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Investigations on Metallographic Structure of Sparks formed as the Severe Overload Melts a Stranded Copper Conductor

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Abstract. If the overload is severe, the conductor may become hot enough to ignite fuels in contact with it as insulation melts off. The sleeved insulation is the typical effects indicating the overload causes the fire. However, it may be difficult to identify the overload in the circuit because the sleeved insulation disappears easily in fire. Compared to the sleeved insulation, the re-solidified copper sparks are less easily to be damaged for locating lower in fire. Those sparks can assist in identifying that some circuit, which became hot and was melted by a large overload before the fire. In this paper, the 2.5mm^2 PVC stranded copper conductors, as the most common in Chinese residential electrical systems, was melted by large overload at different current in order to produce overload sparks. Through the analysis of internal metallographic structure of overload sparks, there are significant differences from sparks formed by short circuit and globules exposed to laboratory flame testing. The results reveal that when the current through the conductor is greater than $5I_e$(I_e=34A), the conductor would be melted in two and produce a parting arc throwing some sparks; the larger current through the conductor was, the more luminous the parting arc was, and the more sparks produced; In the internal metallographic structure of sparks caused by large overload, there are more dendritic segregations than that of globules caused by flame testing and less dendritic segregations than that of short-circuit beads. The larger the current flows in a conductor, the more serious dendritic segregations in internal structure of sparks are. Those metallographic structure features can be used to identify the sparks formed by the large overload as opposed to other globules and sparks in fire investigations.

1. Introduction

Before a fire can properly be determined to have been caused by electricity, the source of electrical heat must be identified. At the point of origin, there must be an electrical source that can ignite a close combustible material. If wiring systems and device are not designed properly and in compliance with the codes, there might be high enough resistance of some current-carrying parts or connections that could be overheat. This is by far the most common cause of electrical ignition [1]. Resistance heating involves the following three forms: heating producing devices, poor connections, and overcurrent. Overcurrent that is large enough and persist long enough to cause damage or create a danger of fire are called overload [2]. Sleeving of thermoplastic conductor insulation caused by internal heating of conductor is the significant effects indicating the overload have occurred. However, when exposed to fire and glowing embers, this sleeving of insulation may disappear. Therefore, it is necessary to find overload damage of the conductor to identify whether or not the fault has happened during the fire. Large overcurrent that persist (i.e., overload) can bring a conductor up to its meltingtemperature. There is a brief parting arc as the conductor melts in two.

Overload is a common electrical fault which causes fire [3, 4]. January 2, 2015 Harbin TaiGu Street

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warehouse large fire, the cause is the electric heater illegally used, resulting in large overload in wire. The fire burned an area up to 11 thousand square meters. The consequences of 5 firefighters sacrificing heroically and 14 people injured, caused great repercussions in society. Currently the studies on overload are mainly about overload ignition capability [5, 6]. Zhang Jin-zhuan studied on the metallographic structure of the unmelted conductor with different cross section copper conductor, different overloading time, heating temperature and so on [7]. This study is a relatively effective complement to metallographic identification for overload. However, the metallographic structure of the unmelted conductor under overload is similar to the structure of the effects by fire attack, and they are difficult to distinguish. In America, 《NFPA921-2014》 indicates that globules are created by nonlocalized heating such as overload or fire melting[1]. And Wright proposed that the conductor may melt and blisters form on the surface of the conductor in the condition of overcurrent or flashover [8]. These studies only focused on the effects which located on the conductor end, but ignored the sparks thrown from the conductor with the influence of parting arc when conductors fused. However, the other investigations haven't covered sparks by overload as the same, and the experimental data are rare.

2. Experiments

The material selected for test in this study is 2.5mm^2 PVC stranded copper conductors, which is most common in the electrical system of Chinese residential building. To determine if the overload conductors at different current values create the identifiable characteristics in the metallographic structure of sparks, the DC welder with 220VAC powers 25cm wire sample with PVC insulation and modifies the values of current flowing the conductor. According to the indication of the DC ammeter, seven values of currents flowing are 4I_e (I=34A), 4.5I_e, 5I_e, 5.5I_e, 6I_e, 6.5I_e, and 7I_e respectively. When the value of the current is less than 5Ie, the conductor only become hot, but be not melted in two. When the current is increased above 5.5I_e, it brings the conductor up to its melting temperature and produce parting arcs at the point of melting, as showed in Figure 1, 2. Simultaneously, some sparks are thrown out of the conductor and drop into the ground. At each current value, five parallel tests are done. All sparks of all tests are collected and counted. First, stereomicroscope was used to observe the external appearance of sparks in order to analyze the char debris, shape, size, and so on. All metal sparks collected are mounted in phenolic molds, ground, polished and etched with $FeCl_3$: HCl: H_2O (10g, 10mL, 100mL) for metallographic examination.

