Computational Methods for Calculating Metallographic Geometric Parameters of Melted Marks Caused by Short-circuits in Electrical Fires

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Abstract—The primary short-circuited melted marks(PSMs) are caused by short circuits before the fire occurs, usually PSMs are direct evidences that relate to the causes of electrical fire. The metallographic methods are the most common scientific methods to analyze and identify PSMs. Presently metallographic analysis of melted marks in electrical fires is still based on experience and anecdotal evidence, therefore the use of computer aided quantitative metallographic analysis in other material fields is becoming more popular. The process of melted mark crystallization includes the formation and growth of the nucleus, in which inhibitions between nuclei occur regularly; in this case, each grain has a similar formation process, and the metallographic structure of grains develop both irregularity and self-similarity. Based on fractal theory and using digital image processing, this paper analyzes the features of metallographic structures of melted marks that are caused by short-circuits, and proposes a method to classify the geometric parameters of grains of their microstructure, including the perimeter C, area S, equivalent diameter R, density P and shape factor F. Furthermore, this paper aims to discuss quantitative methods that describe the formation discipline of metallographic organization of melted marks in electrical fires.

Keywords—melted mark; metallographic structure; geometric parameter; first short circuit

I. Preface

Electrical fires are characterized by the release of high amounts of heat, electric arcs, electric sparks and other thermal energies, and ignition of the object or other inflammable substances. They are caused by the combustible conditions from faults of electrical circuits, electric equipment, appliances and power supply and distribution equipment. Electrical fires account for 40% of all fires, and short circuits are the most serious failure mode that causes electrical fires [1]. The melted marks formed by the most common short circuit failure modes are divided into primary short-circuited melted marks (PSMs) and secondary short-circuited melted marks (SSMs). PSMs are caused by short circuits before the fire occurs, while SSMs are formed by short circuits due to the destruction of the equipment's insulation by the fire. Analyzing and identifying the causes of fires crucially relies on distinguishing and determining the properties of PSMs.

The most commonly used method to identify the causes of electrical fires is the analysis of the metallographic structure after the fire, which analyzes the residual metallic conductor melted marks at the source of the fire and near the fire scene. This method analyzes the solidified metallographic structure of the conductive metal, particularly the different signatures of various heating methods and the thermal insulation and cooling properties associated with the short circuit [1]. The method is able to distinguish between several causes of fires, including overloading, too much contact resistance, electrical leakage and fire heating effects. The metallographic methods have the advantages of utilizing simple equipment while maintaining a low cost and broad development prospects, and thus have become the most common scientific methods to analyze fires.

At present, the metallographic analytic methods in China have formed relevant national standards through in-depth research, which is Technical determination for electrical fire evidence (GB/T 16840-1997), and the standards qualitatively discriminate between the three types of melted marks, namely burn, PSMs and SSMs, but on the whole, the appraisal work is empirical or anecdotal and the appraisal efficiency and technological methods require great improvement [2]. Presently, the electrical fire melted mark appraisers lack relevant standard reference micrographs, and the appraisers of fire accidents depend on their own experience of many years and mainly adopt descriptive statements. The staff use their own experience to describe and judge different types of metallographic micrographs, and there is no unified quantitative standard, often leading to cases where subjective decisions made by various appraisers do not agree, and the same appraiser could even make different judgments of the same metallographic figure at different times [2]. The traditional methods mainly rely on human eyes and personal experience to judge and classify the metallographic microstructure and the requirements on the experience of the appraiser are very high. This situation lacks objectivity and universality, and misjudgment can occur easily.

Using stereology and metallographic quantitative analysis theory, image processing based on modern computational image analysis techniques has achieved successful application in the material science industry. Metallographic quantitative analysis seeks to quantify the relationship among the

constituents, microstructures and performances of materials more accurately, recording the quantity, size, shape and distribution of the features [5]. Compared with traditional artificial metallographic analysis, computer aided quantitative metallographic analysis has the advantages of rapid processing speed, accurate and reliable data collection, repeatability of experimental results, and objectivity. In the future, this will replace the more subjective traditional metallographic analysis [5].

