JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, January 2012, Vol. 57, No. 1
doi: 10.1111/j.1556-4029.2011.01948.x
Available online at: onlinelibrary.wiley.com

CASE REPORT

ENGINEERING SCIENCES

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Metallographic Analysis and Fire Dynamics Simulation for Electrical Fire Scene Reconstruction

ABSTRACT: This study demonstrated the use of metallographic analysis and NIST's Fire Dynamics Simulator (FDS) program to identify the cause of an actual electrical fire. A severely carbonized steel plate and a cable with a bead were found inside a damaged switchboard from the debris of a factory fire. By metallographic analysis, the copper spatter on the steel plate was found to imply a short circuit has occurred and that this was the probable ignition source of the fire was supported by the presence of a small amount of copper oxide and by the cavities with the tree-like grain microstructures in the bead. The heat estimated to have been released per unit area of the switchboard in question (approximately 236.29 MJ/m^2) served as key input data for applying the FDS simulation of the blaze. The simulation indicated that thermal insulation polyethylene (PE) played an important role in the rapid fire spread.

KEYWORDS: forensic science, fire investigation, electrical fire, metallographic analysis, Fire Dynamics Simulator, molten bead, fire scene

Fire statistics for Taiwan reveal that an average of 9670 fires occurred annually during 1998–2008. Of these, electrical fires comprised approximately 1800, or about 18.6%, which makes them the most common type of fire (http://www.nfa.gov.tw/upload/FTB/UpFiles/[accessed July 22, 2009]). Similarly, electrical fires comprised about 15% of the fires in Japan between 2000 and 2008 and were the second highest fire frequency (http://www.fdma.go.jp/neuter/topics/fieldList8_3.html [accessed July 22, 2009]). In the United States, electrical fires comprised 6% of residential fires during 2003–2007, which made them the third most common type of fire (1). In China, 35.6% of the massive fires between 1993 and 2002 were electrical fires (2). The high percentage of electrical fires demonstrates the need to improve identification of causes and accumulate empirical data for this type of fire.

When analyzing the causes of an electrical fire, the possible ignition point is first sought by examining the primary or secondary molten mark from any short-circuited wire. Although both primary and secondary molten marks have obvious beads, they are easily distinguishable by their different internal cavities and crystallization patterns (3). This study employed metallographic analysis as part of its investigation of probable ignition points of a particular large-scale fire. Data were also collected from eyewitness accounts, fire debris, and other evidences. The Fire Dynamics Simulator (FDS) software application was used to reconstruct the fire scene to help explain the extensive damage caused by the fire and to further develop this protocol so that it may take its place as a tool for fire forensics (4).

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Received 10 Mar. 2010; and in revised form 12 Aug. 2010; accepted 20 Nov. 2010.

Fire Scene Observation

The examined factory fire occurred in October 2006 in Taiwan. Substantial fire debris was collected from the fire site and visually examined. Notably, one switchboard from the site exhibited significantly more damage compared with the others from the site. Figure 1 shows the carbonization of the inner steel plate and three molded case circuit breakers (MCCB) of this switchboard. Figure 2 shows an electrical cable with a bead at one end that was found inside the switchboard. The bead would have been produced when high temperatures melted the electrical cable, which then resolidified into a bead upon cooling (5). That the electrical cable was shown to have been exposed to very high temperatures provided a clue as to the ignition source in this fire (6). This was the starting point for the various research performed in this investigation.

Experiment and Results

The steel plate near the contact of the burned MCCB and the cable was cut into samples and mounted in resin. After they solidified, a variable speed grinder-polisher (EcoMet® Twin; BUEHLER, Lake Bluff, IL) was used to grind and polish the samples for further metallographic examinations. Microscopic study indicated that one steel plate was covered with copper spatter (Fig. 3). Hypothesizing that this spatter on the unmelted steel plate came from a spark-induced melting of the copper wire (5), we concluded that the most likely source of ignition was a short circuit at the contact of the cable and the MCCB.

