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Enhanced welding efficiency in laser welding of highly reflective pure copper

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ABSTRACT

A critical challenge in laser welding of pure copper and its alloys is low welding efficiency due to high laser beam reflectivity and high thermal conductivity of the materials. In order to improve laser welding efficiency, a copper-based nano-composite material was developed as absorber for laser welding of pure copper and its alloys. The aim of this study is to investigate the influence of applying this copper-based nano-composite absorber in laser welding of pure copper. Welding efficiency and weld quality were compared between laser welding of pure copper with and without this absorber. Metallographic, mechanical, chemical and electrical properties of welds were studied. Experimental results show that laser welding efficiency was significantly increased after applying the copper-based nano-composite absorber. No significant change of weld quality in terms of chemical composition, electrical properties and hardness was observed. Compared to as-received pure copper coupons, the tensile strength of the welds was 88% of that of the base material.

1. Introduction

High laser beam reflectivity and thermal conductivity of pure copper and its alloys are the main reasons behind low welding efficiency and unstable weld quality in laser welding. A higher heat input is usually required to perform a penetration weld in laser welding of pure copper and its alloys as compared to welding of other engineering-graded metals. Dong and Xiao (2009) reported that only welding conditions which surpassed certain heat input threshold could achieve repeatable weld qualities in laser lap welding of dissimilar copper alloys. Petring and Goneghany (2011) investigated the relationship between the weld geometry and the amount of heat input applied in laser welding of copper alloys. They reported that weld depth was mainly determined by laser power and welding speed. A weld with a high aspect ratio between depth and width can be obtained by either increasing the laser power or reducing the welding speed. Heider et al. (2012) found that the melting pool can be stabilised by applying a power modulation approach in laser welding of copper alloys.

Several methods aiming laser weldability improvement of pure copper and its alloys have been reported. Firstly, coating a low reflective layer on the top surface of highly reflective metals, such as copper alloys, is commonly used in laser welding. For example, Bolin (1977) coated a low reflective layer on copper to overcome the high reflectivity issue. However, the mechanical properties of the welds were affected due to the formation of intermetallics. The second approach is supplying an oxygenated assisted gas jet for the laser welding process. Biro et al. (2001) demonstrated that welding efficiency was improved by using the O_2–Ar assisted gas jet in laser welding of pure copper. They also found that laser energy absorption increased from 4.89% to 16.10% when a pure copper coupon was heated from 25 °C to 1085 °C. Gao et al. (2011) improved the efficiency of the laser welding process of copper alloys by adding copper powder filler. However, welds presented minor effects on microstructure and chemical compositions.

Laser welding of copper alloys with dual laser beams or applying a short wavelength laser beam are other methods suggested to improve the laser beam energy absorption and therefore increasing welding efficiency. Steen and Mazumder (2010) identified the important role of the laser beam wavelength into its energy absorption during laser welding of pure copper. For example, the laser beam energy absorption increased from ∼3% to ∼40% when the beam wavelength was shifted from 1000 nm to 500 nm. Hess et al. (2011) combined a green (515 nm) and an infrared (1030 nm) laser beams for laser welding of copper alloys. In their work, the green laser was used for heating the materials. When their temperature increased, the infrared laser beam energy was effectively absorbed. This increased the efficiency of the welding process. Engler et al.

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Table 1
Material properties of pure copper.

Material properties	Value
Melting point	1084 °C
Boiling point	2595 °C
Density	8.94 g/cm^3
Specific heat	384 J/kg K
Thermal conductivity	398 W/m K
Mean hardness[a]	Hv 88.9
Average tensile strength[a]	189.85 ± 1.29 MPa
Average surface roughness[a]	603.2 μm

[a] Values obtained from as-received pure copper coupons.

(2011) also found higher laser energy absorption while using a short wavelength green laser beam rather than an infrared laser source.

In recent years, the use of metal nanoparticles has gradually increased in applied science. Govorov and Richardson (2007) found that light energy can be efficiently absorbed by metal nanoparticles and transformed into thermal energy when they are under electromagnetic irradiation. Heat will be accumulated in the nanoparticles and at their surrounding areas. In this study, a copper-based nanocomposite material was incorporated in the laser welding of pure copper process as absorber. Investigations into the improvement of laser welding efficiency and weld quality were conducted. Experimental results were compared between laser welding of pure copper with and without the use of nano-composite material as absorber.

