STRAIN RATE EFFECTS ON SOLDER JOINT FAILURE BEHAVIOR

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

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Abstract

The effects of strain rate on bulk tensile stress strain properties of solder have been investigated by many researchers, however the effects of strain rate on stress strain properties of solder joint requires further study. Another aspect which is important for solder joint failure study is the effects of mixed mode loading on solder joint failure behavior and mixed mode fracture toughness measurement and analysis.

In this PhD thesis, the strain rate dependent mechanical properties and stress strain behavior of 95.5Sn3.8Ag0.7Cu (SAC387) lead-free solder are investigated for a range of strain rates. The strain rate dependent elastic modulus, yield stress properties and stress strain constitutive model of the solder material are characterized using tensile tests. Tensile tests on dog-bone shaped bulk solder specimens were conducted using a non-contact video extensometer system. Iso-strain rate uni-axial tensile tests were conducted over the strain rates of 0.001, 0.01, 0.1 and 1 (s⁻¹) at 25°C. For all the tests conducted, higher strain rate is well correlated with higher elastic modulus and yield stress of the solder.

Nanoindentation tests were conducted from slow to intermediate strain rates of 0.001, 0.01, 0.1, 1 and 10 (s⁻¹) by using the continuous stiffness measurement (CSM) technique. The strain rate dependent yield stress results from nanoindentation test are expressed in a Cowper-Symonds model where the dynamic flow stress can be estimated over a wide range of strain rates. Strain rate sensitivity effects on the plastic yield stress behavior of SAC387 solder from nanoindentation and tensile test were investigated.
The stress strain constitutive model behavior of 95.5Sn3.8Ag0.7Cu solder was investigated further under compression over strain rates ranging from 0.022 s$^{-1}$ to 9.266 s$^{-1}$ and under tension over strain rates ranging from 0.001 s$^{-1}$ to 1.0 s$^{-1}$. A new Ramberg-Osgood model is developed to describe the stress strain curve model at one particular strain rate. Modifications are done on the original Ramberg-Osgood model in order to form a strain rate dependent model that can describe stress strain curves over all range of strain rates. The model expressions are able to capture the strain rate dependence of the yield and work hardening parameters within the range of the test conditions reported in this thesis. A modified Ramberg-Osgood model consisting of ten constants is derived for strain rate dependent expressions by using linear regression curve fitting.

Fracture behavior of solder joints were investigated for soldered tensile test specimens and for a complex combined loading complex mixed mode (CMM) test fixture developed for tensile and shear combined load tests over an intermediate strain rate range from 0.001s$^{-1}$ to 0.1s$^{-1}$. The fracture behavior of solder joints subjected to pure tensile, pure shear or varying combination of mixed-mode (tensile and shear) loading combinations were investigated in detail. The observed failure modes vary from brittle intermetallic (IMC) layer failure to ductile bulk solder shear failure. Under mixed-mode loading, a complex combination of IMC and solder failure mechanism was observed.
The CMM tests were investigated with cracks fabricated in the solder joint and the fracture behavior of solder joint subject to mode mixity is reported. A fracture mechanics based failure assessment curve (FAC) criteria approach is proposed using interfacial fracture mechanics theory. Finite element analysis results provided mixed mode stress intensity factors for interface cracks used to calculate the fracture toughness parameters.
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<th>Description</th>
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<tr>
<td>SAC387</td>
<td>95.5%Sn3.8%Ag0.7%Cu solder alloy</td>
</tr>
<tr>
<td>CSM</td>
<td>Continuous stiffness measurement</td>
</tr>
<tr>
<td>CMM</td>
<td>Compact mixed mode</td>
</tr>
<tr>
<td>IMC</td>
<td>Intermetallic compound</td>
</tr>
<tr>
<td>FAC</td>
<td>Failure assessment curve</td>
</tr>
<tr>
<td>OSP</td>
<td>Organic solderability preservative</td>
</tr>
<tr>
<td>ENIG</td>
<td>Electroless nickel immersion gold</td>
</tr>
<tr>
<td>RoHS</td>
<td>Restriction of the use of certain hazardous substances</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate tensile stress</td>
</tr>
<tr>
<td>GND</td>
<td>Geometrically necessary dislocation</td>
</tr>
<tr>
<td>SSD</td>
<td>Statistically stored dislocation</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element modeling</td>
</tr>
<tr>
<td>SIF</td>
<td>Stress intensity factor</td>
</tr>
<tr>
<td>CTOD</td>
<td>Crack-tip opening displacement</td>
</tr>
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CHAPTER 1

1 Introduction

1.1 Background to the Research Study

The use of portable electronic devices is prevalent in modern living. In these devices there are many electronic components that are connected together using solder joints. These solder joints are subjected to shock induced strain rate dependent loading as the devices are dropped or mishandled during daily usage. These loadings cause elastic-plastic deformation in the solders joints, which can lead to failure at the solder joint and interconnecting interfaces in the electronic device.

Strain rate effect is crucial to solder joint range from $10^{-5}$ to $10^3$ s$^{-1}$. In Figure 1, the strain rate regime within $10^{-5}$ to $10^{-1}$ s$^{-1}$, it is named as low strain rate regime and it encounters with creep and fatigue behavior. In the high strain rate regime, the strain rate dependent properties are significant for drop and impact test. In the intermediate strain rate regime, which is from $10^{-1}$ to $10^1$ s$^{-1}$, it basically covers the transition of solder joint behavior under loading from low strain rate to high strain rate, for example, PCB bending and low strain rate mechanical shock. Hence, it is necessary to research on the mechanical properties of SAC solder within the intermediate strain rate regime.
Solder joint failure and reliability is an important area of research as the solder material properties and the solder joint strength needs to be characterized for strength and failure analysis. Characterization of the mechanical properties of the solder material help to provide test data for material selection to choose suitable solder alloy for specific purpose with adequate solder joint strength.

Iso-strain rate test data are often used for characterizing bulk solder strain rate dependent stress strain properties. Thus, it is essential to characterize solder and solder joint properties and failure mode over typical strain rates of $10^{-3}$ to 1 (s$^{-1}$) as shown in Figure 2, which covers the transition from slow strain rate to intermediate strain rate. In this study, iso-strain rate tensile specimen tests and nanoindentation tests were conducted to make comparisons between the strain rate dependent yield stresses for a selected 95.5Sn3.8Ag0.7Cu (SAC387) solder.
In application of soldering, the size of solder joint can be in range of 100 microns to one millimeter. Therefore, in this study nanoindentation was used to evaluate the strain rate dependent hardness \( (H) \) for SAC387 solder. The strain rate dependent hardness \( (H) \) can be converted to strain rate dependent yield stress and compared to the corresponding yield stress measured from iso-strain rate tensile tests.

In this study, the author has characterized SAC387 lead-free solder by using tensile test and nanoindentation test methods respectively. The strain rate dependent yield stress behaviors of these alloys were compared. Normally, tensile test is used to characterize strain rate dependent properties within slow strain rate regime \( (10^{-3} \text{ s}^{-1} \text{ to } 10^{-1} \text{ s}^{-1}) \) and nanoindentation test is used for intermediate strain rate regime \( (10^{-1} \text{ s}^{-1} \text{ to } 10^{1} \text{ s}^{-1}) \) characterization.

Based on the author’s test specimen sizes, the tensile test and nanoindentation test volumes are different by 9 orders of magnitude. Figure 3 illustrates the difference in plastic flow volume for nanoindentation test and tensile test. The
Nanoindentation test has a plastic flow volume of \(3.27 \times 10^{-17} \text{ m}^3\) compared to a tensile test plastic flow volume of \(7.07 \times 10^{-8} \text{ m}^3\). With the vast difference in plastic flow volume by about nine orders of magnitude it is interesting to compare the strain rate sensitivity index \(m\) analysis derived from nanoindentation and tensile tests. In the author’s investigations, the author hypothesizes that the strain rate dependent yield stress properties from tensile test and nanoindentation test results can be correlated to model the two different test methods.

![Figure 3 Illustration of Plastic Flow Volume for Nanoindentation Test and Tensile Test](image)

The aim of the present study is to compare the strain rate sensitivity effects on yield stress measured from nanoindentation hardness to the traditional strain rate sensitivity measurements derived from tensile test. It is clear that nanoindentation test and tensile test have vastly different plastic flow volumes. Hence, there is a need to determine the strain rate dependent properties from nanoindentation test and tensile test at intermediate strain rate of \(10^{-1}\) to \(10\) \(\text{(s}^{-1})\) for comparison and correlation.
In order to understand the fracture mechanism of solder joint failure better, solder joint tensile, shear and mixed mode (tensile and shear) tests were devised using a CMM test fixture. Test were conducted to study the failure mode of solder joints under combined (tensile & shear) loading. In solder assembly testing, there is always difficulty of getting consistent failure mode out of an assembly test with many solder joints. It shows a combination of failure modes including ductile bulk solder failure, brittle interfacial failure. The assembly also has substrate and pad lift-off failure. Hence, a single solder joint test was conducted to observe ductile to brittle failure mode using soldered tensile specimen test and a compact mixed mode (CMM) test specimen.

There are many factors that would influence the mechanical property of the solder joint in the electronic assembly such as, the type of joint that is employed in the assembly, the type of metal pad and coating that is used to connect with the solder which will have an effect on the intermetallic compound (IMC) and its failure mode. An important factor in determining the strength of the solder joints in the electronic assembly is the type of solder used in the joints. Solder is a ductile material, but when subjected to high strain rates the behavior of the solder joint would change from ductile failure mode in the solder towards brittle failure at the IMC or interface with the copper pad.

In this thesis, the focus of the study involves two important areas of research in: 1) The effects of strain rate on bulk tensile stress strain properties of solder and solder
joint strength; 2) The effects of mixed mode (Tensile and Shear) loading on solder joint strength and mixed-mode fracture toughness measurements and analysis.

1.2 Objective

The objectives of this study are as follows:

1. To characterize the strain rate, $10^{-3}$ to $10 \, (s^{-1})$, effects on the elastic-plastic properties for lead-free 95.5Sn3.8Ag0.7Cu (SAC387) solder. To develop a new strain rate dependent modified Ramberg-Osgood stress strain constitutive model taking into account strain rate effects for SAC387 solder.

2. To characterize the intermediate strain rate, $10^{-1}$ to $10 \, (s^{-1})$, dependent yield stress properties for SAC387 solder derived from both tensile test and nanoindentation test data and develop correlations between these two different test approaches. To develop a strain rate dependent Cowper Symond constitutive model.

3. To develop single solder joint test to characterize strain rate effects on actual solder joint using copper-solder-copper single solder joint specimen for SAC387 solder.

4. To characterize mixed-mode (Tensile and Shear) solder joint strength failure assessment curve (FAC) criteria using a compact mixed mode (CMM) test method over strain rate 0.1, 0.01 and 0.001 \,(s^{-1}).
5. To characterize mixed-mode fracture toughness ($K_I$ and $K_{II}$) test using a compact mixed mode (CMM) test specimen with embedded interface crack flaw over strain rate 0.1, 0.01 and 0.001 (s$^{-1}$).

1.3 Scope
Chapter 1 of this thesis introduces the motivation, objective and scope of this research study. Chapter 2 covers literature review of relevant work from other researchers including stress strain behavior of solder material from tensile and nanoindentation characterization. Chapter 3 conveys the experimental procedures and test vehicles used by the author such as tensile test on bulk and single solder joint solder specimen, nanoindentation test and compact mixed mode test. The effects of strain rate on bulk tensile stress strain properties of solder and solder joint strength are reported in chapter 4, 5 and 6.

In Chapter 4, strain rate effects on bulk solder tensile stress strain properties have been characterized and analyzed. The chapter documents tensile tests that were carried out with strain rate range from $10^{-3}$ s$^{-1}$ to 1 s$^{-1}$ on lead-free SAC387 specimens at room temperature. Strain rate sensitivity analysis on the stress strain behavior of the lead-free solders was done. The Ramberg-Osgood model was employed to characterize the full elastic-plastic stress strain curve response. The author then developed a strain rate dependent modified Ramberg-Osgood stress strain curve model.
In Chapter 5, Strain rate effects on bulk solder nanoindentation experiments have been characterized and analyzed. Iso-strain rate nanoindentation test and analysis of strain effect on the mechanical properties of modulus and harness were characterized for SAC387 solder. Nanoindentation test were carried out with strain rate range from $10^{-2}\text{s}^{-1}$ to $10\text{s}^{-1}$ at room temperature. The strain rate dependent yield stress can be derived from the hardness result and hence the strain rate sensitivity index of SAC387 solder can be determined. The dynamic flow stress over the range of strain rates tested can then be fitted to a Cowper-Symonds model.

In Chapter 6, strain rate effects on solder joint strength measurements have been characterized and analyzed. The chapter documents single solder joint test method under tensile condition to study various mechanical properties, which are closer to an actual solder joint.

The effects of mixed mode (tensile and shear) loading on solder joint strength and mixed-mode fracture toughness measurements and analysis is documented in chapter 7.

In Chapter 7.2, Mixed-mode (tensile and Shear) loading test and analysis for solder joint failure behavior will be discussed. The chapter documents test and results at different strain rates for specimens with embedded interface cracks. It can be observed that the tensile and shear properties of the SAC387 solder alloy are highly dependent on the strain rate, where as the mechanical strength of the solder alloy increases with increasing strain rates.
In Chapter 7.3, Mixed-mode ($K_I$ and $K_{II}$) fracture toughness test and analysis for solder joint specimens with embedded interface cracks will be discussed. The chapter documents detailed fracture mechanics analysis was carried out on both interfacial and interlayer cracked problem for a range of fracture modes using finite element method. Compact mixed mode specimen was used to determine stress intensity factor with respect to thickness and fracture toughness of solder bonded joint. From the finite element results, the mixed mode stress intensity factor for solder bonded joint was evaluated using the theory of linear elastic fracture mechanics. The stress intensity factor may also be determined experimentally using the CMM specimen.
CHAPTER 2

2 Literature Review

2.1 Lead-free Solder Materials Properties

Mechanical testing of solder is used for two primary purposes: 1. Alloy development and selection; 2. Determining properties for failure analysis use in modeling and simulation of failure modes. There are several mechanical test methods, which put the material under different types of loading, for example in tension, shear, torsion, bending and nanoindentation [1-10]. For any particular test, the specimen can be fabricated purely of the bulk alloy or it can also be an actual solder joint specimen or an array of joint.

