Abstract—The use of Low Temperature Solders (LTS) as an alternative to high temperature Sn-Ag-Cu (SAC) alloys has gained increasing interest owing to the benefits associated with low reflow temperatures such as decrease in warpage during assembly, nontoxicity, and lower operating and energy costs. Sn-Bi alloy system, with reduced reflow temperature of approximately 183°C, is a popular LTS alloy system. In addition to the existing literature on microstructural properties, there is a need to study and compare the mechanical properties of the new LTS solders. As part of this study, a baseline mechanical characterization of Sn3.0Ag0.5Cu and Sn58Bi solder compositions is first performed. Several alloying elements have been suggested to improve the reliability of Sn-Bi system, of which Ag, In and Sb have been studied in this work. Mechanical behavior of Sn57Bi1Ag, HRL3 (by MacDermid Alpha), L27 and L29 (by Senju Metal Industry) alloys are presented here. In addition, the effect of pretest aging (after reflow and aged to 10 days at 85°C/125°C) on the mechanical behavior of the alloy system is studied. A comprehensive comparison of the mechanical behavior of the four new LTS alloys against the baseline alloys is presented. A custom designed micro-precision mechanical tester is used to perform isothermal creep, monotonic and fatigue testing of the solder test specimen under shear at room temperature and an elevated temperature of 70°C.

Index Terms—Low temperature alloys, eutectic SnBi, SAC, microalloys, solder joint reliability, mechanical characterization, constitutive behavior, fatigue life

I. INTRODUCTION

With increasing demand on reliable and energy efficient electronic packaging, optimizing the material sets in the package is of paramount importance. Solder joints increasingly made of complex multi-element alloys serve as a both mechanical and electrical connections between chips and printed circuit boards. Over the past two decades the solder compositions have evolved towards leadfree alloys. The widely used Sn3.0Ag0.5Cu (SAC305) is the standard Sn-Ag-Cu (SAC) alloys alternative. However, owing to its melting temperature of 220°C, the solder reflow temperatures are usually around 245-250°C [1]. These high reflow temperatures lead to significant CTE mismatch between the dies and boards which in turn induce warpage of the substrate and loss of assembly yield. The failures manifest as open circuits caused by loss in contact or short circuit due to bridging of solder between to high reflow temperatures, low temperature soldering (LTS) systems are increasingly under consideration. Solders based on eutectic Sn-Bi alloys with melting temperatures of 183°C are popular candidates for low temperature soldering due to their low eutectic temperature [2].

While there have been studies on the microstructural analysis of the Sn-Bi alloy systems [3], the corresponding mechanical behavior of varying alloying compositions in the Sn-Bi systems is not widely understood. Solder joints typically fail under ductile creep-fatigue fracture near the intermetallic compound (IMC) interface but in the bulk solder and/or brittle fracture through the IMC. While ductile fatigue fracture typically occurs in stationary office equipment, brittle fracture due to impact usually occurs in portable electronic equipment. The mechanical behavior of the bulk alloy may be in general modeled as a viscoplastic (strain rate-dependent) material. In the present study, fatigue experiments are carried out to provide an estimate of the life of the solder joints with different alloying compositions, and constitutive behavior of the alloys are captured using load controlled creep tests and rate controlled monotonic tests. A series of fatigue, creep and monotonic experiments are performed and the results are used to compare the mechanical behavior of five different Sn-Bi based LTS alloys with Organic Substrate Preservative (OSP) surface finish and compared to the behavior of the baseline SAC305 alloy. In all the test samples, the solder joint is made entirely of the chosen alloy formed between the pads of OSP finish.

II. MICRO-PRECISION MECHANICAL TESTER

The micro-precision tester used in this study is a custom machine designed to overcome the challenges typical to commercial mechanical testing machines. The primary challenge is associated with displacement measurement. Commercial testing machines determine position using an encoder mounted at the actuator, and claim sub-micron accuracy based on measurement at the actuator as opposed to the sample. However, measurement of the actuator position is not an adequate measure of the strain at the sample due to load train compliance. The behavior of solder is strongly strain-rate dependent, and requires closed-loop control with measurements
of displacement as close to the sample as possible, so as to minimize load train compliance. The next issue is in reference to cyclic testing, which for solder requires the load train to support compressive loads. The load train of commercial testing machines use ball joints to absorb off-axis loading produced by misalignment, rather than transfer the off-axis loads to the sample. However, these joints cannot transfer compressive loads without backlash making it challenging for cyclic testing of solder. The design of the custom tester overcomes these issues. This section provides a brief overview of the design and features of the micro-precision tester designed by the authors [4]. The tester design presented here is a revision of the tester designed by Dale [5]. The micro-precision tester is a universal mechanical tester designed on the same principles as Instron and MTS testing machines. The tester is designed for testing solder samples in shear, or combined shear and compression. The overall design can be seen in the CAD model as well as a photograph of the tester in Fig. 1 and Fig. 2.