A bead also appeared at the end of cable (2) (Fig. 2). The beaded area had a larger diameter than the original cable did and had a smooth yet nonglossy surface. Another series of metallographic studies examined the cross-section of the bead at the end of the cable, after it was removed with an abrasive cutter (ISOMET

FIG. 1—*Fire damage inside switchboard. The rectangle region of the steel plate was removed for metallographic analysis.*

FIG. 2—*View of cable with bead at the end (arrow indicates), the cross-section of the bead was used for further metallographic examinations.*

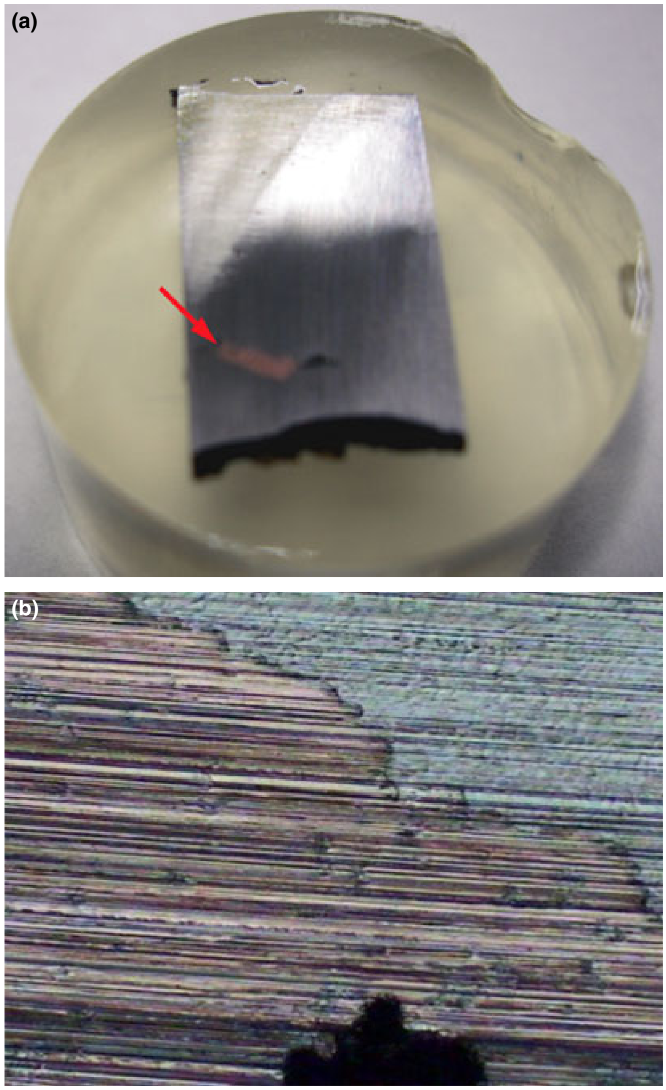

FIG. 3—*Specimen consisting of a portion of the steel plate backing the damaged switchboard. (a) Copper spatter on the steel plate (arrow). (b) Microscope image of copper spatter.*

1000; BUEHLER). Figure 4*a* shows the fragmentary cavities and the small amounts of copper oxide (Cu_2O) on the cross-sectional surface. Further microscope study under high magnification (1000×) revealed tree-like elongated grain microstructures within the cavity (Fig. 4*b*). According to a study by Yu (3), these characteristics indicated that this bead should be a primary molten mark. We infer that the transient high-temperature arc produced by the short circuit ignited the nearby combustibles and induced further spread of the fire, immediately after which the temperature in the area of origin decreased. Because the cable at the short-circuit site melted and then resolidified within a short period of time, gases were entrapped in the resulting copper bead, leading to the formation of small fragmentary cavities. Entrapped oxygen also generated a small amount of CuO_2 on the surface of the bead (7). Additionally, recrystallization caused by the temperature swing would have converted the original equal-axis fiber-like microstructure of the copper wire into an anisotropic tree-like grain (7,8).

Computerized Fire Simulation

This fire was reported by an on-duty factory worker, who saw the fire on the roof 1 min after hearing an explosion. In <5 min, the area behind the factory was engulfed in flame, and emergency units were called. The fire fighters arrived within 6 min. Despite the rapid response, fire damage to the 5000 square meters of space in the closely spaced 11 factories constituted a $US 64,000,000 loss. To determine why there was such unusually severe damage and why the fire spread so quickly after ignition, we used FDS version 5.4.3 to simulate the fire development.

The FDS software, developed by the U.S. National Institute of Standards and Technology (NIST), is designed to analyze computational fluid dynamics. After fire scene data are entered, the program can identify possible routes of fire and smoke. The heat released per unit area of the carbonized switchboard was an essential simulation variable in this case. Therefore, an undamaged switchboard similar to the one suspected of igniting the fire was retrieved from the fire debris to be used as an exemplar. The mass of each combustible within the exemplar was multiplied by the related heat of combustion and summed to obtain the total heat released while burning. Then, the total was multiplied by a factor 1.15 (to account for latent heat release) and divided by the area of the switchboard to arrive at the heat released per unit area of 236.29 MJ/m^2, as

