DISTINGUISHING BETWEEN ARCING AND MELTING DAMAGE IN ELECTRICAL RECEPTACLES

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ABSTRACT

The majority of fire-investigation related literature on electrical arcing focuses on copper wiring, both stranded and solid, with some attention paid to steel (i.e., conduit), and relatively little mention of brass. This is despite the relatively equal presence of copper, steel, and brass in receptacles and similar electrical devices. Changes to NFPA 921 in the 2014 edition of the guide expand upon the characteristic traits which can be used to assess whether arcing or melting is present in a conductor. However, most of the characteristic traits of arcing and melting are qualitative and not well defined in NFPA 921, which leads to more subjective evaluations. In addition, a myopic examination of evidence with respect to the presence of one or two characteristic traits can lead to a false indication of arcing. In cases such as this, other evidence of melting (i.e., in close proximity to the area in question) could preclude confirmation of arcing.

The purpose of this work was to determine which characteristic traits are effective in assessing potential arcing damage on receptacle components and wiring. A total of 86 receptacles were evaluated in this study. Thirty-nine receptacles failed as a result of an overheating connection resulting in arcing damage; this included 95 individual conductors. Forty-seven receptacles with fire-induced arcing were also evaluated; this included 87 individual conductors. All of the evaluated receptacles with fire-induced arcing were energized or energized with a load during testing. In contrast, thirty-seven non-energized receptacles with fire induced melting were evaluated with 57 individual conductors.

The characteristic arcing traits which were evaluated include: corresponding damage on the opposing conductor; localized point of contact with a sharp line of demarcation between undamaged and damaged areas; round, smooth shape; resolidification waves; tooling marks visible outside the area of damage; internal porosity; spatter deposits; and small beads and divots over a limited area. The characteristic traits of melting which were evaluated include: visible effects of gravity; gradual necking of the conductor; and pitting, thinning, and presence of holes in the conductor. These traits were taken from the literature (e.g., NFPA 921) and from observations made during the forensic examinations of receptacles and wiring conducted as part of this work. For each characteristic, there were three possible outcomes: Yes, No, and Possible. Yes indicated that the characteristic was judged to be present on the particular conductor; no indicated that the characteristic was judged not to be present on the conductor. Possible indicated that confirmation could not be made either for or against the presence of the characteristic. All of the evaluations were conducted by the same person.

Corresponding damage on the opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage; these characteristics were found to be strong indicators of arcing.

Using multiple characteristic traits and contextual information for determination of arcing vs. fire-melting provides greater confidence in the evaluation of damage. In addition, visual examinations were found to be reliable indicators of both arcing and fire-melting for most conductors. However, there are some cases which would benefit from more advanced examination techniques including SEM/EDS examinations, X-ray, CT scanning (X-ray computed tomography), cross-sectioning and polishing, or other metallurgical methods.

INTRODUCTION

A common task of the fire investigator is to determine whether the metallic components exhibit signs of electrical activity (i.e., arcing) or whether the damage is due to fire attack (i.e., melting).The majority of research related to arcing has been conducted with copper wiring. Some work has been conducted with brass and aluminum; however, there has been no systematic study of characteristics of arcing in receptacles or plugs either from fire exposure or due to overheating connections. The recent changes to NFPA 921 regarding arcing characteristics are a step in the right direction in terms of moving towards characteristics with a sound scientific basis [1]. However, these characteristics are very qualitative and still generally geared towards arcing in copper wiring. Additional research into arcing in receptacles and plugs is necessary to provide a scientific basis for arcing in components other than copper wiring.

BACKGROUND

An electrical arc is a high-temperature (>5000°C) electric discharge between two conductors across an air gap or a medium such as char, degraded insulation, or a wet surface [2]. Arcing across an air gap must occur either over a very small gap or using a very high voltage due to the high dielectric strength of air (3 x 10^3 V/mm) [3]. More information regarding the dependence of arcing on the air gap distance and the breakdown voltage can be found in [4].

The presence of arcing is often used as an indication that the particular conductor was energized at the time of the fire. This may have implications for determining whether or not certain items could have been the cause of a fire. Both arcing and melting of conductors arise from thermal events. The underlying reasoning behind why there should be any differences between an arc site and damage from melting are the differences in temperature and time between these two types of events. Individual arcs last for times on the order of 1 second or less whereas melting from fire usually occurs over much longer times (i.e., minutes or longer). Also, arc temperatures are much higher (> 5000°C) and have steep temperature gradients compared to fire temperatures (~1100–1300°C max).

