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A Novel Method for Direct Solder Bump Pull Testing Using Lead-Free Solders

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A NOVEL METHOD FOR DIRECT SOLDER BUMP PULL TESTING USING LEAD-
FREE SOLDERS

BY

GREGORY ALAN TURNER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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OF
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ABSTRACT

This thesis focuses on the design, fabrication, and evaluation of a new method for testing the adhesion strength of lead-free solders, named the Isotraction Bump Pull method (IBP). In order to develop a direct solder joint-strength testing method that did not require customization for different solder types, bump sizes, specific equipment, or trial-and-error, a combination of two widely used and accepted standards was created. First, solder bumps were made from three types of lead free solder were generated on untreated copper PCB substrates using an in-house fabricated solder bump-on-demand generator. Following this, the newly developed method made use of a polymer epoxy to encapsulate the solder bumps that could then be tested under tension using a high precision universal vertical load machine.

The tests produced repeatable and predictable results for each of the three alloys tested that were in agreement with the relative behavior of the same alloys using other testing methods in the literature. The median peak stress at failure for the three solders tested were 2020.52 psi, 940.57 psi, and 2781.0 psi, and were within one standard deviation of the of all data collected for each solder. The assumptions in this work that brittle fracture occurred through the Intermetallic Compound layer (IMC) were validated with the use of Energy-Dispersive X-Ray Spectrometry and high magnification of the fractured surface of both newly exposed sides of the test specimens. Following this, an examination of the process to apply the results from the tensile tests into standard material science equations for the fracture of the systems was performed.

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CHAPTER 1

INTRODUCTION

To understand the purpose of this research, one must first understand what solder is, and why it is important. In the electronics industry specifically, solder is an alloy used to create mechanical and electrical connections between components. In the case of printed circuit boards (PCBs), connections traditionally consist of either through-hole or surface mount connections, where an electrical component, a resistor for example, is attached to a non-conductive board and is connected by way of a thin copper pathway to other components on the board. PCBs are often made of one or more layers of non-conductive fiberglass coated with a thin copper surface. This copper is etched away where it is not needed to leave the pathways between components, then the components are attached to the board. These PCBs are present in the most advanced super computers and satellites, mobile music players, and everything in between, as in the illustration of PCB production of **Figure 1**.

Figure 1: Production of a PCB from blank to finished product (A) untreated PCB, (B) finished, no components added [1]

Unlike in welding, where similar alloys are joined together using a filler material with similar structural and thermal properties, soldering can join together similar or dissimilar alloys with a filler material with a lower melting temperature alloy. This means that in soldering, only the filler reaches a molten state, whereas in welding all objects present will be molten at one point during the process. This process creates both a mechanical bond between the objects, as well as a chemical one. The chemical bond is composed of Intermetallic compound (IMC), which is a brittle alloy of the solder and the objects it is connecting. **Figure 2** depicts a comparison of soldering versus welding. To clarify, soldering is the same process as brazing. However, it occurs at lower temperature ranges, with a molten filler metal temperature cutoff for soldering up to 450°C, while brazing has a cutoff temperature above 450°C. Unlike in welding, where the weld is often stronger than the material around it, solder joints are often the point of failure in these systems.

Figure 2: Welding on left vs Soldering on right

In years past, tin-lead alloys were used to solder electrical components together. These alloys were desirable due to their high electrical conductivity, low melting temperature, high availability and relatively low costs. The lead helped to stabilize the tin and reduce the chance of the spontaneous formation of tin whiskers, which form

beneath the surface of the solidified tin and can extend far beyond the intended connection, creating electrical shorts that can cause a system to fail.

However, health concerns arose from the issues surrounding the use and disposal of heavy metals such as lead. Thus, after the passing of the Lead Exposure Reduction Act in 1993 in the U.S., and the European Union's ban of lead in electronics becoming law in 2003, and going into effect in 2006, there has been a large push in industry to find suitable alternatives for tin-lead solders.

To-date, legislation has yet to be passed regarding the sale or production of consumer electronics containing lead in many of other major global economic powers, such as in the U.S., Japan, and China. Despite this however, many organizations, including Samsung, Apple, Google, and JEDEC (Joint Electron Device Engineering Council) have made efforts to move towards reducing or eliminating lead from the products and technologies they produce, support, or recommend.

To examine one aspect of the impact of this change, refer to the sales growth rate in the electronics industry of 3% in 2013 and the projected growth rates of 5% and 6% in 2014 and 2015 [2]. This, coupled with the positive trends in global sales growth rates in years past, give strong support to the projection that production and sales growth will continue. Due to the international nature of many of the products in the electronics industry, such as smartphones, televisions, digital media players and even automotive control systems, the option to have a lead-free zone surrounding the EU would not be economically feasible as it would create two separate marketplaces. This means that the discussion of the benefits of lead-free solder is no longer merely of academic or environmental interest, but also economical. Global smartphone sales

alone, with more than 680 million units sold in 2012, experienced a one year growth rate exceeding 40% with more than 960 million units sold in 2013 [3]. In much the same way as California vehicular legislation can regulate national behavior due to automotive suppliers wishing to sell cars which are "50 State legal", so too has the EU legislation impacted the global electronics industry.

For this reason, extensive studies on the material properties of lead-free solders and fluxes have been performed [4-11]. These studies have a focused interest on ever smaller systems due to their reduced packaging size, the materials needed and general mobility. This market-pull for pocket-sized devices has made surface mount technology a major source of development and growth in the electronics industry [11-17]. As such, the need then for further understanding of this technology in an applied manor is deepened.

The study of solder for surface mount systems (SMDs) from a structural [11,18] or even material science [19] perspective is not a novel concept. Developing this further, in recent years there has been significant research looking into the concepts of grain development [8], crack growth and fracturing of solder [14, 19-22]. This work has made it possible for the development of numerous industry standards and best practice methods to become available [21, 22].

It is the purpose of the current work described in this thesis, to experimentally study three lead-free soldering alternatives and compare those results to the material's microscopic structure to create a mathematical model which could aid future scientists and engineers in the selection of lead-free soldering alternatives in the future.

CHAPTER 2

REVIEW OF LITERATURE

In the world of electronics, solder serves a fundamental role connecting electronic components together. Forming both a structural and electrical connection between integrated circuits (ICs), printed circuit boards (PCBs), capacitors, resistors, and more, solder connects the various components that make up the hardware within such everyday devices as desktop and laptop computers, cell phones, wearables, watches and more. Soldering, shown in **Figure 3**, is the act of connecting metal objects together through the use of a filler metal. This process is accomplished in the same way as brazing, in which a filler metal with a lower melting temperature than the objects it is intended to connect is heated until it becomes a liquid. It is then applied at the junction of the other objects and allowed to cool. Common methods of soldering include through hole, surface mount, and wiring connections, and can be applied through various methods, such as wave soldering, pastes, drop deposition, and the classic use of an iron and solder wire.

Figure 3: Example of a Simple Soldered Connection

Soldering, like brazing, forms both a mechanical and chemical connection between the filler and non-melted metals. At the interface, the filler wets the other objects and an alloy layer is formed; this Intermetallic Compound, or IMC, as it is often referred to, shown in **Figure 4**, is a stoichiometric phase composed of the solder and the substrate to which it is connected [6]. IMCs are normally composed of covalently bonded atoms, are brittle and have a higher melting temperature than the solder which was used to form them. This is part of the reason why a discoloration is often left behind on the surface of a substrate after solder has been removed.

Figure 4: IMC of solder and copper substrate (a) Sn-3.5Ag and (b) Sn-3.5Ag-0.3Cu [23]

As lead-free solders gain a dominant market share over leaded solders worldwide due to environmental concerns and legislation, the need to create, test, and validate the properties of these new solder alloys has also risen. The requirements of lead-free solders are much the same as traditional leaded solders; they must have similar melting temperatures, strength and durability, ductility, thermal fatigue resistance, electrical resistance, should use the same manufacturing processes wherever possible, and allow for the continued miniaturization of the electronics industry. Other key

variables, such as the operating constraints for the substrate materials used as a support structure for these devices, the operating temperature of the circuitry, the properties of the electronic components, and the solder material costs play large roles in solder selection as well.

In 1994, Glazer *et al.* performed a literature review of the impact of the microstructure of various solders, as well as their mechanical properties in the effort to classify what one should look for in leaded solder replacements [6]. By looking at the key factors of the physical metallurgy, mechanical properties and oxidation and corrosion behavior, the work shed light onto some of the key factors that would be of great interest in future studies. At the time, lead had yet to be banned from use in electronic devices, but was no longer allowed in plumbing construction in many countries, and it was widely believed that similar legislation could pass as a blanket standard within these countries in the future. Thus, some lead-free solders were already in use, but only in a select few industries and the research into lead-free alternatives was limited. This early review of the key factors in selecting, developing and using lead-free solders highlights many of the criteria that would be tested in the twenty years that have followed.

Following this, extensive research has been performed into the optimum levels of other metals within the tin-based alloy mixtures of lead-free solders as well as investigating ways of optimizing and testing such properties as the IMC composition, size and wettability of assorted solders on varying substrates [4-11, 20, 24 - 27].

Simultaneously to the work developing different compositions for solder alloys, much research has been done to test the wetting behavior of these new materials on

assorted substrates, with a focus on the contact angle and formation of the IMC and comparing these results to those of leaded solders [24, 26-32]. The wettability of solder is the ease at which molten solder will form a connection to the substrate it is coming into contact with by dissolving a small layer of the substrate to create an IMC. In solders, this behavior is often monitored by measuring the contact angle of cured solder on a substrate after the sample has been bisected and examined under a microscope. It can also be done using photos of the profile of a drop of any fluid, or a solidified solder bump on a substrate. This wetting process can be aided by using higher temperatures, with clean and non-oxidized substrates. **Figure 5** depicts the process to measure the contact angle of a solidified solder bump.

Figure 5: Contact angle of solder on substrate

While many non tin-based solutions have been examined in the search to find suitable lead-free solder alternatives, a large majority are tin-based or contain tin to some degree. The reason for this is clearly stated by Glazer in 1994, where it is noted that tin is an abundant, low melting temperature metal, with the ability to form chemical connections with many of the pre-existing components in the electronics industry. There are, however, numerous possible issues that may arise from the use of

tin, and the mitigation of these issues has also been studied at length [4-11]. Previously, lead could be used to help hinder some of these concerns, like the formation of tin whiskers or tin pest. However other elements would instead be needed to be used to help mitigate these issues in new solder alloys.

It is also important that one recognizes the reason why lead was used in the soldering process at all, due to the fact that its dangers have been well-known for decades. Lead, like tin, is abundant, inexpensive, has a low melting temperature and bonds well to other metals. There was also the possibility to create a eutectic mixture of tin and lead with desirable characteristics. The eutectic mixture is composed of 63% tin, 37% lead, and was one of the many common solders used by numerous industries to make connections. Eutectic alloys are mixtures of elements which have a homogeneous bulk that solidifies all molten content at the same time and temperature and have the lowest melting point for the alloy for any other ratio [25]. This eutectic behavior, in combination with higher cooling rates and low melting temperature, leads to smaller, more uniform grain structures and helps to mitigate the formation of dendrites within the cooled bulk. Ratios with higher lead content, such as 50/50 mixtures were also commonly used. A phase diagram is shown in **Figure 6**, and can be used to identify the solubility of one element in another as well as the behavior of the alloy through a range of temperatures from a solid to molten state. In non-eutectic structures, large dendrites resembling fern branches of the phase which has solidified first will be formed. Not only can these dendrites pose a risk as locations of possible weakness within the solder, but they can also create deficits of the element surrounding itself. In other words, a lead-rich dendrite would be surrounded by lead

poor material after cooling. It is the goal of many lead-free solders which are used to replace leaded solders in a one-to-one fashion that they behave in such a manner as 63/37 ratio solder.

Figure 6: Phase diagram of tin-lead solder [33]

The formation of tin whiskers, shown in **Figure 7**, is the phenomenon in which thin, single crystal structures of pure tin spontaneously grow from the surface of solidified tin. These whiskers have been found to cause tremendous damage to essential electronics in many devices by causing shorts between connections and can grow in all open directions from the solidified tin [34, 35].

Figure 7: Example of Tin Whiskers [34]

Another major issue to mitigate while using tin, called tin pest, shown in **Figure 8**, takes place over time with a solid tin specimen, and is the process in which a decay of tin will occur at low temperatures. This degradation is a transformation of tin from beta form to white alpha form tin, where the solidified body will break down to a powder and could lead to eventual voids in the electronics, and ultimately mechanical failure [36]. One should note however, that tin pest is not the same as electromigration, where material in a conductor will change location due to the movements of ions caused by the flowing electrons within the body.

