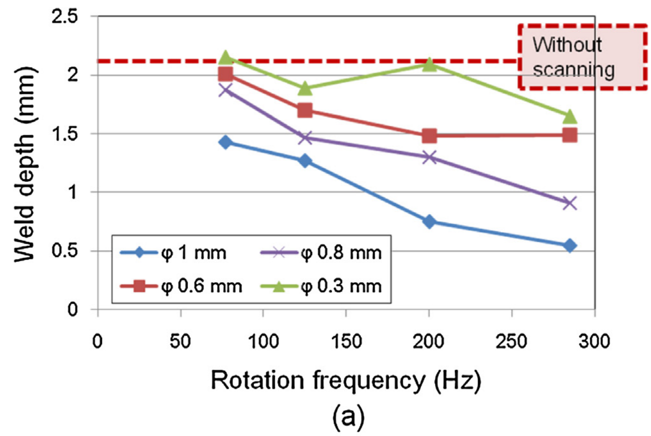

Fig. 3. Weld depth and bead width obtained with different rotation diameters and rotation frequencies (laser power = 1500 W, welding speed = 16.7 mm/s, Df = 0 mm).

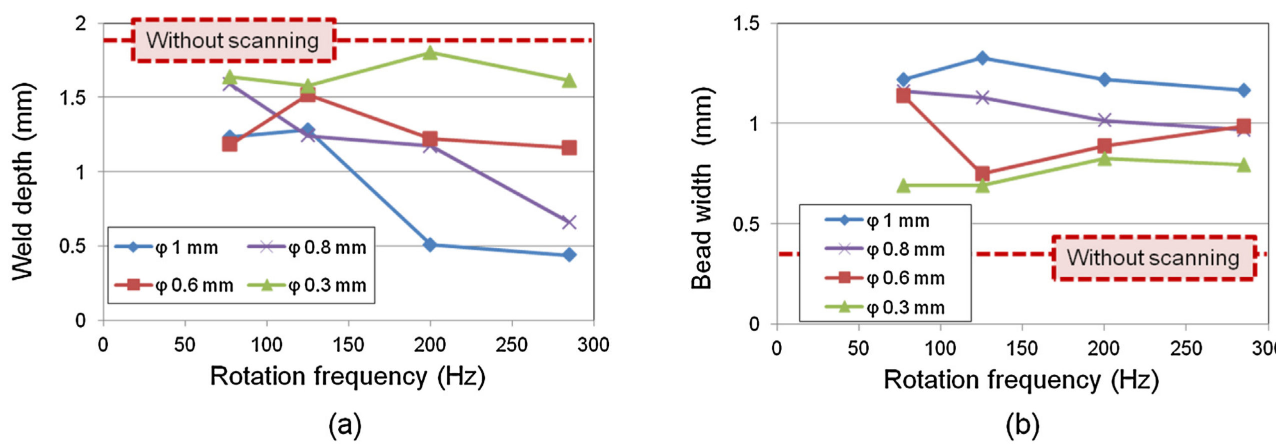

Fig. 4. Weld depth and bead width obtained with different rotation diameters and rotation frequencies (laser power = 1500 W, welding speed = 50 mm/s, Df = 0 mm).

Table 1
Laser welding conditions.

	Laser power (W)	Welding speed (mm/s)	Df (mm)	Rotation diameter (mm)	Rotation frequency (Hz)
Without scanning	1500	16.7, 50	0	–	–
With scanning	1500	16.7, 50	0	0.3–1.0	77–285

Df: Defocus.

3. Results and discussion

Although it was confirmed by Miyagi and Zhang (2015) that welding copper at a high speed (167 mm/s) can suppress spattering and the formation of surface voids, high-speed welding is subject to defects related to misalignment due to narrow bead width. To ensure the compatibility with suppression of spatter, surface voids, and wide bead shape, laser welding with scanning was conducted. Fig. 2(a)–(d) shows the appearance and cross section of welds obtained with different welding speeds, rotation diameters, and rotation frequencies. In Fig. 2(a) one sees from the appearance of the weld obtained without scanning that many surface voids were evident on it. And one sees in the corresponding cross section that part of weld metal on the surface was lost. It is assumed that those surface voids obtained in the without-scanning condition were formed by melt pool ejection. With scanning, the number of surface voids decreased as the rotation frequency increased. Over 200 Hz, hardly any surface voids were evident. The welding quality obtained with scanning is drastically improved compared to that obtained without scanning. In the cross sections, however, some porosity was evident.

