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Tin Whisker Growth from Electroplated Finishes

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Abstract

Tin whiskers are filamentary growths that are formed on the surface of electrodeposited tin, which is used extensively in the electronics industry. The presence of whiskers on electroplated finishes has been observed for more than 60 years, but, despite a huge amount of work in this area, a definite mechanism by which whiskers grow remains unidentified. Whiskers pose a significant problem for manufacturers of electrical and electronic equipment, since they are able to grow across and bridge the gap between adjacent electrical components, resulting in short-circuits and other associated failures. For many years, whisker growth was effectively mitigated by the addition of lead to tin electrodeposits. However, recent legislation prohibits the use of lead in new electrical and electronic devices, as such alternative whisker mitigation techniques are being sought. Effective mitigation is critical in ensuring that widespread whisker initiated failures can be avoided. However, since the mechanism, or mechanisms, which cause whisker growth remain unknown, the development of effective mitigation techniques is a significant industrial challenge, but a challenge which must be undertaken.

This review examines some of the work undertaken to elucidate the whisker growth phenomenon. A brief history of whisker initiated failures along with key developments in whisker theory is presented. This is followed by a more detailed assessment of the several growth mechanisms hypothesised; dislocation-based, recrystallisation-based and compressive stress-based theories. The structure and properties of tin whiskers, along with factors that affect whisker growth and potential mitigation techniques are discussed.

1. Introduction

Tin (Sn) whiskers are characterised as filamentary surface protrusions that appear on electroplated Sn finishes [1]. Such finishes are commonly used on a wide variety of electrical and electronic components. A protrusion may be classified as a whisker if it has an aspect; length to diameter ratio of greater than 5, although whiskers often have aspect ratios in excess of 1000 [2]. Whiskers are commonly straight, but may also be kinked and may take the form of nodules and other odd shaped eruptions from the surface [3]. Generally, whiskers have a uniform cross section along their entire length [3]. Their formation is spontaneous and may occur after a matter of seconds or may take several years to initiate [1]. It is estimated that, under ambient conditions, a Sn whisker grows at a rate of 0.01 nm per second [1]. Examples of typical Sn whisker morphologies can be seen in Figure 1 below.

Very short whiskers are not thought to be problematic; however, longer filament whiskers can cause significant reliability issues within electrical devices. Sn whiskers are highly conductive [1] and if long enough are able to bridge the gap between adjacent electrical components, creating a short and causing either intermittent or total failure of the device.

Whisker initiated failures are not a new phenomenon and were in fact first observed over 60 years ago and have been a significant problem for the electronics industry ever since. Failures have ranged from capacitor plates on World War 2 radios (cadmium electroplating in this particular case) to satellite arrays. All such failures have significant monetary costs attached to them for the manufacturer, whether it is the loss of a single, highly expensive satellite or the need for a complete recall of a product which may have sold in the hundreds of thousands of units. There are, however, some critical applications, such as on manned space craft and in medical applications, where the failure of an electrical component as a result of whisker formation may in fact cost the life/lives of the people who rely on the operational reliability of an electrical device. Indeed both the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) have been highly active in research into Sn whisker phenomena.

Much work has been carried out since whiskers were first observed in an attempt to identify the reasons for whisker formation and the mechanisms through which they grow, with the aim being to avoid or mitigate their formation. Many whisker formation and growth mechanisms have been hypothesised, but even to this day, no single hypothesis, or indeed combination of hypotheses on the formation of whiskers has achieved universal acceptance, with published works providing highly interesting, but often contradictory information.

It was discovered that the formation of Sn whiskers could be suppressed by alloying Sn electrodeposits with lead (Pb) and for several decades this has been industries' chosen method for preventing Sn whisker growth. However, the European Union (EU) Restriction of Hazardous Substances Directive (RoHS), which came into force in 2006, prohibits the use of a number of materials in new electrical and electronic products, one of which is Pb. The introduction of this directive and similar initiatives has, in recent years, generated renewed interest in the field of Sn whiskers, since the principal solution to the problem is no longer an option in most applications. As such, renewed efforts are being made to understand the reasons for whisker formation and to identify alternative mitigation strategies, as industry is forced to break away from traditional methods.

The problem with Sn whisker formation is further exacerbated by increasing miniaturisation within the electronics industry. Electrical devices are becoming ever smaller with more functionality and as a result individual electrical components have to be designed closer to one another in order to meet packaging requirements. This means that shorter whiskers may now also lead to failure of electronic devices, as the gaps to bridge are correspondingly smaller. The need to effectively mitigate against the formation of Sn whiskers is essential in the development of future electronic devices, in order to avoid mass in-service failures as a result of uninhibited whisker growth.

At this stage it is important to note that Sn is not the only electrodeposited metal which has been observed to produce whiskers. Other well-known whisker forming electrodeposits are cadmium (Cd) and zinc (Zn), although whiskers have also been observed on bismuth (Bi), silver (Ag), aluminium (Al), indium (In) and gold (Au) electrodeposits, albeit to a lesser extent [5]. These materials may also pose the risk of whisker initiated failures if used in electrical and electronic applications and much like Sn whiskers, the driving force for their growth is still largely unidentified. Of the listed metals, Zn provides the next greatest concern alongside Sn, primarily due to its widespread use, particularly in electronics packaging.

