

Robert N. Anderson,¹ Ph.D.

Surface Analysis of Electrical Arc Residues in Fire Investigation

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ABSTRACT: Fires caused by electrical shorting are difficult to identify with certainty from fire pattern analysis alone. Surface analysis techniques, such as electron spectroscopy for chemical analysis (ESCA) and auger electron spectroscopy (AES), can be used to determine the history of an electrical short circuit by characterizing the environment in which the electrical arc residues were formed. In a fire that destroys insulation, the surface of the arc bead formed from the resultant electrical short circuit would show the presence of combustion products. If the electrical short circuit occurred before the fire had started, then arc bead analysis would show the absence of combustion products.

KEYWORDS: engineering, fires, electricity, electrical arc residues

There is a basic need in fire investigations, in which an electrical short circuit is found, to determine whether the short circuit was the cause of the fire or resulted from the fire. The presence of an electrical short circuit usually is identifiable by the residue in or on a melted ball of metal called an arc bead or a melted metal track. Visually, even under high-power optical magnification, arc beads usually appear similar. The only difference is that the more oxidizing the atmosphere the less porosity is observed in the arc bead. Other information, such as fire pattern analysis, must be used to assess the importance of the arc. The history of the arc, and hence, the identification of a fire caused by an electrical source, can be determined through information available by surface analysis and depth profiling of the arc bead.

In understanding the theory behind this analysis, note that the temperature of the arc necessary to produce a molten bead of metal is far in excess of the melting point of the metal in which the bead was formed. Dissolved gases are trapped when the arcing ceases because of rapid cooling which, in turn, is due to the small size of the arc bead and its high surface-to-volume ratio. (It should be pointed out that this small size also limits the amount of energy available in an arc to start a fire.) The material of the arc bead can be considered as if it were a liquid instead of a solid with respect to its gas solubility. This process is similar to inert gas (tungsten-inert-gas) arc-welding. Gas solubilities in liquid metals follow Sieverts' rule [1], which states that solubility is proportional to the square root of the gas pressure and increases with increasing temperature. The concentration of dissolved gases in the arc bead are proportional to the square root of their mole fraction in the atmosphere.

Because of the short time duration of the typical arc, the amount of gas dissolved in the arc bead is below an equilibrium value. The surface of the metal bead is the area most rich in

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¹Professor of materials engineering, Department of Materials Engineering, School of Engineering, San Jose State University, San Jose, CA.

gases from the environment during the time of the arcing. But simple analysis of the surface, without depth profiling, is not recommended because of the contamination of the bead after the arcing and the fire. It will certainly have picked up moisture, smoke residues, and possibly fingerprints.

The arc bead specimen should be handled carefully to guard against contamination. Contamination does not destroy the evidence, but it does make interpretation more difficult by adding spurious materials to the analysis. The preferred handling procedure is to use plastic gloves and to limit direct contact with the bead. It is acceptable to handle the bead by its wires. The bead can be wrapped in aluminum foil for storage or transportation or both. Arc beads may be accurately characterized even years after the arc has occurred as long as it has not been reheated.

Analytical Techniques

Electron Spectroscopy for Chemical Analysis

Two analytical techniques can be used to determine the environment at the time the arc occurred. The first is electron spectroscopy for chemical analysis (ESCA). ESCA uses low energy X-rays to excite the atoms of the sample. X-rays interact with atoms, causing outer-core electrons to be emitted with a kinetic energy characteristic of the difference between the X-ray photon energy and the binding energy of the electron. The energy of the photoelectrons emitted from the top one to ten monolayers determines the type of atom detected. A broad energy scan will cover the entire range of detectable elements (hydrogen and helium are not detectable because they only have a single electron energy level). This technique provides chemical bonding information as well as the elemental composition.

Some ESCA systems are slow and mainly useful for large areas. However, small-spot ESCA, with the capability of focusing the primary X-ray beam on an area for analysis of less than 12 μm^2 , is ideally suited for fire analysis. It has the added advantage that it does not destroy the evidence. The depth profiling is carried out by etching the bead surface with an argon ion beam and then repeating the analysis for the set of elements present. The atomic concentration is determined by measuring the area under each peak and normalizing for atomic cross sections for the major elements present.

