THE THEORY OF TIN WHISKERS GROWTH BEHAVIOUR FOR PURE TIN SURFACE FINISH

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ABSTRACT The ban on lead in electronic industry caused manufacturers to search for alternative ways to replace lead without affecting the performance of electronic products. Among lead-free alternative surface finishes, pure tin plating has attracted greater attention as potential candidate to replace hot air solder levelling (HASL) process in electronic application. However, tin whiskers (Fig. 1) were reported to form and growth on tin surface finishes and have caused the failure to electronic components. The study regarding whiskers phenomenon is important especially with the miniaturisation of electronic components in the electronic industry because whiskers from adjacent area may touch each other, causing short circuit. The article discusses on tin whiskers behaviours formed and grown on the tin surface finishes. The discussions emphasis on the theories developed worldwide in order to understand the behaviour of tin whiskers formation and growth on the pure tin surface finish.

1. INTRODUCTION

Over the past few decades, Sn-Pb alloys have been widely used in electronics industries that are important to wide range of application from household to aerospace fields. However, due to concerns towards environmental and human health, the European Union has banned the use of Pb in electronic products sold effectively on 1st July 2006 [1]. Hence the industry has been urged to remove Pb in their products in order to move towards lead-free environment. Many researchers and manufacturers conducted research on finding alternatives to replace lead in surface finish. Pure tin has been chosen because of the non-toxicity of tin and the fact that it's inexpensive and has good solderability [2]. The nearly pure tin or tin-based alloys including Sn-Bi and Sn-Ag also have been used even though those alloys may cause tin whiskers formation [3-5]. As stated in previous research, the eutectic Sn-Ag-Cu alloys have been extensively used in electronic packaging due to its superior physical properties to replace Sn-Pb alloys [6].

The strategies of using pure tin or nearly pure tin has created a new challenging issue with formation of tin whiskers on tin plating surface [7]. The tin whiskers phenomenon has been documented since 1940s by the National Aeronautics and Space Administration (NASA) [8]. Many studies have been conducted to ensure better understanding regarding the fundamentals of tin whiskers formation thus can establish the mitigation method for whiskers to growth. Many researchers agree that tin whiskers can cause a short circuit, hence breaking off the components, resulting in the degradation of electrical or mechanical parts performance [4]. However, whiskers do not only form in tin but previous researchers found that similar whiskers were observed in other metals such as zinc, gold, and cadmium [8].

2. TIN WHISKERS

Based on the literatures, tin whiskers can be defined as spontaneous single crystals that grow out from the surface finish which is caused by the formation and growth of intermetallic that would generate the compressive stress in tin surface finishes [9]. The definition of whiskers is supported in some previous research that the growth of whiskers occurs from the base of the whisker, not at the tip of the whiskers [10]. Koonce and Arnold [11] have observed the growth of whiskers and found that the whiskers length gets longer while maintaining the whiskers tip which indicates the whiskers were being pushed up from its base.

Tin whiskers were not formed in unidirectional shapes. Researchers found whiskers in various forms such as hillocks, needle, bent, kinked or twisted [12]. Most of the whiskers formed in striation shape; where it has striations along the length of its column. Figure 1 shows some of the examples whiskers found on the immersion tin surface finish [13].

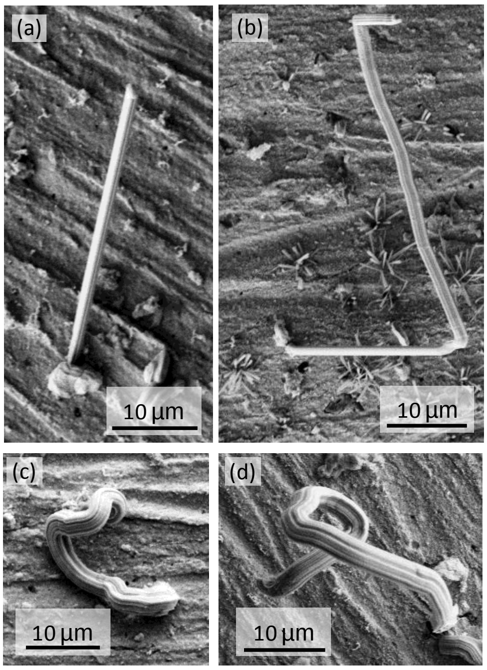

Figure 1: FESEM images of the whiskers formed on the non-indented surfaces in the (a) straight, (b) bent, (c) striation shapes, and (d) twist [14].

