UNDERSTANDING WHISKER PHENOMENON –
PART I: GROWTH RATES

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The Electronic Industry is at the crossroad of moving forward with lead-free solders at the assembly and component level. Tin and tin alloys have been considered as alternatives for component finishes. Among a few remaining issues regarding plating processes, the whisker growth phenomenon has not been understood satisfactorily.

In this paper, we will discuss our understanding on key factors that promote whisker growth and the whisker growth kinetics.

Recommendations for using tin and tin alloys as a component finish will be given.

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INTRODUCTION

The electronic industry relies extensively on tin/lead solders, and yet in the near future it will eliminate its dependence on lead for environmental and technological reasons [1 - 4]. In this regard, a number of alternatives are challenging the dominance of HASL and electroplated tin/lead as board and component finishes [5, 6]. Among them, are Ni/Au, Ni/Pd, Ni/Pd/Au, electroplated Sn, Sn-alloys, OSPs, immersion Sn and Ag. Electroplated pure tin, may be the simplest process as a "drop-in" replacement for tin-lead [7] for component finishes.

Unlike other lead-free alternatives, pure tin is unique since it has co-existed with tin-lead as a solderable material for centuries. It is the main constituent of solder joints; it is compatible with tin-lead, tin-silver and tin-bismuth. It is non-toxic and does not leach significantly into groundwater because most tin salts are not water soluble at room temperature [8]. Furthermore, tin recovery is well established in the recycling industry.

Compared with electroplated pure tin, other alternatives are less characterized and have much shorter reliability histories. Though each of them has significant merit in their own right, they have inherent limitations. For instance, solder joint embrittlement is a reliability issue when precious metals are involved [5]. Tin alloys such as SnCu, SnBi and SnAg, on the other hand, have the following limitations:

- Stability of plating process
  - √ Immersion plating
  - √ Sn (II) oxidation
- Alloy composition control
  - √ Dramatic impact on alloy properties
- Quality control procedures
  - √ Measuring thickness and composition when plated on Cu alloys
- Metal cost and availability
- Compatibility with existing tin-lead solders (e.g. Bi and Ag)

The above issues must be carefully considered when replacing the well-characterized and ubiquitous tin-lead solder system.

Operationally, the most significant development in the electrodeposition of tin during the past 40 years has been the introduction of commercially viable electroplating processes. These are based mostly on acid stannous sulfate or stannous fluoborate solutions and, more recently, on alkyl or alkyol sulfonate solutions [9 – 11].

Regardless of the type of electrolyte used, electroplated tin coatings are generally soft and ductile, and have a relatively low melting point, 232°C (450°F). Like cadmium and zinc, electroplated tin is known to grow whiskers[12] which can be detrimental for microelectronic applications.

Tin whisker formation appears to be favored by the presence of internal stress and the application of external mechanical stress [12]. Bright tin finishes, which possess significant internal stress [13], are therefore prohibited on microelectronics parts since such whiskers have been identified as the cause of short circuit failures [14 – 18]. The presence of an electric field is also suspected of inducing whisker growth. Therefore, with the drive toward miniaturization for ICs and the increasing packing density for PCBs, this phenomenon will become more problematic in the future.

Several remedies have been proposed to overcome the problem of whiskering: alloying with a small percentage of other metals (e.g. Pb, Bi), hot dipped tin, as well as reflow tin after plating are some common practices [12]. Nonetheless, the phenomena of "whiskering" must be thoroughly investigated and quantitatively understood if pure tin and tin alloys are to be taken as serious contenders to replace tin/lead.

In our previous work [19], we established a test that reproducibly induced the growth of whiskers. In addition, correlation was found between whisker growth and coating properties such as grain size and carbon content. In this paper, we will discuss our quantitative characterization of the whisker growth phenomenon.

EXPERIMENTAL DESIGN

The whisker test utilized in this work has been described in reference 19. The experimental matrix is summarized below:

- Internal stress
  - √ Dependent on plating processes and the resulting coating properties such as grain size and carbon content
- External stress
  - √ Mechanical deformation
- Environmental conditions
  - √ Temperature
  - √ Time of aging

It is well understood that intermetallic compounds (IMC) form at the tin substrate (typically copper or copper alloys) interface shortly after deposition. The growth rate depends on time, temperature, and the substrate material. Since the densities of the intermetallic compounds such as Cn_6Sn_5 (8.3 gm/cm^3) and Ni_3Sn_4 (8.4 gm/cm^3) are higher than that of tin (7.3 gm/cm^3), a compressive stress would be generated in the tin layer [20]. In order to alleviate this potential problem and reduce the rate of intermetallic compound formation, therefore the stress, a nickel underlayer can be deposited over the substrate [21].

