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Interface flow mechanism for tin whisker growth

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Abstract

Tin coatings, widely used in electronics, are susceptible to the spontaneous eruption of fine metal filaments or “whiskers”. Tin whiskers are a serious reliability issue in microelectronics, as they can cause short circuits and device failure. While it is generally accepted that whiskers grow to relieve compressive stresses, the specific mechanism for whisker formation is yet unknown. Data are presented to support an interface-transport mechanism for whisker nucleation and growth. This mechanism, involving the formation of a viscous layer at the interface between substrate and coating, could explain the extremely rapid growth of whiskers that has been observed experimentally.

Keywords: Crystal; Growth; Whiskers; Coatings; Interfaces

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1. Introduction

As the electronics industry moves towards the elimination of lead-containing components, tin-based solders and pure tin coatings are used with increasing frequency. Copper conductors are often plated with tin to prevent corrosion and to improve solderability for use with tin-based solder [1–3]. However, tin whiskers grow spontaneously from electroplated [3–5] and vapor-deposited [5–7] tin films at room temperature. Whiskers can grow to several millimeters in length, long enough to bridge neighboring conductors and create short circuits in electronic devices. Such unexpected shorts pose a reliability concern to critical microelectronics systems.

It is widely accepted that compressive stress drives metal whisker growth [1–3,8–14]. The required compressive stress may be provided chemically, thermally, or mechanically [8,10–12]. The formation of intermetallic compounds between the substrate and tin plating, such as Cu_6Sn_5, which forms between copper and tin at room temperature, and the subsequent diffusion of Cu into the tin grain boundaries is one source of the compressive stress required for whisker formation [2,6,12,15]. However, the stress in a tin film resulting from the formation of intermetallics is difficult to quantify accurately (although Lee and Lee [3] made a good attempt to measure it). Mechanical test methods have been used experimentally to force whisker growth, with the benefit of enabling accurate measurements of the compressive stresses applied to the sample.

Fisher et al. [9] accelerated whisker growth dramatically by applying pressure to tin-plated specimens using a clamp. Pitt and Henning [16], Glazunova [17] and Franks [18] followed up on this work by conducting similar clamp pressure experiments. The results reported by these authors varied significantly. Fisher et al. reported a maximum growth rate of 10,000 $\text{Å}\,\text{s}^{-1}$ using 7400 psi (51 MPa) pressure, while Pitt and Henning reported a maximum rate of only 593 $\text{Å}\,\text{s}^{-1}$ using a clamp pressure of 8000 psi (55 MPa). These accelerated growth studies provided the motivation for the present work.

In this study, tin-plated specimens were clamped and observed at regular intervals under an optical microscope. The applied stress was within the range used in previous accelerated whisker growth experiments [9,16–18]. In some

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Table 1
Experimental parameters.

Sample	Current density (mA cm^{-2})	Plating time (min)	Grain size (μm)	Tin layer thickness size (μm)	Clamp pressure (MPa)	Average temperature
Sample I	9.70	5	2.84	0.85	9.21 ± 0.12	3 days at 186 °C in vacuum oven, followed by 2 days at 21 °C ambient
Sample II	5.69	10	5.22	2.59	6.84 ± 0.15	Ambient; 21.3 ± 1.6 °C
Sample III	9.24	12	6.0	2.68	12.0 ± 0.87	Ambient; 20.7 ± 0.4 °C
Sample IV	11.05	30	10.4	7.87	0.48 ± 0.02	Ambient; 20.8 ± 0.4 °C
Sample V	9.58	10	4.17	2.17	2.95 ± 0.02	Ambient; 20.7 ± 0.5 °C

preliminary experiments, whiskers appeared to grow from the interface between the substrate and the coating, suggesting that tin flowed to the whisker via the interface. An interface fluid flow mechanism is proposed for tin whisker growth and evaluated with respect to experimental data.

