

## Tin Whiskers in Electronic Circuits

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<p>Fibrous, conducting "whiskers" often grow on pure tin plating. These tin whiskers have, for many years, been known to pose a reliability problem in electronic circuitry. The use of pure tin coatings in any critical electronic application is therefore not recommended. Despite the warnings of the experts, tin plating is still found on electronic and mechanical components and problems with whiskers still arise. This document summarizes what is known about the growth of tin whiskers. A number of factors (e.g., coating thickness, plating conditions) are thought to be important in determining whether whiskers will grow. Although tin whiskers have been investigated from some decades, there is still disagreement on the effects of virtually every coating parameter. There is no disagreement, however, on the essential fact that it is very difficult to predict with certainty whether whiskers will grow on any specific tin-plated component, which of course is the basis of the "experts" advice not to use pure tin plating.</p> <p>If tin-plated components are found in an electronic system, replacement is the safest policy. Some additional recommendations to minimize risk are presented here that may be of use in situations in which replacement of all suspect components is not the option of choice because of cost or schedule constraints.</p>			
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## CONTENTS

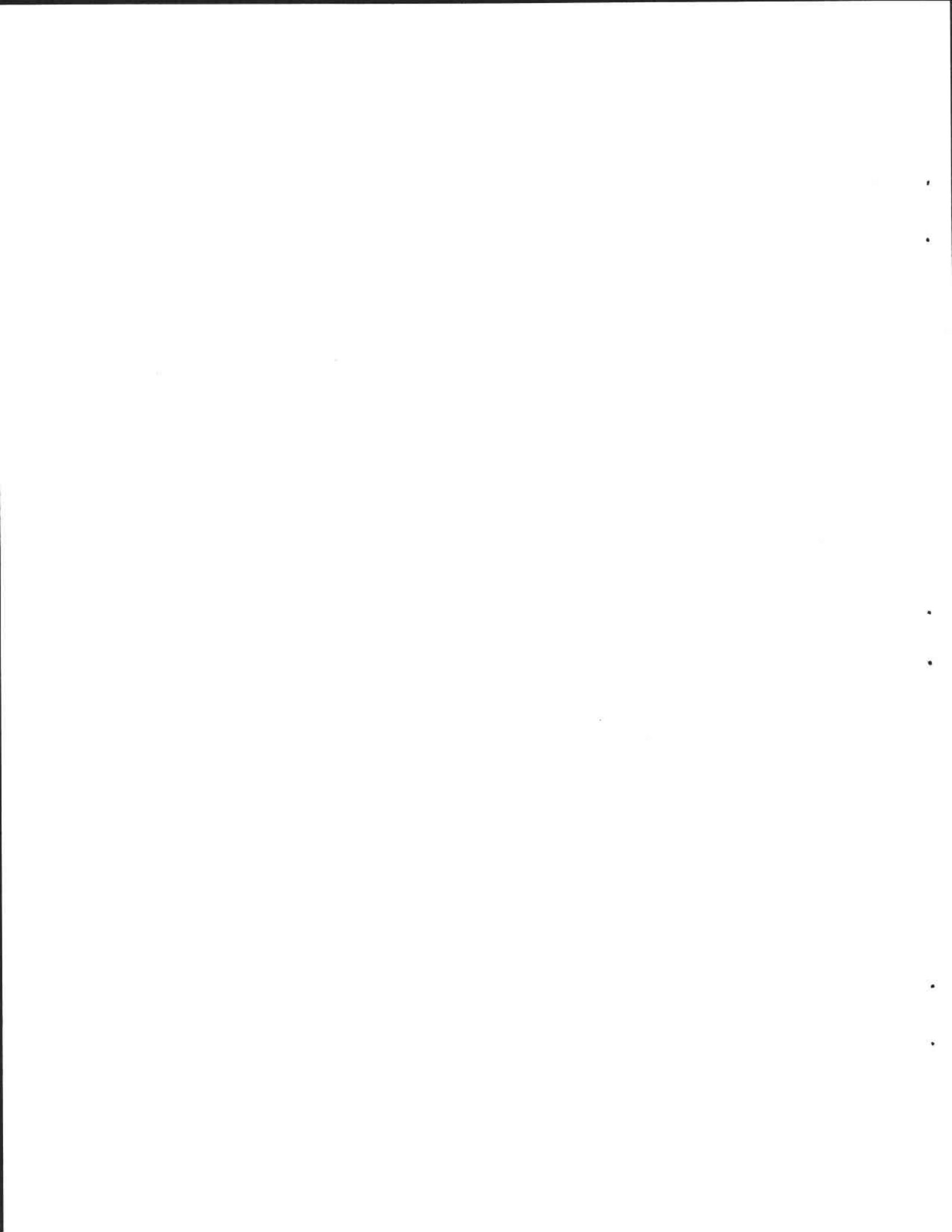
I.	INTRODUCTION.....	3
II.	PHENOMENOLOGICAL OBSERVATIONS.....	5
	A. Physical Appearance .....	5
	B. Growth Rates .....	5
	C. Mechanical Properties .....	8
	D. Current-Carrying Capacity .....	8
	E. Electrical Discharge.....	9
III	DISCUSSION .....	11
	A. Whisker Growth Mechanism .....	11
	B. Current-Carrying Capacity .....	12
	C. Discharge Phenomena .....	13
	D. Prevention and Amelioration of Whisker Problems.....	13
IV.	SUMMARY AND CONCLUSIONS.....	15
	REFERENCES.....	17
	APPENDIX .....	19

