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Analyzing the contact resistance for the penetration brazing of Cu/Ni metal wires

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Abstract. The electrical contact resistance behavior of the interface between the copper electrode and the graphite welding pool plays an important role in penetration brazing of Cu/Ni metal wires. Based on the fractal contact resistance model, the contact resistance between the copper electrode and the graphite welding pool is established by taking the oxide ablation of the graphite surface into account. The influences of the graphite ablation on the contact resistance for different pressure and different graphite materials are experimentally investigated. The ablation phenomenon on the surface of the graphite welding pool is observed during the welding process. It is found that the contact resistance slowly increases as the ablation degree of the graphite welding pool surface increases. The present work shows that the impact of the common graphite ablation on the interface contact resistance is more obvious than that of fine graphite.

1. Introduction

The heating cable has been extensively used in indoor heating, road snow melting, and other fields. Its core technology is the manufacture of heating cable core. The wire core of an exothermic cable is manufactured by brazing the unequal-diameter copper wire (0.4~1.13 mm diameter cold wire) and the Ni-based alloy heating wire (0.3~0.85 mm diameter hot wire) in a non-metal heating element (porous graphite) [1, 2]. Graphite materials are usually used to make graphite weld pool (GWP) in penetration brazing of Cu/Ni metal wires. The Joule heat generated from the contact resistance between the copper electrode and the graphite welding pool (GWP) is transmitted to the welding point through the welding pool, which is the main source of the heat for the melting solder in the welding. Therefore, the study of the interface contact resistance behavior is the key factor to generate a stable welding heat source [3].

There is still a lack of thorough study of the heat of contact resistance between metal and non-metal in the field of welding. This work employs methods and theories of the contact resistance in the fields of resistance welding, fuel cells, etc., to provide a reference for the study of the welding contact resistance issue. The first systematic study of the effects of different gas diffusion layer materials and contact pressure on the electrical contact resistance was reported by Mishra *et al* [4]. They proposed a fractal model of electrical contact resistance between gas diffusion layers and graphite bipolar in a PEM fuel cell to predict the effects of pressure, material properties and surface geometry on contact resistance. Zhai *et al* [5] experimentally studied the electrical contact resistance between the contacting rough surfaces of aluminium disks under various compressive stress. They found that the measured resistance is closely relevant to measurement time, testing current, surface topology, and mechanical loading. Moreover, Riba *et al* [6]. employed the finite element method to analyze characteristics of the interface contact resistance and clarified the correlation of the contact resistance to pressure, temperature and surface roughness. The majority of the above studies analyzed the contact resistance based on the assumption that the contact sample has no macro-deformation and the effect of the dynamic characteristics of the contact process on the contact resistance is not taken into account.

Graphite materials are prone to oxidation at high temperatures, and the graphite surface reacts with oxygen in the air to contribute to ablation [7, 8]. The morphology of the rough surface has a great influence on the thermal and electrical conduction between two surfaces in contact. Experimental measurements indicate that their structure follows a fractal geometry [9]. Therefore, based on the fractal theory and the ablation mechanism of the graphite, a new mathematical model for the contact resistance between the electrode and the graphite welding pool is established. Furthermore, the influence of the graphite surface ablation on the contact resistance is discussed by the experiment. It is intended to provide theoretical guidance for the penetration brazing process of Cu/Ni metal wires.

2. Penetration brazing technology

Penetration brazing of Cu/Ni dissimilar metal wires refers to the inserting of Cu and Ni-base materials and Ag-based solder into the center hole of the graphite welding pool and melting the Ag-based solder by the heat generated from the contact resistance of the electrode and the graphite welding pool. The Ag-based solder liquid infiltrates and spreads on the interface of the Cu/Ni-based material and fills the interval to form a joint. The principle is presented in figure 1. It must be pointed out that the welding temperature is approximately 700°C, which is used to melt Ag solder but not affects the Cu/Ni alloy since their melting point temperature is higher (Cu alloy =1083°C, Ni alloy =1455°C) [10].