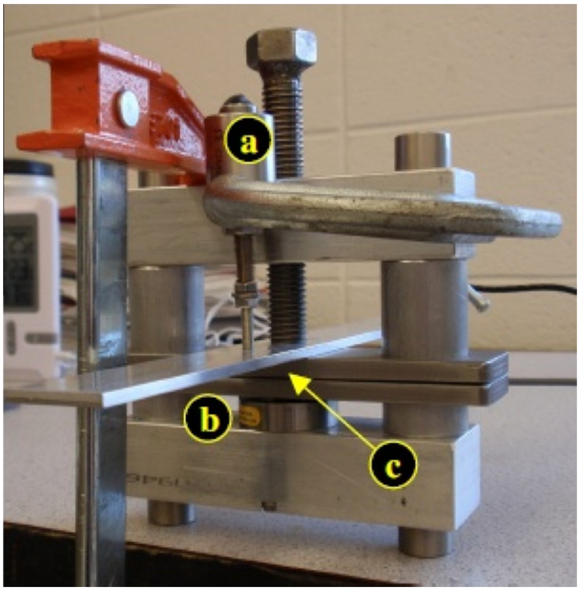

Fig. 1. Custom screw-type clamp, including (a) high-resolution LVDT, (b) 1000-lb button load cell, and (c) specimen loaded between two parallel steel plates.

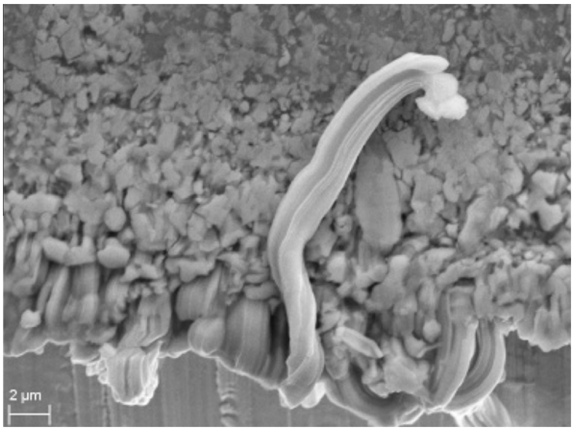

Fig. 2. SEM image of a whisker that nucleated at the substrate/tin coating interface. To observe the whisker growth on the sample's edge, the sample was tilted in the scanning electron microscope.

2. Experiment

Rectangular stainless steel substrates measuring ~1.00 × 0.50 × 0.005 in. were electroplated with tin using a commercial sulfuric acid-based plating bath (Caswell Inc.). Tin

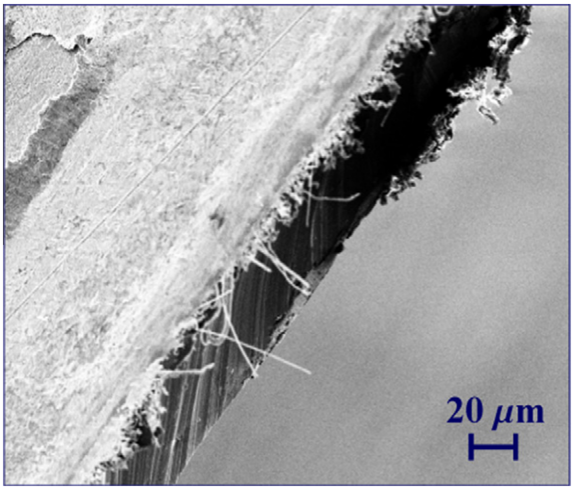

Fig. 3. Whiskers growing from the edge of Sample I after 5 days.

