Microelectronics Reliability xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Tin whisker analysis of an automotive engine control unit

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ARTICLE INFO

Article history:
Received 2 April 2013
Received in revised form 25 July 2013
Accepted 26 July 2013
Available online xxxx

ABSTRACT

Since the 1970s, automobile manufacturers have used electronics for safety–critical automobile control systems such as acceleration, braking, and steering. These electronic systems introduced functionalities in automobiles that were not feasible in a purely mechanical framework, such as anti-lock braking systems and electronic stability control. However, failures of these electronic systems can lead to fatalities, financial losses, legal ramifications, and reputational liabilities for manufacturers. Therefore, automotive electronics must be designed to have minimum failures during use.

In this paper, materials used in an automotive engine control unit (ECU) from a 2008 Toyota Tundra truck were analyzed. It was found that pure tin with a nickel underlayer was used as the connector finish in the unit, and analysis revealed tin whiskers on the connector surface. The use of pure tin finishes in electronics can produce conductive tin whiskers capable of creating unintended electrical failures such as short circuits. To assess tin whisker growth and the use of nickel as an underlayer material, the engine control unit was subjected to a standard temperature–humidity cycling test. The connectors showed tin whisker growth after testing, raising additional reliability and safety concerns. Recommendations for the automotive industry and National Highway Traffic Safety Administration are offered.

1. Introduction

Since the introduction of the electric voltage regulator, electric ignition, and microprocessors in automobiles in the 1970s, automotive electronics use has steadily increased [1]. Automotive electronics include engine controls and transmission, safety systems (e.g. anti-lock braking systems, air bags), chassis controls, measurement and diagnostic modules, driver assistance, and infotainment and navigation systems [2]. For instance, a mid-sized Ford vehicle manufactured in 2010 used 60 microcomputers, up from 15 microcomputers in a vehicle manufactured in 2000 [3]. In addition, the cost of electronics as a percentage of the cost of a vehicle has increased from 5% in the late 1970s [4] to nearly 50% in 2011 [2].

Electronic engine controls in automobiles regulate vehicle emissions, improve the average fuel economy [5], increase reliability, and lower costs. The engine control unit (ECU) coordinates spark ignition, air-to-fuel ratios, idle speed, and complex variable valve timing, and provides vehicle performance benefits compared to pneumatic and mechanical systems [2,6]. The ECU also plays a critical role in the driver's control of a vehicle. For example, when the accelerator pedal is pressed, an accelerator pedal position sensor (APPS) provides a voltage output to the engine control unit (Fig. 1). Based on the vehicle speed, the APPS signal, and inputs from the idle speed control sensor, cruise control, transmission shift control, and vehicle stability control, the ECU analyzes the intent of the driver, calculates the required engine torque, calculates the required throttle plate movement, and transmits a command to the throttle body actuator. The results are also communicated to other electronic control units through a controller area network (CAN) bus [6]. Other electronic control units include the brake control unit, transmission control unit, speed control unit, and body electronics.

In the design of automotive electronics, especially the ECU, reliability best practices are increasingly critical. In particular, the increased use of electronics in automobiles has increased the complexity of design-for-reliability, fault diagnosis and isolation [2]. For example, in 2010, Toyota recalled 1.33 million vehicles due to reliability issues in the engine control unit that could cause a vehicle to fail to start or stall while driving [8]. The possibility of a crack at certain solder points or varistors in the ECU [8] indicates faulty design and testing procedures.

A major concern addressed in design-for-reliability is the use of pure tin finishes in electronics, as tin whiskers can grow spontaneously under ambient conditions [9,10]. Tin whiskers are elongated or needle-like structures of pure tin that grow from pure tin and tin alloy surfaces. Tin whiskers were first recognized as a threat to the electronics industry in studies by Bell Telephone Labs in 1951 [11], because they can cause leakage currents and short circuits in electronics systems. Studies have shown that tin whiskers can lead to field failures that are intermittent, because at high electrical potentials, conductive tin whiskers can melt or vaporize after they in-

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http://dx.doi.org/10.1016/j.microrel.2013.07.134