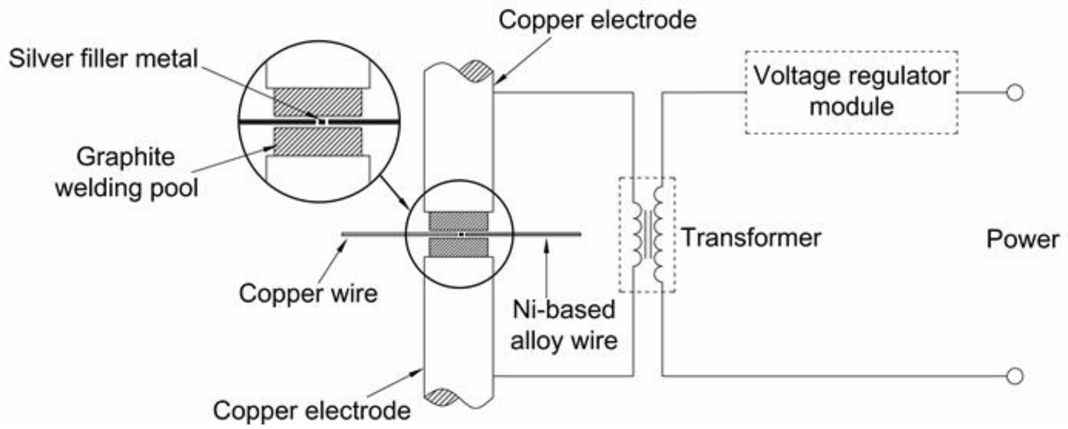


Figure 1. The principle of penetration brazing.

3. The model of the contact resistance

The contact behavior of the copper electrode and the graphite welding pool during the welding process, such as pressure, contact form, surface morphology and the distribution of contact asperities are the important factors affecting the contact resistance. The fractal theory is utilized in the present work to further study the effect of the micro-contact behavior of the interface on the contact resistance.

3.1. Fractal contact resistance

It is well-known that the Weierstrass-Mandelbrot (W-M) function can be used to simulate the profile curves of rough surfaces with fractal features [11]. The W-M function is given as:

$$z(x) = G^{(D-1)} \sum_{n=n_1}^{\infty} \frac{\cos 2\pi\gamma^n x}{\gamma^{(2-D)n}} \quad 1<D<2 \quad \gamma>1 \tag{1}$$

IOP Conf. Series: Materials Science and Engineering **770** (2020) 012006 doi:10.1088/1757-899X/770/1/012006

where *D*, *G* and *n* are the fractal dimension of a surface profile, a surface characterization parameter and the frequency index, respectively. Furthermore, γ is a parameter that controls density frequencies. It is set to 1.5, which enables the frequency spectrum formed not a multiple of the fundamental frequency [11].

Based on the modeling method of the contact resistance of the fractal rough surface, each independent micro-bulge resistance is assumed to be a basic unit in a series-parallel resistance network. The mathematic model of the contact resistance between the copper electrode and the graphite welding pool is expressed as [9]:

$$R_c = \frac{G^{(D-1)}}{L^D \lambda}\left(\frac{D}{(2-D)A_r^*}\right)^{D/2} f\left(D, A_r^*\right) \tag{2}$$

where the relationship of contact area A_r^* and dimensionless load P^* is given as in [12]:

$$P^* = \frac{4\sqrt{\pi}}{3} G^{*(D-1)} g_1(D) A_r^{*D/2} \cdot \left\{ \left[\frac{(2-D)A_r^*}{D}\right]^{(3-2D)/2} - a_c^{*(3-2D)/2} \right\} + K\phi g_2(D) A_r^{*D/2} a_c^{*(2-D)/2} \tag{3}$$

Other symbols in equations (2) and (3) are described in detail elsewhere [9, 2].