## FIGURES

1.	Tin whiskers .....	6
2.	Burn-out characteristics of tin whiskers.....	9
3.	A screw dislocation in a crystal lattice .....	11

## TABLE

1.	Measured Current -Carrying Capacity of Tin Whiskers .....	9
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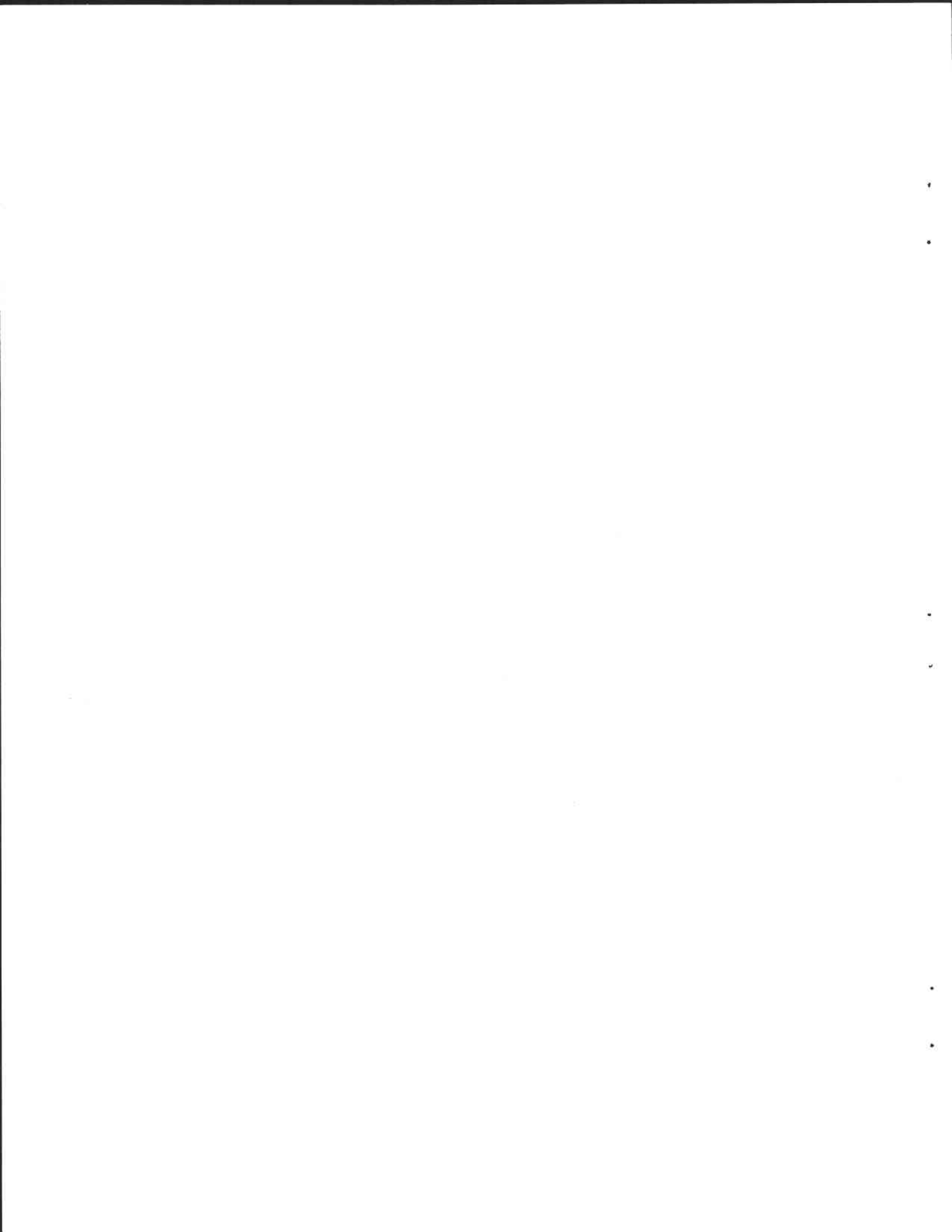
## I. INTRODUCTION