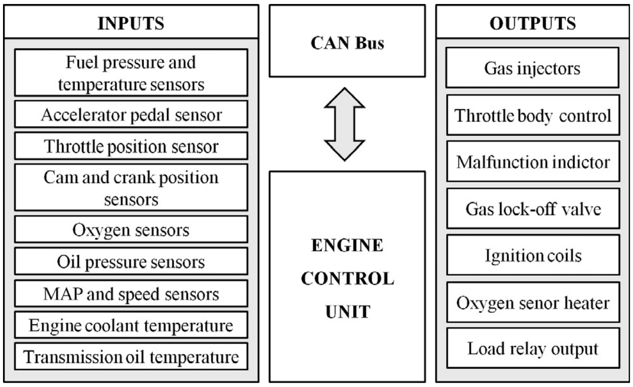

Fig. 1. Schematic representation of a typical engine control unit (adapted from [7]).

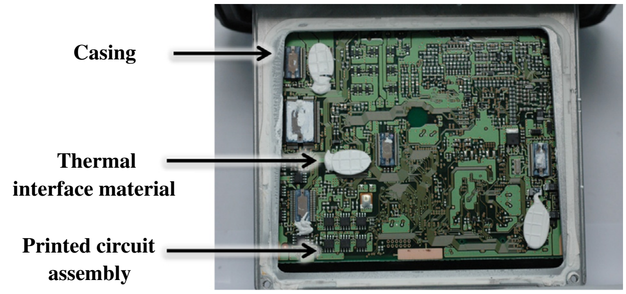

Fig. 2. Printed circuit assembly in the ECU (bottom side of the board).

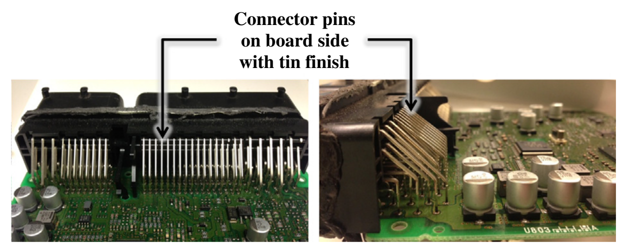

Fig. 3. ECU connector pins on the board side (top side of the board).

duce failure, thus removing the failure condition [9,12]. Additionally, field failures may be difficult to duplicate, as the failure-producing whisker may dislodge after the intermittent failure [9]. In automotive electronics, tin whisker formation due to the use of pure tin finishes has been shown to cause intermittent failures [6,13].

The unpredictable nature of whisker incubation and subsequent growth is of particular concern to systems requiring reliable operation over a 10-year lifespan, such as in automotive electronics. In such applications, if the circuit formed by the whisker carries a current greater than the fusing current of the whisker, the whisker may melt, resulting in an intermittent failure. In low voltage or high impedance circuits, the whisker will not melt, resulting in a short circuit and causing a permanent failure [14,15]. These electrical failures can lead to unintended voltages in the connected power, signal, or ground circuits. Additionally, whiskers may break loose and become airborne, thereby bridging isolated conductors remote from the original site of whisker growth and causing failure of the ECU. Further, vibrations due to handling or use of the ECU may shed the tin whiskers from the surface. The shed whiskers may then produce shorts within the system. Since tin whiskers have the ability to move, the neighboring parts are at risk of forming shorts. NASA has reported several instances of system failures in earth- and space-based applications due to tin whiskers [16].

Although tin whiskers have been studied for many years, there is no consensus in the industry on the mechanism that causes the formation of whiskers. The primary attributed cause for the formation of whiskers is the compressive stresses within the tin finish. There may be residual stresses from the electroplating process itself. The compressive stresses may also be due to intermetallic compound formation between the plating material and substrate. The coefficient of thermal expansion mismatch between the plating material, underlayer, and substrate can also cause whiskers to grow. Other causes include extrinsic compressive stresses such as bending of the surface and scratches on the plating caused by handling [9,10,14,15]. Since the mechanisms and root causes are not well known, the industry best practice is not to use tin plating. The use of pure tin plating in electronics was prohibited by the US military in the early 1990s and by NASA in 1998 [17]. Various aerospace manufacturers, including Boeing Satellite Systems and Raytheon Systems Ltd., also followed suit by prohibiting tin plating on electronic products [18]. However, neither the National Highway Traffic Safety Administration (NHTSA) nor any automobile manufacturers have any policy on the prohibition of tin finish.