This paper utilizes digital image processing technology to analyze and process the metallographic images of PSMs in electrical fires. We discuss and analyze the metallographic microstructure features and formation rules for PSMs, and propose geometric feature parameters for characterization, including the perimeter C, area S, equivalent diameter R, density P, shape factor F and other parameters. The analysis and calculation of these microstructures are presented, and the application of the computer-aided quantitative analysis is discussed.

II. METALLOGRAPHIC IMAGE PROCESSING OF SHORT CIRCUITED MELTED MARKS

A. Metallographic Micrographs of the Melted Marks

The simulation experiment condition of the primary short circuit is shown in Table 1.

TABLE I. SIMULATION EXPERIMENT CONDITION OF THE PRIMARY SHORT CIRCUIT

No	Item	Experiment condition
1	Experimental materials	1.5mm² single-core polyvinyl chloride copper wire
2	Short circuit power supply	Gaoxin Welding and Cutting - ZX7 series IGBT inverter DC argon welder
3	Sample preparation	YMP-2 metallographic sample grinder and PG-2 metallographic sample polisher
4	Sample corrosion	$FeCL_3$ hydrochloric acid solution
5	Metallographic observation	Leica DMI5000 metallographic microscope
6	Grain identification and grain size analysis	Image-Pro Plus 6.0 Software
7	Grain size data statistics	Microsoft Office Excel 2007 Software

The short circuit currents are set to 110A and 210A, respectively, and the contact of the copper wire core leads to the primary short circuit. The metallographic microstructure images of the primary short circuited melted mark is obtained by observing and analyzing the shape, color, gloss and porosity of the sample grains through the metallographic microscope system (Leica DMI5000).

When the metal wire has short circuit faults, the contact surface of the short-circuit point is broken down and produces the short circuit arc. The temperature of the contact surface rises rapidly under the effect of the electric arc. As the arc reaches a very high temperature (2000 -3000℃), the metal at the contact surface melts, and an open circuit and separation will occur on the contact surface due to melting and arc blowout. Eventually, the short circuit arc is extinguished and the short circuit point of the wire will solidify immediately after losing the heat source. Therefore, when the primary short circuited melted mark forms, the ambient temperature is very low and only the short-circuit point is subject to high temperature at the moment of the short circuit. While the temperature of the whole wire is about 70℃,, the ambient temperature is much lower, thus the cooling speed is much faster. The time to solidify is shorter and the gas inside the melted mark cannot be released immediately, but there are few combustible products and vapor. There are many pores inside the polished metallographic surface of the melted mark. These are much smaller and the pore shape is mainly circular.
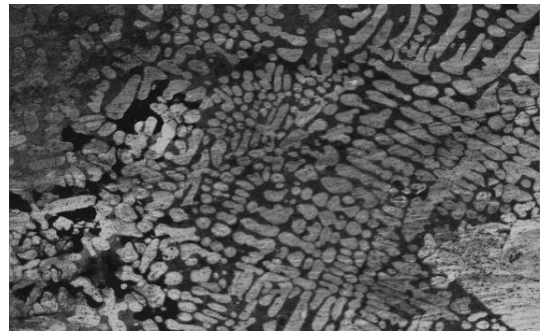

FIGURE I. METALLOGRAPHIC MICROSTRUCTURE OF THE PRIMARY SHORT CIRCUITED MELTED MARK (110A, 100X)
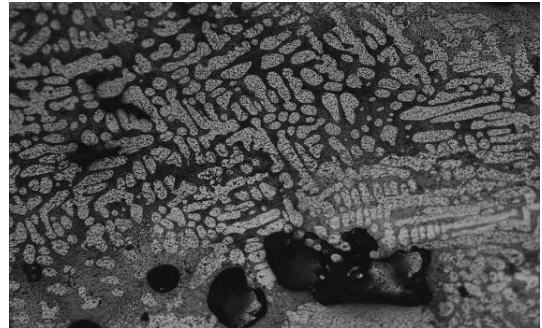

FIGURE II. METALLOGRAPHIC MICROSTRUCTURE OF THE PRIMARY SHORT CIRCUITED MELTED MARK (210A, 100X)

Figure1 and Figure2 show Metallographic microstructure of the primary short circuited melted mark under different condition, correspondingly the short-circuit current are 110 amperes and 210 amperes. According to the above metallographic microstructure image observation, the metallographic microstructure of the primary short circuited melted mark is mainly comprised of dendrite, columnar, and cellular grains, with tiny grain boundaries and obvious lattice divisions.