![Fig. 1. CAD model of the micro-precision mechanical tester [4].](image1)

![Fig. 2. Image of the micro-precision mechanical tester with the environmental chamber.](image2)

The main hardware components include Newmark NLS4-2-11 linear stage, ATI Gamma 6-axis load cell, Lion Precision CPL190 and a custom environmental chamber. NLS4 series uses a trapezoidal leadscrew with a plastic nut to assure minimal or zero backlash. Even so, the actuator position and the position measured by the capacitance sensor do show a difference under cyclic positioning experiments carried out without any applied load. The observed backlash is between 6 and 8 µm, as shown in Fig 3. The shear load on the sample is measured by the z-axis, which has a range and resolution ±200 N and 0.025 N, respectively. For both x- and y-axes, range and resolution are ±65 N and 0.0125 N, respectively. The capacitance sensor has a range of 250 µm and a resolution of 7.5 nm. The capacitance sensor is mounted as close to the sample as possible in order to minimize measurement of load train compliance. This is especially relevant for solder joint testing, as these materials display strongly strain rate dependent mechanical behavior. The measurement from the capacitance sensor is used for closed-loop control, so as to avoid the challenge of load train compliance affecting the strain rate at the sample. Temperature at the sample is measured and controlled using a thermocouple placed next to the sample. The chamber operates by forcing heated air over the sample with a high temperature fan. The environmental chamber can maintain a constant temperature to within ±0.5 °C. The data acquisition and control is handled by a desktop computer running a custom LabVIEW program. The overall design of the micro-precision tester was verified by determining the elastic modulus from tensile testing and comparing to the accepted value. AISI 1010 steel, with a commonly accepted elastic modulus of 200 GPa, and UNS 6061 aluminum, with a modulus of 69 GPa were used. The mean absolute errors were 3.3% and 2.6% for steel and aluminum, respectively.

![Fig. 3. Commanded and measured positions of the NLS4 actuator while unloaded.](image3)

Sample Specifications

![Sample Specifications](image4)

The solder test specimen were designed as an assembly consisting of squat-joints, with a diameter of 730 µm and standoff height of 150 µm. Eight joints were sandwiched
between two FR4 substrates that were single layer PCBs with mask defined copper pads and Electroless Nickel Immersion Gold (ENIG) or OSP surface finishes as shown in Fig. 4. A study by Bhate [6] showed that lower aspect ratio joints generate a more homogeneous shear stress at the pad interface. Hence, low aspect ratio squat joints were used to produce a more uniform state of stress at the solder-pad interface, thereby relating a given applied load to a unique state of stress at the interface. In order to test the samples, they were attached to removable fixtures with cyanoacrylate 4 adhesive. Additionally, the removable glue fixtures allow for preservation of the sample after testing for microstructure and failure analysis.

III. EXPERIMENTAL METHODOLOGY

Design of Experiments

Starting with Sn-Bi eutectic composition, compositions with varying microalloys such as Ag, Cu, Ni and Sb were studied in this work. The surface finish on the samples used in this study was OSP. The L27 (Sn-40Bi-Cu-Ni) and L29 (Sn-58Bi-Sb-Ni) compositions are propriety of Senju Metal Industry and HRL3 of MacDermid Alpha. While the microstructural analysis are studied in [3], the mechanical behaviour of these viscoplastic alloy compositions have not been thoroughly studied. In this work, a thorough study of comparative mechanical behaviour has been conducted by performing fatigue experiments to provide an estimate of the life of the solder joints, and creep and monotonic experiments to capture the constitutive behavior of the alloys.

In order to compare the reliability of these alloys, accelerated fatigue tests were performed at two different test temperatures as shown in Fig. 5. In addition, load controlled creep tests at a stress of 25.9 MPa (50N) and strain rate of $7.7 \times 10^{-4}$ (displacement-rate of $0.2 \mu m/s$) controlled monotonic tests were also performed. The table containing the list of conducted experiments is shown in Fig. 6 and Fig. 7. A total of 12 experiments each of creep and monotonic tests in addition to 24 experiments of fatigue tests were performed.