In this study, the use of tin finish was observed on the connector pins of an engine control unit (ECU) from a 2008 Toyota Tundra vehicle. The connectors in the ECU provide an interface to transmit the input signals from the sensors and output signals, some of which are commands for essential functions such as throttle blade movement and brake application. Preliminary inspection of the tin-finished pins using an optical microscope revealed the presence of tin whisker growth. The ECU was subjected to a temperature–humidity test to determine whether the tin-finished pins with nickel underlayer were resistant to tin whisker growth.

This paper identifies the design aspects, in particular the finish used, in the ECU that resulted in tin whisker growth. An evaluation of the materials used in the ECU is provided in Section 2. A test that simulates actual usage conditions was then implemented to observe continued whisker growth on the connector pins. The results from the test are provided in Section 3. This is followed by conclusions and recommendations to the automotive industry and the NHTSA in Section 4.

2. Evaluation of an engine control unit

An ECU[1] was taken from a 2008 Toyota Tundra. The ECU was manufactured by Denso. It consisted of a sealed casing enclosing a printed circuit assembly with electronic components (e.g. resistors, capacitors, and integrated circuits) soldered on both sides of the board. A white thermal interface material was used to transfer the heat generated by the integrated circuit packages to the casing for apparent thermal management (Fig. 2).

The ECU connectors (Fig. 3), which are used to send and receive electrical signals as well as provide power, were copper pins with a nickel layer under the connector finish. Some of the ECU connector pins outside the casing were finished with tin and others with gold. All the pins inside the casing on the board side were tin-finished. The finishes of the connectors were characterized using energy dispersive spectroscopy (EDS) analysis (see Fig. 4). The average thicknesses of the tin and nickel layers as characterized using X-ray fluorescence (XRF) were 1.1 μm (standard deviation = 0.06 μm) and 1.2 μm (standard deviation = 0.09 μm), respectively. The ECU pins on the board side were of two different thicknesses: 0.65 mm and 1.2 mm. The in-plane distance between the 0.65 mm thick pins

[1] ECU (part number: 89661-0CC12) is compatible with a 2008 Toyota Tundra (SR5 and LIMD).

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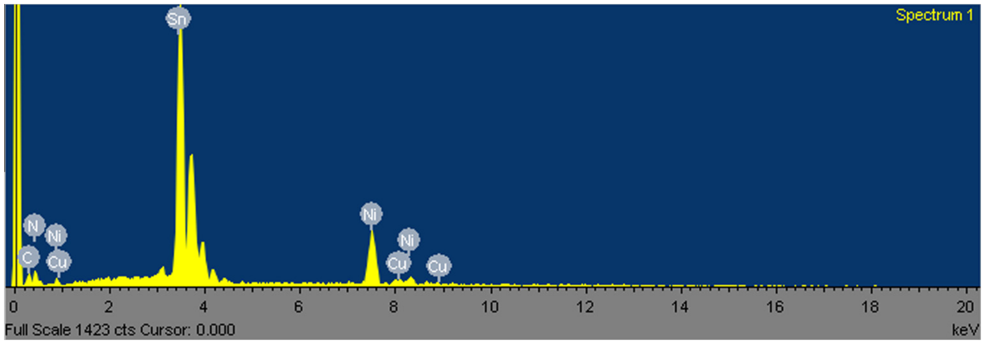

Fig. 4. EDS spectrum of the tin-finished copper connector pin with a nickel underlayer in the ECU.

was approximately 2.3 mm, and the distance between the 1.2 mm thick pins was 3.75 mm. These distances require that pure tin not be used or that there are adequate tin whisker mitigation techniques implemented to prevent failures due to tin whisker bridging.

