Heat transfer characteristics of graphite welding pool in penetration brazing of Cu/Ni dissimilar metal wires

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Abstract. In order to discuss the heat transfer characteristics of the graphite welding pool and the copper electrode, in penetration brazing of Cu/Ni dissimilar metal wire. A mathematical model for electrothermal coupling, on penetration brazing of Cu/Ni dissimilar metal wire, is developed, to describe temperature distribution and influence factors of different types of graphite welding pool and copper electrode, using simulation and experimental tests. The simulation results show that temperatures of the common graphite welding pool is 749.88°C, while the experimental results show that temperatures of the common graphite welding pool is 752.23°C, and the corresponding temperature range of the copper electrode is 236.5°C to 752.23°C, respectively. Furthermore, the length of the copper electrode at high temperature is 16 mm. Since the common graphite has the lowest thermal conductivity, higher thermal resistance, at the contact interface, is developed, while the contact heat, transferred to electrode, is reduced. Last, the heat transfer effect of the common graphite is stronger than that of fine graphite, isostatic graphite and molded graphite.

NOMENCLATURE

- **Q**: Heat generation[J]
- **T**: Temperature[K]
- **\( \lambda \)**: Thermal conductivity[\( \text{w} \cdot (\text{m} \cdot \text{C})^{-1} \)]
- **\( \rho \)**: Material density[\( \text{kg} \cdot \text{m}^{-3} \)]
- **\( c \)**: Specific heat[\( \text{J} / (\text{kg} \cdot \text{C}) \)]
- **I**: Current density[A]
- **\( R_c \)**: Contact resistance[\( \Omega \)]
- **\( A_a \)**: Copper electrode and graphite welding pool contact area[\( \text{m}^2 \)]
- **\( \varepsilon \)**: Copper electrode and graphite welding pool contact interval[\( \text{m} \)]
- **\( \sigma \)**: Conductivity[\( \Omega^{-1} \cdot \text{m}^{-1} \)]
- **\( F \)**: Copper electrode holding force[\( \text{N} \)]
- **\( R \)**: Graphite welding pool radius size[\( \text{m} \)]
- **\( \nu \)**: Poisson ratio
1. Introduction

Heating cables are widely used in low-temperature radiant heating systems and are the core components of low-temperature radiant heating systems. The heating cable core is made by pairing copper wires of different diameters (∅0.4–1.13 mm) and nickel-based alloy heating wires (∅0.3–0.85 mm) by deep penetration brazing. A special welding method, similar to heat conduction welding and brazing [1]. The graphite welding pool with a through hole in the center is mainly used to short-circuit the static copper electrode, and Joule heat will be generated at the contact resistance of the two [2]. Then graphite transfers heat to form a stable heat source, which is used to melt the solder Ag in soldering. Next, the brazing of the Cu/Ni dissimilar metal wires, in the holed graphite welding pool, is realized [3]. A stable heat source can improve the quality of the heating wire welding joint, which is a key factor affecting the heating effect and service life of the heating cable[4]. Therefore, it is important and necessary to study the heat transfer characteristics of graphite.

Liu Meihui et al[5,6] used ANSYS software to establish the electric-thermal-structural coupling field of graphite electric heating elements, and analyzed the heat conduction process of graphite materials containing impurities under the condition of electric heating, and the thermal conductivity of graphite materials coefficient, impurity content, shape and other factors on the heat transfer mechanism of graphite; Zhao Yuzheng et al [7] used classical heat transfer formulas to calculate the radial temperature distribution of graphite electrodes in a step-by-step simulation method; Dong Qinxiao [5] and others established a one-dimensional graphite heat conduction equation based on the heat conduction equation; Patidar B et al [9] established a mathematical model of graphite crucible temperature rise under high-frequency induction heating based on Maxwell's equation and Fourier's equation; Thomas Meier et al [10] used modeling and simulation to describe Graphite electrodes consider the heat transfer characteristics of convection and radiation in an electric arc furnace. Rafiey et al [11] used the finite element simulation method to analyze the nonlinear relationship between the temperature gradient of the graphite electrode and the thermal conductivity of the material for the temperature distribution of the graphite electrode in the arc furnace. Based on the heat conduction equation and related boundary conditions, Yin Youfa [12] and others used the finite difference method to establish a temperature field calculation model in the graphite electrode, and calculated the temperature field change of the electrode's natural heat dissipation at high temperature. However, the paper does not consider the change of graphite thermal conductivity with temperature. Ather Hashim, Si Kyaw, et al [13] used the finite element analysis software Abaqus to perform thermal analysis calculations on the established 2D graphite brick model, and found that the temperature distribution inside the graphite brick is non-radial.