The majority of research into the evidence produced by arcing has been focused on arcing in stranded and solid copper conductors. Arcing events can produce damage on copper conductors having round beads, notches, or severed conductors [1]. Stranded conductors may have some or all of the strands severed or fused together. Arcing through char can produce several points of arcing or severing of small segments of wire. NFPA 921 does not attempt to differentiate between arcing that caused a fire or was caused by the fire.

Recent changes to NFPA 921 in the 2014 edition of the guide, attempted to reinforce the prior description of arcing evidence with the findings from recent research. Some characteristics of arcing damage that were added include: re-solidification waves, locally enlarged grain size, and high internal porosity. The characteristics of melting in copper conductors are also discussed in detail in NFPA 921: fire melting of copper wiring can produce thinning, tapering, and blistering of the conductor; globules may form on melted copper conductors, but these globules may show effects of gravity (i.e., dripping); and melting of copper wiring from fire may also obliterate the copper drawing lines, formed as a result of the manufacturing process, outside of the damaged area [1].

Much of the research into characteristics of arcing and melting presents discussion of one or two characteristics individually [5-9]. Re-solidification waves were discussed by Murray and Ajersch [5] who proposed that the waves arise as a result of the rapid re-solidification of the metals involved in arcing, which had been rapidly vaporized to a plasma state by the arc. The rapid re-solidification is attributed to the large temperature gradient between the metal plasma and the solid, un-melted metal. Re-solidification waves appear as concentric rings emanating from the arc location and have been observed on both steel and copper.

Murray and Ajersch [5] also observed changes in the grain size of the base metals at the point of arcing. This was observed for arcing in aluminum and copper wiring. For copper, the grains affected by the arcing showed an oriented and linear shape. For arcing between aluminum and steel, the grains were larger in the interaction area between the two metals. Lewis and Templeton [6] found a region of non-directional grain growth in the vicinity of the arc location for all of their 51 cases of arcing. They referenced the grain size of the base metal (#6–#7 based on ASTM E112) but did not measure the grain size near the arcing.

Lewis and Templeton [6] saw significant levels of porosity in arc beads and concluded that this characteristic was a definitive feature of arced copper conductors. In arc damage, the authors observed various sizes and shapes of pores and a line of demarcation between the areas having pores and those not having pores. Buc [7] also states that internal irregular porosity and an internal line of demarcation are key indicators of arcing damage. However, Levinson [8] observed substantial porosity in both non-arc melted and arc melted copper as long as the molten material was in contact with carbonaceous reducing agents and solidification occurred rapidly. None of the research regarding porosity in damage to conductors from melting or arcing has yet to characterize the porosity in any quantitative manner with respect to pore size distribution, pore quantity, or location of the pores. Both porosity and grain size characteristics are rather qualitative and dependent on the person conducting the examination. Therefore these characteristics should not be used as the sole criteria in judging whether a piece of evidence is from arcing or melting.

Many attempts have been made to characterize the metallurgical changes that take place during arcing and as a result of fire exposure. Babrauskas [10] provides a review of some proposed methods for evaluating beads that occur on wires as a result of arcing. Some of these methods include surface and metallurgical examination of the bead using scanning electron microscopes (SEM), Raman spectroscopy, and auger electron spectroscopy (AES) techniques. Overall, his assessment is that these methods are unable to provide conclusive determination of whether the bead is indicative of the cause of the fire or was a victim of the fire. His criticism is based in part on claims that the methods have been based on extremely small number of experiments and that the work has not been independently validated. Even though authors continue to search for a defining characteristic of arcing that will aid in the determination of fire cause versus fire effect, there has been no successful method developed.

