Research on metal wire blowing mechanism and performance

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Abstract
A short metal wire can be used as a fuse in a circuit. Using ANSYS software simulations combined with experiments, it was verified that the highest temperature region during the blowing process of the wire and the most blowing position is near the middle. When a direct current flows through a measurement circuit was established to study the effect of fuse length, and current on fuse blowing time. The results show that for 0.05 mm diameter copper wire, the blowing time decreases rapidly with the increase of length when the length is within 1 cm under the action of 3.16 A direct current, and the blowing time is basically stable at 0.04 s when the length exceeds 1 cm due to the limitation of heat transfer distance. The blowing time of copper wire decreases with the increase of current, and the blowing time is basically stable at 0.05 s after the current reaches 3.5 A; the melting time of three materials (Cu, Ag, Pb-Sb) all satisfy the theoretical prediction that the product of current density squared and time is constant; the equivalent current density is introduced to modify the theoretical formula, which makes the theory and experiment more in agreement. This study provides a more comprehensive description of the blowing time and characteristics of short metal wires under the action of high current (DC) from both theoretical and experimental aspects.

1. Introduction
A fuse is usually a short piece of wire, a material that conducts electricity easily. It is an integral part of an electronic circuit system, and its function is vital to protect the circuit from damage. Fuses come in a variety of shapes, sizes, and ratings for each of the different circuits. A fuse works by breaking a circuit when it absorbs a higher current than expected, thus preventing damage due to a short circuit. The simplest fuse consists of a resistive element, carefully chosen according to its melting point [1]. When a current flows through this element, a small voltage drop is generated and the current generates heat, thus increasing the temperature of the element. For normal currents, this temperature rise is not sufficient to melt the fuse. However, if the current exceeds the rated current of the fuse, the melting point is quickly reached, the fuse melts and the circuit is interrupted [2]. The thickness and length of the fuse determine the current rating. Generally, fuses are made of zinc, copper, silver, aluminum or other alloys that provide a predictable melting current [3].

The heat distribution during fuse operation and melting have been studied by many authors. Hoffmann G et al described a thermal model of fused wires based on a thermal network approach [4]. Garrido C and Psomopoulos C S gave some mathematical models describing the operation of fuses with different fuse link geometries [5, 6]. Torres E described in the paper the transient thermal processes associated with current-limiting fuses [7]. Kawase Y presented a thermal analysis of a fuse for short-circuit prevention in power semiconductor devices, using a three-dimensional finite element method to obtain the temperature distribution [8]. Beaujean D A et al performed a relatively simple thermal analysis of a fuse element based on a commercial finite element method package [9]. Hamler A et al used a finite element method to calculate the pre-arc time and obtained time-current relationship characteristics [10]. Recently, the melting characteristics of some new materials have also been studied. Wang Xiao Yu studied the effects of melting time and temperature on the micro structure and thermoelectric properties of p-type Bi0.3Sb1.7Te3 alloy [11]. Choi J S investigated the
electrochemical reaction between lead borate glass frit doped with Sn metal filler and Ni-Cr wire of a J-type resistor during a term of Joule heating. The materials provided great potential for fusible resistor applications [12].

The focus of fuse research is on the melting mechanism and the physical characteristics of the melting process. The difficulty of the study is how to accurately and quantitatively characterize the physical quantities of the melting process, and how well the theoretical simulations match the experimental results. Chen S analyzed the changes of electrical signals in the melting process and transition behavior of metal wire and studied the influence of current waveform and current magnitude on the metal melt [13]. Yuan C studied the mechanism of continuous melting and secondary contact melting in resistance heating metal wire additive manufacturing and the difference between the second contact melting of the disconnected metal melt and the continuous melting of the metal wire as well as eliminated the problem of the uneven heat dissipation of the base metal deposition on the melting process of the metal wire [14]. In this paper, the blowing parameters of three different materials of short wires under direct current are studied, and the blowing time and material parameters are quantitatively characterized, and empirical formulas are obtained that are more consistent with the theory.