Solder joints are mechanically constrained at the interface between the substrate and the solder because the substrate is deforming elastically as the solder deforms inelastically. In most cases, a joint size is much smaller than a bulk specimen. Hence, the alloy microstructure of a joint is often difficult to reproduce in bulk [11, 12]. The advantage of testing actual joints is that one can simulate the effects of soldering on the test material [13-18]. As reported by Darveaux [19], solder joint creep resistance increased with joint size and larger joints were more prone to brittle interface failure than smaller joints. This was true in both package level tests and board level tests.

Clearly, solder joint specimen effects give arise to gradients strain and for solder joint, the strain concentration especially at the solder joint interface results in high strain gradients. Thus, these effects are expected to be significant when the
material is plastically deformed near small volumes, at the solder interface with the substrate and at the tips of cracks or in sub-micrometers indentations test regions [20-23]. However, other effects that do not appear to be associated with strain gradients can also be large when plasticity is constrained to occur in small volumes, and they should be distinguished from strain gradient effects [24-26]. Even when these materials are deformed homogeneously under biaxial loading, it is still not possible to use the constitutive properties of bulk materials to make predictions about the mechanical behavior. The constitutive properties of the actual solder joint materials must be used for such predictions [27-29].

The modulus and hardness of solder material can be measured by nanoindentation continuous stiffness measurement [30-34]. Based on Xu's investigation [35, 36], the hardness changes were subjected to the loading parameters. The indentation strain rate ($\dot{h}/h$) changes continuously within one test, both during loading and during the subsequent hold segment at constant load [37-40]. For the measurement of the steady-state stress strain rate curve from the bulk SAC solder specimen, it is well understood that the stress for a viscoplastic material is a function of applied strain rate and temperature, so the indentation hardness, or mean stress, should be expected to vary in an analogous way. Lucas [37] proposed an indentation experiment to study the creep behavior of indium-based alloy using the Berkovich tip, during which the indentation strain rate and, therefore, hardness remain constant. This method will be discussed in the later chapter.
Nanoindentation technique can also be used to measure modulus and hardness of IMC layer. Typical studies reported previously employ cross section specimens with thick IMC layers for nanoindentation tests [41]. Due to the very thin IMC layer, nanoindentation measurement on IMC layer in actual solder joint can be extremely difficult. In Xu’s study [36], novel plan view nanoindentation measurements for IMC layers were conducted on actual BGA SnAgCu solder joint interfaces with organic solderability preservative (OSP) and electroless nickel immersion gold (ENIG) surface finish. The plan view tests produces stable result for modulus and hardness even when the IMC layer was as thin as 1-2μm.

Not long ago, because of the EU RoHS (restriction of the use of certain hazardous substances in electrical and electronic equipment) [42] which was implemented on July 1, 2006, and the China RoHS (Management Methods for Control of Pollution Caused by Electronic Information Products) which was implemented on March 1, 2007, lead (Pb) is banned in most of the electronics products. Recently, many researchers have been devoted to slightly modify the existing SnAgCu by adding a very low level of doping X, and develop new lead-free solder alloys SnAgCuX with almost the same melting point as SnAgCu, however with better thermal and drop performances [43-46].

2.2 Stress Strain Behavior of Solder Material

For solder material under tensile loading condition, the engineering stress typically goes beyond the yield stress, $\sigma_y$ and continues to deform plastically till the ultimate tensile strength, $\sigma_{UTS}$, is reached before exhibiting saturation and subsequent
instability leading to ductile rupture failure. Figure 4 shows a typical stress strain curve of a ductile material under tensile loading. The yield stress, $\sigma_y$ can be determined by the 0.2% offset intersection method, the ultimate tensile strength $\sigma_{UTS}$, is determined at the maximum peak stress.

![Stress Strain Behavior of Solder under Tensile Loading](image)

**Figure 4 Stress Strain Behavior of Solder under Tensile Loading**

### 2.3 Nanoindentation Test on Lead-Free Solder

The indentation strain rate ($\dot{h}/h$) also changes continuously within one test circle, during loading and the subsequent load-held segment. For the measurement of steady state stress strain rate curve from bulk solder specimen, it has been well understood that the stress for a viscoplastic material is a function of applied strain rate and temperature, so the indentation hardness, or mean stress should be expected to vary in an analogous way. The indentation hardness of a material [35] is given by

$$H = \frac{P}{A} = \frac{P}{ch^2}$$

(1)
where $H$ is the hardness, $P$ is the load, $A$ is the projected contact area, $h$ is the displacement (contact depth), and $c$ is a constant that depends upon the geometry of the indenter.

A simple estimation of the relationship between yield stress and hardness \[32\] is given by

$$H = 3\sigma_y$$  \hspace{1cm} (2)

The yield stress of 95.5Sn3.8Ag0.7Cu solder can be estimated at different strain rate using this method.

2.3.1 Power-Law Hardness-Strain Rate Relationship

To find the steady state hardness at different indentation strain rate, a series of experiments at varying of $\dot{P}/P$ value were conducted \[36\]. The loading rate was controlled in such a way as to maintain the instantaneous value of $\dot{P}/P$ constant till the indentation depth reaches 1000nm. The $\dot{P}/P$ values of 0.002, 0.02, 0.10, 0.2, 1.0 and 20 (s\(^{-1}\)) were used. Figure 5 shows an indentation strain rate dependant load-displacement curve of SnAgCu solder.

After a short transient period, the calculated hardness become stable and is subject to the value of $\dot{P}/P$. By differentiation on Equation (1), if hardness becomes constant and $\dot{H} = 0$, the indentation strain rate ($\dot{h}/h$) equals half of $\dot{P}/P$. Since the constant $\dot{P}/P$ was used, $\dot{h}/h$ was also constant during the test. For example, when the value of $\dot{P}/P$ was 0.002, 0.02, 0.2, 2.0 and 20 s\(^{-1}\), the corresponding indentation
strain rate $\dot{h}/h$ was 0.001, 0.01, 0.1, 1 and 10, respectively. Thus, for each $\dot{P}/P$ experiment, a corresponding constant $\dot{h}/h$ and $H$ were achieved, which is considered as “steady state” indentation strain rate.

![Figure 5 Load vs. Displacement Curve of Nanoindentation Test [35]](image)

The relationship between indentation strain rate and hardness at room temperature is reported as

$$H = K(\dot{\varepsilon})^n = K(\dot{h}/h)^n$$

where $K=0.3466$ is material constant, $H$ is hardness, $n=0.1507$ is strain exponent. The range of strain exponent is between 0.1 to 0.3, depending on the materials composition and temperature.
2.4  Tensile Properties

2.4.1  Tensile Properties of Bulk 95.5Sn3.8Ag0.7Cu (SAC387) Solder

The concerned tensile properties for solder materials are elastic modulus, yield stress and ultimate tensile stress (UTS), which are strain rate and temperature dependent properties. Pang [47-49] reported that the mechanical properties of 95.5Sn3.8Ag0.7Cu solder are strongly dependent on the strain rate and test temperature parameters. The strain rates reported are $5.6 \times 10^{-4}$, $5.6 \times 10^{-3}$ and $5.6 \times 10^{-2}$ (s⁻¹). The stress strain curves of test conducted at different strain rate and test temperature are shown in Figure 6.

![Figure 6 Tensile Test Stress Strain Curves at (a) 25°C and (b) 125°C [49]](image)

With increasing strain rate, the stress strain curve shifts upwards along the vertical axis with higher yield stress and elastic modulus. For increase in test temperature, the curve shifts downwards along the vertical axis while lower yield stress and elastic modulus were observed.
2.4.1.1 Elastic Modulus

The curves demonstrate linear relationship between the elastic modulus and the temperature and elastic modulus decrease with the increase of temperature. The elastic modulus has a linear function of logarithmic strain rate and elastic modulus increase with increase in strain rate.

![Graph showing the effect of temperature and strain rate on elastic modulus](image)

Figure 7 Effect of (a) Temperature and (b) Strain Rate on Elastic Modulus [49]

2.4.1.2 Yield Stress

There is a linear relationship between the yield stress versus temperature plot, and yield stress versus logarithmic strain rate. The yield stress increases with increase in strain rate, and decreases with increase in temperature.

![Graph showing the effect of temperature and strain rate on yield stress](image)

Figure 8 Effect of (a) Temperature and (b) Strain Rate on Yield Stress [49]
2.4.1.3 Ultimate Tensile Stress

The UTS results follow a similar trend as the yield stress results. UTS increases with increase in strain rate, and decreases with increase in temperature.

Figure 9 (a) Effect of Temperature on UTS (b) Effect of Strain Rate on UTS [49]

2.4.2 Constitutive Model for Tensile Properties

In the same work, a statistical method incorporating linear regression was employed [48] to quantify the temperature and strain rate dependent mechanical properties of 95.5Sn3.8Ag0.7Cu solder. The elastic modulus, yield stress and UTS of SAC387 were established and expressed individually as follows

\[ E(T, \dot{\varepsilon}) = (-0.0005T + 6.4625) \cdot \log(\dot{\varepsilon}) + (-0.2512T + 71.123) \]  \hspace{1cm} (4)

\[ \sigma_y(T, \dot{\varepsilon}) = (-0.1362T + 67.54) \cdot \dot{\varepsilon} \cdot \exp(5.59 \times 10^{-6}T + 0.0675) \]  \hspace{1cm} (5)

\[ \text{UTS}(T, \dot{\varepsilon}) = (-0.1124T + 72.46) \cdot \dot{\varepsilon} \cdot \exp(5.8 \times 10^{-4}T + 0.0583) \]  \hspace{1cm} (6)
2.5 Compression Properties at Slow to Fast Strain Rates

Wong [50] characterizes the stress strain properties of Sn3.0Ag0.5Cu under compression loading condition in the range of strain rates between 0.005 to 300 (s\(^{-1}\)). The true stress strain characteristics of Sn3.0Ag0.5Cu solder alloy are presented in Figure 10.

![Figure 10 True Stress Strain Characteristics of Sn3.0Ag0.5Cu [50]](image)

Another study from Long [51] reported the plastic flow properties of 95.5Sn3.8Ag0.7Cu solder under compression condition. The plastic flow curves (true stress versus true plastic strain) at 25°C, 75°C, and 125°C, respectively, at six different strain rates from 0.1s\(^{-1}\) to 30s\(^{-1}\) are presented in Figure 11. Clearly, both the yield stress and the work hardening rate increase with increasing strain rate. The yield and strain hardening parameters were determined by fitting the plastic flow curves to the Hollomon model, which is given by

\[
\sigma = K\dot{\epsilon}_p^n
\]  

(7)
where $\varepsilon_p$ is the plastic strain, $K$ is the strain hardening coefficient, and $n$ is the strain hardening exponent.

![Figure 11 Plastic Flow Curves of the As-Reflowed Solder [51]](image)

2.5.1 Strain Rate Sensitivity Study

The log-log plot of the flow stress at 10% plastic strain across the range of strain rate from Wong’s study [50] is shown in Figure 12. The strain rate sensitivity of Sn3.0Ag0.5Cu solder, as expressed in the gradient of the straight line in pink color, was 0.11.

![Figure 12 Strain Rate Sensitivity Analysis [50]](image)
From Long’s study [52], the strain rate sensitivity of the solder was computed from the strain rate hardening law, or the Hollomon model:

\[ \sigma = C\dot{\varepsilon}^m_p \]  

where \( C \) is the strain rate hardening coefficient, and \( m \) is the strain rate sensitivity of flow stress.

These parameters may be obtained by plotting the flow stress at a given plastic strain level (e.g., 2%) versus the strain rate, as shown in Figure 13, yielding:

\[ \sigma_{\text{flow,2\%}} = 106.87\dot{\varepsilon}_p^{0.11} \text{ at } 25^\circ\text{C} \]  

\[ \sigma_{\text{flow,2\%}} = 80.01\dot{\varepsilon}_p^{0.12} \text{ at } 75^\circ\text{C} \]  

\[ \sigma_{\text{flow,2\%}} = 59.56\dot{\varepsilon}_p^{0.13} \text{ at } 125^\circ\text{C} \]

The yield strength and work hardening rate were observed to increase substantially with increasing strain rate, with the strain rate sensitivity at increases with increasing temperatures.

![Figure 13 Plot of 2% Offset Flow Stress vs. Strain Rate [52]](image)
CHAPTER 3

3 Experimental Procedure

3.1 Nanoindentation Test Method

The nanoindentation hardness of a material is given by

$$H = \frac{P}{A} = \frac{P}{cn^2}$$  \hspace{1cm} (12)

where $H$ is the hardness, $P$ is the maximum load, $A$ is the projected contact area, $h$ is the displacement, and $c$ is a constant which is equal to 24.56 for a Berkovich indenter tip. The relationship between yield stress and indentation hardness can be approximated by Atkin and Tabor [53] constant given by

$$H = 3\sigma_y$$  \hspace{1cm} (13)

Hence, the strain rate dependent hardness and yield stress can be determined from constant strain rate nanoindentation hardness measurements [54, 55].

3.1.1 Specimen Preparation

As mechanical properties are calculated from the contact depth and contact area function on the presumption that surface is flat, surface roughness is extremely important. Uniform surface height is an imperative aspect to proceed with the experiments. Uneven surface will not yield reliable modulus and hardness values due to indentation at angles. The MTS guidelines states that surface roughness must be kept within 5% of the desired indentation depth. For example, performing an indentation of 2000nm, surface roughness shall not be more than 100nm.
Specimen was also scanned by the Confocal imaging profiler to check the surface roughness and to ensure the height of the specimen is constant. An image captured by the profiler is shown in Figure 14. The average hardness obtained from Confocal Imaging Profiler was 11nm for the specimen as shown, which satisfied the requirement to proceed for nanoindentation test.

