B.D. Dunn

Materials and Processes Division, European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Mechanical and Electrical Characteristics of Tin Whiskers with Special Reference to Spacecraft Systems

Abstract

Tin-whisker samples have been harvested from the surfaces of tin-plated parts from electronic equipment and subjected to laboratory tests. These whiskers were found to have a low strength (Young's modulus of 8.0—85 GPa and UTS of approx. 8 MPa). Whiskers with a diameter of 3 μm are capable of carrying a current flow of 32 mA. They remain undisturbed by subjection to either a wide vibration spectrum or to mechanical shocks reaching 200 g. Spark discharges have been shown to emanate from the sides and tips of tin whiskers in vacuum. Unwanted growths can severely jeopardise the reliability of spacecraft subsystems.

1. Introduction

A recent study of whisker growths protruding from electroplated tin coatings on both stressed and unstressed metallic substrates has attempted to account of the different morphological features of tin whiskers[1]. It was noted that the majority of sample substrates were seen to nucleate and grow whiskers even when certain recommended precautions[2,3] for reducing the risk of growth were taken by either utilising a copper barrier layer between a brass substrate and the plating, or by melting the tin electro-deposit. Nucleation periods were observed to range from between 3 d for whiskers growing on tin-plated barrier layers, to approximately 3.5 yrs for found on a fused tin coating. The tin whiskers were found to be single crystals having lengths of up to 1.6 mm. They range in diameter from 6 nm to 6—7 μm and have a population density in the order of 300 mm^{-2}.

A five-stage model for whisker growth has been proposed in Reference 1; it is based on the premise that local micro-stresses in the tin-plate can be eliminated by the ejection of tin atoms from the plated layer at sites of rotating screw dislocations. It is also postulated that a long-range atom-transport mechanism (diffusion) sustains these growths, which may be single crystals having either straight parallel sides or pyramid-like shapes.

Unwanted growths of tin whiskers represent novel defects that are known to severely jeopardise the reliability of electronic circuits[2—6]. This is particularly true if the whiskers are long (in the order of 1 or 2 mm) and produce electrical short-circuits in low-voltage equipment.

However, the acceptance of whisker growth as a prominent failure mechanism is not widespread among the designers and fabricators of electronic equipment and, even when the facts are known, some electronics continue to be constructed from materials known to develop whiskers. Such equipment might develop intermittent short-circuits and these will be particularly vexing when present during the ground testing of a spacecraft system. Unless the phenomenon is well-understood, events that might be labelled as 'mysterious' or 'random' failures and rated to be insignificant could well become spacecraft 'mission terminators'.

Financial constraints now necessitate that both high-reliability and commercial electronic systems, such as televisions, computer hardware and even land-based data-relay stations, incorporate the technique of redundant circuits and throw-away modules. This means that there is seldom a requirement for engineers to investigate the mechanisms that cause failures and it appears likely that a percentage of such rejected modules will support ubiquitous colonies of microscopic whiskers that will never be detected during any post-mortem by the 'forensic scientist'. Other factors in this argument include the growing shortage of skilled maintenance technicians and the wide availability of mass-produced low-cost circuits, making the throw-away maintenance philosophy more and more appealing.

This describes investigations performed to characterise a number of important mechanical and electrical properties of tin whiskers. Such whisker properties are related to the dynamic loading conditions associated with satellite subsystems that are subjected to handling during ground activities, and acceleration, shock and vibration during the launch and ascent stages prior to operational service.

The possible damage to whiskers caused by dynamic environments can be assessed by comparison with the documented laboratory test conditions. Additional influences of whisker growths on spacecraft reliability are considered, particularly their contribution to discharges and electrical insulation degradation whilst in Earth orbit. These effects, together with an evaluation of the current-carrying capacity of tin whiskers, are discussed below.

2. Experimental procedures

2.1 Mechanical properties of tin whiskers

2.1.1 Elastic properties determined by the Cantilever Method

Using a wide-angle stereo zoom microscope, tin whiskers were carefully plucked from the surfaces of a steel electronic circuit box housing that had been electroplated with an 8—10 μm finish or pure tin. As shown in Figure 1, this coating supported prolific growths of long whiskers.

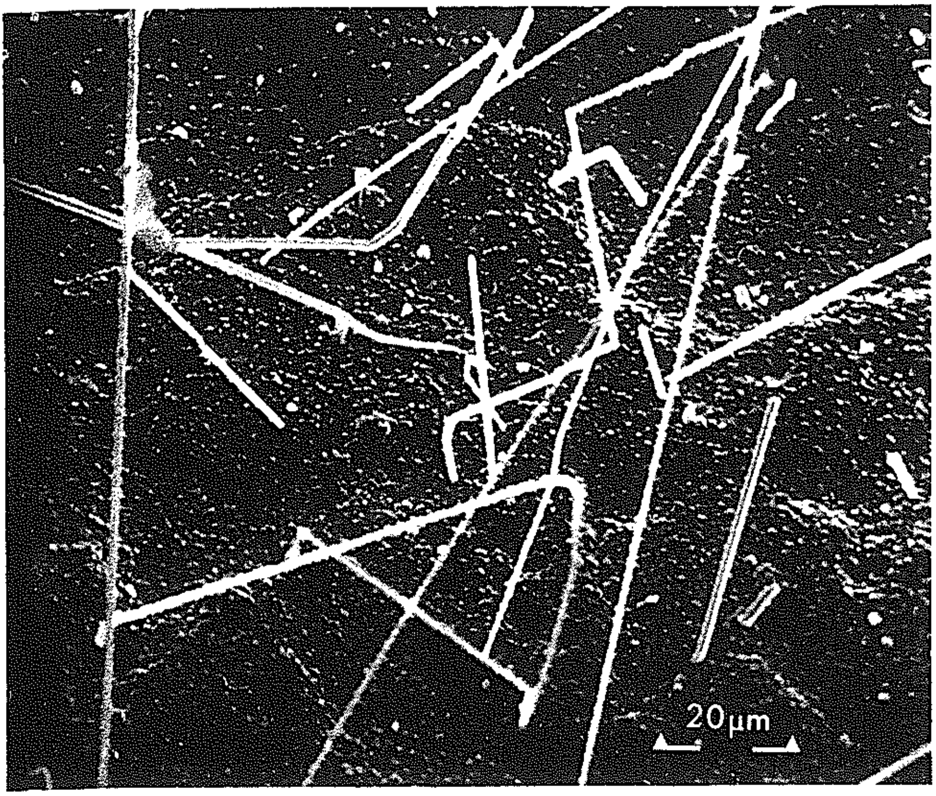


Figure 1. Scanning electron micrograph of whiskers present on tin-plated mild steel electronic housing

Individual whiskers were fixed at one end by partially embedding them into either a mound of freshly prepared epoxy resin, or the sides of molten hemispheres of indium solder located on the surface of small glass microscope cover slides. The slides supporting the indium alloy were heated in contact with a hot soldering iron held at 160°C. The heat source was removed and the whisker carefully held in place until the molten metal had solidified.

The dimensions of each projecting whisker were measured beneath the graticule of an optical microscope. Microfine gold wire, having a diameter of 40 μm and of the kind used for the interconnection of modern integrated circuits, was cut into known lengths and pre-formed at one end as a bent hook. This shaped end was first smeared with epoxy resin and then carefully slipped over individual whiskers. The gold wires were then initially resting on the horizontally protruding whiskers, as shown in Figure 2.

The glass slides were rotated, one at a time, through 90° so that each gold wire was made to hang onto the protruding whisker, which was now stressed in the manner of a cantilever beam.

The deflections, *d*, and the precise distance of the suspension point from the fixed end of the whisker *l*, were measured either with a travelling microscope or by reading off the re-focussing distance under a conventional microscope.