The authors believe that the manufacturer included a nickel underlayer as a whisker mitigator, because studies in the literature have shown that a nickel underlayer mitigates whisker formation. The reason for having a nickel underlayer is to reduce the compressive stress buildup of Cu_6Sn_5 intermetallics associated with tin over a pure copper-based substrate [19]. Some studies [20,21] have shown that the whisker density and length were lower in a Cu–Ni–Sn interface compared to a Cu–Sn interface. In contrast, other studies [19,22] have shown that the use of nickel underlayer does not mitigate tin whisker growth. Panashchenko and Osterman [22] studied the effect of a nickel underlayer on tin whisker growth on tin-finished samples (2.5 years after plating) subjected to 1000 temperature cycles (−55 °C to +85 °C, 10 min dwells) followed by two months of elevated temperature humidity exposure (60 °C and 85% RH). After temperature cycling, samples with a nickel underlayer had a higher whisker density (2900 whiskers/mm^2) than pure tin-finished samples (1800 whiskers/mm^2). After temperature cycling, the tin whisker lengths were the same (12 μm) for samples with and without a nickel underlayer. However, further exposure to elevated temperature–humidity conditions produced whiskers longer than 200 μm on samples with a nickel underlayer. Panashchenko and Osterman [22] concluded that the nickel underlayer did not inhibit the growth of tin whiskers and resulted in increased whisker length under elevated temperature–humidity conditions, a condition common in automotive applications.

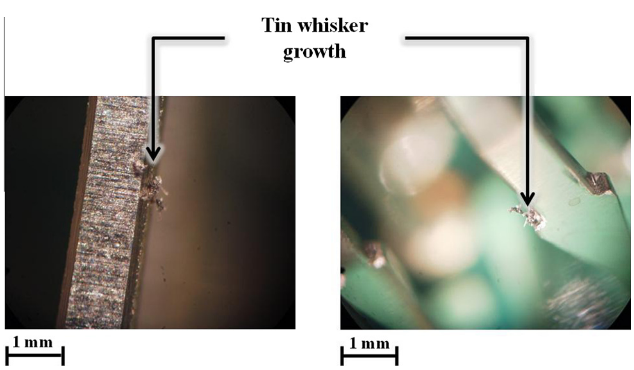

Fig. 5. Tin whisker growth on the tin-finished connector pins.

3. Tin whiskers in ECU connector pins

Optical inspection of the tin-finished connector pins on the board side inside the casing showed the presence of tin whiskers (Fig. 5). Due to the size restriction of the ESEM chamber, ESEM inspection would not have been possible without clipping the tin-finished pins from the ECU. Since clipping of the pins could dislodge whiskers from the surface, ESEM inspection was not carried out at this stage.

To check the proclivity of tin finishes to grow tin whiskers, environmental testing was conducted. Various industry standards [23,24] provide guidelines to assess tin whisker growth under environmental testing, including JESD22-A121A [25], JESD201 [26] (issued by the Joint Electron Devices Engineering Council (JEDEC)), IEC 60068-2-82 [27] (issued by the International Electro-

Table 1
Environmental tests specified in standards for whisker evaluation [23,28].

Standard	IEC60068-82-2	JESD22-A121A	JESD201	ET-7410
Optional preconditioning	Soldering simulation Lead forming	Reflow Lead forming	Reflow Lead forming	Lead forming
Ambient storage	30 °C, 60% RH 25 °C, 55% RH 4000 h	30 °C, 60% RH	30 °C, 60% RH 4000 h (Class 1 and 2) 1000 h (Class 1A)	30 °C, 60% RH 4000 h
Elevated temperature humidity storage (ETH)	55 °C, 85% RH 2000 h	55 °C, 85% RH 60 °C, 87% RH	55 °C, 85% RH 4000 h (Class 1 and 2) 1000 h (Class 1A)	55 °C, 85% RH 2000 h
Temperature cycling (TC)	Min: −55 °C or −40 °C Max: 85 °C or 125 °C 1000 or 2000 Cycles	Min: −55 °C or −40 °C Max: 85 (+10/−0)°C 1000 or 2000 Cycles	Min: −55 °C or −40 °C Max: 85 (+10/−0)°C 1500 h (Class 1 and 2) 1000 h (Class 1A)	−40 °C to 85 °C 1000 Cycles
Acceptance criteria	50 μm	–	40 or 45 μm (Class 2) 50 or 100 μm (Class 1) 20 or 75 μm (Class 1A)	–

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technical Commission (IEC)), and ET-7410 [28] (issued by the Japan Electronics and Information Technology Industries Association (JEITA)), as shown in Table 1. In 2001, the International Electronics Manufacturing Initiative (iNEMI) conducted studies to evaluate the environmental test conditions to grow tin whiskers. As a result, they developed the JEDEC test standards JESD22-A121A [25] and JESD201 [26]. The standard developed three environmental test conditions for assessing tin whisker growth: a temperature cycling condition, an elevated temperature humidity condition, and a temperature storage condition. The IEC 60068-2-82 [27] and ET-7410 [28] standards developed similar test conditions to grow whiskers. The environmental tests specified in the standards were designed to assess whether the tin finish is prone to whisker growth.