![Surface captured by Confocal Imaging Profiler](image)

**Figure 14 Surface captured by Confocal Imaging Profiler**

3.1.2 MTS Nanoindenter XP

Nanoindentation test were conducted at room temperature using MTS nanoindentation XP system as shown in Figure 15. A berkovich indenter tip was used for all the experiments done with this machine. Friction is assumed negligible between the indenter and the specimen. The indenter was considered to be perfectly rigid. This indenter sits on a mechanical vibration isolation table and its container has sound – dampening materials inside. The load frame is essentially the gantry of the indenter and should be as stiff as possible, thus not to contribute significantly to the displacement of the load train.
The force on the indenter is generated using a coil in a permanent magnet assembly (loading actuator). The generated force is simply the vector product of the current through the coil and the magnetic field strength of the permanent magnet ($F = B \times I$). This type of force application is very simple as well as very linear in its calibration. It allows for very quick closed-loop feedback control over the displacement as it completely separates the force application system and the displacement measuring system.

The resolution of the loading system is based on the load calibration, load voltage range of the DA converter and the number of bits of resolution of the DA converter. The load sensor, directly beneath the loading actuator, senses load by either a load cell or a strain gauge. A load cell works by sensing the voltage change across a piezoelectric material when load is applied.
A strain gauge directly measures strain, but knowing the stiffness of the gauge this strain can be correlated to a force measurement. Theoretically, the actuator and sensor setup will result in a typical resolution of about 5nN, but in practice a resolution in the µN range is realistic. It has the ability to operate the head over a range of displacements approximately displacement measuring system. The resolution of the loading system is based on the load calibration, load voltage range of the DA converter and the number of bits of resolution of the DA converter. The load sensor, directly beneath the loading actuator, senses load by either a load cell or a strain gauge. The load head can apply forces up to about 733µN with 15mm of allowed travel total. The MTS set up diagram is as shown in Figure 16.

![Figure 16 Schematic Diagram of MTS Nanoindenter Setup](image)

3.1.3 Continuous Sensing Method (CSM)

The nanoindentation hardness and modulus of SnAgCu solder were reported by using of continuous sensing method (CSM). The calculation of elastic modulus and hardness for nanoindentation CSM was based on the Oliver and Pharr Method. The difference for CSM and conventional method is how contact stiffness (S) was
obtained. Figure 17 shows the schematic load-displacement diagram of CSM and conventional methods.

![Figure 17 Schematic Diagrams of (a) Conventional and (b) CSM Loading Cycle](image)

For conventional nanoindentation, stiffness is the differentiation of load over penetration at the maximum depth of the unloading curve. For CSM, stiffness is determined by the harmonic oscillating force and the displacement response of the indenter superimposed onto the nominally increasing load. During the measurement, the contact stiffness is output continuously from the nanoindentation system.

The CSM technique consists of applying a small harmonic, high frequency amplitude during indentation loading and measuring the contact stiffness of the specimen from the displacement response at the excitation frequency. The CSM test work program was used to tabulate the mechanical properties of the tested specimen. In all experiments, parameters in CSM program were as follows:
- Poisson Ratio: 0.34
- Surface Approach (nm/s): 10
- Depth Limit (nm): 2000
- Delta X for finding surface: -50
- Delta Y for finding surface: -50
- Allowable Drift Rate (nm/s): 0.05
- Harmonic Displacement Target (nm): 2
- Approach Distance to Store (nm): 1000
- Frequency Target (Hz): 45
- Surface Approach Distance (nm): 1000
- Surface Approach Sensitivity (%): 40

### 3.2 Tensile Test Method

SHIMADZU AG-X Precision Tester was used to perform tensile, shear and mixed mode tests by using different type of solder specimen. For tensile test, a conventional dog bone-shaped solder specimen was used. For shear and mixed mode test, a compact mixed mode specimen was used, which is able to produce pure tensile behavior as well. The same tester was used to perform tensile tests on single solder joint specimen as mentioned in section 3.4. Computer equipped with software called TRAPEZIUMX controls the tester. A pair of non-contact video extensometer was employed in order to capture the extension or deformation of the test specimen. Figure 18 illustrates the complete precision tester set up.
3.2.1 Tensile Test on Dog bone-shaped Bulk Solder Specimen

The bulk solder tensile test specimens were machined from supplied solder bars. The specimens are annealed for 24 hours at 60°C in vacuum to eliminate the surface residual stresses. Tensile tests were carried out at room temperature of 25°C. Non-contact video extensometer was employed in the specimen gauge length of 10mm to measure the true extension of the specimen by tracking two markers over the gauge length of 10mm on the test specimen. The specimen has an overall length of 65mm, a gauge length of 10mm with a diameter of 3mm as shown in Figure 19.
With two DVE cameras, there is a cross over for measurement during the test, which means one captures the initial zoomed-in displacement (right column in Figure 20) while the other one captures the following wider range displacement (left column in Figure 20). It can be seen that a sharp tip is shown when the marker is captured correctly for measurement of the specimen gauge length displacement without any contact with the specimen. The reading at the top left corner shows the elongation of the gauge length.

3.3 Compact Mixed Mode Test Method
The CMM specimen is fabricated by two copper specimens as shown in Figure 21, bonded with Indium 5.1 AT Sn3.8Ag0.7Cu lead-free solder paste to form a
butterfly-shaped test specimen. The copper specimens are machined from 99.9% Cu (copper) plate by precision machining and are polished to a 0.05µm surface finish at the bonded surface after going through polishing with diamond paste following by polishing with alumina.

![Figure 21 Copper Specimen prepared by Precision Machining](image)

The loading frame shown in Figure 22 is able to perform mixed-mode test at multiple loading angles, i.e. 0°, 22.5°, 45°, 67.5° and 90°. The CMM specimen is slotted into the frame and is locked by pin locking mechanism as shown in Figure 23.

![Figure 22 (a) Actual and (b) Schematic of CMM loading frame with Multiple Loading Angles](image)
3.4 Single Solder Joint Test

It is well known that the tensile strength of a thin transverse solder joint can be considerably higher than the unconstrained strength of the bulk solder material. The high load-carrying capacity of such joints is a result of the development of tri-axial stresses within the joint due to the differences in yield strength (or stress level in the circumferential notch case) between the joint material and the base material.

A thin transverse solder joint that consists of a ball-shaped solder joint in between two copper rod can be tested under uni-axial loading condition to investigate the size effect of the solder joint with respect to the solder joint reliability. The test specimen is shown in Figure 24.
Under uni-axial tensile loading any axial plastic extension of the joint is accompanied by a transverse contraction. The purpose of the this study is to obtain extensive experimental data concerning the influence of joint geometry on the mechanical properties of the solder joint and relate these data to the existing theory concerning joint strength. The approach was primarily an attempt to predict the strength of single solder joint in terms of the solder joint size.

Copper rods are being jointed by solder paste with standardized reflow process. Soldering surface of copper rods is polished to minimum grade of 0.005μm surface roughness to ensure high quality solder joint.

A solder fixture as shown in Figure 25 was used to hold solder rods during the reflow process. A solder reserve groove was created in the middle of the fixture in
order for excessive solder to flow around during reflow process to ensure appropriate solder volume at respective solder joints.

![Solder Joint Fabrication Reflow Fixture](image)

**Figure 25 Solder Joint Fabrication Reflow Fixture**

Removal of excessive solder around the joint area was carried out after reflow process to ensure constant size for all solder joints was achieved. A final product of the solder joint specimen is shown below in Figure 26.

![Joint Specimens](image)

**Figure 26 Joint Specimens**

The SHIMADZU AG-X Precision Tester was used to perform tensile tests on different type of solder joint specimens. For the tensile test, two copper rod specimens soldered using SAC387 solder paste was tested. The length of the
solder joints measured were 1.0mm and were tested over strain rates of $10^{-3}$, $10^{-2}$ and $10^{-1}$ (s$^{-1}$). The setup of the SHIMADZU AG-X Precision Tester is shown in Figure 27.

Figure 27 Setup of the SHIMADZU AG-X Precision Tester
CHAPTER 4

4 Strain Rate Effects on Tensile Properties

4.1 Iso-Strain Rate Tensile Test and Analysis

For solder materials under tensile loading, when the applied stress goes beyond the yield stress, $\sigma_y$, it continues to deform plastically until instability is reached. The stress, at which instability occurs, $\sigma_{UTS}$, is the ultimate tensile strength. A stress strain curve of solder material under tensile condition that up to $\sigma_{UTS}$, the strain is distributed uniformly in the specimen and beyond $\sigma_{UTS}$, it is concentrated in the region where a neck develops and eventually fracture occurs is shown in Figure 28. For compression loading, similarly, the stress strain curve goes to the yield stress, $\sigma_y$, before it starts to have plastic deformation. Further deformation continues without occurrence of instability meaning no ultimate stress can be observed in compression stress strain curve. In this work, experimental data are collected from compression test, in order to do comparable study to tensile data, the stress strain curves are only presented up to region near 0.1 strain.

![Figure 28 Uniaxial Stress Strain Curve for Elastic-plastic Material](image)
In this chapter, constant strain rate tensile tests on bulk solder dog-bone type cylindrical tensile specimens were investigated. Tensile tests were carried out on the universal tester at room temperature of 25°C, for four different strain rate conditions of $10^{-3}$, $10^{-2}$, $10^{-1}$ and 1 (s$^{-1}$), respectively. Constitutive models based on the Hollomon and Ramberg-Osgood models were fitted for the tensile test results to describe the elastic-plastic behavior of solder.

### 4.2 95.5Sn3.8Ag0.7Cu Solder Characterization Result

#### 4.2.1 95.5Sn3.8Ag0.7Cu Tensile Test Results

The stress strain curves of 95.5Sn3.8Ag0.7Cu solder at strain rates of 0.001, 0.01, 0.1 and 1.0 (s$^{-1}$) are shown in Figure 29. When strain rate increases the stress strain curves move upwards and with an increase in the apparent elastic modulus, yield stress and tensile strength.

![Figure 29 Tensile Stress Strain Behavior for SAC387 at Strain Rate of 0.001, 0.01, 0.1 and 1.0s$^{-1}$](image-url)
The strain rate effects on the apparent elastic modulus, yield stress and ultimate tensile stress for SAC387 solder can be expressed in power law equations (14) to (16), respectively.

\[ E = 80.959 \dot{\varepsilon}^{0.1659} \]  
\[ \sigma_y = 73.661 \dot{\varepsilon}^{0.0759} \]  
\[ \sigma_{UTS} = 78.148 \dot{\varepsilon}^{0.0780} \]  

The apparent elastic modulus, yield stress and ultimate tensile strength plots against strain rate is shown in Figures 30 to 32 respectively.

**Figure 30 Elastic Modulus vs. Strain Rate of 0.001, 0.01, 0.1 and 1.0s\(^{-1}\)**

In Figure 31, the strain rate sensitivity on yield stress of SAC387 solder shows a dependence on strain rate resulting from dynamic hardening strain rate effects on the yield stress.
Strain rate sensitivity \((m)\) is defined as \([56]\):

\[
m = \frac{\partial \ln \sigma}{\partial \ln \alpha}
\]  

(17)
where $\sigma$ is the yield strength and $\alpha$ is the strain rate. Figure 32 shows the double logarithmic plot of flow strength with respect to strain rate, in which the slope gives the $m$ value. The common ranges for strain rate testing are between $10^{-1}$ s$^{-1}$ and $10^3$ s$^{-1}$ (quasi-static) and $10$ s$^{-1}$ to $10^3$ s$^{-1}$ (dynamic). Due to equipment constraint, the highest strain rate that we can use is $10^1$ s$^{-1}$. The strain rate used in this study ranged between $10^1$ s$^{-1}$ and $10^3$ s$^{-1}$, which is the range for quasi-static loading.

4.2.2 Strain Rate Effects on Plastic Strain

Conventional strength and strain-hardening parameters have been derived for idealized true-stress/true-strain curves obeying the Hollomon equation $\sigma = K \varepsilon_t^n$, where $K$ and $n$ have values typical of real metals. All stress parameters are proportional to the constant $K$. The true tensile strength is almost independent of $n$, but the stress at 0.2% plastic strain is strongly dependent on $n$.

In most of the physical approaches the evolution of the flow stress is governed by the dislocation kinetics. For most material such as solder alloy, the shape of stress strain curves is usually represented by a simple power law expression, known as the Holloman equation:

$$
\sigma_t = K \varepsilon_t^n
$$

(18)

where $\sigma_t$ is the true flow stress, $K$ is the strength coefficient, $\varepsilon_t$ is the true plastic strain and $n$ is the strain hardening exponent.
By manipulating the equation, it implies that the increase in stress caused by a small plastic strain can be significant. The larger the stress increment, for a given strain, the larger the cold worked yield strength, this useful parameter known as the work hardening exponent and can be derived by plotting equation (18) in logarithmic mode as

$$\ln(\sigma) = \ln(K) + n \cdot \ln(\varepsilon)$$ \hspace{1cm} (19)

The values of $n$ and $K$ for Holloman model fitted curve for SAC387 at respective strain rate are summarized in Table 1. The markers indicate the experimental data while the lines present the Hollomon model. The curve-fitted Hollomon models in Figure 33 show fairly good fit of Hollomon model with the experimental data.

**Figure 33 Curve-fitted Holloman Model Plots for SAC387 at Iso-strain rate Condition**
The strain-hardening rate $d\sigma/d\varepsilon_p$ is significantly affected by $n$ only when $\varepsilon_p<0.01$; then $d\sigma/d\varepsilon_p$ increases with increasing $n$ when $n<0.2$ and decreases with increasing $n$ when $n>0.2$. The strain-hardening rate is not easily related to the parameters $n\sigma_{\text{max}}$, $nK$ or the 0.2% proof-stress/true-tensile-strength ratio. The magnitude of the strain hardening, given by $\Delta\sigma = (\sigma_2 - \sigma_1)$, also has a maximum between $n=0.1$ and 0.3.

With these results, assumptions and conclusions in the published literature are discussed and some are shown to be incorrect. It is concluded that for maximum strength and strain hardening in materials obeying the Hollomon equation, large values of $K$ and $n$ values between 0.1 and 0.3 are required.

