Fretting Corrosion of Tin Contacts -- A Growing Problem in the Automotive Industry

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For over a century since its invention, the car could be described as "four wheels with a motor". Nowadays, it is rapidly becoming the same four wheels, but with a computer. Regardless what it is called, the electronic content of modern vehicles is increasing rapidly. Electronics run the engine, control the transmission, and watch over a number of auxiliary functions, like tire pressure, air bag monitoring, proximity radar, rear-view and other cameras, among others. Computers are increasingly taking over the driving task, with systems (like Subaru's EyeSight®) assisting drivers with the aid of cameras, eventually culminating in wider use of self-driving (or autonomous) vehicles.

Reliability of automotive electronics is a major concern - unlike most consumer electronics products, electronics in a vehicle are potentially exposed to a variety of extreme conditions: vibration, mechanical stresses due to acceleration and braking, temperature variations, humidity, fuel / chemicals, moisture, dust, fumes, etc. These circumstances, together with constraints present in the automotive industry (competition, cost considerations, regulatory requirements) results in a significant pressure on designers to provide useful, reliable solutions at a reasonable cost.

Reliability of connector contacts is a major factor influencing overall system reliability. This is especially true with automotive electronics. There are different routes to achieve the desired degree of contact interface reliability. For example, excellent reliability could be achieved by using a fairly thick gold finish (at least one micron, or 40 microinches), in combination with an adequate diffusion barrier, such as nickel, which separates the gold finish from direct contact with the copper alloy substrate that is typically used for contacts. Although historically this is a proven, sound solution, thick gold raises a number of problems of its own. Most obvious is cost, but quite often the contacts are soldered in the assembly process. Reliably soldering to gold is possible, but can present difficulties. The problem is due to a high level of gold content that ends up in the resulting solder joint. Gold reacts with the tin in solder, forming a brittle gold-tin intermetallic compound (IMC). When the gold content reaches a certain level, solder becomes brittle, i.e. mechanically weak. (Fig. 1). This is unacceptable, especially in automotive applications since the presence of gold in a solder joint makes it more likely to fail when stressed.
The use of a contact interface based on tin and/or tin alloys is attractive for several reasons. Two most important aspects are lower cost compared to gold, and excellent compatibility with soldering processes. However, there are potential problems with a tin contact finish. Tin is not a noble metal, and as a result it quickly oxidizes when exposed to air. This oxidation process is self-limiting - that is a key part of the reason why tin can be effectively used as a contact material. After forming a thin oxide layer (up to about 200 nanometers), the oxidation process stops. The initial layer of oxide serves as a diffusion barrier against oxygen in the air, preventing any further oxidation. This oxide layer is hard and brittle, while the tin underneath remains ductile and soft. Electrical connection is established by breaking up the oxide to enable metal to metal contact (Fig. 2). This contact is reliable as long as it remains positionally stable. However, in many applications this is not the case, and is particularly true in many automotive applications.
When there is movement at the tin to tin contact interface, a serious problem arises - fretting corrosion. The basic mechanisms of fretting corrosion are illustrated by Figure 3. This is a classic representation of fretting corrosion - the actual mechanism can be more complicated, depending on the application.

![Figure 3. Schematic illustration of the kinetics of fretting corrosion (Ref.2).](image)

For example, recent work in this area developed the concept of fretting corrosion "maps", based on four different mechanisms of fretting corrosion (Ref. 3). This research segmented fretting corrosion maps into various regimes: oxidation-dominant, oxidation–fretting, fretting–oxidation, and fretting wear-dominant. An example of such a map, "Frequency vs. Normal Load", is shown here. The complete paper displays maps for additional fretting parameters - such as amplitude, temperature, current load, and relative humidity.

![Figure 4. An example of a fretting corrosion map (Ref. 3)](image)
Fretting corrosion was rather extensively studied by a number of researchers. Modern research techniques were used in such studies, such as scanning electron microscopy (SEM), in combination with energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), X-ray fluorescence (XRF), high-resolution profilometry, etc. Below is an example of fretting corrosion investigated by means of SEM with EDS (Ref. 3). This combination of techniques produces an image of the corrosion, plus element maps that show the distribution of various elements in the corrosion area.

Figure 5. EDS elemental mapping of oxygen, tin and copper in the fretted zone taken after 20,000 fretting cycles indicating the removal of the tin coating, exposure of copper substrate, and oxidation of tin and copper (Ref. 3). Top left - an SEM image of the fretted zone.

