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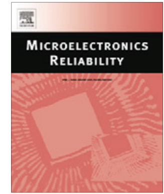

Review

# No-fault-found and intermittent failures in electronic products

Haiyu Qi *, Sanka Ganesan [1], Michael Pecht

*CALCE Electronic Products and Systems, University of Maryland, College Park, MD 20742, United States*

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A B S T R A C T

This paper reviews the possible causes and effects for no-fault-found observations and intermittent failures in electronic products and summarizes them into cause and effect diagrams. Several types of intermittent hardware failures of electronic assemblies are investigated, and their characteristics and mechanisms are explored. One solder joint intermittent failure case study is presented. The paper then discusses when no-fault-found observations should be considered as failures. Guidelines for assessment of intermittent failures are then provided in the discussion and conclusions.

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## 1. Introduction

A failure in a product occurs when it no longer performs its intended function. An intermittent failure is the loss of some function or performance characteristic in a product for a limited period of time and subsequent recovery of the function [1,2]. The "failure" of the product may not be easily predicted, nor is it necessarily repeatable. However, an intermittent failure can be, and often is, recurrent.

Intermittent failures can be a cause of no-fault-found (NFF) occurrences in electronic products and systems. NFF implies that a failure (fault) occurred or was reported to have occurred during a product's use. The product was analyzed or tested to confirm the failure, but "a failure or fault" could be not found. A common example of the NFF phenomenon occurs when your computer "hangs up". Clearly a "failure" has occurred. However, if the computer is rebooted, it often works again.

* Corresponding author.
*E-mail address:* haiyuqi@yahoo.com (H. Qi).
[1] Intel Corporation, Chandler, AZ 85226, United States.

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Terms related to NFF include trouble-not-identified (TNI), cannot duplicate (CND), no-trouble-found (NTF), and retest OK (RTOK) [1–7]. The commonality of these terms is that a failure may have occurred but cannot be verified, replicated at will, or attributed to a specific root cause, failure site, or failure mode. In this paper, we will use the generic term NFF.

The impact of NFF and intermittent failures can be profound. Due to their characteristics, manufacturers may assume a cause(s) rather than spend the time and cost to determine a root-cause. For example, a hard drive supplier claimed NFFs were not failures and allowed all NFF products to be return back into the field. Later it was determined that these products had a significantly higher return rate, suggesting that the NFF condition was actually a result of intermittent failures in the product. The result was increased maintenance costs, decreased equipment availability, increased customer inconvenience, reduced customer confidence, damaged company reputation, and in some cases potential safety hazards.

NFF and intermittent failures have been reported in the automotive, avionics and telecommunications, computer and consumer industries where they represent a significant percentage of reported warranty returns and field returns [8], resulting in significant costs. The percentage of NFF and intermittent failures varies with the industry and products. For example, Sorensen [9] stated the occurrence of intermittent and NFF failures on military aircraft can be as high as 50% percentage based on information from Defense Electronics Magazine (see Fig. 1).

An avionics field failure study, conducted in 1990, showed that NFF observations of electronics in avionics systems represented 21–70% of the total failures depending on the application [5]. NFF observations reported by commercial airlines and military repair depots have been found to be as high as 50–60 percent [7].

Ford's thick film ignition (TFI) module may well be the most widespread intermittent failure condition ever reported. The failed TFI module could cause the vehicle to stall and "die" on the highway at any time [10]. However, the failed ignition modules often passed the required engineering tests established to reflect the design intent. In October 2001, Ford agreed to the largest automotive class-action settlement in history, promising to reimburse drivers for the TFI that could cause their cars to stall [10].

Kimseng et al. [4] studied an intermittent failure in digital electronic cruise control modules (CCM) used in automobiles. This intermittent was corroborated by the fact that 96% of the modulus returned to the vehicle manufacturer due to customer complaints, operated properly and passed the bench tests. Kimseng concluded that the tests conducted by the vehicle manufacturer on returned products were not representative of the actual automotive environments, nor were they conducted in a manner to assess actual failures. This inappropriate testing may also lead to the high percentage of NFF.

Although NFF and intermittent failures have been widely observed in electronic products and reported in field and laboratory tests, few systematic analyses have been performed to study the intermittent nature of the failures. This paper analyzes the possible causes and effects for NFF observations and intermittent failures in electronic products and assemblies using the cause-and-effect diagram approach. Several types of intermittent hardware failures on electronic assemblies are investigated, and their mechanisms and characteristics are analyzed. The paper then discusses when NFF observations should be considered as failures.

## 2. An approach to assess NFF

To evaluate the possible causes of NFF and intermittent failures in an electronic product, a systematic method is required. As a first step, we employ a cause and effect diagram (also called an Ishikawa diagram or fishbone diagram) [11] to identify, explore, and display the relationships between an effect and its potential causes.

Fig. 2 is a fishbone diagram for NFF in electronic products. The general causes of NFF can be categorized into people (human), machine, methods, and intermittent failures. In each category, the causes are further broken down into sub-categories. For example, people causes are sub-divided into communication, skills and behavior. Machine causes are sub-divided into measurement tools and test equipments. Methods causes are sub-divided into test methods, handling methods and failure analysis methods. Intermittent failure causes are grouped under five categories: printed circuit boards (PCB), components, interconnects, connectors and software. There may be other categories and sub-categories based on the specific product and its life cycle profile.

### 2.1. People category

Lack of skills or proper behavior of engineers, maintenance personnel and technicians can contribute to NFF. For example, "sneak circuits" are well-known electrical design causes of latent failures. A sneak circuit is an unexpected path or logic flow within a system which, under certain unique conditions, can initiate an undesired function or inhibit a desired function. The path may arise from hardware, software, operator actions, or combinations of these elements. Sneak circuits are not the result of hardware failure but are latent conditions, inadvertently designed into the system, coded into the software program, or triggered by human error. These conditions generally require rigorous system-level tests to uncover [12].

Communications can also precipitate NFF observations. For example, consider the customer of a car which experiences an