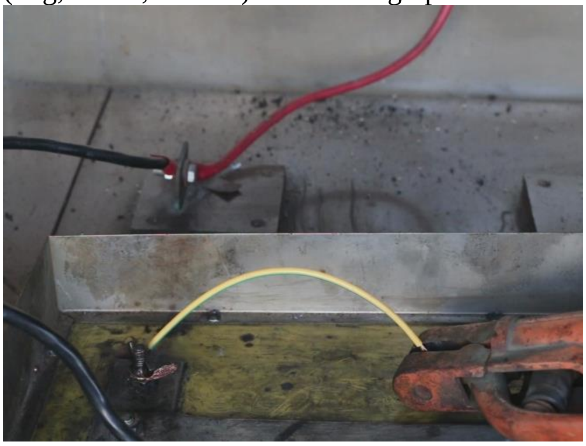

Figure 1 The image of unpowered taken by video photography before the experiment

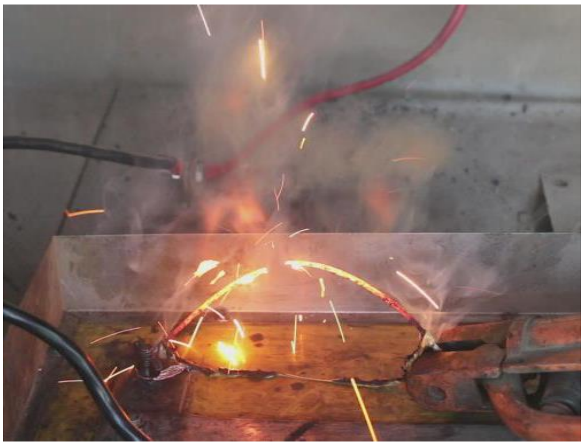

Figure 2 The image of the parting arc taken by video photography when the conductor is melted

3. Results and Discussion

When the current through stranded copper conductor is lower than $5I_e$, the conductor produces heat. The sleeved insulation is thermally decomposed and accompanied by large amounts of smoke. But the stranded copper conductor will not fuse, and the overload will remain on power fever. When the overload is greater than $5I_e$, the faulty stranded copper conductor will fuse with an obvious parting arc. Due to the both action of the extremely thermal parting arc and the heating effect of the current, the stranded copper conductor will melt. With the influent of the parting arc and its own gravity, a part of the liquid metal on the fusing point moves away from faulty conductor, and produces sparks. The sparks become cooling in air, and gradually solidify. They are the representative effects that are investigated in this paper.

Table 1 shows the number of experimental groups with the condition of different current values; the total number of sparks generated in the parallel experiments of each current value of the 5 groups; and the average number of sparks in each parallel experiment.

Table 1 The number of sparks with the condition of different current values

Current Value	Number of Experimental	Number of Sparks	Average Number of Sparks Per Group
$5I_e$	5	5	1
$5.5I_e$	5	7	1.4
$6I_e$	5	10	2
$6.5I_e$	5	12	2.4
$7I_e$	5	13	2.6

According to table 1, with current increased, there existed more sparks. Because the brief parting arc was more powerful, stranded copper conductor was more likely to melt, resulting in more liquid metal. Therefore, in these experiments, there existed the most sparks by overload at $7I_e$.

3.1 Macroscopic Identification of Sparks by Overload

Figure 3 external appearance of a spark generated at $5I_e$ 16×

Figure 4 external appearance of a spark generated at $5.5I_e$ 8×

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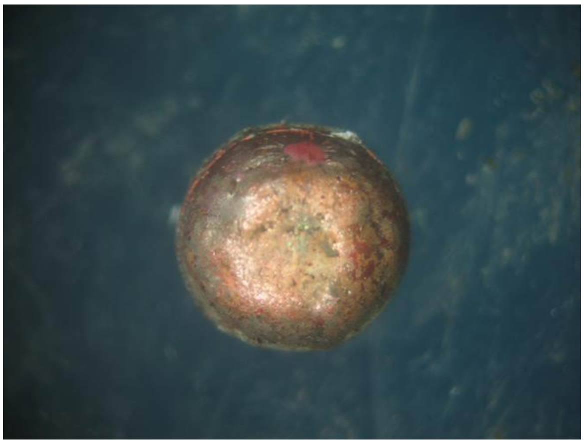