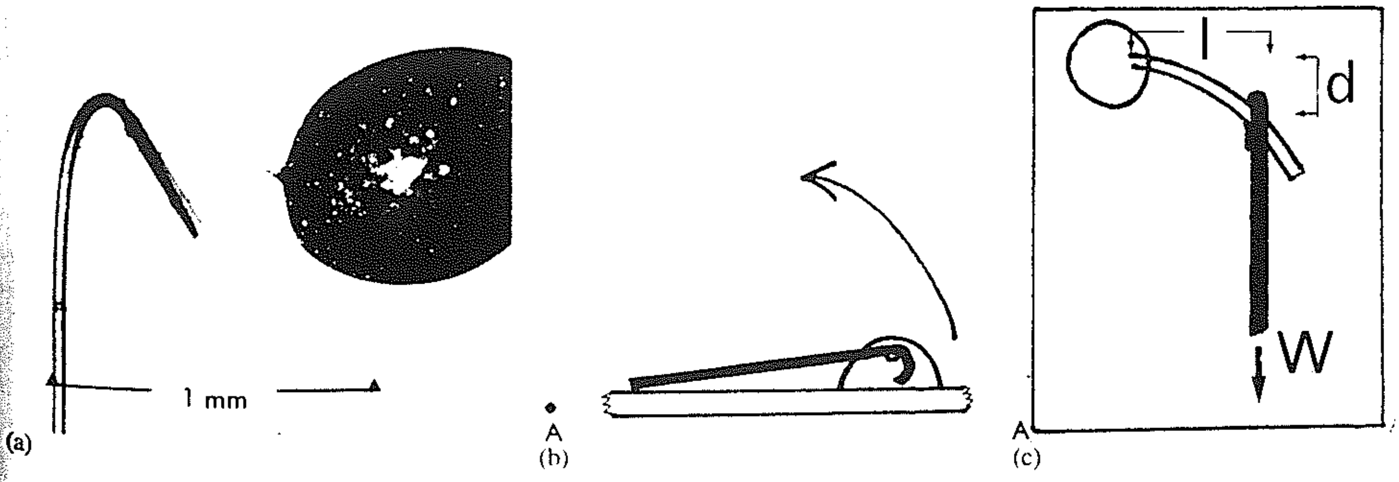


Figure 2. Cantilever beam loading of whisker

(a) Top view of gold weight resting on a whisker protruding from a hemisphere of indium alloy (optical photograph)

(b) Schematic side view of photograph in (a)

(c) Schematic front view after slide has been rotated 90° about line AA

These experiments, although difficult to perform, represent a fairly straightforward example of the application of bending-beam theory. As each whisker is relatively long compared to its diameter, the shear forces can be neglected and the Young's Modulus E calculated from

$$E = \frac{4Wl^3}{3d\pi R^4} \tag{1}$$

where W = the weight of the gold wire in grams
l = horizontal distance between fixed point and gold wire
d = the static deflection
R = radius of the whisker.

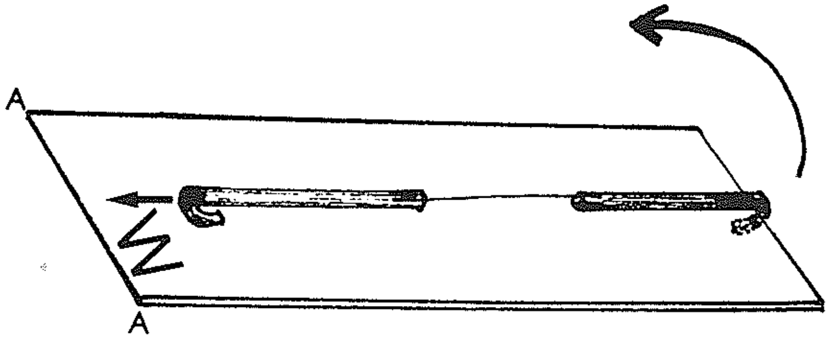
2.1.2 Uni-axial tensile strength

Tin whiskers of the size found on the tin-plated steel housing are far thinne d more delicate than those grown by, for instance, chemical means, during si - crystal production. It is thought unlikely that any commercial micro-tensile testing equipment exists that would be suitable for determining the tensile strengths of the whiskers under study.

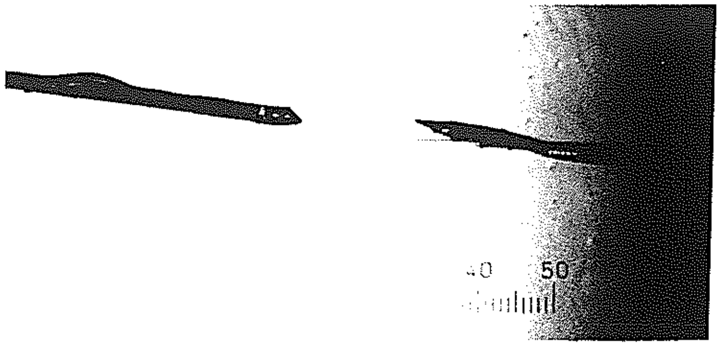
By means of a micro-manipulator tool and carefully hand held tweezers it was found possible to bond long whiskers to specially cut and formed lengths of gold wire. A fast-curing epoxy resin was applied to the gold wire ends by a smearing process. Adequate adhesion was achieved by embedding the whisker ends into this medium. The gold wire extensions to the whisker are shown in Figure 3. One wire could be around the edge of a supporting thin glass sheet. Once the glass slide was raised into a vertical position, additional wires could be hung from the hook on the lower gold attachment. The load on the free-hanging whisker was calculated from the sum of the lengths of suspended gold wires.

The tensile strength (UTS) of these whiskers is calculated from

$$\text{UTS} = W/\pi R^2 \tag{2}$$



(a)



(b)

Figure 3. Tensile test set-up is shown schematically in (a), rotation of glass slide around line AA brings load into vertical position, (b) shows whisker adhesively bonded to gold wire, its gauge length is about 450 micrometres. Tensile loading caused fracture at mid-gauge length point

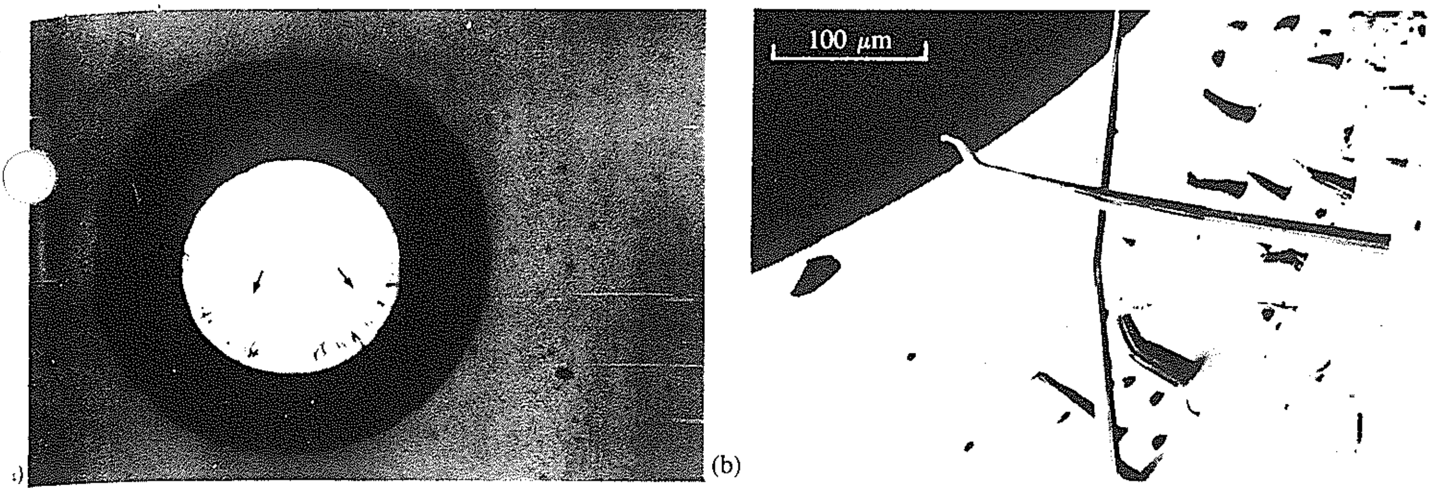


Figure 4. Micrographs of typical whiskers growing within the tin-plated copper through holes of a printed circuit board
(a) Optical shadowgraph; (b) SEM micrograph

2.1.3 The natural frequencies of whiskers and the effect of vibration on growths

(i) Natural frequencies

Spacecraft are subjected to vibration environments during ground operation, ascent, stage separation and, in the case of Spacelab, re-entry. Electronic equipment is generally hard-mounted to the spacecraft structure and will receive vibration and shock over a wide frequency range, from 5 to 2000 Hz. The manner in which a whisker can vibrate is known as its vibration mode and this is associated with its natural frequency. Calculations have been made of the theoretical natural frequency of a wide range of tin-whisker sizes and these results are presented in Table 1.

(ii) Effect of vibration on whisker growths

Rectangular samples were cut from two whisker-growing substrates, the tin-plated steel (Fig. 1) and tin-plated printed circuit boards (Fig. 4). Each sample had a surface a of approximately 6 cm^2 and supported a variety of whisker sizes, including some long ones (0.8—1 mm long and 1—4 μm in diameter).

Although most samples supported whiskers growing vertically from their top surfaces, samples were also selected which supported edge or side-of-hole growths, so that both axial and flexural loadings would be experienced.

Selected areas of each as-received sample were macro-photographed and sketched so that damage or whisker breakages caused during vibration testing could be assessed by reference to these comparators. The sample were then bonded flat-wise in pairs, (one piece of tin-plated steel together with one printed circuit board (PCB)), to a thick steel plate that could be mechanically attached by screwing onto the vibration test equipment.