Many researchers agree that tin whiskers formed from the tin surface finish and grow spontaneously as the tin layer deposited onto the substrate. Jo *et al.*[14] reported in his research that whiskers formed on pure tin surface finish under ambient temperature as early as after one day of tin plating. In addition, researchers had agreed that the growth of tin whiskers occurs from the base of the whiskers [15]. According to the National Electronics Manufacturing Initiative (NEMI) [16] and JEDEC standard No. 22A121A [4], the characteristics of tin whiskers are as follows:

i. An aspect ratio (length/width) is more than 2,
ii. have many shapes such as kinked, bent, and twisted,
iii. generally have a consistent cross-sectional shape
iv. the shape of whiskers is rarely branch,
v. may have striations along the length of the column and/or ring around the circumference of the column, and
vi. length of 10 microns or more

Tin finishes was used as surface finish in Accelerator Pedal Position (APP) sensor for 2002-2005 Toyota Camry models. However electrical failure of an accelerator pedal position sensor board has reported by one of the customer who owned a 2003 Toyota Camry. In 2009, the accelerator system of the car failed, after six years of manufacturing where engine was suddenly stopped while driving [17]. After two years of investigation, Toyota concluded that the failure of APP in 2002-2003 Toyota Camry model was caused by tin whiskers that induced a short circuit. After the inspection towards the APP, the tin whiskers were found on the surface and edge of the acceleration position sensor board connection terminal.

3. MECHANISMS OF TIN WHISKERS GROWTH

In recent years, there are several mechanisms proposed by researchers on tin whiskers growth, yet there is no concrete mechanisms have been published due to conflicts among their proposed theories. The proposed mechanisms are grain boundary diffusion [18], oxidation theory [19], recrystallisation theory, and dislocation theory [20]. The proposed mechanisms are only true for the specific plating process, plating thickness, and substrate composition since the formation of tin whiskers were based on multi-factors that influence the whiskers formation. Hence further study of mechanisms was needed in order to create the best mitigation method in future.

3.1 Grain Boundary Diffusion

Most researchers agreed that grain boundary diffusion was the mechanism for tin whiskers growth [21]. Diffusion of atoms occurs from high energy to low energy regions and provides the atomic mass transfer for whiskers growth. Dudek and Chawla [22] concluded that the formation and the growth of intermetallic namely Cu_6Sn_5 resulted in the formation of high compressive stress in tin film. Therefore Sn atoms move from high compressive stress to stress free region by diffusion along the Sn grain boundary.

Tu et al. [23] have reported that the spontaneous growth of whiskers was an irreversible process whereby the Cu atoms diffuse from the substrate to solder finish driven by chemical potential gradient to form intermetallic compound of Cu_6Sn_5 in the grain boundaries of the solder. Thus the Cu_6Sn_5 intermetallic would grow over time and induce compressive stresses on Sn-Cu layer as schematically depicted by Figure 2 [24].

Thermal expansion mismatch occurs during thermal cycling due to large gap of the coefficient of thermal expansion, α between tin plating and substrates. Examples of substrates with low thermal expansion coefficient are ceramics and 42 alloy [25]. According to Vicenzo [26], the temperature cycling would generate stress within tin-substrate layers due to thermal expansion mismatch between the tin and substrate hence promote whiskers to form and grow. Figure 3 shows the schematic diagram of coefficient of thermal expansion between tin-substrate that creates the whiskers formation [27].

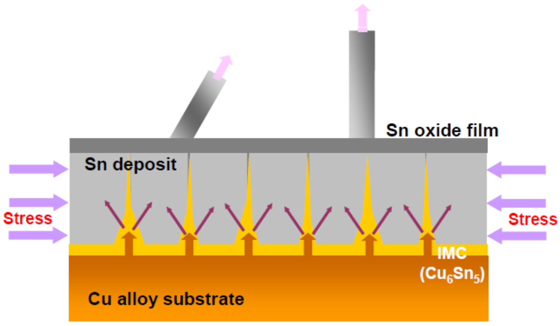

Figure 2: Schematic diagram of grain boundary diffusion [24]

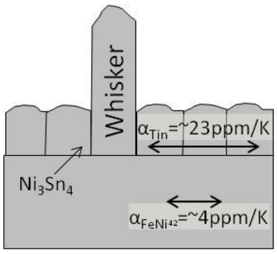

Figure 3: Schematic diagram of coefficient of thermal expansion mismatch between tin-substrate [27]

3.2 Oxidation Theory

Oxidation theory is one of the mechanisms proposed which is related to exposure of samples on high humidity environment condition to promote whiskers growth by oxidation process. The whiskers formed when the oxide layer on top of tin coating layers inhibit the uniform relaxation of compressive stress. Without the oxide layer, it is impossible to form the whiskers since the compressive stress can relieve uniformly [23, 26].

