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Analysis of Laser Micro Welding of Copper-Aluminum Dissimilar Metals and Its Mechanism

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Abstract

Micro welding of dissimilar metals can meet many performance requirements for modern engineering structures. In this experiment, laser micro welding of copper-aluminum dissimilar metals was conducted with an HWLW-300A energy negative feedback Nd:YAG pulse laser. By using the overlap welding method with copper on aluminum, with the laser energy being distributed unevenly, good weld joints were obtained. In this paper, the welding mechanism was analyzed from aspects such as welding temperature and the specific heat capacity of the solid metal. Existing defects were identified, and a feasible improvement scheme was proposed.

Keywords

Mciro Welding, Laser Welding, Copper-Aluminum, Dissimilar Metals, Mechanism

1. Introduction

Modern engineering structures require micro welding of dissimilar metals. Micro welding of dissimilar metals not only can meet the needs in the manufacturing industry but also is an effective way to realize multiple performance requirements, especially for microelectronics and with sensitive materials. There are numerous common micro welding methods, e.g., electric resistance welding [1], friction welding [2], laser welding [3], and electron beam welding [4]. Laser micro welding has gained popularity owing to advantages as such as its high energy density, concentrated heat source, small heat affected zone, good controllability, and low environmental requirements. Since the 1970s when laser micro welding appeared, laser micro welding technology has developed rapidly and has currently become one of the most important and advanced manufacturing technologies in fields ranging from the aerospace industry to ship building and automobile manufacturing. Through half a century of development, laser micro welding of multiple dissimilar metals has been realized [5] [6] [7]. Nevertheless, this does not mean that laser micro welding of all dissimilar metals can be realized. The process of laser micro welding of dissimilar metals relates to multiple physical effects [8], so there are still many difficult problems to solve both experimentally and theoretically. Studying laser micro welding of more dissimilar metals and its mechanism remains a theme explored by researchers.

Copper and aluminum metals are widely used in electronics. Partial substitution of copper with aluminum can not only save cost and reduce weight but, more importantly, optimize the manufacturing processes to meet multiple performance requirements. However, the thermal physical performances differ greatly between copper and aluminum, so obtaining a satisfactory copper-aluminum weld joint is the target that researchers try to achieve. At present, much progress has been made for laser micro welding of copper-aluminum dissimilar metals. Mai *et al.* [9] performed welding of dissimilar metals, including copper and aluminum, using a fluxless laser welding method, and they believe that the melting proportion of two materials is the key factor controlling welding results. Lee *et al.* [10] studied welding of copper-aluminum dissimilar metal plates and proposed a method for reducing the development of a brittle intermetallic compound. Turichin *et al.* [11] studied laser welding of dissimilar metals, including copper-aluminum and titanium-aluminum, from a metallographic perspective and through simulation.

In this paper, an HWLW-300A energy negative feedback Nd:YAG pulse laser was used to successfully realize laser micro welding of copper-aluminum dissimilar metals, and the welding effect was good. This paper is organized as follows: Section 2 introduces the experiment in detail, including various the laser parameters and material parameters of copper and aluminum metals. In addition, this section provides a scanning electron micrograph of a weld joint. Section 3 gives the corresponding interpretation for the welding mechanism from aspects such as the welding temperature condition and specific heat capacity of solid copper and aluminum metals, respectively, and some welding defects are analyzed. Section 4 gives a brief summary of the whole text.

2. Experiment

In the experiment, an HWLW-300A energy negative feedback Nd:YAG pulse laser, equipped with a CCD monitor, was used. The laser had an operating frequency range of 1 - 99 Hz, a single pulse energy range of 0.3 - 100 J, and a pulse duration of 1 - 15 ms. The focused laser beam had a diameter of ~0.3 mm and a wavelength of 1.064 um. The maximum output power was 300 W, with an error within 3%. The thin copper wire used in the experiment was a commercial copper with a purity of 99.99% and a diameter of 0.25 mm (Henan excellent electronic materials limited company, China). The aluminum electrode was from an ordinary integrated circuit, and its width was ~0.4 mm. The basic thermophysical characteristics of copper and aluminum metals are listed in **Table 1** [12].

