Experimental study on microstructure of overcurrent fault of copper conductor

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Abstract. This study aims to more accurately identify the microstructure characteristics of copper wire when overcurrent fault occurs, and further improve the accuracy of electrical fire investigation. In this paper, the overcurrent fault of copper conductor under 4-7 times rated current is simulated. The difference of metallurgical structure under different current is analyzed by metallographic microscope. Image-Pro-Plus software is used to measure grain perimeter, and the quantitative criterion and change rule of metallurgical structure are studied. The experimental results show that with the increase of current, the diameter and area of the grains tend to increase. When Ie = 128A, the grains are mainly slender dendritic and columnar, accompanied by a small amount of cellular crystal distribution. The grain directions are different, and the boundary between grains is large; when Ie = 160A, the grains continue to grow, the number of dendritic crystals increases, and the grain boundary becomes fine; when Ie = 192A, the grains are mainly columnar and cellular, with clear grain boundaries, obvious lattice and generally consistent grain directions; when Ie = 224A, the dendritic grains decrease obviously, and the grain diameter and area have little change compared with 192A.

1. Introduction
Electric fire generally refers to the fire caused by the release of heat energy from faulty or non-faulty electrical equipment or electrical lines and the ignition of itself or its surroundings[1]. It mainly includes some distribution, cables, transformers, meters, power conversion devices, sockets, wire mesh, lamps and arcing caused by fire. According to the latest statistical data of the Fire Bureau of the Ministry of Public Security of China, as shown in Figure 1, the total number of national fires and the proportion of electrical fires in China in recent ten years are shown in the statistical chart. In general, the fires in our country increased first and then decreased, but the direct economic losses are still serious, because the fire of electrical control has been high, the annual electrical fire accounted for more than 20%, electrical fire is still the most important cause of fire. In 2019, for example, there were 233,000 fires across the country, killing 1,335 people, injuring 837 and causing direct property losses of 3.6 billion yuan. It is worth noting that in residential fires, electrical fires account for up to 52% of the identified fire causes, especially the fires caused by all kinds of household appliances, electric vehicles, electrical lines and so on are becoming more and more prominent, which has produced a great threat to the fire safety of our society.

In recent years, China has witnessed a number of serious electric fire accidents[11]. For example, in 2015, a huge fire occurred in Kangyuuan Apartment for the Elder in Lushan County, Henan Province on May 25. In 2017, there was a major fire in Jufuyuan Apartment, Dahongmen, Daxing District, Beijing
on "November 18", and in 2018, there was a major fire in Beilong Hot Spring Hotel, Songbei District, Harbin on "August 25". These fires are closely related to wire overcurrent.

Figure 1. Statistics of the total number of fires and the proportion of electrical fires in China in recent ten years

Takaki[2] used metallographic method for the first time to distinguish wire short-circuit melting mark and fire melting mark. Barauskas[3] used Arc Mapping technology to reconstruct the field Arc distribution map and judge the location of the fire point according to the characteristics of the field Arc. Zhang Jinzhuan[4] et al. made the single-core copper wire pass through different current values and control different overload time, and used muffle furnace to control different subsequent heating temperatures and heating times, and changed different cooling methods, and studied the influence of different conditions on the metallostructure of the overloaded copper wire.

To sum up, this paper used metallographic microscope to study the characteristics of metallographic structure under different rated current, and combined with the theory of metal solidification to reveal the characteristics and formation mechanism of copper wire overcurrent fault fusion marks, providing theoretical basis for fire investigation and identification of material evidence.

2. Experiment

2.1. The experimental device
The Fire Evidence Identification Center of People's Police University of China has a considerable accumulation of work in electrical fault simulation. After a long period of beginning and improvement, the electrical fault simulation and trace preparation device can accurately meet the experimental requirements. The experimental device diagram and system diagram are shown in Figure 2. It is mainly composed of the following parts: sample preparation equipment, welding handle, test wire, plastic board, test platform, etc. The sample preparation equipment adopts the "electrical fault simulation and trace preparation device" independently developed by People's Police University of China, which can output 220V AC voltage with the current adjustment range of 30~300A, meeting the requirements of experimental sample preparation. The output current precision is 0.1A, the maximum fault simulation power is 80kw, and the current and voltage acquisition frequency is 1.5104Hz.
2.2. The experimental results

Figure 3. shows the metallographic structure under different current currents. Under the condition of overcurrent, the metallographic grains of copper wire are fuller, the number of grains is increased obviously, and the grain structure is more obvious, and there are obvious boundaries between grains. When the current is 128A, the grain size grows significantly compared with the rated current condition, and its diameter and area increase obviously. The grain size is mainly slender dendritic crystal and columnar crystal, accompanied by a small amount of cellular crystal distribution. The grain direction is different, and the boundary between grains is large; when the current increased to 160A, the grains continued to grow, the number of dendritic crystal deformation increased, and the grain boundary became smaller. The grain direction was more regular than that at 128A; when the current increased to 192A, the grain diameter and area continued to increase, and the grains were mainly columnar and cellular grains, with clear grain boundaries, obvious lattice, and generally the same grain direction; when the current is 224A, the dendritic grains decrease obviously, and the grain diameter and area have little change compared with 192A.
Figure 3. Metallographic structure of arc trace under overcurrent condition of copper conductor.