Auger Electron Spectroscopy

The auger electron spectroscopy (AES) technique involves the ionization of inner shell electrons by an energetic electron beam. The transition energy released when an outer electron fills the vacancy created by the loss of the inner shell electron is imparted to another electron which is ejected from the atom. The energy of the ejected "auger" electron is characteristic of the type of atom involved. There are several AES transitions for most elements. With AES, the specimen surface can also be raster scanned. By setting the detection system to the energy level of a particular elemental peak, a map of the surface distribution of that element is generated. The surface is then ion etched in conjunction with auger analysis to produce concentration depth profiles of elements within a sample. The principal advantage of AES is the extremely shallow depth from which auger electrons are generated, in conjunction with a small primary electron beam diameter. As a result of these parameters, this method has the ability to determine elemental composition and distribution in three dimensions while only changing the evidence in a microscopically small volume of material.

A typical AES spectral response is shown in Fig. 1.

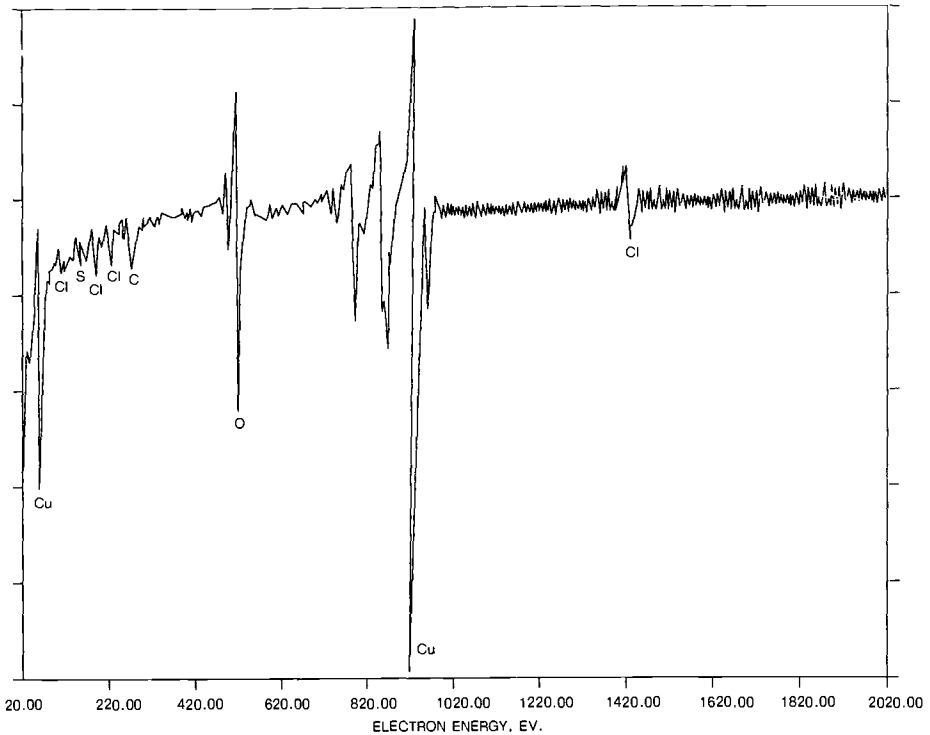


FIG. 1—Typical AES spectral response for Arc 2.

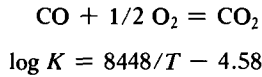
Arc Bead Analysis

Studying the results of the analysis of the arc bead requires experience in its interpretation. Thus, testing of many exemplar samples may be desirable in the case of arcs of unusual alloys or gases or both. Small additions of impurities or additives in the metal can significantly affect the arc behavior and the analysis results.

Fortunately, most arcs occur between high purity copper conductors, and the results are quite reproducible. For unusual alloys such as found in aircraft or computer fires, testing would consist of producing comparison arcs of the unusual alloys in a chamber containing the appropriate gases. Tests of the before-fire and during-fire gas condition would be run and compared to the results determined for the actual arc bead.