In Fig. 2(b) one sees from the appearance of welds obtained with scanning that the number of surface voids decreased as rotation diameter increased. Over φ = 0.6 mm, hardly any surface voids were evident. Some porosity, however, was evident in the corresponding cross sections.

In Fig. 2(c) one sees from the appearance of the weld obtained without scanning that many surface voids were evident on it. And one sees from the corresponding cross section that part of the weld metal on the surface was lost. It is assumed that those surface voids obtained in the without-scanning were formed by melt pool ejection. With scanning, the number of surface voids decreased as rotation frequency increased. Over 200 Hz, hardly any surface voids were evident. The welding quality obtained with scanning is drastically improved compared to that obtained without scanning. A little porosity, however, was evident in the corresponding cross section.

In Fig. 2(d) one sees from the appearance of the welds obtained with scanning that the number of surface voids decreased as rotation diameter increased. Over φ = 0.6 mm, hardly any surface voids

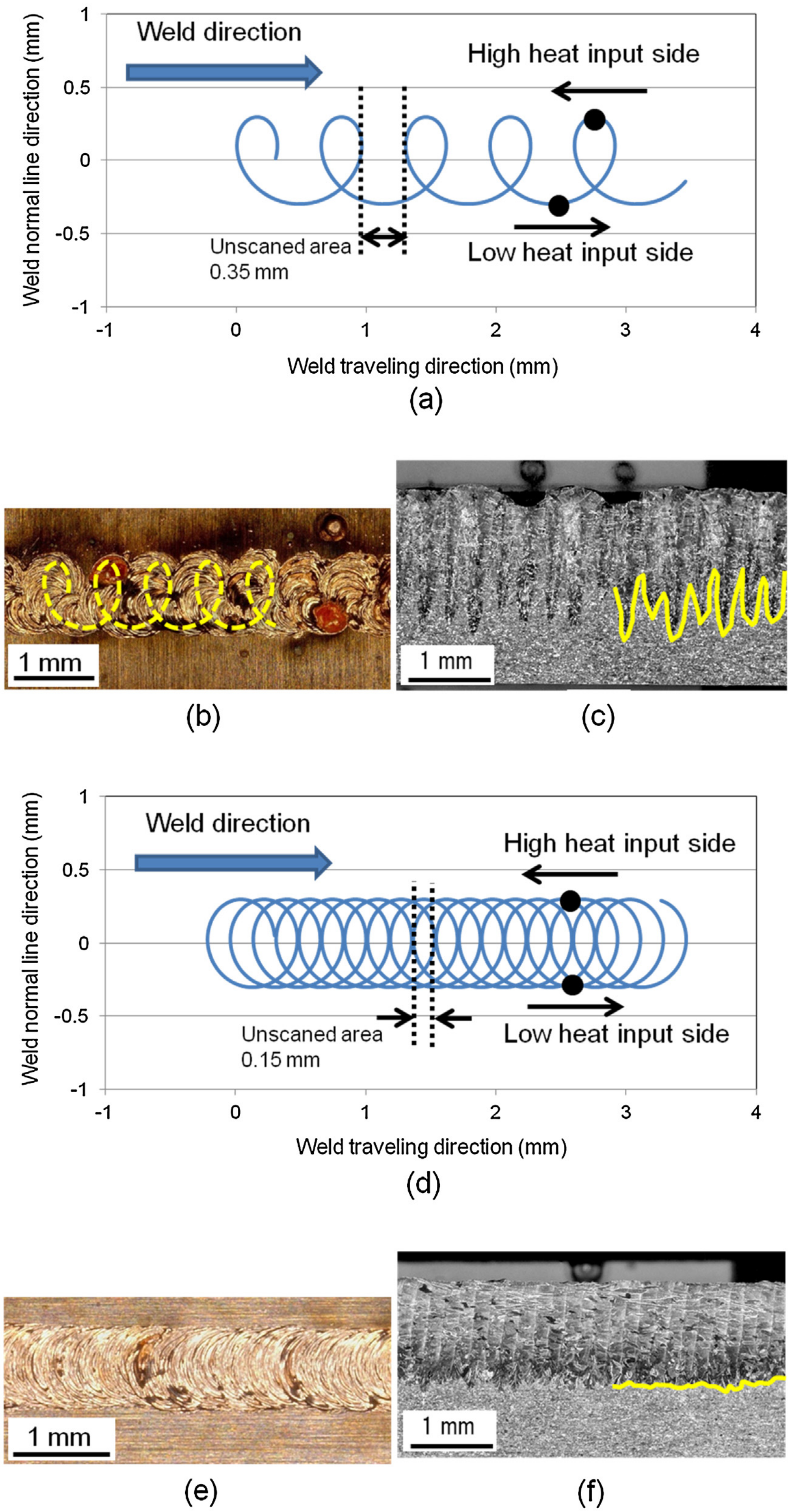

Fig. 5. (a) Laser scanning track, (b) appearance, and (c) longitudinal section obtained at rotation diameter = 0.6 mm, rotation frequency = 77 Hz, welding speed = 50 mm/s; (d) laser scanning track, (e) appearance, and (f) longitudinal section obtained at rotation diameter = 0.6 mm, rotation frequency = 285 Hz, welding speed = 50 mm/s.

were evident. Some porosity, however, was evident in the corresponding cross sections. These results indicate that surface void formation by melt pool ejection is more likely to be suppressed with larger rotation diameters and higher rotation frequencies.

Fig. 3(a) and (b) shows the weld depths and the bead widths obtained with different rotation diameters and rotation frequencies at a welding speed of 16.7 mm/s. The weld depth obtained with scanning is smaller than that obtained without scanning. The weld depth decreases as rotation frequency increases, regardless of the

