Wire ends yield failure clues

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Say “failure analysis,” and most engineers will think of damaged semiconductors or circuit boards. But even basic devices such as transformers, inductors, relays, solenoids, and motors can experience catastrophic electrical failures. These devices rely on current that passes through small-diameter solid “magnet” wire wound on a form or bobbin.

Figure 1. The end of typical corroded wire shows a cupped end and bulging insulation.

Figure 2. A build up of corrosion products split insulation in the area of a corrosion-induced failure.
Figure 3. Although oddly shaped, this wire end shows signs of corrosion damage.

Figure 4. A slowly increasing current caused the copper to bulge and burned the insulation near the ends of a failed wire.

Figure 5. A short-duration current pulse melted this copper wire and caused a failure.
Figure 6. Excessive tension stretched this copper wire until it separated.

Figure 7. Bending a wire many times at one point caused this fatigued-wire failure.

Figure 8. A nick in this wire concentrated stress at one point and led to this fracture.

Figure 9. A transverse knife cut through a wire leaves score marks and a small insulation lip where the knife exited the cut.
Figure 10. Wire severed with a knife at an angle shows score marks and tear-out of copper and insulation at the exit point of the knife.

Figure 11. Well-sharpened diagonal wire cutters leave a characteristic ridge in the center of a wire.

Figure 12. Shear cutters leave a characteristic mark such as the one that is visible on this cut-wire end.
When a wire breaks, the device fails, and engineers and failure analysts must determine what went wrong so they can correct manufacturing problems and prevent future failures. Careful inspection of the failed wire ends can provide clues about environmental factors and failure mechanisms that caused a break. In some cases, the broken-wire ends can show signs of multiple failure mechanisms.

To start an analysis, you may have to remove coil-impregnation material—perhaps charred—that adheres to a wire and often obscures the cause of failure. You can chemically remove the coil-impregnating material and the wire insulation to reveal the appearance of the wire end.

Of course, before you apply any chemicals to a failed wire, you must determine the compositions of materials, particularly the products of corrosive chemical reactions, in the vicinity of the break. To detect the presence of specific chemical elements and compounds, you can use energy-dispersive x-ray spectroscopy (EDS), the preferred method, as well as wet-chemistry analysis, atomic-emission spectroscopy, and other analytical tools and techniques.

After you have a clear view of the wire ends, you can refer to the 13 scanning-electron micrographs in this article to home in on a failure mechanism. Most of the micrographs illustrate failures that were produced under lab conditions, so they show almost ideal failure characteristics. The micrographs can help you identify the following problems:

**Corrosion**

Corrosion probably causes the most failures of wires in coils (Refs. 1 and 2). Ends of corroded wires vary widely in appearance, but they usually have odd shapes and appear rough and dirty. Insulation may be split or cracked by the build up of corrosion products between the wire and its insulation.

Close inspection may reveal some green-colored materials—the products of corrosion—on or near the wire end. (You cannot see the green material in the monochrome micrographs in this article.) EDS analysis of the corrosion products often reveals high chlorine content and may disclose other potentially corrosive elements, such as bromine or organic-acid residues. Usually, these corrosive materials come from solder flux improperly or incompletely removed from the coils. But corrosive materials also may exist in the operating environment of a device. Corrosive salt fog, for example, is common near a seashore.

**Figures 1 and 2** illustrate the characteristics typical of corroded wire ends: bulging or split insulation (caused by build up of corrosion products), cupped or pitted end, and a rough, dirty appearance.

The oddly shaped end of the wire shown in **Figure 3** has the characteristics of a corrosion failure.
and includes evidence of a second corrosion site (the “necked” region) that had not corroded deeply enough to cause failure.

**Fusing**

Excessive current can cause copper magnet wire to fuse or melt, and the ends of the failed wire can reveal what happened. Typically, the rate of increase, or rise time, of the current can affect the shape of the wire end. If current increases slowly to the conductor's fusing limit, wire ends generally appear rounded and show signs of burned insulation and slightly melted or bulged copper (**Figure 4**). Aside from localized signs of burning, the insulation on the wire usually looks clean.

In contrast, if current increases suddenly, perhaps due to a short circuit, you often see a small ball of copper on one of the fused wire ends (**Figure 5**). In general, surface-tension forces in the liquid copper—melted by the high current—can form a ball or can round the end of a wire.

**Tensile failure**

The “necked” region and small cupped fracture zone shown in **Figure 6** characterize a break caused by excessive tension on the wire. Generally, the insulation appears clean and free of corrosion products. A tensile break in fine-gauge magnet wire usually occurs because of an improperly secured lead wire or terminal connected to the magnet wire. The loose lead wire or terminal can transmit excessive tension to the wire. This type of failure usually occurs close to a terminal or lead-wire attachment point.

**Metal fatigue**

Metal fatigue, caused by cyclic bending of a magnet wire, produces a rough but relatively flat end (**Figure 7**) when the wire fails. Insulation that surrounds the broken end may have pulled away from the metal conductor as shown in Figure 7. Despite its roughness, the wire end does not have the dirty look and green deposits associated with a corrosion failure.

A nick, scratch, or abrasion in the wire surface concentrates stress at this point and increases the susceptibility of the wire to tensile or bending stress. Intentionally nicking the wire surface with a sharp knife and then cyclically bending the wire until fatigue failure occurred produced the wire end shown in **Figure 8**. This wire end shows evidence of the nick, but the remainder of the surface is characteristic of a fatigue failure.

In properly manufactured and protected coils, mechanical damage to fine magnet wire occurs rarely. But something or someone may stretch coil wires until they break, wires may suffer from fatigue caused by vibration, or someone may cut wires either accidentally or intentionally.

**Tool cuts**

When investigating a wire failure, engineers and analysts should keep in mind that an unintentional cut with a tool could have severed the wire. Careful analysis of the wire-end marks can indicate the type of tool used and even the “angle of attack” on the wire.

The appearance of a cut end varies with the type of cutter that severed the wire. **Figure 9** shows a wire cut transversely with a sharp knife, and **Figure 10** shows the effect of a similar knife cut made at an angle. Score marks that run parallel to the direction of the knife blade’s travel characterize
these types of cuts.

A conventional pair of diagonal wire cutters leaves a ridge on the end of the wire as shown in Figure 11. Properly sharpened cutter blades produce equal slopes on each side of the central ridge. Because the cutter's blade pushes insulation into a cut, you often observe insulation “smearing” on the cut end.

Figure 12 shows a wire cut with a shear cutter. Score marks and a lip appear in this cut, as does some insulation smearing. The many parallel score marks show the direction of tool motion. When you see insulation smearing in this type of cut, the insulation is clean and neither burned nor pulled away from the wire.

**Multiple causes**

At times, more than one mechanism may cause a wire to fail. Generally, you can see evidence or characteristics of each mechanism, but they may not appear as clearly as those shown in the accompanying micrographs of single-cause failures.

The wire end shown in Figure 13, for example, resulted from a combination of corrosion and fusing. Attack by a corrosive substance reduced the cross section of the wire and increased its local resistance. The normal operating current caused this region of the conductor to fuse, so the wire end has the rough, dirty appearance and green, chlorine-containing deposits commonly associated with a corrosion failure. Additionally, it has a small copper ball, which indicates that current-induced fusing caused the final failure.

Although many mechanisms can cause a wire to fail, each one leaves a signature that helps engineers and failure analysts diagnose the cause or causes.

**REFERENCES**


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