Figure 34(a)-(d) shows that the Hollomon model is able to curve-fit the stress versus plastic strain test data. The stress versus plastic strain curves were re-plotted on logarithmic axes in Figures 35(a)-(d). The curve-fitted Holloman models for the strain rate condition of 0.001, 0.01, 0.1 and 1.0 $(s^{-1})$ on logarithmic axes show fairly good fit to the test data. The constants value, $n$ and $K$, are used commonly to assess behavior of material in both uniaxial tension and compression tests at room temperature and at elevated temperatures. Generally, most metallic materials show positive strain rate dependence of strength, which often evaluated by the strain rate sensitivity parameter.
Figure 34(a)-(d) Hollomon Model at (a) 0.001 s\(^{-1}\), (b) 0.01 s\(^{-1}\), (c) 0.1 s\(^{-1}\), and (d) 1.0 s\(^{-1}\) Strain Rate

Figure 35(a)-(d) Logarithmic Plot at (a) 0.001 s\(^{-1}\), (b) 0.01 s\(^{-1}\), (c) 0.1 s\(^{-1}\), and (d) 1.0 s\(^{-1}\) Strain Rate
There are some expected differences as the plastic strain approaches very small plastic strain values due to the use of a simple power law expression [57]. To be able to capture the elastic-plastic transition region of the stress strain curve, the Ramberg-Osgood model is preferred and will be discussed in the next section.

### 4.3 Modified Ramberg-Osgood Stress Strain Model

The stress strain curves were curve-fitted to the Ramberg-Osgood model [58, 59]:

\[
\varepsilon = \frac{\sigma}{E} + \alpha \cdot \left(\frac{\sigma}{\sigma_0}\right)^n
\]  

(20)

where \( \varepsilon \) is the true strain, \( \sigma \) is the true stress, \( E \) is the elastic modulus, \( \sigma_0 \) is the stress coefficient, \( \alpha \) is the strain hardening coefficient, and \( n \) is the strain hardening exponent.

The Ramberg-Osgood model is used to curve-fit the stress strain curves at each strain rate.

The first component at right hand side describes the elastic region of a stress strain curve while the second component is in charge of the plastic region. In order to compensate the mismatch due to transition from elastic to plastic deformation, equation (20) needs to be further modified to:

\[
\varepsilon = \frac{\sigma}{E} + \alpha \cdot \varepsilon_0 \cdot \left(\frac{\sigma}{\sigma_0}\right)^n
\]  

(21)

where \( \varepsilon_0 = \sigma_0 / E \).
4.3.1 Modified Ramberg-Osgood Stress Strain Model on SAC387 Tensile Behavior

Ramberg-Osgood model is suitable for modeling the elastic-plastic transition region and subsequent power-law relationship between stress and total strain plot. For low applied stresses, the plastic strain term is negligible compared to the elastic strain obtained by the first term in equation (20). For stress levels higher than the yield stress, the plastic strain transition region models the smooth transition from elastic to total strain, which includes the summation of the elastic and plastic strain. Hence, the smooth stress strain curves of SAC387 solder can be curve-fitted to the Ramberg-Osgood model.

The Ramberg-Osgood model was used to curve-fit the stress strain curves at the four strain rates tested. The solid lines in Figure 36 indicate the curve-fitted Ramberg-Osgood models, while the dash lines indicate the experimental stress strain curve test data. The Ramberg-Osgood model is able to fit the stress strain curves at the four tested strain rates of 0.001, 0.01, 0.1 and 1.0 (s^{-1}).

![Figure 36 Curve-fitted Stress Strain Curve versus Experimental Stress Strain Curves](image-url)
The Ramberg-Osgood model equations at each strain rate are given in equations (22) to (25) respectively:

\[
0.001: \varepsilon = \frac{\sigma}{75651} + 1.38 \cdot \left( \frac{\sigma}{36.92} \right)^{10.18} \\
0.01: \varepsilon = \frac{\sigma}{85508} + 2.35 \cdot \left( \frac{\sigma}{49.34} \right)^{10.64} \\
0.1: \varepsilon = \frac{\sigma}{100947} + 3.14 \cdot \left( \frac{\sigma}{57.11} \right)^{15.57} \\
1.0: \varepsilon = \frac{\sigma}{126198} + 5.30 \cdot \left( \frac{\sigma}{76.50} \right)^{21.20}
\]

Based on equations (22) to (25), it is noted that all four constants \((E, \alpha, \sigma_0\) and \(n)\), increase with increasing strain rate. This contributes to a smooth shift in the stress strain curves upwards with increase in strain rate effect.

4.3.2 Modified Ramberg-Osgood Stress Strain Model on SAC387 Compression Behavior

The stress strain curves of the bulk 95.5Sn3.8Ag0.7Cu solder specimen under compression testing at 25°C are plotted in Figure 37. The stress strain curve increases along the y-direction with increase in strain rate. The elastic modulus and yield stress eventually increases with increasing strain rate.
Figure 37 Experimental Compression Stress Strain Curves at 25°C (true stress vs. true strain)

The curve-fitted stress strain curve in Figure 38 confirms that the Ramberg-Osgood model is able to curve-fit the stress strain curves at particular strain rate. The solid lines show the curve-fitted Ramberg-Osgood models and the dash lines indicate the experimental stress strain curves. Based on equation (21), The Ramberg-Osgood models at respective strain rate are:

0.022: \( \varepsilon = \frac{\sigma}{4745} + 4.24 \times 10^{-1} \cdot \frac{50.56}{4745} \cdot \left(\frac{\sigma}{50.56}\right)^{7.572} \)  
(26)

0.751: \( \varepsilon = \frac{\sigma}{4670} + 3.15 \times 10^{-1} \cdot \frac{72.76}{4670} \cdot \left(\frac{\sigma}{72.76}\right)^{5.914} \)  
(27)

3.149: \( \varepsilon = \frac{\sigma}{7520} + 3.36 \times 10^{-1} \cdot \frac{81.56}{7520} \cdot \left(\frac{\sigma}{81.56}\right)^{4.862} \)  
(28)

9.266: \( \varepsilon = \frac{\sigma}{8510} + 3.06 \times 10^{-1} \cdot \frac{89.66}{8510} \cdot \left(\frac{\sigma}{89.66}\right)^{5.029} \)  
(29)
It is necessary to study the relationship of $E$, $\alpha$, $\sigma_0$, and $n$ with respect to strain rate ($\dot{\varepsilon}$) before curve-fitting of the stress strain curve to the strain rate dependent Ramberg-Osgood model. In Figures 39 and 40, the graphs plot the relationship of $E$, $\alpha$, $\sigma_0$, and $n$ as functions of $\dot{\varepsilon}$. Figures 39 (i) and (ii) show that the properties of $E$ and $\sigma_0$ as:

$$E = 723.19 \cdot \log(\dot{\varepsilon}) + 6049.1$$  \hfill (30)

$$\sigma_0 = 0.4924 \cdot (\dot{\varepsilon}) + 22.712$$  \hfill (31)
Both $\alpha$ and $n$ have a second order polynomial relationship with respect to $\dot{\varepsilon}$ as illustrated in Figure 40 (i) and (ii) where

$$\alpha = 3 \times 10^{-5} \cdot (\dot{\varepsilon})^2 - 0.0004 \cdot (\dot{\varepsilon}) + 0.0023 \quad (32)$$

$$n = 0.0824 \cdot (\dot{\varepsilon})^2 - 0.9761 \cdot (\dot{\varepsilon}) + 7.5313 \quad (33)$$

With the aid of study on relationship of $E$, $\alpha$, $\sigma_0$, and $n$ with respect to $\dot{\varepsilon}$, regression curve-fitting of the stress strain curve is discussed in the next section.

![Graphs](image)

**Figure 40 (i) and (ii) show the Relationships of $\alpha$ and $n$ with respect to Strain Rate**

By substituting equations (28) to (31) into equation (21), a modified Ramberg-Osgood model is derived as below

$$\varepsilon = \frac{\sigma}{C1 \cdot \log(\dot{\varepsilon}) + C2} + [C3 \cdot (\dot{\varepsilon})^2 + C4 \cdot (\dot{\varepsilon}) + C5] \cdot \left[ \frac{C6 \cdot (\dot{\varepsilon}) + C7}{C1 \cdot \log(\dot{\varepsilon}) + C2} \right]^n \quad (34)$$

where $n = C8 \cdot (\dot{\varepsilon})^2 + C9 \cdot (\dot{\varepsilon}) + C1$. Using regression curve-fitting with constants in equations (22) to (25) are used as references can derive the constants C1-C10.

Figure 41 shows the experimental stress strain curves and the curve-fitted stress strain curves by using strain rate dependent modified Ramberg-Osgood model. The 10
Constants are 723.19 (C1), 6049.10 (C2), 9.74E-03 (C3), -6.46E-03 (C4), 3E-04 (C5), 11.54 (C6), 13.85 (C7), 0.1085 (C8), -1.1647 (C9), 6.9552 (C10).

Figure 41 Curve-fitted Stress Strain Curve versus Experimental Stress Strain Curves at 25°C (solid lines: curve-fitted modified Ramberg-Osgood models; dash lines: experimental curves)
CHAPTER 5

5 Strain Rate Effects on Nanoindentation Measurement

Researchers such as Xiao and Jia [56, 60] have reported nanoindentation characterization of strain rate sensitivity of solder. The aim of this chapter is to examine if the strain rate sensitivity effects measured indentation test such as from nanoindentation hardness measurements can be correlated with traditional strain rate sensitivity measurements derived from tensile test.

5.1 Strain Rate Effect on Nanoindentation Hardness

The indentation strain rate is defined as the indentation tip moving-in rate divided by the depth into the surface is

\[ \dot{\varepsilon} = \frac{\dot{h}}{h} \]  (35)

In a conventional constant load or displacement control indentation test, the indentation strain rate is not constant. The indentation hardness of a material is given by

\[ H = \frac{P}{A} = \frac{P}{c h^2} \]  (36)

where \( H \) is the hardness, \( P \) is the load, \( A \) is the projected contact area, \( h \) is the displacement (contact depth), and \( c \) is a constant that depends upon the geometry of the indenter tip (for perfect Berkovich tip, \( c=24.56 \)). The relationship between yield stress and hardness is given by

\[ H = 3\sigma_y \]  (37)

Hence the strain rate dependent yield stress can be determined from the Hardness measurements from nanoindentation tests at iso-strain rate conditions.
The depth of the indentation was measured relative to the intact surface of the target. The idea is to develop a simple and efficient way to characterize strain rate sensitivity of materials. Since the load is the direct measure of the average stress underneath the indenter, this process variable is affected by the strain rate for rate-sensitive materials during the indentation. Unlike a nearly parabolic shape of the load-displacement curve at the early stage of the indentation, the rate of increase in the load was substantially reduced at the later stages of the indentation since the average strain rate reduces considerably. The measured load can be regarded as a global effective measure of the overall material resistance with respect to the indenter.

Based on the fact that the effective strain rate by the indentation method is close to the strain rate range of the well-established Kolsky (split Hopkinson) pressure bar technique, the dynamic indentation is by no means a replacement of the existing techniques. Instead, besides providing an additional and efficient means of estimating the strain rate sensitivity, dynamic indentation can also be used to study the effect of normal stress/pressure on dynamic behavior of materials.

Nanoindentation test on SAC387 solder were reported earlier by the authors [54, 55]. An integrated continuous stiffness measurement (CSM) nanoindentation test method was employed to carry out the test. Figure 42 shows the load-displacement curve of both the conventional and the integrated continuous stiffness measurement (CSM) nanoindentation test method. A Berkovich tip was used on test samples extracted from bulk solder material obtained by cross-section, then polished and mounted for
nanoindentation tests. The calculation of elastic modulus and hardness for nanoindentation was based on the Oliver and Pharr method.

At room temperature, the relationship between indentation strain rate and hardness can be expressed as:

$$H = K(\dot{\epsilon})^n = K\left(\frac{\dot{h}}{h}\right)^n$$

where $K = 0.3466$ for the SAC387 material, $H$ is the hardness, and the strain rate dependent exponent, $n = 0.1507$. Hence, the strain rate dependent yield stress can be determined from nanoindentation hardness measurements at iso-strain rate test conditions.

The relationship between yield stress and hardness is given by:

$$H = 3\sigma_y$$
Hence, the strain rate dependent yield stress can be determined from nanoindentation hardness measurements at iso-strain rate test conditions.

5.1.1 Iso-Strain Rate Nanoindentation Test

A constant strain rate indentation expression can be derived by differentiating Equation (38) with time and expressing the indentation depth rate as a function of the load rate and hardness rate by

\[
\frac{\dot{h}}{h} = \frac{1}{2} \left( \frac{\dot{p}}{P} - \frac{\dot{H}}{H} \right) = \dot{\varepsilon}_r
\]

(40)

where \( \dot{\varepsilon}_r \) or \( \dot{h}/h \) is the indentation strain rate.

Equation (40) can be employed in an instrumented nanoindentation test by controlling the loading rate to applied load parameter, \( \dot{P}/P \) to give a constant indentation strain rate when a stable value of hardness is reached with, \( H = 0 \). \( \dot{P}/P \) is a control parameter in the nanoindentation system used.

5.1.2 Indentation Size Effect

This hardness-displacement graph represents a complete single cycle of indentation. From the loading to holding until the ejection of the indenter tip form the sample surface, we can see the continuous stiffness measurement indenter records hardness values continuously as the indenter performs the indentation.

For solder material, from a total displacement of approximately 2000nm, it can be observed that the results shows high hardness value as the indenter is indenting into
the sample specimen from range of 0 to 100nm. As the indenter displaces deeper from the sample surface, the hardness value drops drastically and eventually reach a constant value of 0.2GPa after 800nm. Eventually, the hardness prolongs till the desired displacement of 2000nm is reached and ejects out of the sample as indicated in Figure 43.