A number of programs have recently encountered whiskers on tin-plated electronic components. Whiskers, as their name implies, are fibrous growths that characteristically have lengths much greater than their cross-sectional dimensions. These conducting metal whiskers can cause electrical shorting. This document briefly summarizes what is known about the growth of tin whiskers and, just as importantly, points out what is not known with certainty. Despite the fact that whisker growth on electronic components has been a matter of concern for more than 40 years,<sup>1,2</sup> many aspects of the phenomenon are still not completely understood. Contradictory results abound in the literature.

Metal whiskers are single crystals and are very strong because of the absence of internal defects such as dislocations. Their interesting mechanical properties made whiskers a very popular research area in the 1950s and 1960s. In recent decades, interest has largely centered on the use of whiskers in fundamental investigations of superconductivity.

Whiskers are known to grow spontaneously from the surfaces of a number of metals including tin, cadmium, antimony, indium, and zinc and less frequently from lead, iron, silver, gold, nickel, and palladium.<sup>3</sup> Whisker growth is, however, most commonly associated with coatings of tin.

This discussion is limited to the growth of whiskers on tin coatings. The available experimental data on tin whiskers will first be summarized. Theories of the physical mechanisms of whisker growth will then be described in order to gain a better understanding of the phenomenological observations. Finally, recommendations on how best to deal with whiskers in practical situations will be offered.





## II. PHENOMENOLOGICAL OBSERVATIONS

Studies of whisker growth have tended to employ very simple and not very well controlled experimental methods. Typically, tin-plated specimens have been prepared and placed in storage. The investigators then sit back and wait, observing the specimens at intervals.<sup>4</sup> Among the variables that might influence whisker growth on tin coatings are: coating thickness; impurity concentration; the nature of the substrate on which the coating is deposited, temperature, plating process parameters, and the applied stress. These variables have been poorly defined in many experiments.

### A. PHYSICAL APPEARANCE

Tin whiskers have a distinctive appearance. Their size varies, with the smallest reported whiskers having diameters of about 6 nm and the largest having diameters of 6  $\mu\text{m}$ . Diameters of 3 to 4  $\mu\text{m}$  are most common.<sup>1,2</sup> Whiskers are quite straight, although they may jog abruptly (Fig. 1). The angles through which the whiskers suddenly turn are not arbitrary, but are related to their crystal structure. Whisker population densities typically range between 5 - 300 /mm<sup>2</sup>.<sup>5</sup> Whiskers are visible using an optical microscope at relatively low (3-10 X) magnification. Lighting conditions are critical, however, and whiskers can easily be overlooked. The whiskers themselves are often associated with larger eruptions of the tin termed "nodules". Nodules have no particular orientation and are reminiscent in appearance of toothpaste squeezed from a tube.