3.2. *The model of the contact resistance with graphite ablation*

The fractal model of the contact resistance established in the previous section, is not taking the ablation of the graphite welding pool into account. Figure 2 shows that in order to clarify the effect of the graphite welding pool surface ablation on the contact resistance during the welding process, the surface ablation of graphite welding pool is equivalently simplified based on the ablation mechanism of the graphite [13]. Figure 2(a) reveals that the contact surface between the graphite welding pool and the copper electrode is uniformly ablation recession in the macroscopical field. Figure 2(b) illustrates that in this process, the contact surface between the copper electrode and the graphite welding pool is modeled as the contact between one equivalent rough surface with a rigid smooth plane [14]. The ablation recession behavior of the graphite welding pool surface leads to a change of the interface contact rate and then impacts the contact resistance.

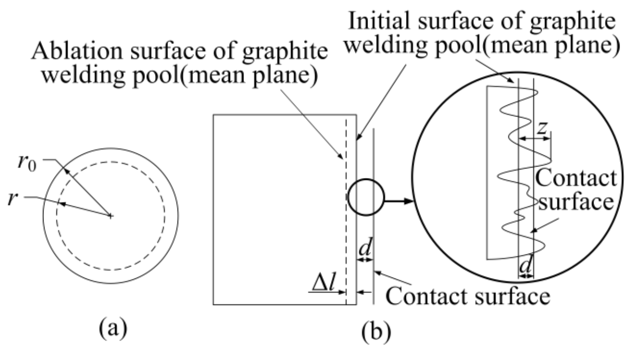


Figure 2. The equivalent principle of the graphite surface ablation.

The surface height of the rough surface of the graphite welding pool generally follows Gaussian distribution. The separation between the mean planes of surfaces of the copper electrode and the graphite welding pool is set to *d*. The contact only occurs at the position, where the profile height $z > d$. Therefore, the correlation between the contact area A_r^* and the separation *d* is established as the following:

$$A_r^* = \frac{A_r}{A_a} = \int_d^{+\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{z^2}{2\sigma^2}} dz = \frac{1}{2} erfc\left(\frac{d}{\sqrt{2}\sigma}\right) \tag{4}$$

where σ, *z* and erfc( ) are the root mean square of the surface roughness, profiled height of the rough surface, and the complementary error function, respectively. When the ablation recession value of the graphite welding pool surface is $\Delta l=r_0-r$, the separation between two mean planes increases by $d+\Delta l$, then the contact area is rewritten as:

$$A_{r_1}^{*}=\int_{d+\Delta l}^{+\infty}\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{z^2}{2\sigma^2}}dz=\frac{1}{2}erfc(\frac{d+\Delta l}{\sqrt{2}\sigma}) \tag{5}$$

The substitution of equation (4) into equation (2) yields the contact resistance of the interface of the copper electrode and the graphite welding pool with ablation.

Some parameters in the above mathematic model, such as L, λ, K, and ϕ, need to be obtained experimentally, and their lack makes the numerical calculation quite problematic. Therefore, the theoretical analysis and experimental verification are combined in the present work to investigate the effect of the graphite ablation on the contact resistance between the copper electrode and graphite welding pool.

4. Experiment material and method

Two types of graphite materials – the common graphite (battery carbon) and the fine graphite (lubricate graphite) – are selected as the graphite welding pool in the experiment. Table 1 shows the chemical composition of the selected materials. Moreover, figure 3 illustrates the V-type copper electrodes are used to clamp the cylinder graphite welding pool and current transmission.

Table 1. The chemical composition of the graphite material.

	Mass fraction (%)				
Types	C	O	Si	S	Other
Common graphite	89.05	6.95	2.25	0.15	1.15
Fine graphite	97.8	1.77	0.06	0.29	0.08

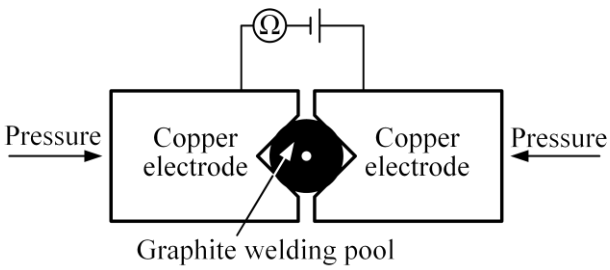


Figure 3. The measurement method of the contact resistance.