The test samples were subjected to the full range of frequencies that would cause each whisker to oscillate at its natural frequency and hence be loaded to a maximum stress level. Vibration testing was performed in air. Firstly, Test A, sinusoidal sweep between 10 and 2000 Hz, was conducted, divided into three groups of accelerations as shown in Figure 5. The samples were then inspected and subjected to vibration Test B, at defined frequencies of 50, 100, 200 and 250 Hz, each at 6 g and for a duration of 60 s. After re-inspection, the same samples were finally submerged in a commercial ultrasonic cleaning bath filled with isopropyl alcohol (Test C) operating at a nominal frequency of 20—25 kHz for a period of 2 min.

2.1.4 Mechanical shock on tin whiskers

Spacecraft electrical systems will be subjected to mechanical shock at various stages during their shelf and operational lives. The same form of whisker growth samples were used during the vibration tests were subjected to controlled shock testing on unegan Model 4501 tester. These samples were also initially macro-photographed. The samples were attached with a thick water-soluble coupling oil to the shock table. Shock loads were increased from 20 to 2000 g (the equipment's upper limit), at a pulse width of less than 1 ms. During this test, each sample was periodically removed from the table for comparative inspection against its initial macro-photograph.

Table 1. The theoretical natural frequency of tin whiskers

Whisker dimensions (mm)		Theoretical natural frequency f_n (Hz)
Length	Radius	
4.0	0.0020	36
4.0	0.0010	18
4.0	0.0005	9
2.0	0.0020	143
2.0	0.0010	71
2.0	0.0005	36
0.5	0.0020	2281
0.5	0.0010	1141
0.5	0.0005	570
0.2	0.0020	14260
0.2	0.0010	7130
0.2	0.0005	3565

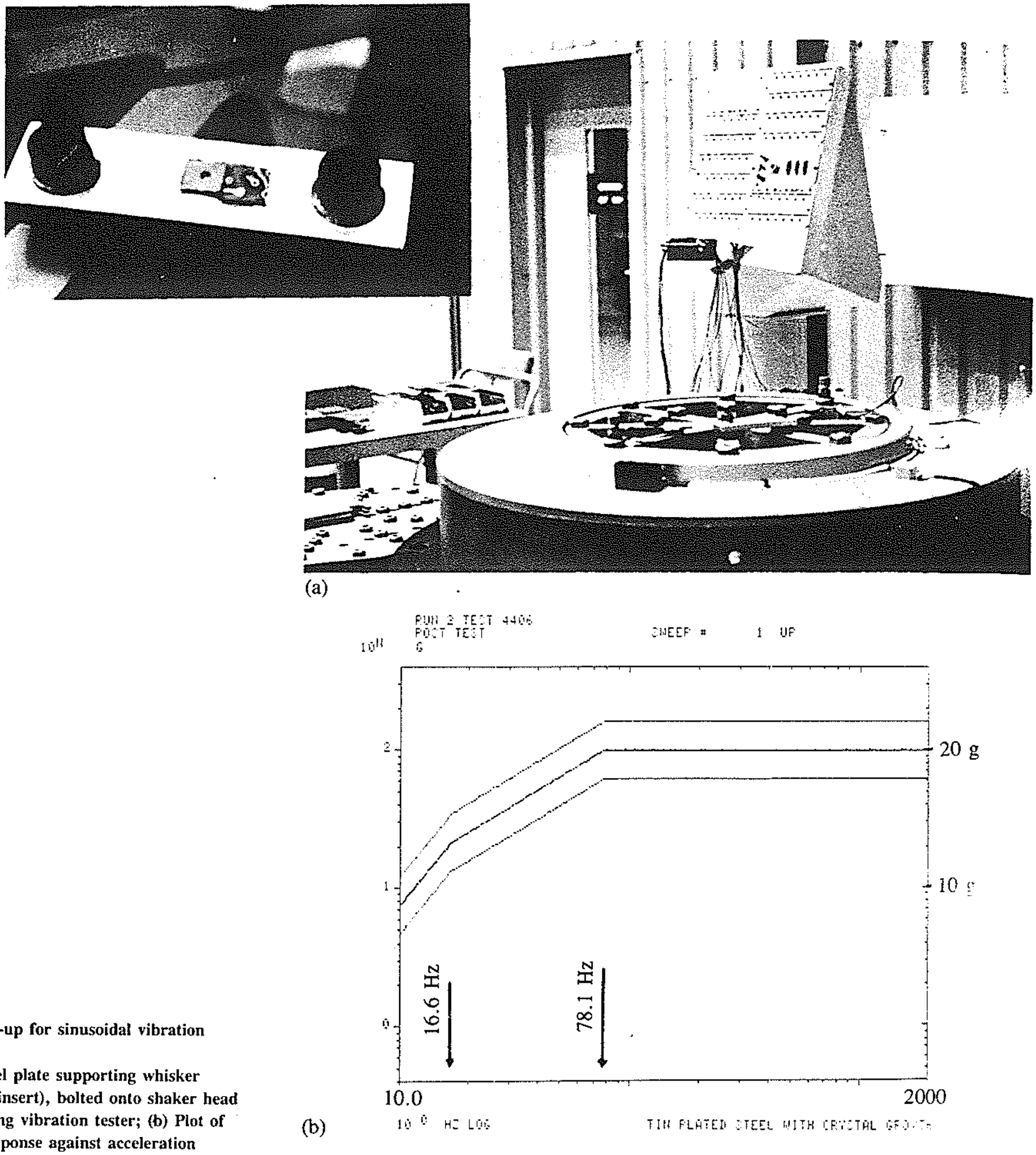


Figure 5. Set-up for sinusoidal vibration testing
(a) Thick steel plate supporting whisker samples (see insert), bolted onto shaker head of a 7 ton Ling vibration tester; (b) Plot of frequency response against acceleration

2.2 Electrical properties of tin whiskers

2.2.1 Current-carrying characteristics

Attention was first drawn by Arnold in the 1950s to the serious threat that spontaneous tin-whisker growths posed to the reliability of densely packed electronic assemblies[5,6]. These filaments had lengths of 2 mm and were reported to be capable of carrying currents of the order of 10 mA. The method for achieving the measurements was not described.

The following tests were made on whiskers longer than 1.5 mm that had been carefully plucked from the tin-plated sample seen in Figure 1.

The ends of these single filament whiskers were attached to clean glass microscope slides with small deposits of 'conductive' silver-loaded epoxy resin. Each glass slide was placed onto a microprobe station possessing a microscope stage and a TV video display, as shown in Figure 6. The microprobes were made of platinum-coated tungsten and could be connected to a Tektronic 576 visual display unit for monitoring electrical parameters, as highlighted in the photographs. Two probes manipulated onto the silver-loaded epoxy mounds, but this composite material had insufficient conductance for any meaningful current-carrying measurement to be made. Instead, the thoroughly cleaned probes were slowly positioned to rest on the whisker surfaces. Successful current-carrying measurements were obtained at carefully measured probe separation distances (0.3—0.8 mm). Applied currents were increased and corresponding voltages were recorded until the moment just prior to the burning-out of each whisker.

2.2.2 *Field emission study*

The final test was designed to establish whether it is possible for tin whiskers to act as the source of microscopic electrical discharges (such as observed during the corona breakdown of vacuum gaps). Several flakes of tin were detached from the tin-plated mild steel. Those supporting whiskers were placed onto the adhesive glue surface of a square of double-sided tape that was attached to a small brass specimen stub of a Scanning Electron Microscope (SEM).

A schematic and photograph of a typical flake are shown in Figure 7. Small pointed lengths of aluminium electrically conductive tape were positioned (by manipulation under a zoom stereo-microscope) in the vicinity of the protruding whiskers. The aluminium tape was in firm electrical contact with the SEM specimen stub and hence to ground. This setup was investigated at various electron energies (1—35 keV) within the JEOL SEM. The probe current is an instrument constant of 1 nA.