![Figure 43 Size Effect Zone for Hardness vs. Displacement of SnPb Solder](image)

The dotted zone denotes the phenomenon of Indentation Size Effect (ISE) [61]. ISE has been long discussed in many papers. Many authors have experimented and witnessed this phenomenon and given their explanation for it. For instance, Nix [62] have explained ISE with their Strain Gradient Plasticity Theory. Strain Gradient Plasticity Theory explained that at low indent depths, there is a generation of two types of dislocations, mainly Geometrically Necessary Dislocations (GNDs) and Statistically Stored Dislocations (SSDs). SSD occurs when the generated dislocations
randomly trap each other. On the other hand, when these dislocations are required for compatibility purposes, they are known to be GNDs.

5.2 Nanoindentation Test Results and Constitutive Models for 95.5Sn3.8Ag0.7Cu Solder

Due to the presence of indentation size effect, hardness values decreases as the indentation depth increases from 0nm to 1000nm. Generally, hardness values become consistent approximately after 1000nm. The indentation marks observed under SEM are shown in Figure 44.

![Figure 44 SEM images of Indentation Marks on 95.5Sn3.8Ag0.7Cu](image)

The Hardness-Displacement behavior of SAC387 is presented in Figure 45. It can be easily observed that hardness value increases with increasing strain rate thus confirming the presence of strain effect in sample SAC387. In terms of percentage increment, the graph shows an approximate value of 50% and 40% increment in hardness value when strain rate increases from 0.01s\(^{-1}\) to 0.1s\(^{-1}\) and from 1.0s\(^{-1}\) to 10.0s\(^{-1}\) respectively. A greater increment of 70% was observed when the strain rate increases from 0.1s\(^{-1}\) to 1.0s\(^{-1}\). It can be observed that SAC387 experienced a relatively
uniform increment of at least 50% in magnitude when strain rate is increased by an order.

![Graph](image)

**Figure 45** Hardness vs. Displacement of 95.5Sn3.8Ag0.7Cu

At room temperature, the relationship between indentation strain rate and hardness could be expressed as the equation below

\[ H = K(\dot{\varepsilon})^n = K\left(\frac{h}{h_0}\right)^n \]  

(41)

With the indentation results, we are able to evaluate the relationship equation for SAC387 through simple mathematical formulation from Figure 46 and it is calculated to be

\[ H_{\text{SAC387}} = 0.7(\dot{\varepsilon})^{0.1878} \]  

(42)

where 0.7 is the material constant \((K)\) and 0.1878 is the strain exponent \((n)\) [63].
Figure 46 Logarithm Plot of Hardness vs. Strain Rate of 95.5Sn3.8Ag0.7Cu

On the other hand, Figure 47 shows the yield stress with respect to strain rate where yield stress is evaluated from the average hardness obtained at each strain rate with reference to Tabor’s value of 3 [53].

Figure 47 Yield Stress vs. Logarithm Strain Rate of 95.5Sn3.8Ag0.7Cu
5.3 Comparison of Iso-Strain Rate Nanoindentation Test Result with Tensile Test on 95.5Sn3.8Ag0.7Cu

In this section, nanoindentation results for 95.5Sn3.8Ag0.7Cu was compared and analysed with tensile test yield stress results presented in previous chapter over the range of strain rates from $10^{-3}$ to 1 (s$^{-1}$).

A comparison between the strain rate dependent yield stress from nanoindentation and tensile tests is given in Table 2. The yield stress from nanonindentation and tensile tests are plotted against strain rate in Figure 48. It shows that the yield stress derived from nanoindentation test is increasingly higher by a factor 1.38 to 1.65 than the corresponding value from tensile test for higher strain rates of 0.1 s$^{-1}$ to 1.0 s$^{-1}$, respectively. This reflects the expected differences due to the different test methods employed.

<table>
<thead>
<tr>
<th>Strain Rate</th>
<th>Nanoindentation $\sigma_y$ (MPa)</th>
<th>Tensile Test $\sigma_y$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001s$^{-1}$</td>
<td>43.0</td>
<td>43.5</td>
</tr>
<tr>
<td>0.01s$^{-1}$</td>
<td>55.7</td>
<td>50.2</td>
</tr>
<tr>
<td>0.1s$^{-1}$</td>
<td>83.0</td>
<td>60.1</td>
</tr>
<tr>
<td>1.0s$^{-1}$</td>
<td>117.3</td>
<td>71.2</td>
</tr>
<tr>
<td>10s$^{-1}$</td>
<td>173.0</td>
<td>-</td>
</tr>
</tbody>
</table>
The strain rate sensitivity index \((m)\) is given by the exponent of the power law fit to the logarithmic plot of Yield Stress versus Strain Rate as shown in Figure 49. The exponents are 0.1477 from nanoindentation and 0.1013 from tensile test respectively.

The nanoindentation test result has a higher strain rate sensitivity effects compared to tensile test result. The much smaller plastic flow volume and anticipated strain
gradient effects from nanoindentation hardness measurements are possible reasons why the nanoindentation result show higher strain rate sensitivity effects than tensile test data. In this study, a Berkovich tip was used, the total length of geometrically necessary dislocations forced into the solder by the indenter scales with the square of the indentation depth, while the volume in which these dislocations are found scales with the cube of the indentation depth. The higher dislocation densities expected at smaller indentation depths lead naturally to higher strength, and this leads to higher strain rate sensitivity compared to tensile test. It is useful to express the strain rate sensitivity results in a dynamic flow stress expression and the Cowper-Symonds model \[64\] is chosen in this study.

Wang and Boyce \[65, 66\] reported the tensile mechanical properties of air-cooled Sn37Pb specimen at low to high strain rate by using tensile testing and a compression split Hopkinson bar test system. The strain rate flow stress or yield stress for eutectic Sn-37Pb is shown in Figure 50. The test data can be curve-fitted to the Cowper and Symonds model,

\[
\frac{\sigma}{\sigma_0} = 1 + \left(\frac{D}{q}\right)^\frac{1}{q}
\]

(6)

where \(\sigma\) is the dynamic flow stress, \(\sigma_0\) is the associate static flow stress and \(\dot{\varepsilon}\) is the uni-axial plastic strain rate. \(D\) and \(q\) are constants for a particular material. The rate of sensitivity of the flow stress can be calculated as

\[
\beta = \frac{d \log \sigma}{d \log \dot{\varepsilon}}.
\]

(7)
The nanoindentation test data for Sn37Pb and SAC387 are presented on a log (Flow Stress) versus log (Strain Rate) plots in Figures 50 and 51 respectively. The values for $D$ and $q$ can be calculated as $D = 0.1 \text{s}^{-1}$ and $q = 6.7$ and this fits the test data reported in Figure 50 very well.

![Figure 50 Log-Log Plot of Flow Stress versus Strain Rate for Sn37Pb](image)

![Figure 51 Log-Log Plot of Flow Stress versus Strain Rate for SAC387](image)

The yield stress derived from the iso-strain rate nanoindentation test results for SAC387 can also be fitted to the Cowper-Symonds strain rate sensitive model for flow stress. Summary of the Cowper-Symonds model values for $D$, $q$ and $\beta$ of Sn-37Pb and SAC387 are presented in Table 3.
Table 3 Values of $D$, $q$ and $\beta$

<table>
<thead>
<tr>
<th></th>
<th>$D$</th>
<th>$q$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-37Pb</td>
<td>0.1</td>
<td>6.7</td>
<td>0.12</td>
</tr>
<tr>
<td>SAC387</td>
<td>2.6</td>
<td>6.4</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The strain rate sensitivity exponent, $\beta$, of SAC387 solder is 0.16 is slightly higher than 0.12 for Sn-37Pb solder. The implication is that at a particular strain rate resulting from dynamic loading the SAC387 solder will transfer a much higher load to the solder joint as the dynamic flow stress is much higher compared to Sn-37Pb solder.
CHAPTER 6

6 Single Solder Joint Test vs. Bulk Solder Properties of 95.5Sn3.8Ag0.7Cu at Specific Strain Rates

In order to better understand stress strain behavior of actual solder joint over a range of specific strain rates, a single solder joint test under tensile condition was developed to study various mechanical properties, which are closer to an actual solder joint. [67-73] Comparison and analysis of single solder joint test and bulk solder test were conducted in the later part of the chapter to illustrate difference between the two specimens under the same loading conditions.

6.1 Strain Rate Effect on Bulk Specimen and Single Solder Joint Specimen

In this single solder joint characterization study, one batch of bulk specimen test result was gathered to serve as a comparison with the single solder joint test results. The bulk solder specimens were tested over the strain rates range from 0.001s\(^{-1}\), 0.01s\(^{-1}\) to 0.1s\(^{-1}\). The Load-displacement curves are measured in Newtons (N) and millimeters (mm). The stress strain curves plotted here are engineering stress (MPa) against engineering strain.

6.1.1 Bulk Specimen Results

Similar bulk specimens of 95.5Sn3.8Ag0.7Cu reported in chapter 4 were tested using SHIMADZU AG-X precision tester. Figure 52 shows the load-displacements curves at various strain rates for SAC387 bulk specimen. An increase in maximum load from 304.51N to 490.53N was observed as the strain rates increased.
Figure 52 Load-displacement Curves for SAC387 Bulk Specimen at (a) 0.001s$^{-1}$, (b) 0.01s$^{-1}$ to (c) 0.1s$^{-1}$

Similar to the load-displacement curves, the stress strain curves in Figure 53 exhibit the trend of increasing maximum tensile stress with increasing strain rates. The values
ranged from 43.08MPa to 69.40MPa. Summary of experimental data is presented in Table 4.

Figure 53 Stress Strain Curves for SAC387 Bulk Specimen
at (a) 0.001s\(^{-1}\), (b) 0.01s\(^{-1}\) to (c) 0.1s\(^{-1}\)
6.1.2 Single Joint Specimen Results

Single solder joint test specimens consist of two copper rods with 1mm SAC387 solder joint were tested under the same instrument and loading conditions as the bulk specimens. Similarly, the load-displacement curves are measured in Newtons (N) and millimeters (mm). The stress strain curves plotted here are engineering stress (MPa) against engineering strain.

Two sets of test results were shown at each strain rate in Figures 54 and 55 over the strain rate range from 0.001s\(^{-1}\) to 0.1s\(^{-1}\). From Figure 54, it can be observed that the peak load from different sets of test results at same strain rate show consistency despite difference in displacement. Overall, an increase in maximum load from 1182N to 2617N was observed as the strain rates increased. The significant difference in displacement discovered in Figure 54 is due to lack of precision control in solder joint gap length during fabrication of the single solder joints.

The stress strain curves are presented in Figure 55 with highest ultimate tensile stress of 59.68MPa at 0.1s\(^{-1}\) and lowest of 41.82MPa at 0.001s\(^{-1}\). As the aspect ratio of the single solder joint of its width to length is high, the maximum load and ultimate tensile strength derived from the tests are still reliable and summary of test data is presented in Table 5.

<table>
<thead>
<tr>
<th>Strain Rate (1/s)</th>
<th>Max Load (N)</th>
<th>Ultimate Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>304.51</td>
<td>43.0793</td>
</tr>
<tr>
<td>0.01</td>
<td>450.709</td>
<td>63.7623</td>
</tr>
<tr>
<td>0.1</td>
<td>490.53</td>
<td>69.3957</td>
</tr>
</tbody>
</table>

Table 4 Maximum Load and Ultimate Tensile Strength of Bulk Specimen
Figure 54 Load-displacement Curves for SAC387 Single Solder Joint Specimen
at (a) 0.001s\(^{-1}\), (b) 0.01s\(^{-1}\) to (c) 0.1s\(^{-1}\)
Figure 55 Stress Strain Curves for SAC387 Single Solder Joint Specimen
at (a) 0.001s$^{-1}$, (b) 0.01s$^{-1}$ to (c) 0.1s$^{-1}$
Table 5 Maximum Load and Ultimate Tensile Strength of Single Joint Specimen

<table>
<thead>
<tr>
<th>Strain Rate (1/s)</th>
<th>Avg. Max Load (N)</th>
<th>Avg. Ultimate Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1203.00</td>
<td>42.55</td>
</tr>
<tr>
<td>0.01</td>
<td>1225.15</td>
<td>43.33</td>
</tr>
<tr>
<td>0.1</td>
<td>1638.52</td>
<td>57.95</td>
</tr>
</tbody>
</table>

6.2 Discussion on Test Results

The mode of failure for the bulk specimens show that the failure region of the specimens in the middle of the gauge length exhibits necking as shown in Figure 56.

![Figure 56 Fractured Bulk Solder Specimen](image)

For solder joint failure, fracture occurred very closely to the interface between the copper and the solder. However, instead of breaking off nicely at the interface, the fracture occurred at the Inter-metallic region because on both sides of the copper rods, solder was present. If it were an interface failure the solder would have “lift off” from the interface [74].

Based on visual inspection, solder was present at both ends of the copper rods as shown in Figure 57. The single solder joint test results are given in Table 6. As the strain rate increases from 0.001 to 0.1 (s⁻¹), the ultimate tensile stress (UTS) also increases from 42.5MPa to 58.0MPa.
Table 6 Experimental Results of Single Solder Joint Test

<table>
<thead>
<tr>
<th>Strain Rate</th>
<th>Single Joint Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001s$^{-1}$</td>
<td>42.5MPa</td>
</tr>
<tr>
<td>0.01s$^{-1}$</td>
<td>43.3MPa</td>
</tr>
<tr>
<td>0.1s$^{-1}$</td>
<td>58.0MPa</td>
</tr>
</tbody>
</table>

The reason to cause the difference in results from finite element modeling and single joint test are inherited from the imperfect soldering process for the actual single solder joint. The process of melting the solder and then allowing it to solidify again caused cavities to be present in the solder material. These cavities then greatly compromise the strength of the solder and as such, the difference in stress level can be observed between the experiment values and finite element model values. On the other hand, delamination is occurred during the experiment due to interface induced fracture mechanism. This phenomenon happens when constrain effect takes part for joint specimen instead of bulk solder specimen.
CHAPTER 7

7 Compact Mixed Mode (CMM) Loading Test and Analysis

7.1 Mixed Mode (Tensile and Shear) Loading Solder Joint Strength Test and Analysis

Tensile tests and lap shear tests are often done to test the strength of bonded joints [75-80]. However, solder joints typically fail by initiation and propagation of flaws. A compact mixed-mode (CMM) fracture specimen is employed to study the three different kinds of failure modes for a bonded joint - pure tensile, pure shear and mixed-mode (combined failure mode of tensile and shear). By conducting the different modes of tests, it will provide a greater understanding of the fracture mechanics of a soldered joint which experiences mixed-mode loading in service.