2. Whisker History

The formation of whiskers on electrodeposited films is by no means a new problem, having been of interest since the 1940's. This section will give a brief overview of the key history of whiskers including published work together with some confirmed whisker attributed failures. The reader is also encouraged to look at the excellent reviews by Galyon [1][4].

Year	Event
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1946	The formation of metallic whiskers was first observed after the Second World War and was documented by Cobb [6]. Electronic capacitor plates used in radios were electroplated using Cd, which has a propensity to form whiskers. Cobb [6] observed that over time the Cd electroplating produced whiskers, which if long enough were able to reach adjacent capacitor plates and shorting them out, rendering the radio useless.
1948	Bell Telephone Corporation suffers failures of channel filters, which maintain frequency bands on multi-channel telephone lines [4]. It is found that the cause of these failures is the presence of Cd whiskers formed from cadmium electroplate.
1951	First publication by Compton, Mendizza and Arnold [7], of Bell Laboratories on the topic of whisker formation.
1953	Koonce and Arnold [8] publish the first electron micrographs of Sn whiskers, concluding that whiskers grow from the base, not from the tip.
1954	Koonce and Arnold [9] publish further electron micrographs showing kinked Sn whiskers.
1955	Fisher, Darken and Carroll [10] of U.S. Steel observe that Sn electroplated steel when clamped exhibited a tendency to form Sn whiskers, concluding that compressive stresses are the cause of whiskers.
1956	Arnold [11] of Bell Laboratories publishes the first report on whisker mitigation strategies.
1958	First work published indicating that recrystallisation is a factor in the growth of Sn whiskers [4].
1959	Arnold [12] publishes work detailing the whisker mitigation effects of Pb additions to Sn coatings.
1964	Britton and Clarke [13] publish data indicating that copper (Cu) and nickel (Ni) underlay coatings provide some whisker mitigation on brass substrates.
1966-1968	Northern Electric Corporation (NEC) has whisker problems on Sn coated wires which have been electroplated using the stannate process [4]. Subsequently, NEC published a number of review articles focused on whisker mitigation practices between 1968 and 1976.
1974	Britton [14] of the Tin Research Institute (now the International Tin

	Research Institute, ITRI), published a review paper of the previous 20 years of tin whisker research.
1975-1976	Dunn [15][16] of the ESA published high quality SEM micrographs of whiskers along with work on the conductivity of Sn whiskers.
1977	Investigations conducted by General Electric (GE) on Sn whisker growth on lead frames which are used to connect electronic chips to printed circuit boards [4].
1978	Hitachi, Ltd conduct a study on failures of electromagnetic relays attributed to Sn whisker formation [4].
1980	Fujiwara and Kawanaka [17] of Mitsubishi Electric Corporation publish the first Auger depth profiling work on Sn whiskers.
1984	A review of Sn whisker growth mechanisms is published by Gorbunova and Glazunova [18].
1986	A publication by Nordwall [19] was the first to indicate Sn whisker problems encountered by the United States (US) military. Whiskers were forming on Sn-electroplated lids to hybrid circuitry on radar systems and eventually falling from the lid onto the circuit causing intermittent failures.
1986	Product recall of heart pacemakers due to loss of output as a result of whisker growth from Sn-electroplated casing [20]
1987	Dunn [21] of the ESA published data on the mechanical and electrical properties of Sn whiskers, providing values of Young's modulus, ultimate tensile strength (UTS) and electrical conductivity.
1988	Sn whiskers found on Sn-electroplated relays used as part of a US missile programme [22]
1992	Sn whiskers form from transistor cans causing electrical shorting, US missile programme [22]
1993	The USAF decides not to prohibit the use of Sn-electroplating within its electronic systems, which, as documented by Galyon [4], would prove costly as several USAF equipment failures in the years to follow were attributed to the formation of Sn whiskers.
1993	Burndy Connector Company adopted the practice of adding lead to the Sn electroplating used for all their connector products, in order to reduce Sn whisker formation and improve reliability [4].

1994	Downs [23] publishes an article regarding a Zn whisker lawsuit related to failures of critical medical equipment as a result of the formation of Zn whiskers. Despite being unaware that Zn had whisker formation tendencies, the company suffered financial damage as a result of the failures.
1995	Formation of the International Electronics Manufacturing Initiative (iNEMI) to study the challenges facing the electronics industry [24]
1998	Failure of PanAmSat Galaxy 4 satellite due to tin whisker growth which bridged and shorted metal contacts in the satellite's control processor [22][25].
1998	Lee and Lee [26] publish some of the first directly measured residual stresses in electroplated Sn.
1998	A review paper by Erwell and Moore [27], of the Aerospace Corporation and Boeing Corporation respectively, shows that whisker mitigation practices had been effectively implemented on capacitor and resistor components for up to 35 years.
1999	Ishii, et al [28] published a report outlining failures of ultra-fine pitch circuits as a result of Sn whisker formation. Annealing treatment was found to resolve this issue.
1999	The U.S. Nuclear Regulatory Commission (USNRC), reports that Sn electroplated contact support arms on relays have produced whiskers, causing a resistive shunt path [29].
1999-2000	Announcement of the European Union RoHS directive [30], to come into effect in 2006 and which will largely rule out the use of Pb as an alloying element in Sn electroplating, generates renewed interest in the study of Sn whiskers. It is noted by Galyon [4] that in the first two years of the 21 st century a greater number of presentations and papers on Sn whiskers were produced than in the preceding 15 years, as industries strived for a better understanding of Sn whisker growth mechanisms, influencing factors and viable whisker mitigation processes to replace the additions of Pb traditionally employed.
2000	Complete failure of SatMex Solidaridad satellite [5][22].
2000	Complete failure of the PanAmSat Galaxy VII satellite [5][22].
2000	Sn whiskers observed on Sn electroplated terminals on Raytheon's