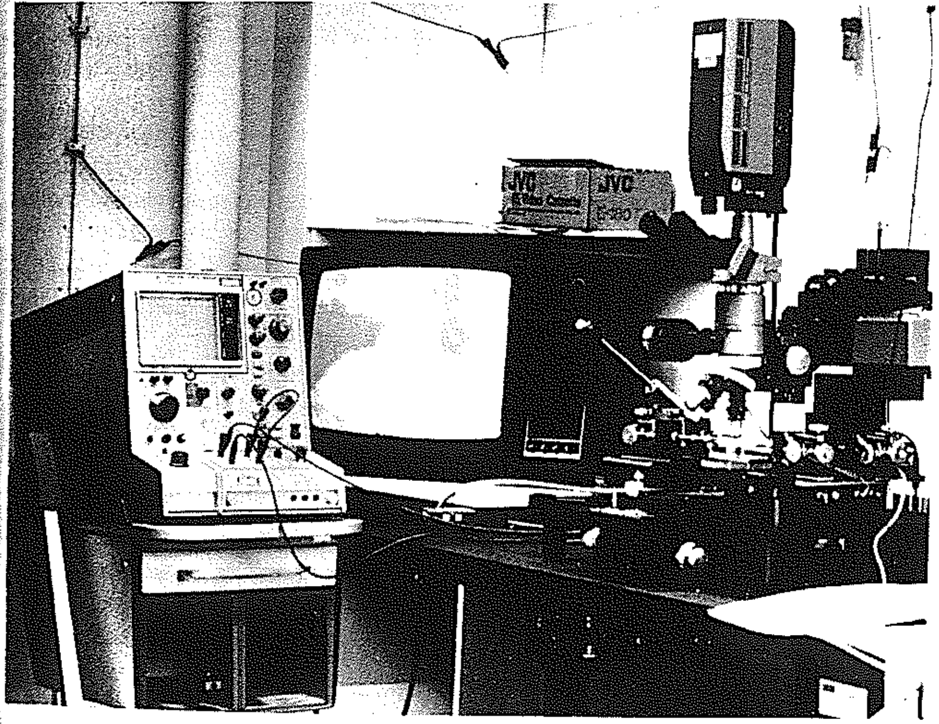
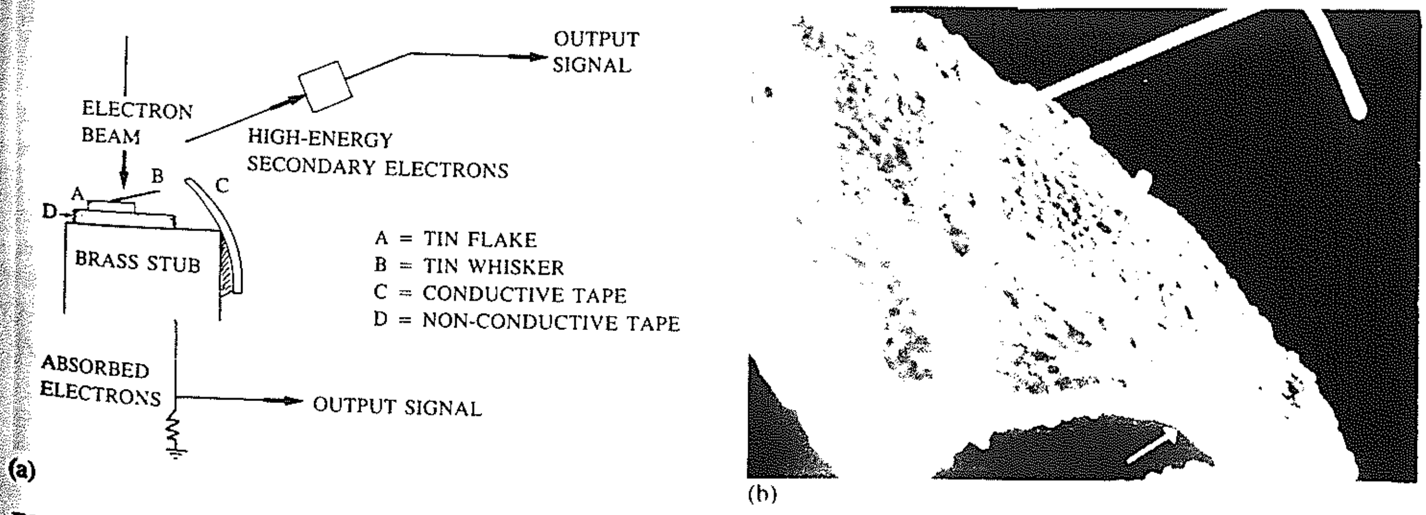


Figure 6. Test set-up for measurement of electrical characteristics of tin whiskers showing the microprobe station with auxiliary equipment such as T.V. monitor and resultant VI display on the Tektronix curve tracer

Figure 7. Charging and Field Emission simulated in a Scanning Electron Microscope. The schematic drawing (a), and photograph (b) of a tin flake (the arrow indicates where the flake is glued to non-conductive tape). A fine electron beam is focused onto the tin flake which become charged. The tapered point of a length of conductive aluminium tape is positioned to face the whisker, the other end is grounded to the specimen stub



3. Results and discussion

3.1 Mechanical properties of tin whiskers

3.1.1 Elastic properties

The various measurements made during the testing of five different whiskers have been tabulated and the calculated values of their corresponding Young's moduli are given in Table 2. These values range from 802 to 8480 kg/mm^2 and involved what was initially regarded to be a large degree of scatter. Indeed, one of the most difficult dimensions to measure experimentally is the radius of the whisker and, as may be noted from Equation 1, this value will greatly affect the accuracy of the final calculations (in which R^4 is used).

A literature search was made to determine whether other experiments had been made to establish the Young's modulus of tin whiskers. The only reference to be found was that data for large single crystals from Schmid and Boas, which is quoted by Barrett[7]. It would appear that single crystals of white beta tin possess at least two growth directions, and that formulae relating stress to strain must take into account the variation in 'stiffness' attributed to these different directions. According to data quoted by Barrett, the variation in Young's modulus (E) for beta tin single crystals is:

— E_{maximum} in the [001] direction = 8640 kg/mm^2.
— E_{minimum} in the [110] direction = 2680 kg/mm^2.

Except for one anomalous value, the results presented in Table 2 are similar to those given by Barrett. The average Young's modulus from Table 2 is 3200 kg/mm^2 and this value will be employed in subsequent calculations in Section 3.1.2.

As an additional remark, the anomalously low value of E listed in Table 2 (sample c) with a modulus of 802 kg/mm^2) may result from the mathematical calculation which assumes whisker cross-sections to be circular. As will be described in Section 3.3.1 and in Figure 9, certain whiskers appear to have a rosette-shaped cross-section and these may be expected to have an actual cross-sectional area somewhat smaller than that determined from the optical measurements of whisker diameter.

3.1.2 Uni-axial tensile strength

Three whiskers were tested in the manner illustrated in Figure 3. Fracture was observed to be instantaneous at a stage when additional weights were being added to the lower hook. Minute shocks during the loading operation are thought to have contributed to these slightly premature whisker breakages.

Three whiskers were noted to support a gold wire having a maximum length of 10 cm. High magnification measurements as shown in Figure 3 confirmed each whisker to be initially straight and have uniform diameters of approximately 2 μm. Measurements of the amount of plastic deformation occurring within the "gauge lengths', up to the moment of fracture proved difficult to assess, but it was considered to be about 20%. The plastically deformed whisker was noted to have lost its characteristic longitudinal striation pattern and local glide planes or slip bands were just distinguishable on the surface of the necked region adjacent to the fracture.

Table 2. Calculated values of the Young's Modulus from loading tin whiskers in the bent-beam mode

No.	Whisker dimensions (mm) Length (l)	Radius (R)	Deflection (d)	Weight of gold wire ($W \times 10^{-5}$)	Young's Modulus* E (from Eqn. 1) (kg/mm^2)
a	0.5	0.0015	0.2	3.64	1907
b	0.6	0.0020	0.1	3.64	2085
c	0.5	0.0020	0.2	4.84	802
d	0.5	0.0010	0.3	4.84	8480
e	0.3	0.0010	0.2	4.84	2774

* The average Young's Modulus is noted to be 3200 kg/mm^2

Determination of the Ultimate Tensile Strength (UTS) of these whiskers, from Equation 2, gave a result of 0.8 kg/mm^2.

Comparative values for the strength of tin whiskers could not be found in the literature. In a recent review Donald[8] has tabulated the properties of fine metallic nd intermetallic filaments having diameters in the 1—100 μm range. Although tin is amongst those filaments produced by a number of available methods, these are no data listed regarding its mechanical or electrical properties. The Tin Research Institute (TRI) were also unaware of published data, but were able to provide room-temperature data for pure polycrystalline cast tin tested at a very slow strain rate of 0.0114 cm/cm/min: 0.60 kg/mm^2 yield point and 1.04 kg/mm^2 UTS.

The laboratory ad-hoc test result for the tin whiskers cannot be directly compared with the TRI data, due to the different mechanism of loading, but it does appear to be in the same order of magnitude.

These results are considered to be, at best, only an approximation of the tensile properties of tin whiskers, as many uncertainties are associated with the method of testing and once suspended the whisker will be subject to the effects of creep. On the basis of this experimental work it is concluded that tin whiskers possess a low tensile strength and are highly ductile.

3.1.3 Effect of vibration on growths

Detailed assessments of the theoretical natural frequencies of tin whiskers possessing various shaft diameters and different lengths were given in Table 1. The range is expected to vary from 36 to 14 260 Hz. The vibration spectrum encountered by electronic packages during, for instance, a spacecraft launch, is severely limited by the damping effects of the metal structure, bolts and packages, so that the very high whisker resonance frequencies will never be encountered and only the range 10—2000 Hz need be considered.