Figure 8: Example of Tin Pest [36]

In addition to generating increasingly complex alloys to achieve desirable solder behaviors like those discussed above, additional processes and elements have been added to substrates and components to achieve superior bonding [24, 28, 38]. Numerous studies have taken place to observe the reaction between assorted lead-free solders and different surface treatments [24, 28, 38]. Within these studies, the IMC, wetting behavior, mechanical strength, and other important bond criteria have been studied extensively. It is of special note, that these extra processes do not positively impact the soldering process in all ways. Black pad, for example, can occur when an Electroless Nickel/Immersion Gold (ENIG) coating is applied to the substrate [39-41]. ENIG coatings are applied to substrates to help mitigate the oxidation of the copper contacts, aid in the bonding of aluminum wires, give a more uniform surface for soldered connections and have desirable wear characteristics. Black pad has a black appearance where the nickel has corroded, as can be seen in **Figure 9**, and is present at locations of weakness in the connection. This corrosion decreases the solderability of

the joint and will often cause failures in use when the connection experiences stresses from thermal or mechanical changes.

Figure 9: Example of black pad [31]

Through the work of the above mentioned studies, industry suppliers and developers, numerous lead-free solder alternatives have been developed [38]. These solders are in turn, tested through a number of well described physical and simulated tests. A few of the more well-known among these tests are the drop impact test; bending test; hot bump pull (HBP); and the cold bump pull (CBP), officially called the JEDEC JESD 200-B115; and numerous computational studies.

Due to both the fiscal and time costs that traditional experimentation can have on development of new products, regardless of industry or application, Finite Element Analysis (FEA) is often used to create a baseline of performance expectations. One must be sure however, that even in complex build structures under dynamic loading conditions that the results are accurate and usable in real world applications. To this

end, numerous FEA models have been developed to test these materials [16, 19, 20]. The focus of many of these studies pertains to testing the accuracy of the results against experimental data to make recommendations to future users. This enables other researchers to create detailed simulations of some of the more recent advances in microelectronics packaging, like flip-chip assembly, shown in **Figure 10**.

Figure 10: Example of flip-chip assembly

Flip-chip assembly is very similar to standard surface mount assemblies, where contacts are made at the periphery of the component and are connected to the PCB, however flip-chip allows for multiple input and output contact points to be placed over the entirety of the bottom face of an integrated circuit component. These ICs are prepared with a large number of contacts on their bottom faces, then solder is placed and melted on each contact while the IC is upside down and is separated by a small air gap. The solder volumes are often referred to as bumps, and can be applied through wave soldering, using pastes, or direct placement. The IC is then placed right side up onto the contacts of the PCB and heat is applied to liquefy the solder at the points of contact. This process is referred to as reflowing, and normally takes place in highly controlled ovens. One can then recognize the importance of the works mentioned above in simulating these assemblies, as the numerous contacts and surface area create

a significantly more complex structure to simulate. Of note within these works is Darveaux's work to improve modeling of the initiations of cracks within solder, as well as the growth of cracks within solder once they form; Liu and Madeni's work towards discerning the fundamental properties of solders under normal usage conditions and Tamin's simulations of twisting forces on solder connections [16, 18, 19]. Darveaux's work in particular, is often referenced by other researchers.

The different behaviors and properties of lead-free solders under numerous thermal conditions have also been extensively experimentally studied [4, 7, 27, 28, 42]. Due to the fact that the operating temperature of many electronics can frequently be in excess of 60 degrees Celsius, which is above half the melting point of many of the solders used to hold them together, thermal issues causing creep, microstructure recrystallization, changes in plasticity and more can become significant problems [25]. This is clear when examining the ways in which solder fails, where failure in real world applications is often led by the formation of cracks [18, 43]. It is because of this that it was also important to develop a phase diagram of Sn-Ag-Cu and other lead-free alloys replacing the well studied tin-lead solders in order to be able to predict the behavior of the new solder as their temperatures changed [7]. Additionally, there has also been work done using thermal cycling of the components, which allows for accelerated aging of solders to test their long-term properties. This accelerated aging, along with studies into the inconsistencies in thermal expansion between alloys and substrates, allows for a better understanding of the temperature driven creep and failure, mentioned above [25, 27].

It is also necessary to describe some of the major changes that occur during solder aging under different thermal conditions, such as those described by Nishikawa *et al.* in 2007. It is possible during the reflowing process or at the higher working temperatures of these alloys that the interior structure can change and that the physical properties of the material can be altered with age [44]. As the solder is heated to high temperatures, recrystallization can occur, wherein new grains will nucleate and grow, and will take the place of the smaller, disconnected grains. This leads to an increase in ductility of the material, but at a loss of strength and the hardness associated with it, and can be detrimental to the solder's performance later [44]. Additionally, the size of the IMC can grow during this period as well as during normal operations, as shown in **Figure 11**, and can take on a thickness similar to the IMC formed by other alloys.

Figure 11: Change in IMC thickness of Sn-Ag solder on copper substrate after 6 weeks [44]

The growth of the IMC can also pose an issue to the strength of the connection, as it is traditionally more brittle than the metal that surrounds it and thus larger IMC layers can lead to a greater possible number of crack nucleation sites. Nishikawa found that the growth of the IMC is not limitless, however, and will peak after enough time has passed [44].

As electronics have become smaller, so too have the solder connections that bind them. The use of Ball Grid Arrays (BGAs) can help to accommodate this. However, it is of great interest to many researchers to what limit this reduction is due, based on the reduced contact size causing a reduction in overall robustness of the system [14]. This decrease in size can also yield higher current densities, returning then, to the possible problem of electromigration mentioned above. One must then also anticipate changes to experimental results of these smaller systems based upon the age of the solder connections [23, 42, 44]. An example method of accelerated aging being used to test solder was performed by Raiser *et al.* in 2005, where the solder is aged at higher temperatures in oil baths to create simulated older joints for testing. Other researchers have also used dry ovens to achieve similar results [44]. These tests are then often performed shortly after the solder has originally been placed, as well as throughout the simulated lifetime of the connection.

Building on the types of equipment usage expected of soldered connects, it is also important to experimentally study the behavior of solders under impact loading conditions. This is due to the fact that many electronics have the possibility of experiencing multiple impacts throughout their usage lifetime and this is one of the leading causes of failure of hand-held electronic devices [15]. To simulate this type of abuse, ball shear and impact tests have been developed [15, 42]. These tests can be either direct solder shearing tests, or an impact to the components or devices. In **Figure 12** is an example of a direct impact setup as performed by Ou *et al.* in 2005.

Figure 12: Left: Full impact testing assembly, Right: Diagram of impact test [15]

Ou *et al.* used the justification for this test stating that solder ball shearing and pulling tests could not easily reproduce the jolt caused in accidental dropping of a device. One key conclusion from this work would at first appear counter to others: the impact toughness of the solders increased with age. This is then explained due to the softening of the solder over time and the increased size of the IMC, allowing the solder bumps to perform better than when they were first formed.

In addition to simulating the varying real-world usages of soldered connections between multiple components, as the tests performed using drop-impact assemblies do, it is also important to fully understand the strength and behavior of the solder joint connections under applied load conditions without additional components attached. For this, numerous pull tests have been developed. However this work will focus mainly on the Hot Bump and Cold Bump Pull tests, (HBP, CBP), where solder bumps that have been connected to a substrate are pulled off vertically from the substrate. These testing methods have been widely used with a large number of solder and substrate materials [11, 22, 23 37, 44, 45]. The HBP, shown in **Figure 13**, is a

method in which a hot pin is forced into the solidified solder bulk, causing the solder to become molten at the point of contact, the system is then allowed to cool, and finally the pin is pulled upward, causing the soldered connection to break away from the substrate.

Figure 13: Hot Bump Pull (HBP) testing diagram [45]

While this testing method has been found to be effective, there are concerns with its accuracy [45, 44]. The main reasons for this are the recrystallization that occurs within the solder when the pin is applied, possible changes to the chemical composition of the solder from molecular exchange with the pin, and the formation of the IMC between the pin and the solder. It is also extremely important to clarify the anticipated results of these pull-off tests; using the work of Darveax and others, Zaal states that it should be possible to create one hundred percent brittle failure of the solder. This is due to the condition, where under lower strain rates the solder will fail in a ductile manner in the bulk of the body, but under high rates of strain the junction will fail in a brittle manner at the IMC. An example of this transition of the tensile strength and failure modes can be seen in **Figure 14**.

Figure 14: Solder tensile strength and ductility changing with strain rates [20]

In their study, Zaal *et al.* and others have sought to validate the results of their work by demonstrating that the solder bumps would fail in a ductile manner when pulled at lower strain rates, and would fail in a brittle manner at the IMC with higher strain rates. To do so, values for the system extension rates were used based on the JEDEC standard, which is self-described to be a 'low speed testing procedure', with values up to 0.3 millimeters per second. Thus by beginning with a low extension rate and increasing towards the 0.3 millimeters per second limit, these studies were able to transition from ductile failure of the solder bulk to failure of the IMC. In this way, it was stated that a bias in the testing procedure could be identified, and if a solder bump could fail both in a ductile and brittle manner, that the test itself was not impacting the mode of failure. Examples of the differences between these two failure modes are shown in **Figure 15**.

Figure 15: Examples of ductile and brittle solder failures [22]

To avoid many of the complications caused from using HBP, many researchers have instead opted to use the Cold Bump Pull (CBP) method, as shown in **Figure 16**. In the CBP method the solder bump is instead gripped by a mechanical tweezing system, squeezed to achieve a mechanical grip, and then forcibly removed. This method has also been used extensively with relatively consistent results [20, 23, 45].

Figure 16: Cold Bump Pull testing diagram [45]

One of the key issues with the CBP testing method however, as discussed by Zaal *et al.* in 2009, is that a number of other variables arise from the use of tweezers to test solder [20]. The added variables pertain to the application of force from the

tweezers. The closing speed, pressure, jaw size, and jaw height relative to the PCB and center of the solder all pose significant challenges in achieving reliable and repeatable results. Both Zaal and Gerbracht discuss this method at length, however the JEDEC B115A standard which is used to control these tests is relatively limited in these regards [13, 20, 21]. Zaal then performed a number of experiments to determine the effect of jaw closing speeds, pressures and biases caused from the use of this system. As **Figure 17** illustrates, the application of the tweezers causes a distortion of the solder bump in order to achieve a mechanical grip of the solder. This distortion, driven by the closing of the jaws, can happen at speeds exceeding 25 ms closing time and can cause strain rates of 10^{-1} s [20].

Figure 17: Distortion of solder bump due to jaw closing for CBP testing [20]

As mentioned earlier, the distortion of the solder bump can create cracks within the solder, which can then cause the solder to bias brittle failure during testing. This has a direct impact on the value of the results that are gained from the experiments, and means that the values of the test can be impacted before the experiments have even begun. This pre-test impact of results is the same type of issue that is a complaint of the HBP. For this reason, Zaal *et al.* sought to experimentally test the application and amount of pressure of the tweezers, but these results would be

specific to the solder type tested, as well as the tweezers, substrate, and testing equipment used. Zaal *et al.* were attempting to produce results that had a 100% brittle failure at higher strain rates, and a 100% ductile failure at lower strain rates, as to comply with the work of Darveaux *et al.* in 1995, and were able to do so. However, this required numerous experiments requiring a trial-and-error approach to all variables.

CHAPTER 3

METHODOLOGY

3.1 Introduction to a New Solder Testing Methodology

Due to the increasing number of lead-free alloys that manufacturers and researchers have access to while working with solders, a standardized, simple, versatile and universal testing method for evaluating the joint strength between solders and printed circuit boards (PCBs) is developed in this research. To-date, numerous sources have sought to classify solder alloys with existing testing methods, as well as to compare testing methods using various solder alloys [4-11, 13, 15, 16, 19, 20]. One of the main issues with these current testing methods is the need for specific manufacturers' equipment or a large number of test-specific independent variables. These independent variables include, but are not limited to, the physical properties of the tweezers or hot metal pin, or other test-specific peripheral equipment being used, and must first be addressed before testing and analysis of the solders can begin. It was the goal of this research to produce a direct solder joint-strength testing method that does not require customization for different solder types, does not create a bias towards a specific failure mode due to the method of testing, requires no brand-specific machinery, requires no specific preparation of the PCB surface, and works to eliminate the variables produced in other testing methods that one must first "optimize" through trial-and-error before beginning testing.

In order to accomplish this goal, an examination of the current testing methods and standards was conducted in the literature review. These include such methods as

shearing tests, the Hot Bump Pull (HBP) and Cold Bump Pull (CBP) methods, as well as indirect tensile methods like the JEITA EIAJ ED-4701, all shown in **Figure 18**.

Figure 18: (A) Shearing Test [15], (B) Hot Bump Pull [45], (C) Cold Bump Pull [45]

Examining these current testing methods led to the generation of a list of variables that each method would need to establish as a baseline before the results of one research group with a given alloy could be compared to the results for different alloys from other research groups. For the HBP method, for example, these variables include the pin size, composition, temperature and depth-of-pin penetration; for the

CBP method one must consider jaw size, clamping speed, force and depth, jaw height and pulling speed. It was the aim of the research described in this work to combine the processes of these various testing methods to eliminate all trial-and-error, as well as to remove the failure mode bias that many testing methods can produce when performed incorrectly [20, 21].