The intermetallic compounds are generally brittle materials with higher melting points, so they tend to fail by fracture process. These trends are shown in Figure 58. The transition in failure mode happens when the bulk solder strength has increased beyond the interface strength. The ductile-to-brittle fracture is defined at the point where 50% of the joints fail at the pad interface. It is usually desirable to have a high ductile-to-brittle fracture, so that the bulk solder can deform to accommodate rapidly applied loads, without fracturing the interface.

Fracture behavior of a ductile layer constrained by stiff substrates by using brass/sandwich/brass specimen was reported earlier by Choi [74]. For pure tensile loading of the solder joint, the crack initiates by near tip void growth or by ductile de-
bonding. Brittle de-bonding also occurs at a distance of several layer thicknesses ahead of the crack, for the case of thinner solder layer.

In this study, the CMM specimen comprised of a thin solder joint of SAC387 solder between two copper substrates. Based on this uniform solder joint, another type of compact mixed-mode specimen was fabricated with a crack created at one of the interface between the solder and the copper substrate. This type of specimen is utilized to study interfacial fracture mechanism with the presence of crack at the interface [81-83]. The joint size is critical to the failure mode as larger joints are more prone to brittle interface failure than smaller joints and creep resistance of the joints also increase with joint size. The compact mixed-mode specimen with crack, as shown in Figure 59, were tested to determine the fracture toughness under pure mode I (tensile),
pure mode II (shear) and mixed-mode with combination of mode I and mode II loading conditions.

The CMM test is a useful tool for the measurement of interface fracture toughness for various adhesively bonded joints. The CMM fixture allows the changing of the loading angle from $0^\circ$ to $90^\circ$ with respect to the specimen axis in increments of $22.5^\circ$. Other than tensile and shear tests, the CMM specimen can be used to test for mixed mode fracture at $22.5^\circ$, $45^\circ$ and $67.5^\circ$.

Fracture mechanics tests were conducted on samples comprising a 1mm thick solder joint between two copper substrates in the modified compact mixed mode (CMM) configuration, with joint length ($W$) of 8mm. Since a small section of the Cu surface is not wetted by solder, a sharp interfacial crack length ($a$) was formed, where $a/W=0.5$. Tests were conducted using a loading frame at strain rates of $0.01\text{s}^{-1}$ to $0.1\text{s}^{-1}$ with the Instron universal test machine. A custom made loading fixture, shown in Figure 60, enables changing the loading angle from $0^\circ$ to $90^\circ$ relative to the specimen axis in $22.5^\circ$ increments.
7.2 CMM Methodology of Fracture Toughness Analysis (with cracks)

Finite-element modeling (FEM) was used to obtain stress intensity factors in modes I and II ($K_I$ and $K_{II}$) and will be discussed in details in the last section of this chapter. Five modes of loading angles, which are 0º, 22.5º, 45º, 67.5º and 90º were investigated in this section. The stress intensity factor for CMM specimen were presented as $K_I$ and $K_{II}$, which describes the state of stress field at the tip of the crack due to stress and strain respectively.

Using the data obtained from FEM, the actual stress intensity factors would then be calculated, simply by substituting the actual load sustained and the thickness of the specimen using formulae below.

$$f_I \left( \frac{a}{w} \right) = \frac{K_I' \times w \times t}{P \sqrt{\pi a}}$$  \hspace{1cm} (43)

$$f_{II} \left( \frac{a}{w} \right) = \frac{K_{II}' \times w \times t}{P \sqrt{\pi a}}$$  \hspace{1cm} (44)
Since P=1N and t= 0.001m as the FEM was conducted under unit load and unit thickness condition, equations (43) and (44) can be derived into:

\[
K'_I = \frac{P \cos\phi}{\sqrt{\pi a}} \cdot f_I \left( \frac{a}{w} \right) \tag{45}
\]

\[
K'_II = \frac{P \sin\phi}{\sqrt{\pi a}} \cdot f_I \left( \frac{a}{w} \right) \tag{46}
\]

After the individual stress intensity factors were calculated, the critical energy release rate, which is another measure of the interface fracture toughness to present the failure criterion of solder bonded joint subjected to mixed mode loading was calculated with the formula below. The material properties of solder and copper are listed in Table 7.

\[
G = \frac{K'^2_1 + K'^2_{II}}{E'a \cos h^2(\pi\epsilon)} \tag{47}
\]

where \(E'_a = 2 \frac{E_1' \cdot E_2'}{E_1' + E_2'}\), \(E'_1 = \frac{E_1}{1 - v_1^2}\) and \(E'_2 = \frac{E_2}{1 - v_2^2}\)

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Young’s Modulus, (E_1) 110 GPa</td>
</tr>
<tr>
<td>Shear Modulus, (\mu_1) 46 GPa</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio, (v_1) 0.34</td>
<td></td>
</tr>
<tr>
<td>Solder</td>
<td>Young’s Modulus, (E_1) 50 GPa</td>
</tr>
<tr>
<td>Shear Modulus, (\mu_1) 27 GPa</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio, (v_1) 0.35</td>
<td></td>
</tr>
</tbody>
</table>

### 7.3 Mixed Mode Loading Solder Joint Strength Test Results and Analysis

#### 7.3.1 Pure Mode I (0°) Loading

At pure mode I, the specimens failed in a brittle manner over all strain rates (0.1s\(^{-1}\), 0.01s\(^{-1}\) and 0.001s\(^{-1}\)) with higher critical failure load at higher strain rate as shown in
Figure 61. Specimens at strain rate 0.01s$^{-1}$ and 0.001s$^{-1}$ showed that the solder joint specimens started to yield before finally failing at the critical load. An overall summary of the test results is given in Table 8.

![Figure 61 Pure Mode I (0°) loading at strain rates of 0.1, 0.01 and 0.001 s$^{-1}$](image)

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s$^{-1}$)</th>
<th>Critical Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.001</td>
<td>280.2</td>
</tr>
<tr>
<td>0°</td>
<td>0.01</td>
<td>348.5</td>
</tr>
<tr>
<td>0°</td>
<td>0.1</td>
<td>401.4</td>
</tr>
</tbody>
</table>

Pure mode I loading generally produces interface failure, where fracture at its copper-solder interface of the solder joints was found. The fracture took place without any appreciable deformation and by rapid crack propagation. Hence brittle fracture occurs for mode I loading. Based on fracture surface of the specimens shown in Table 9, all specimens have very clean and un-deformed fracture surfaces that demonstrate brittle failure occurred. The direction of crack motion was almost perpendicular to the direction of the applied tensile stress and hence it yielded a relatively flat fracture surface.
Table 9 Failure Site Investigation of Specimens at 0° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Crack Path</th>
<th>Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.001</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>0</td>
<td>0.1</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

7.3.2 Mixed Mode (22.5°) Loading

When the loading angle shifted from 0° to 22.5°, shearing effect was expected to take effect in the failure mechanism. The CMM specimens show significant mixture of brittle and ductile failure at the interface region for both strain rates of 0.01s\(^{-1}\) and 0.001s\(^{-1}\). With increasing strain rate, the critical failure load was found increasing as shown in Table 10.

Table 10 Test Results at 22.5° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Critical Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5°</td>
<td>0.001</td>
<td>368.7</td>
</tr>
<tr>
<td>22.5°</td>
<td>0.01</td>
<td>478.2</td>
</tr>
<tr>
<td>22.5°</td>
<td>0.1</td>
<td>546.5</td>
</tr>
</tbody>
</table>

It can be observed that the slower test strain rate is, the more ductile behavior in deformation is displayed during the test. At strain rates of 0.01s\(^{-1}\) and 0.001s\(^{-1}\), it can be seen that the load sustained by each specimen slowly increased until it peaked at
the critical load, indicating a failure in the solder joint before further displacement occurred and led to the final fracture.

Figure 62 Mixed mode (22.5°) loading at strain rates of 0.1, 0.01 and 0.001 s\(^{-1}\)

The reason for the further displacement was due to plastic deformation, as the specimen did not fully fail at its critical load. Based on inspection in Table 11, it can be seen prominently that failure of the solder joint in mixed mode (22.5°) loading occurred in the solder bulk area near to the copper-solder interface. In addition, a small amount of deformation of the interface could be seen on the specimens, which conform to Figure 62 that shows brittle and ductile mixed failure mode.
Table 11 Failure Site Investigation of Specimens at 22.5° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Crack Path</th>
<th>Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5</td>
<td>0.001</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>22.5</td>
<td>0.01</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>22.5</td>
<td>0.1</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
</tbody>
</table>

7.3.3 Mixed Mode (45°) Loading

Similarly to 22.5° loading angle case, at 45° loading angle, the specimens behave in the same manner throughout different strain rates displaying brittle and ductile failure as shown in Figure 63. Shearing effect is more significant compared to 22.5° loading angle case as the extension beyond critical failure load point is larger. The test results of 45° loading angle are summarized in Table 12.

![Figure 63 Mixed mode (45°) loading at strain rates of 0.1, 0.01 and 0.001 s\(^{-1}\)](image7)
Table 12 Test Results at 45° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s⁻¹)</th>
<th>Critical Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>0.001</td>
<td>384.2</td>
</tr>
<tr>
<td>45°</td>
<td>0.01</td>
<td>451.3</td>
</tr>
<tr>
<td>45°</td>
<td>0.1</td>
<td>554.4</td>
</tr>
</tbody>
</table>

The critical failure loads are very close to critical failure loads of 22.5° loading angle case at all three strain rates despite much higher extension observed. In Table 13, it can be easily observed that the failure of the solder joint in mixed mode (45°) loading resulted in interface failure.

Table 13 Failure Site Investigation of Specimens at 45° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s⁻¹)</th>
<th>Crack Path</th>
<th>Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>0.001</td>
<td><img src="image1" alt="Crack Path" /></td>
<td><img src="image2" alt="Fracture Surface" /></td>
</tr>
<tr>
<td>45</td>
<td>0.01</td>
<td><img src="image3" alt="Crack Path" /></td>
<td><img src="image4" alt="Fracture Surface" /></td>
</tr>
<tr>
<td>45</td>
<td>0.1</td>
<td><img src="image5" alt="Crack Path" /></td>
<td><img src="image6" alt="Fracture Surface" /></td>
</tr>
</tbody>
</table>

7.3.4 Mixed Mode (67.5°) Loading

In 67.5° loading angle case, it has the lowest critical failure over whole range of strain rates compared to other loading angle cases and closest critical failure load among all three strain rates as shown in Figure 64. This phenomenon can be explained as at 67.5°
loading angle, the CMM solder joint is least responsive to strain rate effect and has weakest strength among all the loading angles cases.

![Figure 64 Mixed mode (67.5°) loading at strain rates of 0.1, 0.01 and 0.001 s⁻¹](image)

Summary of test results are presented in Table 14. As seen in Table 15, it is very obvious that the further displacement beyond critical failure load point was predominantly undergoing shear.

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s⁻¹)</th>
<th>Critical Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.5°</td>
<td>0.001</td>
<td>287.3</td>
</tr>
<tr>
<td>67.5°</td>
<td>0.01</td>
<td>378.1</td>
</tr>
<tr>
<td>67.5°</td>
<td>0.1</td>
<td>392.5</td>
</tr>
</tbody>
</table>
### Table 15 Failure Site Investigation of Specimens at 67.5° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s⁻¹)</th>
<th>Crack Path</th>
<th>Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.5</td>
<td>0.001</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>67.5</td>
<td>0.01</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>67.5</td>
<td>0.1</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

7.3.5 Pure Mode II (90°) Loading

Pure mode II loading specimens have shown the most ductile failure mechanism at all strain rates. For strain rate of 0.1s⁻¹, there was a sudden drop in load at the critical load due to ductile to brittle transition. This occurs when the bulk solder strength has increased beyond the interface strength. The corresponding ductility of the solder joint also decreases dramatically when this transition occurs. At strain rates of 0.01s⁻¹ and 0.001s⁻¹, it can be seen that the load the load sustained by each specimen slowly increased until it peaked at its critical load.
Based on failure site investigation in Table 17, it was observed that that pure mode II loading generally produced a “flat-pulled wave liked” surface due to the large amount of deformation from the shearing motions. In addition, a larger amount of deformation of the interface than mixed mode (67.5°) loading could be seen throughout all the specimens.

**Table 16 Test Results at 90° Loading Angle at Various Strain Rate**

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Critical Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>0.001</td>
<td>324.1</td>
</tr>
<tr>
<td>90°</td>
<td>0.01</td>
<td>458.4</td>
</tr>
<tr>
<td>90°</td>
<td>0.1</td>
<td>516.5</td>
</tr>
</tbody>
</table>
Table 17 Failure Site Investigation of Specimens at 90° Loading Angle at Various Strain Rate

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Crack Path</th>
<th>Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.001</td>
<td>![Crack Path Image]</td>
<td>![Fracture Surface Image]</td>
</tr>
<tr>
<td>90</td>
<td>0.01</td>
<td>![Crack Path Image]</td>
<td>![Fracture Surface Image]</td>
</tr>
<tr>
<td>90</td>
<td>0.1</td>
<td>![Crack Path Image]</td>
<td>![Fracture Surface Image]</td>
</tr>
</tbody>
</table>

7.4 Fracture Toughness, Effect of Strain Rate and Loading Mode Analysis

Stress intensity factor (SIF) is generally lower at a lower strain rate. It can be seen in Figure 66 that at loading angles 0° to 45°, the work hardening effect is predominantly present, while at loading angles 67.5° to 90°, the solder joint specimen is shear-dominant. It was also observed that at 22.5° and 45°, there was deviation from the ideal scenario where all the points would tend to follow the curve.