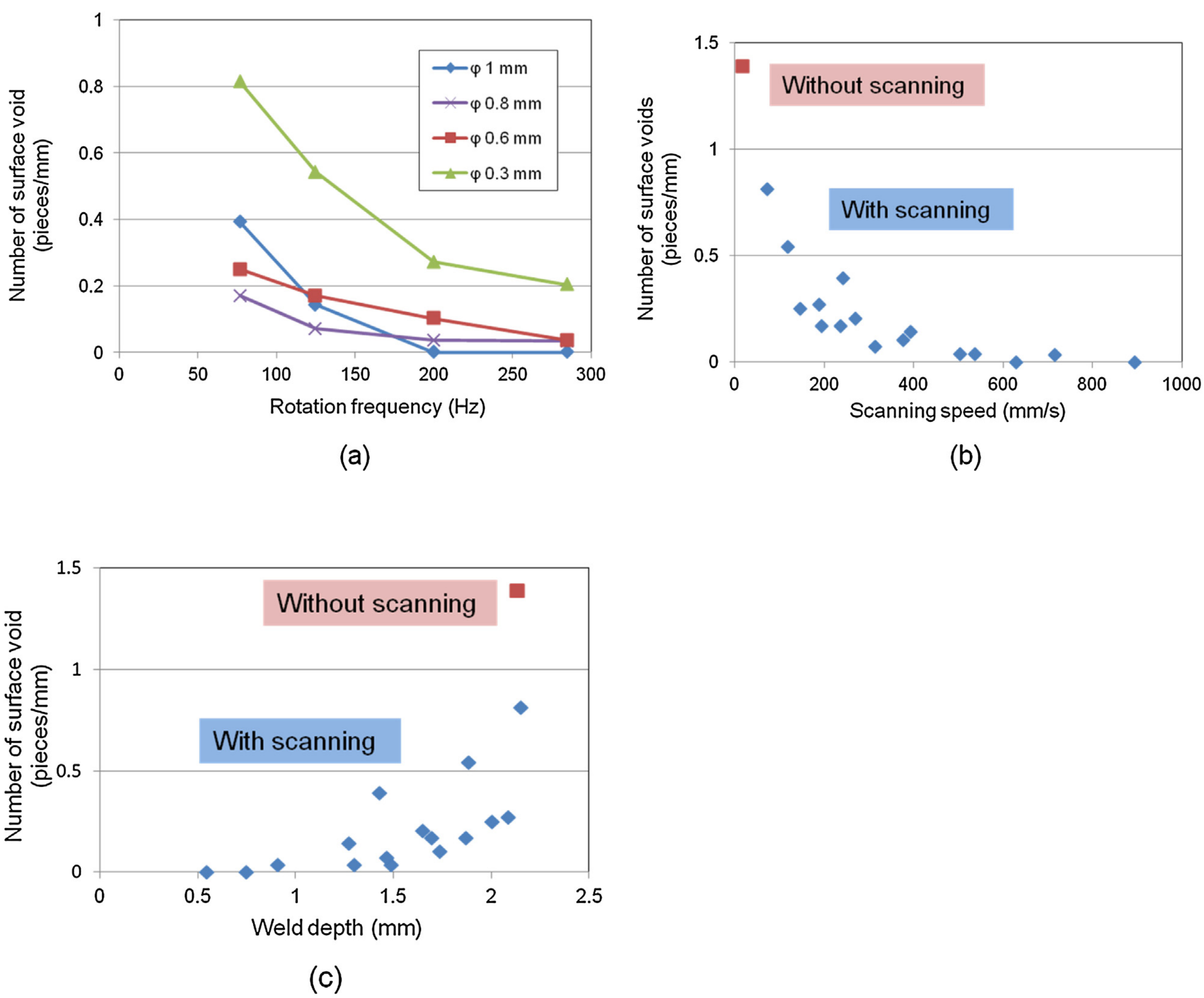

Fig. 6. Trend of surface void formation in case of 16.7-mm/s welding speed: (a) relationship between the number of surface voids and rotation frequency, (b) relationship between the number of surface voids and scanning speed, (c) relationship between the number of surface voids and weld depth.

rotation diameter. That trend is especially significant with large rotation diameter (e.g., 1.0 and 0.8 mm) because scanning speed is very large in the large-rotation-diameter conditions. The bead width obtained with scanning is larger than that obtained without scanning because of the larger laser radiation area.

Fig. 4(a) and (b) shows the weld depths and the bead widths obtained with different rotation diameters and rotation frequencies at a welding speed of 50 mm/s. The trend of weld geometry is almost same as that seen with the 16.7-mm welding speed.

Fig. 5(a)–(c) shows the laser scanning track, and weld appearance, and longitudinal section obtained at a welding speed of 50 mm/s with φ of 0.6 mm rotation diameter and a rotation frequency of 77 Hz. There is a certain unscanned area estimated to be about 0.35 mm. From weld appearance, the weld bead shape corresponds to the laser scanning track. The periodic weld depth is observed from the longitudinal section. This weld depth variation is based on the unscanned area in the laser scanning track. In case of 0.6-mm rotation diameter and 285-Hz rotation frequency, the unscanned area is estimated to be 0.15 mm as shown in Fig. 5(d). In this scanning condition, characteristic weld bead shape was not evident from the weld appearance because of the dense laser scanning track shown in Fig. 5(e) and (f). The