Journal of Magnetics 31(2), 269-273 (2026)

ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
https://doi.org/10.4283/JMAG.2026.31.2.269

Magnetic Response of Arc-Melted and Fire-Melted Beads on Copper Wires

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(Received 2 June 2026, Received in final form 17 June 2026, Accepted 17 June 2026)

Distinguishing arc-melted from fire-melted beads on copper wires is important for interpreting electrical causation in fire investigations. Magnetization measurements were applied as a non-destructive method for characterizing the magnetic behavior of the two bead types at room temperature. Arc-melted beads exhibited paramagnetic behavior, whereas fire-melted beads showed predominantly diamagnetic behavior. This contrast is interpreted in relation to the oxide phases formed under different oxygen environments, where CuO is favored in oxygen-rich conditions and Cu_2O becomes relatively more favorable in oxygen-deficient conditions. The absence of hysteresis with no ferromagnetic contaminants in the energy-dispersive spectroscopy results confirms that the paramagnetic signal in arc-melted beads is intrinsic to the CuO-containing oxide. Arc-melted beads also showed weak magnetic anisotropy, whereas fire-melted beads showed isotropic behavior. These results suggest that non-destructive magnetization measurements may serve as a useful preliminary screening method for bead discrimination, preserving the specimen for subsequent analysis.

Keywords : SQUID magnetometry, arc-melted bead, fire-melted bead, copper oxide, fire investigation

1. Introduction

Discrimination between arc-melted and fire-melted beads on copper wires is an important issue in the interpretation of electrical damage in fire scenes [1-3]. When a copper conductor is exposed to intense thermal input, local melting and re-solidification produce bead-like structures. In general, arc-melted beads are formed under energized conditions by electrical arcing, whereas fire-melted beads are formed by external thermal exposure under non-energized conditions. Representative examples of the two bead types are shown in Fig. 1.

The two bead types are produced under different oxygen conditions. Arc-melted beads are typically formed in oxygen-rich ambient air and are exposed to a momentary high-temperature arc, whereas fire-melted beads are formed in oxygen-depleted fire environments [3,4]. As shown in Fig. 1, arc-melted beads typically exhibit a smoother and more lustrous surface, while fire-melted beads tend to show a rougher and more irregular surface, consistent with descriptions in NFPA 921 [1]. However, such morphological distinctions are not always reliable, particularly for specimens recovered from fire scenes where complex thermal histories may obscure typical visual features, underscoring the need for additional analytical methods. These differences are also expected to affect the oxide phases formed on and within the beads, as CuO formation is favored under oxygen-rich conditions while Cu_2O becomes relatively favorable as the oxygen concentration decreases [5-7].

Conventional discrimination methods have mainly relied on morphology, metallography, porosity, elemental analysis, and microstructural characterization such as scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) and electron backscatter diffraction (EBSD) [2-4, 8-10]. Although these methods provide useful information, they often require sectioning or polishing of the specimen. In the context of fire investigation, this is a significant drawback, as destructive preparation of a bead reduces its availability for subsequent or independent examination. A non-destructive approach is therefore particularly valuable as a preliminary screening step that can be performed before any irreversible sample preparation, allowing the original evidence

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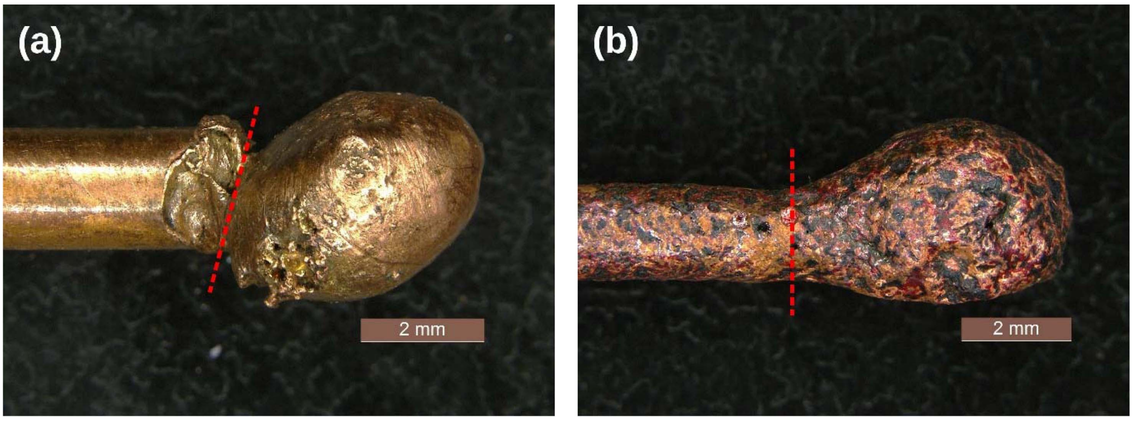