In order to achieve these aims, a combination of the Hot Bump Pull and Cold Bump Pull methods was developed. This new method, illustrated in **Figure 19**, uses an external solder gripping system which was inspired by the CBP method, but in place of using stiff mechanical jaws to deform the bottom curvature of the solder bumps to achieve a mechanical grip upon application of an upward force, grip on the bump is achieved by surrounding the bump with a stiff epoxy, creating a uniform traction. The epoxy envelopes the entire bottom curvature of the bump without causing any plastic deformation to the sample prior to testing. A load is then applied through a pin located above the solder bump as one would find with the HBP. To achieve this, a stainless steel screw is inserted head first into the epoxy directly above the solder bump during the epoxy curing process to function as the pin. Once the system has cured, the screw is installed in a tensile loading machine and is pulled away from the PCB upon which the solder is connected. The tension applied to the stainless steel screw is transferred into the epoxy, which then applies uniform tractions to the entire solder bump.

Figure 19: (A) Isotraction Bump Pull (IBP) assembly, (B) IBP testing

This method, referred to hereafter as the Isotraction Bump Pull Method, or IBP, removes the variables pertaining to the gripping process of the CBP, namely the jaw size, jaw clamping depth, clamping speed and clamping pressure, as well as the introduction of a new Intermetallic Compound (IMC) layer produced in the solder with a hot pin via the HBP method. In order to use this new IBP method, the following steps were taken: solder joints were made on untreated pieces of PCB that were as delivered from the manufacturer, the solder was encapsulated using the casting method mentioned above, then the samples underwent tensile loading, where the applied load and extension were monitored and recorded. Following this, the results from these tensile tests were analyzed, and lastly, a group of untested samples were cut in half and examined using optical microscopy to observe the internal structure of the bumps. This final step allowed for an examination of the alloy grain structure, the grain boundary curvatures within the bump, and the evaluation of the IMC layer, which was formed between the alloy and PCB substrate surface. This is a key advantage of the testing method, as the IBP does not cause deformation or recrystallization of the solder bump prior to testing, unlike the HBP and CBP methods.

The primary advantage that the IBP process yields is therefore a more accurate representation of the bump microstructure precisely as it was created and tested. Conversely, the CBP and HBP methods require microscopy after bump generation, as well as after the test-specific processes were conducted, to gain a full understanding of the bump characteristics prior to, and during testing. Additionally, the IBP method does not cause a change in the bumps between the stages of generation and testing that could yield a bias in the tests. Examples of these biases in other popular testing methods are the micro-cracks which can form within the bump during CBP prior to testing, creating a bias towards brittle failure before testing begins, and with the system recrystallization and the generation of a second IMC layer that must be formed, and acts as a site of failure in the HBP method.

3.1.1 Development of the Isotraction Bump Pull (IBP) Solder Testing Method

Once the concept for a new testing method had been identified, it was important to determine the number of variables present, and thus the appropriate number of experiments that must be performed to determine the behavior of the test itself, as well as various lead-free solders that could be examined using this method. To do this analysis, the Buckingham Pi Theorem was used [46]. This is a method that creates dimensionless groups of the variables of a system that allow for comparison and evaluation of changing variables and their relative importance in affecting an outcome. Five key parameters were identified for these experiments and are listed in Table 1 as either a variable, controlled variable or fixed parameter. These parameters are then combined into dimensionless groups based on the base units that they contain. For this

study the base units of F, L and t were used for force, length and time, respectively. These base units are generic units, and take the place of more specific terms, thus acceleration written as ft/s^2 or m/s^2 would both be distilled into L/t^2 . In order to determine the number of Pi groups to derive from this list, the following equation is used:

$$p = n - k \quad \text{Equation 1}$$

Where p is the number of dimensionless groups, n is the number of dimensional parameters, and k is the number of physical dimensions, force (F), length (L) and time (t). Given as there are five parameters and three physical dimensions for the pull-off tests, there are then two Pi groups that are formed, shown below.

Table 1: Variables for The IBP Testing Method

Symbol	Parameter Description	Units	Type
F_P	Peak Load	F	Variable
V_P	Pull Speed	L/t	Controlled Variable
E	Young's Modulus	FL^2	Fixed Parameter
A_{IMC}	IMC Area	L^2	Fixed Parameter
t	Time to failure	t	Variable

$$\Pi 1 = \frac{V_P^2 * t^2}{A_{IMC}}, \quad \Pi 2 = \frac{F_P * A_{IMC}}{E}$$

In addition to the dimensionless groups formed above for the tensile experiments, the same process was conducted for the interior structure of the solder bumps which was to be evaluated in parallel with the tensile testing.

Table 2: Parameters for the Bump Microscopy

Symbol	Parameter Description	Units	Type
R_a	Surface Roughness	L	Fixed Parameter
Θ	Contact Angle	--	Variable
K_o	Curvature	L^{-1}	Variable
A_G	Grain Size (area)	L^2	Variable
K_i	Inhomogeneity Curvature	L^{-1}	Variable
I	IMC Layer Thickness	L	Variable

$$\Pi_3 = \frac{R_a}{I} , \quad \Pi_4 = \frac{A_G}{R_a * I} , \quad \Pi_5 = I * K_i$$

These Pi groups were used to determine that all variables were tested across their entire range in this study, and that none of the parameters were accounted for more than once. Due to the fact however, that the only controlled variable in this study was the tensile pulling speed and that this was dictated by the CBP standard, changing of this value was not required. Thus, instead of needing to conduct multiple experiments with numerous alloys, as one must do with other bump testing methods, there are no values to vary during these experiments, and thus numerous alloys can be used to determine the validity of this experimental method while simultaneously creating usable data to compare from alloy to alloy.

3.2 Solder Bump Generation

While many possible methods for the generation of solder bumps exist, for instance the use of solder pastes and resists, hand soldering, soldering masks and large scale industrial soldering methods; a solder bump-on-demand generator was used for this work. The system was fabricated based on the designs of numerous researchers,

such as Amirzadeh, Cheng, Chandra, Jivraj and Li, with slight alterations [47-51]. At its core, the system uses the application of positive pressure pulses of nitrogen gas to drive small volumes of molten material from a crucible onto a substrate positioned below. A photo of this system can be seen in **Figure 20: Desktop Solder Bump-On-Demand Generator Setup**. One of the key advantages of this method over the others mentioned above is that it allows for a higher degree of accuracy than hand-soldering, but does not require the same level of peripheral equipment that other large scale methods do. For example, the crucible used for this work was found to produce samples with an accuracy of ± 20 mg, or 13% of the 150 mg average mass, but was self-contained and required no large-scale industrial equipment to operate.

Figure 20: Desktop Solder Bump-On-Demand Generator Setup

The crucible for the generator was fabricated from a hollow, three inch diameter, four inch long stainless steel cylinder with an internal diameter of three-quarters of an inch. It was heated with two 200-Watt cartridge heaters (McMaster Carr, Part# 3618K403) inserted vertically into the cylinder walls on opposing sides. A synthetic sapphire orifice with a hole diameter of 0.04 inches, shown below, was imbedded into a stainless steel nozzle and is inserted into a circular plate at the bottom of the crucible, and the cavity of the crucible was filled with the alloy to be tested. A major design change of the crucible used for this research versus numerous other on-demand-generators was the use of the pre-fabricated nozzle assemblies in which the synthetic sapphire, in red on the expanded view of **Figure 21**, was installed into a stainless steel fixture by the manufacturer (Diamond Technology Innovations, Olympia, WA). This was done in an attempt to minimize the chance of the nozzles breaking during installation and change-over. Direct manual insertion of the nozzles without a fixture into the bottom of the crucible was believed to be a possible source of system failure, should the sapphire crack.

Figure 21: Diagram of Solder Bump-on-Demand Generator and Nozzle Holder Assembly

In addition to the main body and bottom plate, a second circular plate was attached at the top of the crucible main body and a brass quarter-inch plumbing t-fitting was attached to a through-hole in the center. This t-fitting was used to supply nitrogen gas into the cavity of the crucible above the molten alloy and create high pressure pulses inside the system, as well as to allow for the gas to be subsequently vented after each bump had been generated. Once the system had been assembled, the crucible was encased in a six-inch ring of mineral wool insulation inside a steel shell and heated to a temperature of 340 °C using cartridge heaters (McMaster Carr, Part# 3618K403), a K-type thermocouple (McMaster Carr, Part# 9251T93) on the exterior surface of the crucible wall and a temperature controller (Omron, E5EC, Japan). An on/off control sequence was used for this control, and allowed the temperature of the crucible to fluctuate by $\pm 5^{\circ}\text{C}$. The body of the crucible was supported on a steel plate, which was in turn supported by a set of four threaded rods and could be leveled above the surface which held the PCB substrate.

The process under which solder bumps were generated is shown in **Figure 22**. Under normal operating conditions, the solder was held in place in the body of the crucible due to capillary action. When a signal was sent from the control system, a pulse of nitrogen gas entered the crucible; this increased pressure would cause a small volume of the molten solder to descend through a 0.04" diameter hole in the sapphire nozzle, down and away from the main body of the solder towards the PCB substrate positioned below the system. The nitrogen was then vented from the top of the system into the environment. In **Figure 22**, panels c and d, this venting would then cause a pressure drop inside the crucible and the main volume of the descending solder to

return towards the bulk. During this return process, a small volume of the solder would destabilize from the returning volume and fall away, assuming a nearly spherical form. This volume of molten solder then impacted the PCB below the crucible and a solder-PCB contact joint was formed.

Figure 22: Solder bump generation process. (A) Normal operating condition, (B) Introduction of high pressure nitrogen gas forming downward conical shape, (C) Venting of nitrogen gas causing solder to return towards crucible and tip destabilization, (D) Solder separation and bump free-fall

The size of the solder bumps was controlled by changing the size of the nozzle used, as well as by changing the magnitude and duration of the pressure pulse used to generate the bumps. This yielded a highly repeatable process in which the volume of the solder that impacted the PCB could be increased or decreased, per the requirements of the system, and required no physical adjustments of the system during each production run. The pressure pulses used in this study had a magnitude of 10 psi and were sent in 160 ms pulses for each of the three lead-free solder alloys, $\text{Sn}_{96.5}\text{Ag}_{3.5}$, $\text{Sn}_{99.3}\text{Cu}_{0.7}$, and $\text{Sn}_{96.5}\text{Ag}_{3.0}\text{Cu}_{0.5}$, used in the experiments. The pressure pulses were controlled by the use of a physical valve system and by sending a five volt

signal to a solenoid valve (Clippard, model 2013, Cincinnati, OH), directly upstream of the t-junction, via a custom LabView (LabView, Austin, TX) control program with an Arduino Uno (Arduino, Italy) input/output (I/O). Examples of solder bumps at the completion of this process are seen in **Figure 23**.

Figure 23: Examples of (A) SnAg, (B) SAC 305, (C) SnCu solder bumps on FR4 PCB

Additionally, the substrate that was used in this study was a commonly used and available material referred to as FR-4 PBC (McMaster Carr, Part# 8521K35), composed of a multilayer fiberglass wafer with a single copper foil top surface. The substrate pieces were cut into one-inch by one-inch squares using a sheet metal shear, and were used as-manufactured. There was no cleaning process, deoxidizing or fluxing process used, and each substrate piece was processed by hand. To ensure proper soldering, the substrates were placed onto a hotplate (Fisher Scientific Isotemp, Pittsburg, PA) at a temperature of 200°C directly before testing, at a distance one-half inch below the crucible nozzle. During this process, the substrate pieces would reach a temperature of approximately 180°C before the solder impacted them.

3.3 Solder Bump-Epoxy Encapsulation

Once the solder bump samples were generated, they were encapsulated in a steel reinforced epoxy (JB Weld, Sulphur Springs, TX). This was accomplished using two custom-made casting mold assemblies, shown in **Figures 24 and 25**, composed of aluminum centering base plates, split Teflon (PTFE) molding cups, PVC support washers, aluminum lower pressure plates and a top pressure plate. Each casting mold assembly was capable of producing six samples at a time, thus twelve samples could be produced simultaneously with the two assemblies.

Figure 24: Assembled Solder Bump Casting Mold

Figure 25: Disassembled Solder Bump Casting Mold

Teflon was selected for the mold forms due to its long chain non-polar molecular structure, to which the epoxy will not readily bond [54]. Additionally, to ensure that the epoxy did not bond to the copper-faced PCB, a Teflon spray was applied to the surface of the PCB after the bump had been deposited. This was done using a thin applicator dipped into the Teflon spray and did not come into contact with the solder bump. The split casting molds were fabricated in-house from a one-inch outer diameter and half inch inner diameter Teflon tubing. Twelve total one-inch tall molds were produced, which were subsequently cut in half vertically; this allowed for the mold to be split apart and removed easily after the epoxy had cured.

To create the pull-off samples, the solder samples were held in place using an aluminum base plate with milled reliefs for one inch squares of the PCB. The Teflon molds were then placed surrounding each sample, and two PVC washer plates were used to hold the molds in place. Epoxy was piped into each mold prior to the attachment of a top plate, through the use of a heavy duty plastic food storage bag, similar to an icing bag. Lastly, the systems were placed under compression using two-inch long stainless steel screws passing through the aluminum base plates up through polycarbonate top plates. In addition to the six holes used to clamp them in place, these top plates had holes drilled at the corresponding centers of each of the six molds for that assembly, and allowed for the stainless steel screws that functioned as the pull-off pins to be passed through them and held in place during the curing process. Additionally, the top plates were used to ensure that the Teflon molds were held closed during the curing process. The top plate was then bolted into place and the

epoxy was allowed to cure for eighteen hours, per the epoxy manufacturer's recommendation.