	Patriot II missile system [22][31]
2001	Schetty, et al [32] show that using thicker Sn coatings serves to reduce whisker formation. The same paper also documented that Ni underlay coatings were effective at reducing whisker formation and that increased Cu bath content increased the propensity for whisker formation.
2001	First reports of a propriety Sn-electroplating process which showed no whisker formation tendencies [4].
2001	Foxboro Company present a case study of relay failures used in nuclear facilities which had been in service for 8 years and were attributed to the formation and growth of Sn whiskers [33]. Due to the nature of their application, all in-service relays were replaced as a matter of caution.
2001	The US government's National Institute of Standards and Technology (NIST) enters into the field of Sn whisker research and indicate that whisker growth may be attributed to the deposition of impurities during the electroplating process [4].
2002	Publication of an article by Davy [34] documenting Sn whisker failures of relays utilized on military aircraft.
2002	Westinghouse Electric Company issue a technical bulletin concerning the failure of power supply components caused by the formation of Sn whiskers, causing intermittent operation and unit tripping [35]
2005	Sn whiskers are found to have grown across a pressure sensor card at Millstone power station in the US, resulting in the sudden and spontaneous shutdown of the plant [36]
2006	As of the 1 st January all EU automotive OEM's (Original Equipment Manufacturers) are required to comply with the ELVD (End of Life Vehicle Directive), which encourages the reduction of use of hazardous materials, such as Pb, by forcing OEM's to take back and recycle end of life vehicles [37]. This requires OEM's to produce vehicles with a recyclability of greater than 80% and hence reduce the levels of unrecyclable, or difficult to recycle materials.
2006	The EU RoHS directive comes into force on the 1 st July, severely restricting the use of Pb in new electrical and electronic equipment [30].
2006	Complete failure of PanAmSat Galaxy IIIR satellite [5]
2007	The first stages of the WEEE (Waste Electrical and Electronic

	Equipment) directive come into force on the 1 st April and 1 st July [38], further prohibiting the use of Pb in electrical and electronic equipment.
2008	Amended WEEE regulations come into force on the 1 st January [39].
2008	Updated RoHS directive is enforced as of the 1 st February which has an amended list of exceptions to the use of hazardous substances such as Pb.
2010	Further amendments to the WEEE directive come into force on the 1 st January [40].

As can be seen from this history, the industry most affected by the formation of whiskers, from both Sn and Zn, is the electronics industry, along with related end-user industries. As a result much of the work that has been carried out to determine the cause and mechanism of whisker growth has come from these sectors. Equally, electronics applications are most likely to suffer failures as a result of whisker formation, since many components are within very close proximity to one another, meaning whiskers are able to grow across the gap and short out the system.

A number of major failures have also been observed within the defence and aerospace industries which have been attributed to the formation of whiskers, which subsequently shorted out some electrical device. These failures were in critical applications and as such have been scrutinised and investigated thoroughly. However, there may be hundreds, if not thousands, of whisker initiated failures in less critical applications that have not been as widely publicised or even definitely proven.

3. Theories of Tin Whisker Growth

Ever since whiskers were first observed in the 1940's, research groups and individuals have studied the possible reasons for their formation. Based on a huge array of work, many differing hypotheses have been proposed in an attempt to identify the fundamental phenomena which cause the formation and growth of whiskers. These have ranged from dislocation based theories, to recrystallisation effects and to the presence of internal compressive stresses. The following sections review of some of the key theories proposed.

3.1 Dislocation Theories

The first hypotheses to appear regarding the formation and growth of whiskers were based on the movement of dislocations through the electrodeposit, towards the surface, where extra atoms coalesced to form the protruding whiskers. The first of

these theories was proposed by Peach [4][41], in 1953, who hypothesised that whiskers were formed by migrating Sn atoms through a screw dislocation. These atoms migrated through the centre of the whisker to be deposited at the tip of the whisker [41], increasing its length. Later in 1953 Koonce and Arnold [8] published the first electron micrographs, from which they concluded that whiskers in fact grew from the base not from the tip, thus nullifying Peach's theory.

Following the observation that whiskers grew from the base, several other dislocation based hypotheses were proposed. The first of these, made by Eshelby [42] in 1953, was a mechanism whereby dislocation loops emitted from a Frank-Read source glided to the surface of the electrodeposit, adding an extra layer of atoms. Also in 1953, Frank [43], proposed a mechanism consisting of a rotating edge dislocation pinned by a screw dislocation, which is perpendicular to the surface of the electrodeposit, with the revolutions of the dislocation feeding extra half planes of atoms to the surface. A schematic of this mechanism can be seen below in Figure 1.