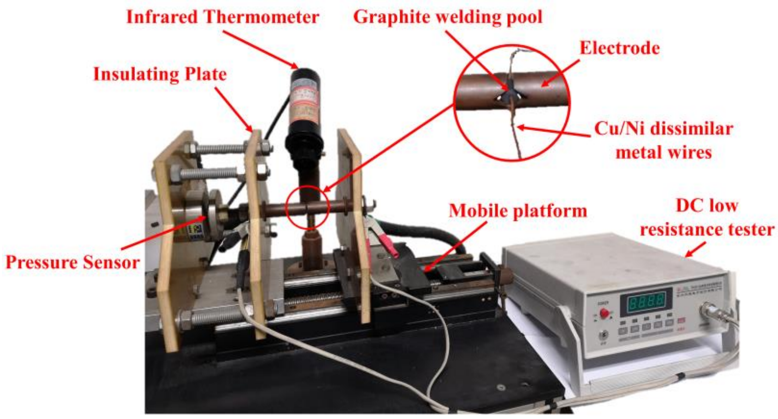


Figure 4. Test platform of welding.

IOP Conf. Series: Materials Science and Engineering **770** (2020) 012006 doi:10.1088/1757-899X/770/1/012006

Figure 4 shows the welding test platform. The spiral micrometer is applied to measure the geometric dimensions of the cylindrical graphite welding pool before and after the ablation. The surface morphology of the original and ablated graphite welding pool is analyzed by means of the scanning electron microscope (SEM) with a Quanta FEG 250. Moreover, the contact resistance is measured by a DC resistance tester.

Two electrodes are fixed in the insulator supports. The test is carried out with an applied voltage of 2.5 V with applied clamping forces of 10, 15, and 20 N. The transmitting electric current varies from 150 to 200 A. The conduction time of each test and the heating times of each sample are set to 6 and 20 s, respectively.

5. Results and discussion

5.1. Analysis of the graphite ablation

The influence of the ablation on the graphite welding pool is mainly reflected in the change of the microscopic topography and the dimensional changes of the macroscopic diameter and height.

Figures 5(a) and 5(c) indicate that the surface roughness of the common graphite welding pool is more than that of the fine graphite welding pool. The former has a higher porosity due to the distinction of the material composition. Comparison of figures 5(b) and 5(d) reveals that the surface roughness and porosity of both two samples increase after ablation.

Moreover, figure 6 illustrates that for the same contact pressure, the variation in the diameter and height of the common graphite welding pools (CGWP) is larger than that of the fine graphite welding pools (FGWP). Larger porosity and higher surface roughness of common graphite welding pools (CGWP) account for the larger diameter and height. The porosity also accounts for the better heating effect, as porosity facilitates more electrical contact resistance which generates heat for brazing. In addition, the variation in the diameter and height of both graphite welding pools, tends to decrease with the increasing contact force. The higher contact force leads to the larger number of conductive spots and conductive pathways, which decreases the Joule heat generated in the graphite welding pool.