Fig. 1. (Color online) Photographs of copper electrical wire beads: (a) arc-melted bead formed on an electrically live wire at ambient temperature and (b) fire-melted bead formed on a non-energized wire by external fire heat. The dashed red line in each image indicates the demarcation line at the bead boundary, which was used to define the out-of-plane (OOP) and in-plane (IP) measurement directions for the magnetization measurements.

to be preserved for further analysis by complementary methods.

This possibility is supported by the intrinsic magnetic difference between the major copper oxides. CuO, containing Cu^{2+} ($3d^9$), exhibits paramagnetic behavior at room temperature, whereas Cu_2O, containing Cu^+ ($3d^{10}$), is diamagnetic [11-13]. Therefore, if the relative fractions of CuO and Cu_2O depend on the bead formation environment, the magnetic response may provide a useful indicator for distinguishing between arc-melted and fire-melted beads.

In the present study, room-temperature magnetic measurements were performed on arc-melted and fire-melted copper wire beads using a SQUID-VSM magnetometer. The results show that arc-melted beads exhibit paramagnetic behavior, whereas fire-melted beads show predominantly diamagnetic behavior, providing a magnetic basis for bead discrimination. In addition, a weak magnetic anisotropy was observed in arc-melted beads but not in fire-melted beads. The possible origins of these contrasts are discussed in relation to the oxygen environment and solidification conditions during bead formation.

2. Experimental Methods

2.1. Sample Preparation

Two types of copper wire bead samples were examined: arc-melted beads and fire-melted beads. Arc-melted bead samples included laboratory-prepared specimens and field-collected specimens recovered from fire scenes. The laboratory-prepared arc-melted specimen was produced by inducing a short circuit in a standard copper electrical wire (IEC 60227, 2.5 mm², single core) in ambient air at room temperature. The arc was initiated by direct conductor contact, and bead formation occurred at the wire end after momentary exposure to the electrical arc and subsequent re-solidification. Fire-melted bead samples included laboratory-prepared specimens obtained from full-scale fire reproduction tests and field-collected specimens recovered from fire scenes. In the laboratory-prepared fire-melted specimens, the fire reproduction tests represented typical residential compartment fire conditions, with a maximum recorded temperature of approximately 1,155 °C, which was close to the upper measurement limit of the K-type thermocouple, and sustained temperatures of 700-900 °C for 10 min. In these fire tests, non-energized copper wires were placed in the fire environment, and the resulting beads were collected after cooling.

2.2. Magnetic Measurements

Magnetic measurements were carried out using a Quantum Design MPMS3 SQUID-VSM system. The instrument provides a magnetic moment sensitivity better than 10^{-8} emu, a temperature range of 1.8-400 K, and magnetic fields up to 7 T. A total of six specimens were measured for each bead type. Individual bead samples with masses of about 0.02-0.09 g were mounted in the sample holder. Magnetization values are reported per unit mass (emu/g).

Isothermal magnetization measurements were performed at 300 K over the field range from −7 to +7 T. To examine magnetic anisotropy, the measurements were conducted in two orthogonal directions defined with respect to the demarcation line at the bead boundary (see Fig. 1): out-of-plane (OOP) perpendicular to the demarcation line and in-plane (IP) parallel to the demarcation line.

3. Results and Discussion

3.1. Magnetic Properties

The arc-melted beads exhibited characteristic paramagnetic behavior in the room-temperature *M–H* measurements. In all arc-melted specimens, the magnetization increased positively with applied field, and the overall *M–H* response was clearly different from that of the fire-melted beads. The measured magnetization curves indicate the presence of a paramagnetic component associated with the oxidation state formed under arc conditions. This behavior is consistent with a significant contribution from CuO-related oxidation products, although the exact phase fraction cannot be determined from magnetization data alone. As shown in Fig. 2, this paramagnetic tendency was observed in both the laboratory-prepared specimen and the field-collected specimen.

