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# Study of Lead-Free Solder Joint Reliability

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## Abstrak

Solder merupakan material penting dalam banyak proses pembuatan bahan teknik. Penggunaan solder dalam proses pengemasan elektronik menjadi hal yang sangat penting di dunia saat ini. Pada industry manufaktur elektronik, bahan solder alternatif berbasis logam timah telah berkembang secara bertahap selama dua dekade terakhir. Utamanya, perusahaan manufaktur yang sangat memperhatikan terkait penggunaan timbal dalam proses penyolderan dan proses daur ulang limbah tersebut yang coba dialihkan kepada penggunaan solder bebas tima (*lead-free solder*). Lingkungan dan kesehatan manusia yang paling mudah mendapatkan dampak negatif dari paparan timbal tersebut. Industri manufaktur telah beralih ke penyolderan bebas timah untuk mendukung inisiatif dan tanggung jawab sosial. Tiga kategori solder bebas timah diklasifikasikan menurut kisaran temperatur: solder temperatur tinggi, solder temperatur sedang, dan solder temperatur rendah. Penelitian ini dilakukan berdasarkan pendekatan studi literatur yang diperoleh dari beberapa penelitian yang secara umum menjelaskan mengenai solder *lead-free*. Memberikan tambahan pengetahuan yang diharapkan dapat menambah wawasan baru mengenai pentingnya penggunaan solder bebas timbal (*lead-free*) serta mengenal perilakunya.

**Kata Kunci**: *lead-free, reliability, solder joint*

## Abstract

Solders are essential for the construction of many engineering materials. The use of soldering in electronic packaging has become increasingly critical in today's world. In the electronic manufacturing industry, alternative soldering materials based on tin metal have developed gradually over the last two decades. Manufacturing companies are primarily concerned about removing lead from electronic manufacturing and waste recycling by switching to the lead-free solder. Environmental and human health are adversely affected by exposure to high lead levels in consumer products. The manufacturing industry has switched to lead-free soldering to support their social responsibility initiatives. The three categories of lead-free solder are classified according to temperature range: high-temperature solder, medium-temperature solder, and low-temperature solder. This research is conducted based on the approach of study literature, which is obtained from some papers that generally explain lead-free solder. To provide additional knowledge which is expected to add new insights about the importance of lead-free usage and its behavior.

**Keywords:** lead-free, reliability, solder joint

## 1. Introduction

Solders are essential for the construction of many engineering materials. The use of soldering in electronic packaging has become increasingly critical in today's world. As a filler, it employs solder with a melting temperature of less than 425°C, which forms a metallurgical joining technique [1]. Throughout time, the electronics industry preferred tin/lead solder (Sn/Pb) due to its exceptional solderability and reliability [2]. Nevertheless, the European directive Restriction of Use Hazardous Substances (RoHS), which bans the use of lead and other hazardous substances in electrical and electronic equipment, forced the electronics industry to modify their materials selection [3]. In the electronic manufacturing industry, alternative soldering materials based on tin metal have developed gradually over the last two decades. As well as military applications, devices exposed to harsh conditions like those found in automotive, avionics, and oil-exploration sectors require reliable lead-free solders. Solders may be exposed to high temperatures (for example, 200 C) in such extreme conditions, which are relatively near the melting points of the different Sn-Ag-Cu (SAC) solders used in industries. The extended exposure to such high temperatures might also cause severe mechanical property degradation and changes in their microstructure as a result of aging [4]. A Pb free solder joint's characteristics are greatly affected by the microstructure of near eutectic Sn-Ag-Cu (SAC). Pb-free SAC solder alloys have the most abundant element, Sn, due to its large thermomechanical anisotropies. There has been some evidence that differences in Sn grain shape have an impact on the thermal cycling performance of SAC solder joints [5]. Manufacturing companies are primarily concerned about removing lead from electronic manufacturing and waste recycling by switching to the lead-free solder. Environmental and human health are adversely affected by exposure to high lead levels in consumer products. The manufacturing industry has switched to lead-free soldering to support their social responsibility initiatives. The three categories of lead-free solder are classified according to temperature range: high-temperature solder, medium-temperature solder, and low-temperature solder. Lead-free high-temperature solder is commonly used as a die-attach medium for power semiconductor devices [6]. It is typically considered lead-free in solder if lead (Pb) levels are less than 0.1% by weight, although there is no general definition of lead-free solder [7, 8]. Among the factors examined are mechanical qualities, thermal-aging characteristics, and SEM pictures of solder layer cross-sections as they relate to the reliability of solder joint layers. [9]. Lead poisoning of underground water may occur in landfills where electronic products are discarded, as well as health risks to humans. In today's society, consumer devices are usually only used for a short period of time, which impacts the environment. Consequently, it is crucial to know how lead-free solder compares to lead-solder and decide which is the preferred alternative. In addition to lead-free solders Sn-Sb, Sn-Ag, Sn-Cu, and Sn-Ag-Cu have been developed.