Recent work by Man et al. [11] has attempted to use SEM, AES, and Energy-dispersive X-ray Spectroscopy (EDS) to determine whether an arc occurred in a normal atmosphere or a fire atmosphere. The work showed that for arc beads in copper wiring that occurred due to a fire, on average the surface and subsurface concentrations of oxygen and carbon were approximately two to three times higher than for arcing occurring in air. The authors did mention that the insulation was adhered to the arc melted copper after the fire exposure. However, it was unclear whether any surface cleaning of the arc beads was performed after the fire. Also, it does not appear that the arc beads from arcing in air were subjected to subsequent fire as would be expected of an arc that was the fire cause. A similar method was proposed by Anderson [12]. The presence of oxygen and carbon in the arc bead was predicated on the belief that some of the surrounding atmosphere would be absorbed in the molten metal during the arcing process and that for arcing in a fire environment this would primarily be CO_2, CO, etc. However, as Babrauskas [10] pointed out, this methodology does not take into account that even for arcing not in a fire environment; wires are typically insulated with some plastic, usually PVC, which may be vaporized regardless of whether the arcing was a cause or victim of the fire. At present, there are no metallurgical examination methods which can conclusively determine whether an arc bead was the cause of a fire or created as a result of fire exposure.

A study by Carey and Daeid [13] conducted experimental research with electrical wiring installed in test compartments and exposed to fire. The non-metallic sheathed cabling used in this testing was installed at the ceiling of the test compartment. This cabling was either supported by pairs of screws or wood blocks. This location of the wiring within the compartment and the support methods are highly irregular. Carey and Daeid [13] classified nine types of arcing damage for energized wiring based on the physical appearance of the arc beads, but did not note any evidence of conductors melting. These researchers also claimed to be able to differentiate between arcing damage occurring because of a short and damage from arcing through char. Their substantiation for this claim was based on an observation that arcing through char occurred more when the wiring was supported by wood block rather than metal screws which could short the wiring. Carey and Daeid did not discuss fire induced melting, pitting, or other wire damage which could have occurred during testing.

EXPERIMENTAL APPROACH

The arcing and melting evidence analyzed in this work was created as part of a larger research effort [14]. One of the global objectives of this work was to improve the forensic examination of electrical receptacles. Laboratory testing of receptacles and fire exposures to exemplar receptacles were used to accomplish the objectives of this research. The two types of fire exposures were single-room compartment fires and an intermediate scale furnace.

Laboratory Testing

The laboratory testing was designed to expose various receptacle configurations to operating conditions resembling a wide range of residential and commercial applications. The testing allowed for overheating connections to develop naturally over extended periods of time such that the failures encountered would be representative of what could happen in real scenarios. The receptacles were mounted directly to steel test racks, which served as the common ground. Each rack consisted of 52 to 78 receptacles, and receptacles on each rack were wired using a feed through method such that the applied current was passed through both the hot and neutral terminals of every receptacle. The wiring used to connect the receptacles was 14 AWG non-metallic (NM) sheathed cable. Each test rack was connected to a separate 20A circuit breaker. The electrical load for the test racks was provided by tungsten-filament light bulbs arranged in a load bank capable of providing a maximum current draw of 20A. A separate load bank was used for each test rack.

Fire Exposure Testing

The exposure of receptacles to compartment fires and an intermediate scale furnace had two purposes. Both the compartment and furnace exposures were used to assess the impact of certain variables relative to thermal damage and fire-induced electrical arcing in receptacles. The furnace fire exposures were also used to create elevated temperatures capable of melting receptacle components since melting never occurred in the compartment fires conducted. Compared to the compartment fires, the intermediate scale furnace allowed for controlled temperature exposures to the receptacles, representative of flashed over fire conditions at thermal levels above those reached in the compartment fires. The compartment fires consisted of a single room furnished with upholstered furniture. The intermediate scale furnace was a premixed, natural gas fed, forced air furnace. A maximum furnace temperature of nominally 1100 °C for approximately 15 minutes was selected to provide an exposure that could potentially melt brass receptacle components. Additional details regarding the fire testing and laboratory testing can be found in the full report [14].

Evaluation of Arcing and Melting Damage

The presence of visual indicators of arcing damage was assessed. The following characteristics are listed in the recent changes to NFPA 921 as "commonly exhibited for arc damaged conductors:"

- Localized point of contact
- Sharp demarcation between damaged and undamaged area
- Copper drawing lines visible outside of damaged area
- Corresponding damage on the opposing conductor
- Resolidification waves
- Locally enlarged grain size
- High internal porosity when viewed in a cross-section
- Localized round depressions
- Small beads & divots over a limited area
- Round, smooth shape of artifact

The presence of tooling marks, such as defined edges and stamped lettering outside of the damaged area, for arcing in brass and steel receptacle components was used as an analogous characteristic to the presence of copper drawing lines for copper wiring. A portion of the receptacles from the larger test program were evaluated for the presence of the aforementioned characteristic traits of arcing damage. The purpose of this exercise was to assess which characteristic traits were effective in assessing potential arcing damage on receptacle components and wiring. Thirty-nine receptacles which failed during laboratory testing and also had arcing damage were evaluated; this included 95 individual conductors. Forty-seven receptacles with fire induced arcing were evaluated; this included 87 individual conductors. All of the evaluated receptacles with fire-induced arcing were energized or energized with a load. Thirty-seven non-energized receptacles with fire induced melting were evaluated; this included 57 individual conductors. All of the receptacles evaluated for melting were non-energized receptacles.

