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ARTICLE

Electrical Conductivity Models and Theoretical Value Calculation of W-Cu Alloy

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Abstract: W-Cu alloy has been applied in metallurgy, materials, electronics, military and other fields because it has good arc-resistance, anti-welding, conduct heat and electricity and so on. Electrical conductivity is one of the important material performance indexes and has attracted much attention. The electrical conductivity models of W-Cu alloy with different content of Cu were studied in this paper. The characteristics and applicable ranges of these models were also discussed. The conductivity was calculated using these models and compared with the experimental results and theoretical values. The suitable theoretical values of W-Cu alloy were selected and compared to the experimental values. The results show that the experimental conductivity of the W-Cu alloy with low or high Cu component is basically consistent with the theoretical values. Increasing copper content and reducing porosity can increase the conductivity of W-Cu alloy. This offers a theoretical basis for designing the constituent and electrical conductivity of W-Cu alloy.

Key words: W-Cu alloy; electrical conductivity; theoretical model

Tungsten has a low coefficient of thermal expansion, high melting point and hardness. Copper has good ductility, high conductivity and thermal conductivity. Tungsten-copper alloy combines the excellent properties of both components and has been applied in metallurgy, materials, electronics, military and other fields[1-7]. In recent years, electric devices have been constantly developed, transmission network has been continuously extended, automatic control technologies have been rapidly enhanced and electronic technology has been increasingly popularized. These have given higher demands on W-Cu contacts, such as good arc-resistance, high heat and electrical conductivity, excellent fusion welding and electrical wear resistant ability[8]. Because the contact material takes the responsibility for switching on or interrupting current, it directly affects the working reliability and life of the circuit converter and electrical components. So the electrical conductivity is a key performance index for W-Cu alloy. Scholars have never shifted their attention away from the study of alloy electrical conductivity and established the related models. The classical models of alloy electrical conductivity are volume mixing model, matrix model, multiphase alloy model, and so on[9]. Lee et al[10]. have the conductivity of W-Cu composites was evaluated through estimating topological microstructures. Lin et al [11]. analyzed the electrical conductivity of Cu-Cr and Ag-W by three dimensional finite element model and proved that this approach is effective. These approaches have their own characteristics and application conditions.

In this paper, based on the different models of conductivity, the theoretical values of W-Cu alloy were calculated and compared with the experiment values. The application scope and limitation of these models were also analyzed. The influence factors of the conductivity were preliminary studies, which provides a theoretical basis for the components and conductivity design of W-Cu alloy.

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1 Theoretical Models of Conductivity

1.1 Volume mixing model[9]

$$\sigma_{comp}=\sigma_W V_W+\sigma_{Cu}V_{Cu} \quad (1)$$

where, σ_{comp}, σ_W, σ_{Cu} are the conductivity of W-Cu alloy, tungsten and copper, respectively; V_w and V_{Cu} are volume fraction of tungsten and copper, respectively.

1.2 Matrix model[9]

In matrix model, one phase was as matrix and the secondary phase particles are embedded in body material. These particles are unconnected with each other. The sketch map of this model and structure are shown in Fig.1. The calculation formula of the two phase alloys for the matrix model is as follow

$$\sigma_{comp}=\sigma_{matrix}\left[1+\frac{V_{impurity}}{\frac{1-V_{impurity}}{3}+\frac{\sigma_{matrix}}{\sigma_{impurity}-\sigma_{matrix}}}\right] \quad (2)$$

In calculation process, it may be regarded as a copper matrix when V_{Cu} is greater than 50%.

1.3 Statistics model

Disorder crystals form material and their distribution is very irregular in the statistics model, as shown in Fig.1. The calculation formula of this model is Eq.(3)[9].

$$\sigma_{comp}=\frac{[(3V_W-1)\sigma_W+(3V_{Cu}-1)\sigma_{Cu}]}{4}+\sqrt{\frac{[(3V_W-1)\sigma_W+(3V_{Cu}-1)\sigma_{Cu}]^2}{16}+\frac{\sigma_W\sigma_{Cu}}{2}} \quad (3)$$

1.4 Multiphase alloy conductivity of model

The general formula[9] of multiphase alloy conductivity is as follow

$$\sum_i\frac{\sigma_i-\sigma}{\sigma_i+2\sigma}C_i=0 \quad (4)$$

where σ, σ_i and C_i are multiphase alloy conductivity, the conductivity of the i-th phase and the volume fraction of the i-th phase, respectively.