## 2. Methods

This research is conducted based on the approach of study literature, which is obtained from some papers that generally explain lead-free solder. To provide additional knowledge which is expected to add new insights about the importance of lead-free usage and its behavior.

TABLE I

Comparison of Solder Material

| Method | Author | Investigation | Solder Material |
|---|---|---|---|
| **A** | **Tatsuya K** | Microstructures (Low cycle fatigue test) | Sn-Sb |
| **B** | **Yoshinori I** | Microstructures (Power cycle test) | Sn-Sb and Sn-Ag |
| **C** | **M. Berthou** | Microstructures (Accelerated thermal cycles) | Sn-Ag-Cu |
| **D** | **Babak A** | Microstructures (Thermal Cycle) | Sn-Ag-Cu |

### METHOD A

In this study, they investigate the tensile and low cycle endurance characteristics of Sn-5Sb (mass%) and Sn-10Sb (mass%) alloys using small specimens with microstructures that are representative of the real solder connections. The investigation involved microstructural observation, tensile testing, and low cycle fatigue testing. First, specimen preparation becomes the most critical part of the process before starting all subsequent steps. Sn-5Sb and Sn-10Sb are the specimens used in this study. A miniature size specimen was cast with a gage length and diameter of 2.0 ± 0.2 mm, as well as a gage length and diameter of 0.50 ± 0.05 mm, in as-cast form. During this investigation, as-cast tiny size specimens were tested for tensile and low cycle fatigue. To investigate microstructures of as-cast miniature size specimens, subsequent layers of epoxy resin were implanted into the specimens, and cross sections were taken perpendicular to the longitudinal direction. The specimen's cross section was examined using an electron probe X-ray microanalyzer (EPMA) and a laser microscope after polishing. Then, tensile tests were conducted using a micro lead test system (Saginomiya Seisakusho LMH207-10). After the test, the specimens were examined using EPMA to evaluate their appearances and fracture surfaces. Low cycle fatigue tests were also performed using the micro load test equipment. In order to evaluate fatigue life, we counted the cycles that the maximum load was lowered. After the test was completed, laser microscopes and EPMAs were used to examine the fracture surfaces of the specimens.

### METHOD B

In this study, the solder joints of Insulated Gate Bipolar Transistors (IGBT) chip surfaces are analyzed in power cycle tests on a lead-frame structure. To connect a lead-frame with a Ni and Au-plated chip surface, lead-free solders are used as a heat-spreader (H/S). As for lead-free solders, for the Sn-Ag and Sn-Sb systems, two types are used: a normal lead-free solder and an alloy containing solid solution hardening. SEM images of solder joint layers and mechanical properties are used to evaluate the layer's reliability. Thermal-aging characteristics are also assessed in this investigation. Among the solders used in this study were Sn-3.5wt% Ag and Sn-5wt% Sb. Various mechanical tests were conducted to determine the mechanical properties of the lead-free solder, including tensile and thermal-aging tests. As a method of examining the reliability of the solder joint, power cycling tests were used.

**METHOD C**

A thermomechanical fatigue study has been conducted on the microstructure revealed by SAC solder joints. A cross section of the specimens was taken after they had been mounted in epoxy resin. First stage of the process, in grades 4000 and below, SiC paper is used. The surface will be polished using polishing cloths and spray diamonds until 0.25 µm is reached. In addition to the cross section, samples must also be etched using an abrasive solution comprising colloidal silica suspension ($SiO_2$) with a pH of 9.8 (grain size of around 0.04 µm). The end result is presented. Using Accelerated Thermal Cycles (ATC) and Thermal Storage, this study investigates failure mechanisms associated with thermo mechanical aging and thermal fatigue, respectively. The fatigue damage in SAC solder joints was assessed using Accelerated Thermal Cycles (ATC). An Accelerated Thermal Cycle (ATC) correlates with microstructure evolution and recrystallization analysis. In addition, thermal storage results in few changes to the microstructure and the intermetallic compounds (IMC).

**METHOD D**

Under standard conditions (0/100°C or -40/125°C) and with components designed to reduce warpage and assure lateral uniformity, thermal cycle tests were conducted. Under standard accelerated thermal cycle conditions, -40 and 125°C, dwell periods between extreme temperatures are 10 minutes, and transition speeds are 9°C per minute. Each component pad had a solder mask hole with a diameter of 15 mils. For the current stage of the study, spheres of SAC305 with diameters of 10 and 16 mm were used for the test vehicles.