Researchers have shown that environmental conditions, such as temperature and humidity, along with time, can impact the growth of whiskers on tin-finished parts [29–39]. One of the earliest reported studies to grow tin whiskers was by Arnold [29] in 1956. Arnold [30] reported that tin whiskers developed under conditions ranging from high vacuum to high relative humidity. Harris [31] reported that 50 °C was the optimum temperature for accelerated growth of whiskers due to more rapid diffusion of tin atoms than at room temperature. However, other studies have shown that tin whisker growth was greater at ambient room temperatures than at 50 °C [32,33]. Woodrow [34] showed that a 50 °C/50% RH environment increased the rate of whisker formation compared to ambient conditions. A multi-year iNEMI study [35] begun in 2001 established a set of temperature cycling and temperature–humidity tests that provided input data for JEDEC standards. Another multiyear iNEMI study [36] begun in 2007 examined tin whisker growth on tin-plated surfaces from three industrial suppliers for two plating thicknesses. The surfaces were subjected to ten different temperature and humidity conditions. iNEMI reported that 60 °C and 87% RH were the optimal conditions for the growth of tin whiskers on tin-finished copper substrates. Hong et al. [37] showed that high temperature–humidity storage at 85 °C and 85% RH produced whiskers at a faster rate than temperature cycling (−40 °C to 85 °C) and ambient temperature–humidity storage (25 °C and 50% RH). High temperature–humidity storage resulted in tin oxide and IMC formation from tin grains, resulting in volume expansion and compressive stresses between tin-plated grains [37]. Tin whiskers were also found to grow under temperature cycling conditions [38,39].

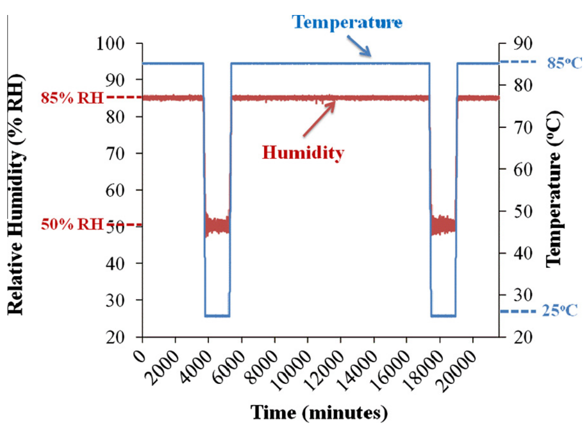

Fig. 6. Temperature–humidity test profile.

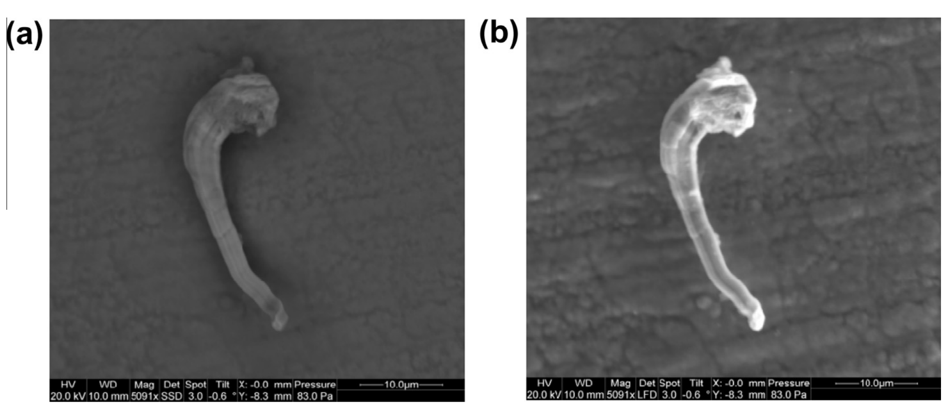

Fig. 7. (a) Back scattered electron image and (b) secondary electron image of a tin whisker.