An alternative mechanism, proposed by Amelinckx et al in 1957 [44], suggested that a helical dislocation could move towards the surface through a glide mechanism, depositing extra half planes of atoms. It is noted by Galyon [1], that many other dislocation based theories were proposed which were variations of either Eshelby's, Frank's or Amelinckx's theories, but that there is no experimental evidence in support of any dislocation based growth mechanism and it is believed that dislocations do not contribute to the formation and growth of whiskers.

3.2 Recrystallisation Theories

A 1958 paper by Ellis et al. [45] was the first to provide evidence that dislocations played no part in the formation and growth of whiskers, by virtue of the fact that whiskers could grow in directions which did not correspond to glide directions in the electrodeposit and so could not be the driving force for whisker growth. Based on this, it was concluded that dislocations most probably did not contribute to the formation and growth of whiskers regardless of whisker growth direction. Instead, Ellis et al [45] hypothesized that the growth of whiskers was via a unique form of recrystallisation. It was proposed that the growth of whiskers did not occur at the surface of the electrodeposit, but rather by the migration of atoms across a fixed, sub surface grain boundary into a 'whisker grain'. The principal being that as atoms move from the grain boundary into the 'whisker grain', the whole grain is moved upwards by an atomic layer for each atomic layer which passed across the grain boundary. Continued cycles of this migration would cause the 'whisker grain' to move further, increasing the length of the whisker.

Ellis et al [45] also suggested that the formation of whiskers could not occur on as-plated electrodeposits, due to their structure, and that some form of recrystallisation needed to take place in order to produce a structure that would permit the formation of whiskers.

3.3 Compressive Stress Theories

3.3.1 External Stresses

There have been several investigations into the effects of compressive stress on the formation of whiskers and as such this has formed a large part of the suggested mechanisms for whisker formation and growth. The first investigation was carried out by Fisher et al [10]. Their experiments involved clamping Sn electroplated steel and applying varying levels of compressive stress to assess the effect this had on whisker growth rate. It was found that pressures up to ~ 52 MPa caused significant acceleration in whisker growth rates, increasing from ~ 0.1 nm/sec up to 1000 nm/sec. Whilst Fisher et al [10] showed that compressive stress accelerated whisker growth rate, they did not prove that compressive stress was responsible for initial whisker formation. It is possible that whiskers are formed by some other mechanism, for example the migration across a fixed grain boundary as proposed by Ellis et al [45], the effects of which are amplified by the application of increasing levels of compressive stress. It was speculated by Galyon [1], that the compressive stress applied by Fisher et al [10] also accelerated the recrystallisation of the electrodeposit. If this is the case, then this suggests that it is not the compressive stress which directly causes the formation of the whiskers, but rather it contributes to a chain of events which ultimately results in whisker formation. Galyon [1] also documented that the work of Fisher et al [10] had been corroborated by other researchers, the first being Glazunova [46] in 1962 and the other Pitt and Henning [47] in 1964. Interestingly these studies used different substrate materials; Glazunova used tin electroplated steel and brass whilst Pitt et al used steel and Cu as substrates

A paper by Dunn [48] of the ESA, published in 1987, however, provided contradictory evidence to that proposed by Fisher et al [10], Glazunova [46] and Pitt and Henning [47]. Dunn also conducted experiments to assess the effects of mechanical stressing on the propensity for whisker formation and ultimately concluded that mechanical stressing did not cause an increase in whisker formation and growth. It was noted by Galyon [1] that the clamping apparatus used by Dunn was significantly different from that used by Fisher et al and as such induced different levels of compressive stress in the electrodeposited Sn, with Dunn's being much lower than the compressive stresses used in the work of Fisher et al. A

comparison of the clamp arrangements used by Fisher et al and Dunn can be seen in Figure 3.

From Figure 3(a) it can be seen that the clamp used by Fisher et al [10] clamped directly onto a Sn electroplated sample, whereas Dunn's clamp (Figure 3(b)) was electroplated on its internal surface so that when clamped a compressive stress was introduced into the electrodeposit. Galyon suggested that the lower compressive stress might have resulted in Dunn's contradictory results. However, if it is indeed the presence of compressive stress which drives the formation and growth of whiskers then Dunn should still have observed some acceleration in whisker formation and growth during his experiment. Galyon [1] postulated that due to the nature of the clamping arrangement in Dunn's experiment it did not affect the recrystallisation of the Sn electrodeposit. If this is indeed the case, then this confirms that the presence of compressive stress in the Sn electrodeposit is not sufficient to cause whisker formation and growth in its own right and that it instead contributes to a more complex overall process.