As previously stated, heat treatment, including reflow, have been suggested as a remedy for preventing whisker growth [12]. It is commonly believed that stress relaxation takes place in the tin layer during the reflow process. Simultaneously, IMC forms at tin substrate interface. We included reflow in our whisker testing program to understand the relative importance of stress relaxation and stress generation by intermetallic compound formation. We chose a reflow peak temperature of 260 °C.

We included two pure tin finishes in this study: full bright and satin bright. The specifics of how they were plated, their deposit characteristics and microstructures are described elsewhere [19,22]. Key attributes of these finishes are summarized in Table I.

In order to obtain a "statistically" representative view of our observations, it must be noted that each coupon was examined over an area of 0.5 mm x 27 mm as shown in Figure 1. Furthermore, each spot was examined at four different magnifications: 500 x, 1000 x, 5000 x, and 10,000 x. This ensures that we would observe large (length > 50μm) and small (length < 5 μm) whiskers.

In the quantitative analysis, the number of whiskers was "manually" counted, and length and diameter were obtained from SEM photos.

Whisker Index (WI), defined as a function of number (n), length (L), and diameter (d) of the whiskers is described by the equation below:

$$WI = \Sigma \text{ Function}\{n,d,L, f(L)\} \;\ldots\ldots\ldots\; (1)$$

Practical considerations (i.e., fine pitch connectors or IC applications) dictate that we utilize a "weighing factor" for length, f, which differentiates short and long whiskers. Table II summarizes the relationship between the factor, f, and the length of the whisker, L.

RESULTS

In order to understand the whisker phenomenon, we investigated the fundamental driving forces for whisker formation, and growth mechanism(s). To achieve this goal, it is critical that we determine the whisker growth rates of certain deposits, which is the focus of this paper.

It is an established fact that bright finishes show the highest propensity for whisker growth, and that satin bright finishes show the least propensity. Compressive stress, internal or externally applied, induced and accelerated whisker growth. In this regard, it has been shown that the externally applied stress has more appreciable effect on the bright finish than on the satin bright finish [19].

To demonstrate the above in a quantitative manner, Figure 2 displays the maximum length of whiskers observed for bright and satin bright finish over a period of ten months. Samples were aged in a dry oven maintained at 50° C. No external mechanical stress was applied.

Figure 3 shows a similar comparison between bright and satin bright finishes that have been subjected to a 90° compressive bent.

Figure 4 compares the results for the bright finish with and without compressive stress.

As one can see clearly, these data support the aforementioned statements in a quantitative fashion. In addition, the data demonstrates that whisker can grow 30 to 40 µm in a relatively short period of time. If occurring in fine pitch devices, these needle-like whiskers could cause electronic failures. This is the motivation for including a "weight factor", f, for the length of the whiskers as described in Table II.

As we have pointed out earlier, to accurately describe the whisker growth phenomenon, it is insufficient to measure merely the length of the whisker. We also need to take into consideration the number and diameter of the whiskers as described in our whisker index formula (equation 1).

Table III summarizes the whisker index calculation obtained for selected samples aged at 50°C up to ten months. We will discuss the results as follows:

- Bright vs. satin bright
- Bright
  - √ External stress vs. internal stress
- Satin bright
  - √ Plated
  - √ Reflowed
  - √ Ni underlayer
- Satin bright tin vs. satin bright 90/10 tin/lead

Bright vs. Satin Bright

The whisker index data shown in Figure 5 clearly demonstrates that the bright finish is about 1,000 times more prone to whisker formation than the satin bright finish. This result was expected; however, the data also implies that while the whiskers from the bright finish show continued growth after ten months aging, the satin bright finish seems to have reached equilibrium, i.e., no further growth.

Examination of the whiskers observed on the satin bright sample are classified as mounds [19] of ~ 5 µm. This is in direct contrast with our observations for the bright tin, where the initial growth stage (~ first three months) produced nodules, followed by needle-like whiskers (filaments) emanating from the nodules. This suggests that the growth pattern or mechanism is different between these two coatings. In addition, it raised the question as whether the mounds observed on the satin bright finish are indeed "whiskers". This matter is under further investigation and will be presented in future papers.