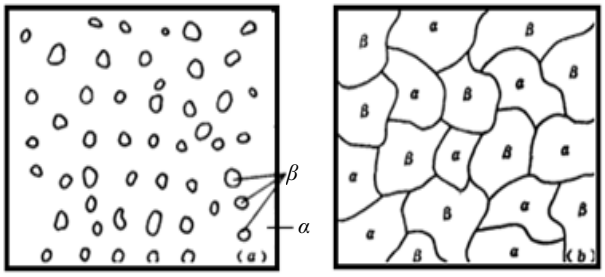

Fig.1 Matrix and statistics models (a) and microstructure sketch (b) [9]

1.5 German model

German considered that the microstructure of W-Cu alloy is an interconnected structure, which is composed of the tungsten skeleton and solidified copper distributed along the skeleton. He also proposed that the calculation formula of thermal conductivity (Q_{comp}) for W-Cu alloy, seen the in following equation [12].

$$Q_{comp}=\pi R^2Q_{Cu}+(1-2R)^2Q_W+\frac{Q_WQ_{Cu}(4R-4R^2-\pi R^2)}{\frac{3}{2}RQ_W+(1-\frac{3}{2}R)Q_{Cu}} \quad (5)$$

where, $R=0.0113+1.58V_{Cu}-1.83V_{Cu}^{3/2}+1.06V_{Cu}^3$, Q_{comp}, Q_{Cu} and Q_W are the thermal conductivity of W-Cu alloy, tungsten and copper, respectively. In the calculation process, V_W and V_{Cu}, Q_{Cu} and Q_W are interchangeable when $V_{Cu}\geqslant 70\%$.

The thermal conductivity is in accordance with Wiedemann-Franz law. Eq.(5) is substituted in to Eq.(6) to calculate the W-Cu conductivity.

$$L=\frac{Q_{comp}}{\sigma T} \quad (6)$$

where L is Lorentz constant; Q_{comp} and σ are thermal conductivity and conductivity of W-Cu alloy, respectively.

Lorentz constant is revised by volume mixing law. L_W is $3.30\times10^{-8}(W\cdot\Omega)/K^2$ and L_{Cu} is $2.30\times10^{-8}(W\cdot\Omega)/K^2$ when thermodynamic temperature (T) is 293 K. Eq.(7) [13]is used to calculate Lorentz constant.

$$L=L_WV_W+L_{Cu}V_{Cu} \quad (7)$$

where L_W, L_{Cu} are Lorentz constant of tungsten and copper, V_W, V_{Cu} are volume fraction of tungsten and copper, respectively. The plausible assumptions of this model are strainless, non-porosity and ideal interface combination.

2 Calculated Values of Different Models and Analyses

The characteristic parameters of tungsten and copper are Cu density of 8.69 g/cm^3, tungsten density of 19.32 g/cm^3, copper conductivity of 100%IACS and tungsten conductivity of 30.05% IACS. Table 1 shows the dependence of the experimental results of the conductivity and the relative density on the Cu component in W-Cu alloy.

2.1 Experimental results vs the calculated value of volume mixing model

The calculated values of the volume model are obtained by Eq.(1) and compared with the experimental values. Their dependence on copper mass fraction is shown in Fig.2. It can be seen from Fig.2 that the calculated values are larger than the experimental values, and a similar conclusion is obtained in the calculation of CuCr alloy conductivity[19]. This model does not consider the influence of material, crystal size, distribution and morphology of the two phases, grain boundary,

Table 1 Dependence of the experimental results of the conductivity and the relative density on Cu component in W-Cu alloy

Cu mass fraction, ω_{Cu}/%	10	20	30	40	50	60	70	80	90
Conductivity, σ/%IACS	33.43[14]	45.91[14]	54.22[14]	59.27[15]	64.9[16]	73.3[17]	85.0[18]	90.2	94.0
Relative density/%	94.35	96.68	99.57	98.11	99.6	99.2	99.6	99.5	99.2

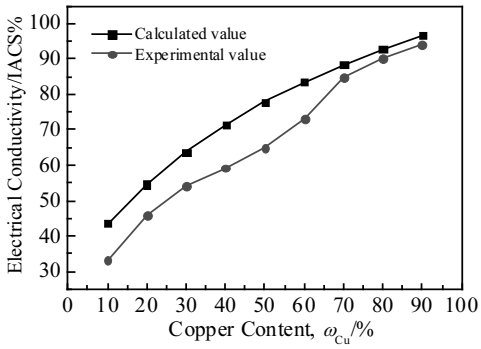

Fig.2 Curves of the calculated values of volume mixing model and the experimental values changing with copper content

