Limitation Analysis of Electrical Fire Metallographic Identification Technology

WANG Yue\textsuperscript{a,b}, MO Shan-jun\textsuperscript{a,b}, LIANG Dong\textsuperscript{a,b,*}, YANG Wen-bing\textsuperscript{a,b}, WANG Li\textsuperscript{a,b}, ZHENG Fang-jie\textsuperscript{a,b}

\textsuperscript{a}School of Engineering, Sun Yat-sen University, Guangzhou 510006, China
\textsuperscript{b}Guangdong Provincial Key Laboratory of Fire Science and Technology, Guangzhou 510006, China

Abstract

Review of the principle of electrical ignition causes and identification technology in this paper. Primary or secondary short circuited melted marks could be identified in actual fire cases to a certain extent. Respecting complicated external environment, standard metallographic identification technology is not available for all melted marks. Combining analysis technologies of phase structure, components and morphology with metallographic identification technology is introduced for further study.

© 2013 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of School of Engineering of Sun Yat-sen University

Keywords: electrical fire; identification technology; metallographic structure

1. Introduction

In recently years, a large number of fires happen in China every year. According to statistics of Department of Public Security Fire, the fire cases were total about 2.95 million from 1990 to 2010, which caused significant loss to the state and citizen\textsuperscript{[1]}. In 2010, fire occurred about 0.132 million. Electric fire of short circuit, overload, and electrical equipment failure are about 41.2 thousand, which accounted for 31.1% and was the main reason of fire\textsuperscript{[2]}. Therefore, it is essential to provide electrical fire identification technologies for firefighter or researcher to find the ignition cause.

2. Electric Fires Causes

Various reasons may cause fire, but electrical fire mainly caused by overheating or arcing\textsuperscript{[3]}. The common reasons are presented as follow\textsuperscript{[3,4]}:

- Short circuit. As resistance of electrical circuit and devices sharply decreased, and load current abruptly increased, hyperthermia produced in instantaneous time which might ignite itself and surrounding combustibles to cause fire.
- Overloading. Electrical circuit or devices at high temperature might ignite itself and surrounding combustibles to cause fire when current exceed the safety value.
- Bad connection. In circuit, bad connections always occur in the joints of two conductors, wire and equipment, power parts or other parts. High resistivity of bad connections produced high heat when current flow the connections. Electric arc would be produced with the mechanical movement of connections, which might ignite various decomposed gases.
- Leak of electricity. Current circuit ways switched when the wire insulating coating without insulation property suffered from the extern force, environment and aging, etc. Current have changed to flow though insulation, insulating coating or air.

* Corresponding author. Tel.: +86-20-39332927; fax: +86-20-39332927.
E-mail address: gzliangd@163.com
The melted marks could be found in the wires when fire caused by electrothermal or non-electrothermal effect as Table.1 shown.

Table 1. Electrical fire trace and melted marks

| Electrical fire trace | Marks                          |
|----------------------|-------------------------------|
| Electrothermal effect| Short circuit mark            |
|                      | Overcurrent mark              |
|                      | Bad connection mark           |
|                      | Leakage of electricity mark   |
|                      | Local overheating mark        |
| Non-electrothermal effect | Burning mark                 |
|                      | Hot corrosion mark            |
|                      | Exogenic action mark          |

3. Identification technologies

3.1. Metallography identification technology

According to China National Standards GB16840.4-1997, distinguish metallographic structure of melted beads or melted marks of Cu wire or Al wire in order to hunt for the ignition cause. That means we can judge fire marks, primary or secondary short circuited melted marks from metallographic structure. In metallographic preparation process, the choice of etchant directly affects metallographic observation. Table.1 shows the standard etchant. However, we recommend etchant as shown in Table.2 in actual detection due to the various Cu wires. 1# and 2# are commonly used etchant.

Table 2. Standard Etchant

| Sample Name    | Ration of Etchant | Specification | Etching Time (Second) |
|----------------|-------------------|---------------|-----------------------|
| Cuprum Wire    | FeCl₃             | 5g            | 6~8s                  |
|                | HCl               | 50mL          |                       |
|                | H₂O(or C₂H₅OH)   | 100mL         |                       |
| Aluminum Wire  | NaOH              | 1~2g          | Several Seconds       |
|                | H₂O               | 100mL         |                       |
| Steel          | HNO₃              | 2~4mL         | Several Seconds       |
|                | C₂H₅OH            | 98~96mL       |                       |

Table 3. Common Used Etchant

| Sample Name    | Ration of Etchant | Specification | Etching Time (Second) |
|----------------|-------------------|---------------|-----------------------|
| Cuprum Wire    | FeCl₃             | 5g            | 6~8s                  |
|                | HCl               | 50mL          |                       |
|                | H₂O(or C₂H₅OH)   | 100mL         |                       |
| Aluminum Wire  | NaOH              | 1~2g          | Several Seconds       |
|                | H₂O               | 100mL         |                       |
| Steel          | HNO₃              | 2~4mL         | Several Seconds       |
|                | C₂H₅OH            | 98~96mL       |                       |