Figure 4. shows the statistical diagram of the proportion of grain microstructure under different current conditions. The results show that when the current is different, the grain diameter and microstructure change in different degrees. When the current is 128A, the particle size in the range of 15-18 accounts for the largest proportion, accounting for 56.8% of the total, the minimum diameter is 1.23, the maximum diameter is 30.01, most of the area concentrated in the range of 300-400, the corresponding microstructure is mainly dendritic crystal and columnar crystal, accounting for 37% and 43%, respectively. When current is added to 160 A, particle diameter, particle size of most concentrated between 18 to 27, the minimum diameter is 4.07, the largest diameter is 34.56, size effect is remarkable, the area is larger than 400 grain in more than 90%, compared to grain microstructure is 160 A, dendritic crystal increased significantly, the proportion increased from 37% to 50%, from 43% down to 27% of the columnar crystal, the cellular crystal number changed little; when the current was 192A, the particle size of 30-33 gradually increased, with the maximum diameter of 41.79 and the maximum area of about 2500. The number of dendritic crystals decreased significantly, accounting for only 21% of the total, while the number of columnar and cellular crystals increased significantly; when the current is 224A, the number of grains larger than 36 gradually increases, with the maximum diameter reaching 46.44, and the grain area continues to increase,800-3200 up to 87%. Compared with 192A, the number of columnar and cellular grains increases from 37% to 40% and 42% to 47%, respectively, but the effect of increase is not significant. When the current is between 192 and 224A, the change of crystal characteristic parameters is small, indicating that the grain tends to develop stably.
2.3. The theoretical analysis

The nucleation of crystals follows thermodynamic and kinetic conditions. Assuming that the Gibbs free energy, enthalpy and entropy of solid and liquid phase before and after crystal nucleation are $G_S$, $G_L$, $H_S$, $H_L$, $S_S$ and $S_L$ respectively, and the melt temperature is $T$, then the change of free energy in the system before and after solidification is:

$$
\Delta G = G_S - G_L = (H_S - S_S T) - (H_L - S_L T) \tag{1}
$$

$$
\Delta G = \Delta H - T \Delta S \tag{2}
$$

Usually, is independent of temperature. When the temperature of the melt reaches the solid-phase equilibrium melting point $T_m$, $\Delta G = 0$. So there are:

$$
\Delta S = \frac{\Delta H_m}{T_m} \tag{3}
$$

Where, is the latent heat of melting. Substituting Equation (3) into Equation (2), it can be sorted out as follows:

$$
\Delta G = \frac{\Delta H_m (T_m - T)}{T_m} = \frac{\Delta H_m T_m}{T_m} \tag{4}
$$

According to Equation (4), when $T_m = T$, $\Delta G = 0$. There is no solidification driving force inside the system, so the metal cannot solidify when the temperature of the metal is above or above. Then, $\Delta T > 0$ that is $T_m < T$, there is a thermodynamic driving force for crystal nucleation. The thermodynamic condition of nucleation only provides the possibility of nucleation for crystal nucleation, and the dynamical condition of crystal nucleation must be satisfied at the same time. When the crystal nucleus is formed, the change of free energy of the system is determined by the difference of free energy of liquid-solid product and the energy of liquid-solid interface. Among them, the liquid-solid product free energy difference acts as a driving force and liquid-solid interface energy acts as a hindrance to phase transition.

Assuming that the crystal nucleus is spherical, then the Gibbs free energy of the crystal is:

$$
\Delta G = V \cdot \Delta G_v + A \sigma_{SL} \tag{5}
$$

$$
\Delta G = 4\pi r^3/3 \cdot \Delta G_v + 4\pi r^2 \cdot \sigma_{SL} \tag{6}
$$

Where, is the liquid-solid product free energy difference; $L$ is the liquid-solid interface; $r$ is the nucleus radius.

By taking the first derivative of Equation (6), the critical nucleus radius can be obtained $r^*$:

$$
r^* = \frac{2\sigma_{SL}}{\Delta G_v} = \frac{2\sigma_{SL} T}{\Delta H_m \Delta T} \tag{7}
$$

According to Equation (7), the critical nucleation radius is inversely proportional to the degree of undercooling. With the increase of the degree of undercooling, the critical nucleation radius of crystal decreases gradually. The critical nucleation work can be obtained accordingly $\Delta G^*$:
According to Equation (8), the critical nucleation work is $\Delta G^*$ inversely proportional to the degree of undercooling $\Delta T^2$, and the critical nucleation work decreases with the increase of the degree of undercooling. The critical nucleation surface area is:

$$A^* = 4\pi (r^*)^2 = \frac{16\pi}{3} \sigma_{SL}^2 \left( \frac{T_m}{\Delta H_m \Delta T} \right)^2$$

(9)

During the solidification process of metal, the nucleation rate of its grain is:

$$I = C \exp \left( -\frac{\Delta G^*}{kT} \right) \exp \left( -\frac{\Delta G^*}{kT} \right)$$

(10)

Where $\Delta G_A$ is diffusion activation energy. Since the degree of undercooling has little influence on it, it can be seen from Equation (8) that $\Delta G^*$ it is closely related to the degree of undercooling $\Delta T$. Therefore, the nucleation rate can be expressed as:

$$I \propto e^{-1/(\Delta T)^2}$$

(11)

3. conclusion

(1) The nucleation rate and nucleation work of grain are closely related to the degree of undercooling. When the degree of undercooling increases, the nucleation rate and nucleation work of grain decrease.

(2) With the increase of current, the grain diameter increases, and the grain morphology also changes with the current. When the current is 128A, the main dendritic and columnar crystals are slender, accompanied by a small amount of cellular crystal distribution; when the current is 160A, the number of dendritic crystals increases, the grain boundary becomes small, and the grain direction is more regular; when the current increased to 192A, the grain diameter and area continued to increase, and the grains were mainly columnar and cellular grains, with clear grain boundaries, obvious lattice, and generally the same grain direction; when the current is 224A, the dendritic grains decrease obviously, and the grain diameter and area have little change compared with 192A.

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