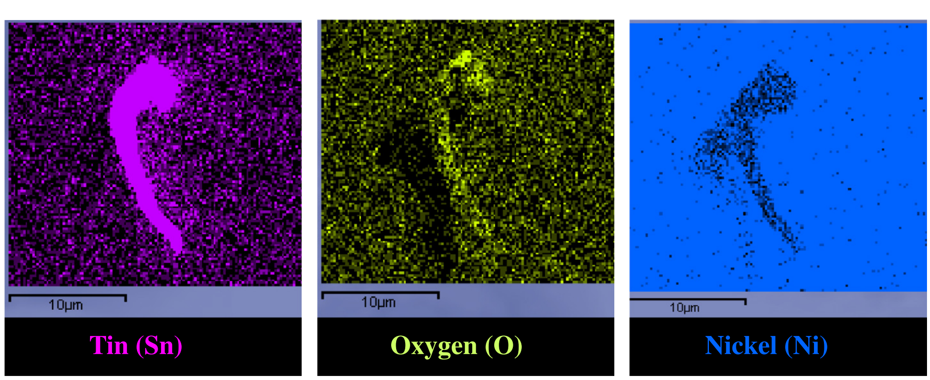

Fig. 8. EDS area spectrum of the tin whisker in Fig. 7.

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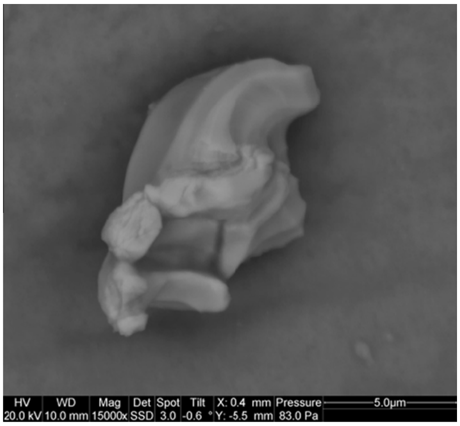

Fig. 9. A tin whisker nodule.

The test conducted in our study was a cyclic temperature humidity test (see Fig. 6), which combines temperature cycling and elevated temperature–humidity conditions. The test profile was a standard temperature–humidity profile with extended dwells at both extremes to simulate the use conditions of the ECU. During usage, the ECU experiences fluctuations in ambient temperature and humidity conditions. Hence, a temperature–humidity cycling profile simulates a more realistic usage condition experienced by the ECU than the tests specified in tin whisker standards [25–28]. The lower extreme of the dwell was at 25 °C and 50% relative humidity (RH), and the higher extreme was at 85 °C and 85% RH. The tolerance specified for the temperature extremes was ±3 °C, and it was ±5% RH for the humidity extremes. The maximum ramp time for heating and cooling was two hours each. The dwell time was 200 h at the higher extreme and 24 h at the lower extreme. The printed circuit assembly in the ECU was subjected to 5 cycles of the temperature–humidity profile of approximately 1250 h in total length.

As noted, prior to the testing, we optically observed tin whiskers. After test completion, post-test images of the pins revealed the presence of additional tin whisker growth. Environmental scanning electron microscopy (ESEM) revealed the crystalline microstructure of the whisker. Fig. 7 shows an example of whisker growth on the tin-finished connector pins. The secondary electron (SE) image in Fig. 7(b) shows the topography of the whisker growth. EDS analysis of the whisker confirmed that the whisker was made of pure tin (see Fig. 8). The whiskers had a crystalline structure and striations on the surface (see Fig. 7(b) and Fig. 9).

4. Conclusions and recommendations

The use of tin finish on the connector pins resulted in the growth of tin whiskers. If the tin whiskers grow long enough to bridge adjacent conductive surfaces, an electrical short can occur. The formation of an electrical short may result in intermittent and/or permanent electrical failure of any of the numerous performance characteristics and functionalities of the ECU. Because the tin whiskers are so prevalent, combinations of intermittent and/or permanent short circuit (or generally resistive) current paths can also induce multiple simultaneous failure modes.