Another gentle thermal cycling experiment was conducted with test boards (referred to as board B) composed of phenolic FR4 filled with a high glass transition temperature, Tg. A solderable finish was achieved by using immersion silver (ImAg). During this experiment, two rather moderate accelerated thermal cycle settings were employed (0/100°C and 20/80°C). As part of the 0/100°C test profile, 15-minute ramp times were used in conjunction with 30-minute hot and cold dwell times; however, for the 20/80°C test, 25-minute ramp times were used in conjunction with 30-minute hot and cold dwell times. As part of the microstructure examination, the samples were mounted, cut into slices, and polished with diamond and colloidal silica solutions.

## 3. Results and Discussion

**RESULTS A**

In relation to the microstructure results. In order to capture the results, SEM with back-scattered electrons (BSE) was employed. The dark gray and bright gray phases in both alloys are very fine, measuring sub-micrometer in diameter. Additionally, Tatsuya captured the Sn-Sb phase diagram. In accordance with the phase diagram, Sn-5Sb and Sn-10Sb contain phases of β-Sn and SbSn. A dark gray phase and a bright gray compound were determined respectively from the β-Sn phase and the SbSn compound.

It was found that the tensile strength of Sn-5Sb rises either at ambient or at elevated strain rates, independent of the temperature studied. However, at ambient temperature this trend does not exist for Sn-10Sb. Experimental conditions ranged from $2 \times 10^{-3}\ s^{-1}$ to $2 \times 10^{-1}\ s^{-1}$ at 25°C and 150°C. Also, the Sn-5Sb elongation at 150°C and Sn-10Sb elongation at both temperatures appears to increase as strain rate increases.

Detecting the increased level of β-Sn at 150°C is due to the dissolution of SbSn compounds at high temperatures and the decrease in ratio of the compound. As the temperature increases, Sn-5Sb's elongation decreases. In comparison, Sn-10Sb grows when the temperature rises. At 25°C, Sn-10Sb elongates more slowly than Sn-5Sb, but at 150°C, the difference between the two is insignificant.

Moreover, because of its low cycle fatigue properties, production of coarse SbSn compounds in the Sn-Sb alloy has been shown to slow down the crack progression, thus improving the fatigue properties.

**RESULTS B**

In this study, the focus was on mechanical properties and the reliability of the solder joints.

The first topic was mechanical properties. During the tensile tests at 25°C, 150°C, and 175°C, the strain rate was 0.2%/sec. Sn-3.5wt% Ag and Sn-5wt% Sb solder's yield stress has decreased with an increase in temperature. Due to higher temperatures, both solders have experienced a loss of strength in tensile testing. As a result, if the temperature is 25°C, the tensile strength of Sn-3.5wt% Ag solder is higher than that of Sn-5wt%Sb solder. The temperature dependence of Sn-5wt%Sb solder is less than that of Sn-3.5wt%Ag solder based on tensile test results.

During thermal-aging tests, 60°C was applied for 24 hours, 150°C for 1000 hours, and 175°C for 1000 hours. As the tensile tests were conducted after thermal aging, the strain rate was 0.2%/sec. According to the results of tensile tests and thermal aging testing, lead-free Sn-5wt%-Sb solder may be suitable for high temperature applications of IGBT modules.

As a result of the large area solder joints of lead-frame structures, their reliability might be affected.

In particular, IGBT modules are to be tested for their reliability by power cycling (P/C), especially when it comes to the solder joint layer. Testing P/C was carried out using an operating current rated at the rated operating current (Ic). This investigation conducted P/C tests with Tj=100°C.

A Sn-5wt% Sb solder's P/C capacity is three times higher than that of a Sn-3.5wt% Ag solder when F(t) = 1%. For Sn-3.5wt% Ag solder, the inclination of the plotted line is also smaller than for Sn-5wt% Sb solder. According to this analysis, the Sn-5wt% Sb solder joint layer is more reliable and stable.

It is discovered that the solder connection layer between the H/S and IGBT surface electrode has cracks. There were a few fractures found in the Sn-3.5wt% Ag solder layer following the grain growth, curved in nature along the grain interface.

By comparison, cracks found in the Sn-5wt percent Sb solder layer propagate as straight lines. A few grain structures are visible in the Sn-5wt%Sb solder layer.

## RESULTS C

A study conducted in this study investigated the microstructure of SAC solder joints, failure in thermo-mechanical aging: accelerated thermal cycles and failure mechanism in thermal fatigue: thermal storage.