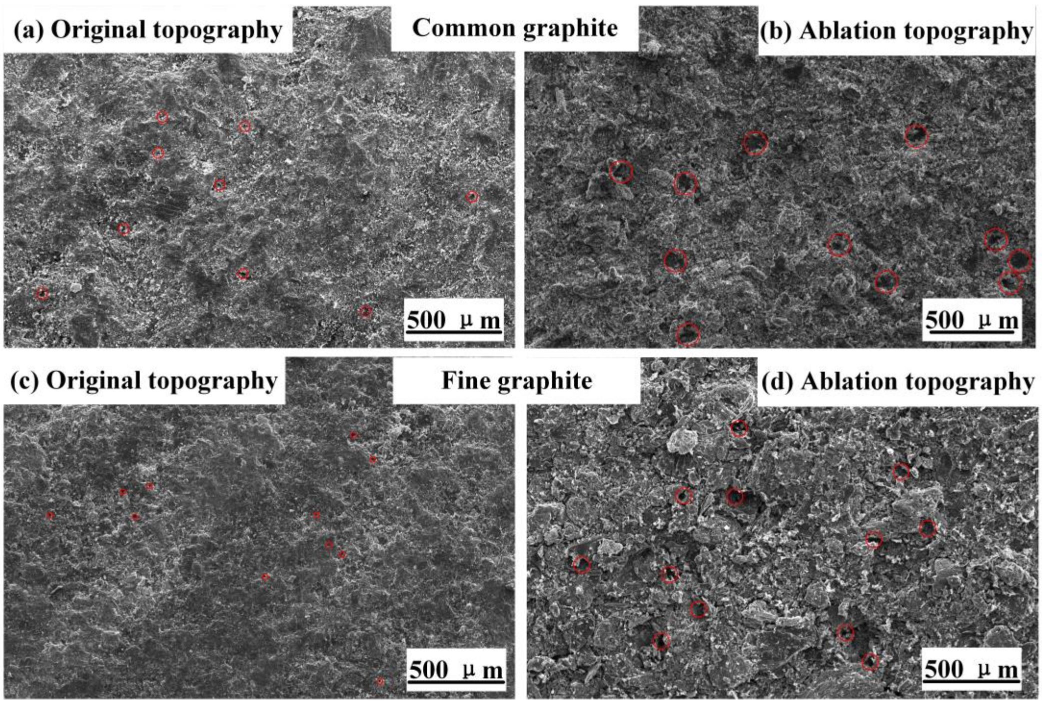
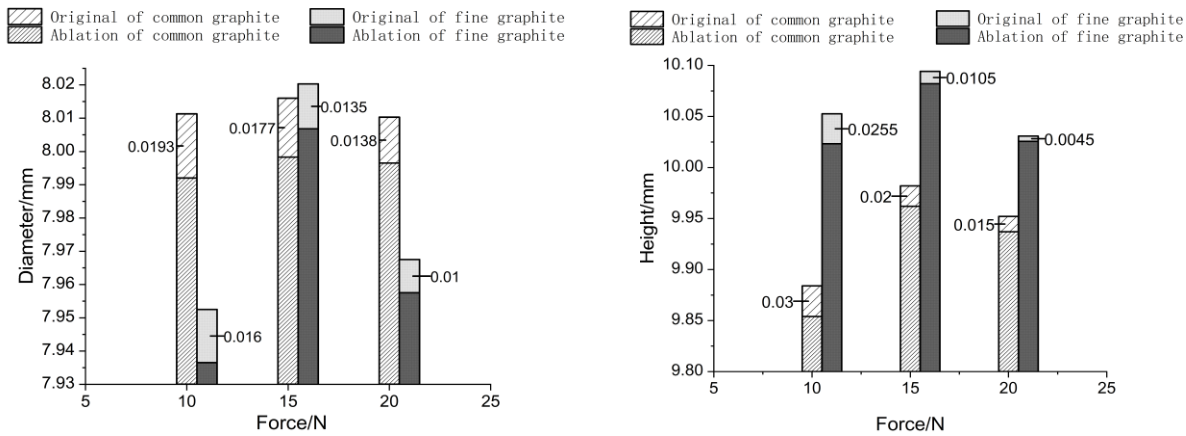


Figure 5. SEM images of the surface of graphite welding pool.

IOP Conf. Series: Materials Science and Engineering **770** (2020) 012006 doi:10.1088/1757-899X/770/1/012006



a) b)

Figure 6. Variation in diameter (a) and height (b) of the graphite welding pool.

5.2. Impact of the ablation on the contact resistance for different pressures

Figure 7 shows the contact resistance with the ablation recession amount of the graphite welding pool surface for different applied clamping forces of 10, 15, and 20 N.