Manufacturers should avoid the use of pure tin finishes in the design of automotive electronics so as to eliminate tin whisker growth. We further recommend that the National Highway Traffic Safety Administration (NHTSA) impose restrictions on the use of pure tin finishes in automotive electronics. Currently, NHTSA has no policy on the use of pure tin in automotive electronics. There are numerous alternatives to pure tin used in the consumer industry where cost is an issue. Alternatives, including NiPd, NiAu, NiPdAu, and Ag-based finishes [19,40], are not prone to tin whiskering. Furthermore, many of the alternative finishes, including immersion Ag, hot air solder level (HASL), and electroless Ni/Au (ENIG), cost only pennies per square feet more to implement [41]. Our study showed that nickel did not prevent the growth of tin whiskers in tin finished connector pins, which was consistent with the observations from [19,22].

If pure tin-finished pins cannot be avoided, the application of a conformal coating may be used to prevent tin whisker–induced failures. The use of conformal coating prevents tin whiskers from shorting exposed conductors [14,15,37]. However, the application of a conformal coating is limited by the material set, the coating method, and constraints with the geometry and spacing of the connector pins and neighboring components. Furthermore, NASA observed that whiskers can penetrate through conformal coatings [42]. Hence, the most effective strategy to prevent tin whisker growth is to avoid the use of pure tin finishes in automotive electronics.

References

[1] IHS Global Insight. Resistance is futile – electronics are on the rise: electronic control units and communication protocols. IHS Global Insight Inc.; 2009.
[2] Center for Automotive Research. Automotive technology: greener vehicles, changing skills. Electronics, Software & Controls Report; 2011.
[3] Barkholz D. Fixing cars' brains saves ford millions. Automotive News. May 10, 2010. <http://www.autonews.com/article/20100510/OEM06/305109998#axzz2PFDlrEA0> [accessed 31.03.13].
[4] Charette R. This car runs on code. IEEE spectrum, green tech/advanced cars. February, 2009. <http://spectrum.ieee.org/green-tech/advanced-cars/this-car-runs-on-code/0> [accessed 31.03.13].
[5] Ribbens W. Understanding automotive electronics. 6th ed. Newnes; 2002. p. 157 [Chapter 5].
[6] Sood B, Osterman M, Pecht M. Tin whisker analysis of Toyota's electronic throttle controls. Circuit World 2011;37(3):4–9.
[7] Westport. Engine control unit functionality. <http://www.westport.com/products/engines/2.4/ecu> [accessed 13.06.13].
[8] Toyota. Toyota announces voluntary safety recall on certain toyota corolla and corolla matrix models; 2010. <http://pressroom.toyota.com/article_display.cfm?article_id=2056> [accessed 31.03.13].
[9] Qi H, Ganesan S, Pecht M. No-fault-found and intermittent failures in electronic products. Microelectron Reliab 2008;48(5):663–74.
[10] Cheng J, Vianco P, Zhang B, Li J. Nucleation and growth of tin whiskers. Appl Phys Lett 2011;98(24).
[11] Campton K, Mendizza A, Arnold S. Filamentary growth on metal surface-'Whiskers'. Corrosion 1951;7:327–34.
[12] Ganesan S, Pecht M. Lead-free electronics. New Jersey: Wiley-Interscience; 2006. p. 140–50 [Chapter 10].
[13] Leidecker H, Panashchenko L, Brusse J. Electrical failure of an accelerator pedal position sensor caused by a tin whisker and investigative techniques used for whisker detection. In: 5th International tin whisker symposium, September 2011.
[14] Han S, Osterman M, Meschter S, Pecht M. Evaluation of effectiveness of conformal coatings as tin whisker mitigation. J Electron Mater 2012.
[15] Shibutani T, Yu Q, Pecht M. Tin whisker reliability in microelectronics. Micromater Nanomater 2009;9:49–53.
[16] NASA. Tin (and other metal) whisker induced failures. 'Publicly' reported failure references. last updated, August 3, 2009. <http://nepp.nasa.gov/whisker/failures/index.htm#military> [accessed 31.03.2013].
[17] NASA Advisory NA-044. Tin Whiskers; October 23, 1998.
[18] Osterman M. Assessing the risk posed by tin whiskers. Presentation, SMTA Capitol Vendor Show, Columbia, MD, September 7, 2006. <http://www.calce.umd.edu/lead-free/STMAKeyNote.pdf> [accessed 27.03.13].
[19] Smetana J. iNEMI Tin Whisker User Group. iNEMI recommendations on lead free finishes for components used in high reliability products. In: Proceedings of IPC printed circuits exposition, apex, and the designers summit. Anaheim, CA, February 5–10, 2006.
[20] Mathew S, Osterman M, Pecht M. Evaluation of pure tin plated copper alloy substrates for tin whiskers. Circuit World 2009;35(1):3–8.
[21] Xu C, Zhang Y, Fan C, Abys J, Hopkins L, Stevie F. Understanding whisker phenomenon: the driving force for whisker formation. Circuit Tree(USA) 2002;15(5).
[22] Panashchenko L, Osterman M. Examination of nickel underlayer as a tin whisker mitigator. In: Electronic components and technology conference; May 26–29, 2009. p 1037–43.
[23] Shibutani T, Osterman M, Pecht M. Standards for tin whisker test methods on lead-free components. IEEE Trans Compon Pack Technol 2009;32(1):216–9.