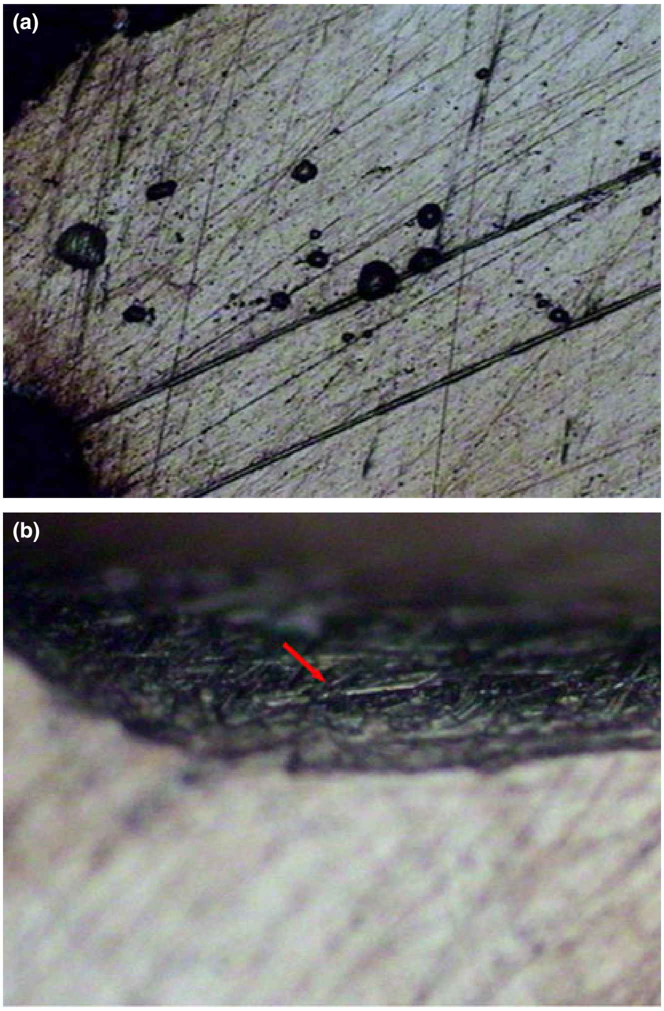

FIG. 4—*Primary mark of the bead. (a) Metallographic section of the bead (200×). (b) Tree-like microstructures with elongated grain (arrow) (1000×).*