Once the epoxy had fully cured, the molds were disassembled and the samples removed. Flashing from the epoxy at the seam of the Teflon molds was removed and all samples were subsequently labeled using the format: Alloy-Production Run, Mold, Position. As there were three lead-free solder alloys tested, SnAg, SAC 305 and SnCu, and an example of this notation would be SnAg 216. All of the SnCu samples that were tested in this study can be seen in **Figure 26**. This system was used to ensure that in addition to the ability to gather bulk information on the performance of a given alloy in this test, that one could ensure that the solder bump-epoxy assembly fabrication process produced consistent results in each of the twelve production locations and that no bias was being created in the tests due to fabrication errors.

Figure 26: SnCu samples encapsulated in epoxy, ready for tensile testing

3.4 Tensile Testing

3.4.1 Introduction to Tensile Testing with the IBP Method

Once the lead-free solder samples had been produced and encapsulated in epoxy, they could then undergo tensile testing. This was done using an Instron 3345 Single Column universal testing machine. However, any high-accuracy tensile testing system could be used. Due to the IBP method functioning as a hybrid of the HBP and CBP solder testing methods, it was a goal of this study to develop a method that could conform to the mechanical limitations of the machines used for these tests, thus the tests were performed at a constant displacement rate of 0.3 mm/s, per the recommendations of the CBP method.

3.4.2 Tensile Testing of IBP Samples

In order to apply load to the samples tested in this study, custom load fixtures were designed and fabricated in-house for use in an Instron universal vertical testing machine (Instron, model 3345, Norwood, MA). A diagram and image of this system can be seen in **Figure 27**, and is composed of the top collar, fixture, top fixture locking nut, top pin, top plate, bottom plate, bottom fixture, bottom locking nut and bottom pin.

Figure 27: Tensile Test Fixture Assembly

The bottom of the system was fixed in place on the Instron machine and the top fixture was pulled upwards during testing. In order to accomplish this, the stainless steel screw embedded in the epoxy was threaded into the top fixture. The top assembly was then lowered into position with the bottom fixture and a square steel plate, referred to as the top plate was bolted into place on the bottom plate, which was in turn fixed to the bottom of the Instron. A hole was drilled into the center of the top plate which allowed for the epoxy to pass through it, but held the PCB in place while the stainless steel screw was pulled upwards during testing.

To perform these tests, each sample was individually loaded into the fixture system, then positioned and clamped in place. The results were monitored using the Instron Merlin computer software (Instron, Norwood, MA), and the system displacement and load were monitored and recorded for future analysis. Twenty-four

samples of both SnAg and SnCu were tested in this manner, as well as thirty-six SAC 305 samples. The reason for the sample size increase for SAC 305 was due to difficulty in achieving consistent results, and so additional tests were conducted to produce a larger set of viable data. Once each lead-free solder alloy had been tested, the results were then imported individually into a Microsoft Excel file, and then processed simultaneously with a custom MATLAB (Mathworks, Inc., Natick, MA) script. In addition to interpretation and comparison of the pull-off test data, this script was used to calculate the Young's Modulus of the alloys, ensure that unsuccessful tests were identified, and was used for the statistical analysis that followed. An additional MATLAB script was created to determine the area of the IMC of each sample after testing and was used to convert the measured loads on the system in pound force to the stress values of lb_f/in^2 , knowing the areas.

3.4.2 Accuracy of the Load Results at Low Loads

The Instron 3345 used in this study is rated to have a load accuracy of $\pm 0.5\%$ down to one-one hundredth of the load cell capacity. For these experiments a 5000 newton (N) load cell was used, which would then hold that level of accuracy above a value of 50N, or 11.24 lb_f . Due to the process of the experiments in which load was increased through the specimen from a beginning value of zero through the critical load of the solder-PCB contact joints, it was then important to determine the accuracy of the Instron at low loads with the custom jaw setup used. This was accomplished using the setup shown in **Figure 28**.

Figure 28: Low Load Accuracy Testing Assembly. Weights are added to the custom fixture that was used in all pull-off tests.

The results of these tests showed that at loads less than 1 lb_f with the fixture system used for the entire study, that the error ranged from 0.7% to 0.9 %, and was in excess of the 0.5%, but for loads above 1.1 lb_f the errors of the results from the Instron machine were less than the 0.5% rating. Due to this behavior, the results from the experiments that follow do not use loads of less than 1.1 lb_f for the statistical analysis performed in Chapter 4.

In addition to this evaluation of the load cell accuracy, if the results of raw data are considered, one can see in **Figure 29** that at lower loads the system produces data which can be considered to be inaccurate. During standard testing, there is a period of time in which the system is allowed to ascend freely. This is made possible by the

oversized gap between the two steel plates that are used to hold the PCB in place during testing and was necessary to the assembly to ensure that the system was not under tension prior to the controlled start of the experiment. After the experiment had started and the PCB ascended and eventually made contact, the load perceived by the load cell underwent a sudden rise, despite experiencing a constant system displacement rate. After the completion of this low load evaluation study, values that were below the threshold of 1.1 lb_f were removed to normalize the data and remove the variance of distance covered before each individual PCB made contact with the top plate. The displacement for all systems was then normalized at a value of zero when each system rose above the 1.1 lb_f threshold.

Figure 29: Shifting of Load Displacement, (A) Comparison of Raw and Shifted Data, (B) Example of Low Load Behavior

3.4.4 Identification of Different Result Types

There were two types of test results from the pull-off process described above: unsuccessful tests due to epoxy-solder interface failure and successful pull-off tests. These two types of test results can be easily identified from their plots or physical differences, shown in **Figure 30**, where the data in blue is a SnAg solder bump that experienced a failure of the epoxy-solder interface, and the green line represents a successful test of a SnCu sample.

Figure 30: Example plots of a successful pull-off test and an unsuccessful pull-off test

Figure 31: Examples of pull-off test physical results. Left: Unsuccessful, Right: Successful Test

The distinction between these results can be described as the following: unsuccessful tests were those in which the epoxy has failed due to plastic deformation at the epoxy-solder interface during testing and the bumps were not removed from the PCB as a result. The successful tests were all of those in which the bumps separated from the PCB with a brittle failure of the IMC. Due to the relatively high speed at which these tests were performed, per the CBP method guidelines, there were no ductile failures of the solder bumps. These types of tests would have resulted in failure of the solder bulk during testing, rather than a failure of the IMC.

3.4.5 Identification of the Intermetallic Compound (IMC) Area

Upon the completion of the pull-off tensile tests, the tensile loads in pound-force applied to all samples were converted to stress values of pound-force per square-inch, or psi based on the area of the contact. This was done to allow for comparisons to

solder alloy data from other sources using conventional pull-off testing methods, as well as to allow for a normalization of the results for all solder bumps tested in this study. This was done by using the cross-sectional area of the IMC layer, through which all loads were applied and where fracture occurred. **Figure 32** shows the newly exposed faces created by the fracture of the sample, as an example of a solder bump post-tensile test.

Figure 32: Post Pull-Off Test Example

In order to accurately analyze the size of the IMC for each solder bump tested, a single photo of the full grouping of PCB squares was taken for each alloy. These photos, like the one shown in **Figure 33**, captured each square with the same scale. Following this, each PCB square was isolated and analyzed in MATLAB using a custom image processing script.

Figure 33: SAC 305 PCB Samples - Post Pull-Off Testing

In order to analyze the size of each IMC area, the photos of each sample's PCB were processed individually. Shown in **Figure 34**, each PCB square was converted to a grey-scale image, and the contrast was increased to make identification of the IMC from the copper substrate easier for the program to distinguish. The image was converted to black and white, and the "islands" inside the IMC area were removed and the centroid of the IMC was identified with a red dot. Once these steps had been taken, the size of the IMC was stored by the program as a number of pixels. This pixel count was then converted to a square area using the scale in the original PCB grouping

image and a final area in square inches was calculated. While it would have been possible to assess the size of the IMCs using the bottom face of the solder bumps, the high level of contrast of the IMC and copper substrate yielded a more repeatable process than using the solder face. The calculated area of each sample's IMC was then used to calculate the stress each system was exposed to during testing from the measured forces.

Figure 34: Processing of SAC 305, Sample 216 IMC; (A) Original Grey-Scale Image, (B) High Contrast Image, (C) Color Inversion, (D) IMC Identification and Analysis

3.5 Microscopy

3.5.1 Optical Microscopy

In addition to the tensile tests performed on the solder bump samples, five samples of each alloy were also examined using optical microscopy. This was accomplished through the use of a diamond embedded wafering blade on a low-speed

specimen saw (Buehler 11-1180, Road Lake Bluff, Illinois) to vertically cut the specimens in half. Once the samples were bisected, they were mounted into clear epoxy pucks, like the one shown in **Figure 35**, and polished to remove the tooling marks from the bisection process. This was accomplished using a rotary polishing wheel and a wet sanding process with a progression from 400 grit sanding paper to 1200 grit paper, then 3.0 μm and finally 0.5 μm aluminum oxide polishing compounds on rotating felt pads. The samples were then chemically etched using an etching solution of 2% NaCl 5% HCl, 93% Methanol for thirty seconds each, per the notation of the 8th Edition of the Metals Handbook [55]. Once this process had been completed, the samples were analyzed using a lower power (Leica, Stereo Zoom 4, Wetzlar, Germany) and high power optical microscope (Nikon, Optihot-100, Tokyo, Japan).

Figure 35: Progression of Sample Preparation (A) Solder bump, (B) Bisected bump, (C) Five Samples Mounted in Epoxy

The purpose of this analysis was to determine the number of grains per solder sample, the size of the grains, the solder contact angle with the PCB and the characteristics of the IMC at the joint contact.

3.5.2 Scanning Electron Microscopy

In addition to optical microscopy, a scanning electron microscope was used to take high magnification images of the post-fracture surfaces and to perform a process called Energy-Dispersive X-Ray Spectrometry, or EDS. Samples were mounted on a sample holder, as shown in **Figure 36**, and examined using a JEOL JSM-5900LV Scanning Electron Microscope (JEOL USA Inc, Peabody, MA). This examination allowed for high quality secondary and back scatter electron imagery (SEI and BEI) of both newly created surfaces for examples of each of the three alloys, shown in **Figure 37**.

Figure 36: Sample Holder with Solder Bump Samples for SEM Analysis

Figure 37: Examples of SEM Imagery (A) back scatter electron **BEI**; (B) secondary scatter electron **SEI**

Secondary Electron Imagery gives information pertaining to the surface topography and morphology, where more electrons will escape from a higher surface point than a lower surface point, and yields a very clear image of the surface properties of the subject, while backscattered images are grey scale images in which darker colors represent elements with a higher relative atomic number and lighter colored sections represent lower atomic number, thus the image gives a compositional depiction of the subject. By examining both of these types of images, it is possible to tell where the peaks and valleys of the material are, as well as their relative composition.

More importantly to this aspect of the study however, this process was performed to confirm the assumption that the fracture of these systems occurred through the IMC and not at an interface between the IMC and the solder. To evaluate the results of the EDS, one would take each newly exposed face, position multiple points of evaluation along said face, and examine the EDS spectrum plot that was then produced. This plot shows the number of hits that are produced as electrons are emitted at different energy

levels. Each element has different characteristics under this process, and so the presence of individual elements and their relative quantities in an area may be identified. An example of this process can be seen in **Figure 38**.

Figure 38: Example of EDS Process (A) $\text{Sn}_{99.3}\text{Cu}_{0.7}$ PCB Face (B) Bump Face (C) EDS Summary

CHAPTER 4

FINDINGS

4.1 Tensile Tests

During the course of this study, three lead-free solders were tested using the IBP testing method. These alloys, $\text{Sn}_{96.5}\text{Ag}_{3.5}$, $\text{Sn}_{99.3}\text{Cu}_{0.7}$, and $\text{Sn}_{96.5}\text{Ag}_{3.0}\text{Cu}_{0.5}$, referred to as SnAg, SnCu as SAC305, were tested as solder bumps on a consumer-available FR4 PCB substrate, and were soldered using a solder bump-on-demand generator fabricated in-house. The bumps underwent a novel tensile testing procedure to evaluate both the viability of this new testing method, as well as to compare the results of each solder to the others. The tests were performed in conformance with the testing parameters of the CBP method and produced brittle fractures of the IMC, which had been generated during the soldering process at the interface of the solder and substrate.