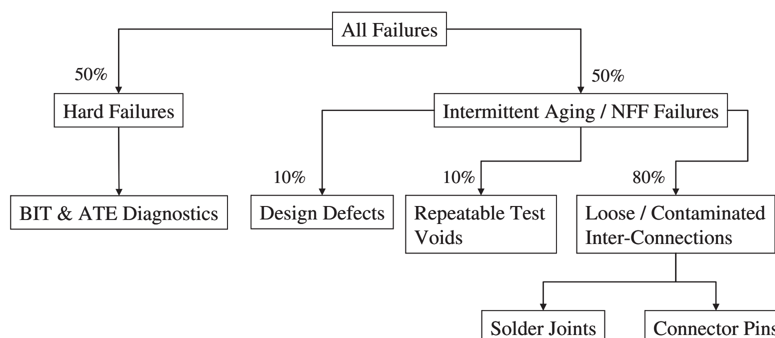


**Fig. 1.** Hard failures and NFF failures on military aircraft [9].

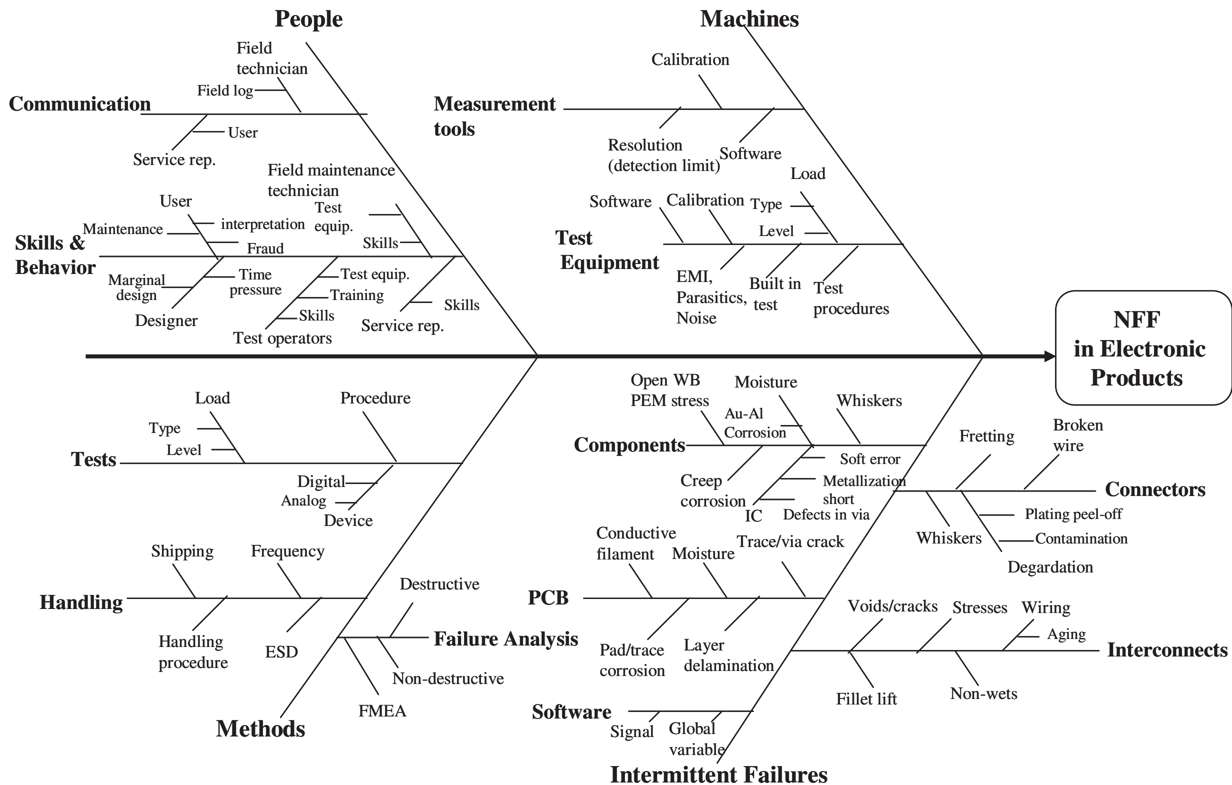


**Fig. 2.** An example cause and effect diagram for No-Fault-Found (NFF) conditions in electronic products.

intermittent failure. The customer reports this problem to the service depot, where the service clerk documents the problem in a service request. At this step alone, people's ability to communicate, understand and summarize the problem as well as the condition leading to the problem, play a key role in its correct documentation of the problem. This includes the ability of the customer to clearly explain the problem, the service clerk's ability to understand the customer's problem, and the service clerk's ability to document the problem correctly. Without correct problem identification, the service technician could come to the erroneous conclusion of NFF, even if the problem actually exists.

NFF observations can also occur by people driven by warranty or insurance claims, who replace multiple items to repair one fault or resort to fraudulent reporting of a problem which never occurred. For example, AAA stated "At least 10 percent of all reported claims are fraudulent in some way, according to industry reports" [13]. In some cases, car dealers may replace multiple sub-systems under warranty to find a problem. Those sub-systems which were removed but had not failed, will be identified as NFF when tested.

### 2.2. Machine category

The limitations of test equipment and measurement tools can lead to the conclusion of NFF. For example, limits on measurement resolutions and measurement intervals can result in the inability to detect intermittent failures. In addition, the incapability of test equipment to simulate the actual loading conditions (e.g., vibrations, temperatures, human operations, etc.) exhibited in the field can also contribute the NFF conclusion.

The regular and proper calibration on equipments is also the key to avoid NFF conclusions. Without accurate, capable and reliable test equipment and measurement tools, the failed products from the field may pass bench tests.

### 2.3. Method category

An inadequate or improper test procedure may lead to NFF. For example, complex products such as microprocessors may not be 100% testable if the allowable test time is too short. In addition, if the combinations of diagnostic test conditions (e.g., temperature, humidity, vibration) are different from the field conditions where failure occurred, the failure may not be duplicated. A failure can occur due to a unique combination of loading conditions. Thus diagnostic tests may require the combined loading conditions that can occur in the field.

Properly handling the returned electronic hardware is also a key to detect NFF conditions. Handling methods should follow the established procedures in preventing uncontrolled effects. For example, anti-electrostatic discharge (ESD) packages are required for ESD sensitive products. To prevent deformation due to handling, the vibration environment should be well controlled. Clean room storage may be also necessary for debris sensitive products. Improper handling can both "heal" some failure mechanisms or induce problems that can mask the real problem reported in the field.

The failure analysis methods also play a key role in the verification of failure. Failure analysis should include non-destructive methods followed by destructive analysis as needed. Before embarking on failure analysis, it is good practice to develop a failure modes, mechanisms and effects analysis (FMMEA) document [14,15]. Incomplete or insufficient failure analysis can lead to erroneous conclusions.

### 2.4. Intermittent failure category

Intermittent failure is one of the main causes of NFF. Intermittent failures in products can be caused by software or hardware.

For example, if a global variable is read and rewritten over another global variable, a miscalculation can arise and lead to product fail [16]. However, when the global variables are reset, perhaps upon rebooting the computer, the product can return to normal function.

Intermittent failures of hardware, e.g., electronic assemblies, can be divided into four categories: printed circuit board, components, connectors, and interconnects. In each category, the causes can be furthered sub-divided as shown in Fig. 2. The key causes are discussed in the next section.

## 3. An approach to assess intermittent failure

To evaluate the possible causes of intermittent failures in an electronic assembly, a cause and effect diagram was developed in this study (see Fig. 3). The major causes are categorized into printed circuit board (PCB), components, connectors and component-PCB interconnects. Some examples of failure mechanisms observed in the field and laboratory tests for each category of intermittent failures are presented.

### 3.1. Printed circuit board category

There are many failure mechanisms that can cause intermittent failures of a printed circuit board (PCB). For example, PCB warpage due to temperature may cause intermittent electrical opens on copper traces. Moisture and contamination can lead to electrochemical migration on a PCB and cause intermittent shorts or leakage current between adjacent traces. Via cracking due to environmental stress or manufacturing method can also contribute to intermittent failures. Under vibration and convection air flow conditions, whiskers may separate from an original source and migrate to and bridge traces, which cause intermittent shorts on PCB. Some specific examples are given below.

#### 3.1.1. Via plating separation and open trace

A via is a structural feature created during multi-layer PCB fabrication to provide electrical connection between circuit board layers. A via can be created by mechanical drilling, laser drilling or using a photolithographic process. Electrical connection is usually achieved by plating the via structure during PCB fabrication.

An example of intermittent failure in printed circuit board (PCB) due to via cracking on a computer graphics board can be found in [17]. Cross sectioning of the suspected vias in the PCB revealed a plating separation at the base of the via. The separation of via plating can occur due to many causes that include non-uniform plating, surface contamination on the base pad and large mismatch in thermal expansion coefficient between the plating material and the resin surrounding it. Under the field operation conditions, via separation may close due to external forces, such as the compressive stress on the board, which lead to electrical connection intermittents.

Fig. 4 shows a trace that has progressed to an open. However, prior to this, it exhibited intermittent separation dependent on the thermal condition of the PCB due to the differences in the thermal expansion of the board and copper materials and manifested itself as an intermittent failure mode at different intervals during the thermal cycling in the field.