The following test exposures were devised to cover the predominant frequency nges and magnitudes that may be encountered during spacecraft ground handling and in particular during launch, when much additional vibration is derived from acoustic noise (i.e. the sound field developed by the extreme turbulence of the jet exhaust downstream from the rocket engine):

Test A: Sinusoidal sweep

When starting testing, it was considered that because the internal damping of these whiskers would be extremely low, resonance would soon break the majority of whiskers. To avoid this, the first test was devised to be a fast frequency sweep, so that excessive dwells in the vicinity of any natural frequency would be avoided. Detailed optical examination following this preliminary test revealed no damage to have been incurred by any whiskers; selected areas of view were identical to the original photographs and sketches.

The 10—2000 Hz range of frequencies was then covered in two sweeps, at a speed of 2 oct/min. These frequencies were split into three groups of accelerations:

10 —16.6 Hz	38 mm peak-to-peak
16.6—78.1 Hz	200 cm/s
78.1—2000 Hz	100 g.

The output measurements from two accelerometers screwed onto the sample mount and the vibration control monitor are shown in Figure 5.

A very detailed visual examination of the samples was made after the two sweeps of this test. Inspection at magnifications of up to ×40 under a stereo-zoom microscope *iled to detect any evidence of broken or deformed whiskers, and all appeared iden- al to the original macro-photographs.*

Test B: Long-term vibration at defined frequencies

The time spent at any one resonance frequency in Test A was designed to be short to avoid excessive whisker damage. The samples were then removed from the Ling equipment and replaced onto a small Dunegan Model 4501 laboratory system, which was more cost-effective for longer duration vibration runs. The model 4501 was programmed to vibrate each sample at a series of preselected frequencies: 50, 100, 200 and 250 Hz, each at 6 g and for a duration of 60 s.

Undoubtedly, whiskers having the natural frequencies of this test series existed on the samples under test, but again meticulous microscopical inspection revealed *no evidence of damaged or detached whiskers after exposure to this test.*

All materials can fracture when they are subjected to repeated stresses that are siderably less than their ultimate static strength, but testing under conditions A or B did not exceed the fatigue life of a single whisker.

This may be accounted for by three factors (in any combination):

- the endurance limit stresses were not reached
- the number of fatigue cycles did not reach an end of life value, and
- the whiskers are so homogeneous and free from surface discontinuities that no surface stress concentrations are available for fracture initiation.

Test C: Ultrasonic vibration in liquid

The test specimens were finally placed into a metal basket and lowered into a commercial ultrasonic cleaning bath filled with isopropyl alcohol. The bath was operating at nominal frequency in the range 20—25 kHz, this being above the 16 kc/s frequency limit of human audibility. The vibrations were produced by means of an ultrasonic transducer welded to the base of the cleaning bath. The 'cleaning cycle' was maintained for 2 min.

The results of the final visual inspection revealed that the majority of surface whiskers had been removed from the tin-plated steel sample, but that little alteration had occurred to the growths of whiskers present within the PCB plated-through holes.

3.1.4 The effect of mechanical shock

Shock loading is a transient condition where the equilibrium of a system is disrupted by a sudden applied force. Electronics may be exposed to shock as a result of accidental rough handling during transportation, at the moment of launch-vehicle ignition, and at the moment of pyrotechnic actuation. Such impact forces can result in the generation of stresses up to and beyond the elastic limits of materials.

During vibration testing, tin whiskers were exposed to accelerations 100 times greater than that produced by the Earth's gravity, but no whisker damage occurred.

It is surprising to record that *no examples of damage to any whiskers* were observed, even though some samples had been subjected to 50 shocks at a displayed level of 2060 g. As no whiskers were noted to break or deform during shock loading, neither their yield or UTS had been reached, presumably due to the very low inertia of each whisker.

3.2 Electrical properties of whiskers

3.2.1 Current-carrying capability

Current-carrying capacities of several whiskers were established by increasing the applied current and recording the corresponding voltages. The expected $V=IR$ straight-line relationship was observed until Joule heating effects progressively increased (for these whisker dimensions) the specific resistance of each whisker, finally resulting in whisker melting ('burnout').

The current/voltage curves for four typical whiskers (identified as A—D) are shown in Figure 8.

The full results of the electrical measurements are given in Table 3. It is interesting to note that the whiskers designated A and B have electrical resistivity values almost identical to that quoted in reference books for pure tin (i.e. 11.3 $\mu\Omega$ cm). The thicker whiskers, C and D, have slightly larger resistivities and lower current-carrying capabilities, which might indicate that they possess internal defects. These latter results appear at first sight to be unusual, but it should be noted that other experiments, which used radioactive tin as a tracer element to study the actual growth mechanism of tin whiskers, concluded that whiskers were in fact often hollow[9]. This observation was made by comparing the physical dimensions of whiskers with their determined weights. The reduced density may also result from their rosette-like cross-

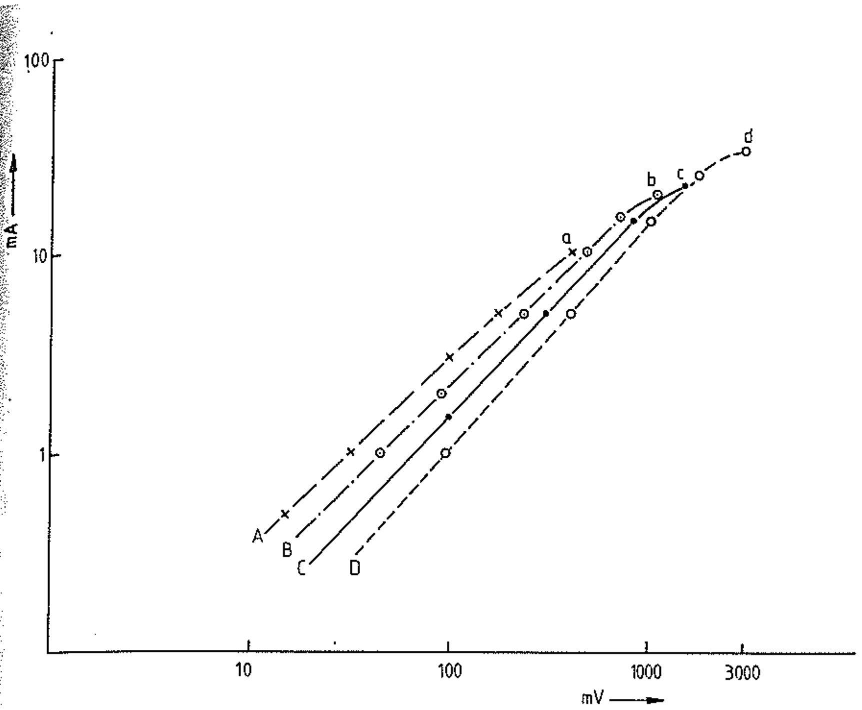


Figure 8. Logarithmic plots of current vs voltage for four whiskers. Relationship is linear until heating effects cause burn-out at a, b, c and d

section. As illustrated in Figure 9, the cross-sectional area of a rosette shape is, of course, somewhat less for a circular section of identical diameter.

3.2.2 Field-emission results

The scanning electron microscope was usefully adapted to apply an electric charge to the tin whiskers attached to electrically insulating tape. The great depth of field of the SEM revealed a remarkably captivating display of charge build-up (shown as light regions on the TV monitor) on the insulating film and along the edges of the tin flake and whisker. At an accelerating voltage of 1 kV, no charging is evident. At higher voltages an extremely dynamic image of charging patterns, visible as light concentric areas and fringes, is observed due to the small but finite conductivity of the adhesive surface. At 5 kV and higher, certain areas of the specimen become so highly charged that the electron beam apears to deflect away from it and the image become intermittently distorted.

By selectively tilting, the specimen stub streaks of light were seen to flash across the screen, each being emitted from a whisker tip. The streaks were either momentary or lasted several seconds. Usually these pulses of electron discharge interferred with the electrical circuitry of the SEM, terminating with a 'white-out'. It was not possible to record these short-term events on the 90 s exposure camera system built into the microscope.

Table 3. The electrical characteristics of four typical tin whiskers

Specimen	Dimensions of whisker between probes		Applied current (mA)	Measured voltage (mV)	Resistance (Ω)	Resistivity (10^{-8} Ω m)	Current-carrying capacity (A/cm$^2 \times 10^{-5}$)
	Diameter (μm)	Length (mm)					
A (a)	1.1	0.3	5	170	34	10.8	
(b)			10	400	40	12.7	10.0
B (a)	1.5	0.7	5	225	45	11.4	
(b)			20	1050	52	13.1	11.0
C (a)	3.0	0.8	15	1000	67	59.2	
(b)			32	3000	94	83.1	4.5
D (a)	2.8	0.8	15	800	53	41.0	
(b)			22	1500	68	52.5	3.5

(a) at room temperature; (b) at high temperature of burn-out

Note: The resistivity of pure polycrystalline tin at room temperature is 11.3×10^{-8} Ω m.