In the above studies, the heating temperature range is more than 2000°C, while there is lack of reports on the analytical calculation methods and non-linear heat transfer mechanisms, for the temperature range about 700°C[14] heating of graphite. Also, the research of domestic and foreign scholars is mostly based on the external heating source or the Joule heat source of the graphite body under the action of current, and the lack of consideration of the influence of the contact resistance formed by the graphite and metal substance on the thermal field distribution of graphite. Therefore, in this study, based on the theory of heat transfer, a mathematical model of the electro-thermal coupling, between electrode and graphite welding pool, is established. Simulation and welding experimental methods are used to study the effect of heat transfer characteristics and temperature field distribution, in a common graphite, fine graphite, moulded graphite and isostatic graphite welding pool. This could provide theoretical guidance for the penetration brazing process of Cu/Ni dissimilar metal wires.
2. Mathematical Model of The Graphite Welding Pool

The heat transfer characteristics of the graphite welding pool, in the welding process, is affected by the properties of the graphite material, the contact resistance, between the copper electrode and the cylindrical graphite welding pool, as well as the contact behavior. In this paper, based on the mathematical model of the interface contact resistance, between the copper electrode and the graphite welding pool, as it was established in Fractal network model of Majumdar A et al[1], the nonlinear transient heat conduction theory is used, to further explore the electro-thermal coupling effect, between these two elements.

Figure 1. Copper electrode contact with graphite welding pool.

Figure 1 shows the contact status of a copper electrode and a cylindrical graphite welding pool. In order to establish the electrothermal coupled model of the welding process and clarify the heat transfer mechanism of the graphite welding pool, the following assumptions are made:

- the contact surface between the copper electrode and the graphite welding pool was simplified to a contact between a rigid smooth surface and a fractal rough surface;
- copper electrode and graphite material isotropic are considered;
- no oxidation ablation of the graphite welding pool is considered;
- the contact changes, caused by the difference in the coefficient of expansion of the copper electrode and graphite weld pool, during welding, are ignored;
- copper electrode and graphite weld pool body do not produce Joule heat.

Considering the heat generation, due to electric current (Joule heat) and assuming nonlinear transient condition, the governing heat conduction equation is as follows [16,17]

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q = \rho c \frac{\partial T}{\partial t}
\]

(1)

Joule heat is the main heat generation mechanism, in the nonlinear transient operation state of penetration brazing of Cu/Ni dissimilar metal wires. The Joule heat equation [18,19] is:

\[
Q = I^2 \left( R_e \right) \left( \frac{1}{A_d f} + \frac{1}{A_d g} \right)
\]

(2)

Using Hertz ’s theory [17] and elasticity contact theory [20,21], regarding the contact area between copper electrode and graphite welding pool, the solving equation is as follows:

\[
A_d = 2aL = 4L \left( \frac{FR(1-\nu^2)}{\pi E \nu} \right)^{1/2}
\]

(3)

The contact resistance \( R_e \), between the copper electrode and the graphite welding pool, is calculated by equation (4) as proposed in the study [22,23]:

\[
R_c = \frac{A_d}{L_d} \left( \frac{D}{(2\pi)^{D/2}} \right)^{D/2}
\]

(4)

The distribution of the temperature field, during the welding process of the graphite welding pool, is calculated by equations (1), (2), (3) and (4). Related parameters such as \( \lambda, E, D, G \) etc, included in the above mathematical model, cause difficulty in the model numerical calculation. Therefore, the heat transfer characteristic and temperature distribution of the graphite welding pool, during the welding process, was analyzed by using simulation and experimental verification methods.