#### 3.1.2. Electrochemical migration

Electrochemical migration (ECM) is a possible cause for intermittent failure in PCBs. Electrochemical migration is the growth of electrically conductive filaments in a PCB under the influence of a voltage bias. For example, surface dendrites have been observed to form between adjacent traces in the PCB under an applied voltage when surface contaminants and moisture are present (see Fig. 5 [18,19]). These filaments are fragile and may be destroyed by oxidation, changes in surface tension during moisture absorption, drying, cooling or heating, or burned if the current

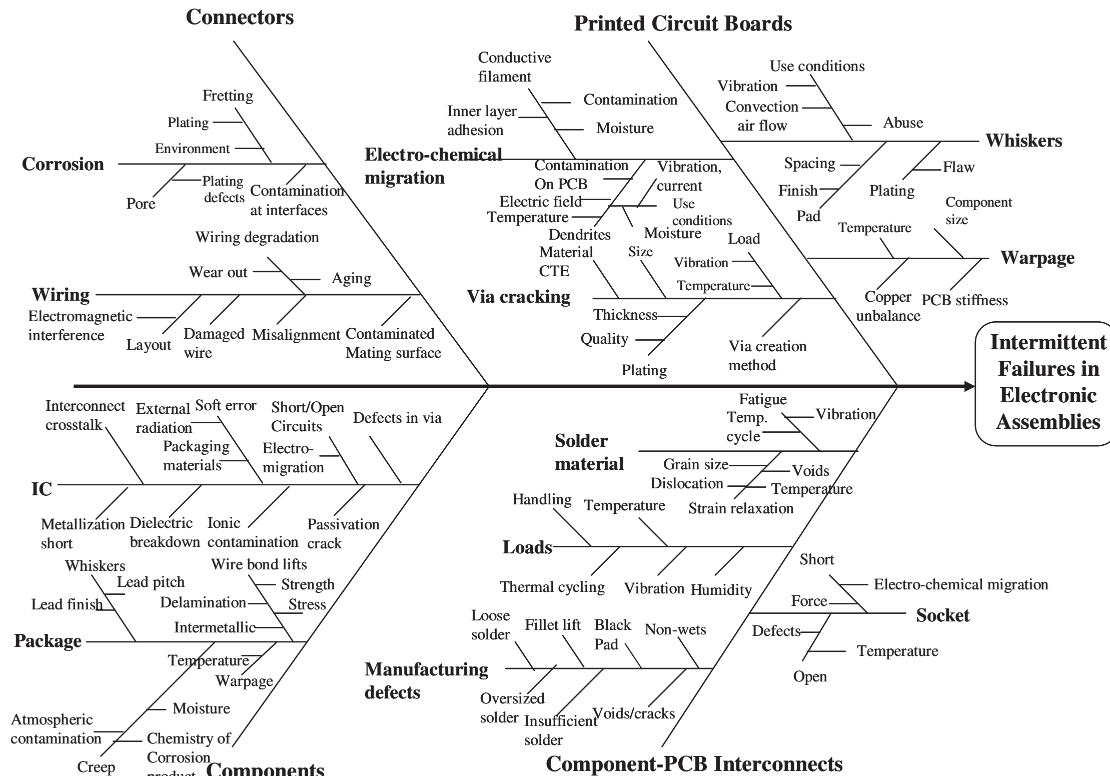


**Fig. 3.** An example cause-and-effect diagram of intermittent failures in electronic assemblies.

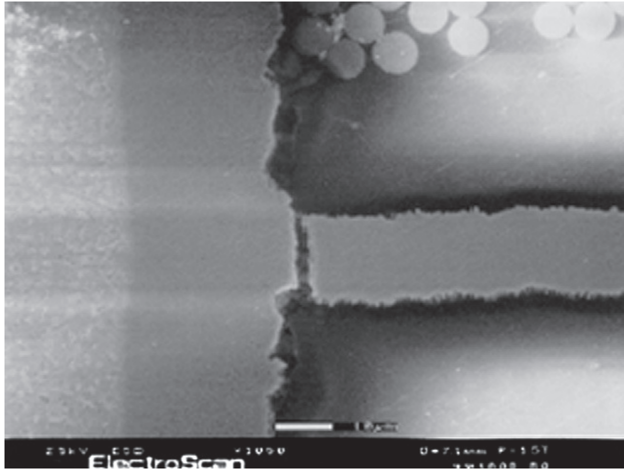

**Fig. 4.** Open trace on a PCB.

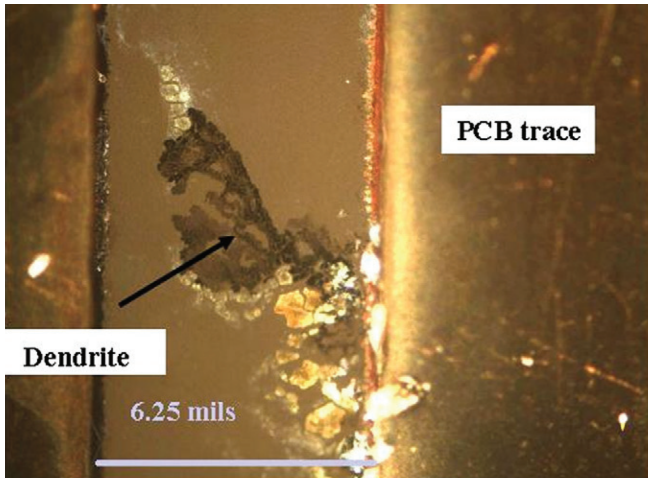


**Fig. 5.** Dendritic growth between adjacent traces on a PCB [19].

is sufficient. As of result, leakage short circuits created by dendrites tend to be intermittent.

Another form of electrochemical migration is conductive filament formation (CFF), also referred to as conductive anodic filament (CAF) formation (see Fig. 6). This phenomenon occurs internally to the PCB, not on the surface. In CFF, the filament is composed of metallic salt, not neutral metal atoms as is typical of dendritic growth. The conductive filament can bridge two conductors and lead to intermittent electrical short and then burn out due to a high current density in the filament (similar to a fuse). The conductive filament can then reform again. These intermittent phenomena tend to be diagnosed as no fault found (NFF) or cannot duplicate (CND) failures [20–22].

*3.1.3. Black pad phenomena*

Printed circuit boards with electroless nickel/immersion gold (ENIG) finish are used throughout the electronics industry for surface mount and wave soldering operations. Composition uniformity, corrosion resistance, multi-functionality (for example, wire bonding to PCB pad) and good solderability make electroless nickel (EN) a very useful diffusion barrier between copper (Cu) substrate surfaces and coatings such as gold (Au), tin (Sn) and tin-lead (Sn/Pb) [23].

ENIG pad finish involves the deposition of Au over Ni layer on the copper pad of a PCB. In the plating process phosphorus is present as a reducing agent in the plating bath and deposited as a Ni-P layer. During soldering, Au dissolves in the solder and the solder interacts with underlying Ni-P layer. The interaction results in the formation of $Ni_3Sn_4$ intermetallics and a phosphorus rich layer which segregates at the interface between $Ni_3Sn_4$ and the Ni-P layer. This phosphorus segregation is characterized as a gray to black area and named as 'Black Pad'. Fig. 7 shows the presence of the black pad observed along a $Ni_3Sn_4$ and EN coating. The Black Pad defect can cause brittle fracture at the interface between the solder and metal pad. Therefore, the 'Black Pad' phenomenon is coupled with either poor solderability or solder connection that leads to electrical continuity failures where stresses are induced by thermal and mechanical excursions [24,25]. The failure typically occurs during mechanical or thermal-mechanical testing. The worst cases are BGA package solder joint failure during a customer's surface mount assembly process, or in the product's final use by a consumer.