2. Theoretical background

2.1. Physical mechanism of wire fusion

The process of metal wire fusion is more complex and involves more physicochemical processes, and the qualitative analysis mainly consists of the following stages. After the current is applied, the wire fixed at both ends expands between the immovable contacts; other lengths and areas expand; local bending may form, leading to microcracks and lattice defects, thermal corrosion or oxidation on the surface; the area gets hotter and causes more intense surface evaporation; the wire resistivity increases rapidly with temperature; due to the plasticity of the material leads to a softer area that will be more elastic part of the accumulated mechanical tension crushes the wire; partial melting or local liquefaction, evaporation at the surface with the internal region, micro-droplets leave the surface; particle explosion, rapid loss of material at one or several points; the whole region breaks and the circuit is interrupted [15].

2.2. Temperature distribution in the wire

The heat conduction of the current in the metal wire is shown specifically in the temperature distribution in the wire, taking the unit element part \( dx \) of the wire for thermal equilibrium analysis [16, 17], as shown in figure 1.

\[
P_1 + P_2 = P_c + P_a
\]

where \( P_1 \) is the thermal power of the current in the micro-element \( dx \); \( P_2 \) the thermal power caused by the uneven temperature distribution on the wire; \( P_c \) is the thermal power to be absorbed by the micro-element \( dx \) to warm up; and \( P_a \) is the thermal power dissipated to the surrounding area from the outer surface of the micro-element \( dx \) [18].

For this circuit, it can be written specifically as

\[
AC\sigma \frac{d\Delta T}{dr} + \kappa S \Delta T = \frac{LA}{d\Delta T} + \frac{I^2\rho}{A}(1 + \alpha \Delta T)
\]

Where \( A \) is the cross-sectional area of the fuse, \( C \) is the specific heat of the fuse, \( \sigma \) is the wire density of the fuse, \( \kappa \) is coefficient of the heat transfer from the fuse element to the surrounding area, \( S \) is the cross-sectional perimeter of the fuse, \( \lambda \) is the thermal conductivity of the fuse, \( \rho \) is the resistivity of the fuse, and \( \alpha \) is the resistance temperature coefficient.

2.3. Analysis of the heat in the fuse blowing process

According to the first law of thermodynamics: the heat generated by the thermal effect of current is equal to the sum of the energy stored in the wire and the heat dissipation. From the two extreme cases to analyze: wire slowly heated, assuming that the blowing time tends to be infinite, heat loss is equal to the current thermal effect heat.
production. The wire is heated rapidly and the blowing time tends to be infinitely short, and the energy stored in the wire is equal to the current heat effect heat production [10]. If a short wire is able to function as a fuse, then its fusing time needs to meet the characteristics of the fuse, and it will blow quickly in a very short time. The stored heat is therefore the mass of the conductor multiplied by the enthalpy change required to go from a solid at the initial conductor temperature to a liquid at the melting point temperature. The energy conservation equation will be simplified as follows.

\[ \sigma AL [h_i(T_m) - h_i(T_0) + \Delta h_m] = i^2Rt \]  

Schwartz and James considered the two terms of thermal radiation and thermal convection as heat dissipation terms, which are expressed as

\[ \sigma A(T^4_m - T^4_0) + hA(T_m - T_0) = i^2R \]

where \( L \) is the fuse length, \( h_i \) is the enthalpy of solid relative to 298 K (J.kg\(^{-1}\)), \( T_m \) is the melting point (°C), \( T_0 \) is the ambient temperature (°C), \( \Delta h_m \) is the latent heat of fusion (J.kg\(^{-1}\)), \( i \) = current (A), \( R \) is the resistance (Ω), and \( t \) is the time (s). The value of the emissivity \( \varepsilon \) depends on the condition of the surface. For the purposes here, it is most appropriate to assume that, by the time it gets heated to \( T_m \), the copper surface will have oxidized and will comprise a coating of cuprous oxide, \( Cu_2O \). The emissivity of \( Cu_2O \) at 1083 °C is approximately \( \varepsilon = 0.55 \) [19].

E.R. Stauffacher divided Onderdonk’s equation into two sub-processes according to the wire fusion process in his book at 1928 [2]. Heating process:

\[ \sigma AL [h_i(T_m) - h_i(T_0)] = i^2Rt \]

\[ R(T) = \frac{R_o L}{A} [2 + \alpha(T - T_{ref})] \]

Melting process:

\[ \rho AL [\Delta h_m] = i^2R(T_m)t_2 \]

where \( R_o = 1.7241 \times 10^{-8} \)Ω.m is the resistivity of copper at \( T_{ref} = 20 \)°C, and \( \alpha = 0.00393 \) is the temperature coefficient of copper (°C\(^{-1}\)).