Twenty four samples each of SnAg and SnCu were tested in this study, as well as thirty six samples of SAC305. Due to the adherence to the testing parameters of the CBP method, all successful tests that were performed in this study generated brittle failure of the IMC. The distinction between 'successful' and 'unsuccessful' tests was as follows: all successful tests were those which produced a failure of the soldered joint; unsuccessful tests were those that did not produce a failure of the joint, and could not be tested further. The only circumstance under which this would occur was when the epoxy used to encapsulate the bumps would plastically deform to the point that the solder would no longer be supported and would slip from its hold. For the 84 tests conducted in this study, unsuccessful tests occurred a total of 5 times, accounting for

5.9% of the total tests. Of the SnAg samples tested, this occurred for 1 test, or 4.2% of the sample group, for SAC305, 1 of the 36, or 2.8% of the set was not successfully tested. Lastly, there were 3 unsuccessful for SnCu, which represents 12.5% of the final alloy set. Through examination of the ring formed in epoxy cylinders used to support the solder during testing, it was noted that each of the unsuccessfully tested samples contained trapped air pockets at the interface between the solder and the epoxy which functioned as a void in the supporting ring. Refer to **Figure 39** for greater detail. It is proposed that these voids decreased the overall strength of the epoxy to the extent that it could not perform its task as desired. All unsuccessfully tested samples contained at least one such void. Additionally it is proposed that unsuccessful tests occurred more often for SnCu than the other two alloys due to the higher loads necessary for failure that this alloy required, thus exposing these systems to higher peak stress values.

Figure 39: Example of an unsuccessfully tested sample (A) Profile View (B) Surface View

Of the successful tests, there were then three sub-sections of the tested population. Low peak value samples, high peak value samples, and testing samples which produced bond failure between the wafer substrate and the copper foil of the FR4 PCB. While it was possible to create a threshold to separate the first two sub-

groups of this set to decrease the spread in the final testing values, this was seen as an evaluation of the soldering process rather than the solders or testing methods, which were the main focus of this study. Therefore a threshold value was not established. For the third subset of the successfully tested sample group, those which caused pad failure of the PCB, the data was still used for comparison of the average peak stress to failure due to the fact that if a soldered contact fails through the IMC or at the PCB, either circumstance will result in a failure of the system. If the system transitions from a failure at the IMC to a failure instead at the PCB, the new testing method is still valid. However, it shows the mechanical strength of the solder and IMC no longer are the weak links in the system chain, yet the testing method itself is still valid. For these specific tests, if the area of the IMC was easily identified for the stress calculations, an average value for the IMC area for the entire alloy-specific data set was used.

At the conclusion of the testing sequence, a plot containing all of the test results for each alloy was produced, like the one shown in **Figure 40 A**. In this plot, one can see both successful and unsuccessful tests that were produced from this sample set. A further clarification of the distinct form of these plots can be seen in **Figure 40 B**. One should note in these plots that there are distinct first and second peak values of these tests, as is pointed out in **Figure 40 B**. The first peak occurs due to the increasing curvature of the PCB not being matched by the matching opposing face of the epoxy which was cast upon it; as the PCB curvature increases there is a suction between the PCB and epoxy that is overcome and the sudden and sharp drop in load can be observed. A residual layer of the Teflon release agent is present between these faces and creates an airtight seal which the increasing curvature of the PCB breaks.

Unsuccessful tests, like the example in **Figure 40 B**, are easily identified by the curved shape of their testing results, which is caused by the plastic deformation of the epoxy that surrounds the lower curvature of the solder bump.

Figure 40: Example Plots of Pull-off Tests (A) All SnCu Samples, (B) Unsuccessful and Successful Test

At the conclusion of these tensile tests for the three alloys in question, a statistical analysis was performed. This analysis was used to compare the various solders to one another. Due to the fact that the peak load values were converted to stress values, this

method would ideally be used in the future to compare any soldered joint for any given alloy to those of known values of other solders, regardless of PCB pad size. This analysis is represented by typical box and whisker plots generated in **Figure 41**. The mean peak stress value for each solder are shown at roughly the center of each box, with the standard deviation illustrated with the vertical whisker lines which terminate at their maximum and minimum values with horizontal lines, and for each solder the first and third quartile of the peak results are represented by the bottom and top horizontal bars of each box. The first quartile represent the median values of the lower 50% of the data set, and the third quartile represent the median value of the upper 50% of the data set. It is through this graphical representation that one may identify the true behavior of the solders when compared to one another.

Figure 41: Box Plots of the Peak Tensile Stress Values

To this end, the mean peak stress values for the three solders were 1948.63 psi, 1097.28 psi and 2769.73 psi for the SnAg, SAC305 and SnCu solders, respectively, and median peak values were 2020.52 psi, 940.57 psi, and 2781.0 psi, and all of which were in agreement with trends identified in the literature [44, 45]. The raw data for each solder was normally distributed and the mean and median values for each solder were calculated within one standard deviation of the mean of each original data set. By using the box plot to examine the median values of the data, it is clear the two bi-metallic alloys performed with superior mean peak testing values, and of those two, that SnCu was the leading alloy. In addition to the mean and median peak values for the SAC305 solder being lower than the two other solders tests, it also had the largest amount of deviation, while the SnCu solder had both the highest mean and median values and the lowest deviation.

4.2 Microscopy

4.2.1 Optical Microscopy

In conjunction with the tensile tests that were conducted for this study, five randomly selected solder bumps from each solder alloy were selected for optical microscopy. These samples were prepared using the method described in **Chapter 4**, and examples of the final results can be seen in **Figure 42**.

Figure 42: Bump Optical Microscopy For Each Solder Type at Increasing Magnification

The optical microscopy allowed for the initial identification and characterization of the IMC layer present in each bump at the interface of the joint, and for the measurement of the contact angle formed between the solder and the substrate. The IMC thickness for the samples shown in **Figure 42**, for example, varied approximately from 0 to 5 μm for SnAg, 0 to 2 μm for SAC305 and 0 to 1 μm for SnCu. The average contact angles for the bumps in this study were 149.3° , 150.8° , and 150.6° for the five selected samples each of SnAg, SAC and SnCu alloys, respectively. It was originally proposed that an increased contact angle would yield stronger adhesion to the solder bump by the epoxy, and that these values could be used to evaluate the behavior of one solder versus another. However, as the angles are so similar, no such distinction can be made.

4.2.2 Scanning Electron Microscopy (SEM)

Once the optical microscopy process had been completed, a scanning electron microscope was used for further visual and chemical analysis of the newly exposed faces created on the PCB and solder pieces of the broken test samples. Examples of the surface topography can be seen in **Figure 43**. One should note the presence of complementary patterns in these images, as the newly exposed faces of both the PCB and solder bump are the near opposite of each other.

Figure 43: Low Magnification Results of SEM Images of Newly Exposed Faces After Fracture (A) SnAg PCB Face, (B) SnAg Solder Face, (C) SAC305 PCB Face, (D) SAC305 Solder Face, (E) SnCu PCB Face, (F) SnCu Solder Face

The EDS tests that were performed using these samples were conducted using four points of reference on each newly exposed face. The results from this were then displayed in individual plots and recorded. The final results for these tests were then compared to ensure that the same elements were present on both sides of the newly exposed faces. An example of this process can be seen in **Figure 44**. Although the plots are not a perfect match for one another, the correlation between the paired points was seen to be strong enough to confirm the original assumption that the fracture occurs through the IMC layer and not at the interface of the IMC and the solder, or the interface of the IMC and the copper substrate. This strong correlation of surface chemistry was present for all three alloys tested.

Figure 44: Example of EDS Comparison (A) SnCu Exposed PCB Face, (B) SnCu Exposed Bump Face, (C) PCB Face EDS, (D) Bump Face EDS

Note, that while the IMC layer thickness is too small to be analyzed as a homogeneous Mode I failure, if a fracture analysis were pursued, it must be performed for a Mixed Mode I/II interface fracture using a complex variable method. The energy release rate may then be used to determine the magnitude of the stress intensity factor for the interface.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

A solder bump-on-demand generator was fabricated in the URI Manufacturing Laboratory, customized for this work and used successfully to generate solder bumps of three types of lead-free solder onto LR4 PCB for tensile testing.

A new method of directly tensile-testing the adhesion strength of solder bumps, the Isotraction Bump Pull (IBP), was developed and used successfully to test three solders under similar conditions to produce material-specific results. This method was shown to produce similar statistical clustering of results with relative ease, and could be adapted to numerous types of tensile testing machines from other manufacturers.

For the three solders tested in this work, SnAg, SAC305 and SnCu, The median peak stress at failure for the three solders tested were 2020.52 psi, 940.57 psi, and 2781.0 psi, and were within one standard deviation of the of all data collected for each solder.

Optical and Scanning Electron Microscopy were successfully utilized in this study to observe the interior macro and micro structure of lead-free solder bumps. Use of the SEM to perform EDS on fractured samples was also used to validate the supposition that the fracture which occurred during tensile testing, took place through the IMC layer formed.

By performing high magnification examination of the newly exposed faces after fracture on the surfaces of the PCB and solder bump, visual confirmation was made

that the fracture which occurred in this study was brittle. Additionally, by examining the results of the EDS raw data performed on both the PCB and bump faces, it was shown that the same materials were present in the same relative concentrations. Furthermore this process showed for the SnAg tests that material present in the PCB but not originally found in the solder, namely copper, could be found in fractured surface of the solder bumps, meaning that an exchange of elements had occurred and that this exchange continued in the bump direction above the point of fracture.

Lastly, while the IMC thickness is too small to be analyzed as a homogeneous Mode I failure, if a fracture analysis were pursued, it must be performed for a Mixed Mode I/II interface fracture using a complex variable method. resulting in the magnitude of the stress intensity factor for the interface. The energy release rate may then be used to determine the magnitude of the stress intensity factor for the interface.

5.2 Future Work

Moving forward with this work, there are a number of small changes that may yield improvements on the system and procedures created in this study. These changes pertain to the crucible fabrication, substrate usage, casting method and tensile testing apparatus. Additionally, an expansion of the testing procedure with additional solders would also be beneficial in demonstrating the flexibility of the testing method. Lastly, this method could be adapted for use with other adhesion testing conditions, such as the adhesion strength of concrete to rebar, and the testing of adhesives.

5.2.1 Crucible Design Changes

In order to improve the deposition of solder onto the PCB substrate, simple and effective changes to the crucible are proposed. By changing the material of the crucible itself, from stainless steel with a relatively low level of thermal conduction to more conductive aluminum body with a stainless steel internal sleeve, one may be able to more quickly heat and cool the system for filling and changing solders during testing, and ensure a more even distribution of temperature throughout the entire system. This may also allow for faster fabrication of the crucible itself as aluminum has higher machining rates than stainless steel. Additionally, by reducing the internal size of the crucible to a standard drill size, the machining process would also be accelerated as only a drilling process, with a boring process no longer required.

5.2.2 Substrate Usage Changes

In order to produce more consistent bonding of the solder to the substrate, two changes to the system are proposed. The first is the addition of flux to the soldering process. Originally flux was not used in this study to reduce the number of variables involved in the testing procedure. However, if one were seeking only to test the tensile testing method itself, flux would not increase the level of complexity of this system and may aid in producing yet more consistent results with a potentially smaller standard deviation. The second system change would be the addition of solder resists on the surface of the PCB surrounding the targeted area where the soldered joint is to be made. This may allow for more control over the bonding area and may ensure that the IMC is formed only at the area of intent.

5.2.3 Tensile Testing Apparatus

In order to minimize the degree of deflection present in the tensile testing apparatus, minor design changes are proposed to the testing apparatus. Under the current design, there is a gap of twice the PCB thickness between the bottom and top support plates of the bottom half of the custom fixture. While this design was intended to ensure that the specimens were not under tension prior to testing, this allowed for two negative effects to take place. The first was a varied period of 'float' displacement at the beginning of each test where the sample would need to rise vertically and make contact before any relative load was observed, and that the PCB was then able to flex significantly after contact was made due to the large cavity in which it was held. By making the gap between these two plates smaller it may have minimized both of these effects. Additionally, the load cell that was used was appropriate for loads up to 5000 newtons, while the greatest load in this study was less than 445N, the use of a lower maximum load cell may have eliminated the need to remove data below the 1.1 lb_f threshold discussed in Chapter 3.

5.2.4 Further Development of Casting Molds and Process

One of the greatest difficulties in this study was ensuring that the cast epoxy cylinders surrounding the solder bumps were made consistently and with as little trapped air as possible. To this end, mixing the epoxy inside of a sealed plastic bag was helpful. However further improvements are possible. Degassing the freshly poured epoxy was attempted, however, due the rising epoxy make contact with undesired locations of the mold while not removing the entirety of the trapped gasses,

this technique was not further developed. Instead, slight modifications to the casting molds themselves, as well as the casting process are proposed. By decreasing the diameter and increasing the height of the Teflon casting mold cups, there may be a smaller change of trapped air pockets around the level of the solder bumps and may allow for a greater depth of penetration of the stainless steel screw into the epoxy, yielding a lower impact per air pocket than was present under the current configuration. Additionally, where the epoxy in the study was piped into the top of each cup individually, by way of an icing bag technique, the use of a syringe that was placed at the bottom of the cup and filled upwards would displace many of the gas bubbles, instead of trapping them at the bottom. It may also be possible in the future to use pre-fabricated polymers or heat activated powders to completely replace the epoxy. This type of change would allow higher accuracy materials to be utilized and could help to avoid inconsistencies caused from manual mixing.