Observing melted marks by metallographic technique, different characters of marks as follow. Metallographic structure of fire mark is big equiaxed grains with less hole and contraction cavities, except stranded wires. The feature of primary
short circuited melted mark is smaller cellular structure or columnar crystals with fewer holes and Cu-Cu$_2$O eutecticums. Clear boundaries between metal and marked bead are observed. The large columnar crystals with big holes inside are the characteristic of secondary short circuited melted mark. Cu-Cu$_2$O eutecticums are around the holes which present the bright red. Boundaries between metal and marked bead are indistinct.

Table 4. Common Used Etchant

| Element (primary) | Alloy in Surface | Luster | Color   | Charcoal | Cavity | Veiny | Light Spot | Difference of luster in connection of wire and metal marks |
|-------------------|------------------|--------|---------|----------|--------|-------|------------|----------------------------------------------------------|
| Cu (primary)      | CuO              | Week   | Crimson | Slight   | Slight | None  | None       | Similar                                                  |
| Cu (secondary)    | Cu$_2$O          | Luster | Bright Red | Much    | Much   | Much  | Much       | Bright in wire, Dark in bead |
| Al (primary)      | Al$_2$O$_3$      | Week   | Deep Grey | Slight  | Slight | Less  | Less       | Bright in wire, Dark in bead |
| Al (secondary)    | Al$_2$O$_3$      | Luster | Light Gray | Much    | Much   | Moire | Much       | Similar                                                  |

3.2. Metallography identification cases and limitation

Fig. 1. show appearance and metallographic structure of Cu wires. The wires were taken at scene of fire. From Fig. 1. (a1), melted mark of stranded Cu wires appears bright luster and less charcoal. Metallographic structure of melted mark is smaller dendrite structures without hole inside. Dendrite structures are typical characteristics of primary short circuit. In Fig. 1. (b1), surface of melted marks is covered much charcoal and present big holes. Big columnar crystals and holes are inside of marks, which are the typical features of secondary short circuit melted marks. However, Cu$_2$O with bright red seldom been found in melted marks, which inconsistent with Table 4. Therefore, features of melted marks at scene of fire always differ form the standard features.
Fig. 1. Images of Cu wires: (a1) appearance of primary short circuited melted mark; (a2) metallographic structure of (a1); (b1) appearance of secondary short circuited melted mark; (b2) metallographic structure of (b1)

Fig. 2. showed metallographic structure of wires which were found at scene of fire. By observing appearances and metallographic structure of wires or beads, the wires or melted beads could not be identified. The melted mark covered charcoal in Fig. 2. (a1), whose metallographic structure differs from wires in Fig. 2. (a2). We speculated the melted was Cu alloy, and thawed Cu alloy in high temperature has dript on the wires. Fig. 2. (b1) was argentate wires which was unreactive to NaOH. Thus the wires might be tin solder rather than Al wires in Fig. 2. (b2). The above cases are interpreted that wires found at scene of fire might be the alloys or other materials, which could not be identified by metallographic technology.

Fig. 2. Images of uncertain metallographic structure of marks: (a1) appearance of melted mark; (a2) metallographic structure of (a1); (b1) appearance of melted mark; (b2) metallographic structure of (b1);

Fig. 3. (a1) and (b1) showed Cu wires, which could not be identified thought metallographic technology due to metallographic structures is far from the standard metallographic structures. Fig. 3. (a1) shows thin wires with big and luster
melted bead. In the Fig. 3. (a2), big columnar crystals and small holes are found, and boundary between bead and wires is not clear. Big columnar crystals and clear boundary are features of secondary short circuit, smaller and fewer holes are characters of primary short circuit. Thus, we could not identify ignition cause. Melted bead covered red materials, which are Cu2O. Bigger grains and smaller gas holes is inside of beads in Fig. 3. (b2). Metallographic structure present neither primary nor secondary short circuit.