Compressive Stress: External vs. Internal

Figure 6 displays the whisker index obtained with the bright finishes up to ten months. This data clearly shows that the compressive external stress significantly accelerates whisker growth relative to the reference samples. However, the external stress does not have as nearly a large impact on the satin bright as that on the bright finish, Figure 7. This is not unexpected owing to the stable microstructure for the satin bright finish.

Satin Bright - Effect of Reflow and Ni Underlayer

To gain a quantitative understanding of the reflow and the underlayer effect, we compared the whisker index for satin bright tin, satin bright tin after reflow and satin bright tin over a nickel underlayer, Figure 8. It is evident that both reflow and nickel underlayer further reduce the propensity of whisker formation. By utilizing a nickel underlayer, one effectively eliminates whisker formation with the satin bright tin finish.

Satin Bright Tin vs. Satin Bright 90/10 Tin/lead

90/10 tin/lead finish has been the benchmark as a component finish. Figure 9 illustrates the comparison of whisker formation between the satin bright tin and a satin bright 90/10 finish. As shown, for the first six months, the behavior is similar (Table III) between the two. It is most interesting that after ten months, the satin bright 90/10 tin/lead showed significantly higher propensity for whisker formation than the satin bright tin finish.

DISCUSSIONS

In-situ internal stress measurements yield a 5 N/mm^2 compressive stress for the bright finish and zero stress for the satin bright coating (Table I). The stress data on the bright coating agrees well with the common belief that internal stress is a driving force for whisker formation. However, it does not explain why we observed small whiskers on the satin bright sample where internal stress is zero. Examining data in Figure 7 suggests that interfacial diffusion may play an important role.

In summary, our observations indicate that internal stress and interfacial diffusion are two key factors that promote whisker growth. The former is dominant if the internal stress level is relatively high (i.e, in the case of bright finish). The latter becomes operative when the internal stress level is low or zero (i.e, in the case of the satin bright finish). Of the two factors, the internal stress is more critical. Detailed discussions regarding whisker growth mechanisms will be presented in Part II of this series.

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Table I. Key Attributes of Bright and Satin Bright Finishes

Finish	Grain Size, μm	Carbon Content, Wt%	Internal Stress, MPa
Bright	< 0.2	0.2	– 5
Satin Bright	2 - 5	0.004	0

Table II. Relationship between Factor f and Whisker Length

Length, μm	Weight Factor, f
< 1	0
1 - 5	1
5 - 10	5
10 - 50	50
> 50	500

Table III. Whisker Index Calculations

Finish	4 Months	6 Months	10 Months	Longest*, μm
Bright	279	13,000	63,400	600
Bright + Compressive	3850	13500	193,000	750
Satin Bright	3.2	10.5	10	5
Satin Bright + Compressive	30.5	22.5	40.7	5
Satin Bright / Reflow	2.1	4.0	8.9	4
Satin Bright / Ni	0.2	0	0	2
Satin Bright 90/10	4.1	8.6	907	10