Instead, attempts to photograph the phenomena were made with a hand-held 35 mm camera. The results are shown in Figures 10—12. Although the majority of spark discharges are bright white, it was noted that several whiskers, possibly those having a special orientation, have a dark, nonluminous tip that is surrounded by a 'dark glow'. None of the whiskers were observed to melt or break as a result of the charging/discharging.

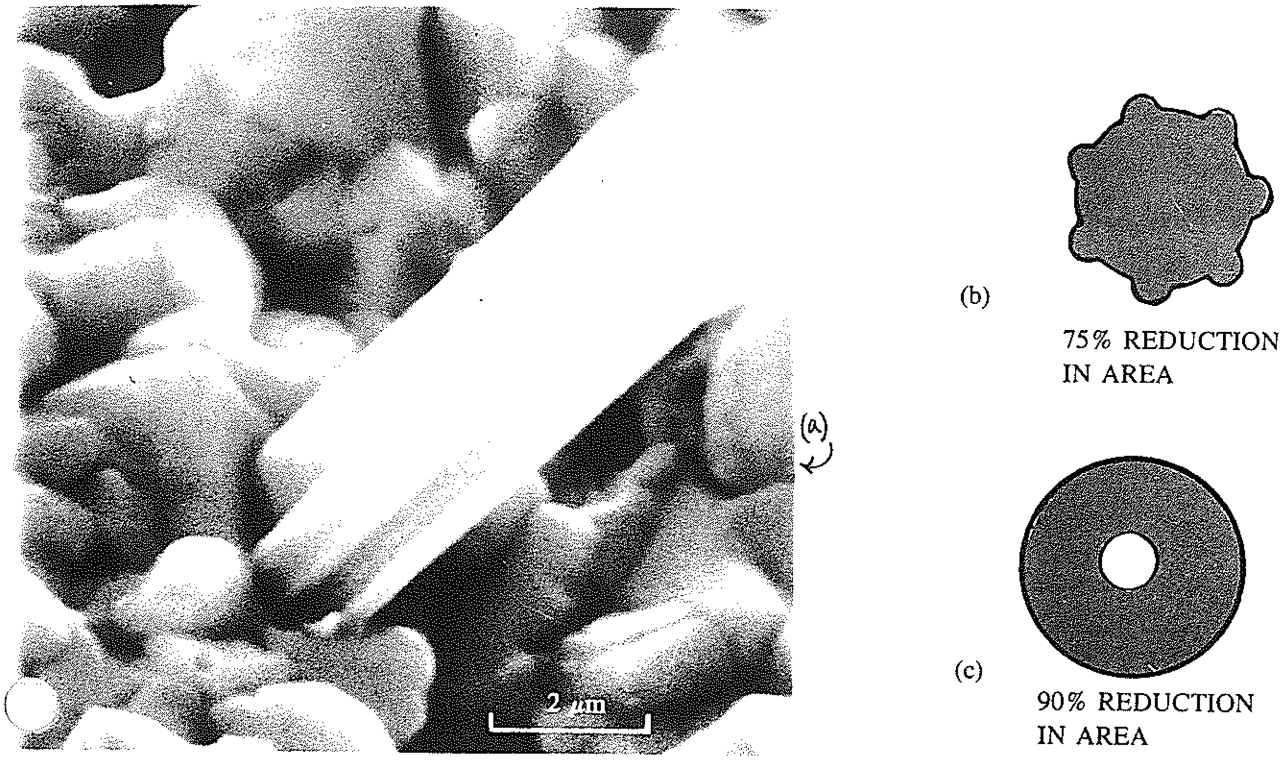
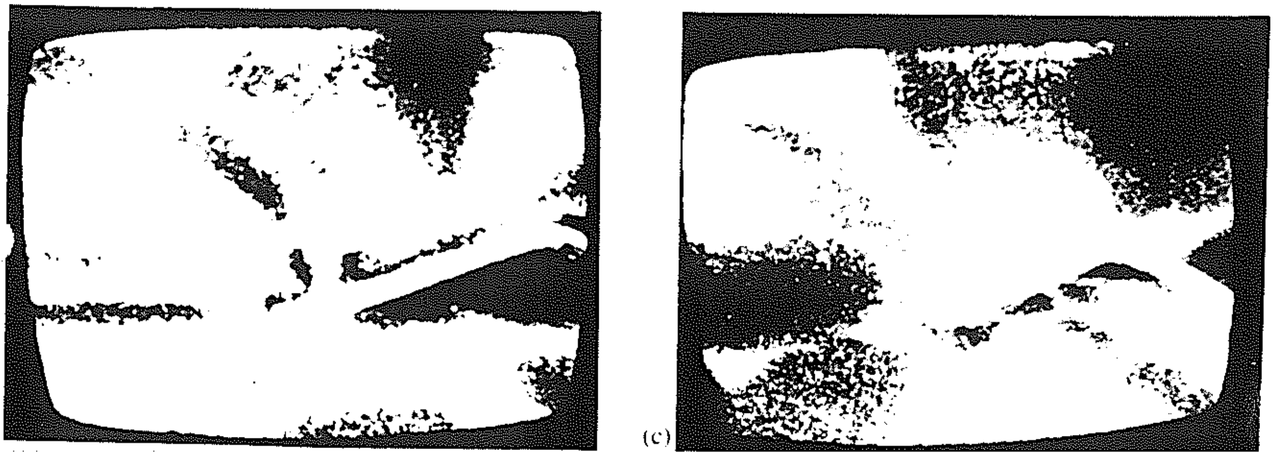


Figure 9. Illustrations to account for the apparent reduced cross-sectional area of some whiskers
Detail of the flutes or striations on shaft of a whisker emerging from plating (SEM image); (b) Rosette shape of some whisker shafts; (c) Hollow whiskers as proposed in Fig. 9

Figure 10. Spark discharges originating from the white, highly charged tip of a tin whisker. Each photograph was taken after a time interval of 20 seconds (whisker movement required the image to be refocused before 1/60 second film exposure). Magnification approximately ×1000

(a)



(b) (c)

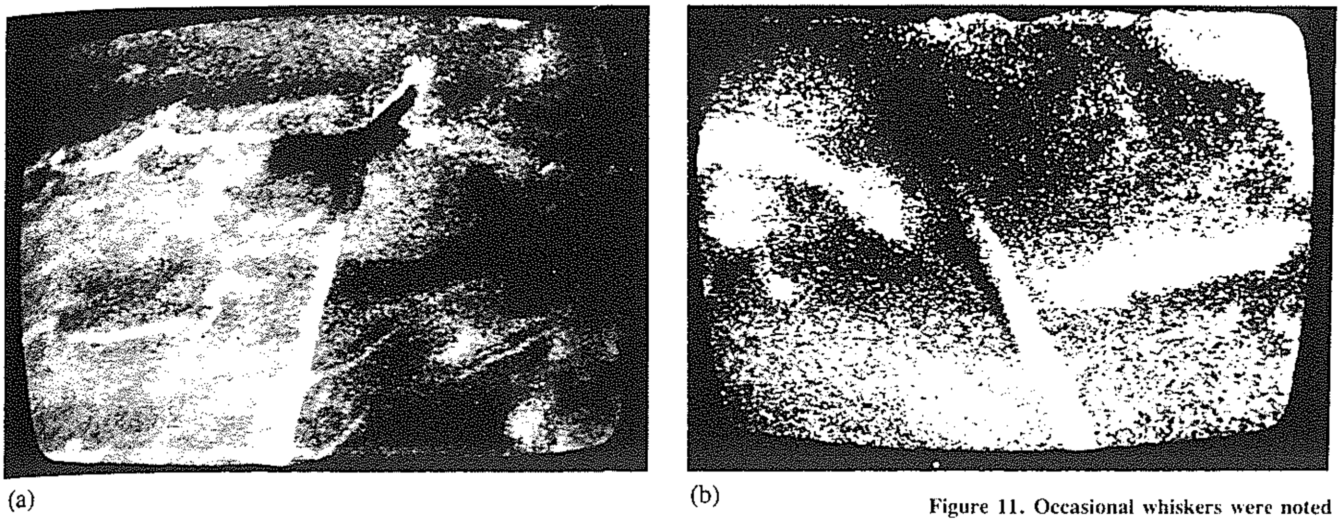

(a) (b)

Figure 11. Occasional whiskers were noted to have a dark, non-luminating tip that is surrounded by a dark 'glow'

