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Failure analysis of printed circuit boards in the main telephone system of marine product factory

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ABSTRACT

The failure of the main telephone system in a marine product factory due to copper sulfide (Cu_2S) creep was analyzed by the measurement of hydrogen sulfide (H_2S) in the atmosphere, elemental analysis with energy dispersive X-ray spectroscopy, and cross-sectional observation of vias in the printed circuit boards. Indoor H_2S concentrations were higher than outdoor ones and these corresponded to the G2 and/or G3 levels defined in ISA S71.04-1985. The chemical composition of the copper sulfide creep indicates that it consisted of copper, oxygen, and sulfur. Cross-sectional observation and elemental mapping analysis showed that Cu_2S creep initiated not at the edge of the organic coating (organic solder preservative, OSP) inside the vias but mainly at defects in the organic coating covering the copper.

1. Introduction

Copper sulfide (Cu_2S) creep is a common phenomenon and a major cause of IT equipment failure [1]. Frant investigated Cu_2S creep on tin (Sn) electroplated over copper and showed that Cu_2S film can grow on a variety of metals and even on nonmetals [2]. The simultaneous diffusion of sulfur and copper could account for the growth of Cu_2S creep.

Gold-plated copper or a copper alloy had been conventionally used to apply electrical contacts while a gold–nickel–copper is now commonly used. The latter is called ENIG in the field of electrical contacts. When the electrical contacts having either of these gold-plated structures with exposed copper areas are exposed in an atmosphere containing reduced sulfur such as hydrogen sulfide (H_2S), migration of Cu_2S over the gold can be observed. Tierney investigated the creepage of copper sulfide over gold in flowers of sulfur and H_2S [3]. He showed that the creepage first exhibited parabolic behavior and then reached a certain extent. Enos exposed a gold-plated copper and a gold-plated-copper-with-nickel underplate to a Battelle Class 2 environment and evaluated the role of the underplates [4].

The corrosivity of the atmospheres where our telecommunication equipment is installed varies remarkably. It is generally benign, but sometime it is harsh, such as in areas with hot springs containing H_2S. A previous field study revealed that H_2S can accelerate atmospheric copper corrosion significantly even if the average H_2S concentration is as low as 13 ppb [5,6].

We recently experienced the failure of the main telephone system in a marine products factory. The system comprised a central unit and multiple terminals. Four terminals and the central unit failed within two years of installation. Visual observation revealed Cu_2S creep in the vias in the printed circuit boards (PCBs) in the terminals and central unit. The vias were not plated by gold or

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gold/nickel but were covered by a thin organic coating, i.e., organic solder preservative (OSP). In this paper, we describe this failure case and present the results of our observation and analysis of the observed Cu_2S creep.

2. Material and methods

2.1. Measurement of H_2S concentration

An H_2S analyzer (Jerome J-605, Arizona Instrument Corporation) was used to measure the H_2S concentrations. Its detection range is 0.003 to 10 ppm, and it was calibrated before measurement. We measured the H_2S concentrations at the four indoor sites where the terminals and central unit failed, near to where the terminals and central unit were located. The outdoor H_2S concentrations were also measured for comparison. Three measurements were made at each site in the morning and again in the afternoon in mid-February.

2.2. Preparation of cross-section samples

Cross-section samples were prepared by cutting a failed PCB into sections with a sawing machine. Each section was placed in a small circular plastic container with a diameter of 21 mm, and the container was then filled with epoxy resin. After the resin had solidified, the container was polished using sandpaper (#320) and then two grades of diamond paste (9 and then 3 μm) to make the cross-section samples.

2.3. Observation and analysis

We used a VHX-1000 digital microscope (Keyence Corp.) and a Miniscope TM 3030 (Hitachi High Technologies) for observation. The latter, a scanning electron microscope (SEM), is equipped with an energy dispersive spectroscopy (EDS) system (Quantax 70, Bruker AXS K.K), which was used to perform qualitative and semiquantitative elemental analyses.

3. Results and discussion

3.1. H_2S concentrations

Table 1 summarizes the measured H_2S concentrations. The concentration indoors (except for the storage room) were higher than those outdoors. The highest concentration, 11 ppb, was observed in an office room on the first floor. These measurements indicate that there was a H_2S source in the factory. A previous study found that H_2S was formed by the reaction between organic compounds and sulfate ions in the drainage water of a marine product factory with the aid of sulfate-reducing bacteria under anaerobic conditions [7]. The indoor H_2S concentrations correspond to level G2 and/or G3 as defined in ISA S71.04-1985 [8], levels at which electronic components can be corroded. Although we did not measure the H_2S concentrations during other seasons, such as the summer, they are likely to become higher in the summer, and higher H_2S concentrations possibly accelerate Cu_2S creep on PCBs.

3.2. Copper sulfide creep

Fig. 1 shows an image of a PCB removed from a failed terminal. Copper sulfide creep was observed over part of the surface area. There were two severely corroded areas, which are labeled A and B. Fig. 2 shows higher magnification images of these areas: images (a) and (c) show the Cu_2S creep in areas A and B, respectively, and images (b) and (d) show the details of the areas marked in (a) and (c), respectively.

As shown in Fig. 2(a), the Cu_2S creep areas grew and overlapped each other. Assuming that the creep started at the inner edge of the via, the creepage distance was more than 500 μm. Given that the failure occurred about two years after installation, we calculated the creepage rate to be about 0.7 μm/day. Tierney reported a creepage rate of about 49 μm/day when a 3-μm-thick gold layer deposited on 10-μm-thick copper film was exposed in 4-ppm H_2S for 49 h [3]. While our calculated creepage rate was two orders of magnitude lower than that calculated from reported data, the low H_2S concentrations in the marine product factory undoubtly affected the reliability of the PCBs and caused the failures that occurred within two years of installation. It is worth noting that the via located at the bottom right in Fig. 2(b) had a metallic luster of copper. This could have been due to the absence of defects in the OSP. The Cu_2S creep

Table 1
Measured H_2S concentrations (ppb).

Site	Morning	Afternoon	Sampling height (m)
Office room (1st floor)	5 to 9	8 to 11	2.3
Storage room (1st floor)	<3	<3	0.8
Office room (2nd floor)	6 to 7	4 to 6	0.8
Dining room (2nd floor)	<3	4	1.4
Outdoors	Not measured	3 to 4	1.0