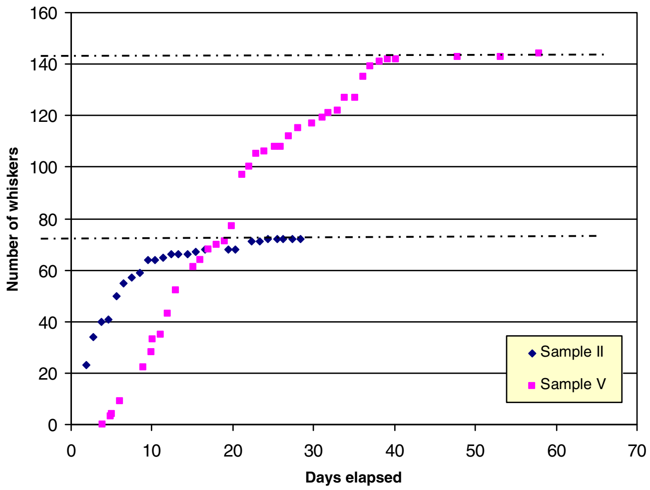

Fig. 4. Number of whiskers observed on Samples II and V over time, with whisker saturation levels marked with dashed line.

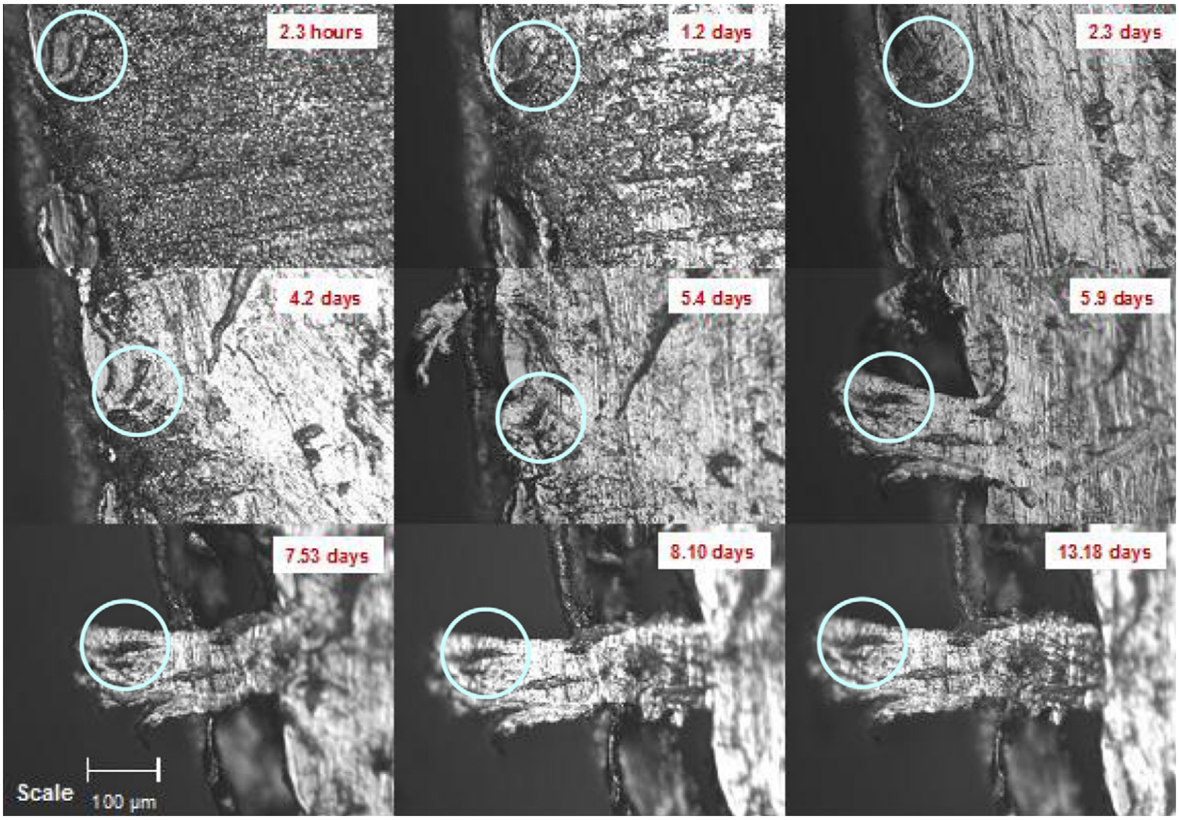

Fig. 5. Micrographs showing the development of an extruded tin “ribbon” on Sample III, with a surface imperfection circled in each image to illustrate its travel.