![Stress Intensity Factor $K_I'$ and $K_{II}'$ at Various Strain Rates](image)

Figure 66 Stress Intensity Factor $K_I'$ and $K_{II}'$ at Various Strain Rates
On the other hand, the critical energy release rate is generally higher at a higher strain rate as shown in Figure 67. The work hardening effect is predominantly found at loading angles from 0° to 45° and shearing effect is predominant at loading angles 67.5° to 90°. Table 18 summarizes the calibrated stress intensity factor and critical energy release rate at strain rates of 0.1, 0.01 and 0.001s⁻¹

![Figure 67 Effect of Fracture Toughness on Loading Angles for Solder Joint Specimen with Pre-crack of a/w=0.5 at Various Strain Rate](image)

The stress intensity factor (SIF) is generally lower at a slower strain rate. At loading angles 0° to 45° for all strain rates, the work hardening effect is predominantly present, which states that at a higher strain rate, the solder will become stronger and more difficult to deform since there is insufficient time for creep and stress relaxation to occur. At loading angle 67.5° to 90°, the solder joint specimen is shear-dominant with shear strength lowered as strain rate decreases due to creep and stress relaxation effects that causes softening of the material.
Table 18 Summary of Parameter for Study of Fracture Toughness of Solder Joint Specimen with Pre-crack of a/w=0.5 at Strain Rates of 0.1, 0.01 and 0.001 s⁻¹

<table>
<thead>
<tr>
<th>Loading Angle (°)</th>
<th>Strain Rate (s⁻¹)</th>
<th>Calibrated Average Mixed-Mode Stress Intensity Factors (SIF)</th>
<th>Critical Energy Release Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( K'_I ) (MPa√m)</td>
<td>( K''_I ) (MPa√m)</td>
</tr>
<tr>
<td>Pure Mode I (0°)</td>
<td>0.1</td>
<td>5.031</td>
<td>0.000</td>
</tr>
<tr>
<td>Mixed Mode (22.5°)</td>
<td>0.1</td>
<td>6.722</td>
<td>0.765</td>
</tr>
<tr>
<td>Mixed Mode (45°)</td>
<td>0.1</td>
<td>5.230</td>
<td>1.996</td>
</tr>
<tr>
<td>Mixed Mode (67.5°)</td>
<td>0.1</td>
<td>1.675</td>
<td>2.106</td>
</tr>
<tr>
<td>Pure Mode II (90°)</td>
<td>0.1</td>
<td>0.000</td>
<td>3.151</td>
</tr>
<tr>
<td>Pure Mode I (0°)</td>
<td>0.01</td>
<td>4.368</td>
<td>0.000</td>
</tr>
<tr>
<td>Mixed Mode (22.5°)</td>
<td>0.01</td>
<td>5.882</td>
<td>0.669</td>
</tr>
<tr>
<td>Mixed Mode (45°)</td>
<td>0.01</td>
<td>4.257</td>
<td>1.625</td>
</tr>
<tr>
<td>Mixed Mode (67.5°)</td>
<td>0.01</td>
<td>1.613</td>
<td>2.029</td>
</tr>
<tr>
<td>Pure Mode II (90°)</td>
<td>0.01</td>
<td>0.000</td>
<td>2.796</td>
</tr>
<tr>
<td>Pure Mode I (0°)</td>
<td>0.001</td>
<td>3.512</td>
<td>0.000</td>
</tr>
<tr>
<td>Mixed Mode (22.5°)</td>
<td>0.001</td>
<td>4.535</td>
<td>0.516</td>
</tr>
<tr>
<td>Mixed Mode (45°)</td>
<td>0.001</td>
<td>3.624</td>
<td>1.383</td>
</tr>
<tr>
<td>Mixed Mode (67.5°)</td>
<td>0.001</td>
<td>1.226</td>
<td>1.542</td>
</tr>
<tr>
<td>Pure Mode II (90°)</td>
<td>0.001</td>
<td>0.000</td>
<td>1.977</td>
</tr>
</tbody>
</table>

A possible reason for loading angle 67.5° deviating from the ideal case could be due to the roughness of the IMC layer as it would affect the fracture toughness of the solder joints. A rougher IMC would be able to provide more interfacial area between IMC and the solder and thus provides sites of strain concentration at the scallop tips, which would promote early micro void nucleation and adhesive fracture along the solder-IMC surface fracture initiation. Hence, a joint with rough IMC is more prone to fracture along the solder–IMC interface leading to low fracture toughness. Thus resulting in loading angle 67.5° having a smaller SIF \( K''_I \) than loading angle 90°. Whereas for 22.5° and 45°, a possible reason for deviation in the SIF could be due to the specimen being resistant to the change in loading angles. As the crack usually propagates at the IMC for specimens with crack, in this case, the crack could have...
meandered into the bulk solder region thus resulting in the specimens having a higher SIF.

At loading angles 0° to 45° for all three strain rates, the work hardening effect is predominantly present, which states that at a higher strain rate, the solder will become stronger and more difficult to deform since there is insufficient time for creep and stress relaxation to occur. At loading angle 67.5° to 90°, the solder joint specimen is shear-dominant with shear strength lowered as strain rate decreases due to creep and stress relaxation effects that causes softening of the material. However it was also noted that at loading angle 22.5°, the critical energy was higher than loading angle 0° whereas at loading angle 67.5°, it is found to be slightly lower than loading angle 90°. The reason for this phenomenon was because critical energy is derived from SIF. Thus, if the SIF at a certain loading angle were higher, the critical energy would be higher as well and vice versa.

For mixed mode loading at 22.5° and 45°, the displacements were due to plastic deformation at the solder joint as it did not fail completely at its critical load, thus resulting in the joint to continue to sustain load before it fractures. Whereas for mixed mode loading at 67.5° and pure mode II (90°), the displacements were due to the shearing effect being predominately present in the joint. For small elongations, stress increases rapidly until a maximum stress is reached (shear strength). The samples do not then break abruptly; instead, a slow decrease in stress appears that ends when the inner stress resistance becomes zero (maximum shear strain).
The calibrated SIF $K'_I$ decreases while the calibrated SIF $K''_I$ increases along loading angle from 0° to 90°. Therefore, it is considered that the interface is strong to the shear mode but weak to the opening mode. From the calibrated SIF calculated, it can be observed that they were consistent with the visual analysis conducted. Table 19 shows a summary of the failure mode at different loading angles. It conforms to the author’s hypothesis, which is to have brittle failure mode at pure mode I and ductile failure mode at pure mode II with ductile to brittle transition mixed mode occurred in between.

**Table 19 Summary of Failure Mode at Various Loading Angles**

<table>
<thead>
<tr>
<th>Loading Angle</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mode I (0°)</td>
<td>Brittle</td>
</tr>
<tr>
<td>Mixed Mode (22.5°)</td>
<td>Brittle and Ductile</td>
</tr>
<tr>
<td>Mixed Mode (45°)</td>
<td>Brittle and Ductile</td>
</tr>
<tr>
<td>Mixed Mode (67.5°)</td>
<td>Brittle and Ductile</td>
</tr>
<tr>
<td>Pure Mode II (90°)</td>
<td>Ductile</td>
</tr>
</tbody>
</table>
7.5 Finite Element Analysis of CMM Specimen under Mixed Mode Loading

The finite element analysis on a CMM specimen consists of subdividing the joint into discrete elements, then translating the geometry values of the elements, all loads and boundary conditions into mathematical conditions that can be solved using finite element technology. In the present study, a commercial FEM package ANSYS Mechanical is adopted to analyze the stress intensity factor solder bonded joint. In this study, the finite element meshes uses PLANE82, which is 8 nodes 2-D space elements.

The interface crack-tip experiences both normal and shear stress due to material elasticity mismatch [84-87]. For plane strain condition, the elasticity mismatch between the two materials is governed by the Dundurs’ parameters [86] and given by

\[
\alpha = \frac{(1-v_2)/(1-v_1)/\mu_2}{(1-v_2)/(1-v_1)/\mu_1},
\]

\[
\beta = \frac{1}{2} \frac{(1-2v_2)/(1-2v_1)/\mu_2}{(1-2v_2)/(1-2v_1)/\mu_1}
\]

where \(v_i\) and \(\mu_i\) are the Poisson’s ratio and shear modulus of the two materials, respectively; \(i = 1\) or \(2\), the subscripts 1 and 2 refer to materials across the interface.

\[
\sigma_{ij}(r, \theta) = \frac{1}{\sqrt{2\pi r}} \{Re[Kr^{i\epsilon}]\hat{\sigma}_{ij}^l(\theta) + Im[Kr^{i\epsilon}]\hat{\sigma}_{ij}^t(\theta)\}
\]

where \(r\) and \(\theta\) are the polar coordinates with local Cartesian \(x\) along the material interface ; \(\hat{\sigma}_{ij}^l\) and \(\hat{\sigma}_{ij}^t\) are the dimensionless angular distributions which correspond to tractions across the interface; \(K\) is the complex SIF defined as

\[
K = K_l + iK_{lt}
\]
where \( i = \sqrt{-1} \); \( K_I \) and \( K_{II} \) are the SIFs related to mode I and mode II loading configurations, respectively, and \( \epsilon \) is the oscillatory index

\[
\epsilon = \frac{1}{2\pi} \ln(1-\beta) \quad (52)
\]

By introducing a characteristic length parameter \( \iota \) into equation (54), the complex SIF can be expressed as

\[
K^{ie} = |K| e^{i\psi} \quad (53)
\]

where \( \psi \) is the phase angle of the complex quantity \( K^{ie} \), representing the mixity of mode II SIF to mode I SIF at the crack-tip. Thus, the local stress field ahead of the interfacial crack (\( \theta = 0 \)) can be obtained by

\[
\sigma_y + i \tau_{xy} = \frac{K}{\sqrt{(2\pi\iota)}} \left( \frac{r}{\iota} \right)^i \epsilon \quad (54)
\]

where \( \sigma_y \) and \( \tau_{xy} \) are the normal stress and shear stress at the crack-tip, respectively.

The displacement field along the crack face (\( \theta = \pi \)) can be deduced

\[
\delta_y + i \delta_x = \frac{\frac{n}{1+2\nu} E^* \cosh(\pi e)}{2} \left( \frac{r}{\iota} \right) \left( \frac{r}{\iota} \right)^i \epsilon (K_I + i K_{II}) \quad (55)
\]

where \( \delta_y \) and \( \delta_x \) are the crack-tip opening displacements (CTODs) in the \( x \) and \( y \) directions, respectively, \( E^* \) is the effective Young’s modulus given by

\[
\frac{2}{E^*} = \frac{1}{E_1} + \frac{1}{E_2} \quad (56)
\]

where \( E_i = E_i/(1-\nu_i) \) for plane strain; \( E_i \) is the elastic modulus of the two materials, \( i = 1 \) or 2, the subscripts 1 and 2 refer to materials across the interface.
By solving equation (54), the individual SIF at the crack-tip can be obtained based on the stress distribution around the crack-tip [87].

\[ K_I = \lim_{r \to 0} \sqrt{2\pi r} \left( \sigma y \cos Q + \tau xy \sin Q \right) \]

when \( r \to 0 \) \hspace{1cm} (57)

\[ K_{II} = \lim_{r \to 0} \sqrt{2\pi r} \left( \tau xy \cos Q - \sigma y \sin Q \right) \]

when \( r \to 0 \) \hspace{1cm} (58)

where \( Q = \epsilon \cdot \ln(r/l) \)

Similarly, by solving equation (54), the individual SIF at the crack-tip can be determined from the displacement field near the crack-tip.

\[ K_I = \left\{ A \cos \left[ \epsilon \ln \left( \frac{r}{l} \right) \right] + B \sin \left[ \epsilon \ln \left( \frac{r}{l} \right) \right] \right\} \frac{D}{D} \]

(59)

\[ K_{II} = \left\{ B \cos \left[ \epsilon \ln \left( \frac{r}{l} \right) \right] + A \sin \left[ \epsilon \ln \left( \frac{r}{l} \right) \right] \right\} \frac{D}{D} \]

(60)

where

\[ A = \delta y - 2\epsilon \delta x \]

(61)

\[ B = \delta x + 2\epsilon \delta y \]

(62)

\[ D = \frac{8}{E \ast \cosh(\pi \epsilon)} \sqrt{r/(2\pi)} \]

(63)

When the stress and displacement fields near the crack-tip are predicted from FE simulation, the SIF at the crack-tip can be determined by the extrapolation method. Thus, the interface strain energy release rate \( G \) and phase angle \( \psi \) can be obtained, respectively, by

\[ G = \frac{K_{eff}^2}{E'_{nl} \cosh^2(\pi \epsilon)} \]

(64)
\[
\psi = \tan^{-1}\left(\frac{K_{II}}{K_I}\right)
\]

where \(K_{eff}\) is the effective SIF given by

\[
K_{eff} = \sqrt{\left(K_I^2 + K_{II}^2\right)}
\]

The specimen being meshed using element type PLANE82 as shown in Figure 69. PLANE82 provides accurate results for mixed (quadrilateral-triangular) automatic meshes and can tolerate irregular shapes without as much loss of accuracy. The eight-node elements have compatible displacement shapes and are well suited to model curved boundaries.

![Figure 69 ANSYS Model of (a) Test Fixture and (b) CMM Specimen using PLANE82 Elements](image)

The 8-node element is defined by eight nodes having two degrees of freedom at each node: translations in the nodal \(x\) and \(y\) directions. The element may be used as a plane element or as an axis-symmetric element. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. PLANE82 will be used
in all the meshing done in this FEM work. Dimensions and materials properties of the CMM specimen used in the finite element analysis are listed in Table 20.