The formation of an arc bead is somewhat analogous to the melting and casting of a metal. Three conditions affect the relative gas composition on the surface of the arc bead: (1) the temperature the bead reaches, (2) the composition of the gases in the area of the bead at the time of the arc, and (3) diffusivity of the gases into the metal. The melting point of copper is 1357K (1981°F), and the ionized gases in the arc are considerably hotter, as evidenced by the splattering of the metal. However, it appears to be a valid assumption to take thermodynamic values at the melting point of the metal in question [2]. The diffusivity of the gases in the molten metal may be important or not, depending on the forced ventilation to the area of the arc. If the arc is in a shielded location, then the atmosphere exchange may be principally diffusion or, if the fire has started, convection. If the arc occurred in an exposed location, then the free or forced convection may be operating to provide the atmosphere.

The gases before a fire starts are basically 21% by volume oxygen, with the residual mainly nitrogen. Stray gases such as sulfur dioxide (SO₂), ammonia (NH₃), and carbon monoxide (CO) should be taken into account. The gases that are generated during the fire will contain CO and carbon dioxide (CO₂), and possibly sulfur, chlorine, and fluorine from wallboard and electrical insulation. There is a thermodynamic relationship between the amount of oxygen and the relative amounts of CO and CO₂ in a molten metal. For a typical metal such as iron, this relationship is given by the equilibrium constant for the equation:



where K is the equilibrium constant and T is the temperature in degrees Kelvin. Therefore, besides determining the presence of combustion residues on the surface, oxide ratios also can be used as a guide. For example, in the case of copper, the presence of a reducing atmosphere of CO changes the normal ratio of cuprous oxide/cupric oxide (Cu₂O/CuO from 25:1 (determined at the melting point) when the arc occurs in air (that is, the arc starts the fire), to some higher ratio, depending on the concentration of CO in the environment.

The chemical analysis of a copper conductor, which was arced under various experimental and actual conditions, is given in Table 1. The arc occurred in a reducing environment that was quite high in carbon, but low in oxygen. This trend reversed as the analysis was carried out more deeply beneath the surface. An arc occurring in air was significantly higher in oxygen below the surface than in carbon. For example, in Table 1, Arc 1 occurred as a result of a fire in a very poorly ventilated area. The high chlorine was due to insulation residues that would not have been present if the arc had preceded the fire. The arc in the presence of wallboard showed higher sulfur and calcium content, as would be expected. It was clearly evident that these analyses reflected the environmental composition quite satisfactorily.

TABLE 1—Actual compositions for copper arc beads analyzed by AES and ion etched. The values are expressed as atom % for the elements that were detected. Etch depth is in units of angstroms.

Arc Condition	Etch Depth	Oxygen	Carbon	Chlorine	Sulfur
Natural Gas	as received	2.4	86	0.72	...
	30 off	7.0	66	0.66	0.72
	100 off	15	38	1.4	0.81
	215 off	15	32	1.4	0.89
Oxygen	as received	21	26	9.1	0.68
	30 off	28	17	1.1	...
	140 off	24	11	1.6	0.91
	215 off	23	15	2.6	0.80
Air	as received	21	49	0.95	...
	30 off	33	16	1.6	...
	60 off	34	20	1.2	...
	90 off	36	15	1.3	...
	140 off	36	12	1.8	...
	215 off	36	8.8	1.0	...
Arc 1 ^a	as received	4.2	5.3	24	...
	30 off	5.6	4.8	16	...
	380 off	3.4	3.9	15	...
Arc 2 ^b	30 off	24	40	2.4	8.0
	90 off	29	20	2.6	6.2
	140 off	30	20	1.8	6.5
	215 off	30	15	1.5	7.2

^aArc 1 is a typical case of the fire causing the arc to occur. The arc was in a very poorly ventilated area, which kept smoke to a minimum. Note that the high chlorine values are from the insulation residual.

^bArc 2 is typical of a fire causing the arc to occur in proximity of wallboard. This arc bead had readings of 11 to 13 atom % calcium.

Conclusion

The discussed surface analytical techniques are powerful tools for the analysis of metal beads that are recovered after electrical fires. They provide a definitive answer to the actual time the short circuit occurred in the history of a fire.

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