3.3.2 Internal Stresses

The effects of residual compressive stresses, within the Sn electrodeposit, have also been linked with the growth of Sn whiskers. A study conducted by Sheng et al [49], investigated the whisker growth rate of pure Sn and a eutectic SnCu alloy electrodeposit, as alternatives to the traditionally utilised SnPb materials. It was found that in both pure Sn and SnCu electrodeposits formation of Cu_6Sn_5 intermetallic had occurred. For the pure Sn deposit, these precipitates were located primarily at the interface between the deposit and the copper substrate, whilst for the SnCu deposit intermetallic particles were also present at grain boundaries throughout the thickness of the electrodeposited film. It was observed that whiskers which grew on the eutectic SnCu electrodeposit were much longer than those on the pure Sn electrodeposit. This was attributed to increased internal compressive stress within the SnCu electrodeposit as a result of the increased Cu_6Sn_5 precipitation; thereby increasing the driving force for whisker growth and resulting in a shorter incubation period. A schematic of the effects of Cu_6Sn_5 on the stresses in a Sn electrodeposit can be seen in Figure 4 [50].

The effects of Cu_6Sn_5 intermetallic formation were also reported by Tu [51]. It was concluded that interdiffusion between evaporated Sn and Cu films, leading to the formation of Cu_6Sn_5 , was the driving force for whisker growth. It was also observed that whiskers were not formed on pure Sn films deposited without a Cu underlayer. The effects of Cu_6Sn_5 precipitate formation on the tendency for whisker formation and growth have also been reported by Lee and Lee [26] and Fujiwara et al [52],

however, Moon et al [53], concluded that Cu inclusions in Sn electrodeposits did not always contribute to whisker formation. This is another example of contradictory results and indicates that the formation of Cu_6Sn_5 precipitates may not always cause whiskers; thus questioning whether Cu_6Sn_5 formation is in fact always a driving force for whisker growth.

3.4 Summary

At this stage, it is appropriate to note that whilst some of the proposed whisker growth mechanisms have been widely disproved, no single hypothesis has achieved widespread, universal acceptance. It was noted by Galyon [1], that although many of the major whisker formation hypotheses were proposed in the 1950's, these theories still represent the fundamental concepts which are discussed and debated today. Currently, it is the case that the work rather served to identify factors which may contribute to the growth of whiskers than actually cause their formation in the first place.

4. Factors Affecting Tin Whisker Formation

There are a number of factors that have been shown, over the years, to contribute to the formation and growth of Sn whiskers. Some of these, as shown in Section 3, have formed the basis of hypotheses as to the reasons for the formation of whiskers. The factors which affect the propensity for whisker formation are the composition of the Sn alloy used, the substrate material which it is electrodeposited onto, the process parameters used during electrodeposition, including bath chemistry, and the service environment in which the coated component operates.

4.1 Electrodeposition of Tin Alloys

The composition of the electrodeposited Sn alloy can have a significant effect on the propensity for whisker formation. Variations in whisker growth tendencies can be caused by both the composition of the tin and the specific tin electroplating process utilised.

An investigation by Fukuda et al [54], examined the effects of electrical current, heat treatment and mechanical stress on whisker growth tendencies of bright and matte Sn electrodeposits on Cu. This work demonstrated that, regardless of other factors, the bright Sn electrodeposits produced significantly longer whiskers than the matte Sn electrodeposits. It was also shown that the density of whiskers produced from the bright Sn was also considerably higher than that from the matte Sn, again regardless of other factors. Although the reasons for these differences in whisker formation tendencies were not addressed, it should be noted that the grain sizes of the bright

and matte Sn electrodeposits were significantly different, with the grains in the matte Sn being ~ 6 to 7.5 times larger than those in the bright Sn.

The degree to which whiskers are formed on Sn-electrodeposits is also affected by the addition of alloying elements. A study carried out by Boettinger et al [55] looked at the whisker formation tendencies of pure Sn, Sn-Cu and Sn-Pb electrodeposits on a phosphor-bronze substrate. After several days, 20 µm conical hillocks were observed on the pure tin electrodeposit, whilst the Sn-Cu electrodeposit produced 50 µm hillocks and 200 µm whiskers. Conversely, the Sn-Pb finish showed no hillock or whisker formation over the same period of time. The varying degrees of whisker formation and growth were attributed to different levels of compressive stress in the electrodeposits, with the Sn-Cu finish having the highest initial stress levels due to the formation of the intermetallic compound (IMC) Cu_6Sn_5 . The effect of electrodeposit composition has also been addressed by Chen and Wilcox [56], who studied the whisker growth behaviour on Sn-Mn electrodeposited alloys. It was found that after a very short incubation period, Sn-Mn exhibited prolific whisker growth, although it was also determined that the electrodeposit was in a state of residual tensile stress, thus directly contradicting the theories that internal compressive stresses are the driving force for whisker formation.

4.2 Substrate Material

The substrate material can also have a significant effect on the tendency for an electrodeposited Sn finish to produce whiskers. It has clearly been demonstrated that in a number of circumstances, if Cu is present directly under the Sn electrodeposit, then diffusion may occur across the interface leading to the formation of Cu_6Sn_5 intermetallic [26][51][52]. The formation of these intermetallic precipitates has been shown to result in an increased rate in whisker growth, although not under all conditions [53]. Taking this as an indication of whisker growth tendencies, it should be considered that the Sn electroplating of any substrate which contains Cu may result in an increased rate of whisker growth in comparison to other substrate materials such as Alloy 42.