B. Image Preprocessing

The metallographic image is a special microscopic image based on materials and metallographic sciences, which is represented by a discrete data structure. While taking the

images, the pictures obtained by the sensor are continuous functions of two coordinates on the plane, which can be defined to be a two-dimensional function f (x, y), and defined as the gray value of that point.

Analysis of the microstructure shape in the metallographic image is complicated. Compared to normal image processing, there are more influential factors and the image processing must be stricter and more accurate. Therefore, the processing methods that are suitable to analyze the features of the metallographic microstructure must be selected and studied, so as to achieve the anticipated processing effect. The main digital image processing involves binarization, corrosion, expansion, opening-and-closing operation, denoising, etc., and relevant digital morphology methods are combined to filter redundant information and extract the structure features of each lattice in the metallographic image. The image processing adopted in the paper is as shown in Figure 3.
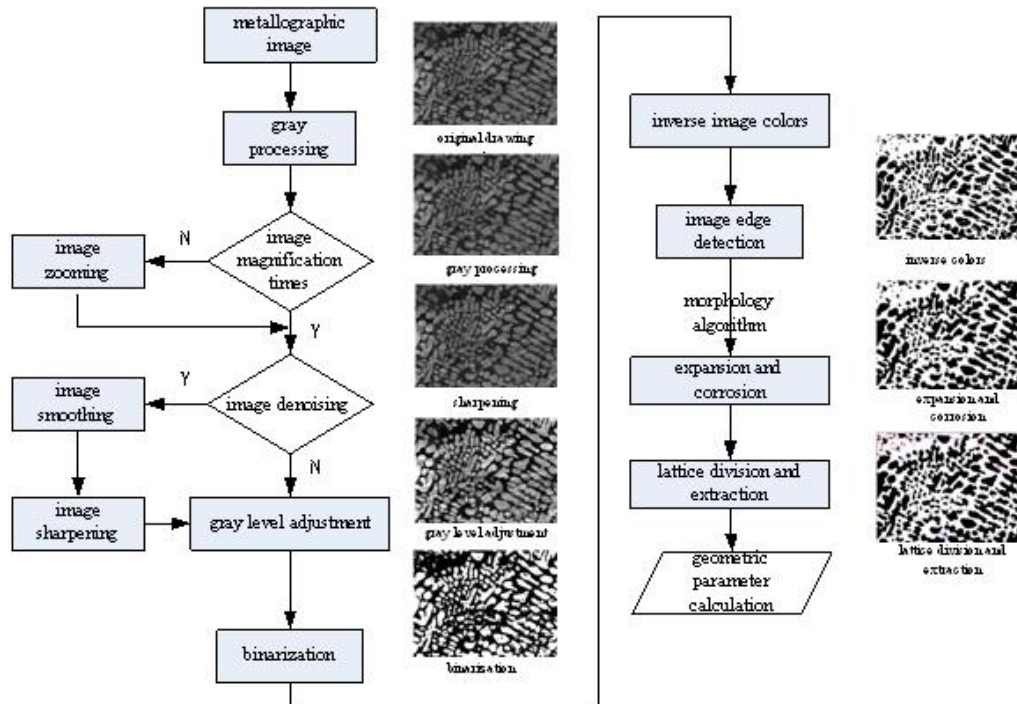