Fretting corrosion is a problem that designers of automotive electronics need to recognize. The phenomenon of fretting corrosion is not just typical in automotive electronics - it has been well-known, occurring in a number of consumer and commercial applications as well. The difference with automotive applications is the increasing use of electronics in vehicles, which challenges automotive engineers in ways they historically have not been exposed to. There are potential performance and safety-related failures inherent with the use of tin contacts.
Tin can provide a reliable electrical connection, but any tin-based design must take into consideration the limitations imposed by tin. Although beyond the scope of this paper, tin has other potential problems, such as the formation of tin whiskers, and tin pest. Fretting corrosion of tin-based finishes must be kept in mind when specifying tin plated contacts.

Moreover, it is not just the outer layer of the finish that must be considered, but the intermediate layers are also important: i.e. the finish must be treated not as a single component, but rather as a "system" comprised of several components. Most fretting corrosion studies were conducted with tin that is plated directly over a copper alloy substrate. In these studies, the intermediate layer is a copper-tin intermetallic compound (IMC). Intermetallics naturally form as a result of direct contact between differing metals, and aid in the adhesion process between them. IMC's are too thin at lower temperatures to substantially influence contact resistance at the mating interface (Fig. 5). However, with time and at elevated temperatures, IMC's increase in thickness to the extent where they cause a significant increase in contact resistance (Ref. 4).

 ![Epoxy, Tin, IMC, Copper, 5 micron](image)

**Figure 6.** An example of Cu-Sn intermetallic compound growth (dark gray areas) in electroplated matte tin over copper (Ref. 5) A backscatter Scanning Electron Microscope (SEM) photograph of a cross-section (Note: epoxy is a result of sample preparation).

Relatively few fretting corrosion studies exist for tin that is plated over substrates other than a copper alloy (Ref. 6). Of particular interest in automotive electrical systems is a combination of tin over nickel. Nickel diffusion barriers are used under gold plating to slow the diffusion of copper through the gold. As copper diffuses through gold, it migrates to the gold surface and oxidizes; this accumulation of oxide increases contact resistance. The growth of copper-tin intermetallic compounds is somewhat similar to the copper-gold diffusion issue, and the use of
nickel as a barrier to stop tin from interacting with copper is now a widely-recognized and accepted solution. Indeed, earlier studies have shown that tin-nickel intermetallic growth rates are much slower as compared to tin-copper intermetallic growth rates (Ref. 7).

Figure 7. Intermetallic growth in matte Sn on Cu and Ni substrates. Solid line — Ni substrates; dotted line — Cu substrates (Ref. 7).

Since IMC growth appears rather uniform at a nickel-tin interface, it provides an apparent advantage over the copper-tin combination. However, those studies were based solely on the existing tin-nickel phase diagram, that shows only the so-called equilibrium (or stable) phases, including stable intermetallic compounds. Since late 1970's, a few studies reported another type of nickel-tin intermetallic (Refs. 8 and 9). Unlike the stable intermetallics, this "unstable" (or metastable) IMC's growth is not confined to just the nickel-tin metallic interface. Rather, its growth appeared as separate platelets; a lot of these platelets are oriented in an upright fashion (Ref. 7).
Figure 8. SEM photographs of platelet-like Ni-Sn IMC. The remaining free tin was etched off to reveal the intermetallic growth in the tin layer (Ref. 11).

This platelet growth occurs rapidly, with a substantial portion of the platelets reaching the surface of the tin.

Several studies have shown that platelet-type IMC causes solderability problems (Refs. 7, 8, 10). No dedicated study was done of the effect of this intermetallic on contact behavior, and more specifically on the effect it has on fretting corrosion. A major concern with intermetallic compounds of tin is that they are much harder, and less conductive, than tin itself. One can reasonably expect that hard, less conductive IMC platelets in the soft matrix of tin will result in severe fretting corrosion, leading to deterioration and rapid failure of the electrical contacts (Ref. 10).

There are various means to detect, and control, the presence of IMC's in electrical contacts; however that can be the focus of another paper. The engineer specifying tin-plated connectors for automotive use needs to be keenly aware that connector performance can be negatively affected by fretting corrosion and intermetallic growth. That said, given strict attention to application details, a tin contact finish can provide a cost-effective and reliable solution.

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