For example, Bulwith et. al. [26] diagnosed numerous Ball Grid Array (BGA) packages with ENIG finishes. The results showed the

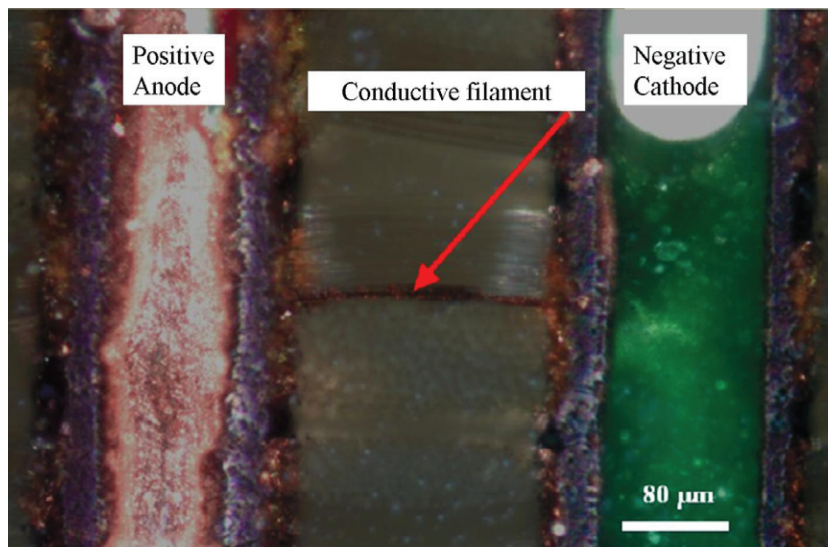


**Fig. 6.** Optical image of a conductive filament bridging two plated through holes in a PCB [20].

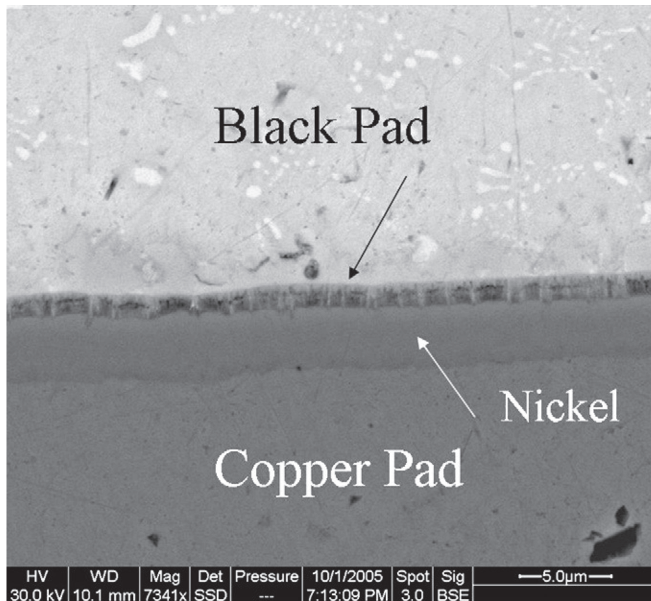


**Fig. 7.** Thin black layer observed at the interfaces between the Ni–Sn IMC reaction layer and the EN coating.

packages associated with 'Black Pad' can be returned as 'field failures' with 'intermittent' signatures.

The root cause for the black pad defect of the ENIG plating has been discussed in the literature and several models were well summarized by Zeng's study [27]. Experimental results confirmed that black pad defect is the result of galvanic hyper-corrosion of the Ni(P) plating by the immersion gold bath. The immersion gold process is a controlled corrosion (displacement) process during which nickel atoms on the surface of the Ni(P) plating are replaced by gold atoms. Theoretically, it is a self-limiting process because once the surface of the Ni(P) plating is covered by the gold, the displacement reaction stops. However, if the process is out of control, hyperactive corrosion may happen. For instance, due to the nodular structure of the surface of the electroless Ni(P) plating, there are boundaries and crevices between the nodules. If a boundary or crevice is too deep and thus the supply of gold atoms to the crevice is slowed down, the gold concentration in the crevice will be different from that of the plating bath. Consequently, a galvanic cell will be set up between the crevice and the surface, resulting in heavy corrosion in the crevice. Another factor to the process is the reducing agent, which can be added to immersion gold baths to deposit the gold more quickly. A poor choice of or poor control of these reducing agents may produce the inconsistent nature of the black pad defect (i.e., not every pad on a substrate shows the same degree of defects). The boundary between the two nodules is voided and its opening to the surface is very narrow. The consumed gold of the plating solution in the void cannot be replenished quickly. The concentration difference leads to galvanic corrosion of the Ni(P) plating around the void. The corrosion converts the dense, amorphous Ni(P) into a porous, micro-crystallized structure into which the gold atoms have penetrated. The rinsing process after plating could not effectively remove the residual plating solution since the plating solution was trapped in it due to the depth of the void and the near-closure of its opening to the surface. Therefore, corrosion would continue until the residual solution was exhausted. Interfacial failure of solder joints with the ENIG plating is the combined effect of hyper-galvanic corrosion of the electroless nickel during gold plating and Kirkendall voiding in the Ni3SnP layer after reflow. To avoid the black pad failure of solder joints, the key is to avoid hyper-galvanic corrosion of the electroless nickel plating during the immersion gold plating process.

### 3.2. Connector category

Connectors and other contacts can cause intermittent failures. A common example is a TV remote control. Sometimes the remote control doesn't work, but after you hit it several times, it works properly again. The problem is often a bad connection between the batteries and the contact. The bad connection can be caused by chemical factors (e.g., an oxidation layer on the battery ends) or mechanical factors (e.g., improper positioning of the batteries). By hitting the remote control, the battery position is changed to displace the oxide layer or reseat the batteries correctly.

Another example of intermittent failures of connectors is the fretting corrosion phenomena. Fretting corrosion is known to occur with tin plated contacts and can lead to short duration (intermittent) electrical discontinuities. This is caused by micro-motion between contacting surfaces due to vibration or temperature excursions [28–32]. Tin can rapidly form a thin, hard oxide. The sliding movements between contact surfaces break the tin oxide film on the surface and expose the fresh tin to oxidation and corrosion. The accumulation of oxides at the contacting interface, due to repetitive sliding movements causes an increase in contact resistance and electrical intermittents. Fig. 8 shows the schematic representation of fretting corrosion [33].

### 3.3. Component-PCB interconnects category

The general types of interconnect between component and PCB include solder joints and sockets. Both can experience intermittent opens due to manufacturing defects.