FIGURE III. METALLOGRAPHIC IMAGE PROCESSING FLOW CHART

The Image-Pro Plus image processing software is applied to preprocess the metallographic microstructure images. It traces and recognizes the outline of the metallographic microstructure grain and indexes it. It then measures the area, perimeter and other geometric feature parameters of each grain and finally conducts the statistical analysis. Two metallographic microstructure images of the melted mark after the image processing are shown in Figure4 and Figure5.
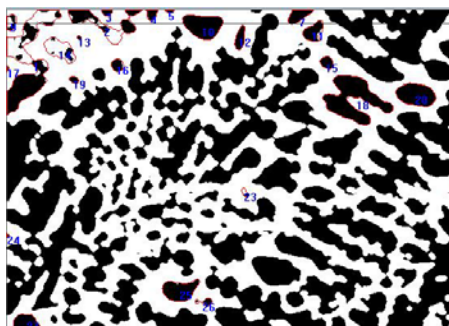

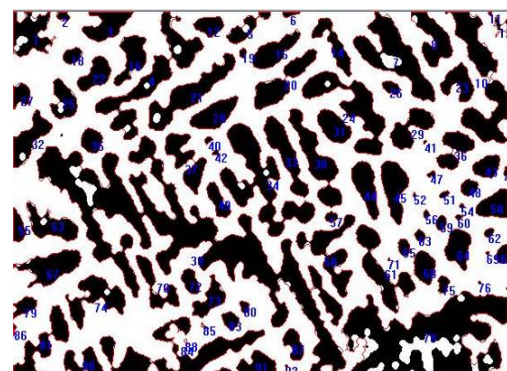FIGURE IV. METALLOGRAPHIC MICROSTRUCTURE IMAGE OF THE MELTED MARK AFTER THE IMAGE PROCESSING (110A)

FIGURE V. METALLOGRAPHIC MICROSTRUCTURE IMAGE OF THE MELTED MARK AFTER THE IMAGE PROCESSING (210A)

III. GEOMETRIC PARAMETER CALCULATION AND ANALYSIS

A. Metallographic Geometric Parameters

The detection of metallographic geometric parameters falls under the field of metallographic quantitative analysis. The basis of metallographic quantitative analysis is stereology,

which determines the three-dimensional morphology of a metallographic microstructure by measuring and calculating the microstructure, either on a substrate surface or on a thin film of two-dimensional metallographic samples. This establishes a quantitative relationship among the alloy compositions, the microstructures, and the materials performance. There are many required measurement components, which chiefly comprise the geometric parameters of the metallographic microstructure. At present, the method cannot complete all of the detections automatically with a computer, which still depends on artificial testing methods to a great extent.

The lattices in the metallographic microstructure images of PSMs have many shapes, and can be large, small, round, flat, wide, long, smooth or faceted. In order to automatically classify these lattices, their features should be analyzed and studied. Shape analysis is an important branch of image analysis, whose emphasis is to describe the shapes in the image and classify them according to the shape description. During image processing analysis, the shape description usually adopts three types of methods: a characterization method (using the characteristics to describe the properties), a shape changing method (using the transition of the parameters of the model from one shape into another) and a relationship-based method (breaking down complicated shapes into simpler elements and describing both the nature and relationship of the elements). In practical applications, the shape analysis should be based on the shape properties, available theories, and technologies. On one hand, one shape property can be described according to the descriptors of different theoretical technologies; on the other hand, different descriptors can also obtained by means of the same theoretical technology, so as to describe different properties of the target shape. The most important step to understand the image data is the recognition of the image, which requires an accurate region description that is suitable for the classifier. The shape is an important attribute of the object, but it is very difficult to define the object shape. Many scholars adopt computer graphics and mathematical methods to effectively describe the shape. At present, the shape representation and description have been widely applied in COR, ECG, EEG analysis, chromosome recognition, automatic detection, technological diagnosis and so on.

There are several geometrical attributes that are useful in characterizing the objects in the image. These are listed as follows.

Perimeter C: the perimeter is the fundamental area attribute of the object boundary outline.

Area S: the simplest and the most natural region attribute is the area. S is computed from the number of pixels contained in the region.