The observed paramagnetic response is one of the most prominent magnetic features distinguishing arc-melted beads from fire-melted beads in the present measurements. Because the bead samples were measured without destructive sectioning or polishing, the result suggests that magnetic measurement can provide direct information on the bead state while preserving the original specimen for subsequent examination.

In contrast, the fire-melted beads showed predominantly diamagnetic behavior at 300 K. Their *M–H* curves were characterized by a negative and nearly linear field dependence, which is clearly distinguishable from the positive paramagnetic response observed for the arc-melted beads. Although some variations in slope and small zero-field signals were observed among the fire-melted specimens, the overall magnetic response remained within the diamagnetic regime, as shown in Fig. 3.

This behavior is consistent with oxide formation under oxygen-deficient fire environments, where Cu_2O is expected to be more favorable than CuO. Since both Cu and Cu_2O are diamagnetic, the negative linear component dominates the measured *M–H* curves of the fire-melted beads.

The contrasting magnetic responses of the two bead types can be interpreted in terms of the oxygen environment during bead formation. During electrical arcing, the copper conductor is exposed to a momentary high-

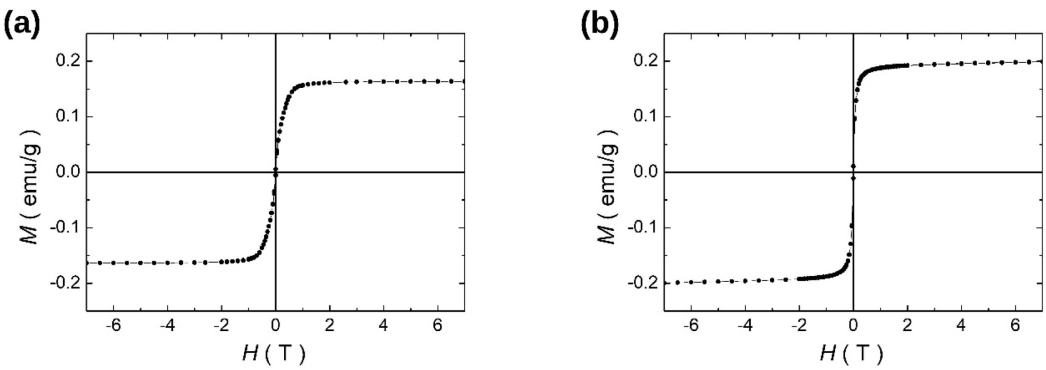

Fig. 2. *M–H* curves at *T* = 300 K for representative arc-melted bead samples obtained from (a) laboratory preparation and (b) fire scene. Both samples exhibit paramagnetic behavior.

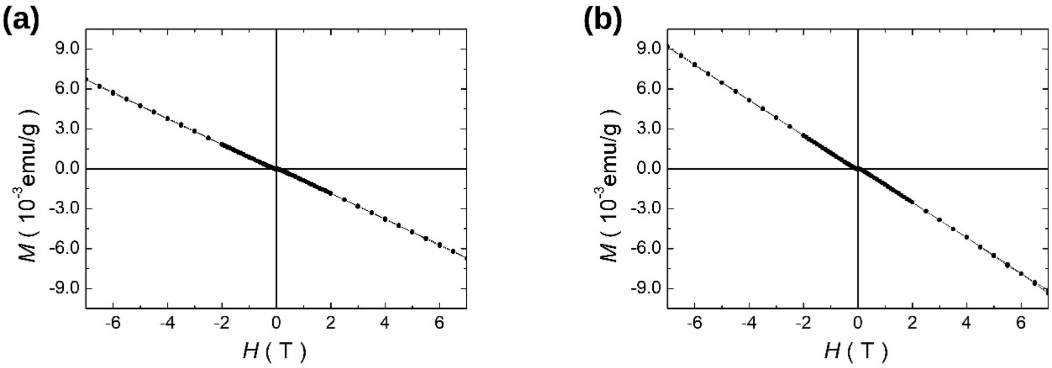

Fig. 3. *M–H* curves at *T* = 300 K for representative fire-melted bead samples obtained from (a) laboratory preparation and (b) fire scene. Both samples exhibit diamagnetic behavior.