An example of intermittent failures of solder joints, occurred with a telecommunications OEM who reported intermittent failures on a BGA device. X-ray inspection of intermittent devices showed that the solder joints were extensively deformed. The deformation was traced to the technicians who were applying excessive pressure to the BGA devices [17]. The excessive deforma-

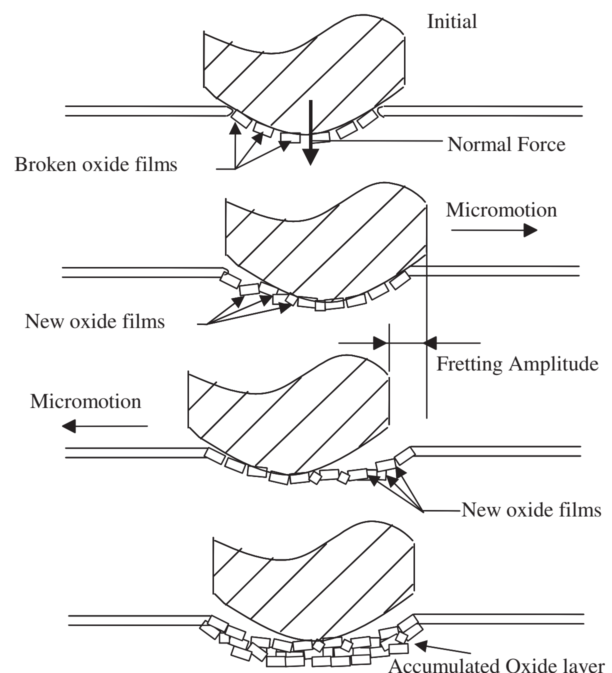


**Fig. 8.** Schematic of fretting corrosion [32].

tion of solder joints can reduce the distance between adjacent solder joints which can result in intermittent shorts (when adjacent joints are barely touching each other) and or signal deterioration. Fig. 9 shows a typical crack on the solder joint of a BGA. Under thermal cycling or vibration environment loading conditions, the electrical continuity will exhibit intermittent behavior.

Localized board flexure can also crack solder joints and result in intermittent failure behavior [34]. In fact, it is possible for strain relaxation to occur in solder materials due to the changes in visco-plastic solder micro-structure at ambient temperature. The solder alloys exhibit high homologous temperature (ratio of the solder temperature to the melting temperature of solder alloy, in which temperature is expressed in Kelvin) of ∼0.65 at ambient temperature. At this homologous temperature, there is sufficient thermal energy available for annihilation of dislocations and recovery of strains in the polycrystalline solder material. This phenomenon can lead to the opposing cracked surfaces to be in direct contact with each other and therefore manifest as intermittent failures of solder joints.

### 3.4. Components category

Intermittent failures on components can be exhibited by improper function, intermittent loss of signal integrity, data error, etc.

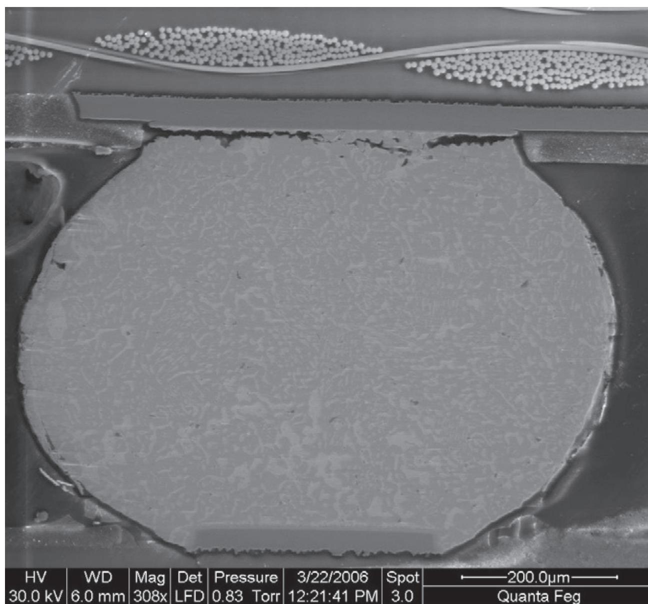


**Fig. 9.** SEM picture of the BGA solder joint shows cracks on the top with some connection.

The failure can occur at either the integrated circuit (IC) level or package level. For example, interconnect crosstalk, poor inner connections and external radiation can contribute to intermittent failures on ICs. Corrosion of I/Os, shorts between leads due to whiskers, and package warpage can also lead to intermittent failures of IC packages.

The following section discusses several different component level failure mechanisms. Examples of intermittent component failures are given.

#### 3.4.1. Creep corrosion

Creep corrosion is a mass transport process in which solid corrosion products migrate over a surface [35]. On integrated circuit (IC) packages, creep corrosion can eventually result in electrical shorts or signal deterioration due to the bridging of corrosion products between isolated leads. Depending on the nature of corrosion products (conductive or semi-conductive, dry or wet), the insulation resistance can vary, thus potentially causing intermittent loss of signal integrity.

Fig. 10 shows an example of field failure due to creep corrosion in a telecommunication electronics device [35]. This is a component with a palladium pre-plated leadframe. This photo highlights the conductive material growth onto the molding compound surface of the plastic package. Due to the application of the noble metal (usually Ni–Pd–Au plating over copper lead frame) pre-plated leadframe in IC packaging, the long-term field reliability may be a concern. In the standard packaging process for plastic components, the "trim and form" process after encapsulation can expose the leadframe material on the leads. When the component operates in a harsh environment, the corrosion process can start from the exposed metal area and spread. Because palladium and gold are noble metals and do not corrode in ambient environments, the plating of palladium-gold provides a surface for the movement of copper corrosion products. Under such circumstances, the corrosion products can move over the lead and gradually migrate up onto the molding surface of the package. When corrosion products from the adjacent leads merge together, intermittent electrical short or signal deterioration on the component [35] can occur depending upon the conductivity of the corrosion products.

#### 3.4.2. Tin whiskers

The use of pure tin finishes is considered as an economical lead-free plating option due to the drive to eliminate lead from electronics. On the other hand, new electronic systems may be at risk due to the introduction of parts with pure tin finishes. This risk is related to tin whiskers growth and has been identified or highly suspected in the costly failure of a number of electronic systems [36]. Although new plating processes have been developed that appear to reduce the risk of tin whisker growth, there is currently no

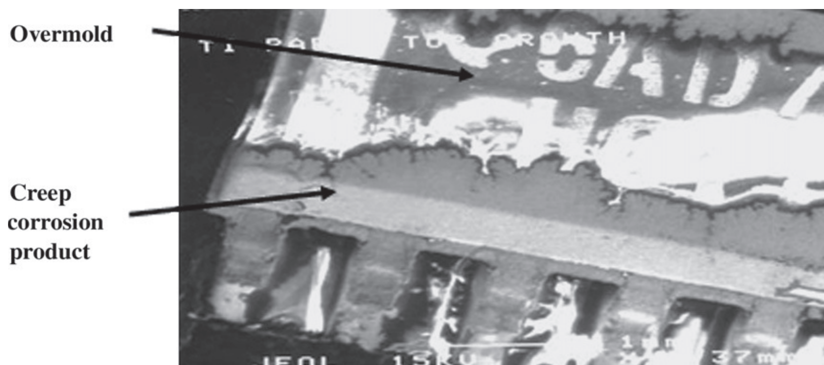


**Fig. 10.** Field failure due to creep corrosion [35].

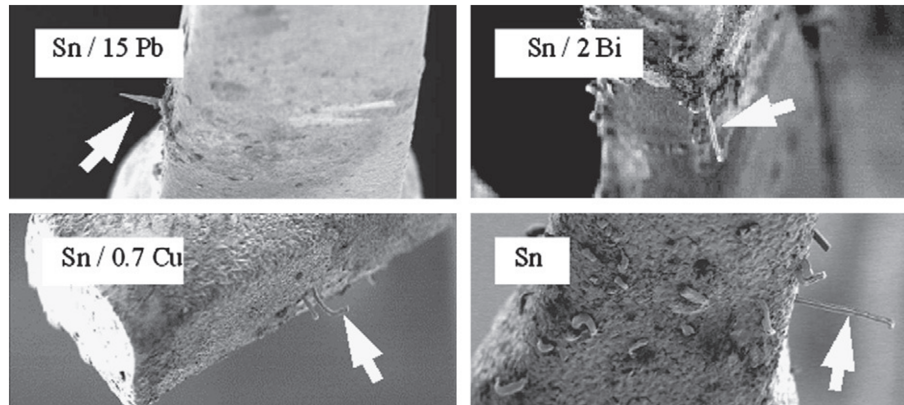


**Fig. 11.** Photograph showing tin whiskers in various lead-free alloys (Courtesy of Motorola).

industry-accepted test for determining the propensity of tin whiskers to grow on a finished surface.