### B. GROWTH RATES

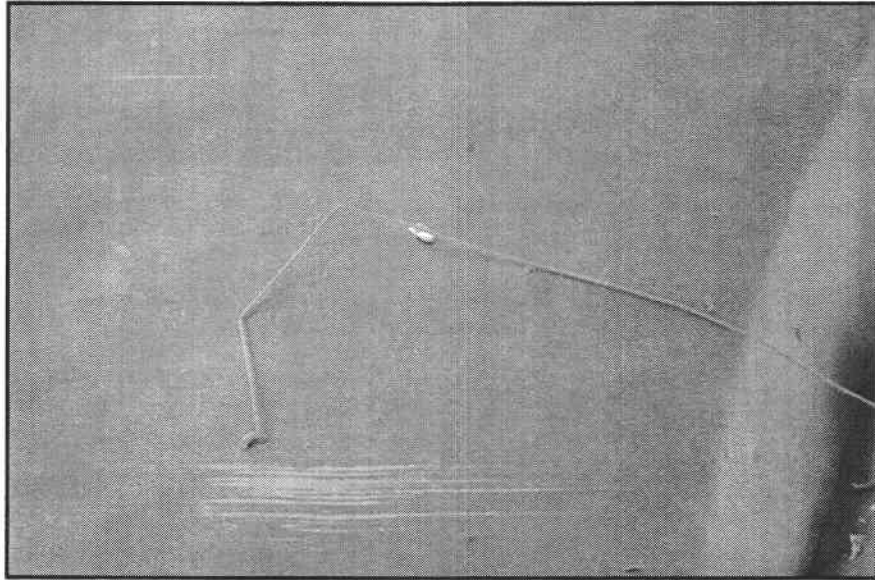
Reported growth rates of tin whiskers range between 0.03 and 9 mm/year.<sup>1</sup> Measurement of growth rates is fairly simple, requiring only occasional optical or electron microscope examination of test specimens. Ambiguities arise in attempting to control the numerous variables that affect the growth rate. Many studies have reported that an "induction period" is associated with whisker growth, i.e., for some time after the coating is deposited, no whisker growth is observed. The growth of whiskers only after 8 to 10 years of storage has been noted.<sup>5</sup> Whiskers do not continue growing indefinitely. Growth eventually slows and stops although maximum lengths can reach several mm.<sup>2</sup>

#### 1. Substrate Effects

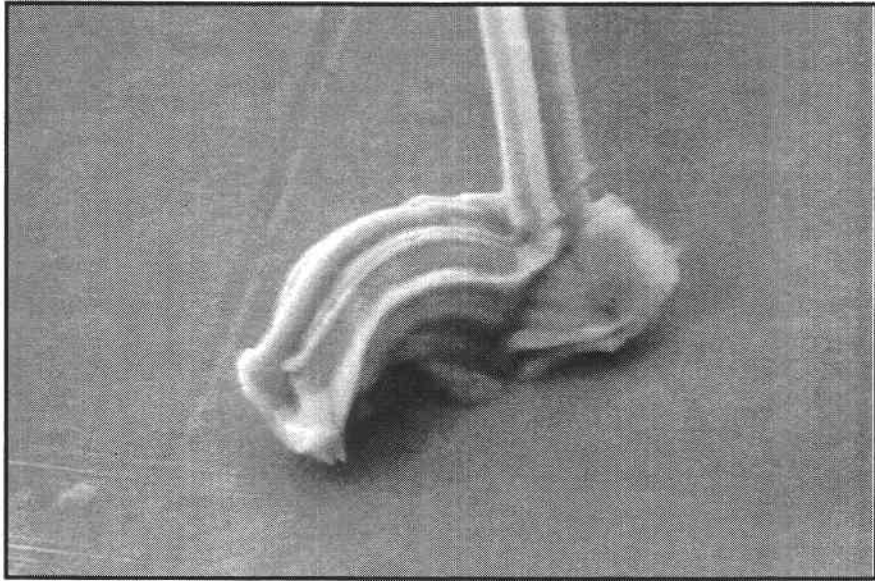
The nature of the substrate on which a tin coating is deposited is reported to be an important factor in whisker growth. The substrates most often studied, steel and brass, are the metals most important in commercial applications of tin plating. Most authors agree that whiskers grow rapidly and with a short induction time (several days) on tin-plated brass. Whiskers on brass have been observed to grow at about 8  $\mu\text{m}/\text{day}$ .<sup>2</sup> Tin-plated steel can take several months to exhibit short whiskers. It should be noted that some earlier workers came to exactly the opposite conclusion, i.e., that whisker growth occurred on tin-plated iron but not on tin-plated brass or copper.<sup>3</sup> Some authors report that copper undercoats are effective in reducing whisker growth on brass substrates.<sup>4</sup> Other researchers differ.<sup>5</sup>