5.2.5 Further Study of IMC Composition

Due to the limitations of the equipment available, it was not possible to accurately analyze the composition of the IMC of the silver alloy solders, namely SnAg and SAC305. This was due to the low resolution of the SEM EDS system available. However, if XPS or AES were to be used with a small enough resolution, this may allow for a more thorough understanding of the IMC and more accurate values of the Poisson's ratio may be selected

APPENDICES

6.1 Tensile Testing MATLAB Analysis Code

```
% Loading Data From Tensile Tests
% SnAg - Referred to as "A"
% SAC 305 - Referred to as "SAC"
% SnCu - Referred to as "C"
% clc
% clear
% close all
% pause(1)
%
% % Load all values from Excel to create workspace.
% % Load SnAG Data from excel file
% A111_x = xlsread('SnAg_Tensile_Experiments.xlsx','111',
'B42:B332');
% A111_yo = xlsread('SnAg_Tensile_Experiments.xlsx','111',
'C42:C332');
% A112_x = xlsread('SnAg_Tensile_Experiments.xlsx','112',
'B42:B332');
% A112_yo = xlsread('SnAg_Tensile_Experiments.xlsx','112',
'C42:C332');
% A113_x = xlsread('SnAg_Tensile_Experiments.xlsx','113',
'B42:B332');
% A113_yo = xlsread('SnAg_Tensile_Experiments.xlsx','113',
'C42:C332');
% A114_x = xlsread('SnAg_Tensile_Experiments.xlsx','114',
'B42:B332');
% A114_yo = xlsread('SnAg_Tensile_Experiments.xlsx','114',
'C42:C332');
% A115_x = xlsread('SnAg_Tensile_Experiments.xlsx','115',
'B42:B332');
% A115_yo = xlsread('SnAg_Tensile_Experiments.xlsx','115',
'C42:C332');
% A116_x = xlsread('SnAg_Tensile_Experiments.xlsx','116',
'B42:B332');
% A116_yo = xlsread('SnAg_Tensile_Experiments.xlsx','116',
'C42:C332');
% A121_x = xlsread('SnAg_Tensile_Experiments.xlsx','121',
'B42:B332');
% A121_yo = xlsread('SnAg_Tensile_Experiments.xlsx','121',
'C42:C332');
% A122_x = xlsread('SnAg_Tensile_Experiments.xlsx','122',
'B42:B332');
% A122_yo = xlsread('SnAg_Tensile_Experiments.xlsx','122',
'C42:C332');
% A123_x = xlsread('SnAg_Tensile_Experiments.xlsx','123',
'B42:B332');
% A123_yo = xlsread('SnAg_Tensile_Experiments.xlsx','123',
'C42:C332');
```

```

% A124_x = xlsread('SnAg_Tensile_Experiments.xlsx','124',
'B42:B332');
% A124_yo = xlsread('SnAg_Tensile_Experiments.xlsx','124',
'C42:C332');
% A125_x = xlsread('SnAg_Tensile_Experiments.xlsx','125',
'B42:B332');
% A125_yo = xlsread('SnAg_Tensile_Experiments.xlsx','125',
'C42:C332');
% A126_x = xlsread('SnAg_Tensile_Experiments.xlsx','126',
'B42:B332');
% A126_yo = xlsread('SnAg_Tensile_Experiments.xlsx','126',
'C42:C332');
% A211_x = xlsread('SnAg_Tensile_Experiments.xlsx','211',
'B42:B332');
% A211_yo = xlsread('SnAg_Tensile_Experiments.xlsx','211',
'C42:C332');
% A212_x = xlsread('SnAg_Tensile_Experiments.xlsx','212',
'B42:B332');
% A212_yo = xlsread('SnAg_Tensile_Experiments.xlsx','212',
'C42:C332');
% A213_x = xlsread('SnAg_Tensile_Experiments.xlsx','213',
'B42:B332');
% A213_yo = xlsread('SnAg_Tensile_Experiments.xlsx','213',
'C42:C332');
% A214_x = xlsread('SnAg_Tensile_Experiments.xlsx','214',
'B42:B332');
% A214_yo = xlsread('SnAg_Tensile_Experiments.xlsx','214',
'C42:C332');
% A215_x = xlsread('SnAg_Tensile_Experiments.xlsx','215',
'B42:B332');
% A215_yo = xlsread('SnAg_Tensile_Experiments.xlsx','215',
'C42:C332');
% A216_x = xlsread('SnAg_Tensile_Experiments.xlsx','216',
'B42:B332');
% A216_yo = xlsread('SnAg_Tensile_Experiments.xlsx','216',
'C42:C332');
% A221_x = xlsread('SnAg_Tensile_Experiments.xlsx','221',
'B42:B332');
% A221_yo = xlsread('SnAg_Tensile_Experiments.xlsx','221',
'C42:C332');
% A222_x = xlsread('SnAg_Tensile_Experiments.xlsx','222',
'B42:B332');
% A222_yo = xlsread('SnAg_Tensile_Experiments.xlsx','222',
'C42:C332');
% A223_x = xlsread('SnAg_Tensile_Experiments.xlsx','223',
'B42:B332');
% A223_yo = xlsread('SnAg_Tensile_Experiments.xlsx','223',
'C42:C332');
% A224_x = xlsread('SnAg_Tensile_Experiments.xlsx','224',
'B42:B332');
% A224_yo = xlsread('SnAg_Tensile_Experiments.xlsx','224',
'C42:C332');
% A225_x = xlsread('SnAg_Tensile_Experiments.xlsx','225',
'B42:B332');
% A225_yo = xlsread('SnAg_Tensile_Experiments.xlsx','225',
'C42:C332');

```

```

% A226_x = xlsread('SnAg_Tensile_Experiments.xlsx','226',
'B42:B332');
% A226_yo = xlsread('SnAg_Tensile_Experiments.xlsx','226',
'C42:C332');
%
%
% % Load SAC Data from excel file
% SAC111_x = xlsread('SAC_Tensile_Experiments.xlsx','111',
'B42:B332');
% SAC111_yo = xlsread('SAC_Tensile_Experiments.xlsx','111',
'C42:C332');
% SAC112_x = xlsread('SAC_Tensile_Experiments.xlsx','112',
'B42:B332');
% SAC112_yo = xlsread('SAC_Tensile_Experiments.xlsx','112',
'C42:C332');
% SAC113_x = xlsread('SAC_Tensile_Experiments.xlsx','113',
'B42:B332');
% SAC113_yo = xlsread('SAC_Tensile_Experiments.xlsx','113',
'C42:C332');
% SAC114_x = xlsread('SAC_Tensile_Experiments.xlsx','114',
'B42:B332');
% SAC114_yo = xlsread('SAC_Tensile_Experiments.xlsx','114',
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% SAC115_x = xlsread('SAC_Tensile_Experiments.xlsx','115',
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% SAC115_yo = xlsread('SAC_Tensile_Experiments.xlsx','115',
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% SAC116_x = xlsread('SAC_Tensile_Experiments.xlsx','116',
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% SAC116_yo = xlsread('SAC_Tensile_Experiments.xlsx','116',
'C42:C332');
% SAC121_x = xlsread('SAC_Tensile_Experiments.xlsx','121',
'B42:B332');
% SAC121_yo = xlsread('SAC_Tensile_Experiments.xlsx','121',
'C42:C332');
% SAC122_x = xlsread('SAC_Tensile_Experiments.xlsx','122',
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% SAC122_yo = xlsread('SAC_Tensile_Experiments.xlsx','122',
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% SAC123_x = xlsread('SAC_Tensile_Experiments.xlsx','123',
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% SAC123_yo = xlsread('SAC_Tensile_Experiments.xlsx','123',
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% SAC124_yo = xlsread('SAC_Tensile_Experiments.xlsx','124',
'C42:C332');
% SAC125_x = xlsread('SAC_Tensile_Experiments.xlsx','125',
'B42:B332');
% SAC125_yo = xlsread('SAC_Tensile_Experiments.xlsx','125',
'C42:C332');
% SAC126_x = xlsread('SAC_Tensile_Experiments.xlsx','126',
'B42:B332');
% SAC126_yo = xlsread('SAC_Tensile_Experiments.xlsx','126',
'C42:C332');
% SAC211_x = xlsread('SAC_Tensile_Experiments.xlsx','211',
'B42:B332');

```

```

% SAC211_yo = xlsread('SAC_Tensile_Experiments.xlsx','211',
'C42:C332');
% SAC212_x = xlsread('SAC_Tensile_Experiments.xlsx','212',
'B42:B332');
% SAC212_yo = xlsread('SAC_Tensile_Experiments.xlsx','212',
'C42:C332');
% SAC213_x = xlsread('SAC_Tensile_Experiments.xlsx','213',
'B42:B332');
% SAC213_yo = xlsread('SAC_Tensile_Experiments.xlsx','213',
'C42:C332');
% SAC214_x = xlsread('SAC_Tensile_Experiments.xlsx','214',
'B42:B332');
% SAC214_yo = xlsread('SAC_Tensile_Experiments.xlsx','214',
'C42:C332');
% SAC215_x = xlsread('SAC_Tensile_Experiments.xlsx','215',
'B42:B332');
% SAC215_yo = xlsread('SAC_Tensile_Experiments.xlsx','215',
'C42:C332');
% SAC216_x = xlsread('SAC_Tensile_Experiments.xlsx','216',
'B42:B332');
% SAC216_yo = xlsread('SAC_Tensile_Experiments.xlsx','216',
'C42:C332');
% SAC221_x = xlsread('SAC_Tensile_Experiments.xlsx','221',
'B42:B332');
% SAC221_yo = xlsread('SAC_Tensile_Experiments.xlsx','221',
'C42:C332');
% SAC222_x = xlsread('SAC_Tensile_Experiments.xlsx','222',
'B42:B332');
% SAC222_yo = xlsread('SAC_Tensile_Experiments.xlsx','222',
'C42:C332');
% SAC223_x = xlsread('SAC_Tensile_Experiments.xlsx','223',
'B42:B332');
% SAC223_yo = xlsread('SAC_Tensile_Experiments.xlsx','223',
'C42:C332');
% SAC224_x = xlsread('SAC_Tensile_Experiments.xlsx','224',
'B42:B332');
% SAC224_yo = xlsread('SAC_Tensile_Experiments.xlsx','224',
'C42:C332');
% SAC225_x = xlsread('SAC_Tensile_Experiments.xlsx','225',
'B42:B332');
% SAC225_yo = xlsread('SAC_Tensile_Experiments.xlsx','225',
'C42:C332');
% SAC226_x = xlsread('SAC_Tensile_Experiments.xlsx','226',
'B42:B332');
% SAC226_yo = xlsread('SAC_Tensile_Experiments.xlsx','226',
'C42:C332');
% SAC311_x = xlsread('SAC_Tensile_Experiments.xlsx','311',
'B42:B332');
% SAC311_yo = xlsread('SAC_Tensile_Experiments.xlsx','311',
'C42:C332');
% SAC312_x = xlsread('SAC_Tensile_Experiments.xlsx','312',
'B42:B332');
% SAC312_yo = xlsread('SAC_Tensile_Experiments.xlsx','312',
'C42:C332');
% SAC313_x = xlsread('SAC_Tensile_Experiments.xlsx','313',
'B42:B332');

```

```

% SAC313_yo = xlsread('SAC_Tensile_Experiments.xlsx','313',
'C42:C332');
% SAC314_x = xlsread('SAC_Tensile_Experiments.xlsx','314',
'B42:B332');
% SAC314_yo = xlsread('SAC_Tensile_Experiments.xlsx','314',
'C42:C332');
% SAC315_x = xlsread('SAC_Tensile_Experiments.xlsx','315',
'B42:B332');
% SAC315_yo = xlsread('SAC_Tensile_Experiments.xlsx','315',
'C42:C332');
% SAC316_x = xlsread('SAC_Tensile_Experiments.xlsx','316',
'B42:B332');
% SAC316_yo = xlsread('SAC_Tensile_Experiments.xlsx','316',
'C42:C332');
% SAC321_x = xlsread('SAC_Tensile_Experiments.xlsx','321',
'B42:B332');
% SAC321_yo = xlsread('SAC_Tensile_Experiments.xlsx','321',
'C42:C332');
% SAC322_x = xlsread('SAC_Tensile_Experiments.xlsx','322',
'B42:B332');
% SAC322_yo = xlsread('SAC_Tensile_Experiments.xlsx','322',
'C42:C332');
% SAC323_x = xlsread('SAC_Tensile_Experiments.xlsx','323',
'B42:B332');
% SAC323_yo = xlsread('SAC_Tensile_Experiments.xlsx','323',
'C42:C332');
% SAC324_x = xlsread('SAC_Tensile_Experiments.xlsx','324',
'B42:B332');
% SAC324_yo = xlsread('SAC_Tensile_Experiments.xlsx','324',
'C42:C332');
% SAC325_x = xlsread('SAC_Tensile_Experiments.xlsx','325',
'B42:B332');
% SAC325_yo = xlsread('SAC_Tensile_Experiments.xlsx','325',
'C42:C332');
% SAC326_x = xlsread('SAC_Tensile_Experiments.xlsx','326',
'B42:B332');
% SAC326_yo = xlsread('SAC_Tensile_Experiments.xlsx','326',
'C42:C332');
%
% % Load SnCu Data from excel file
% SnCu111_x = xlsread('SnCu_Tensile_Experiments.xlsx','111',
'B42:B332');
% SnCu111_yo = xlsread('SnCu_Tensile_Experiments.xlsx','111',
'C42:C332');
% SnCu112_x = xlsread('SnCu_Tensile_Experiments.xlsx','112',
'B42:B332');
% SnCu112_yo = xlsread('SnCu_Tensile_Experiments.xlsx','112',
'C42:C332');
% SnCu113_x = xlsread('SnCu_Tensile_Experiments.xlsx','113',
'B42:B332');
% SnCu113_yo = xlsread('SnCu_Tensile_Experiments.xlsx','113',
'C42:C332');
% SnCu114_x = xlsread('SnCu_Tensile_Experiments.xlsx','114',
'B42:B332');
% SnCu114_yo = xlsread('SnCu_Tensile_Experiments.xlsx','114',
'C42:C332');