Whiskers are elongated single crystals of pure tin that have been reported to grow to more than 10 mm (250 mils) in length (though they are more typically 1 mm or less) and from 0.3 to 10 μm in diameter (typically 1–3 μm). Whiskers grow spontaneously without an applied electric field or moisture (unlike dendrites) and independent of atmospheric pressure (they grow in vacuum). Whiskers may be straight, kinked, hooked, or forked and some are reported to be hollow. Their outer surfaces are usually striated. Whiskers can grow in non-filament type which are sometimes called lumps or flowers. Whisker growth may begin soon after plating. However, initiation of growth may also take years. The unpredictable nature of whisker incubation and subsequent growth is of particular concern to systems requiring long term, reliable operation. Whiskers occur in many plating metallurgies [37], as shown in Fig. 11.

Though the tin whiskers grow mechanism(s) has been studied for many years, no single, widely accepted explanation of this mechanism has been established. There are some commonly agreed factors involved in tin whisker formation. Tin whisker growth is primarily attributed to stresses in the tin plating [38]. These stresses may be from many sources, including:

- Residual stresses in the tin resulting from the plating process. Electrodeposited finishes are considered most susceptible, due to stresses built into the finish as a result of the plating process.

**Fig. 12.** Failed relay due to tin vapor arcing.

- Formation of intermetallic compounds (e.g., $Cu_6Sn_5$), especially within the tin grain boundaries.
- Compressive stresses, such as those introduced by torquing of a nut or a screw.
- Bending or stretching of the surface after plating.
- Scratches or nicks in the plating introduced by handling.
- Coefficient of thermal expansion mismatch between the plating material and substrate.
- Bright tin finishes (shiny) seem to be worse than matte finishes due to the influence of the organic compounds used as brighteners and/or their smaller grain-size structure.

Tin whiskers pose a serious reliability risk to electronic assemblies that are specific to the product that incorporates pure tin plating. The general risks fall into four categories [39]:

- *Stable short circuits in low voltage, high impedance circuits*: In such circuits there may be insufficient current available to fuse the whisker open and a stable short circuit results. Depending on a variety of factors, including the diameter and length of the whisker, it can take more than 50 milliamps (mA) to fuse open a tin whisker.
- *Transient short circuits:* At atmospheric pressure, if the available current exceeds the fusing current of the whisker, the circuit may only experience a transient glitch as the whisker fuses open.
- *Metal vapor arcing (plasma) in vacuum:* In vacuum a much more destructive phenomenon can occur. If currents of above a few amps are available and the supply voltage is above approximately 12 V, the whisker will fuse open but the vaporized tin may initiate plasma that can conduct over 200 amps. An adequate supply of tin from the surrounding plated surface can help to sustain the arc until the available tin is consumed or the supply current is interrupted.
- *Debris/Contamination:* Whiskers or parts of whiskers may break loose and bridge isolated conductors remote from the original site of whisker growth. In addition, whisker debris may interfere with optical surfaces or the smooth operation of micro-electro-mechanical structures (MEMS).

Fig. 12 shows a relay which failed due to tin vapor arcing. Failure analysis concluded that tin whiskers initiated the current surge to the ground. Once a whisker bridged a terminal stud to the armature, plasma arcing could occur with enough voltage and current to damage the relay or just cause an intermittent short [40]. Fig. 13 shows whiskers on the armature of a relay.

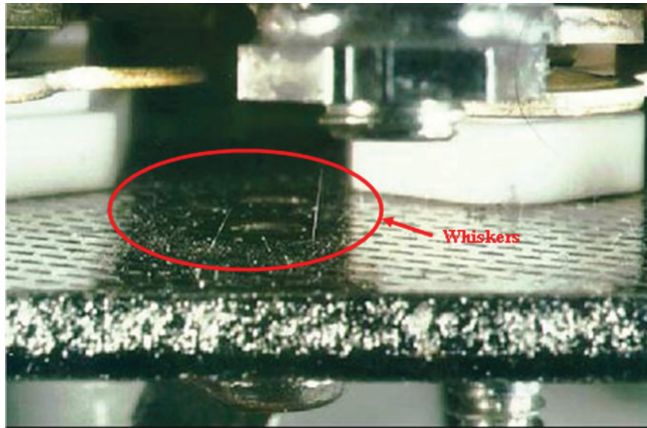


**Fig. 13.** Shapes of tin whiskers observed on tin plated electronic parts (Photo courtesy: Northrop Grumman).

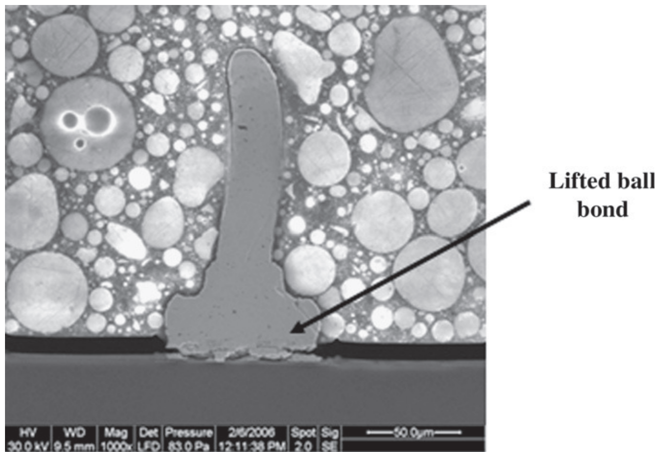


**Fig. 14.** SEM picture shows a lifted ball bonds on a semiconductor device.

Whiskers are also fragile and hence they can be broken off from the growth site due to vibrations or convective air flow present in the electronics enclosures. These broken whiskers can fall between fine pitch terminals potentially causing intermittent shorts or intermittent degradation in the electrical signal integrity [41]. These field failures are difficult to duplicate because disassembly or handling may dislodge a failure-producing whisker [42].

### 3.4.3. Wire bond lifts

Wire bond lifts occur when a wire bond separates from the bonding pad on the die. Wire bond strength is dependent on many factors, including wire bond process parameters (bonding force, temperature, ultrasonic energy, and bonding time) and contamination (both organic and inorganic) present on the bond pad. Thermo-mechanical stresses due to temperature cycling can lift the wire bonds from the bond pad if the silicon die-mold compound interface was delaminated. This is because the entire cyclic load is being supported by wire bonds. In surface mount plastic encapsulated devices, the delamination between die surface and encapsulant during reflow can shear the wire bonds from the pad. Fig. 14 shows an example of a lifted bond.

Oldervoll et. al. [43] confirmed standard plastic encapsulated components has a poor high-temperature reliability due to wire-bond lift issue. Microcracking occurred at the interface between gold ball and aluminium bond pad and gave rise to resistance increase. The intermetallic growth was initiated already in the soldering process and developed further during the three weeks ageing period. At lower temperatures the degradation will evolve at a slower rate, but the results shows that standard PEMs are not suitable solution in the high-temperature range ($T \geqslant 150\,^{\circ}\mathrm{C}$) when long-term reliability is required.