periodic weld depth is not evident in the longitudinal sections. These results show that it is important to consider the laser scanning track if one is to achieve a constant weld depth. In addition, it is confirmed that low and high heat input areas formed at both sides of the weld bead are based on the relative speed difference derived from the relationship between laser scanning rotation direction and the welding direction shown in the laser scanning track. It is assumed that the formation of the asymmetric weld shapes shown in Fig. 2(c) for a 125-Hz rotation frequency and Fig. 2(d) for a 0.8-mm rotation diameter was due to the difference of the heat input.

Fig. 6(a) shows, for different rotation diameters and a welding speed of 16.7 mm/s, the number of surface voids per millimeter of weld length as a function of rotation frequency. With any rotation diameter, the number of surface voids decreases as rotation frequency increases. In case of large rotation diameter, the number of surface voids is smaller than that in case of small rotation diameter. It is supposed that with small rotation diameter, the area of laser radiation is small and the scanning speed is small; therefore heat accumulation occurs easily and leads to keyhole expansion. Fig. 6(b) shows the relationship between scanning speed and the number of surface voids per millimeter of weld length. The number of surface voids shows strong correlation with scanning speed. From this result it is assumed that a scanning speed over 500 mm/s can suppress the formation of surface voids. Miyagi and Zhang (2015) reported that at welding speeds over 10 m/min, keyholes can be kept stable, and high-quality welding can be obtained. It is

