Fig. 1 and 2 (inset) — These show two views of the wire end as it was received. All of the wire insulation had been burned away, as it was on most of the wire recovered. Material appears to have been blown away at the end of the wire.

Evaluation of fire damaged copper wire

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A metallurgical analysis to determine whether a #12 solid, THHN copper wire had been energized and thus could have been the cause of a major fire loss is presented in this article. The wire was used to run temporary lighting in the attic space of a large single-story wooden commercial building under construction. Temporary wiring for light had been strung over wooden ceiling joists and stapled in place.

One theory for the cause of the fire was that the current in the wire induced a current in a staple driven too hard into a wood joist. Adding insulation over this area could trap heat generated in the staple and ignite a fire. The fire started within a few hours of installation of insulation in the attic.

A point of origin of the fire was located in the ceiling of one room in the building. Several pieces of wire were found on the floor of the room after the ceiling collapsed, and fire investigators recovered two wire ends that appeared to show evidence for a parting arc. The parting arc issue was important because the temporary lighting wire represented a possible fire origin, and it was not supposed to be present, much less energized, at the time of the blaze.

The NFPA 921 *Guide for Fire and Explosion Investigations 2004*, provides photographic examples of wires with parting arcs, but it includes no metallurgical investigation. A parting arc in this case would have occurred after the fire had started, as the hot, energized wire was pulled apart. The arc was not considered to be the cause of the fire because of its short duration, but it was evidence for flowing current. The purpose of the following work was to determine if the peculiar nature of the separation showed evidence for a flow of current or only a parting arc.

Examination procedure

Only one of two separate parting arc ends was permitted to be destructively examined. However, other wire samples were allowed to be removed from the collected wire pieces for metallographic evaluation.

Three different new wire samples were purchased to provide a reasonable idea of the as-produced wire structure. (No samples of the original wire without fire damage were available.)

The wire end in question was photographed with both conventional photography and with a scanning

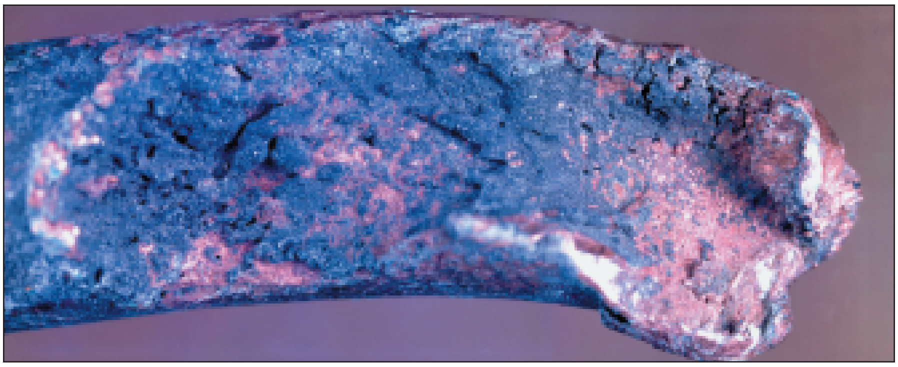

Fig. 3 — This is an image of the broken end of a power line that failed while carrying current.

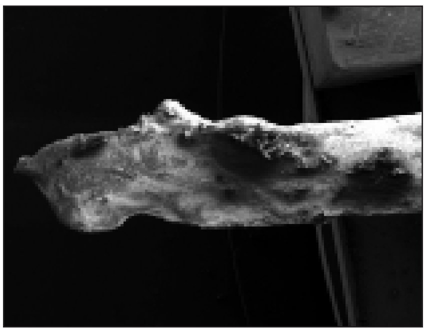

Fig. 4 (top) and 5 — These SEM photos show that a gray glass-like coating covered the rough surface that had lost material.

electron microscope (SEM) prior to mounting the wire for a longitudinal section for metallography. Two different etchants were applied to reveal the grain structure:

- 1:1:1 H_2O_2:NH_4OH:H_2O and
- $K_2Cr_2O_2$, H_2SO_4, NaCl saturated solution

Both enchants yielded the same good delineation of grain size. The hydrogen peroxide etch revealed good grain boundary detail at high magnification, while the potassium dichromate showed good grain contrast.

Wire characteristics

Figures 1 and 2 show two views of the wire end as it was received. All of the wire insulation had been burned away, as it was on most of the wire recovered. Material appears to have been blown away at the end of the wire. (This is typical of arc damage from other cases. For example, Fig. 3 shows the broken end of a bare power line that failed while carrying current, although no fire was involved.)