coating thickness was controlled through the electroplating parameters. The electroplating conditions, resulting microstructural properties of the prepared samples, and pressure/environmental conditions for each test are listed in Table 1. A custom-designed clamp (Fig. 1) was used to apply a compressive stress and drive accelerated tin whisker growth on the samples. The clamp was equipped with a 1000-lb load cell (Futek Advanced Sensor Technology), thermocouple (Omega Engineering) and high-resolution linear variable differential transformer (Omega Engineering). Displacement data tracked changes in the tin film’s thickness, while load cell data were used to calculate the stress level. All data were collected using a LabVIEW data acquisition system. Each experiment continued for 30–60 days, with the samples dismounted from the clamp daily for microscopic observation. A set of micrographs spanning a preselected observation region was prepared during each session.

3. Results

Whiskers grew on Samples I–III and V. Whiskers were not observed on Sample IV because the applied pressure was too low and/or the tin layer was too thick to promote whisker growth. On the other samples, whiskers grew preferentially from the tin/stainless steel interface as shown in Figs. 2 and 3. The whiskers observed did not grow immediately after clamping; in the three daily-observation experiments in which whiskers were observed (Samples II, III and V), the incubation periods were 1.9 days, 5.3 days and 4.9 days, respectively. The number of whiskers on each sample reached an apparent saturation for a given loading; after this saturation point had been reached, no new whiskers grew. This observation is illustrated by the data in Fig. 4 for Samples II and V.

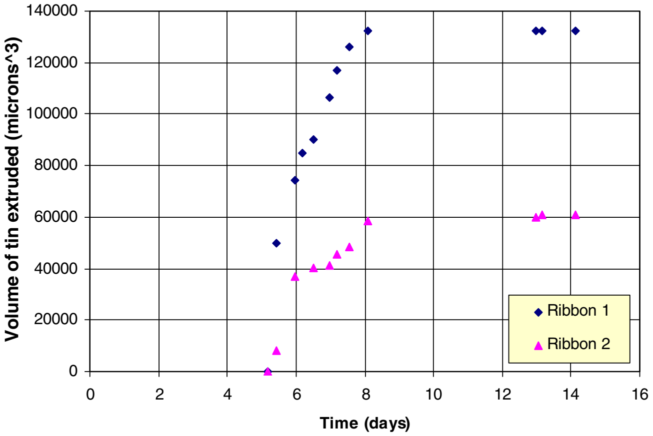

Fig. 6. Volume of tin extruded in “ribbon” growth vs. time.

In addition to whiskers, polycrystalline "ribbons" were also observed to grow from the edge of the tin coating in Sample III. The growth of one ribbon over time is illustrated by the series of micrographs in Fig. 5. The volume of tin moved during the growth of the ribbons, as shown by the plot in Fig. 6, was quite large—significantly greater than the volume of material moved during whisker growth. The volume of a typical 100-μm-long, 1-μm-diameter whisker is ~78.5 μm^3, while the two ribbons measured had final volumes of 1.3×10^5 and 6.1×10^4 μm^3, respectively. Jiang and Xian [19] observed single-crystal whiskers with rectangular cross sections, and Franks [18] also reported evidence of ribbon-like whiskers. However, the whiskers described in these papers are fundamentally different from the ribbons reported here. Unlike whiskers, ribbons were polycrystalline and sheet-like in appearance, as shown by the high-magnification scanning electron microscopy (SEM) images in Fig. 7a–c and f. The geometry and overall appearance of the tin ribbons suggest that they were tin extruded from the coating under the applied compressive stress. The microstructure (Fig. 7c) was consistent with extrusion, and the thickness of the ribbons was equal to the thickness of the tin deposit, indicating that the full thickness of the layer was pushed out through a few weak locations as if through an extrusion die.

A few papers have discussed the presence of extruded tin in clamped samples. Fisher et al. [9] observed a large amount of extruded tin in clamped specimens, and reported that whiskers did not grow from the extruded tin because the pressure there was too low. Franks [18,20] and Hasiguti [21] speculated that whiskers could grow only when general extrusion was inhibited. However, in the experiment described here, whiskers grew directly on extruded ribbons (Fig. 7d) and in their immediate vicinity (Fig. 7e). The shape of the extrusions observed here also differs from past reports, wherein extruded tin was not of significant length or of a well-defined shape.