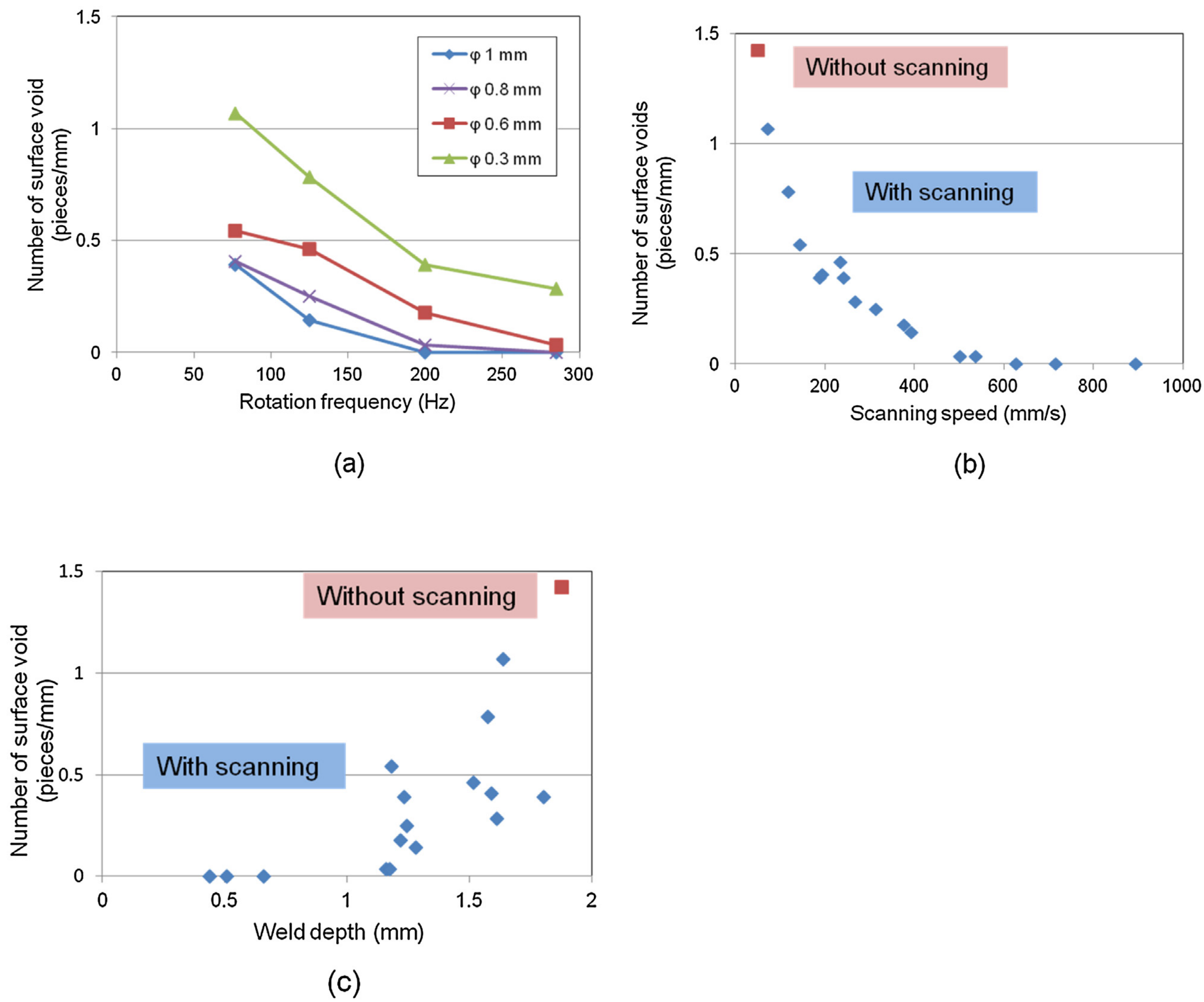

Fig. 7. Trend of surface void formation in case of 50-mm/s welding speed: (a) relationship between the number of surface voids and rotation frequency, (b) relationship between the number of surface voids and scanning speed, (c) relationship between the number of surface voids and weld depth.