The melting point of copper is ~423 K higher than that of aluminum, and the density of copper is a factor of ~3 higher than that of aluminum. If the butt welding method is used, the laser energy will be evenly distributed to the interface of copper and aluminum metals, resulting in a relatively large time interval between melting of the two materials and causing uneven melting. In this case, the aluminum metal may melt in a large area and even gasify, whereas the phase transformation of the copper metal just starts. This finally leads to poor welding quality or failure to realize welding. Therefore, the overlap welding method with copper on aluminum was used in this experiment. The plan view and three-dimensional view of laser micro welding can be seen in **Figure 1**. The thin copper wire had a diameter of 0.25 mm, and the aluminum electrode was relatively wide, ~0.4 mm. The focused diameter of the laser beam was ~0.3 mm. In the overlap welding method with copper on aluminum, more energy of the laser is concentrated on the thin copper wire and less energy is dispersed on the aluminum electrode. Moreover, the mass of the copper was relatively small and that of the aluminum was relatively large, so such an energy distribution tended made the melting of copper and that of aluminum more consistent. In this experiment, the welding was realized successfully, and the welding quality was improved effectively.

3. Results and Analysis of the Welding Mechanism

There are many difficult problems in laser micro welding of copper-aluminum dissimilar metals, making welding difficult and indicating a complex mechanism. Some of these problems are the high reflectivity of copper and aluminum at

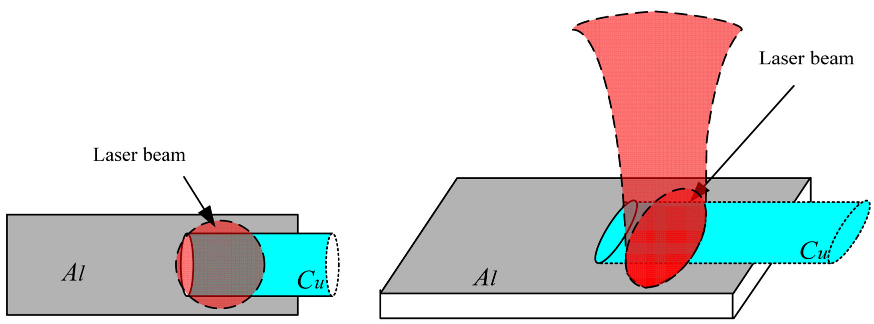

Figure 1. Plan view and three-dimensional view of laser micro welding.

Table 1. Comparison of characteristics between copper and aluminum.

Material	Melting point (K)	Boiling point (K)	Density ($g\cdot cm^{-3}$)	Coefficient of linear thermal expansion $\times 10^{-6}/(K^{-1})$	Specific heat capacity ($J\cdot kg^{-1}\cdot K^{-1}$)	Elasticity modulus $\times 10^{-3}$ (MPa)
Copper	1356	2573	8.92	16.4	390	108.5
Aluminium	983	2335	2.7	24	880	61.68

normal temperature, the large difference in melting point between copper and aluminum, and the easy formation of a brittle intermetallic compound [13] [14]. In this experiment, laser micro welding of copper-aluminum dissimilar metals was realized successfully, and the welding effect was good. As can be discerned from the scanning electron micrograph of the weld (see **Figure 2**), the weld joints have good connection and a smooth surface and are free of evident thermal cracks and air holes. In a tensile test, breakage occurred on the copper side but not at the weld joints, further demonstrating that the weld joints have good quality. In this section we analyze the welding mechanism and point out some existing defects.

3.1. Temperature Condition for Laser Welding

As can be discerned from **Table 1**, the melting and boiling points of copper are 1356 K and 2573 K, respectively, and those of aluminum are 933 K and 2335 K, respectively. These temperatures satisfy $M_{Al} < M_{Cu} < B_{Al} < B_{Cu}$. The boiling point of aluminum is higher than the melting point of copper, and these two temperatures constitute an overlap region. If the temperature at the weld joint can be maintained within this overlap region during welding (shaded part in **Figure 3**), both copper and aluminum metals can melt to realize welding. In this experiment, an HWLW-300A energy negative feedback Nd:YAG pulse laser was used, and its operating temperature was adjusted to the temperature overlap region by reasonably setting the process parameters. Therefore, choosing the laser and process parameters is one of the important factors for completing this experiment.