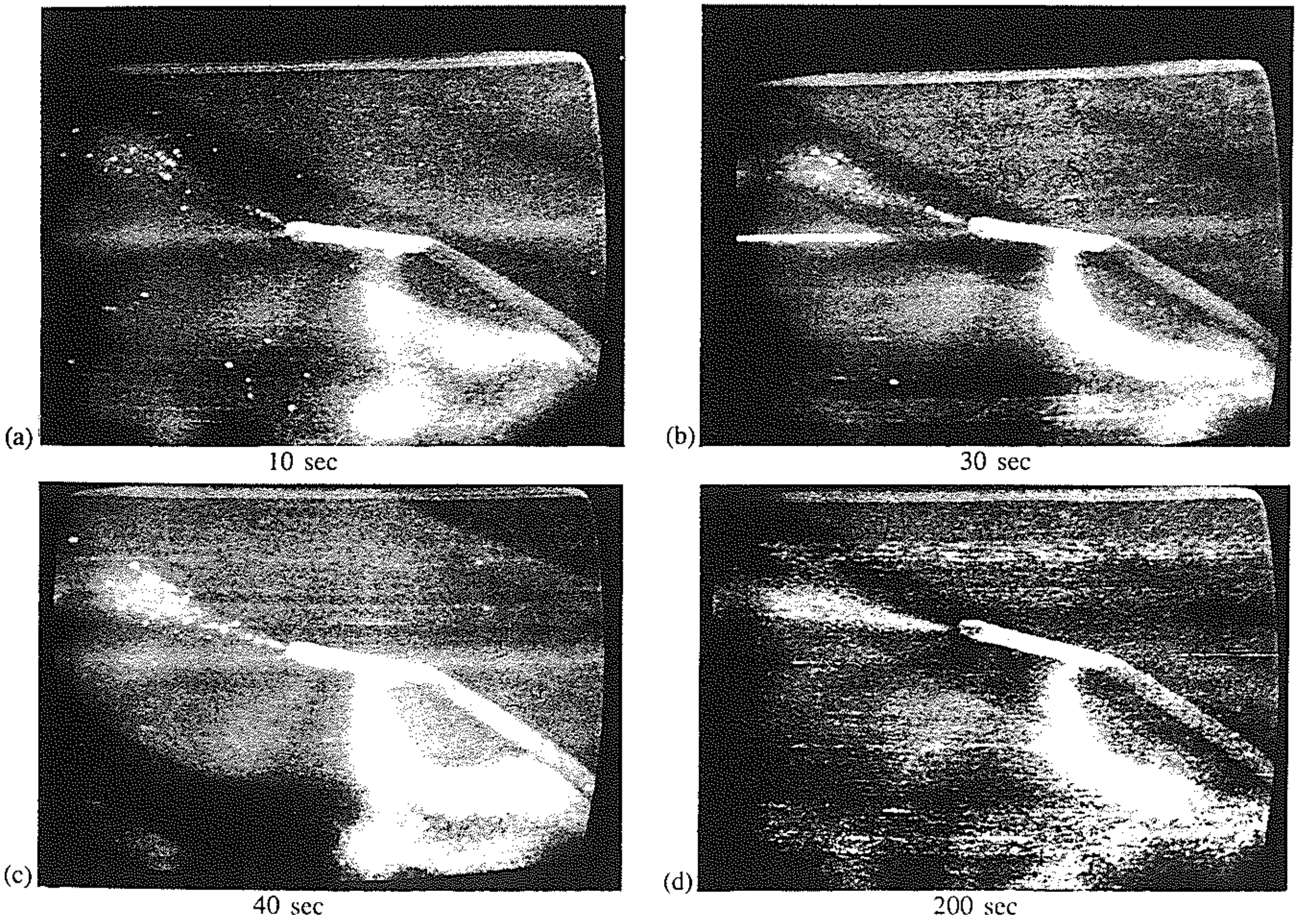

(a) 10 sec (b) 30 sec (c) 40 sec (d) 200 sec

Figure 12. Only the initial length of this whisker is seen to possess a white glow, the remainder of its shaft (after the kink) appears grey. The tip supports a fine point from which sparks discharged for a period of more than 5 minutes. The emissions, all at 20 kV, have the appearance of discrete white 'particles' or a fine spray as shown towards the end of the 5 minute display (d). No damage (erosion or melting of the tip) was observed at the end of this event

4. Review of mechanical and electrical properties of tin whiskers and their effect on spacecraft systems

The laboratory work presented in Reference 1 has demonstrated that whiskers will grow naturally from several tin-plated substrate materials. Clearly, whisker development includes three definite steps: a highly variable incubation period, a period of growth at a reasonably constant rate, and a sudden transition to a far lower growth rate. The detrimental effects that tin whiskers might cause to the miniaturised mechanical and electrical devices contained within spacecraft subsystems are also attributable to whisker-prone surfaces such as cadmium and zinc.

Figure 13 shows the gyrations that take place when whiskers grow. There is a need to consider the effect of such protuberances when they occur in the immediate vicinity of *delicate mechanisms with moving parts.*

Spacecraft consist of many kinds of high-precision moving parts, such as miniature rotary switches, Sun-sensor pivots, bearings, etc. each of which can conceivably become fouled. The long nucleation times and slow whisker growth rates could result in a particular mechanism being tested and qualified satisfactorily for flight usage, only to become jammed by whiskers that attain a critical size during subsequent operations in space.

Electronic hardware launched by both Ariane and the Shuttle can be expected to endure vibrations and shocks in the frequency range 5—2000 Hz. Even though this range was traversed at high loading factors for relatively long periods, conditions causing whisker fracture were not achieved in any of the vibration or shock tests performed in air. This is surprising, as vibration-associated problems, such as the breaking or loosening of parts and fasteners, are renowned design-wreckers during the vibration excitation of spacecraft hardware. Either the endurance limit stresses were not reached, or the number of fatigue cycles did not attain an end-of-life value. These findings are in direct contradiction to the conclusions of other authors who postulate that whiskers can become detached by vibration-induced stresses resulting from the operation of machinery.

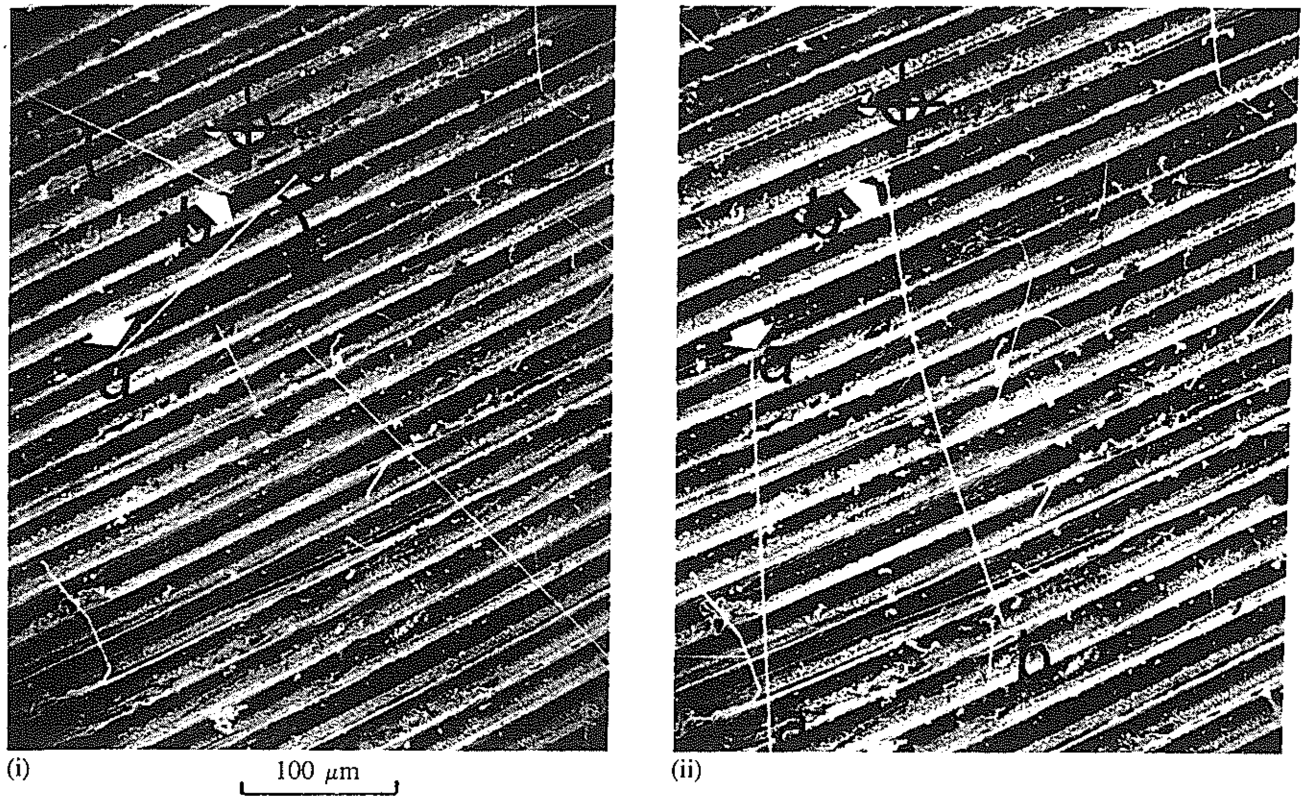
An *effective method for the removal of whiskers* from planar growth sites was found to be immersion the tin-plated steel housing into an ultrasonic bath filled with isopropyl alcohol. Such baths operate at 20—25 kHz, a range that is somewhat greater than the 20 kHz maximum frequency experienced by spacecraft launch vehicles. This method was unable to detach those whiskers growing *within* the plated-through holes of printed circuit boards. The ultrasonic vibrations within a liquid are rather effective for the removal of surface whiskers because the alcohol is continually subjected to acoustic waves that cause local pressure variations. Depending on the vapour pressure of the liquid, small amounts of alcohol evaporate, creating a tiny vapour cavity that will collapse within a fraction of a second. The continual generation and implosion of vapour cavities, called 'cavitation', has a very strong mechanical effect on an adjacent whisker.