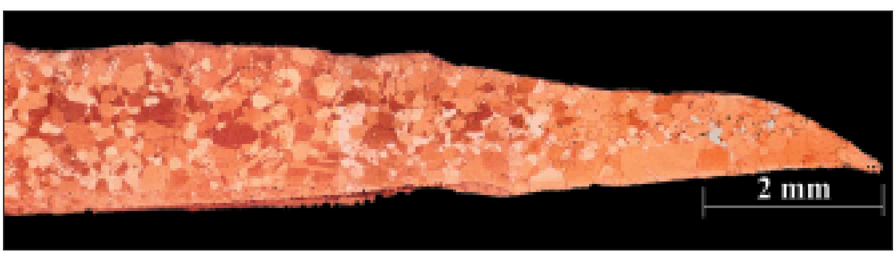

Fig. 6 — This montage shows the wire etched with dichromate, which gives better grain contrast than hydrogen peroxide.

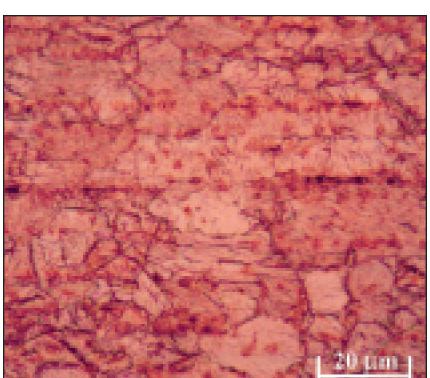

Fig. 7 — This is the microstructure of the new wire for comparison purposes.

In the wire specimen from the fire, a gray glass-like coating covered the rough surface that had lost material, as shown in SEM photos in Fig. 4 and 5. X-ray analysis revealed that the film on the crater surface contained calcium and sulfur, which could be explained by gypsum wallboard. The rough surface shown in Fig. 5 is SiO_2 from the insulation.

A longitudinal cross section through the wire in Fig. 1, 2, 4, and 5 was carefully prepared to reveal the structure at the cratered and back side surfaces. Two different etchants were applied, to assure that grain size was reliably shown.

Figure 6 shows a montage with the dichromate etch because of better grain contrast for reproduction of the photos. The hydrogen peroxide etch gave better detail of grain boundaries at higher magnifications, but both etches revealed the same grain sizes.

Several very large grains can be seen at the surface at the wire tip, but the rest of the grain structure is much smaller. For example, smaller grains can be seen at the far end of the montage, away from the tip. These smaller grains had many more annealing twins than the tip area. Because the original wire had been heavily drawn, the wire has clearly been heated and annealed in the fire. Figure 7 shows new wire for comparison.

Evidence for temperatures at or near the melting point for copper was observed in the tip area in Fig. 6, which shows a Cu:Cu_2O eutectic structure and grain boundary liquation at the very tip. The eutectic melting point is 1066°C, and copper melts at 1084°C. Areas of eutectic are barely visible on the wire surface in Fig. 6 as a rough area on the straight surface. Higher magnification reveals the eutectic as a thin film covering the cratered area and some of the wire surface for a distance of 10.4 mm from the tip. Figure 8 shows the eutectic to be a classic rod-type structure. This eutectic structure was not observed in any of the rest of this wire sample or other wire samples from the fire.

Evidence for grain boundary liquation can be seen at the very tip of the wire in Fig. 9 in one of the large voids at grain boundaries. Liquation is identified by the curved surface of one void ending at a grain boundary. (The fringe around the voids is etchant bleed-out.) Eutectic penetration at the very tip can also be observed. Grain boundary voids were found up to 200 µm from the tip.

The density of annealing twins was low in the large grains at the tip area of the wire shown in Fig. 6, and increased just beyond this area. Both grain size and density of annealing twins were relatively constant in the rest of the specimens from this wire.

Figure 10 provides an example of the typical structure and density of annealing twins in this wire away from the tip. Differential interference contrast accentuates the twins.

Parting arc evidence

Attempts were made to duplicate a parting arc with exemplar wire while under electrical load and heat. Acetylene and butane torches had no success in creating a cratered wire end. Wire failures were either brittle or clearly melted.

Figure 11 shows a brittle type failure from another wire recovered from the fire. The brittle failure results from rapid grain boundary penetration by oxygen at high temperatures and subsequent embrittlement.

Figure 12 shows one of the melted ends resulting from attempts to produce a parting arc. Melting is very clear in the form of rounded and globular ends.

Evidence for very high temperatures only at the wire tip can be summarized as follows:

- Grain boundary liquation, and eutectic penetration within one to two grains at the tip.
- Abnormally large grains at the surface of the wire for several grains.
- $Cu:Cu_2O$ eutectic film only over the length of 10.4 mm from the tip.
- Increased density of annealing twins beyond 10 mm from the tip.
- Material blown away at the tip.