Tin deposition directly onto brass substrates is known to result in an increased propensity for whisker growth compared with deposition onto copper or Alloy 42 [48][57][58]. Accelerated whisker growth results from the diffusion of zinc from the brass substrate through the tin to the surface of the deposit where zinc oxide is formed [13, 17]. Recent XPS studies have shown that the formation of zinc oxide occurs on the surface of a 2 µm tin electrodeposit on brass within 1 day of electroplating [58]. With increasing time after deposition the zinc content at the surface of the deposit increases and the tin grain boundaries at the deposit surface

become decorated with zinc oxide [58, 59] as shown in Figure 5. It is strongly advised that electroplating of tin onto brass without an interlayer should be avoided [14, 60].

It was documented by Pitt and Henning [47] that, when hot dip coating was used to produce a deposit of 50%Sn-50%Pb alloy, more whiskers were observed to have grown with a Cu substrate than the same alloy when deposited onto steel. It should be considered that the thickness of coating deposited using a hot dip process will be considerably higher than for electrodeposition. Indeed, a study by Glazunova and Kudryavstev [61], after Galyon [4], demonstrated that the tendency for whisker growth characteristics were affected by both substrate material and coating thickness, with different Sn electrodeposit thickness yielding different maximum whisker growth rates and densities for a range of substrate materials. A reduction in whisker growth with increased deposit thickness has also been reported elsewhere in the literature [62-65]

4.3 Electroplating Process Parameters

There are a number of aspects of the electroplating process itself which may be related to the propensity for whisker formation on Sn electrodeposits, covering process parameters and electroplating bath composition.

Pinsky [66] reviewed the effects of dissolved hydrogen (H) on the formation of Sn whiskers and stated that the presence of co-deposited H within Sn electrodeposits could have an effect on the whisker formation tendencies of the electrodeposit. Pinsky also stated that the effects of H inclusion in Sn electrodeposition may have largely been overlooked, as whisker theorist's focus on the stress driven route of whisker formation. It was noted that several publications had indicated that low cathode current efficiency (CCE) electroplating processes yielded electrodeposits that exhibited high levels of whisker formation, possibly as a result of increased levels of co-deposited H due to the low CCE.

Work by Moon et al [53] also showed that increasing the level of Cu^{2+} within the electrolyte increased the amount of Cu that was co-electrodeposited along with the Sn. It was found that in some cases this resulted in increased whisker growth, but in other circumstances appeared not to influence whisker formation tendencies. A summary of the effects of co-electrodeposited Cu, from Moon et al [53] can be seen in Table 1 below. This data was obtained from Sn electroplated on top of a 250 μm thick Cu film. It should therefore be considered that some of the whisker growth observed may have been caused by diffusion of Cu into the Sn electrodeposit from the substrate, rather than just the amount of Cu co-electrodeposited.

4.4 Mechanical Stress

As well as the electroplating process and its associated factors, the service environment to which the electrodeposit is subjected can also have an effect on whisker formation tendencies, particularly with respect to the presence of mechanical stresses.

As well as previously mentioned investigations by Fisher et al [10], Glazunova [46] Pitt and Henning [47] and Dunn [48] another study, conducted by Lin and Lin [67], looked at the effects of both compressive, tensile and zero applied stresses on the formation of whiskers from bright Sn electrodeposits. It was found that whiskers grew regardless of the presence of an applied stress, but that both compressive and tensile stresses altered the nature of the whiskers formed. It was concluded that the application of a compressive stress resulted in the formation of longer, denser whiskers; however, further increases in the level of compressive stress led to an increase in whisker density but a reduction in whisker length. Conversely, it was demonstrated that the application of tensile stresses resulted in a reduction in both whisker length and density, but that whiskers were still formed. This adds further weight to the theory that the formation and growth of whiskers is not directly caused by the presence of applied stresses, rather that these stresses affect the actual mechanism by which they are formed.

Chen and Chen [68] also investigated the effects of an applied tensile stress on a Sn film, which had been electrodeposited onto silicon (Si). A tensile stress was induced in the film via three-point bending and it was noted that whiskers still grew on the sample. Interestingly, it was observed that the growth behaviour of the whiskers changed depending on the level of tensile stress induced in different regions of the sample. It was observed that whiskers that formed in a region of high tensile stress grew in random orientations, but that those which grew in a lower tensile stress region exhibited more directionally orientated growth.

4.5 Summary

Many factors have been identified that have an effect on the propensity for a Sn electrodeposit to form whiskers. Whilst experimental evidence has been obtained to verify the effects of these factors, none of them have been definitively established as the sole fundamental cause of whisker formation and growth. Indeed, It is quite likely that these factors are not mutually exclusive, rather having some interdependence on one another and therefore require more studies on their combined effects.

As such, these factors simply form part of the huge wealth of information that has been gathered on Sn whiskers but which is still not fully understood.

5. Whisker Mitigation Techniques

Over the years a number of whisker mitigation techniques have been identified, often as a by-product of an attempt to characterise the formation and growth mechanisms of whiskers. Such techniques include additions of Pb to Sn electrodeposits, the use of underlay coatings and the application of conformal coatings on top of Sn electrodeposits. This section will look at the theories behind each of these methods and their associated benefits.