Each receptacle was evaluated for the aforementioned characteristics of arcing with the exception of the grain structure (i.e., locally enlarged grain size). This characteristic was omitted because it was not able to be evaluated visually. Where multiple conductors exhibited damage, each conductor was evaluated independently. For each characteristic, there were three possible outcomes: Yes, No, and Possible. Possible indicated that confirmation could not be made either for or against the presence of the characteristic. All of the evaluations were conducted by the same person. Every effort was made to evaluate the conductors in a consistent manner; however, there is some subjectivity present in the evaluations due to the qualitative nature of the characteristic traits.

EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 provides an overview of the characteristic traits of arcing that were evaluated as well as a photograph exhibiting each trait. The photographs presented in Table 1 are prime examples of the characteristic traits; however, some traits had a spectrum of possible variations.

Corresponding damage on the opposing conductor is a characteristic of arcing that should be present in every instance of arcing. This is because arcing, at a minimum, requires two conductors, whether they are two parts of the same conductor in series or two separate conductors in parallel. However, dirt, debris, physical damage, thermal damage, or corrosion can destroy or obscure the damage on a conductor. In this study, a large portion of conductors with damage from arcing (93%) had a positive identification of corresponding damage on the opposing conductor. On the other hand, only four (7%) of the conductors with fire melting had corresponding damage on the opposing conductor. These four conductors (two pairs of stranded copper wires) were fused together from the fire exposure. These results indicate that corresponding damage on multiple conductors is a reliable indicator of arcing and rare for melting damage.

Because individual arcs are typically small in size (< 1 cm), short in duration (<< 1 second), and high in temperature (>5000 °C), damage to the conductors tends to be localized with a sharp line of demarcation between damaged and undamaged areas. Where multiple arcs occur in the same location, the damage area can grow in size and thus become non-localized. The authors did not define a cutoff for the size of the damage area for determining whether damage was localized. A large portion of conductors with arcing damage (95%) had a positive identification of localized damage with a sharp line of demarcation. Those few conductors without localized damage with a sharp line of demarcation were brass and steel only. Only 12% of conductors with melting had localized damage with a sharp line of demarcation; all of these instances were observed on solid copper receptacle wiring. The distinct line of demarcation of wire damage can be explained by the directional fire exposure (i.e., from front to back of the receptacle) with the wires located behind the receptacle in the box. Overall, the data clearly shows a strong correlation for a sharp line of demarcation with arcing damage and a weak correlation for melting.

The round, smooth shape often exhibited by arcing damage on wiring has led to the use of the generic term of arc bead for describing arcing damage. While the recent changes to NFPA 921 [1] include the round smooth shape as a characteristic trait of arcing, Section 9.11.1.2 of NFPA 921 states that arcing damage can be "notches in the sides of the conductors, or rounded or irregular-shaped beading on the end of a severed conductor." This information provided by NFPA 921, while accurate, is not clear guidance on differentiating between arcing and melting in that it essentially states that both regular (i.e., round and smooth) as well as irregular arc damage can be observed. Only 40% of the conductors with arcing damage were round and smooth in shape, whereas 12% of melted conductors had a round and smooth shape. While a notable number of arcing conductors had this trait, the lack of a large difference in proportions of arcing and melting damage which are round and smooth in shape suggests that this trait is not as strong a differentiating indicator between arcing and melting.

Resolidification waves in arcing damage arise from the rapid cooling associated with arcing events. This trait appears as concentric rings (i.e., waves or ripples) emanating from the center of the arc location. Only a small portion (12%) of conductors with arcing damage exhibited resolidification waves. No conductors with melting damage were observed with any damage resembling resolidification waves. Resolidification waves were observed on steel, brass, and copper conductors, but were most often located on the steel receptacle components. Despite the low percentages of arc damaged conductors with resolidification waves present, this characteristic trait is a strong indicator that arcing occurred. The resolidification waves themselves are unique compared to the visual appearance of melting. The regular, concentric rings are not able to be produced by fire melting due to the relatively slow process of fire-melting and cooling compared to arcing.