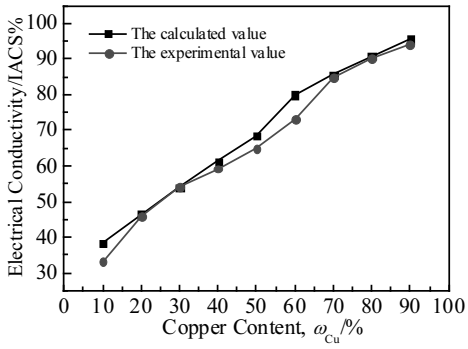

Fig.3 Curve of the calculated values of matrix model and the experimental values

texture, and crystal scattering on the conductivity. The W-Cu alloy can be simply regarded as packing rigid diatomic atoms. So the calculated values of this model are greater than the experimental values.

2.2 Compared and analyzed the experimental results with the calculated value of matrix model

The calculated values of matrix model are derived based on Eq.(2) and compared with the experimental values, as shown in Fig.3. In matrix model, one metal is considered as the matrix while the second phase particles are uniformly dispersed in this matrix. Meanwhile both of the phases cannot interact with each other. Fig.3 shows that the calculation values is well with the experimental results when the mass fraction of copper (ω_{Cu}) $\omega_{Cu}\geqslant 70\%$ or $\omega_{Cu}\leqslant 40\%$. Copper crystal is distributed in the tungsten matrix when $\omega_{Cu}\leqslant 40\%$ in W-Cu alloy while tungsten crystal is distributed in copper matrix when $\omega_{Cu}\geqslant 70\%$.

The more uniform the secondary phase particles are distribution, the more suitable the calculated values of the matrix model. When $40\%<\omega_{Cu}<70\%$, W-Cu alloy no longer belongs to the realm of matrix model. So the calculated values of matrix model and the experimental values have a large difference.

2.3 Compared and analyzed the experimental results with the calculated value of multiphase alloy and statistical models

The calculated values of multiphase alloy and statistical model are estimated using Eq.(3) and (4) and compared with the experimental values, as seen in Fig.4.

The calculated values of both models reveal completely perfect agreement, which can also be found in literature[19]. Alloy is composed of crystals with mess distribution and the

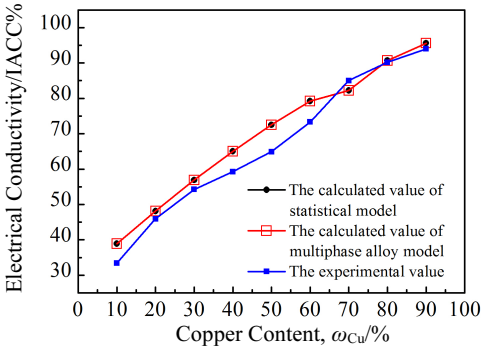

Fig.4 Dependence of the calculated values of multiphase alloy model and statistical models and the experimental values on copper mass fraction

crystal mixture has no regularity in the statistical model. The calculation values are a little large than the experimental results when $\omega_{Cu}\leqslant 30\%$. It is because they have no regard for the influence of tungsten skeleton on the W-Cu alloy properties. The calculation values are consistent with the experimental results when $\omega_{Cu}\geqslant 66.5\%$. By the same token, the more uniform the distribution of the secondary phase particles in the matrix, the more consistent calculated values of the two models with the experimental values are. When $30\%<\omega_{Cu}<66.5\%$, the calculated values of the two models are large than the experimental values.

2.4 Compared and analyzed the experimental results with the calculated value of German model

Based on Eq.(5), (6), the calculated values of interconnection model are obtained. Fig.5 shows that the calculated and

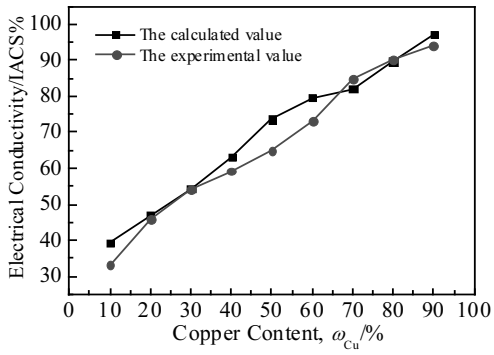

Fig.5 Dependence of the calculated values of German model and the experimental values on copper mass fraction