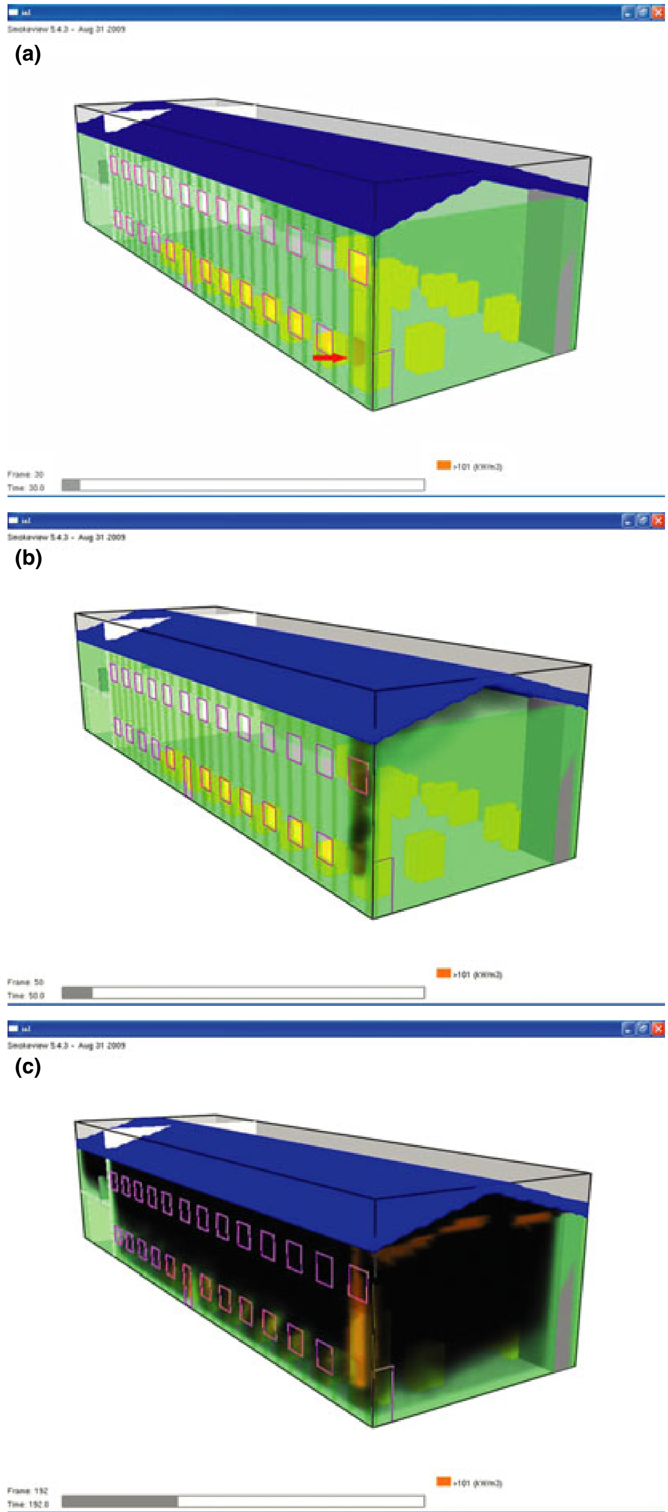

FIG. 5—*Computer simulation of fire scene. The configuration of the factory building was input to the Fire Dynamics Simulator program, including door and windows (hollow rectangles), machinery equipment (light parallelepipeds), duct (gray parallelepiped), the switchboard (arrow), and the polyethylene (PE) thermal insulation inside the wall (not shown). (a) Smoke filled the switchboard and started to emit from the switchboard (arrow indicated) at 30 sec after ignition. (b) Transmission of heat along the wall (with the PE thermal insulation inside it) at 51 sec after ignition and ascent of smoke to the ceiling. (c) Rapid spread of smoke to factory areas at 192 sec after ignition.*

listed in Table 1. This figure was input to the FDS program to generate the simulation, which showed ignition smoke to be emitted from the switchboard about 30 sec after the short-circuit spark discharge, as shown in Fig. 5*a*. Figure 5*b* shows the simulated spread of the fire from the switchboard and indicated that during the first minute after ignition, heat was rapidly transmitted through the thermal insulation polyethylene (PE) inside the back wall on which the switchboard was mounted. The simulation also indicated that the smoke from the fire ascended to the factory ceiling, where it began to accumulate. Owing to the flammable PE, the flames and smoke quickly spread out to the factory's ceiling and surrounding areas. Figure 5*c* shows the FDS simulation, indicating that flash-over occurred about 3 min after the spark that ignited the fire. Figure 6 shows the severe smoke damage to the ceiling steel, which was consistent with the simulation results. The factory where the fire started was only 30 cm away from neighboring factory buildings, and many flammable articles were heaped between the factories. Therefore, when the fire reached the PE inside the iron sidings, it easily spread to these articles. From there, the fire rapidly spread to the neighboring factories, compounding the loss.

Conclusion

Metallographic analysis, which is quickly and easily performed, was used as the primary tool for screening the samples in this

FIG. 6—*Smoke damage of ceiling.*

TABLE 1—*Calculation of heat released per unit area of switchboard.*

Combustibles	Heat of combustion* (MJ/kg)	Mass (kg)	Heat released (MJ)
Cable (250MCM × 3)	26.94	2.50	67.35
MCCB (75A)	28.4	0.86	24.42
MCCB (30A)	28.4	0.43	12.21
MCCB (20A)	28.4	0.39	11.08
Total value			115.06 (MJ)
Design value = total value × 1.15†			132.32 (MJ)
Heat released per unit area = design value/switchboard area‡			236.29 (MJ/m^2)

MCCB, molded case circuit breakers.
*Data sourced from TAOYUAN WIRE.
†An experiential rating, to account for possible combustible loadings in the switchboard.
‡Switchboard area is 0.7 m × 0.8 m = 0.56 m^2.

study. Other ways to distinguish primary and secondary molten marks include X-ray analysis of the internal alloy configuration (to identify the time and temperature that the cable endured in the fire [6]) and analysis of the crystal structure of the carbon in the carbonized residue from PVC insulation remaining in the bead (9). However, those methods would require destructive testing, precluding re-examination of the samples, which increases the importance of the molten mark obtained from actual fires.

Reconstructing a fire scene by analyzing debris is the most difficult task that a fire investigator faces. The FDS program is officially recognized and widely used to simulate various fire scenes (4,10). Combining the FDS program with witness interviews and on-site investigation of the fire evidence assists the investigator to complete the fire scene reconstruction. Owing to its ability to ensure the fairness, objectivity, and accuracy of a fire investigation, the FDS has come to play an essential role in fire forensic science.

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