Tooling marks come from the manufacturing process of metal components of receptacles and wiring. These processes mark the surface with a regular pattern or form a distinct shape. Tooling marks include defined edges and lettering for stamped and bent brass and steel receptacle components and copper drawing lines for copper wires. When exposed to temperatures on the order of the melting temperature of the conductor, these tooling marks can begin to be destroyed. A large portion of conductors with arcing damage (80%) had a positive identification of tooling marks outside the area of damage. Only one conductor (1.7%) with melting damage had tooling marks visible outside a localized damage area; this was a solid copper wire. This characteristic trait of arcing is a parallel method of confirming that damage to the conductor is localized and has a sharp line of demarcation, but is less likely to be present if exposure temperatures were close to the melting temperature of the subject material.

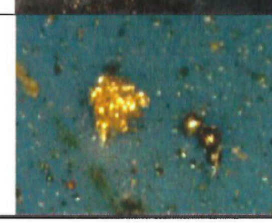
In general, the evaluations of arcing and melting damage were external evaluations of the conductors; the internal structure of the arcing and melting damage was not systematically evaluated. However, some of the arcing locations examined had two conductors fused together by arcing. During the examination, the conductors were pulled apart to reveal the internal structure of the connecting arc bead.

In 21 conductors, large voids were observed inside the arc bead. In 8 conductors, porosity was visually evident on the surface of the conductor, but the amount of internal porosity and size of the voids was not evident. These conductors were classified as having possible high internal porosity. Internal porosity was not examined for all of the conductors with arcing or melting damage. Because there has not been any rigorous study in the literature which quantifies the size and percent by volume of voids in arc beads, the value of this characteristic trait in an arc damage determination is limited.

Spatter, or sprayed molten material, is often ejected outward in all directions from the arc location when arcing occurs. This material is then deposited on surfaces further away from the arcing location. Spatter consists of very small spherical particles of the metal(s) which were involved in arcing. Since the particles cool very quickly, they retain their spherical shape when they impact a surface. These spheres are typically on the order of 0.1 mm or less, but some can be larger. While fire melting can produce molten metal that fall (in the direction of gravity) onto surfaces, these do not tend to cool rapidly and can deform when striking the surface. Therefore, the very small spherical spatter particles from arcing are generally unique compared to the deposits produced by melting.

A small fraction (16%) of receptacles with arcing produced spatter that was identified, while none of the receptacles with melting had evidence that could be visually characterized as spatter. Despite the low percentages of arc-damaged conductors with spatter present, this characteristic trait is a strong indicator that arcing occurred. The small spherical particles are not readily produced by melting and can be deposited in all directions, while melting particles can only fall in the direction of gravity.

Table 1. Overview of characteristic traits of damage from arcing.

Characteristic Trait	**Additional Details**	**Example Photograph from Arcing Damage**
Corresponding Damage on the Opposing Conductor	Damage located on another conductor proximate to the area of interest and in a location where arcing was possible.	
Localized Point of Contact with Sharp Line of Demarcation	N/A	
Round, Smooth Shape	Some or all of the damage is rounded without jagged or rough surfaces and edges.	
Resolidification Waves	Concentric rings emanating from the center of the arcing damage.	
Tooling Marks Visible Outside Damage Area	Stamped lettering, copper drawing lines, crisp edges of receptacle components remain outside of the arcing location.	
High Internal Porosity	Large percentage of voids internal to the arc damage.	
Spatter Deposits	Small spherical globules ejected during arcing; can be located on surfaces away from the arcing location.	

CONCLUSIONS

Arcing and melting damage produced in prior work [14] was evaluated for the presence of nine characteristic traits of arcing damage. These traits were taken from the literature (e.g., NFPA 921 [1]) and from observations made during the forensic examinations conducted as part of this work. Arcing evidence in the receptacles evaluated was identifiable using low powered microscopes; no advanced imaging techniques were required. Corresponding damage on the opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage; these characteristics were found to be strong indicators of arcing. Resolidification waves and spatter deposits were observed in limited conductors with arcing damage; however, no fire-melted conductors were observed with resolidification waves. These characteristics were very distinct from melting damage and were therefore strong indicators of arcing. Although internal porosity was not systematically evaluated, a number of conductors with arcing damage were observed to have significant porosity. This characteristic trait has the possibility of being a strong indicator of arcing if quantitative evaluation criteria are developed. A round, smooth shape; small beads and divots; and localized round depressions were observed in limited numbers on arc damaged conductors and similar characteristic traits were observed in fire-melted conductors. Due to the lack of clear definitions in the literature, these characteristic traits were poorer indicators of arcing.