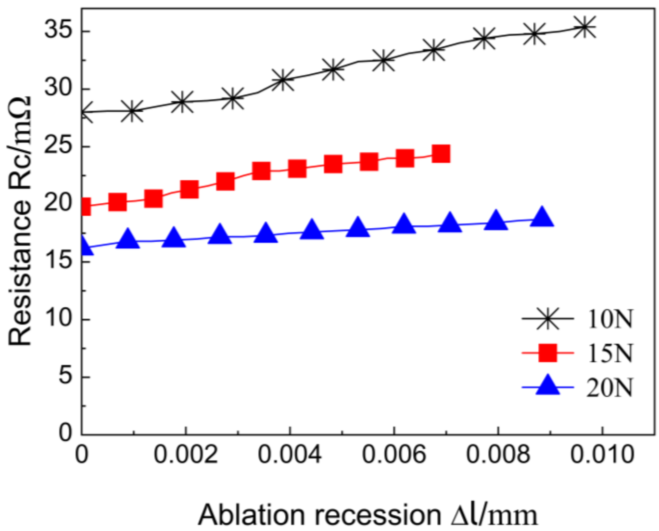


Figure 7. Contact resistance for different clamping forces.

It is observed that the contact resistance decreases as the clamping force increases. This occurs because real surfaces are not perfectly smooth and flat. Real surfaces may be composed of a large number of small but discrete contact points. The number of the surface contact points, as well as the true contact area, gradually increases as the clamping force increases. Moreover, the contact resistance shows a gradually increasing trend with the increase of the graphite ablation recession. The explanation of this phenomenon is that the increasing micro-gap of the contact interface with the graphite ablation leads to the decrease in the number of contact points of asperity and the true contact area. It is found that the contact resistances for different clamping forces are 5.1, 4, and 2.1 mΩ, respectively. This may indicate that the impact of the ablation on the contact resistance is more obvious when the lower force applied to the clamp. Due to the less number of asperities at the contact interface for the lower clamping force, the contact resistance is more easily affected by the increasing micro-gap with the ablation.

5.3. Impact of the ablation on the contact resistance for different graphite materials

Figures 8(a), 8(b) and 8(c) present the distributions for the contact resistance of two types of graphite welding pools as a function of the ablation recession for clamping forces of 10, 15, and 20 N.

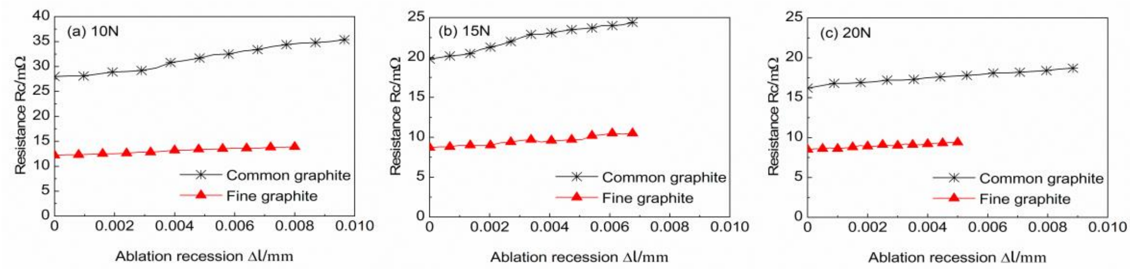


Figure 8. Common and fine graphite performances at different clamping forces: a)10 N; b)15 N; c) 20N.

Figure 8 indicates that, regardless of the ablation, the contact resistance of the common graphite welding pool is greater than that of the fine graphite welding pool for the same clamping force. The increments of the contact resistance of the former one for three clamping forces are 5.1, 4, and 2.1 mΩ, respectively, while the increments for the latter one are 1.9, 1.7, and 0.9 mΩ, respectively. This may indicate that the ablation degree of the former one has more influence on the contact resistance than the latter one.

6. Conclusion

Based on the fractal contact resistance model of the contact interface between the copper electrode and the cylindrical graphite welding pool, the contact rate between the copper electrode and cylindrical graphite welding pool is calculated by the simplified graphite ablation mechanism. Then the contact resistance for the ablation of the graphite welding pool is obtained. The experimental results show that the role of ablation causes a slowly increasing trend in the contact resistance. It is found that the common graphite welding pool has a higher degree of ablation, in comparison with the fine graphite welding pool, as well as the more obvious impact on the contact resistance of interface.

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