*****: Longest whisker up to 10 months

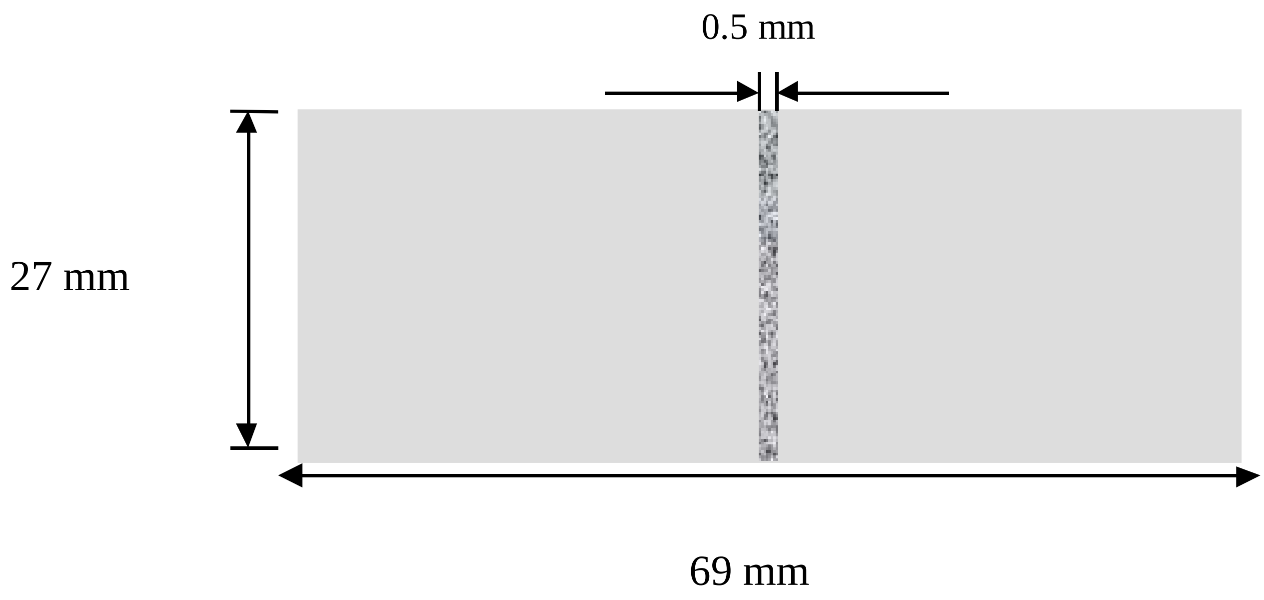

Figure 1 *Illustration of Sample Dimension and Whisker Observation Area.*

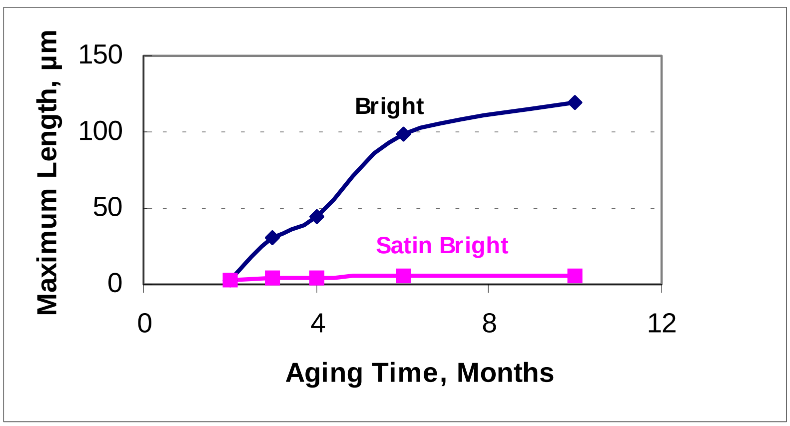

Figure 2 *Plot of Longest Whiskers Observed on No-Bent Samples at Different Time Intervals. Aging condition: 50°C.*

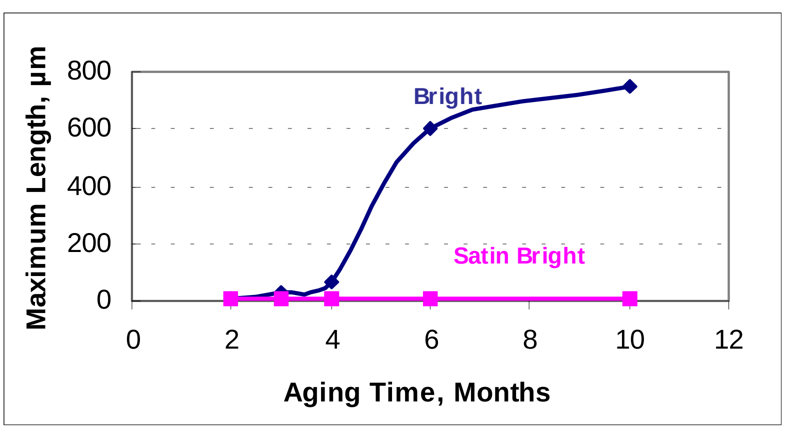

Figure 3 *Plot of Longest Whiskers Observed on 90° Compressivelly Bent Samples. Aging condition: 50°C.*