#### 2. Coating Thickness

Whiskers are not usually seen on bulk tin.<sup>3</sup> This observation implies that there should be some maximum thickness of tin coatings on which whisker growth can occur. Various authors have suggested that this maximum thickness is 8  $\mu\text{m}$ , 12  $\mu\text{m}$ , and 18 to 20  $\mu\text{m}$ .<sup>1,4,5</sup> Given the other uncertainties in the field, this degree of agreement should be considered good. Whisker growth clearly must cease



200  $\mu\text{m}$



10  $\mu\text{m}$

Figure 1. Tin whiskers (ref. 2).

as the coating thickness (i.e., the amount of tin) decreases to zero. Given the lack of growth on bulk material, it is therefore logical to expect that for coatings thinner than the roughly 8-20  $\mu\text{m}$  maximum thickness cited above, whisker growth rate will increase with decreasing thickness until some limiting lower thickness is reached. This expectation is borne out experimentally. Profuse whisker growth has been reported on 1.25- $\mu\text{m}$  thick coatings, while 0.5- $\mu\text{m}$  coatings did not develop whiskers.<sup>6</sup>

### 3. Impurities

Whiskers are not reported to grow on tin-lead alloys, including of course, solder. Concentrations of lead greater than about 1% are said to "greatly reduce" whisker growth.<sup>1, 7</sup> Note that some other elements can be incorporated in small concentrations in tin whiskers. Dunn found that whiskers grown on steel substrates and on brass substrates with a copper intermediate layer were pure tin (within the detection limits of energy dispersive x-ray analysis).<sup>5</sup> Whiskers grown on tin-plated brass incorporated about 2% by weight of zinc. Certain constituents added as brighteners to plating baths supposedly promote whisker growth.<sup>1</sup>

### 4. External Stress

Although the driving force behind whisker growth is certainly mechanical stress, the origin of the stress is in dispute. Consider the following statement:

*Whisker growth rate is almost directly proportional to the compression stress exerted on the material. It is possible, by applying pressure, to accelerate whisker growth to a degree perceptible to the naked eye. As it is, whisker growth can be provoked by subjecting allergic materials to compressive stress, for example, by clamping them in a vise: after a lapse of only a few hours whiskers develop immediately adjacent to the area of clamping ("squeeze" whiskers). On this account, in load-carrying applications, tin coatings must be avoided. Clamped connections, such as in bolted constructions, are rather sensitive and tin whiskers can occur even if the top coat is of hot-dipped tin-lead.<sup>1</sup>*

In other words, it is asserted that externally applied macroscopic stress is an important factor in whisker growth. This view has the support of other authors. Contrast the above statement with quotes from the author of some of the more recent studies who asserts that external stress is not a major factor in whisker growth:

*"Highly" stressed samples do not reflect short nucleation times for whisker growth, or support longer whiskers than observed on the unstressed C-rings. A major finding was that compressive stresses applied to tin plate did not accelerate whisker growth rates.<sup>5</sup>*

At the end of the first of the above quotations, note that the author has added the caveat that "squeeze" whiskers can grow even on tin-lead solder in regions of high compressive stress, e.g., near bolts. The same assertion has been made by at least one other author.<sup>8</sup>

### 5. Temperature

Coating thickness does not appear to decrease even around regions of profuse whisker formation. Tin must clearly be supplied to the growing whiskers by diffusion from considerable distances. Diffusion rates depend on temperature as  $(\exp(-Q/kT))$ , where  $Q$  is an activation energy, and the whisker growth process would be expected to be highly temperature dependent. However, increasing the temperature helps anneal the stress also essential for whisker growth. It has therefore been suggested that each metal should have a temperature range optimal for whisker growth, which for tin is said to be 60 to 70°C.<sup>1</sup> Few, if any, studies of whisker growth as a function of temperature have been reported.

## 6. Ambient Conditions

A hot, humid atmosphere is reported to promote whisker growth. Whisker growth has, however, been seen in vacuum.<sup>1</sup>

## 7. Plating Conditions

Many authors state that whisker growth on electroplated tin depends on the conditions of the plating bath. The bath temperature, plating current, and impurity content are probably important parameters in whisker growth. Unfortunately, these effects have been not quantified to provide predictions of the susceptibility of a coating to whisker formation based on deposition conditions.

## C. MECHANICAL PROPERTIES

The mechanical properties of whiskers have been measured using essentially standard techniques albeit complicated by the small size of the test specimens. Young's modulus, the ratio of applied stress to strain, gives an indication of the stiffness of materials (strain is by definition the change in length of a material divided by its length). Dunn determined the Young's modulus of whiskers by measuring their deflection as a function of the applied force.<sup>9</sup> Measured values fell into two ranges characteristic of two growth directions, with an average value of  $3200 \text{ kg/mm}^2$  ( $3.14 \times 10^{13} \text{ dynes/cm}^2$ ). In contrast, Young's modulus is around  $10^{11} \text{ dynes/cm}^2$  for most bulk metals. Tin whiskers, in other words, are quite stiff. The ultimate tensile strength of the whiskers was found to be  $0.8 \text{ kg/mm}^2$  ( $7.8 \times 10^7 \text{ dynes/cm}^2$ ). The ultimate tensile strength of bulk tin is about  $1 \text{ kg/mm}^2$ . Because they are dislocation free, however, whiskers can withstand considerable strain without breaking. Tin whiskers thus have a relatively low tensile strength and are highly ductile. Dunn also investigated the response of whiskers to mechanical vibration. Whiskers were not broken or dislodged from tin plated specimens even when subjected to accelerations of 6 g for 60 s, in air, at frequencies near their natural mechanical resonance (50 - 250 Hz). Mechanical shock at 2060 g also did not break any whiskers. Ultrasonic vibrations in liquid did remove whiskers from surfaces, although not from the interiors of plated through-holes in printed circuit boards. Once again, as one comes to expect in this field, other workers differ. Some say that whiskers are easily broken by mechanical shocks. In one fairly recent study undertaken to investigate the reliability of electronic systems in U.S. Air Force aircraft, tin whiskers were said to have formed and broken loose inside hybrid circuits used in radar units.<sup>10</sup> Both intermittent and permanent, irreversible failures were attributed to these "floating" whiskers.

## D. CURRENT- CARRYING CAPACITY

The current-carrying capacity of whiskers is a topic which arises frequently in discussions of their potential effects on electronic circuits. Dunn plucked whiskers from a tin-plated specimen using tweezers and attached them to glass microscope slides with silver epoxy adhesive.<sup>9</sup> Electrical contact to the whiskers was made by mechanical probes. The whiskers were observed in an optical microscope, and the current through and the voltage drop across the whiskers were recorded. The current was increased until burn-out. At low currents, the whiskers had the resistivity of pure tin ( $11.3 \mu\Omega/\text{cm}$ ) and their I-V behavior was linear. At higher currents, joule heating became important and the measured resistivity increased. Some of Dunn's data are reproduced in Table 1.