The qualitative differences between whiskers and extruded material are discussed here to emphasize the distinction between these two phenomena. Many researchers

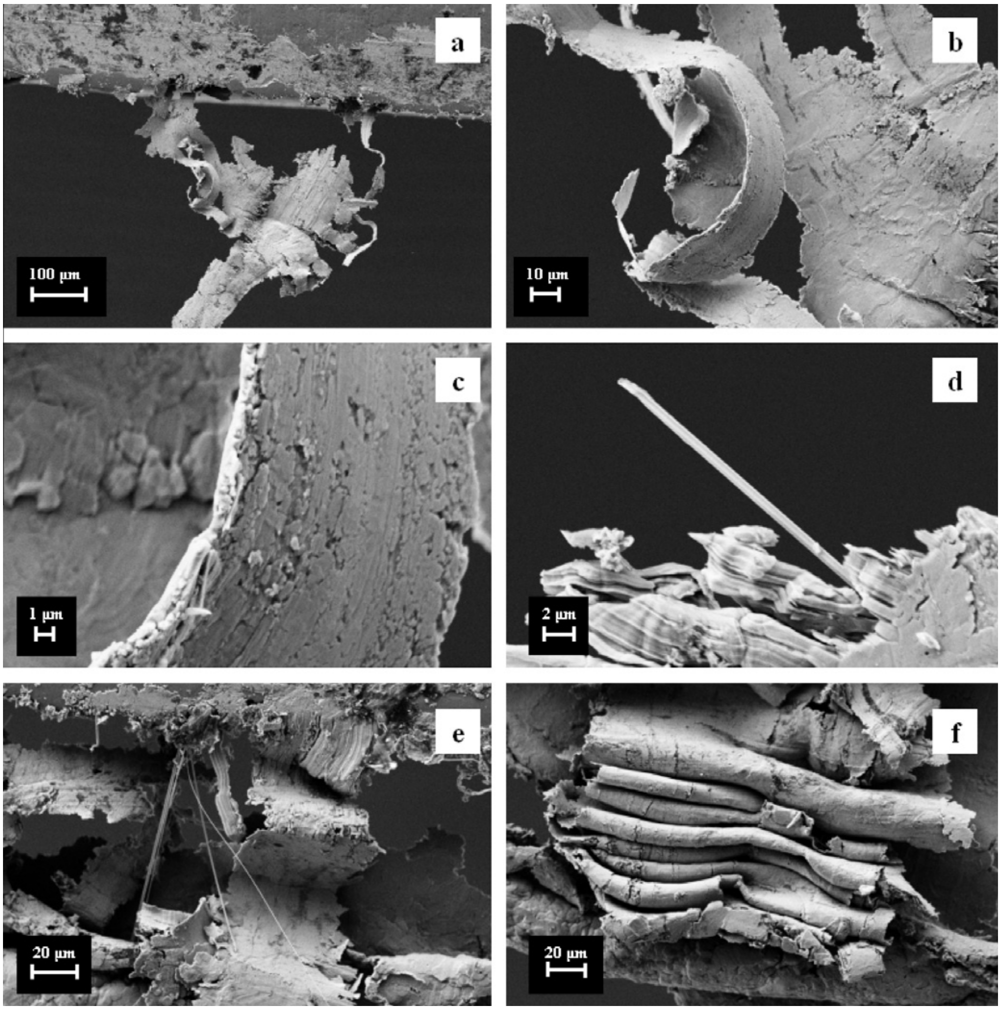

Fig. 7. SEM images of tin ribbons on Sample III: (a) ribbons extruded from tin coating; (b) close-up image of (a); (c) high magnification image, demonstrating the geometry and microstructure of the tin ribbon; (d) a whisker growing on the tin ribbon of (a); (e) whiskers growing together with ribbons; (f) a ribbon that has folded on itself during its growth.