5.1 Lead Additions

The addition of Pb to Sn electrodeposits has been the industry favoured method of whisker mitigation for several decades. Indeed, it is only the recent introduction of new legislation, prohibiting the use of Pb in new electrical and electronic equipment, which has led to renewed interest in alternative whisker mitigation techniques. The whisker mitigation properties of Pb were proposed by Arnold [69] of Bell Laboratories in 1966, but had in fact been indicated by Glazunova and Kudryavstev [61] earlier in 1963.

It is noted that Arnold [69] investigated the whisker mitigation properties of various Sn alloy coatings, including those with additions of Pb, antimony (Sb), cobalt (Co), germanium (Ge), gold (Au) and nickel (Ni). As part of the investigation, Bell Laboratories had studied the whisker growth tendencies of several Sn-Pb coatings over a period of 12 years, at both ambient and high humidity conditions. It was noted that over this period of time only very short, sub-500 μm , whiskers had grown. It is noted by Galyon [4], based largely on the results produced by Bell Laboratories, that the principal whisker mitigation technique to be employed by industry over the next several decades was to alloy Sn electrodeposits with Pb.

The reason for the whisker mitigation effects of Pb addition appears not to have been investigated in any great detail, rather it has been accepted that it works and further investigations focused on attempting to identify the driving force for whisker growth. It was, however, noted by Prakash and Sritharan [70], that the addition of Pb to Sn solder serves to improve wetting, prevents the low temperature transformation of white β Sn to grey α Sn and that it also acts as a solvent. Prakash and Sritharan state that the solvent nature of the Pb additions may serve to reduce the rate of IMC growth, principally Cu_6Sn_5 , at the interface between the Sn solder and a Cu substrate. Indeed, if the growth of whiskers is driven by the formation of Cu_6Sn_5

within the Sn electrodeposit, then the retardation of its formation, through the addition of Pb, would serve to effectively suppress against whisker growth.

The introduction of legislation, such as the RoHS directive, effectively prohibiting the use of Pb in electronics has led to renewed interest in understanding the effect of Pb additions on the structure of the electrodeposited Sn coating. Alloying with Pb results in a number of key changes to the structure of the tin deposit; firstly Pb additions result in the formation of an equiaxed grain structure [55, 71-74] compared with the columnar grain structures developed in pure Sn. Secondly, the addition of Pb results in a transition in the texture of the deposit towards a [220] orientation [71, 74]. Pb additions have also been shown to reduce the level of compressive stress developed within the deposit compared with pure Sn [55, 71] and also to influence the size and distribution of the IMC's formed at the interface with the Cu substrate [71-74]. The presence of Pb-rich grains has also been observed in Sn-Pb deposits [55, 72 and 74]. It is hoped that effective whisker mitigation can be achieved in Pb-free Sn deposits by reproducing the characteristic deposit structures observed for SnPb deposits; either through the use of alternative alloying additions (e.g. Bi or Ag [73]) or by modifications to electroplating parameters and bath chemistry.

5.2 Underlay Coatings

An underlay coating is applied to a substrate material prior to a tin coating and may be applied for a number of reasons; to impart improved corrosion resistance, to act as a diffusion barrier, to change the stress regime in the coating [4] and also to improve 'top coat' adhesion.

Galyon [4] notes that Cu, Ni and Ag underlay coatings have been investigated as potential whisker mitigation systems [14][27][48][75][76]. Galyon [4], documents that Ni underlay coatings have yielded very good whisker mitigation results, although the reasons for this appear unclear. In some cases the retardation of whisker growth is attributed to the Ni underlay acting as a diffusion barrier between the Sn coating and the Cu substrate, thus preventing IMC formation. However, Xu et al [75] documented that the presence of a Ni underlay served to alter the stress regime in the Sn coating from residual compressive to residual tensile. However, based on the work by Chen and Wilcox [56], Lin and Lin [67] and Chen and Chen [68], which showed that whiskers were still formed when the coating was in a tensile stress regime, suggests that the latter of these theories was less likely. Rather, it is more probable that the Ni underlay simply acts as a diffusion barrier preventing IMC formation, assuming of course that whisker growth is indeed controlled by internal stresses as a result of IMC formation. It is noted by Galyon [4], that there have been no reported in-service

failures of Cu electrical components coated with bright Sn which have a Ni underlay coating over a period of 20 years.

Conversely, the use of Cu underlay coatings yielded contradictory results, with suggestions that Cu underlay coatings in some cases reduced whisker growth, in other cases did not and in some it accelerated whisker growth. In this authors' opinion, the choice to investigate the benefits of using a Cu underlay coating is quite interesting in itself. This is due to the fact that it is widely considered that internal compressive stresses, as a result of Cu_6Sn_5 IMC formation, are considered the principal driving force for whisker growth.