These measurements of the current-carrying capacity of whiskers are, for several reasons, not very precise. The surface area of the whiskers is uncertain since they are often fluted cylinders rather than

perfectly circular cylinders. In fact, Dunn points out that a number of studies assert that whiskers are often hollow.<sup>3,11</sup> Connection of probe electrodes, as in the experiments cited in Table 1, can lead to uncertainties in the accurate determination of whisker length. Dunn plotted the data of Table 1 to give designers a quick, though rough, graphical indication of the burn-out characteristics of tin whiskers. His plot has been reproduced in Fig. 2. Note that this graph is based on only the four data points in Table 1 and must be considered qualitative. Additional collaborative data are provided by Arnold who states that tin whiskers 2mm long burned out at 10 mA.<sup>12</sup>

### E. ELECTRICAL DISCHARGE

High electric fields arise at the surfaces of charged conductors with a locally high radius of curvature (i.e., "points"). The sharp ends of tin whiskers are no exception. Electrical discharges at whisker tips are another mechanism by which whiskers may affect electronic circuits even though the whiskers may not actually provide a continuous path between two conductors. Dunn observed discharges from the ends of whiskers being examined in a scanning electron microscope.<sup>9</sup> The electron beam of the microscope itself caused the whiskers to charge and the effects were easily observable.

Table 1. Measured Current-Carrying Capacity of Tin Whiskers

Diam. (μm)	Length (mm)	Max. Curr. (mA)	Max. Curr. Dens. (A/cm <sup>2</sup> )
1.1	0.3	10	10.0 X 10 <sup>5</sup>
1.5	0.7	20	11.0 X 10 <sup>5</sup>
3.0	0.8	32	4.5 X 10 <sup>5</sup>
2.8	0.8	22	3.5 X 10 <sup>5</sup>

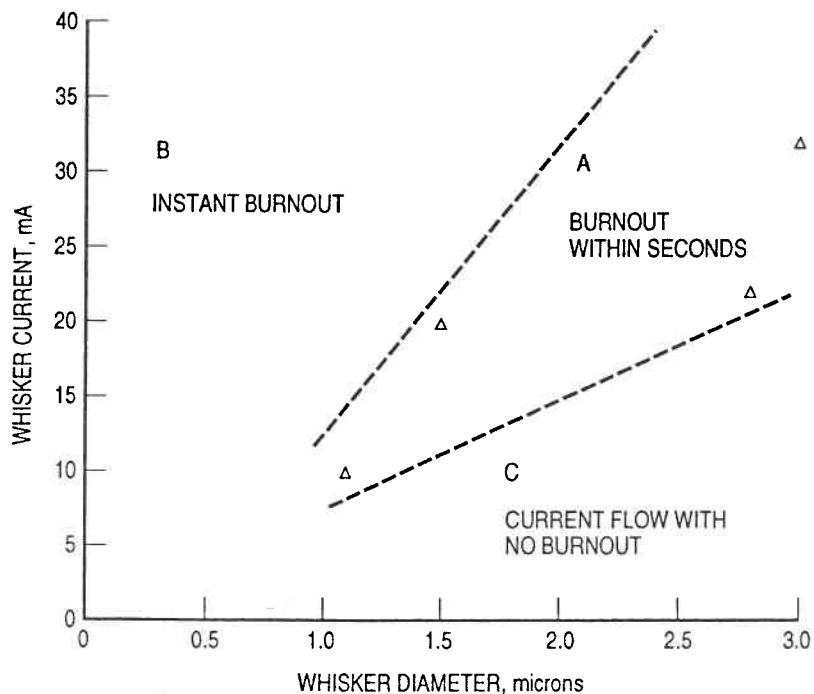


Figure 2. Burn-out characteristic of tin whiskers