3.3. Other identification techniques

Based former description, metallographic technology is not available for all wires. Several developing identification technologies are introduced as follows. By analysis of elements proportions of beads confirm formation circumstance\(^\text{[4,6]}\). This method is not available when melted beads are tiny or could not be found\(^\text{[4]}\). When lightning current flow the wires, nearby Fe-based materials are magnetized\(^\text{[4]}\). By measuring magnetic properties of Fe-based materials and comparing with properties of standard sample to identify short circuit\(^\text{[4,7]}\). Advantage of remanence magnetic technology is whether the marks exist or not, this technology could be widely used\(^\text{[4]}\). Experimental analogical method is the experiments imitation of fire cause reconstruction\(^\text{[4]}\). However, concerning actual environment, current and voltage value, electronic devices and circuit, surrounding inflammable materials, etc. the experimental results might be inconsistent with actual fire. Therefore, it is necessary to explore some new detection techniques. Analyzing the crystalline state of the wires thought XRD\(^\text{[8]}\), confirming components of wires or insulation coating materials by EDS / AES / ESCA / SIMS / XPS\(^\text{[3,6,9,10,11]}\), observing the surface morphology and crystalline of melted marks by SEM should be combined metallographic technology\(^\text{[12,13]}\). Besides, digital image technology of melting trace are developing\(^\text{[14,15]}\). These technologies provide new ideas for further quantitative study of electrical fires identification.

![Fig. 3. Images of uncertain metallographic structure of marks: (a1) appearance of melted mark; (a2) metallographic structure of (a1); (b1) appearance of melted mark; (b2) metallographic structure of (b1); (c1) appearance of melted mark; (c2) metallographic structure of (c1); (d1) appearance of melted mark; (d2) metallographic structure of (d1)](image_url)
4. Identification technologies

Metallographic technology is the most common method of electrical fire identification, which is easy to distinguish a short circuit or secondary short circuit. However, considering various uncertain factors of external environment, standard metallographic feature could not identify all ignition causes. Combining several identification techniques is a trend for further study.

Acknowledgements

This work was supported by funds of Guangdong Provincial Scientific and Technological Project (No. 2011B090400518) and Guangdong Provincial Key Laboratory of Fire Science and Technology (No. 2010A060801010).

References

[1] Chenyp. 1950-2010 fire cases[EB/OL]. (2011-10-21)[2012-11-1] http://www.119.gov.cn/xiaofang/hztj/12241.htm
[2] Chenyp. Fire cases in 2010[EB/OL]. (2011-10-21)[2012-11-1] http://www.119.gov.cn/xiaofang/nbnj/12240.htm
[3] J.D. DeHaan. Kirk’s Fire Investigation (in Chinese)[M]. 5th, ed. Beijing: Chemical Industry Press, 2006.
[4] X.Q. Wang, B.Y. Han, M. Di. Guide for Electrical fire investigation and identification(in Chinese)[M]. Shenyang: Liaoning University Press, 1996.
[5] Shenyang Fire Research Institute. GB16840.4-1997 Technical Determination Methods for Electrical Fire Cause Part 4: Metallographic Method[S].
[6] Shenyang Fire Research Institute. GB16840.3-1997 Technical Determination Methods for Electrical Fire Cause Part 3: Component Analytic Method[S].
[7] Shenyang Fire Research Institute. GB16840.2-1997 Technical Determination Methods for Electrical Fire Cause Part 2: Residual Magnetic Method[S].
[8] H.R. Wang, J.Y. Liu, H.W. Yao, et al. The Microstructure and Phase Composition of Metal Melting Marks Caused by Different Fire(in Chinese)[J]. Spectroscopy and Spectral Analysis, 2012, 32(7): 1984-1988.
[9] C.Y. Chen, Y.C. Ling, J.T. Wang, et al. SIMS depth profiling analysis of electrical arc residues in fire investigation[J]. Applied Surface Science, 2003, (203-204): 779-784.
[10] Y. Wu, D.C. Han. Metallurgical and composition analysis of melted marks due to electrical failures[J]. Mechanika, 2012, 18(2): 227-232.
[11] S.J. Mo, J. Zhang, D. Liang, et al. Analysis of Copper and Copper Alloys Electric Components Short Circuited Melted Mark Metallographic Structure[J]. Advanced Materials Research, 2012, 535-537: 869-874.
[12] S.Y. Wang, X.K. Zhang, Z.P. Zhou. SEM Analysis of Microstructure of the Copper Wire Melted Bead and Trace in the Fire Disaster[J]. Analysis and Testing Technology and Instruments, 2005, 11(1):63-67.
[13] H. Zhang, H. Zou. SEM Analysis of Fire Residue for Home Electrical Appliance[J]. Analysis and Testing Technology and Instruments, 2007, 13(2):93-97.
[14] S.J. Mo, W.J. Peng, D. Liang, et al. Quantitative Analysis of Metallographic Structure Parameters of the Melting Trace Caused by The First Short Circuit(in Chinese)[J]. Journal of Safety Science and Technology, 2012, 8(1): 63-70.
[15] S.J. Mo, H. Shen, J. Zhang. The Metallographic Structure Analysis of the Secondary Short Circuit-Caused Melted Trace Based on Digital Image Technology(in Chinese)[J]. Chinese Journal of Forensic Sciences, 2012, (4):107-111.