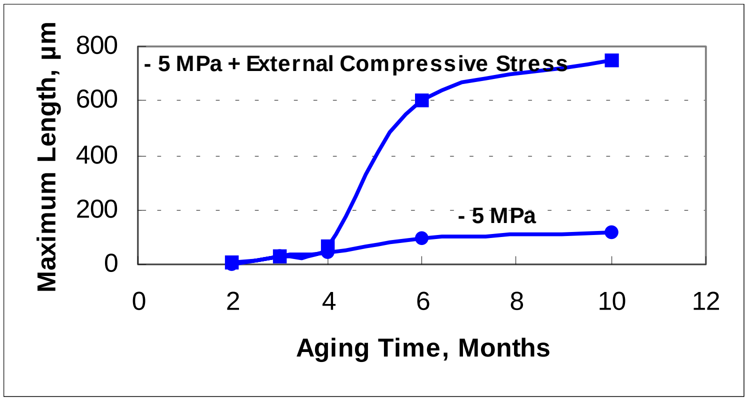

Figure 4 *Plot of Longest Whiskers Observed on the Bright Samples Showing the Effect of Compressive 90° Bent.*

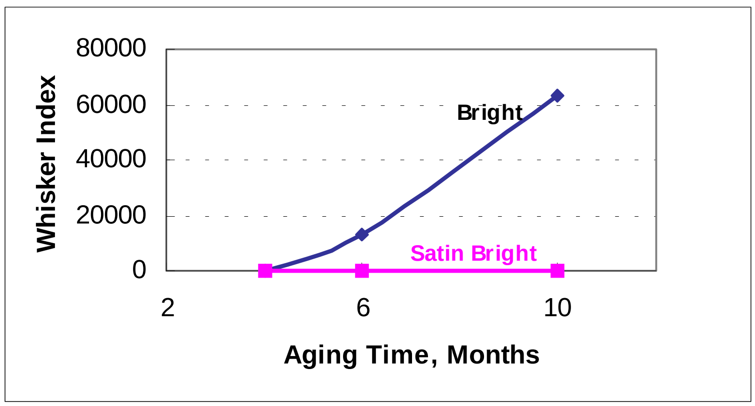

Figure 5 *Comparison of Whisker Index between the Bright and the Satin Bright Tin Finishes.*

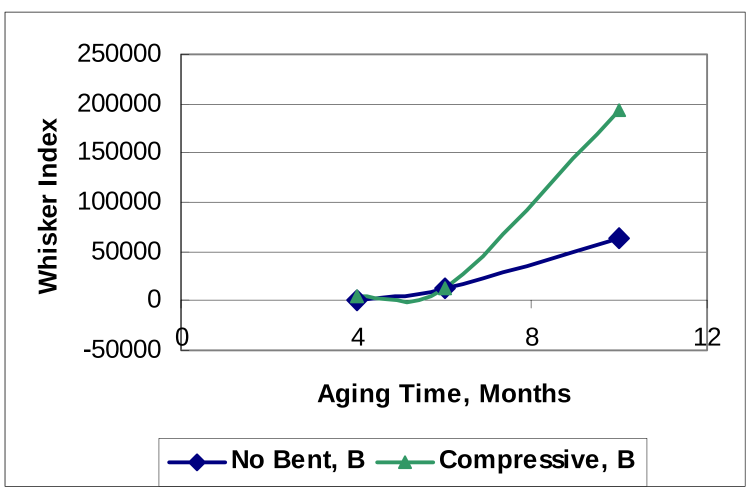

Figure 6 *Whisker Index of Bright Samples Showing the Effects of External Mechanical Bent.*