Microstructure of SAC joints had been revealed previously. Immediately after the cross-section, the samples are etched with a colloidal silica suspension (SiO) that has a pH of 9.8. A dendritic structure may be seen surrounded by eutectic precipitates. With this reproducible and reliable technique, microstructures can be examined during thermo-mechanical fatigue.

To evaluate fatigue damage in the solder joints of Chip resistors 1206 and BGA, we performed accelerated thermal cycle tests: samples were made by combining SAC 305 (Sn-3% Ag-0.5%) paste for a vapour phase reflow profile peaking at 240°C.

A temperature ramp lasting 20 minutes was followed by a dwell period of 125°C followed by 55°C cycles. As the failure analysis technique requires, cross-sections were taken at T = 0, 500, 750, and 1000 heat cycles respectively. A BGA SAC solder ball was described in terms of its microstructure after 1000 heat cycles.

During the next phase of this research on thermal storage, three different temperatures were investigated: 80°C, 125°C, and 150°C. It will take 1000 hours to complete the exam. There is a cross-section every 250 hours.

## RESULTS D

During thermal cycling experiments, the morphology of precipitates was shown to alter, especially in certain areas. Additionally, precipitate coarsening was observed in the smaller sample with the lower standoff height. These samples displayed a crack route substantially different from those in larger samples. As compared to the bigger samples, the coarsening in the smaller samples did not occur in a confined area. Despite coarsening of the precipitate throughout the joint, the crack area seemed to be particularly affected.

We experimented with partial cycling on a few samples from board A. These samples were pulled from the chamber after 50% of the predicted life and cross-sectioned to study how microstructure changed as it was tested. On the component side of the larger sample (beach-ball structure) there is an indication of the beginning of cracking after the component has been cycled for half the expected life. In contrast, microscopic images of the smaller samples do not demonstrate crack initiation, confirming previous claims that the Sn structure is more resistant to crack initiation than the beach ball structure.

Several solder joints on board B samples exposed to modest heat cycling (20/80°C) and severe circumstances (-40/125°C) were examined to determine the mechanism of failure. In the severe cases, a crack in the solder at the component side may have occurred. As with the (-40/125°C) samples, the cracks in the precipitate have spread intergranularly. An optical micrograph showing the new grains created from the break confirms the coarsening of the precipitate around the break. While crack propagation was slower at (20/80°C) than standard ATC profiles, overall results for both standard and moderate thermal cycling procedures were similar. SAC assemblies appear to fail by the same mechanism as the ATC profiles, according to the (20/80°C) reliability testing findings.

Furthermore, the authors may simplify the explanation among 4 different references above. From Tatsuya Kobayashi et al, 2018 and Yoshinori Ikeda, 2008 that discussed more often about Sn-Sb and the correlation of reliability solder joint from the mechanical properties, high temperature condition and microstructures, got a result that in comparison, Sn-10Sb grows when the temperature rises. At 25°C, Sn-10Sb elongates more slowly than Sn-5Sb, but at 150°C, the difference between the two is insignificant. By comparison, cracks found in the Sn-5wt%Sb solder layer propagate as straight lines. A few grain structures are visible in the Sn-5wt%Sb solder layer.

A discussion result from M. Berthou, 2009 and Babak Arfaei, 2013 which focused on Sn-Ag solder joints that examines the mechanical properties and microstructures during thermal cycling experiments. To determine the mechanism of failure, several solder joint samples were subjected to both mild heat cycling (20/80°C) and severe heat cycling (-40/125°C). Microstructure evolution and recrystallization analysis are related to an Accelerated Thermal Cycle (ATC). Additionally, thermal storage alters the microstructure and intermetallic compounds only slightly (IMC).

Based on those statements, in general, the microstructure and mechanical properties of the solder joints Sn-Sb and Sn-Ag-Cu (SAC) are affects by the thermal condition.

## 4. Conclusions

This narrative review was carried out by scientists based on scientific work that became the literature. The characteristics and dependability of lead-free solder materials are discussed. This is useful for doing some mapping or getting a sense of the influence of various temperature fluctuations in the soldering region, also the effects of the cracked progression regarding to the temperature changes.

We have developed a reliable method to analyze SAC solder joints. This technique enables researchers to study how the microstructure of a SAC connection changes as a result of thermo-mechanical aging.

Observations of cracked specimens show that producing coarse SbSn compounds in the Sn-Sb alloy can increase fatigue characteristics by delaying crack progression.

An investigation of lead-free SAC solder joints found that the failure mechanisms were nearly identical. Crack propagation was observed at grain boundaries of recrystallized areas of the sample, which was indicative of solder fatigue.

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