3. Simulation experiment and analysis
3.1. Finite element model and boundary conditions
In this paper, ANSYS is used to analyze the electrothermal coupling, during welding, based on a model, as shown in figure 2. A three-dimensional 20-node thermoelectric coupling unit SOLID226 is used. The grid size of the graphite welding pool is 0.0003 mm, with a total of 94654 units and 132782 nodes, while the copper electrode grid size is 0.001 mm, with a total of 290732 units and 404362 nodes. The contact area between the copper electrode and the cylindrical graphite welding pool is selected by the Targe 170 unit and the Conta 174 unit. The copper electrode is applied with a clamping force of \( F = 15 \)N, while the voltage between the two copper electrodes is \( U = 2.5 \)V, the brazing current is \( I = 120 \text{A} - 150 \text{A} \) and the welding heating time is 6s. The angle of the V-groove, at the end is 60 degrees, while the geometrical dimension of the brazing rod is \( \Phi 16 \text{ mm}\times 45 \text{ mm} \). The geometrical dimensions of the cylindrical graphite weld pool are \( \Phi 8 \text{ mm}\times 10 \text{ mm} \), while the diameter of the center hole is \( \Phi 1.2 \text{ mm} \). The contact resistance thin layer is of actual dimensions: 10 mm\( \times 1.8 \text{ mm}\times 0.1 \text{mm} \) [24]. The simulation used a cylindrical graphite weld pool of ordinary graphite, fine graphite, moulded graphite and isostatic graphite material.

![Figure 2. Meshing model.](image)

3.2. Analysis of simulation results
The simulation process shows that the temperature of the contact surface, between the graphite welding pool and the copper electrode, is rapidly rising, while heat is transferred to the graphite welding pool and the copper electrode. Figure 3 shows the transient temperature field distribution of four cylindrical graphite welding pools, at a heating time of 6s. The maximum welding temperature of the simulation is shown in table 1, which can be seen that the temperature of the common graphite is higher than the other three.

![Figure 3. Temperature field in four cylindrical graphite welding pools.](image)

| Type of graphite | (a) Common | (b) Fine | (c) Moulded | (d) Isostatic |
|------------------|------------|----------|-------------|--------------|
| \( T_{\text{max}} \) (°C) | 749.88     | 708.2    | 463.3       | 459.8        |

Possible reasons for these results are:
- the low degree of graphitization of common graphite and its high porosity;
- the thermal conductivity of the graphite being lower than that of the other three material types;
- the thermal resistance and the interface between the graphite welding pool and the copper electrode are high;
further reducing the degree of heat conduction and air heat radiation, of the common graphite welding pool, the large portion of contact interface is heat transferred to the common graphite welding pool, so the temperature is high.

Figure 4 shows the transient temperature field distribution of a copper electrode heated for 6s. Since the contact point of the thin layer contact resistance unit and the copper electrode are surface contacted by the Conta 174 unit, the maximum temperature of the copper electrode is substantially the temperature of contacting the solid unit. It can be seen that, the temperature, at the end of the copper electrode, is $T(a) = 42.04^\circ C$, $T(b) = 54.18^\circ C$, $T(c) = 66.76^\circ C$, $T(d) = 69.04^\circ C$. While high temperature zone width range (axial length) are $L(a)$ $L(b)$ $L(c)$ $L(d)$, indicating that the thermal resistance of the contact interface decreases, as the thermal conductivity of graphite increases. Furthermore, the copper electrode is gradually increased in heat transferred, by contact heat and temperature difference.

4. Experimental verification and analysis

4.1. Temperature test experiment
A self-built Cu/Ni-based wire deep-fusion brazing test platform, as presented in Fig. 5, is used for graphite, fine graphite, moulded graphite and isostatic graphite. During welding, a CIT-1SJL infrared thermometer (measuring range: 300°C~1200°C) was used to perform real-time detection of point A, while the heat distribution of the electrode and the graphite weld pool were monitored, using a US FLIR E50 thermal imager (measuring range: 0°C~1000°C). The experiment uses welding heating process parameters, consistent with the simulation.