temperature arc in ambient air. Although Cu_2O is thermodynamically more stable than CuO under most conditions, the specific conditions of electrical arcing may favor CuO formation: the relatively higher oxygen partial pressure of ambient air, compared to the oxygen-depleted fire environment, places the cooling bead within the CuO stability field [5, 6], while the rapid solidification characteristic of arcing kinetically traps the resulting oxide before the system can re-equilibrate. In contrast, fire-melted beads are formed in a fire environment where ongoing combustion progressively depletes the local oxygen concentration, shifting the equilibrium toward Cu_2O [5-7]. These differences in oxide phase formation are reflected in the distinct magnetic responses observed in the present measurements: the presence of CuO in arc-melted beads contributes a net paramagnetic response, while the dominance of Cu and Cu_2O in fire-melted beads results in a net diamagnetic response. The SEM-EDS results support this interpretation, showing a higher oxygen content in the arc-melted bead (O: 6.9 at.%) compared to the fire-melted bead (O: 3.2 at.%), consistent with more extensive oxidation under arc conditions.

The absence of hysteresis and coercive field in all measured magnetization curves confirms that the paramagnetic response does not arise from ferromagnetic impurities. This is further supported by the SEM-EDS results, which show no detectable elements other than Cu, O, and C, with no evidence of ferromagnetic contaminants such as Fe or Ni.

3.2. Magnetic Anisotropy

A weak but discernible magnetic anisotropy was observed in the arc-melted beads. As shown in Fig. 4(a), in the representative specimen the magnetic response measured in the out-of-plane direction was larger than that in the in-plane direction, with magnetization values of 0.200 emu/g (OOP) and 0.165 emu/g (IP) at 7 T, yielding an anisotropy ratio of approximately 1.21. This result suggests that the magnetic response of arc-melted beads is not completely isotropic and may reflect directional features developed during rapid solidification under arcing conditions. Previous metallographic studies of arc-related molten marks have reported directional solidification structures, including columnar or dendritic microstructures, in primary beads [3, 4]. In this context, the preferential paramagnetic response observed here may be associated with such directionally developed microstructures.

By contrast, the fire-melted beads showed little difference between the two measurement directions, indicating nearly isotropic magnetic behavior. As shown in Fig. 4(b), this nearly isotropic response accompanies an overall diamagnetic signal. Previous studies have described fire-melted copper marks as tending toward more uniformly recrystallized microstructures after thermal exposure [14]. This difference implies that magnetic anisotropy may serve as a secondary indicator that supplements the primary discrimination based on paramagnetic versus diamagnetic response. However, because the anisotropy is relatively weak and not equally pronounced in all arc-melted specimens, it is better regarded as supporting information rather than a standalone criterion.

4. Conclusions

Magnetization measurements were applied to the discrimination of arc-melted and fire-melted beads formed on copper electrical wires. The room-temperature *M–H* measurements showed a clear contrast between the two bead types: arc-melted beads exhibited paramagnetic behavior, whereas fire-melted beads showed predominantly