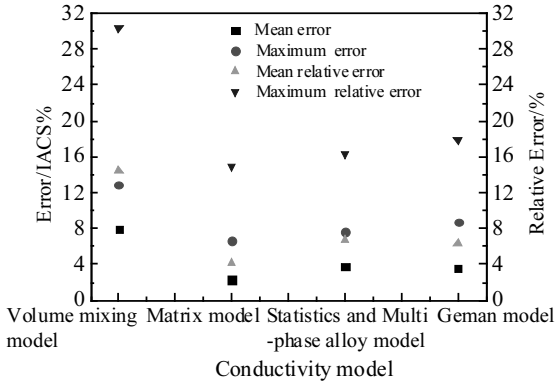

Fig.6 Error between the theoretical value and experimental values for all models

experimental values change with copper component of W-Cu alloy. As shown in Fig.5, W-Cu alloy with $\omega_{Cu}\leqslant 30\%$ conforms to interconnection model proposed by German, which regards that alloy is composed of a tungsten particle skeleton and the solidified copper liquid distributed along the skeleton. So, the theoretical values of the conductivity are calculated by interconnection model under this condition. When $\omega_{Cu}\geqslant 70\%$, the experimental values of conductivity accord basically with the calculated values. It is because the higher component copper forms a continual copper network structure and tungsten particles are distributed in this network. If $30\%<\omega_{Cu}\leqslant 70\%$, the W-Cu alloy has no interconnection structure, so this model is unsuitable and thus the calculation accuracy is low.

It can be found from Fig.2 to Fig.5 that both experimental values and calculated values are all increased with enhancing the copper content. According to the energy-band theory, the energy bands of different metals can partly overlap and form a unfilled conduction band, which makes it easily to conduct electricity [20]. The valences of tungsten and copper are two and six, respectively, and their energy bands can overlap and produce a unfilled conduction band. Because conductivity of the copper is about three times than that of tungsten, it is a main factor affecting the W-Cu alloy conductivity. When copper content in W Cu alloy is higher, the copper phase easily forms the connected networks and the number of the free electrons increases. This leads to an increase in the experimental conductivity. As shown in these four figure, the calculated values of all models are greater than the experimental conductivity when $\omega_{Cu}=10\%$. This is because the density of W-Cu alloy is lower and the residual pores block electron movement leading the conductivity reducing. When $40\%\leqslant\omega_{Cu}<70\%$, the experimental values are in consistent with the calculated values in these model. In this condition, grain size, distribution and morphology of W-Cu alloy and the influence of crystal scatter greatly affect the conductivity. The phase boundary is also increased and exerts a braking to electron movement. These factors lead to decreasing the conductivity and make it to deviate from the calculated values.

2.5 Error analysis between the theoretical value and experimental values

The mean error ($\overline{d}$), maximum error (d_{max}), relative error (Δu) between the theoretical value and experimental value are calculated by Eq.(8), (9) and (10).

$$\overline{d}=\frac{1}{9}\sum\left|\sigma_{exp}-\sigma_{th}\right| \tag{8}$$

$$d_{max}=\left|\sigma_{exp}-\sigma_{th(max)}\right| \tag{9}$$

$$\Delta u=\frac{\left|\sigma_{exp}-\sigma_{th}\right|}{\sigma_{exp}}=\frac{|d|}{\sigma_{exp}}\times 100\% \tag{10}$$

The error analysis results are shown in Fig.6. It shows that in these models, the four errors between the theoretical value of the volume mixing model and the experimental value are the biggest, whose mean error, maximum error, mean relative error and maximum relative error are 8.0 IACS%, 12.9 IACS%, 14.5%, 30.42%, respectively. The four errors of the matrix model are the lowest, which are 2.28 IACS%, 6.6 IACS%, 4.11%, 14.87%, respectively.