Take copper wire as an example(mm\(^2\) units):

\[ t_1 + t_2 = 9.644 \times 10^9 \left( \frac{A}{i} \right)^2 \]

It can be seen from equations (5) and (7) that the product of the square of the current density and the energization time is a constant that reflects the blowing characteristics of the material as a fuse.

\[ j^2 t = C_{\text{material}} \]

where \( j \) is the current density. It is only reflected in the different \( C_{\text{material}} \) constants at the right end of the equation for wires of different materials.

### 3. Experimental arrangement

#### 3.1. Copper wire heat distribution

A long straight copper wire was simulated and analyzed by the thermal/electrical coupling module in multi-physical field coupling with the SOLIDWORKS module in ANSYS software. The temperature distribution on the wire was analyzed by flowing through a current \( I = 0.765 \) A to a copper wire of 5.00 cm length and 0.05 mm diameter using an infrared thermal imaging camera (FOTRIC224s). The temperature distribution on the copper wire of 0.05 mm diameter was further simulated numerically using MATLAB based on the heat conduction equation.

#### 3.2. Blowing time of copper wire

A fuse melted when the current in the circuit exceeded a certain threshold value. The blowing time was an important parameter in fuse design. The effect of current intensity and copper wire length on the blowing time was studied in power supply constant current mode. It was found that the copper wire had a definite blowing current and length when it acted as a fuse. Further, the measurement circuit was designed as in figure 2, and the blowing time (referred to as \( t_1 + t_2 \)) of a copper wire with a diameter of 0.05 mm at different lengths under a current of 3.16 A was analyzed by measuring the voltage across the fixed-value resistor (\( R = 1.00\Omega \)) with an oscilloscope (Tektronic TDS1002C-EDU). On the oscilloscope screen, it was clear that there were two characteristic processes of the fuse blowing, which correspond to the heating process and melting process in the previous analysis. And the data were analyzed quantitatively.
3.3. Effect of current and materials on the blowing time

The characteristics of the blowing process of copper wire were investigated, and then the blowing time of different material wires was studied experimentally. The product of current density and melting time was known to be a constant from equation (9), which was material dependent. Three different materials (Cu, Ag, and Pb-Sn alloys) were selected to measure their blowing times at different currents. The curves of current density versus blowing time were made, and the theoretical expressions were corrected by experimentally fitting the curves.

4. Results and discussion

ANSYS software simulation results were shown in figure 3. The temperature distribution of the cross-section was diffused from the center to the outside, and the highest temperature was at the center. Along the direction of the wire, when the current flows, because the wire was fixed at both ends and the air dissipation rate was slow, its heat dissipation was limited, resulting in the highest temperature in the center of the two fixed ends of the wire, which was the most prone to fuse position.

The results taken with the infrared thermal imaging camera were shown in figure 4, which were match with the heat distribution characteristics of the theoretical analysis. Although the temperature displayed by the thermal imaging camera (301.6 °C) was not the real temperature (probably due to the instrument range), it can be clearly seen that the center of the copper wire has the highest temperature. This provided some evidence for the fuse blowing at the centre of the fuse, and also indicated that the range is not large enough to truly reflect the temperature change during the blowing process because the sampling rate of the thermal imaging camera was not high enough (sampling rate of 0.02s).

The temperature transfer curves on different lengths of copper wires were numerically simulated by MATLAB as shown in figure 5. The results showed that within 0.08 s, \( L > 1.00 \text{ cm} \) copper wires were fused, but the heat transmission distance was only 1.00 cm.

From the simulation and analysis, it can be seen that the fuse had an optimal length limited by the temperature conduction time. Figure 6 showed that in the condition of 3.16A current passed through a copper wire with a diameter of 0.05 mm: when the fuse length \( L < 1.00 \text{ cm} \), the blowing time decreased significantly with the increase of length; when the fuse length \( L > 1.00 \text{ cm} \), the blowing time decreased slowly with the...
Figure 4. Infrared thermal imaging camera photo diagram.

Figure 5. Temperature distribution on copper wire.

Figure 6. Different lengths of 0.05 mm diameter copper wire blowing time relationship graph.
increase of length. If the wire was long enough, the effect of length on the blowing time can be ignored and the blowing time was basically stable at 0.04s. It also meet the requirements of fuse specification.