Some conductors with melting damage were found to also have characteristic traits of arcing (i.e., localized damage with a sharp line of demarcation or corresponding damage on the other conductor). However, other indicators of melting were also present which would preclude identifying the evidence as being a result of arcing.

Most of the characteristic traits of arcing and melting are qualitative and not well defined in NFPA 921 [1], which leads to more subjective evaluations. And though some characteristic traits were strong indicators of either arcing or melting, an investigator should never rely solely on the presence of one characteristic trait for arcing vs. fire-melting determination. Using multiple characteristic traits and contextual information for arcing vs. fire-melting determination provides greater confidence in the evaluation of damage. In addition, visual examinations were found to be reliable indicators of both arcing and fire-melting for most conductors. However, there are some cases which would require more advanced examination techniques including SEM/EDS examinations, X-ray, CT scanning (X-ray computed tomography), cross-sectioning and polishing, or other metallurgical methods.

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REFERENCES

[1] NFPA 921 (2014), "Guide for Fire and Explosion Investigations," National Fire Protection Association, Quincy, MA.

[2] Babrauskas, V. (2003), *Ignition Handbook*, Fire Science Publishers, Issaquah, WA.

[3] Twibell, J.D. (2004), "Electricity and Fire," Chapter 3, *Fire Investigation,* Daeid, N.N. (ed).

[4] Babrauskas, V. (2013), "Arc Breakdown in Air Over Very Small Gap Distances," *Interflam 2013 – Proc. Thirteenth Intl. Conference*, Interscience Communications Ltd., London.

[5] Murray, I. and Ajersch, F. (2009), "New Metallurgical Techniques Applied to Fire Investigation," *Fire and Materials 2009 11th International Conference and Exhibition*, San Francisco, CA.

[6] Lewis, K.H. and Templeton, B. (2008), "Morphological Variation in Copper Arcs During Post-Arc Fire Heating," *ISFI 2008 – Proceedings of the 3rd International Symposium on Fire Investigation Science and Technology*, National Association of Fire Investigators.

[7] Buc, E.C. (2012) "Metallurgy and Fire Investigation," ISFI 2012 – Proceedings of the 5th International Symposium on Fire Investigation Science and Technology, National Association of Fire Investigators.

[8] Levinson, D.W. (1977), "Copper Metallurgy as a Diagnostic Tool for Analysis of the Origin of Building Fires," *Fire Technology*, **13** (3), pp. 12.

[9] Hussain, N. (2012), "Forensic Investigation Techniques for Inspecting Electrical Conductors Involved in Fires for Arc and Melt Beads," Thesis, Master of Science in Fire Protection Engineering, University of Maryland, College Park, MD.

[10] Babrauskas, V. (2004), "Arc Beads from Fires: Can 'Cause' Beads be Distinguished from 'Victim' Beads by Physical or Chemical Testing?" *Journal of Fire Protection Engineering*, **14**, pp. 125–147.

[11] Man, D., Ming, Z., Zi-bo, Q., Da-wei, X., and Ying, W. (2011), "Study of Analyzing Characteristic of Composition on the Surface of Copper Conductor Melted Marks," *Procedia Engineering 11, pp. 68-74.*

[12] Anderson, R.N. (1996), "Which came first... the arcing or the fire: A review of Auger analysis of electrical arc residues," *Fire and Arson Investigator*, **46**, March 1996.

[13] Carey, N. and Daeid, N. (2007), "The Metallic Damage to Electrical Conductors at Fire Scenes," *Interflam 2007 – Proc. Tenth Intl. Conference*, Interscience Communications Ltd., London.

[14] Benfer, M. and Gottuk, D., "Development and Analysis of Electrical Receptacle Fires," Grant No. 2010-DN-BX-K218, Office of Justice Programs, National Institute of Justice, Department of Justice, September 12, 2013.