2. Materials and methods

Oxygen-free pure copper (99.99% copper) sheets with dimensions of 60 mm × 60 mm × 0.5 mm were laser butt welded. All edges of the copper coupons were machined to obtain a neat square butt. Properties of pure copper are listed in Table 1, as obtained from experimental results and reported by Kundig and Cowie (2006). An IPG 6 kW fibre laser with 1070–1080 nm wavelength and integrated with a robotic system was used for the experiments. The configuration of the system is illustrated in Fig. 1. Argon gas was supplied as the shielding gas during laser welding. Table 2 lists all the processing variables used in this study. Each laser welding test was repeated three times to ensure repeatability of the process.

The copper coupons were first cleaned with Isopropyl alcohol and then clamped for the welding process with a customised fixture which ensures zero root opening between two coupons. A low concentration (less than 5 wt%) copper-based nano-composite material (hereafter called the composite absorber) was prepared in-house by mixing of 99.8 wt% purity copper powder

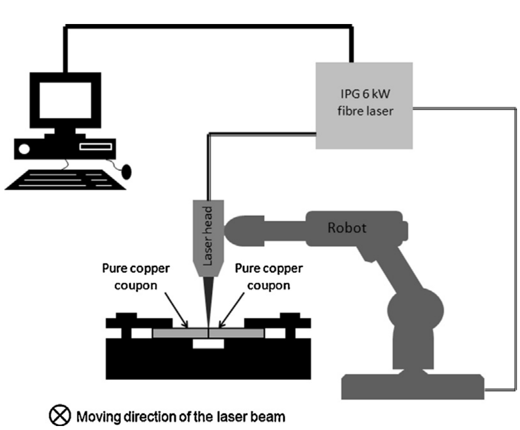

Fig. 1. Illustration of the employed laser welding system.

Table 2
Process variables used in laser welding of pure copper.

Variable	Value
Welding speed (mm/s)	20 and 30
Laser power (kW)	1.00, 1.34, 1.67, 2.00, 2.34 and 2.67
Focal point position	Top surface of the coupons
Surface property of pure copper	As-received
	With the composite absorber

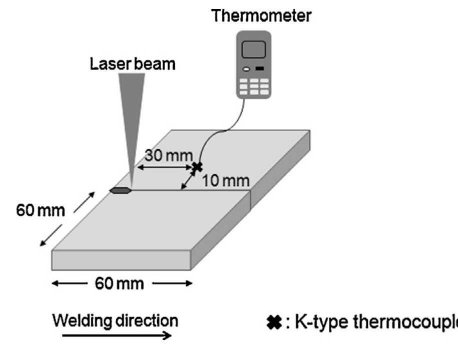

Fig. 2. Schematic diagram for measuring thermal profiles in laser welding.

with polymer-based transparent resin. A layer of nano-composite material of approximate 500 μm thickness was sprayed, on the areas where laser beam was expected to irradiate at, with a customised syringe system. Reflectivity of pure copper coupons with and without the sprayed composite absorber was measured at room temperature over a range of wavelength from 300 nm to 1500 nm using a Shimadzu UV-3101PC UV–VIS–NIR spectrophotometer.

The developing laser welding temperature at the top surface of the coupons was measured with a K-type thermocouple, as illustrated in Fig. 2. A high-resolution monochromatic camera was employed to record the melting pools generated in the laser welding process. Furthermore, the weld appearance of each test was analysed with a stereoscopic microscope. The welds were then cross sectioned, cold mounted, grinded, polished and etched for further metallurgical examinations. An OLYMPUS G51 microscope equipped with analySIS® software was employed to observe the microstructure of the welds. The grain size of welds was measured following the procedures as described in the ASTM E112-13 *Standard Test Methods for Determining Average Grain Size*. Hardness across the welds was measured along a penetration level of 0.2 mm from the top surface of the welds with a Vickers microhardness testing machine with a 50 g load for 15 s. Tensile strength testing of the welds was conducted at room temperature using an INSTRON 4505 universal tensile testing machine operating with a crosshead speed of 1 mm/s. Dimensions of a tensile testing sample are illustrated in Fig. 3. In total five samples were tensile tested for each welding condition. After the tests, the maximum tensile strength of each sample was calculated with the formula: *Maximum tensile strength = Maximum load of the weld/Penetration depth of the weld*.

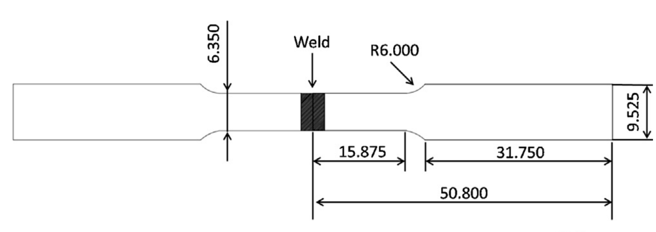

Fig. 3. Dimensions of a tensile testing sample.