3.2. Specific Heat Capacity of the Solid Metal

The specific heat capacity of solid metal has an important influence on the laser welding of dissimilar metals [15]. It relates to energy absorption and melting of

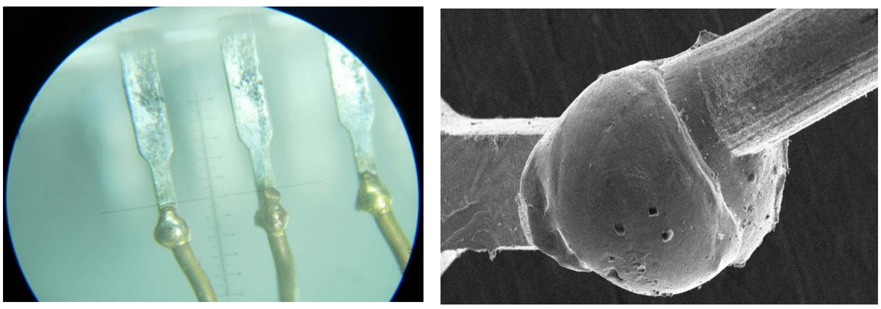

Figure 2. Left: Macro photograph of laser welding (40×). Right: Scanning electron microscope image of welding spot (500×).

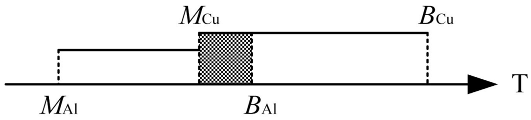

Figure 3. Melting and boiling points of copper-aluminum dissimilar metals.

the metals at the initial stage of welding and determines the quality of the weld joint to a certain extent during solidification. Thermal defects in welding are also closely related to the specific heat capacity of the solid metals. Therefore, many important welding problems can be interpreted essentially through study of the evolutionary characteristics of the specific heat capacity values of solid copper and aluminum.

In thermodynamics, the specific heat capacity of a metal crystal is defined as the rate of change of the mean internal energy with respect to temperature, that is,

$$C_v = \left(\frac{\partial \bar{E}}{\partial T}\right)_V . \tag{1}$$

In a metal crystal, the specific heat capacity includes two parts: One part is from the thermal vibration of the crystal lattice, called the crystal lattice heat capacity, which plays a key role at normal and high temperatures. The other part is from the thermal motion of electrons, called the electron heat capacity, which contributes very little in general and is taken into account only at ultralow temperature. Therefore, only the crystal lattice heat capacity was taken into account in this paper. The Einstein model for the crystal lattice heat capacity can be obtained from quantization of the energy eigenvalue of simple harmonic motion based on quantum theory:

$$C_V = 3Nk_B \frac{\left(\frac{\hbar\omega_0}{k_B T}\right)^2}{\left(e^{\frac{\hbar\omega_0}{k_B T}} - 1\right)^2} e^{\frac{\hbar\omega_0}{k_B T}} . \tag{2}$$

The Einstein-derived crystal lattice heat capacity coincides well with the experimental values within the high temperature range, but it differs greatly from the experimental values within the low temperature range. Debye's T^3 model for the crystal lattice heat capacity uses the pattern of crystal lattice vibration waves:

$$C_V = 9R\left(\frac{T}{\theta_D}\right)^3 \int_0^{\frac{\theta_D}{T}} \frac{\xi^4 e^{\xi}}{(e^{\xi} - 1)^2} d\xi, \tag{3}$$

where θ_D is the Debye temperature. The Debye temperature values of various metals are given in Reference [16]. The Debye temperature of copper is 343 K and that of aluminum is 428 K. In this paper, the change in and influence on the specific heat capacity during welding of copper-aluminum metals were analyzed using the Debye model. It must be pointed out that there is slight difference in the evolution of the specific heat capacity between the actual process and the Debye model [17], but the results in this paper are not influenced. Since an accurate solution cannot be obtained for Equation (3), the evolutionary curves for the specific heat capacity of solid copper and aluminum metals can be obtained only through numerical simulation. In **Figure 4**, the red curve is the specific heat capacity of solid copper metal, and the blue curve is the specific heat capacity of aluminum. As can be seen from **Figure 4**, the specific heat capacity of aluminum