consider whisker growth to be a mass extrusion process [3,22,23]. However, in these experiments, both extruded tin and tin whiskers were observed, and specific differences between the two were noted, including that: (1) whiskers were single crystals, while the extruded tin ribbons were polycrystalline; (2) whiskers are nearly perfect crystals with

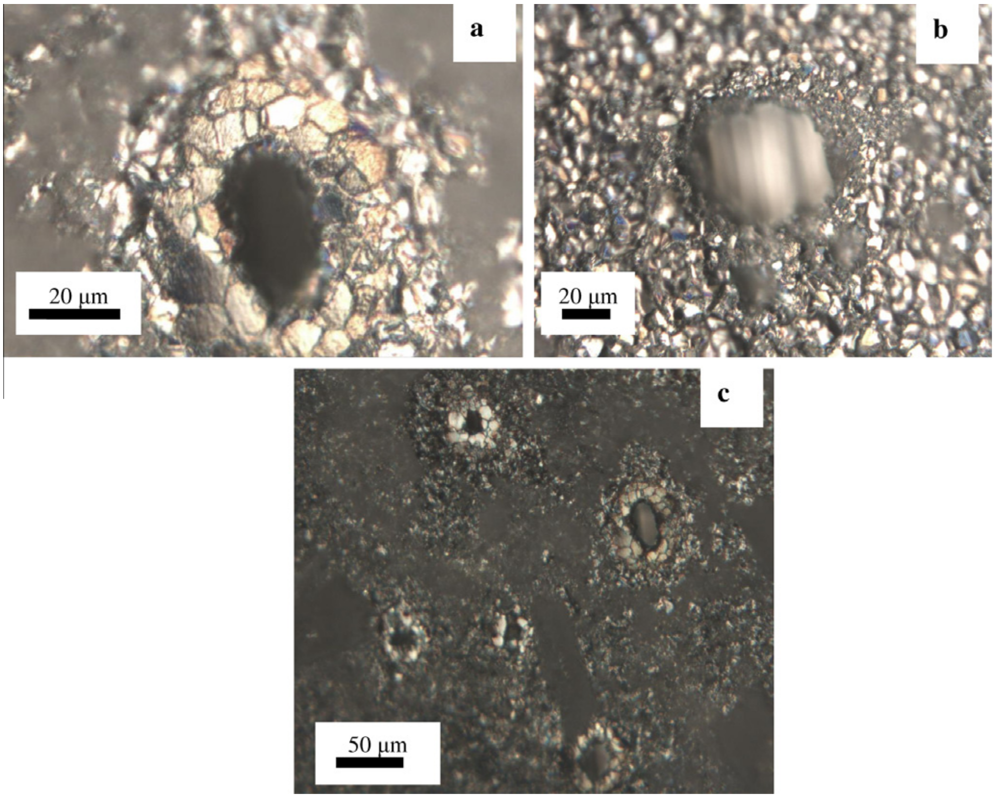

Fig. 8. Micrographs from Sample IV: (a) vacant region; (b) vacant region focused such that the base of the hole can be seen—it is the stainless steel substrate, with no tin residue; (c) overview image of an area in the tin coating including several vacant regions.