4.2. Analysis of experimental results
Figure 6 shows comparisons between the measured values and simulation results of the four graphite welding pools, at the A temperature measurement point. The maximum welding temperature of the experiment is shown in Table 2. Combined simulation and experiment, we can conclude that the common graphite has better heat transfer characteristics than the other three.

| Type of graphite | (a) Common | (b) Fine | (c) Moulded | (d) Isostatic |
|------------------|------------|----------|-------------|--------------|
| $T_{\text{max}}/({}^\circ\text{C})$ | 752.23     | 710.67   | 468.8       | 465.8        |

At the test temperature $T=300^\circ\text{C}$, the heating times corresponding to various graphites are $t(a)=0.78s$, $t(b)=1.83s$, $t(c)=2.57s$, $t(d)=2.72s$. Common graphite welding pool temperature error range is 0~3.28%, while the maximum temperature error of the other three graphite welding pools is greater than 5%. The reasons are:

- in the simulation model, the contact resistance is converted into resistivity and is regarded as uniform contact, which is different from the actual contact state;
the temperature range of the physical parameters of graphite materials is different from the actual welding temperature, leading to differentiations from the default values, according to current temperature;

- the welding heating model is a simplified version of the actual heating state.

### 4.3. Temperature distribution of copper electrode when heating in different graphite welding pools

![Graph showing temperature distribution of copper electrode](image)

Figure 7. Graphite welding pool corresponds to the copper electrode heat.

Figure 7 shows the results of copper electrode temperature distribution test, when four graphite weld pools are heated for 6s. It is evident that the temperature distribution width of the copper electrode clamping end, when the common graphite welding pool is heated, is the narrowest: L(a)=16 mm, while the temperature range is T=236.5~752.23℃. When the isostatic graphite welding pool is heated, the temperature distribution width of the copper electrode clamping end is at its widest: L(d)=51 mm, while the temperature range is T=154.6~435℃. The reasons probably are:

- common graphite has a low thermal conductivity and a slow heat propagation rate;
- high thermal resistance causes the common graphite radiation copper electrode to have low heat.

It can be seen that, during the deep-melting welding process, the heat of the copper electrode is directly transmitted to the electrode, by the contact heat, while the temperature difference between the graphite welding pool and the workpiece causes heat to be conducted, from the graphite welding pool to the electrode. For this reason, under the assumption of the welding process electrical parameters remaining constant, the use of common graphite welding pool can reduce the heat transfer of the electrode, improve the stability of the welding heat source and meet the process requirements of deep-melting brazing.

### 5. Conclusion

Based on the theory of nonlinear transient heat conduction, the electro-thermal coupling mathematical model of Cu/Ni wire deep-melting brazing process is established. The heat transfer characteristics of graphite welding pool and copper electrode, in heating process, are analyzed by simulation and experimental testing. The following conclusions are obtained:

- It can be drawn from the experiment that common graphite has better heat transfer characteristics than fine graphite, molding graphite and isostatic graphite, resulting in a low heat transfer rate, over the graphite temperature gradient time, and a high thermal resistance at the contact interface, which reduces the heat transfer to the electrode. Therefore the common graphite welding pool has high temperature and the best heat transfer effect.
- under the same welding heating process parameters, the simulation temperature of the common graphite welding pool reaches up to 749.88℃. However, in the experiment, the common graphite
welding pool temperature reaches up to 752.23°C, when heated for 6s, the electrode high temperature zone width is 16mm, while the temperature range is 236.5°C~752.23°C, satisfying the welding heat requirement.

Under the premise that the electrical parameters of the welding process are unchanged, the use of ordinary graphite welding pool can reduce the heat transfer of the electrode, improve the stability of the welding heat source, and improve the quality of the welding joint, so as to meet the technical requirements of deep penetration brazing.

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