Please cite this article in press as: George E, Pecht M. Tin whisker analysis of an automotive engine control unit. Microelectron Reliab (2013), http://dx.doi.org/10.1016/j.microrel.2013.07.134

[24] Panashchenko L. Evaluation of environmental tests for tin whisker assessment. M.S. Thesis. Collge Park (MD): University of Maryland. 2009.
[25] JEDEC Standard JESD22-A121A. Test method for measuring whisker growth on tin and tin alloy surface finishes. Arlington (VA): JEDEC Solid State Technology Association; 2008.
[26] JEDEC Standard JESD201. Environmental acceptance requirements for tin whisker susceptibility of tin and tin alloy surface finishes. Arlington (VA): JEDEC Solid State Technology Association; 2006.
[27] IEC 60068–2-82. Ed. 1 Environmental testing – Part 2–82: tests – text TX: Whisker test methods for electronic and electric components; 2007.
[28] JEITA Standard ET-7410. Whisker test methods on components for use in electrical and electronic equipment; 2005.
[29] Arnold S. The growth and propensity of tin metal whiskers. In: Proceedings of annual convention of the American Electroplater's Society; 1956.
[30] Arnold S. Repressing growth of tin whiskers. Plating 1966;53:96–9.
[31] Harris P. The growth of tin whiskers. International Tin Research Institute; 1994. p. 1–19.
[32] Leidecker H, Kadesch J. Effects of uralane conformal coating on tin whisker growth. In: Proceedings of IMAPS nordic annual conference, 10–13 September, 2000. p. 108–16.
[33] Hada Y, Marikawa O, Togami H. Study of tin whiskers on electromagnetic relay parts. In: Proceedings of 26th relay conference. Stillwater, OK, April 1978.
[34] Woodrow T. Evaluation of conformal coatings as a tin whisker mitigation strategy. In: IPC/JEDEC international conference on lead-free electronic components and assemblies. San Jose, CA, April 2005.
[35] Gedney R, Smetana J. Vo N. Galyon G. NEMI tin whisker projects. In: NEMI lead-free summit meeting, October 18, 2004.
[36] Reynolds H. Accelerated tin whisker test committee update – phase 5 evaluation. In: IEEE electronic components and technology conference – tin whisker workshop. Reno, NV, May 2007.
[37] Hong W, Oh C, Kim D. Mitigation and verification methods for Sn whisker growth in Pb-free automotive electronics. J Electron Mater 2013;42(2):332–47.
[38] Nakadaira Y, Vo N, Sundram B. Pb-free plating for peripheral/leadframe packages. In: Proceedings of EcoDesign: second international symposium on environmentally conscious design and inverse manufacturing; 2001.
[39] Wolfert F, Vo N. Assessment of Pb-free finishes for leadframe packaging. In: IPC electronic circuits world convention; 2002.
[40] iNEMI Tin Whisker User Group. iNEMI recommendations on lead-free finishes for components used in high-reliability products, Version 4, December, 2006.
[41] Slocum D. Surface finishes utilized in the PCB industry. MULTEK <http://dcchapters.ipc.org/assets/pnw/presentations/20030925_Finishes.pdf> [accessed 19.06.13].
[42] Kadesch J, Brusse J. The continuing dangers of tin whiskers and attempts to control them with conformal coating. NASA's EEE Links Newsletter; 2001.

Please cite this article in press as: George E, Pecht M. Tin whisker analysis of an automotive engine control unit. Microelectron Reliab (2013), http://dx.doi.org/10.1016/j.microrel.2013.07.134