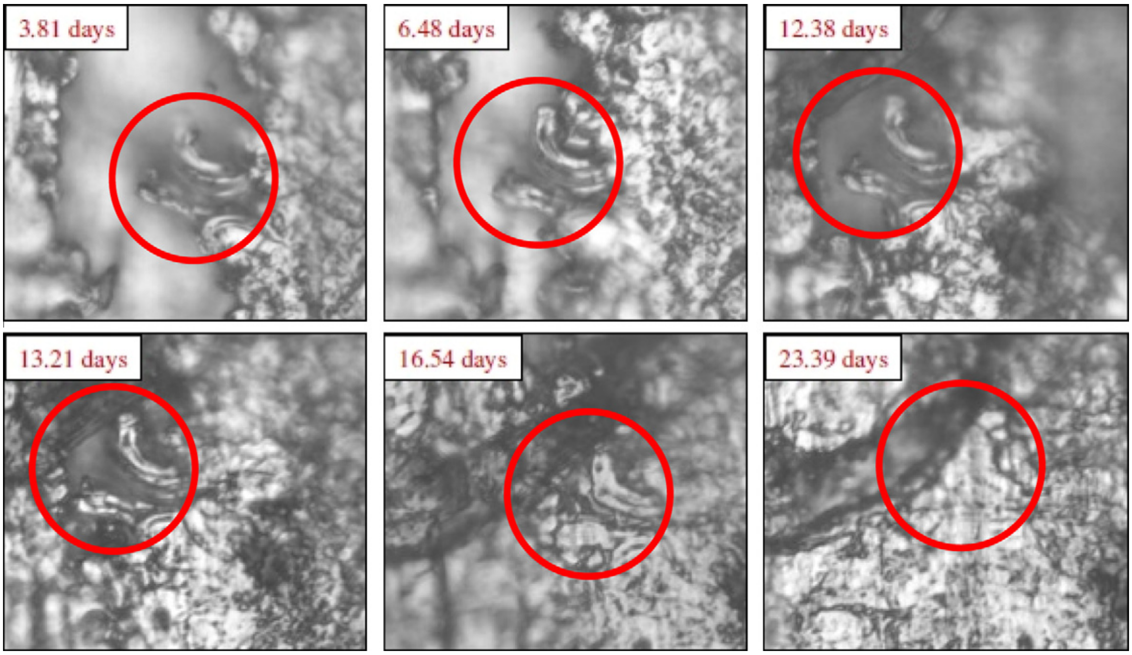

Fig. 9. Micrographs of the same position on Sample II imaged at various times in the experiment, showing that tin flowed to fill a vacant region on the specimen, eventually encompassing two whiskers (circled).

few defects [6,20,24,25], while extruded material can "carry" imperfections from the film (see circled imperfection in Fig. 5, for example); and (3) whiskers' diameters varied widely amongst whiskers grown from the same film, but extruded tin was consistently equal in thickness to the film.

A third phenomenon that was observed in this study was the formation of vacant regions or holes in the tin coating. Vacant (depleted) regions have been discussed only a few times previously in tin-whisker literature [26,27]. Representative micrographs of vacant regions on Sample IV are shown in Fig. 8. Vacant regions were as deep as the tin layer, as illustrated by Fig. 8a and b; the stainless steel substrate is visible at the base of each hole. An overview image of an area that contained several holes is shown in Fig. 8c. Vacant regions rapidly appeared, grew, shrank and disappeared in the tin coating in response to mechanical pressure, as shown by the example in Fig. 9. Whiskers often grew in or near the vacant regions, indicating that these phenomena may be coupled.

4. Interface flow mechanism for whisker growth

Grain boundary diffusion has been suggested by several researchers as a possible mechanism for tin whisker growth [2,15] and hillock growth [28], but it cannot explain the extremely rapid whisker growth rates that have been reported in the literature. See Refs. [12] and [14] for calculations of whisker growth rates predicted by grain boundary diffusion; the rates are much slower than rates observed experimentally [9,16]. It is proposed that the fluid flow theory provides the anomalously fast solid-state mass transport mechanism. Fluid flow is a faster transport process than diffusion, because group motions of atoms are possible in addition to individual motions [12]. In past reports, grain boundary fluid flow theory has been applied to describe material transport phenomena including tin whisker growth [12] and superplastic flow [29,30]. In this paper, it is further proposed that the fluid flow theory can be used to describe an anomalously fast mass transport process of tin atoms along the interface between a substrate and tin coating. Cheng et al. [31] recently proposed such an interface fluid flow mechanism to explain the growth of tin hillocks on vapor-plated films. The variant of Cheng's process, as it is applied to whisker growth, is illustrated schematically in Fig. 10.