Analysis results

Grain boundary liquation and a eutectic liquid penetrating the tip of the wire appear to be very straightforward evidence for incipient melting. The short distance over which these occurred argues for a very steep temperature gradient and/or short time frame.

The fact that half of the side of the wire was missing, combined with very large grain growth at the remaining surface of the wire, and the thin surface film of $Cu:Cu_2O$ eutectic, suggest complex phenomena in addition to a steep thermal gradient from the surface.

A sudden large current flow on the surface for a very short duration could explain the surface heating without causing more uniform thermal conditions through the wire cross-section. Rapid heating would also produce rapidly changing thermal stresses, which would be compressive at the surface and tensile in the center. However, the outer surface would be weak because of the higher temperatures. These conditions may result in a subsurface rupture of the type observed.

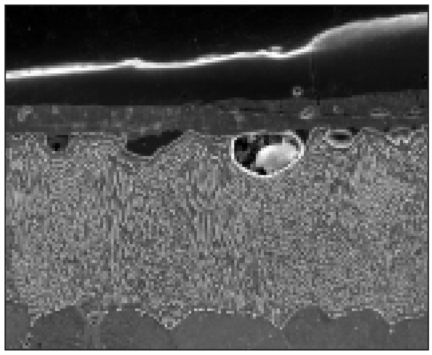

Fig. 8 —The $Cu:Cu_2O$ eutectic shows the classic rod-type structure.

The lower density of annealing twins at the wire tip is also evidence for higher localized temperatures. Annealing twins rarely occur in cast copper, but do develop in recrystallization annealing. Copper heated to 900°C (1650°F) does not appear to exhibit annealing twins. Therefore, temperatures away from the wire tip shown in Fig. 6 by approximately 10 mm or more were considerably lower. This also argues for a steep thermal gradient at the tip of the wire.

Fire damage or the extent of heat was extremely large compared to the short length (approximately 10 mm) shown in Fig. 6, which had evidence for much higher temperatures. All of the other wire samples exhibited evidence of a more constant, lower temperature than the tip area. No other known heat source was in the area, except for a parting arc that could account for the observed metallurgical evidence for steep thermal gradients.

Analysis conclusion

The tip of the wire failed with a parting arc, which in turn was evidence that the wire was energized at the time of the fire. However, this evidence does not mean that the arc caused the fire, because its duration was so short. The wire probably failed because the heat from the fire caused the supporting structure to fall, and the heat weakened the wire.

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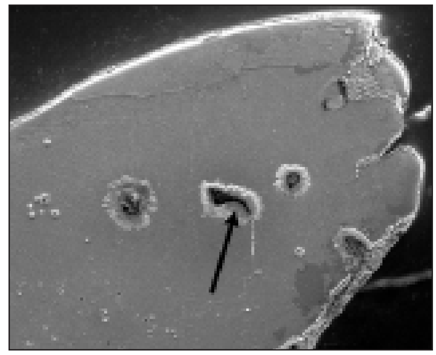

Fig. 9 — Evidence for grain boundary liquation can be seen at the very tip of the wire in one of the large voids at the grain boundary.

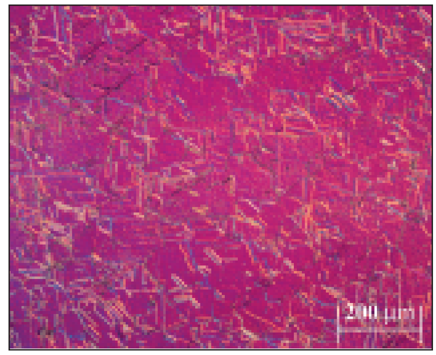

Fig. 10 — This section of wire away from the tip shows the typical structure and density of annealing twins.

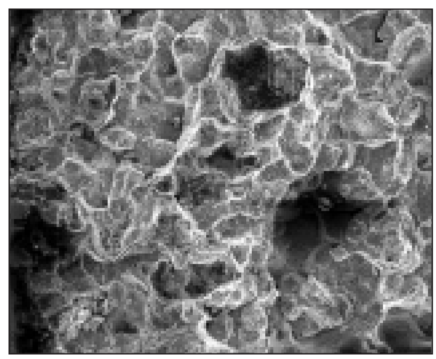

Fig. 11 — A brittle mode of failure is shown in this wire, another recovered from the fire.

Fig. 12 — Melting is very clear in the form of rounded and globular ends in this wire that was subjected to attempts to produce a parting arc.