Figure 5 external appearance of a spark generated at $6I_e$ 8×

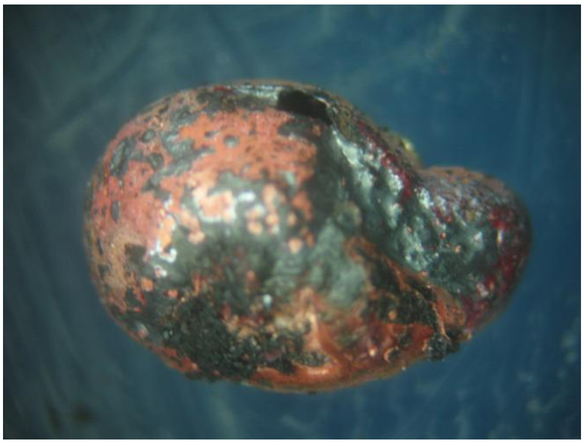

Figure 6 external appearance of a spark generated at $6.5I_e$ 8×

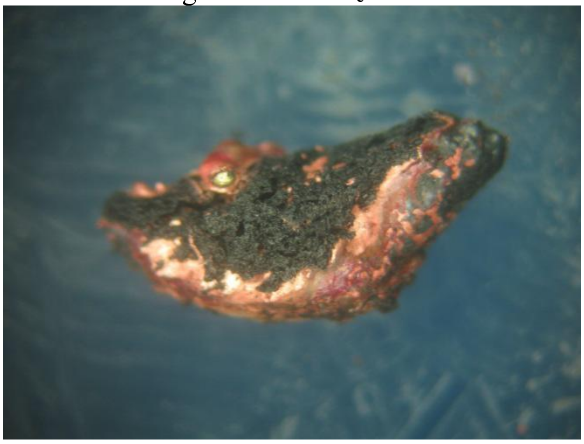

Figure 7 external appearance of a spark generated at $7I_e$ 8×

When the overload occurred in the stranded copper conductor, when $I > 5I_e$, a brief-parting arc would occur. Due to the both action of the extremely thermal arc and the heating effect of the current, the stranded copper conductor would melt, and the liquid metal would drip from the breaking point. And the liquid metal formed the sparks. Through observation and analysis of the sparks forming in the experiments, a series of changes in the macroscopic appearance characteristics were seen: (1) When the current is small, the shape of the spark was regular, and usually the shape was spherical, and the sparks were smaller size, (2) With current increased, the number of the sparks became more, and the shape was no longer regular sphere, and the edge of the spark is convex, (3) The surface of the spark became rough, and there located some pits or pocking marks, (4) The insulation layers which adhered to the surface of spark were more solid, and couldn't be removed easily, (5) When the current is $7I_e$, the metallic luster of the spark is most obvious, as shown in Figure 3~7.

With current increased, the temperature and the energy of the brief parting arc will increase. When the stranded copper conductor fuses, the metal will change from solid state to liquid state, and more liquid metal leaves from the faulty conductor. Moreover, the liquid metal will contain more energy before it leaves the faulty conductor. And more energy will convert into kinetic energy, when the liquid metal drips into air. Therefore, with current increased, the number of sparks becomes more and the sparks will own more extensive location, and get bigger. Moreover, with current increased, the temperature of the liquid metal gets higher, and the insulation layer is seriously carbonized, and the carbide contacts with the liquid metal tightly. Therefore, after the liquid metal solidifies, carbonized insulation layer adheres more tightly to the surface of the sparks.