```

```

% SnCu115_x = xlsread('SnCu_Tensile_Experiments.xlsx','115',
'B42:B332');
% SnCu115_yo = xlsread('SnCu_Tensile_Experiments.xlsx','115',
'C42:C332');
% SnCu116_x = xlsread('SnCu_Tensile_Experiments.xlsx','116',
'B42:B332');
% SnCu116_yo = xlsread('SnCu_Tensile_Experiments.xlsx','116',
'C42:C332');
% SnCu121_x = xlsread('SnCu_Tensile_Experiments.xlsx','121',
'B42:B332');
% SnCu121_yo = xlsread('SnCu_Tensile_Experiments.xlsx','121',
'C42:C332');
% SnCu122_x = xlsread('SnCu_Tensile_Experiments.xlsx','122',
'B42:B332');
% SnCu122_yo = xlsread('SnCu_Tensile_Experiments.xlsx','122',
'C42:C332');
% SnCu123_x = xlsread('SnCu_Tensile_Experiments.xlsx','123',
'B42:B332');
% SnCu123_yo = xlsread('SnCu_Tensile_Experiments.xlsx','123',
'C42:C332');
% SnCu124_x = xlsread('SnCu_Tensile_Experiments.xlsx','124',
'B42:B332');
% SnCu124_yo = xlsread('SnCu_Tensile_Experiments.xlsx','124',
'C42:C332');
% SnCu125_x = xlsread('SnCu_Tensile_Experiments.xlsx','125',
'B42:B332');
% SnCu125_yo = xlsread('SnCu_Tensile_Experiments.xlsx','125',
'C42:C332');
% SnCu126_x = xlsread('SnCu_Tensile_Experiments.xlsx','126',
'B42:B332');
% SnCu126_yo = xlsread('SnCu_Tensile_Experiments.xlsx','126',
'C42:C332');
% SnCu211_x = xlsread('SnCu_Tensile_Experiments.xlsx','211',
'B42:B332');
% SnCu211_yo = xlsread('SnCu_Tensile_Experiments.xlsx','211',
'C42:C332');
% SnCu212_x = xlsread('SnCu_Tensile_Experiments.xlsx','212',
'B42:B332');
% SnCu212_yo = xlsread('SnCu_Tensile_Experiments.xlsx','212',
'C42:C332');
% SnCu213_x = xlsread('SnCu_Tensile_Experiments.xlsx','213',
'B42:B332');
% SnCu213_yo = xlsread('SnCu_Tensile_Experiments.xlsx','213',
'C42:C332');
% SnCu214_x = xlsread('SnCu_Tensile_Experiments.xlsx','214',
'B42:B332');
% SnCu214_yo = xlsread('SnCu_Tensile_Experiments.xlsx','214',
'C42:C332');
% SnCu215_x = xlsread('SnCu_Tensile_Experiments.xlsx','215',
'B42:B332');
% SnCu215_yo = xlsread('SnCu_Tensile_Experiments.xlsx','215',
'C42:C332');
% SnCu216_x = xlsread('SnCu_Tensile_Experiments.xlsx','216',
'B42:B332');
% SnCu216_yo = xlsread('SnCu_Tensile_Experiments.xlsx','216',
'C42:C332');

```

```

% SnCu221_x = xlsread('SnCu_Tensile_Experiments.xlsx','221',
'B42:B332');
% SnCu221_yo = xlsread('SnCu_Tensile_Experiments.xlsx','221',
'C42:C332');
% SnCu222_x = xlsread('SnCu_Tensile_Experiments.xlsx','222',
'B42:B332');
% SnCu222_yo = xlsread('SnCu_Tensile_Experiments.xlsx','222',
'C42:C332');
% SnCu223_x = xlsread('SnCu_Tensile_Experiments.xlsx','223',
'B42:B332');
% SnCu223_yo = xlsread('SnCu_Tensile_Experiments.xlsx','223',
'C42:C332');
% SnCu224_x = xlsread('SnCu_Tensile_Experiments.xlsx','224',
'B42:B332');
% SnCu224_yo = xlsread('SnCu_Tensile_Experiments.xlsx','224',
'C42:C332');
% SnCu225_x = xlsread('SnCu_Tensile_Experiments.xlsx','225',
'B42:B332');
% SnCu225_yo = xlsread('SnCu_Tensile_Experiments.xlsx','225',
'C42:C332');
% SnCu226_x = xlsread('SnCu_Tensile_Experiments.xlsx','226',
'B42:B332');
% SnCu226_yo = xlsread('SnCu_Tensile_Experiments.xlsx','226',
'C42:C332');

%%

% Establishing shifting values for data set using C
c=input('What would you like to use as the threshold value of load?
0.1 lbf perhaps? ');
b=input('What is the lowest stress value you will accept as a good
result for the pull-off tests? Blowouts and PCB failure are not
counted. 1200? ');
% % Attempting to remove system displacement using the stiffnesses
below,
% % can be deleted
% AL=2250;
% AM=1284;
% AS=5000;%1377.75;%1360;

%% SnAG Alloy

% Using Area of IMC to convert the load to a stress (F/A)
A111_y=A111_yo/0.013300247;
A112_y=A112_yo/0.008269195;
A113_y=A113_yo/0.018990126; % PCB rupture
A114_y=A114_yo/0.013395687;
A115_y=A115_yo/0.009693978;
A116_y=A116_yo/0.008869104;
A121_y=A121_yo/0.015618076;
A122_y=A122_yo/0.020635494; % PCB rupture
A123_y=A123_yo/0.018340939; % PCB rupture
A124_y=A124_yo/0.016156631;
A125_y=A125_yo/0.01895166;

```

```

A126_y=A126_yo/0.019053917;
A211_y=A211_yo/0.018910757; % PCB rupture
A212_y=A212_yo/0.014112757; % Matlab couldn't read size, used manual
A213_y=A213_yo/0.015917313; % BLOWOUT, average IMC size was used
A214_y=A214_yo/0.020949083;
A215_y=A215_yo/0.013300247;
A216_y=A216_yo/0.020110574;
A221_y=A221_yo/0.013811533;
A222_y=A222_yo/0.013006317; % Matlab couldn't read size, used manual
A223_y=A223_yo/0.011945037; % Used manual value instead of MATLAB
reading
A224_y=A224_yo/0.015631711;
A225_y=A225_yo/0.025707449;
A226_y=A226_yo/0.021330843;

```

```

% Determine MaxiMCM value of the data sets, this will be useful
later.
MA(1)=max(A111_y); % disp(['The maxiMCM value is: ', num2str(M111)])
MA(2)=max(A112_y);
MA(3)=max(A113_y); % PCB rupture
MA(4)=max(A114_y);
MA(5)=max(A115_y);
MA(6)=max(A116_y);
MA(7)=max(A121_y);
MA(8)=max(A122_y); % PCB rupture
MA(9)=max(A123_y); % PCB rupture
MA(10)=max(A124_y);
MA(11)=max(A125_y);
MA(12)=max(A126_y);
MA(13)=max(A211_y); % PCB rupture
MA(14)=max(A212_y);
MA(15)=max(A213_y); % Blowout
MA(16)=max(A214_y); % PCB rupture
MA(17)=max(A215_y);
MA(18)=max(A216_y);
MA(19)=max(A221_y);
MA(20)=max(A222_y);
MA(21)=max(A223_y);
MA(22)=max(A224_y);
MA(23)=max(A225_y);
MA(24)=max(A226_y);

```

```

a111=find(A111_y>c,1); % disp(['The first time the value
exceeds 1 is: ', num2str(a111)])
b111=find(A111_y>c,1,'last'); % disp(['The last time the value
exceeds 1 is: ', num2str(b111)])
a112=find(A112_y>c,1);
b112=find(A112_y>c,1,'last');
a113=find(A113_y>c,1);
b113=find(A113_y>c,1,'last');
a114=find(A114_y>c,1);
b114=find(A114_y>c,1,'last');
a115=find(A115_y>c,1);
b115=find(A115_y>c,1,'last');

```



```

a116=find(A116_y>c,1);
b116=find(A116_y>c,1,'last');
a121=find(A121_y>c,1);
b121=find(A121_y>c,1,'last');
a122=find(A122_y>c,1);
b122=find(A122_y>c,1,'last');
a123=find(A123_y>c,1);
b123=find(A123_y>c,1,'last');
a124=find(A124_y>c,1);
b124=find(A124_y>c,1,'last');
a125=find(A125_y>c,1);
b125=find(A125_y>c,1,'last');
a126=find(A126_y>c,1);
b126=find(A126_y>c,1,'last');
a211=find(A211_y>c,1);
b211=find(A211_y>c,1,'last');
a212=find(A212_y>c,1);
b212=find(A212_y>c,1,'last');
a213=find(A213_y>c,1);
b213=find(A213_y>c,1,'last');
a214=find(A214_y>c,1);
b214=find(A214_y>c,1,'last');
a215=find(A215_y>c,1);
b215=find(A215_y>c,1,'last');
a216=find(A216_y>c,1);
b216=find(A216_y>c,1,'last');
a221=find(A221_y>c,1);
b221=find(A221_y>c,1,'last');
a222=find(A222_y>c,1);
b222=find(A222_y>c,1,'last');
a223=find(A223_y>c,1);
b223=find(A223_y>c,1,'last');
a224=find(A224_y>c,1);
b224=find(A224_y>c,1,'last');
a225=find(A225_y>c,1);
b225=find(A225_y>c,1,'last');
a226=find(A226_y>c,1);
b226=find(A226_y>c,1,'last');

```

```

% Shift the data sets based on the values found above
A111_x_short=A111_x(a111:b111);    % Create shifted values of
extension based on miniMCm load
A111_y_short=A111_y(a111:b111);    % Create shifted values of load to
then correspond to the shifted extension matrix
m111=min(A111_x_short);            % Find staring displacement for
shifted data set
A111_x_short=A111_x_short-m111;    % Using this displacement, set new
displacement zero value, decrease all extension values to correspond
to this
%A111_x_short=A111_x_short-(A111_y_short/AS); % Remove displacemnt of
the system using stiffness experiment data
A112_x_short=A112_x(a112:b112);
A112_y_short=A112_y(a112:b112);

```

```

m112=min(A112_x_short);
A112_x_short=A112_x_short-m112;
%A112_x_short=A112_x_short-A112_y_short/AS;
A113_x_short=A113_x(a113:b113);
A113_y_short=A113_y(a113:b113);
m113=min(A113_x_short);
A113_x_short=A113_x_short-m113;
%A113_x_short=A113_x_short-A113_x_short/AS;
A114_x_short=A114_x(a114:b114);
A114_y_short=A114_y(a114:b114);
%A114_x_short=A114_x_short-A114_x_short/AS;
m114=min(A114_x_short);
A114_x_short=A114_x_short-m114;
A115_x_short=A115_x(a115:b115);
A115_y_short=A115_y(a115:b115);
% A115_x_short=A115_x_short-A115_x_short/AS;
m115=min(A115_x_short);
A115_x_short=A115_x_short-m115;
A116_x_short=A116_x(a116:b116);
A116_y_short=A116_y(a116:b116);
% A116_x_short=A116_x_short-A116_x_short/AS;
m116=min(A116_x_short);
A116_x_short=A116_x_short-m116;
A121_x_short=A121_x(a121:b121);
A121_y_short=A121_y(a121:b121);
% A121_x_short=A121_x_short-A121_x_short/AS;
m121=min(A121_x_short);
A121_x_short=A121_x_short-m121;
A122_x_short=A122_x(a122:b122);
A122_y_short=A122_y(a122:b122);
% A122_x_short=A122_x_short-A122_x_short/AS;
m122=min(A122_x_short);
A122_x_short=A122_x_short-m122;
A123_x_short=A123_x(a123:b123);
A123_y_short=A123_y(a123:b123);
% A123_x_short=A123_x_short-A123_x_short/AS;
m123=min(A123_x_short);
A123_x_short=A123_x_short-m123;
A124_x_short=A124_x(a124:b124);
A124_y_short=A124_y(a124:b124);
% A124_x_short=A124_x_short-A124_x_short/AS;
m124=min(A124_x_short);
A124_x_short=A124_x_short-m124;
A125_x_short=A125_x(a125:b125);
A125_y_short=A125_y(a125:b125);
% A125_x_short=A125_x_short-A125_x_short/AS;
m125=min(A125_x_short);
A125_x_short=A125_x_short-m125;
A126_x_short=A126_x(a126:b126);
A126_y_short=A126_y(a126:b126);
% A126_x_short=A126_x_short-A126_x_short/AS;
m126=min(A126_x_short);
A126_x_short=A126_x_short-m126;
A211_x_short=A211_x(a211:b211);
A211_y_short=A211_y(a211:b211);
% A211_x_short=A211_x_short-A211_x_short/AS;
m211=min(A211_x_short);