The source of compressive stress was driven by the growth of intermetallic layer Cu_6Sn_5 within Cu-Sn films. With the presence of oxide layer on tin surface, the weak spot or discontinuities on the oxide layer promotes the growth of whiskers out from the surface freely by breaking the oxide surface [26]. Figure 4 explains the oxide theory where the presence of weak spot or fractured oxide of Sn oxide layer has broken by Sn whisker that grows out from the surface [26].

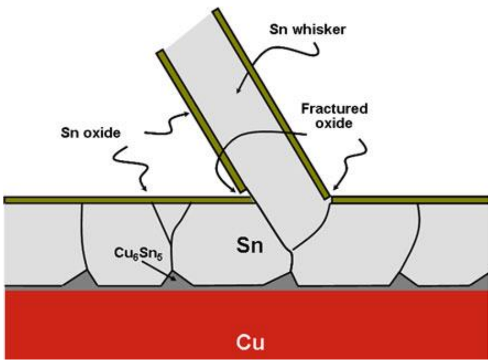

Figure 4: Schematic diagram of oxidation theory [26]

3.3 Recrystallisation Theory

Recrystallsation mechanism was first proposed by Ellis in 1958 then agreed by Glazunova and Kudryavtsev (1963) and later by T. Kakeshitaet al. in 1980. In this theory, they concluded that recrystallisation was necessary to form whiskers which the whiskers grow on recrystallised grains.

According to Smetana [28], recrystallsation occurs due to oblique grain boundary which has lower stress region as compare to vertical grain boundary that has higher stress. Vertical grain boundary formed as-grown grain during plating process. Thus the stress component along oblique grain boundary has promoted the whiskers formation by migrations of Sn atom from high stress region in vertical grain boundary to oblique grain which has lower stress region. Thus oblique grain boundary became the main reason of whiskers formation in the recrystallsation theory. Figure 5 shows (a) schematic diagram of side view tin plating grain boundaries and (b) oblique grain boundary in field ion beam (FIB) cross section on whiskers image [28].

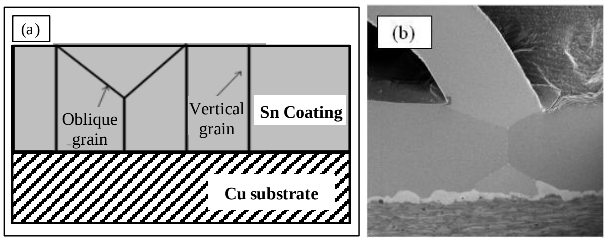

Figure 5: schematic diagram of side view tin plating grain boundaries and (b) oblique grain boundary in field ion beam (FIB) cross section on whiskers image [28]

3.4 Dislocation Theory

Dislocation theory has many conflicts among researchers since it was first established in 1950s. In 1953, Frank and Eshelby have proposed that whiskers formation occur by rotating edge dislocation pinned to its centre [29]. According to their theory, stress created by oxidation layer was the driving force for dislocation to occur. Basically Sn atom moves from high stress region to lower stress region. Thus dislocation mechanism proposed the same theory in order to move the Sn atom. According to the model created by Eshelby, the Sn atom would climb to the grain boundaries of whisker's root before glide to the lower stress-grain surface to initiate the whiskers formation [28-29].

However dislocation theory has not been agreed by other researches since it was first criticised by Ellis in 1958 [26]. According to Ellis [29], the whiskers growth directions must be in the direction of dislocation glide plane if dislocation-glide theory was accepted. However, the kinked whiskers are not consistent to this theory since it was not in the dislocation glide direction. Furthermore in recent years, researchers found that the whiskers formed in many shapes and direction such as twisted, bent, and kinked. Therefore dislocation theory cannot explain the multi-types of whiskers phenomenon.

CONCLUSIONS

In conclusions, the theories explained above describe how the structure and properties of surface finish might influence the formation and growth of tin whiskers. All the theories however agreed that Sn atoms migration influenced by stress generated from intermetallic formation and growth, oxidation, and dislocation. An effective mitigation method should trigger the stress generation in order to eliminate or at least slow down the formation and growth of tin whiskers.

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