5.3 Heat Treatment

Applying an annealing heat treatment to electroplated Sn finishes has also been investigated for many years as a potential whisker mitigation technique. Once again, Galyon [4] documents works by a variety of parties investigating the effects of post electroplating annealing processes on whisker growth. Again many of the results obtained were contradictory, with some suggesting that annealing could be applied to completely eliminate whisker growth, whilst others stated that annealing simply increased incubation periods rather than actually eliminating the problem. However, there appears to have been no standardised methods employed to assess the effects of different annealing processes. Much of the work conducted utilises different substrate materials, with various underlay coatings and different annealing temperatures and times, often within the same publication. The effects of the annealing process are determined by the temperature and time used during the process, and combined with the other factors, which are themselves known to effect whisker growth, makes interpreting these results difficult. It is much the case that there are too many unknown variables; as such, determining which of these has resulted in whisker suppression is almost impossible.

More recent work has again focused on the potential benefits of annealing heat treatments on the retardation of whisker growth. An investigation by Kim, Kim and Han [77], in 2008, looked at the benefits of an annealing treatment on whisker growth for matte Sn electroplated onto Cu substrates. Samples were produced under the same conditions and then half were then annealed at 125°C for 1 hour, within 1 hour of electroplating. The samples were then stored under high temperature and high humidity conditions for 1800 hours. After this period it was observed that the samples which were annealed had grown no whiskers, whilst they were observed on the as-electroplated samples. It was noted that the different samples, with and without annealing treatment, produced different layers of IMC's at the interface between the substrate and the coating. Observation of each of the samples showed

that those which had been subjected to the post-bake treatment had a much more uniform layer of IMC's, which is thought to have prevented the induction of residual compressive stresses in the coating. Since in this investigation, the only variable was that of the heat treatment, it can be concluded that whisker suppression in this instance is as a result of this heat treatment. However, it should be considered that the samples were only stored for a relatively short period of time before inspection, unlike some other publications which involved inspection after a much longer period of time. It may therefore be the case that the post-bake treatment has simply extended the incubation period to above 1800 hours and that whiskers will eventually grow.

5.4 Conformal Overlay Coatings

Another alternative is to apply a conformal coating on top of the electrodeposited Sn to prevent the growth of whiskers. This is a fairly simple principle essentially confining any potential whiskers to within the electroplated finish.

The use of a Uralane conformal coating has been investigated by Kadesh and Leidecker [78] of NASA as a potential whisker mitigation practice. From their work it was found that a Uralane coating of between 50 and 75 μ m thick is sufficient to prevent whisker breakthrough for at least 18 months, although whiskers had still formed underneath the conformal coating. It was concluded that the Uralane coating served to reduce the growth rate of the whiskers but did not eliminate them. As such whiskers may eventually be able to break through the conformal coating but not for at least 18 months; making the use of a 50 μ m thick Uralane coating suitable for short duration space missions but not necessarily for longer service periods [78].

Osterman [79] suggests that the use of conformal coatings may offer benefits in the suppression of whiskers, but that it will not prevent their growth. Osterman notes that there are a number of issues surrounding the use of conformal coatings, such as their interactions with other components and the effectiveness of their application techniques. It is stated that conformal coatings may be applied by either spray or dip coating, but that both of these techniques may result in incomplete or insufficient coating of the components intended. As such, whisker mitigation may be compromised and it is concluded that conformal coatings should not be used in isolation to prevent whisker initiated failures; rather they should be applied in conjunction with another mitigation technique.

5.5 Avoiding Tin Electroplating in Electrical Components

Obviously, one option to prevent Sn whisker initiated failures is simply to avoid the use of Sn electroplated finishes on all electrical and electronic componentry.

However, finding a cost effective alternative material to replace Sn electroplating may be a considerable challenge. Other suitable materials, from an electronics point of view, such as Cd and Ag, also exhibit whisker growth tendencies; indeed even Au has been observed to grow whiskers [5]. Clearly, any alternative material would need to be considered carefully before being utilised as a replacement for Sn electroplating.

5.6 Summary

Several whisker mitigation techniques have been identified; however the most effective and currently applied method in industry, Pb additions, has now been effectively prohibited. With regards to the possible alternatives, the work conducted is rather indicative of the field of whisker phenomena in general, in that much work has been conducted but in the end has produced a vast array of contradictory results. The development of effective mitigation practices is complicated by the fact that the growth mechanism and factors which contribute to whisker growth are also not fully understood and without standardised test procedures, it is all but impossible to determine the true effectiveness of these techniques.

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Figure 1 SEM images showing examples of typical whisker morphologies; (a) filament whisker, (b) nodule and (c) odd shaped eruption

Figure 2 Schematic of Frank's rotating edge dislocation theory. From [1] but originally published in [43]

Figure 3 Schematic illustration showing the clamp arrangements used by (a) Fisher et al [10] and (b) Dunn [48].

Figure 4: Schematic diagram showing the effect of intermetallic formation on whisker growth [50]

Figure 5: SEM micrograph showing the surface of a 3 μm Sn deposit on brass after storage for 9 months. The dark contrast phase coating the Sn grain boundaries corresponds to zinc oxide.

Table 1: Effect of co-electrodeposited copper level on whisker length [53]

Mass Fraction Cu (%) in Electrodeposit	Whisker Length (μm)	
	After 7 Days	After 24 Days
0	No Whiskers	No Whiskers
0.29	No Whiskers	1
0.67	4	4
1.49	55	44
1.42	59	190
2.93	24	160
3.28	19	181