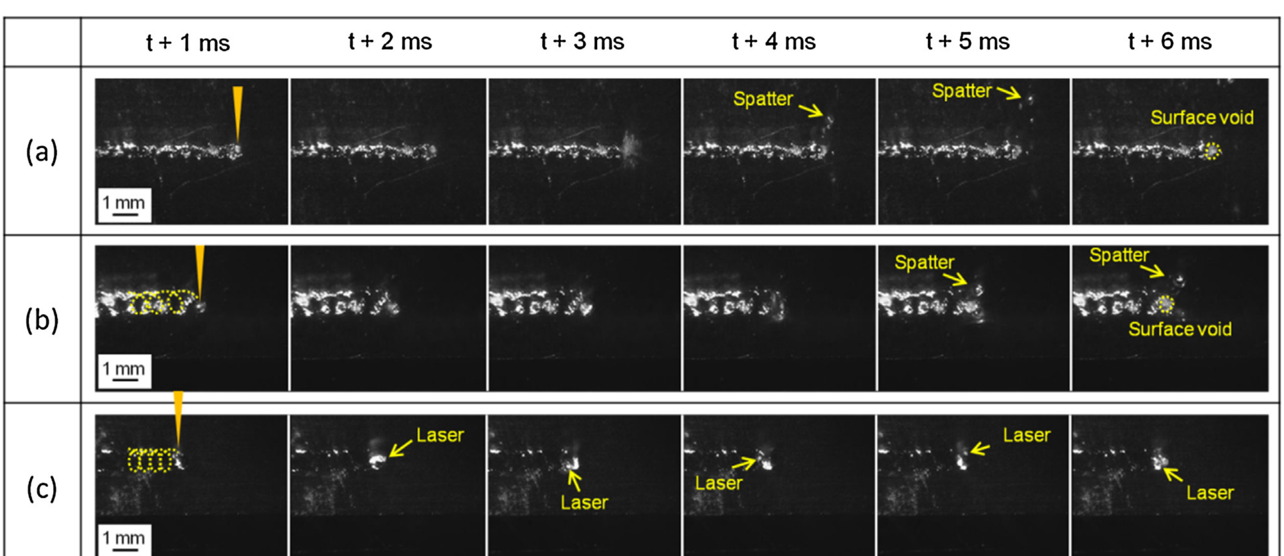

Fig. 8. High-speed camera image (a) without scanning, (b) with rotation frequency = 77 Hz, (c) with rotation frequency = 285 Hz.

supposed that balanced evaporation recoil force with surface tension of melt pool can be easily kept in the welding with scanning, because unexpected interaction between laser and melt pool near weld surface is less likely to occur due to regularized melt pool flow by high speed circle scanning. In addition it is thought that heat input contribute to keyhole stabilization. Heat input at the point laser radiated with scanning is lower than that of without scanning because scanning speed is high compared to welding speed. Low heat input is effective to suppress excessive evaporation in keyhole that lead to melt pool ejection and surface void. Fig. 6(c) shows the relationship between weld depth and the number of surface voids per millimeter of weld length. As the weld depth decrease, the number of surface voids decrease. It is confirmed that it is possible to drastically decrease the number of surface voids keeping around 2 mm weld depth with scanning.

In Fig. 7(a) and (b) the number of voids per millimeter weld length is shown, again for different rotation diameter but this time for a welding speed of 50 mm/s, as a function of rotation frequency and as a function of scanning speed. The trend of the number of surface voids is almost same as that seen with the 16.7-mm/s welding speed. Fig. 7(c) shows the relationship between weld depth and the number of surface voids per millimeter of weld length. As the weld depth decrease, the number of surface voids decrease.

Fig. 8 shows high-speed camera images of welds obtained without scanning and with scanning. Without scanning, the bead surface was rough and welding pool was very small: about 0.4 mm in diameter. It was observed that a spatter the same size as weld pool was formed and ejected from the weld pool. After that, formation of surface void was confirmed. Thus it is supposed that the rough bead surface was derived from frequent melt pool ejection. At a rotation frequency of 77 Hz (Fig. 8(b)), the frequency of melt pool ejection decreased but spatter and surface voids were still observed. At a rotation frequency of 285 Hz (Fig. 8(c)), melt pool ejection was not observed and it was confirmed that the stable weld pools formed at 285 Hz lead to high-quality welding of copper. It is assumed that melt pool ejection and surface void formation can be suppressed by the small local heat input and the balanced evaporation recoil force and surface tension of melt pool obtained by high speed circle scanning.

4. Conclusions

The effect of laser rotation scanning condition on weld shape and surface void formation was investigated and the melt pool phenomenon was observed by using an observation system with a high-speed video camera. The main conclusions are as follows.

1) Surface void has a strong relationship with laser scanning speed, and large spatter and surface voids in laser welding of copper can be suppressed by high-speed laser rotation scanning with over 500 mm/s.
2) In the welding there is an unscanned area, based on the relationship between laser scanning conditions and welding speed, that makes the weld depth periodic.
3) Weld depth can be decreased and the weld bead width increased by using laser scanning.

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