The equivalent uniaxial tensile stress $\sigma$ and engineering strain $\epsilon$ within the solder joints were approximated using the von Mises distortion energy theory as given by Eq. (1). Here $F_z$ is the applied shear load, $A$ the total pad area, $\Delta z$ the measured shear displacement and $h$ the stand off height. Accordingly, the equivalent stress of a 50N load controlled creep test is 25.9 MPa and the equivalent strain rate of monotonic experiments is $7.7 \times 10^{-4} s^{-1}$. For the fatigue experiments, a trapezoidal displacement profile was used, with a rate of $0.2 \mu m/s$ ($7.7 \times 10^{-4} s^{-1}$), a total displacement of 39 $\mu m$ (15% strain), and a dwell of 200 s. This profile emulates the strain profile placed on field solder joints by thermal cycling. This profile was repeated until the peak stress load drop parameter over cycles reached 20% as shown in Fig. 8. Here, $\Delta F$ is the load range over cycles, $\Delta z$ is the normalized load drop parameter. The number of cycles to reach 50% drop in peak load is termed as $N_{50}$ (Fig. 9) and is used to compare fatigue life of candidate alloys.

IV. RESULTS

In this section, the results of fatigue, creep and monotonic experiments of the candidate alloys both under as reflowed and isothermal aging conditions are presented. Firstly, the results of fatigue experiments and the corresponding cycles to 50% drop in peak load - N50 are presented. Fig. 10 provides a comparison of the fatigue life of various compositions subjected to a test temperature of $30^\circ C$. We see that isothermal aging, both at $85^\circ C$ and $125^\circ C$ lead to a decrease in fatigue life of all the compositions except in L27. It was also seen that unaged HRL3 demonstrated higher fatigue life compared to the other Sn-Bi compositions, but exhibited significantly lower life compared to the SAC305 standard. It is to be noted that the result for L29 composition under aged condition is not visible since the sample broke in the first cycle. The test involving L29 sample was repeated three times in order to ensure the observed fracture was not due to testing error. Fig. 11 provides...
a comparison of fatigue life of various compositions subjected to an elevated test temperature of 70°C.

In order to better understand the constitutive mechanical behavior of these alloys, a series of creep and monotonic tests were also performed. A total of 12 creep and 12 monotonic experiments were performed. Fig. 12 presents the creep behavior of as reflowed alloys subjected to a test temperature of 30°C and Fig. 13 corresponds to creep behavior of isothermally aged samples (refer to Fig. 6) at 30°C test temperature. It can be seen that unaged Sn57Bi1Ag and L27 bound the range of minimum creep strain rates. In general, the creep resistance of the LTS alloys improves with aging. However, the creep resistance of SAC305 decreases significantly with aging. Fig. 14 and 15 present the monotonic behavior of the compositions under as reflowed and isothermal aging conditions respectively (refer to Fig. 7). Similar to the trend observed in the creep behavior, the saturation stress increases with aging for the LTS alloy. But, the saturation stress of SAC305 decreases significantly with aging.

V. SUMMARY

In addition to the existing literature on microstructural analysis of SnBi alloying compositions, there is a need to study the mechanical behavior of other alloying compositions. A thorough mechanical characterization was conducted in this study to estimate the fatigue life and capture the constitutive behavior of alloying compositions. A baseline mechanical characterization of Sn3.0Ag0.5Cu and Sn58Bi solder compositions is first performed using fatigue, creep and monotonic experiments, followed by characterization of alloying compositions with microalloying elements such as Ag, Cu, Ni and Sb. A total of five LTS alloy compositions were subjected to mechanical testing, in addition to SAC305. The key inferences from the experiments are summarized in this section.

The results of the fatigue experiments are as shown in Fig. 10 and Fig. 11. It was observed that the fatigue life of SAC305 is significantly higher than those of the LTS alloys tested in this study. The fatigue life of the LTS alloys subject to isothermal aging was observed to be significantly different from that of the unaged alloy with no systematic observable trend between the various alloys in the manner that the life changed with aging. The aged L29 alloy was brittle and failed during the first cycle of the test. Fig. 12 and Fig. 13 provide the comparison of creep behavior of the various alloying compositions. It was seen that the creep behavior of eutectic SnBi is similar to other compositions with microalloying elements. In general, the creep resistance of LTS alloys improved with isothermal aging. Finally, the results of monotonic experiments are as shown in Fig. 14 and Fig. 15. In general, the LTS alloys exhibited larger saturation stress than SAC305. However, saturation stress of eutectic SnBi is less than that of other compositions with microalloying elements. SAC305 saturation stress decreases significantly with aging.

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REFERENCES

Fig. 11. Fatigue life of as received and isothermally aged LTS alloys at 70°C test temperature

Fig. 12. Creep response of LTS alloys at 30°C test temperature

Fig. 13. Creep response of isothermally aged LTS alloys at 30°C test temperature

Fig. 14. Monotonic response of LTS alloys at 30°C test temperature

Fig. 15. Monotonic response of isothermally aged LTS alloys at 30°C test temperature