This wire bond lift-off is also one of main failures which are observed in power module [44,45]. Wire bond connections are susceptible to fatigue as a result of thermomechanical damage mechanism which is due to the large thermal expansion coefficient mismatch between the aluminum wires and the silicon chips during power operation. Ramminger et al. [46] presents their study on the bond wire lift-off. A crack is observed between the wire and the metallization. The highest thermomechanical stress occurs at the wire terminations, where the wire is unable to flex. Consequently, the typical failure sites are the heel and the tail of a wedge bond. The wire is unable to accommodate the locally caused strain at this place and a crack is initiated. During the bonding process, the wire material is strongly deformed and small grains are built in the interface region during the following system soldering process. The grain size in the wire center is much larger than in the welded zone. There are mainly two areas of different grain sizes. Under thermomechanical stress, cracks grow from the heel and the tail along the boundary of fine and coarse aluminum grains into the welded interface [47].

The lifted wire bonds can exhibit of electrically open or short intermittent conditions. For example, swelling of mold compound at the delaminated chip-mold compound interface due to moisture absorption can cause an electrically open condition. On the other hand, the compressive stress generated in the mold compound at ambient temperatures far lower than the zero stress state molding process temperature ($\sim$175 °C) can keep the lifted bond in place to show a ‘‘closed” condition. This application environment dependent behavior can lead to component level intermittent failures and also mask the failure mechanism.

### 3.4.4. Single event upset

Single event upset (SEU) is a potential cause for intermittent failures. SEU is a change of state or a transient caused by ionizing radiation in semiconductor devices. Especially memory cells in semiconductor devices are affected by this phenomenon. Two types of radiation have been the cause of SEU in semiconductor devices: alpha particle radiation and cosmic ray radiation. The source of alpha particles is from the package materials (e.g., filler particles in mold compounds, lead in the solders). Studies conducted over the last 20 years have led to solutions minimizing SEU problems caused by alpha particle radiation. Unavoidable atmospheric neutrons from cosmic rays remain the primary cause for SEU problems today.

SEU is caused by the interaction between the ionizing radiation and the device. This interaction generates electron-hole pairs. As the radiation passes through the device, electrons are dislodged from the crystal lattice sites along the track of the particle. The number of electron-hole pairs generated depends on the energy of the radiation and the density of the material. The amount of energy required to produce an electron-hole pair in silicon is 3.6 eV [48]. If the total number of generated electrons collected by a data storage cell exceeds the number of electrons that differentiate between a ‘‘one” and a ‘‘zero”, this can cause a SEU in the device. The affected bits are no more susceptible to failure than any other bit in the device [49]. The upset causes a data error, but the circuit itself is undamaged. Resetting or rewriting the device will return the device back to normal. Thus this type of events is called a ‘‘soft” error. Normally, SEU appears as transient pulses in logic or support circuitry or as bit-flips in memory cells or registers [48].

## 4. Case study – vibration-induced solder joint intermittent failures

Plastic ball grid array packages (PBGAs) solder joint reliability under vibration stress loading was investigated in previous researches [50–52]. In these researches, the 27 × 27 mm$^2$, 272 balls package was daisy chained, and constructed with non-solder mask defined (NSMD) ball pads of 0.635 mm diameter. The BGA had a partially depopulated array (4 perimeter ball rows and a 4 × 4 thermal ball area). The ball pitch was 1.27 mm.

The test PBGAs were mounted on both sides of an FR4 printed circuit board (PCB). The PCB had a thickness of 1.5 mm and was constructed with 10 Cu layers. The PCB landing pads were 0.58 mm diameter with both solder mask defined (SMD) and NSMD configurations. An organic solderability protectant (OSP) was applied to the landing pads to create a solderable surface. Each side of the PCB had 15 sites for package mounting (all sites were used in this experiment). Two PCBs were used for vibration stress testing; one had underfill, the other did not.

The random vibration level and exposure times during tests are listed in Table 1. The stress level ranged from 0.02 to 0.5 g$^2$/Hz and frequencies were randomly swept across the range of 100–1000 Hz. Fig. 15 shows the vibration table with PCBs mounted in place. One accelerometer (#1 in Fig. 1) was attached on the vibration table plate and two other accelerometers were attached to the PCBs (#2 and #3 in Fig. 1). The table was driven electro-dynamically to produce vibration at the random frequencies.

The resistance of the daisy-chained PBGAs circuits was continuously monitored during vibration tests by an event detector. The event detector would detect a failure event when the resistance was 300 Ohms or higher [53] and persisted for more than 12 ms. An intermittent failure was defined as one that was detected but would go away immediately when the vibration stress was removed. Permanent failures were defined as those which persisted after the vibration loads were turned off.

Table 2 summarizes the occurrence of intermittent and permanent failures at each stress level. Fig. 16 illustrates the vibration step stress process and the occurrence of failures during each stress level. There were no failures at vibration level 0.02 and 0.04 g$^2$/Hz at the end of the 24-h duration. At the vibration level 0.1 g$^2$/Hz, one intermittent failure occurred after 16 h and 19 min on the non-underfill assembly. Seven minutes later, this intermittent failure became a permanent failure. When the vibration stress level was increased to 0.25 g$^2$/Hz, two intermittent failures occurred on the non-underfill assembly and one on the underfill assembly at 23 h and 20 min. With the vibration stress level of 0.5 g$^2$/Hz, two previous intermittent failures on the non-underfilled assembly became permanent failures at 1 h and 10 min and 3 h and 21 min, respectively. At 9 h and 24 min, three more intermittent failures occurred on non-underfilled assembly. The experiments were stopped after 11 h and 3 min at 0.5 g$^2$/Hz vibration level with 4 intermittent failures and 4 permanent failures.

An interesting phenomenon was observed when the vibration stress was removed overnight. The originally identified permanent failures disappeared. The electrical resistances of packages returned to normal (electrical continuity) state. However these failures reappeared immediately when the vibration was re-applied with 0.5 g$^2$/Hz stress level.

Experimental results showed that the percentage of intermittent failure increased with an increase on applied stress. Thus the occurrence of failures (both intermittent and permanent) depends on the accumulation of stress damage. In this case study, failures always followed a pattern. The first failure disappeared immediately when stress was removed. During the continued application of stress, the failures existed even when the vibration stop. This pattern suggests that intermittent failures were precursors to failures of solder joints and could be used to predict permanent failures. However, the time interval between each intermittent failure, as well as the time intervals between the various combinations of intermittent and permanent failures varied considerably.

It was also observed that the permanent failures in this case study could disappear after a period of time (in this case around 12 h) when the stress was removed. The failures "re-appeared" after the stress was reapplied. This phenomenon of failure disappearance may arise due to the micro-structural changes that occur in the visco-plastic Sn-Pb solder alloys. The solder alloys exhibit high homologous temperature (ratio of the solder temperature to

**Table 1**
Vibration stress level and exposure time

| Vibration level (PSD g$^2$/Hz) | Exposure time (h) |
|---|---|
| 0.02 | 24 |
| 0.04 | 24 |
| 0.10 | 24 |
| 0.25 | 24 |
| 0.50 | 24 |