Fig.7 shows the relative error of between the theoretical values of five models and the experimental values in different copper content ranges. It can be seen that when $\omega_{Cu}\leqslant 30\%$, the relative errors of German model and matrix model are small. Because German model is more suitable for reflecting when $\omega_{Cu}\leqslant 30\%$. The results in Fig.7 also show that the relative error of matrix model is the least when $\omega_{Cu}\geqslant 70\%$. So, matrix model is chosen to calculate theoretical conductivity in this range. The relative errors of is the least when $30\%<\omega_{Cu}<70\%$. However, it deviate the basic meanings of matrix model, which leads to the inaccurate calculated value. The relative errors of multiphase alloy or statistical models are less and the meaning of both models is suitable. So when $30\%<\omega_{Cu}<70\%$ the theoretical conductivity of W-Cu alloy is

calculated usingmu ltiphase alloy or statistical models.

2.6 Experimental results vs theoretical values calculated using different modes

The change of the relative density and the experimental results and theoretical conductivity of W-Cu alloy with different copper mass fractions are shown in Fig.8. For W-Cu alloy with low or high copper content, the experimental values of conductivity coincide with the theoretical values. This is because W-Cu alloy after hot-rolling or hot-extrusion has low porosity and high density, leading to an increase in the conductivity. The experimental values are still lower than the theoretical values because the material has crystal defect and others factors, such as impurities and internal stress which affects the conductivity. When 30%<ω_{Cu}<70%, the experimental values deviate from the theoretical values. It is because the influence of size, distribution, morphology of the grains and crystal scatter in W-Cu alloy greatly affect the conductivity.

In order to enhance the conductivity of W-Cu alloy, the following measures can be adopted. First, tungsten-copper powder should reduce impurities and increase purity. Second, the densification techniques are optimized to improve the material density and reduced the porosity and make the density close theoretical value. Thirdly, the suitable annealing processes are adopted to treat the material after cold working for removing of internal stress and lattice distortion, thus increasing the mean free path of electron movement and enhancing the W-Cu conductivity.

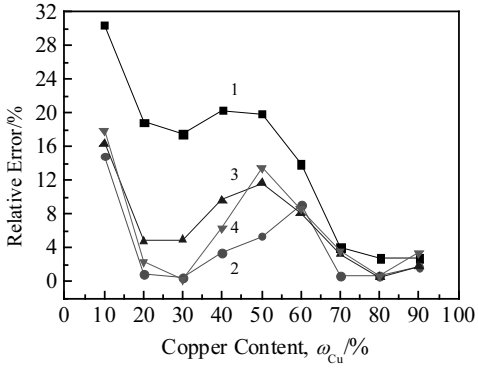

Fig.7 Relation between relative error and copper content of all models (1-volume mixing model, 2-matrix model. 3-statistics model and Multiphase alloy model, 4-geman model)

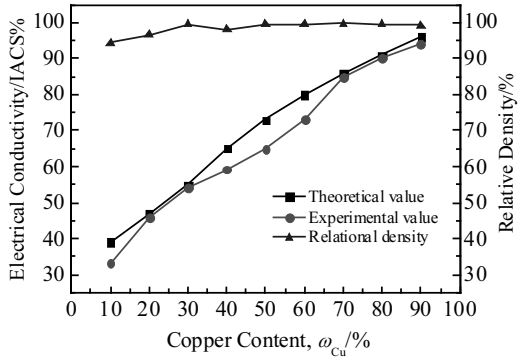

Fig.8 Dependence of the relative density and electrical conductivity of W-Cu alloy on copper mass fraction

3 Conclusions

1) The theoretical conductivity of the W-Cu alloy is calculated using German model, multiphase alloy or statistical models and matrix model when $\omega_{Cu}\leqslant 30$, 30%<ω_{Cu}<70%, and $\omega_{Cu}\geqslant 70\%$, respectively.

2) Comparing the theoretical and experimental conductivity, the results show the experimental conductivity is basically consistent with the theoretical values for the W-Cu alloy with low or high Cu content.

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钨铜合金电导率模型及理论值计算

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摘　要：钨铜合金由于其具有良好的耐电弧烧蚀性、抗熔焊性、高导热导电性等特点，已被应用于冶金、材料、电子、军工等领域。电导率是重要的材料性能指标之一，一直备受大家关注。针对不同成分钨铜合金采用现有的电导率模型进行了归纳总结，并对不同模型的特点和应用进行了讨论，推导出不同模型下的钨铜合金理论电导率；并将合适的模型计算值与实验结果进行了比较。结果表明，低或高铜含量的W-Cu合金的实验电导率与理论值基本符合。提高铜含量和减少空孔隙可提高W-Cu合金的电导率。本研究可为钨铜合金的成分和电导性能设计提供理论依据。

关键词：钨铜合金；电导率；理论模型

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