Table 20 Dimensions and Materials Properties of CMM Specimen

<table>
<thead>
<tr>
<th>CMM Specimen Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen's Width, w</td>
<td>8mm</td>
</tr>
<tr>
<td>Crack Length, a</td>
<td>4mm</td>
</tr>
<tr>
<td>Specimen's Thickness, t</td>
<td>2.5mm</td>
</tr>
<tr>
<td>Solder Thickness, h</td>
<td>1.5mm</td>
</tr>
<tr>
<td>Copper Poisson Ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Copper Young Modulus</td>
<td>111GPa</td>
</tr>
<tr>
<td>Solder Poisson Ratio</td>
<td>0.4</td>
</tr>
<tr>
<td>Solder Young Modulus</td>
<td>55GPa</td>
</tr>
</tbody>
</table>

Mode I and Mode II stress intensity factors for interlayer crack can be computed using the displacement substitution method (D-Sub). The nodal increment displacement, r can be extracted from ANSYS result by selecting the nodes along the crack tip. The following is a sample data extracted from ANSYS for further calculation of stress intensity factor. This section presents the summary of the $K_I$ and $K_{II}$, the deformation, the stress and strain distribution of the interlayer crack (as shown in Figure 70) cases under five different loading condition.

Figure 70 Schematic of CMM Specimen with Interface Crack
A virtual load of 1N is applied to the CMM specimen in the five different loading conditions cases range from loading angle of 0° to 90°. Due to different angles of the load applied and material mismatch, the deformation, stress distribution and strain distribution are observed to be different. The respective stress intensity factor for the CMM specimen with solder bonded joint in the form of interfacial crack was evaluated later in this chapter.

A comparison of $K_I$ and $K_{II}$ for all angles was done. This was done to display the relation of the angles of load application, to the strain and stress that will act at the crack tip in the result of the applied load.

Do note that the results obtained in Table 19 are computed in ANSYS using unit load of 1N and unit thickness of 1mm. $K_I = \sigma \sqrt{\pi a f_I \left(\frac{a}{w}\right)}$ may be further elaborated into

$$K_I = \frac{P \cos \theta \sqrt{\pi a}}{w t} f_I \left(\frac{a}{w}\right),$$

where $P$ is the load, $\theta$ is the angle in which $P$ is applied and $t$ is thickness of the specimen. The data in Table 19 can be used to compute the $f_I \left(\frac{a}{w}\right)$ factor by substituting $K_I$ (Nmm$^{-1.5}$) or $K_{II}$ (Nmm$^{-1.5}$), $t$, $w$, $\theta$ and $P$ into the equation.

Once $f_I \left(\frac{a}{w}\right)$ is found, it is then possible to compute the different stress intensity factors for different loads, angles or thickness. However, do note that this calculation method is only valid for CMM specimens with $\left(\frac{a}{w}\right)=0.5$ and solder thickness, $h=1.5$mm. If other $\left(\frac{a}{w}\right)$ and $h$ were to be considered, a new ANSYS model has to be created by modifying the PREP7 file that the author had created initially.
The relation of stress intensity factors for different angles of load applications are illustrated in Table 21.

1. For 0°: the $K_I$ value is significantly larger than $K_{II}$ value. This is explainable as pure tensile force was expected at the crack tip. It will be more accurate if $K_{II} = 0$ is obtained.

2. For 22.5°: the $K_I$ value is still significantly larger than $K_{II}$ value. This phenomenon is observed due to much higher tensile force applied than the shearing force applied.

3. For 45°: the $K_I$ value is significantly higher than $K_{II}$ value. Due to material mismatch in copper and solder, the copper substrate at the top of the crack deformed less compared to the solder substrate on the bottom of the crack. The crack tip experience higher tensile stress than shearing stress.

4. For 67.5°: the $K_I$ value is significantly smaller than the $K_{II}$ value. At this test angle, shearing stress applied is much higher than the tensile force applied and shearing effect takes charge of the failure mechanism.

5. For 90°: the $K_I$ value is close to 0, while the $K_{II}$ value is significantly higher. Pure shearing stress was expected at the crack tip.

<table>
<thead>
<tr>
<th>Degree (°)</th>
<th>$K_I$ ($Nm m^{-1.5}$)</th>
<th>$K_{II}$ ($Nm m^{-1.5}$)</th>
<th>$K_I$ (MPa$m^{1/2}$)</th>
<th>$K_{II}$ (MPa$m^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.1892</td>
<td>-0.0849</td>
<td>0.0376</td>
<td>-0.0027</td>
</tr>
<tr>
<td>22.5</td>
<td>1.1664</td>
<td>0.1342</td>
<td>0.0369</td>
<td>0.0042</td>
</tr>
<tr>
<td>45</td>
<td>0.8963</td>
<td>0.3429</td>
<td>0.0283</td>
<td>0.0108</td>
</tr>
<tr>
<td>67.5</td>
<td>0.4033</td>
<td>0.5078</td>
<td>0.0128</td>
<td>0.0161</td>
</tr>
<tr>
<td>90</td>
<td>-0.0215</td>
<td>0.5799</td>
<td>-0.0007</td>
<td>0.0183</td>
</tr>
</tbody>
</table>
A comparison is done by comparing the $K_I$ and $K_{II}$ values, which are obtained through ANSYS against the experimental load values obtained experimentally. The average of the critical loads derived from the experiments are to be input into ANSYS simulation. The results obtained are displayed in the right portion of the tables below. The comparison results are stated in the tables below. Table 22 shows results displayed in $Nmm^{-1.5}$ units while Table 23 shows results displayed in $MPa\sqrt{m}$ units.

Table 22 Unit Load vs. Experimental Results of Stress Intensity under Different Loading

<table>
<thead>
<tr>
<th>Degree</th>
<th>ANSYS (Unit load)</th>
<th>ANSYS (Experimental load)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (N)</td>
<td>$K_I$ ($Nmm^{-1.5}$)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1.1892</td>
</tr>
<tr>
<td>22.5</td>
<td>1</td>
<td>1.1664</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>0.8963</td>
</tr>
<tr>
<td>67.5</td>
<td>1</td>
<td>0.4033</td>
</tr>
<tr>
<td>90</td>
<td>1</td>
<td>-0.0215</td>
</tr>
</tbody>
</table>

Table 23 Unit Load vs. Experimental Results of Stress Intensity under Different Loading

<table>
<thead>
<tr>
<th>Degree</th>
<th>ANSYS (Unit load)</th>
<th>ANSYS (Experimental load)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (N)</td>
<td>$K_I$ (MPa$\sqrt{m}$)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.0376</td>
</tr>
<tr>
<td>22.5</td>
<td>1</td>
<td>0.0369</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>0.0283</td>
</tr>
<tr>
<td>67.5</td>
<td>1</td>
<td>0.0128</td>
</tr>
<tr>
<td>90</td>
<td>1</td>
<td>-0.0007</td>
</tr>
</tbody>
</table>
Table 24 Summary of Stress and Strain Distribution at Crack Tip under Various Loading Conditions

<table>
<thead>
<tr>
<th></th>
<th>$0^\circ$</th>
<th>$22.5^\circ$</th>
<th>$45^\circ$</th>
<th>$67.5^\circ$</th>
<th>$90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State</td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
</tr>
<tr>
<td>Deformed State</td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
</tr>
<tr>
<td>Deformed crack tip</td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
</tr>
<tr>
<td>Stress distribution at crack tip</td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
</tr>
<tr>
<td>Strain distribution at crack tip</td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
<td><img src="97.png" alt="Image" /></td>
</tr>
</tbody>
</table>
As the author created a 2D ANSYS model instead of a 3D ANSYS model by using plain strain element, the ANSYS software calculates the $K_I$ and $K_{II}$ values using the default unit thickness of 1mm. On the other hand, the author did the experiment by using specimen of 3mm thickness. According to the stress intensity factor listed in Table 25, the $K_I$ and $K_{II}$ values obtained by experiment have a factor of 3 to the $K_I$ and $K_{II}$ values obtained from ANSYS and both sets of values have good agreement. This is due to the difference in specimen thickness used in the ANSYS simulation and the experiment.

Table 25 Finite Element Analysis vs. Experimental Results under Different Loading Conditions

<table>
<thead>
<tr>
<th>Degree</th>
<th>ANSYS (Unit Thickness Factor)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (N)</td>
<td>$K_I$ (MPa$\sqrt{m}$)</td>
</tr>
<tr>
<td>0</td>
<td>401.4</td>
<td>5.0310</td>
</tr>
<tr>
<td>22.5</td>
<td>546.5</td>
<td>6.7187</td>
</tr>
<tr>
<td>45</td>
<td>554.4</td>
<td>5.2380</td>
</tr>
<tr>
<td>67.5</td>
<td>392.5</td>
<td>1.6688</td>
</tr>
<tr>
<td>90</td>
<td>516.5</td>
<td>-0.1171</td>
</tr>
</tbody>
</table>
Therefore, based on the equation $K_I = \frac{pcos\theta \sqrt{\pi a}}{wt} f_i\left(\frac{a}{w}\right)$, if thickness 3mm is taken into consideration, it can be deduced that the $K_I$ and $K_{II}$ values obtained will be one-third the value of $K_I$ and $K_{II}$ obtained by ANSYS. The author proved that if a direct comparison with exact specimen thickness, the ANSYS simulation would be able to predict the $K_I$ and $K_{II}$ values accurately.
CHAPTER 8

8 Conclusion and Future Work

8.1 Conclusion

8.1.1 In this PhD study, the elastic-plastic properties of lead-free solder, 95.5Sn3.8Ag0.7Cu (SAC387) have been investigated and characterized over strain rate from $10^{-3}$ to 1 (s$^{-1}$). A power law relationship with strain rate has been used to model the elastic modulus, yield stress and ultimate tensile strength of SAC387 respectively. The result is listed below.

Elastic Modulus: $E = 80.959 \varepsilon^{0.1659}$

Yield Stress: $\sigma_y = 73.661 \varepsilon^{0.0759}$

Ultimate Tensile Strength: $\sigma_{UTS} = 78.148 \varepsilon^{0.0780}$

The plastic strain was curve fitted to a Hollomon model, $\sigma_t = K \varepsilon_t^n$, in terms of applied stress with satisfactory agreement. The strength coefficient $K$, range from 45.92 to 80.45 and strain hardening coefficient $n$, range from 0.00522 to 0.00655 over the strain rate of $10^{-3}$ to 1 (s$^{-1}$).

8.1.2 For stress levels higher than the yield stress, the plastic strain transition region models the smooth transition from elastic to total strain, which includes the summation of the elastic and plastic strain. A new strain rate dependent modified Ramberg-Osgood stress strain constitutive model has been developed as below to account strain rate effect for SAC387 solder.
Strain rate dependent modified Ramberg-Osgood model for SAC387:

\[
\varepsilon = \frac{\sigma}{723.19 \log(\dot{\varepsilon}) + 6049.1} + [0.00947(\dot{\varepsilon})^2 - 0.00464(\dot{\varepsilon}) - 0.0003] \cdot \\
\frac{11.54(\dot{\varepsilon}) + 13.85}{723.19 \log(\dot{\varepsilon}) + 6049.1} \cdot \left[ \frac{\sigma}{11.54 \cdot (\dot{\varepsilon}) + 13.85} \right]^{0.1085(\dot{\varepsilon})^2 - 1.1647(\dot{\varepsilon}) + 6.9552}
\]

The strain rate dependent yield stress properties for SAC387 solder derived from both tensile test and nanoindentation test data correlate well with a strain rate dependent Cowper Symond constitutive model developed. From nanoindentation test, SAC387 experienced a relatively uniform increment of at least 50% in magnitude when strain rate is increased by an order. The test data can be curve-fitted to the Cowper and Symonds model below

\[
\frac{\sigma}{\sigma_0} = 1 + \left( \frac{\dot{\varepsilon}}{2.6} \right)^{6.4}
\]

8.1.3 A single solder joint test under tensile condition was developed by the author to study stress strain behavior of actual solder joint over the strain rates range from 0.001s\(^{-1}\), 0.01s\(^{-1}\) to 0.1s\(^{-1}\). Both single solder joint and bulk solder experimental test results were used for comparison with finite element analysis results. The comparison of experimental and finite element analysis results shows good agreement for bulk solder and the solder joint finite element analysis results. The solder joint finite element analysis results and predict the failure strength of the single solder joint test results due to interface solder joint failure modes.
For bulk solder joint test, both finite element analysis and experimental results agree fairly well. In single solder joint cases, finite element analysis results are significantly higher than experimental results. This is owing to imperfect soldering process for the actual single solder joint and also delamination occurred during the experiment due to interface induced fracture mechanism.

8.1.4 The mixed-mode (Tensile and Shear) solder joint strength failure assessment is characterized by using a compact mixed mode (CMM) test method at strain rate of $0.001\,\text{s}^{-1}$, $0.01\,\text{s}^{-1}$ and $0.1\,\text{s}^{-1}$. It was found that the solder joint's overall mechanical reliability and functional integrity significantly decreased due to the crack. Investigation of the solder bonded joint had been focused on the interfacial and interlayer crack. The studies had revealed that at $0^\circ$, the CMM specimen is experiencing pure tensile stress, while at $90^\circ$, it is experiencing pure shear stress. It is observed that the stress intensity factor and the critical energy release rate increase with increase in strain rate.

8.1.5 The experimental results conform to the author’s hypothesis, and were later on compared with the finite element analysis. The comparison shows fairly good agreement in the trend of both $K_I$ and $K_J$. The study has also revealed that the stress decreases with $r$, and the highest stress will concentrate on the crack tip. But it does not mean the stress intensity factor is the highest at the crack tip, the trend may change at certain value.
8.2 Future Work

8.2.1 Compact mixed mode solder joint study shall be conducted more extensively with investigation over a wider range of strain rate (for example: $0.001\text{s}^{-1}$, $0.01\text{s}^{-1}$, $0.1\text{s}^{-1}$, $1\text{s}^{-1}$ and $10\text{s}^{-1}$) in order to have a better and deeper understanding of the strain rate effect on failure mechanism of a solder joint under different mixed mode loading conditions. On the other hand, finite element analysis can be further improved by using 3D modeling to derive results closer to an actual CMM solder joint.

8.2.1 Test methodology of single solder joint test shall be further developed in terms of specimen fabrication. Single solder joint specimens with enhanced joint quality can help to eliminate unnecessary fracture and delamination during the tests for more reliable test results. Furthermore, more precise solder joint thickness control is needed during solder joint reflow process in order to have higher consistency in the test results. With the achievement of these two criteria, single solder joint failure study can be broaden to strain rate effects study on a single solder joint with various solder joint thickness.
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