The relationship between blowing time and current for a copper wire with a length of about 2.00 cm and a diameter of 0.05 mm at different currents was shown in figure 7. From the experimental results, it can be seen that when the current was small: the blowing time decreased significantly with the increase of current; because the current was small, the current heat generation rate was slow, the wire slowly heat up to the melting point and further phase transition occurred, resulting in the wire fusing. When the current was higher (more than 3.50A): the blowing time decreased slowly with the increase of length. Because the heat generation rate was very fast at high current, the thermal conductivity of the air around the wire was small, and the heat does not have time to diffuse to the outside world, the wire quickly reached the melting point and underwent a phase transition or even vaporized and melted directly. The copper wire blowing time remained at about 0.05s, which meet the fuse blowing time (t less than 0.08s) and can be selected as a fuse in a specific circuit (protection current about 3.50A).

The characteristics of the metal wire during the blowing process are obtained by analyzing the current change of the wire. The current value in the copper wire can be calculated from the measured voltage value across the fixed value resistor. The results show that the current has two different curves during the blowing process in figure 8, corresponding to the heating process and the melting process, respectively. The results show that the current has two different curves during the blowing process, corresponding to the heating process and the melting process, respectively. It is fitted with the previous theoretical formulas (5) and (7) respectively, and both have a good degree of fit in figure 9. It can be seen that the above-mentioned two characteristic stages generally exist in the process of blowing.
The experiments of blowing time were carried out on three materials, copper wire, silver wire and Pb-Sb alloy wire with a length of 2.00 cm and a radius of 0.05 mm. The relationship between the blowing time and current density of the metal wire was obtained. The experimental data points were fitted according to the form of equation (9) to obtain the results as shown in Figure 10.

The fitted relationship equations for the three material wires were as follows: Cu wire: \((j^2 - 4.2 \times 10^5) t = 2.0 \times 10^5\); Ag wire: \((j^2 - 3.7 \times 10^5) t = 9.4 \times 10^4\); Pb-Sb alloy wire: \((j^2 - 2.1 \times 10^5) t = 5.2 \times 10^5\). Based on the fitting results, equation (8) was corrected to: \((j^2 - j_{\text{loss}}) t = C_{\text{material}}\), where \(j_{\text{loss}}\) was called the equivalent current density, which meant the energy required to generate the heat dissipation of the wire during the heating and melting process. The heat dissipation term in equation (4) was considered as the equivalent current action effect and is written as

\[\varepsilon \sigma A(T_m^4 - T_0^4) + hA(T_m - T_0) = j_{\text{loss}}^2 A^2 R\]
The theoretical values of \( j_{\text{loss}} \) can be obtained by substituting the relevant parameters of the three materials and environmental parameters, respectively, as shown in Table 1. From the results in Table 1, it can be seen that the theoretical values were consistent with the experimentally fitted values within the error range, indicating the reasonableness of the theoretical corrections.

5. Conclusion

Taking the short copper wire as the research object, the radial temperature distribution was analyzed by infrared thermal imaging camera when the current passed through, and its heat transfer was simulated by heat transfer equation with MATLAB. Both of them show that when the current flowed through the metal wire, due to the heat transfer restriction at the two fixed ends, the center position had the highest temperature and was the easiest position to blow. The blowing characteristics of the short copper wire as a fuse were further explored, and the heat transfer distance during the rapid blowing process was only about 2.00 cm at a high current, which provided some reference for the selection of the fuse length. A simple circuit was designed and the current variation of the short copper wire blowing process was obtained using an oscilloscope with high sampling rate. It was found that the current had two processes with different trends, corresponding to the heating process and the melting process, and the experimental data were compared with the theoretical curve, and the two trends matched well. Finally, the blowing process of several materials was analyzed, and the product of current density and blowing time was a constant related to the material, and the theoretical formula was modified by fitting the experimental data to get an empirical formula that is more in line with the facts. The protection current can be determined based on the characteristic curve of the material and the fuse blowing time requirement, when the material acted as a fuse in a circuit. This paper was a comprehensive and detailed study of the fusing characteristics of short metal wires under the action of direct current and the influencing parameters. The characteristics under alternating current (taking into account the skin effect) can be further studied in the future. This will provide a more comprehensive and systematic study of the possibility of short wires acting as fuses.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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