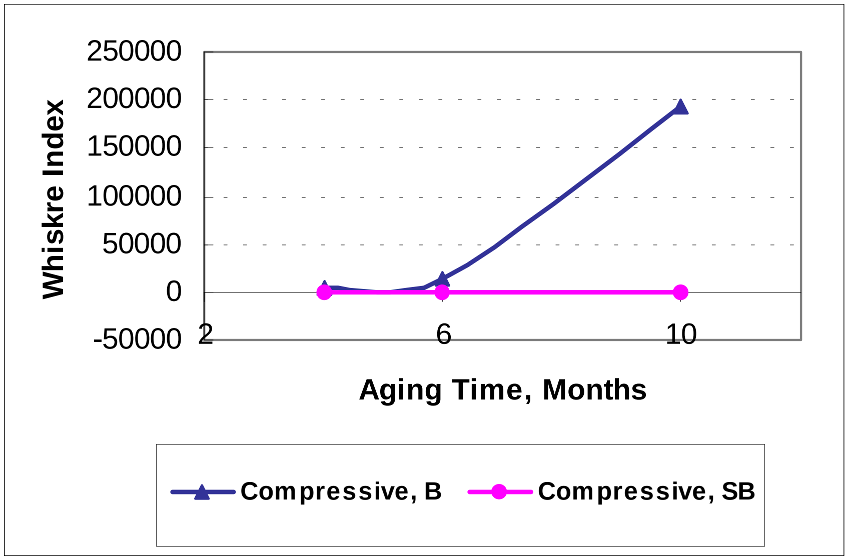

Figure 7 *Whisker Index of Bright and Satin Bright Samples Showing the Relative Importance of the External Stress.*

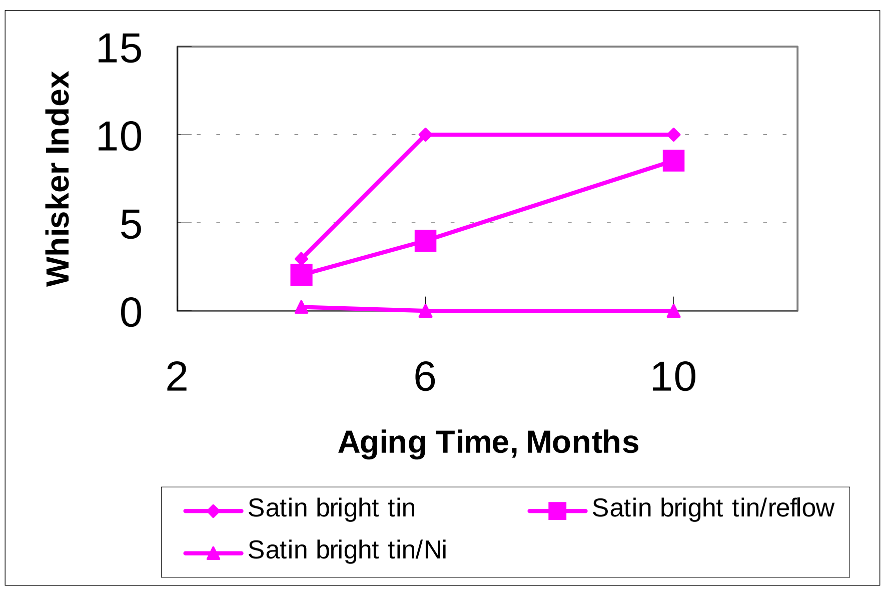

Figure 8 *Whisker Index of Satin Bright Tin Showing the Effects of Reflow and A Ni Underlayer.*

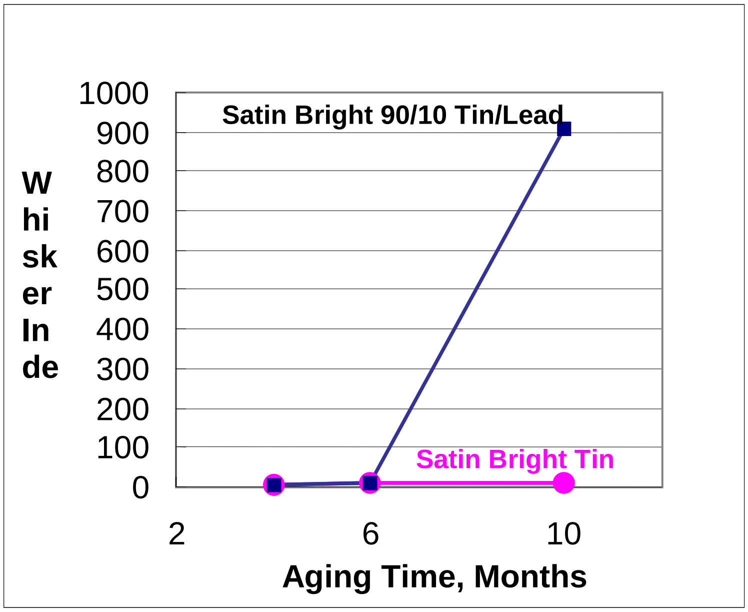

Figure 9 *Comparison of Whisker Index between the Satin Bright Tin and A Satin Bright 90/10 Tin/Lead Finish.*