3.2 Metallographic Identification of Sparks by Overload

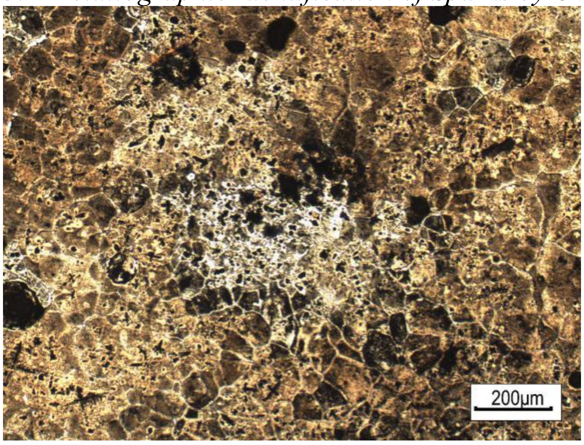

Figure 8 Metallographic structure of a spark generated at 5I$_e$ 50×

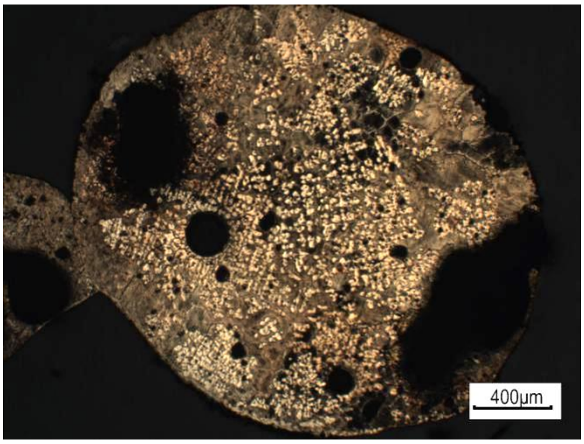

Figure 9 Metallographic structure of a spark generated at 6I$_e$ 25×

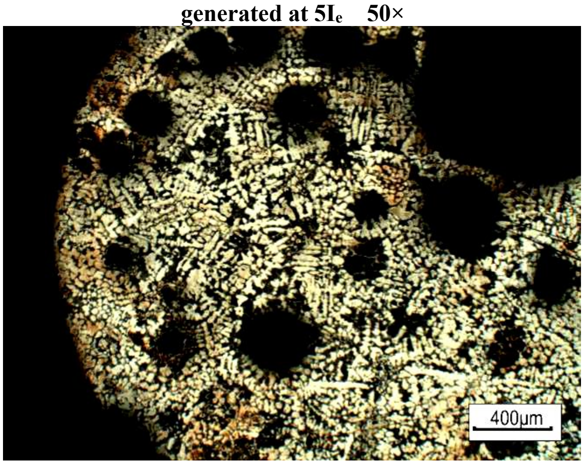

Figure 10 Metallographic structure of a spark generated at 6.5I$_e$ 25×

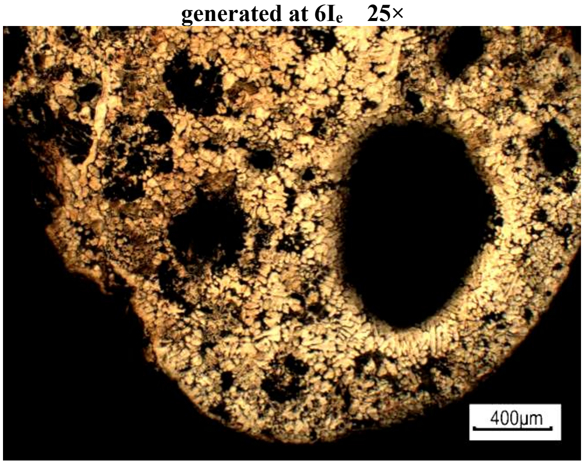

Figure 11 Metallographic structure of a spark generated at 7I$_e$ 25×

There are some characteristics of the metallographic structure of the sparks by overload at 5I$_e$ for the stranded copper conductor: (1) The metallographic structure mainly contained a large number of cottony oxide particles which adhered to substantial numbers of equiaxed grains, (2) The center areas were larger grains but periphery areas were smaller grains, and there existed a large number of dendritic oxides which were easy to appear in ejection of particles in short circuit, (3) Usually the metallographic structure contained a small quantity of pores and the pores were small, (4) The pores were relatively well-distributed, as shown in Figure 8.

There are some characteristics of the metallographic structure of the sparks by overload from 5.5I$_e$ to 7I$_e$ for the stranded copper conductor: (1) The metallographic structure mainly contained dendrite grains growing for long time and mixed up with a lot of cottony oxides, (2) Usually the metallographic structure contained irregularly shaped pores and the pores were large, (3) The distribution of pores was irregular [9], as shown in Figure 9~11.

When the overload value is equal or greater than 5I$_e$, the faulty stranded copper conductor will fuse with an obvious parting arc. Due to the both action of the extremely thermal arc and the heating effect of the current, the stranded copper conductor will melt. Liquid metal on the fusing point moves away from faulty conductor, and the liquid metal generates sparks as a consequence. With the influence of the thermal field formed together by the brief parting arc and the heating effect of the current, the air around the faulty conductor becomes hot and the ambient temperature is higher. When the liquid metal drips into air, its cooling rate is slower than cause bead but faster than globules created by fire melting. Therefore, the grains in sparks by overload are not only different from columnar grains in cause beads but also different from equiaxed grains in globules created by fire melting. Instead dendrite grains account for the majority in its metallographic structure. Because the liquid metal can fully contact with air when it drips, oxidation reaction is sufficient. As a consequence, a lot of cottony oxide particles are widely distributed between the grains. Because the liquid metal is extremely high, gas and liquid metal are able to contact for a long time. As a consequence, a lot of gas dissolves in liquid metal, so the pores are relatively larger and their shapes are relatively irregular [10].