Equivalent diameter R: this is the diameter of the circle with the same area within the lattice,

$$R = \sqrt{(4*S/\pi)}$$

Density P: though the area and perimeter are the common structure descriptors, they are chiefly used under the occasions when the region of concern remains unchanged. Combining the perimeter with the area allows the formation of a more effective descriptor, the density. The density is non-dimensional thus is not sensitive to changes of the uniform scale. In Euclidean space, the density of a circular region is the smallest. It should be noted that the density is also not sensitive to the directionality. The density is a common shape descriptor independent from the linear transformation.

$$P = \frac{C^2}{S}$$

The form factor F: this is calculated according to the perimeter C and area S of the region,

$$F = \frac{\|C\|^2}{4\pi S}$$

When the target region is circular, the form factor is 1 and when the target region is not 1, the form factor is greater than 1. The more circular the region is, the smaller the form factor is. When it is used in the digital image processing field, attention should be paid to the definition of the distance. The form factor describes the compactness of the region, which is also non-dimensional and not sensitive to the scale and direction.
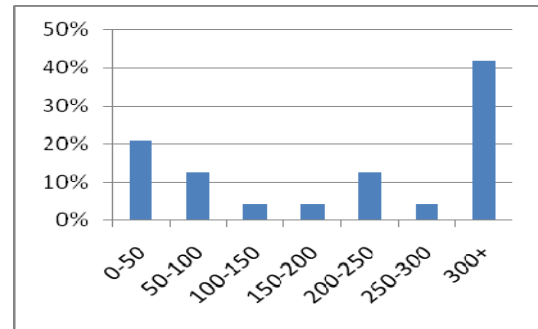
B. Parameter Calculation and Analysis

FIGURE VI. METALLOGRAPHIC MICROSTRUCTURE GAIN AREA DISTRIBUTION DIAGRAM (110A)
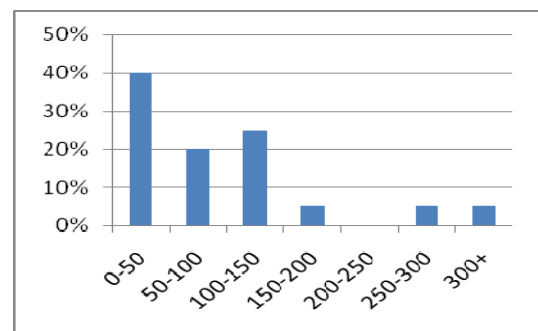

FIGURE VII. METALLOGRAPHIC MICROSTRUCTURE GAIN AREA DISTRIBUTION DIAGRAM (210A)

The x-axis in the diagram is the area value in pixels, and the y-axis is the percentage of the lattices in the region among the detected lattices. According to Figures 6 and 7, the area values of the lattices in the metallographic microstructure under 210A are both at the smaller region, while those under 110A are

concentrated in a much larger region. The mean value of the metallographic microstructure lattice area under 110A is 603.8333 and that under 210A is 94.95, nearly a factor of 7 different.
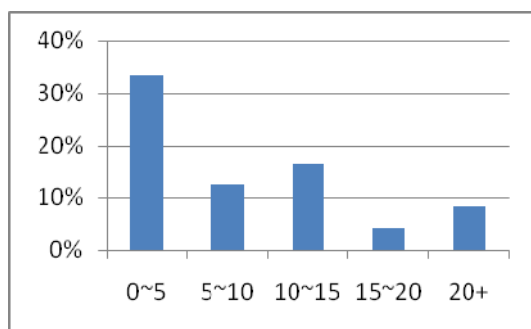

FIGURE VIII. EQUIVALENT DIAMETER DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (110A)
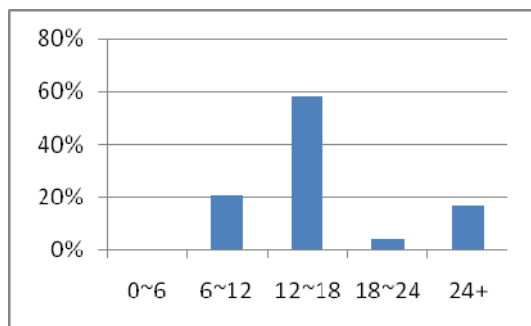

FIGURE IX. EQUIVALENT DIAMETER DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (210A)