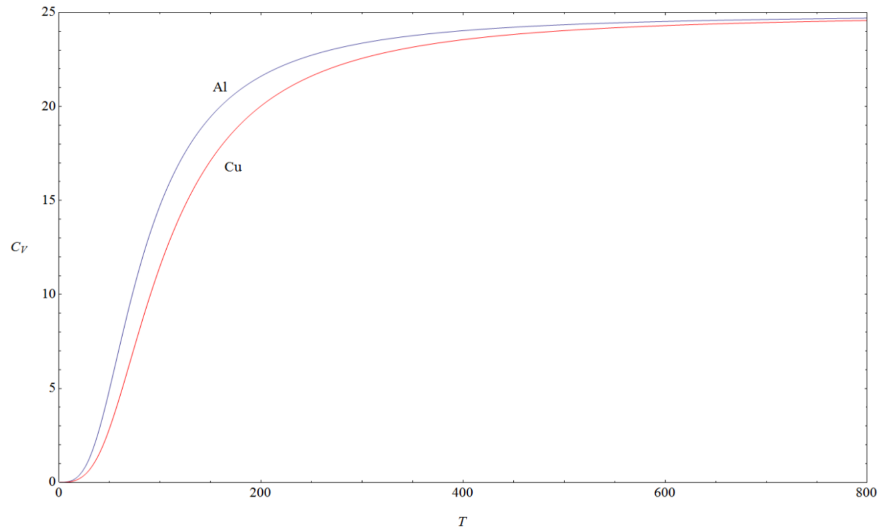

Figure 4. Evolution of specific heat capacity of copper-aluminum dissimilar metals with temperature.

is larger than that of copper at low temperature and normal temperature, whereas the specific heat capacity values are closer together in the high temperature range. As can be discerned from the definition of the specific heat capacity, a material with a larger specific heat capacity undergoes a smaller rise in temperature than a material with a smaller specific heat capacity, with the same heat absorbed and under the same conditions. The melting point of copper is 423 K higher than that of aluminum. To ensure that copper-aluminum dissimilar metals reach their own melting points simultaneously as much as possible, the energy per unit time absorbed by copper metal should be more than that absorbed by aluminum. Consequently, overlap welding with copper on aluminum and with less mass of copper than aluminum was used to unevenly distribute laser energy, ensuring to the maximum extent that both copper and aluminum metals melted at the same time based on their specific heat capacity characteristics. Not only was laser welding of copper-aluminum dissimilar metals realized successfully but also the atoms of both metals combined more closely to improve the welding quality.

3.3. Welding Defects for Copper-Aluminum Dissimilar Metals and Improvement Methods

Laser welding of copper-aluminum dissimilar metals was realized in this experiment, with a secure weld joint obtained. However, there were some thermal defects that were hard to overcome. Owing to differences in thermophysical characteristics between copper and aluminum such as solidification latent heat, thermal expansion coefficient, crystal lattice constant, and specific heat capacity, the occurrence of a few thermal cracks cannot be avoided during solidification. Furthermore, copper and aluminum may produce some brittle compounds at high temperature, e.g., Cu_2Al, Cu_2Al_3, CuAl, and $CuAl_2$ [13] [14], these may also have some influence on the welding quality.

Reducing the solidification rate is a relatively effective method to improve the welding quality. It can be discerned from Fourier's law of heat conduction [18] that the heat transferred through unit area of cross section per unit time is directly proportional to the rate of temperature change in the direction perpendicular to this cross section, and the direction of heat transfer is opposite to that of the temperature rise, namely,

$$\Phi = -\lambda \frac{dT}{dn}, \tag{4}$$

where Φ is the heat transferred through unit area of cross section per unit time, λ is the heat conductivity, the specific value of which depends on the material, and dT/dn represents the rate of temperature change in direction n. Equation (4) shows that the smaller the temperature difference, the slower the heat dissipation. Reduction in the solidification rate can cause the solution in the weld pool to be more evenly distributed, with the solidification latent heat being released fully and the crystal lattices matching better. In general, a method using an external heating source [19] can reduce the solidification rate.

4. Conclusions

1) Welding of copper-aluminum dissimilar metals was conducted with an HWLW-300A energy negative feedback Nd:YAG pulse laser. Welding was realized successfully using the overlap welding method with copper on aluminum and with less copper than aluminum.

2) The process of laser welding of copper-aluminum dissimilar metals includes multiple physical effects. In this paper, the welding mechanism was studied from aspects such as welding temperature condition, the specific heat capacity of solid metals, and laser energy distribution and the internal causes for successful welding were analyzed.

3) Deficiencies existing in this experiment were pointed out, e.g., generation of a few thermal cracks and easy production of some brittle intermetallic compounds. For the above problems, a method of adding an external heating source for further improvement of welding quality was proposed based on Fourier's law of heat conduction and other experiments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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