Implosion of cavities creates local pressures in excess of 100×10^6 Pa and similar effects in sea-water have been seen to wear out a ship's propeller in a short space of time. It would appear that PCB material dampens the acoustic wave, so that there is insufficient energy for cavitation to occur within the small geometry of a plated-through hole. Great risks are involved when electronic systems are subjected to ultrasonic cleaning and experience shows that sinusoidal vibration can stress the internal wires of microcircuit packages and cause fracture of wire-to-chip microweldments.

Cleaning of whiskers from electronic circuits either ultrasonically or by physically brushing them off components can be considered a useful repair procedure. However, this may not permanently prevent the regrowth of whisker remnants or the reoccurrence of electrical/mechanical problems induced by the growth of new whiskers.

Tin whiskers have been found to carry relatively large currents as shown by the 'applied current (*I*) versus measured voltage (*V*) curves' presented in Figure 8. The full results are given in Table 3.

As a useful guide, the maximum electrical currents that could be applied to the tested whiskers immediately before burnout or fusing, have been plotted against the measured diameters of individual whiskers. This graph, Figure 14, is an important illustration of the dangers that whiskers could create in on-board electronics in a space environment. Instant burnout and possible arcing occur in Zone B of this graph. Zone



(i) (ii)

Figure 13. Attention is drawn to the whiskers 'a' and 'b'. The white arrows show where they emerge from the tin-plated copper surface. These SEM images were taken (i) 57 days and (ii) 181 days after tin-plating. During this 124 days period the whiskers' increase in length are 125 μm and 110 μm respectively for 'a' and 'b' (approximate growth rate of 1 μm per day). During growth whiskers have continually rotated in the directions shown by the black arrows on (i). (From Ref. 1)

A is a region where whiskers can cause an electrical short-circuit for a brief time before burning-out. Of great consequence to spacecraft test engineers is the effect of whiskers in Zone C, which do not fuse but remain electrically conducting between two circuit lines.

These kinds of malfunctions, forming wrong connections, leakage currents and other similar problems, are exasperating, costly and often extremely difficult to diagnose in low-voltage electronic equipment. Jammed or noisy lines can cause spacecraft computer systems to malfunction. Whisker short-circuits may change a logic '1' state to a logic '0' state causing a flip/flop, internal to the computer, to set and make the entire unit stay permanently locked into an interrupt service routine. Similarly, onboard computer memories can cause erroneous behaviour that may culminate in a complete memory failure. High-voltage equipment is unlikely to be subject to catastrophic short circuits, as in this case it is probable that the whiskers will burn out.

The phenomenon of static electrification has been known of thousands of years; it is also termed 'electrostatic charging'. One of the greatest hazards to geosynchronous spacecraft is associated with the build-up of charge on exposed external surfaces. This surface charging results from the spacecraft encountering a plasma of ions and electrons that originates either from illumination by sunlight or from geomagnetic substorms. Many recent satellite experiments have evaluated the trapped electron environment that can build up differential voltages of up to 17 kV, resulting in electrostatic discharge from surface materials[10—12].

The discharge is usually (but not always) a luminous glow intermittent in nature between a spark discharge and a non-luminous point discharge[13]. Similar features have been recorded in the present work (see Figure 10—12). These phenomena depend on the electric-field gradient, the ambient pressure and the presence of protrusions such as whiskers which then produce a local field enhancement and result in a field emission current across the vacuum gap separating the cathodic and anodic metallic surfaces.

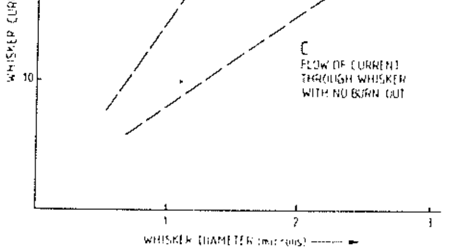


Figure 14. Graph to illustrate the effect of whisker diameter on possible short circuiting whisker (Values from Table 3)

5. Conclusions

Laboratory investigations have provided new data related to the mechanical and electrical properties of tin whiskers. The whisker samples had grown directly from the surfaces of a tin-plated mild steel electronic housing and the tin-coated-copper plated-through hole terminations on a printed circuit board.

The observed scatter in some results is likely to be due to variations in each whisker's unit-cell parameter (there are at least five crystallographic growth directions of tin whiskers) and difficulties in measuring the absolute cross-sectional area of whiskers supporting flutes (with rosette-shaped sections).

The mechanical properties of tin whiskers are approximately:

Young's modulus (E) = 800—8500 kg/mm^2
Ultimate Tensile Strength (UTS) = 0.8 kg/mm^2

They appear to be unaffected by exposure in air to whisker resonance frequencies within the range 10—2000 Hz (i.e. the vibration spectrum encountered by electronic parts during, for instance, a spacecraft launch). Under mechanical shocks at a displayed level of 2060 g, whiskers remained undisturbed owing to their very low inertia.

Only whiskers directly exposed to ultrasonic cleaning in a bath containing isopropyl alcohol (operating at 20—25 kHz) were removed. However, extensive cleaning times failed to dislodge those whiskers that had grown within the plated-through holes of printed circuit boards.

The electrical properties of tin whiskers are dependent on their actual diameters. Room-temperature resistivities can vary from 11 to 60×10^{-8} Ω. Actual current flow through 3 μm diameter whiskers can reach 32 mA. Current-carrying capacities appear to peak at 11×10^{-5} A/cm^2.

High-voltage discharge can emanate from the sides and tips of tin whiskers situated on electrically charged surfaces. Spark discharges (i.e. corona) and nonluminous point discharges from whiskers have been demonstrated in a scanning electron microscope.

The work reported here illustrates the ability of tin whiskers to grow, rotate and provide paths for electrical shorts between adjacent circuits. It is strongly recommended that surfaces known to support whisker growth be excluded from all high-reliability mechanical and electrical devices. Plated layers of tin, cadmium and zinc can be replaced by an electroplated, then fused, tin-lead alloy[14,15].

References

1. Dunn B D 1987, A Laboratory Study of Tin Whisker Growth, ESA STR-223, September 1987.
2. Britton S C 1974, Spontaneous Growth of Whiskers on Tin Coatings, *Trans. IMF*, **52**, p. 95.
3. Gabe D R 1987, Whisker Growth on Tin Electrodeposits, *Trans. IMF*, **65**, p. 115.
4. Nordwall B D 1986, Air Force Links Radar Problems to Growth of Tin Whiskers, *Aviation Week & Space Technology*, 30 June, pp. 65—69.
5. Arnold S M 1956, Growth and Properties of Metal Whiskers, *Proc. 43rd Am. Electroplaters Soc.*, p. 26.
6. Arnold S M 1959, Growth of Metal Whiskers on Electrical Components, *Proc. Electrical Components Conference*, pp. 75—82.
7. Barrett C S 1952, Structure of Metals, McGraw Hill Book Co., New York, p. 533.
8. Donald I W 1987, Review, Production, Properties and Applications of Microwire and Related Products, *J. Mat. Science*, **22**, pp. 2661—2679.
9. Kehrer H P & Kadereit H G 1970, Tracer Experiments on the Growth of Tin Whiskers, *Appl. Phys. Lett.*, **16**, No. 11, pp. 411—412.
10. Elkman W R et al. 1983, Electrostatic Charging and Radiation Shielding Design for Satellites, *J. Spacecraft and Rockets*, **20**, pp. 417—424.

11. Mizera P F 1983, A summary of Spacecraft Charging Results, *Idem.*, pp. 438—443.

12. Balmain K G 1987, Arc Propagation, Emission and Damage on Spacecraft Dielectrics, *AGARD CP-406,* **16**.

13. Frederickson A R 1983, Electric Discharge Pulses in Irradiated Solid Dielectrics in Space, *IEEE Trans.*, **EI-18,** pp. 337—349.

14. Dunn B D 1976, Whisker Formation on Electronic Materials, *ESA Sci. Tech. Rev.*, **2**, pp. 1—22.

15. Dunn B D 1980, The Fusing of Tin-Lead Plating on High Quality Printed Circuit Boards, *Trans. IMF,* **58**, pp. 26—28.

Manuscript received 14 January 1988