The x-axis in the diagram is the equivalent diameter value in pixels and the y-axis is the percentage of the lattices in the region among the detected lattices. The equivalent diameter approximately equals the area, whose distribution has no great difference from the area distribution. However, the lattice area distribution inside the region can be observed from the discrimination, while the equivalent diameter distribution of the metallographic microstructure lattices is more uniform under 210A.
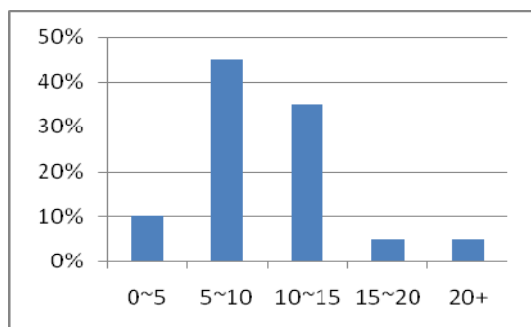

FIGURE X. DENSITY DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (110A)
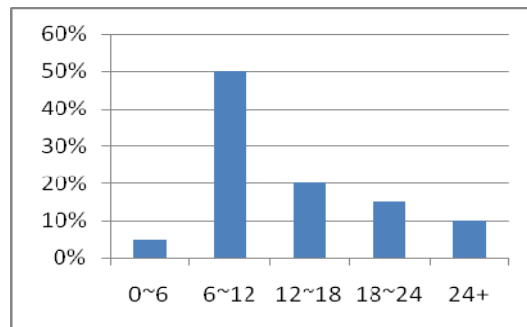

FIGURE XI. DENSITY DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (210A)

The x-axis in the diagram is the dimensionless density value, and the y-axis is the percentage of the lattices in the region among the detected lattices. Both the density and the form factor are used to describe the shape of the lattice, and the density distribution also demonstrates the general morphology of the lattice. From Figure 6, it can be seen that the shape of the lattices in the metallographic microstructures under both conditions are similar.
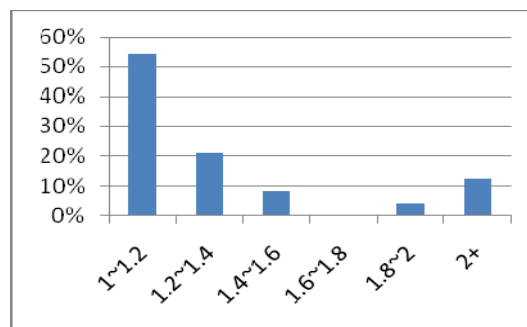

FIGURE XII. FORM FACTOR DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (110A)
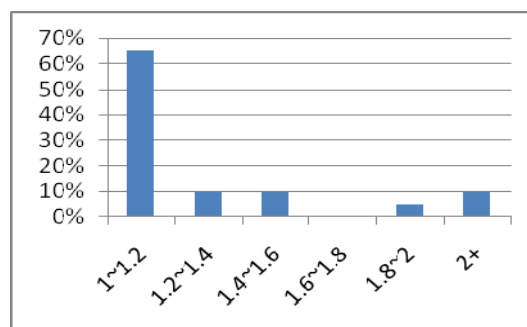

FIGURE XIII. FORM FACTOR DISTRIBUTION DIAGRAMS OF THE GRAINS IN THE METALLOGRAPHIC MICROSTRUCTURE (210A)

The x-axis is the dimensionless form factor and the y-axis is the percentage of the lattices in the region among the detected lattices. According to Figures 12 and 13, the form factor value of the lattice in the metallographic microstructure under 210A concentrates at 1-1.2, which indicates that the shape of most lattices is nearly circular.

IV. CONCLUSION

The primary short circuited simulation experiment on 1.5mm2 copper wires under the two current conditions at 110A and 210A has been conducted, and the metallographic micrograph under both conditions is acquired through metallographic analysis. The paper also introduced concepts from digital image processing to analyze and process the melted mark metallographic images. The metallographic microstructure features and formation rules of the primary short circuited melted mark were discussed, and a proposal to geometrically characterize metallographic microstructure grains was presented, including the perimeter C, area S, equivalent diameter R, density, and form factor. Finally, a quantitative calculation method was presented to analyze the metallographic microstructure geometric parameters of primary short circuited melted marks caused by electrical fires.

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