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

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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.

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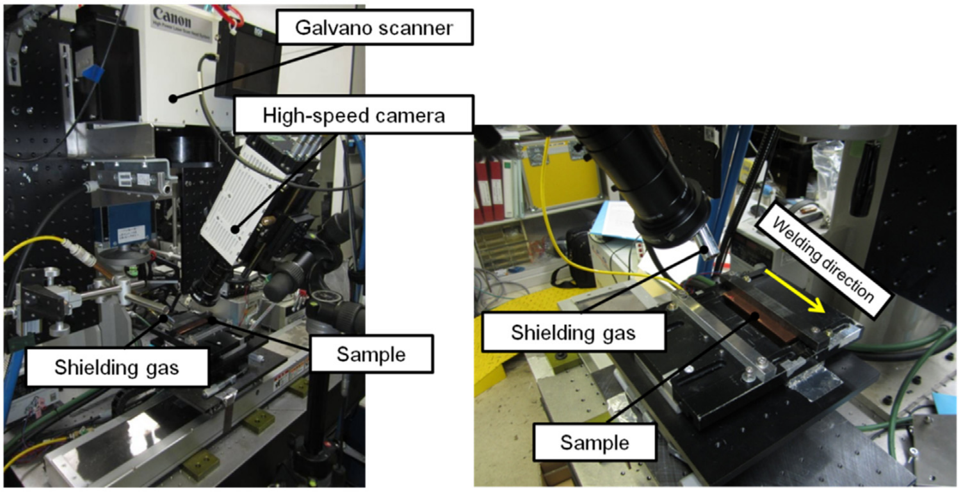

Fig. 1. Experimental setup for laser welding.

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.