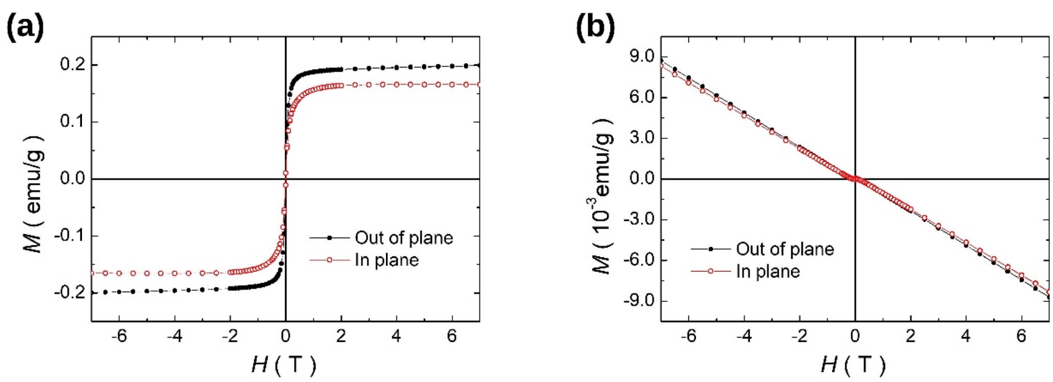

Fig. 4. (Color online) Comparison of magnetization curves measured at $T = 300$ K in out-of-plane and in-plane configurations for (a) an arc-melted bead, which exhibits paramagnetic behavior with weak magnetic anisotropy, and (b) a fire-melted bead, which exhibits diamagnetic behavior with a nearly isotropic magnetic response.

diamagnetic behavior. This contrast provides a simple magnetic basis for bead discrimination.

The observed magnetic difference can be interpreted in terms of the oxide phases formed under different oxygen environments. Arc-melted beads are formed in oxygen-rich ambient air, where CuO formation is favored, while fire-melted beads are formed in oxygen-deficient fire environments, where Cu_2O becomes relatively more favorable. Because CuO is paramagnetic and Cu_2O is diamagnetic, the relative fractions of these oxide phases are considered to contribute to the measured magnetic response. In addition, arc-melted beads showed weak magnetic anisotropy, whereas fire-melted beads were nearly isotropic. This anisotropy contrast may be related to directional solidification features developed during arcing and may provide supplementary information for discrimination between the two bead types.

These results suggest that non-destructive magnetization measurements may serve as a useful method for bead characterization and discrimination. The main advantage of this approach is that magnetic measurements can be performed without damaging the specimen, allowing subsequent examination by conventional microstructural or compositional methods when needed. Because fire scene beads may reflect more complex environmental histories than laboratory-prepared or fire-reproduction specimens, the present method is best understood as a preliminary magnetic screening approach that provides an additional basis for discrimination while preserving the specimen for further examination. Further studies on broader sample sets, ideally combined with phase characterization, will help clarify the range of magnetic variation and strengthen the basis for practical application of this method.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Forensic Service (NFS2025FSA01), Ministry of the Interior and Safety, Republic of Korea, and the National Research Foundation of Korea (NRF) (Grant Nos. RS202500516322 and RS202500512822).

References

[1] NFPA 921, Guide for Fire and Explosion Investigations, National Fire Protection Association, Quincy, MA (2024).
[2] D. G. Howitt, J. Forensic Sci. **42**, 608 (1997).
[3] E.-P. Lee, H. Ohtani, Y. Matsubara, T. Seki, H. Hasegawa, S. Imada, and I. Yashiro, Fire Saf. J. **37**, 353 (2002).
[4] K.-H. Liu, Y.-H. Shih, G.-J. Chen, and J.-M. Chou, Materials **8**, 3776 (2015).
[5] B. Hallstedt, D. Risold, and L. J. Gauckler, J. Phase Equilib. **15**, 483 (1994).
[6] L. Schramm, G. Behr, W. Löser, and K. Wetzig, J. Phase Equilib. Diffus. **26**, 605 (2005).
[7] M. Heinemann, B. Eifert, and C. Heiliger, Phys. Rev. B **87**, 115111 (2013).
[8] Z. Yu, S. Chen, J. Deng, X. Xu, and W. Wang, Materials **13**, 4521 (2020).
[9] J. Park, J.-H. Kang, E. P. Lee, Y. H. Ko, and S. B. Bang, Fire Technol. **57**, 1667 (2021).
[10] J. Park, J.-H. Kang, J. Park, Y. H. Ko, and S. B. Bang, Materials **15**, 8206 (2022).
[11] G. Narsinga Rao, Y. D. Yao, and J. W. Chen, J. Appl. Phys. **105**, 093901 (2009).
[12] T. Shimizu, T. Matsumoto, A. Goto, T. V. Chandrasekhar Rao, K. Yoshimura, and K. Kosuge, Phys. Rev. B **68**, 224433 (2003).
[13] W. L. Roth, J. Appl. Phys. **31**, 2000 (1960).
[14] V. Babrauskas, J. Fire Prot. Eng. **14**, 125 (2004).