With current increased, a series of changes occurred in the characteristics of metallographic structure of sparks by overload: (1) At $5I_e$, the metallographic structure of the sparks mainly contained equiaxed grains, (2) when $I > 5I_e$, there no more existed equiaxed grains in the metallographic structure, and the dendrite grains became the main type instead, (3) With current increased, the pores became larger, and there existed a larger number of pores, (4) With current increased, the pores in metallographic structure became more irregularly shaped, as shown in Figure 8~11.

At $5I_e$, because the temperature and the energy of the parting arc are both relatively low [11], the temperature of liquid metal is relatively low, and its degree of undercooling is lower than which is at $7I_e$. In addition, at $5I_e$, because the heating effect of the current is relatively weak, the ambient air temperature is relatively low. Thermal ambient air blocks the dissipation of heat, so the cooling speed at $5I_e$ is lower than at $7I_e$. Therefore, at $5I_e$, there exist equiaxed grains. With current increased, the temperature and the energy of the parting arc are both higher, so the degree of undercooling is higher. In addition, the heating effect of the current is stronger, so the faulty conductor's temperature is higher. Therefore, there will not be equiaxed grains. Moreover, with current increased, owing to higher temperature of the faulty conductor, the action of internal and external pressure difference become more obvious. Consequently, the liquid metal can contact with gas for longer time, and the liquid metal dissolves more gas. So there are larger pores in sparks by overload at $7I_e$, and the number of pores becomes more [12].

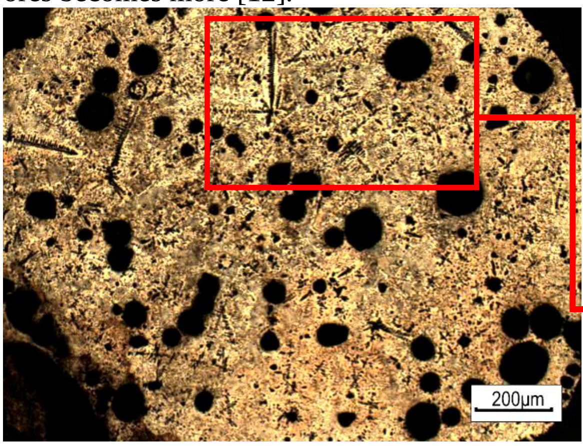

Figure 12 Metallographic structure of a spark generated at $5.5I_e$ 50×

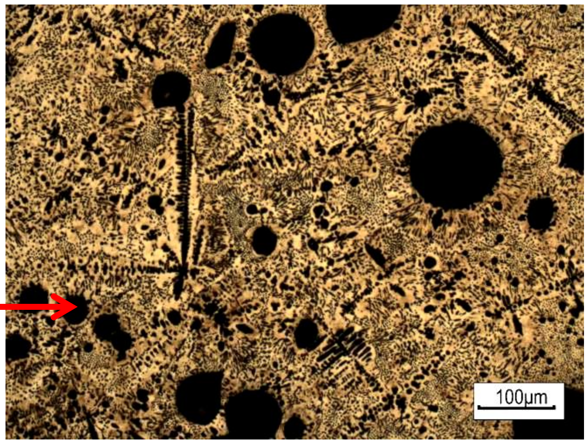

Figure 13 Metallographic structure of a spark generated at $5.5I_e$ 100×

At $5.5I_e$, the special metallographic structure occurred in the sparks: (1) The metallographic structure contained a wealth of cottony oxide particles and a large number of dendritic oxide particles, which were easy to appear in ejection of particles in short circuit, (2) The grains were not obvious, and it was difficult to distinguish the grain type definitely, (3) There existed a large quantity of pores and the pores were small, (4) The pores were relatively well-distributed, as shown in Figure 12, 13.

4. Conclusion

(1) When $I > 5I_e$, overload stranded copper conductor will fuse instantly associating with a brief parting arc. In addition, the metal at the fusing point melts and drips, re-solidifies to form sparks as a consequence.

(2) With current increased, the temperature and the energy of the parting arc increase. The number of the sparks is on rising trend and their shapes become more irregular.

(3) The metallographic structure of the sparks by overload: In most case, dendrite grains account for the majority and mix up with a lot of cottony oxide particles and irregular pores. Sometimes, equiaxed grains account for the majority and mix up with a lot of cottony oxide particles but no pores. Occasionally, the metallographic structure is special structure which consists of a wealth of oxide particles and a large number of small pores.

(4) Sparks by overload are more likely to exist after fire than the typical insulation effects, so they are more stable as core evidence to help fire investigators to identify overload fire.

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