The interface can be an important factor in whisker growth. Whiskers rarely grow on bulk tin [5,22], and the propensity for whisker growth on a tin coating is reduced when the thickness of the film is increased [2,3,32]. The composition of substrate and presence of underlayers have been shown to affect whisker growth significantly [3,13]. In other studies [26,33], materials from the substrate and adhesion layers were found in tin whiskers. For example, in the work of Cheng et al. [26], tin was vapor-deposited onto a silicon wafer over a chromium underlayer, and the wafer was deflected to produce compressive stresses in the tin layer. Whiskers that grew from the tin film contained both Sn and Cr, which was taken as direct evidence of interfacial flow carrying both Sn and Cr into the whisker. Additional specific examples of interface-initiated growth, which corroborate the findings of this study, are discussed in Refs. [13,23,31].

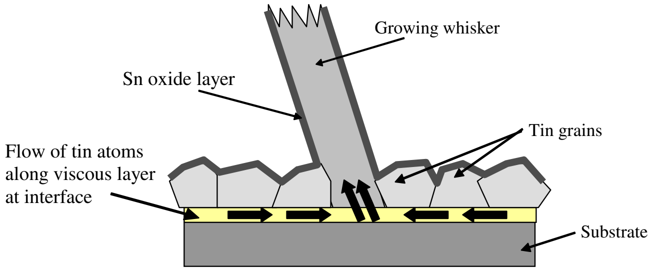

Fig. 10. Schematic illustration of interface fluid flow.

In the interface fluid flow mechanism, it is assumed that tin atoms can flow along a fluid-like layer at the interface between the tin film and the substrate. Tin constantly migrates along this viscous layer, preferentially traveling towards local low-stress regions. As compressive stresses build in the tin film, stress-free whiskers erupt. Preferred crystallographic orientation and weak points in the surface oxide are possible factors influencing whisker initiation. An entire tin grain can be pushed out from its base to nucleate a whisker as tin flows to the region beneath it via the interface. This explains why the tops of whiskers often resemble the grains in the original tin coating, a phenomenon that was observed in this study (see Fig. 2, for example), and has been reported in the literature for both tin whiskers [23] and hillocks [31]. The interface fluid flow theory can also explain the observation [5,6] that whiskers do not grow exclusively from along grain boundaries. Once a whisker has nucleated, tin is continually supplied to the whisker until the local stress gradient is exhausted.

Interface fluid flow could also provide a mechanism for the development of vacant regions, which appear to form, grow and shrink in the stressed tin coatings. Since tin atoms are able to flow along the interface, tin migrates away from those vacant regions to elsewhere in the film along a stress gradient, for example to feed developing whiskers. However, if the stress condition in the film changes locally, tin may diffuse back to a vacant region. Thus these regions can appear, change in size and disappear, despite a constant average stress in the coating. The sequence of micrographs in Fig. 9 illustrates the loss of a vacant region at a given location. The first micrograph (3.81 days) shows a vacant region with two whiskers growing at the boundary between the vacant region and the surrounding tin film. In the days that followed, tin flowed into the vacant region and eventually filled it completely, encompassing the whiskers that had grown there. The rapid motion of tin was supported by the fluid layer along the tin/substrate interface.

5. Conclusions

In this work, tin whisker growth was accelerated by applying mechanical pressure to tin-plated steel specimens.

Following an incubation period that ranged from 1.9 to 5.3 days, whiskers preferentially grew from the coating/substrate interface. Whisker growth in each experiment reached a saturation point for the given loading, after which no new whiskers formed. In addition to whiskers, large amounts of extruded tin were also noted at the sample edges. While both whiskering and extrusion were induced by the high mechanical pressure applied to the samples, the very different appearances of whiskers and extruded material in terms of geometry and morphology indicate that these mass transport phenomena stem from different mechanisms.

An interface fluid flow mechanism for tin whisker growth was proposed and evaluated with respect to experimental data. Fluid flow is a faster process than diffusion, and could explain the extremely high whisker growth rates that have been reported in the literature. The interface-transport mechanism also explains the tendency for whiskers to initiate at the substrate/coating interface, as observed in this work.

Acknowledgment

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