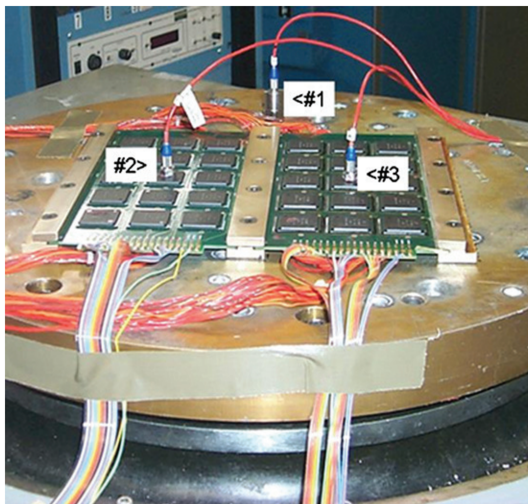


**Fig. 15.** Vibration table with test units.

**Table 2**
Data on occurrence of intermittent and permanent failures

| Stress level (g$^2$/Hz) | Assembly | Intermittent failure | | Permanent failure | |
|---|---|---|---|---|---|
| | | Package ID # | Time (hh:mm) | Package ID # | Time (hh:mm) |
| 0.02 | UF | No failure | 24:00 | No failure | 24:00 |
| | Non-UF | No failure | 24:00 | No failure | 24:00 |
| 0.04 | UF | No failure | 24:00 | No failure | 24:00 |
| | Non-UF | No failure | 24:00 | No failure | 24:00 |
| 0.1 | UF | No failure | 24:00 | No failure | 24:00 |
| | Non-UF | U6 | 16:19 | U6 | 16:26 |
| 0.25 | UF | U15 | 23:20 | No failure | 24:00 |
| | Non-UF | U8 | 23:20 | No failure | 24:00 |
| | | U11 | 23:20 | | |
| 0.5 | UF | U14 | 9:24 | U15 | 3:21 |
| | Non-UF | | | U11 | 1:10 |
| | | | | U8 | 3:21 |
| | | U7 | 9:24 | | |
| | | U9 | 9:24 | | |
| | | U12 | 9:24 | | |

UF – underfill, Non-UF – no underfill, and Time – time at which failure occurred.

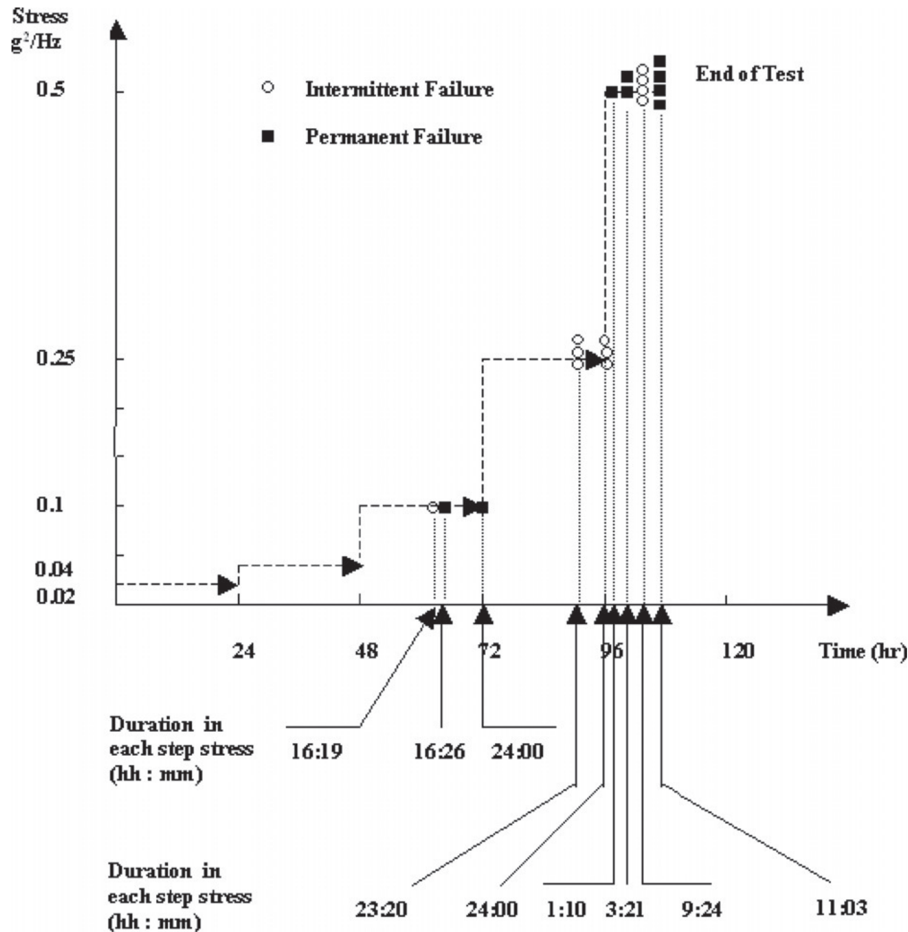


**Fig. 16.** Failures in vibration stress test.

the melting temperature of solder alloy, in which temperature is expressed in Kelvin) of ~0.65 at room temperature. At this homologous temperature, there is sufficient thermal energy available for annihilation of dislocations and recovery of strains in the polycrystalline solder material. These processes may be the contributing factors for the failure disappearance phenomenon.

The disappearance phenomenon may be important in the analysis of field removals and returns. For example, certain loads in a specific time period in the field can cause product failures. When the loads are removed after that time period, the products may be reported as "normal". However, if the loads are imposed again, the failures will occur again. While failed products in the field are tested in laboratory, failures may not be detected due to the differences in the load conditions in laboratory and in the field.

## 5. Discussion and conclusions

A no-fault found (NFF) implies that a failure was reported to have occurred during a product's use, but upon subsequent use, analysis and/or testing, the failure was no longer observable. An intermittent failure is a failure of a product function or performance characteristic over some period of time, followed by the subsequent recovery, generally without any known external corrective action. Intermittent failures are thus common causes of NFF. A typical NFF situation occurs when the user of a product under warranty reports an intermittent failure, but the manufacturer's tests of the returned product cannot detect failure or faults in the product.

In many companies, the NFF category does not constitute a product failure statistic, because it is not considered that a failure has occurred. In some cases, the manufacturer may not understand the need or have little incentive to uncover the root cause of the problem encountered by the user of the product. The impact of this lost opportunity can be profound and generally leads to increased product cost due to extra shipping costs, warranty, diagnostic and labor time. In addition, there can be unknown reliability and potential safety hazards of this product if the NFF product is put back in use. In addition, a high NFF rate in a product can cause customer inconvenience, loss of customer confidence and can damage a company's reputation.

The cause-and-effect diagram is an efficient approach to analyze NFF observations in removed or returned electronic product from the field. Factors to be considered include people related causes such as communication and knowledge of products and equipments, capability of test equipments, test environment and test conditions, test methods, and materials related causes. Using such diagrams, the engineering team can identify the potential causes for the occurrence of intermittent failures or NFF, and isolate the most probable cause by conducting specific tests based on the possible failure mechanisms. The test results can be fed back to manufacturing, design and logistics support teams to improve product reliability.

The cause-and-effect diagram is also an efficient approach to analyze intermittent failure observations in electronic products. The major causes of intermittent failures in electronic assemblies can be placed into four categories: printed circuit board, connectors, components and component-PCB interconnects and specific

failure mechanisms in each category that are prone to cause intermittent failures in electronic assemblies can be identified (examples were given in this paper). The characteristics of intermittent failures can be summarized as unpredictable, unnecessarily repeatable and often recurrent. As with NFF, root cause analysis of intermittent failures can help in manufacturing and design. The analysis can also be used to help tailor tests to locate the intermittent failures in the product qualification process.

It is a good business and engineering practice to start with the premise that field returns are field failures, unless some alternative reason can be verified. It must not be assumed that a returned product that passes tests is necessarily free from faults. Companies should start with the premise that field returns are field failures. NFF statistics should not be used to ignore, mitigate or transfer the field return problem to a non-failure status. Once this premise is accepted, then the comprehensive cause and effect diagram can help identify all the possible causes for a field failure.

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