```

```

A211_x_short=A211_x_short-m211;
A212_x_short=A212_x(a212:b212);
A212_y_short=A212_y(a212:b212);
% A212_x_short=A212_x_short-A212_x_short/AS;
m212=min(A212_x_short);
A212_x_short=A212_x_short-m212;
A213_x_short=A213_x(a213:b213);
A213_y_short=A213_y(a213:b213);
% A213_x_short=A213_x_short-A213_x_short/AS;
m213=min(A213_x_short);
A213_x_short=A213_x_short-m213;
A214_x_short=A214_x(a214:b214);
A214_y_short=A214_y(a214:b214);
% A214_x_short=A214_x_short-A214_x_short/AS;
m214=min(A214_x_short);
A214_x_short=A214_x_short-m214;
A215_x_short=A215_x(a215:b215);
A215_y_short=A215_y(a215:b215);
% A215_x_short=A215_x_short-A215_x_short/AS;
m215=min(A215_x_short);
A215_x_short=A215_x_short-m215;
A216_x_short=A216_x(a216:b216);
A216_y_short=A216_y(a216:b216);
% A216_x_short=A216_x_short-A216_x_short/AS;
m216=min(A216_x_short);
A216_x_short=A216_x_short-m216;
A221_x_short=A221_x(a221:b221);
A221_y_short=A221_y(a221:b221);
% A221_x_short=A221_x_short-A221_x_short/AS;
m221=min(A221_x_short);
A221_x_short=A221_x_short-m221;
A222_x_short=A222_x(a222:b222);
A222_y_short=A222_y(a222:b222);
% A222_x_short=A222_x_short-A222_x_short/AS;
m222=min(A222_x_short);
A222_x_short=A222_x_short-m222;
A223_x_short=A223_x(a223:b223);
A223_y_short=A223_y(a223:b223);
% A223_x_short=A223_x_short-A223_x_short/AS;
m223=min(A223_x_short);
A223_x_short=A223_x_short-m223;
A224_x_short=A224_x(a224:b224);
A224_y_short=A224_y(a224:b224);
% A224_x_short=A224_x_short-A224_x_short/AS;
m224=min(A224_x_short);
A224_x_short=A224_x_short-m224;
A225_x_short=A225_x(a225:b225);
A225_y_short=A225_y(a225:b225);
% A225_x_short=A225_x_short-A225_x_short/AS;
m225=min(A225_x_short);
A225_x_short=A225_x_short-m225;
A226_x_short=A226_x(a226:b226);
A226_y_short=A226_y(a226:b226);
% A226_x_short=A226_x_short-A226_x_short/AS;
m226=min(A226_x_short);
A226_x_short=A226_x_short-m226;

```

```
%% SAC 305 Alloy
```

```
% Using Area of IMC to convert the load to a stress (F/A)
SAC111_y=SAC111_yo/0.003592; % LOW
SAC112_y=SAC112_yo/0.007110;
SAC113_y=SAC113_yo/0.009475;
SAC114_y=SAC114_yo/0.008225035; % BLOWOUT, average IMC size was used
SAC115_y=SAC115_yo/0.005781;
SAC116_y=SAC116_yo/0.005871; % LOW
SAC121_y=SAC121_yo/0.012222; % LOW
SAC122_y=SAC122_yo/0.009333; % LOW
SAC123_y=SAC123_yo/0.009289; % LOW
SAC124_y=SAC124_yo/0.005787;
SAC125_y=SAC125_yo/0.013585;
SAC126_y=SAC126_yo/0.006267; % LOW
SAC211_y=SAC211_yo/0.013353;
SAC212_y=SAC212_yo/0.009333;
SAC213_y=SAC213_yo/0.009289;
SAC214_y=SAC214_yo/0.006714; % Broken, no test
SAC215_y=SAC215_yo/0.013585;
SAC216_y=SAC216_yo/0.006267; % LOW
SAC221_y=SAC221_yo/0.010427; % LOW
SAC222_y=SAC222_yo/0.013827;
SAC223_y=SAC223_yo/0.007451;
SAC224_y=SAC224_yo/0.005306; % LOW
SAC225_y=SAC225_yo/0.008245;
SAC226_y=SAC226_yo/0.005886;
SAC311_y=SAC311_yo/0.007909382; % Manual measurement used
SAC312_y=SAC312_yo/0.009516;
SAC313_y=SAC313_yo/0.007634294; % Manual measurment used
SAC314_y=SAC314_yo/0.009503; % LOW
SAC315_y=SAC315_yo/0.008384; % LOW
SAC316_y=SAC316_yo/0.006162; % Broken, no test
SAC321_y=SAC321_yo/0.008189; % LOW, Matlab couldn't read size, used
manual
SAC322_y=SAC322_yo/0.009358; % LOW, Matlab couldn't read size, used
manual
SAC323_y=SAC323_yo/0.008942;
SAC324_y=SAC324_yo/0.008189; % LOW, Matlab couldn't read size, used
manual
SAC325_y=SAC325_yo/0.008769;
SAC326_y=SAC326_yo/0.005812; % LOW
```

```
% Determine maxIMCm value of the data sets, this will be useful
later.
```

```
MSAC(1)=max(SAC111_y); % Low
MSAC(2)=max(SAC112_y);
MSAC(3)=max(SAC113_y);
%MSAC(4)=max(SAC114_y); % BLOWOUT
```

```

MSAC(4)=max(SAC115_y);
MSAC(5)=max(SAC116_y); % Low
MSAC(6)=max(SAC121_y); % Low
MSAC(7)=max(SAC122_y); % Low
MSAC(8)=max(SAC123_y); % Low
MSAC(9)=max(SAC124_y);
MSAC(10)=max(SAC125_y);
MSAC(11)=max(SAC126_y); % Low
MSAC(12)=max(SAC211_y);
MSAC(13)=max(SAC212_y);
MSAC(14)=max(SAC213_y);
% MSAC(15)=max(SAC214_y); % Broken, no test
MSAC(15)=max(SAC215_y);
MSAC(16)=max(SAC216_y); % Low
MSAC(17)=max(SAC221_y); % Low
MSAC(18)=max(SAC222_y); %%%
MSAC(19)=max(SAC223_y);
MSAC(20)=max(SAC224_y); % Low
MSAC(21)=max(SAC225_y);
MSAC(22)=max(SAC226_y);
MSAC(23)=max(SAC311_y); % Low
MSAC(24)=max(SAC312_y);
MSAC(25)=max(SAC313_y); % Low
MSAC(26)=max(SAC314_y); % Low ---> max(SAC314_y)
MSAC(27)=max(SAC315_y); % Low
%MSAC(28)=max(SAC316_y); % Broken, no test
MSAC(28)=max(SAC321_y); % LOW, Matlab couldn't read size, used
manual
MSAC(29)=max(SAC322_y); % LOW, Matlab couldn't read size, used
manual
MSAC(30)=max(SAC323_y);
MSAC(31)=max(SAC324_y); % LOW, Matlab couldn't read size, used
manual
MSAC(32)=max(SAC325_y);
MSAC(33)=max(SAC326_y); % Low

```

```

% Establishing shiftming values for data set using C
as111=find(SAC111_y>c,1); % disp(['The first time the value
exceeds 1 is: ', num2str(SAC111)])
bs111=find(SAC111_y>c,1,'last'); % disp(['The last time the value
exceeds 1 is: ', num2str(b111)])
as112=find(SAC112_y>c,1);
bs112=find(SAC112_y>c,1,'last');
as113=find(SAC113_y>c,1);
bs113=find(SAC113_y>c,1,'last');
as114=find(SAC114_y>c,1);
bs114=find(SAC114_y>c,1,'last');
as115=find(SAC115_y>c,1);
bs115=find(SAC115_y>c,1,'last');
as116=find(SAC116_y>c,1);
bs116=find(SAC116_y>c,1,'last');
as121=find(SAC121_y>c,1);
bs121=find(SAC121_y>c,1,'last');
as122=find(SAC122_y>c,1);

```

```

bs122=find(SAC122_y>c,1,'last');
as123=find(SAC123_y>c,1);
bs123=find(SAC123_y>c,1,'last');
as124=find(SAC124_y>c,1);
bs124=find(SAC124_y>c,1,'last');
as125=find(SAC125_y>c,1);
bs125=find(SAC125_y>c,1,'last');
as126=find(SAC126_y>c,1);
bs126=find(SAC126_y>c,1,'last');
as211=find(SAC211_y>c,1);
bs211=find(SAC211_y>c,1,'last');
as212=find(SAC212_y>c,1);
bs212=find(SAC212_y>c,1,'last');
as213=find(SAC213_y>c,1);
bs213=find(SAC213_y>c,1,'last');
as214=find(SAC214_y>c,1);
bs214=find(SAC214_y>c,1,'last');
as215=find(SAC215_y>c,1);
bs215=find(SAC215_y>c,1,'last');
as216=find(SAC216_y>c,1);
bs216=find(SAC216_y>c,1,'last');
as221=find(SAC221_y>c,1);
bs221=find(SAC221_y>c,1,'last');
as222=find(SAC222_y>c,1);
bs222=find(SAC222_y>c,1,'last');
as223=find(SAC223_y>c,1);
bs223=find(SAC223_y>c,1,'last');
as224=find(SAC224_y>c,1);
bs224=find(SAC224_y>c,1,'last');
as225=find(SAC225_y>c,1);
bs225=find(SAC225_y>c,1,'last');
as226=find(SAC226_y>c,1);
bs226=find(SAC226_y>c,1,'last');
as311=find(SAC311_y>c,1);
bs311=find(SAC311_y>c,1,'last');
as312=find(SAC312_y>c,1);
bs312=find(SAC312_y>c,1,'last');
as313=find(SAC313_y>c,1);
bs313=find(SAC313_y>c,1,'last');
as314=find(SAC314_y>c,1);
bs314=find(SAC314_y>c,1,'last');
as315=find(SAC315_y>c,1);
bs315=find(SAC315_y>c,1,'last');
as316=find(SAC316_y>c,1);
bs316=find(SAC316_y>c,1,'last');
as321=find(SAC321_y>c,1);
bs321=find(SAC321_y>c,1,'last');
as322=find(SAC322_y>c,1);
bs322=find(SAC322_y>c,1,'last');
as323=find(SAC323_y>c,1);
bs323=find(SAC323_y>c,1,'last');
as324=find(SAC324_y>c,1);
bs324=find(SAC324_y>c,1,'last');
as325=find(SAC325_y>c,1);
bs325=find(SAC325_y>c,1,'last');
as326=find(SAC326_y>c,1);
bs326=find(SAC326_y>c,1,'last');

```

```

% Shift the data sets based on the values found above
SAC111_x_short=SAC111_x(as111:bs111);    % Create shifted values of
extension based on miniMCM load
SAC111_y_short=SAC111_y(as111:bs111);    % Create shifted values of
load to then correspond to the shifted extension MSACtrix
SACm111=min(SAC111_x_short);              % Find staring displacement
for timmed data set
SAC111_x_short=SAC111_x_short-SACm111;    % Using this displacement,
set new displacment zero value, decrease all extension values to
correspond to this
SAC112_x_short=SAC112_x(as112:bs112);
SAC112_y_short=SAC112_y(as112:bs112);
SACm112=min(SAC112_x_short);
SAC112_x_short=SAC112_x_short-SACm112;
SAC113_x_short=SAC113_x(as113:bs113);
SAC113_y_short=SAC113_y(as113:bs113);
SACm113=min(SAC113_x_short);
SAC113_x_short=SAC113_x_short-SACm113;
SAC114_x_short=SAC114_x(as114:bs114);
SAC114_y_short=SAC114_y(as114:bs114);
SACm114=min(SAC114_x_short);
SAC114_x_short=SAC114_x_short-SACm114;
SAC115_x_short=SAC115_x(as115:bs115);
SAC115_y_short=SAC115_y(as115:bs115);
SACm115=min(SAC115_x_short);
SAC115_x_short=SAC115_x_short-SACm115;
SAC116_x_short=SAC116_x(as116:bs116);
SAC116_y_short=SAC116_y(as116:bs116);
SACm116=min(SAC116_x_short);
SAC116_x_short=SAC116_x_short-SACm116;
SAC121_x_short=SAC121_x(as121:bs121);
SAC121_y_short=SAC121_y(as121:bs121);
SACm121=min(SAC121_x_short);
SAC121_x_short=SAC121_x_short-SACm121;
SAC122_x_short=SAC122_x(as122:bs122);
SAC122_y_short=SAC122_y(as122:bs122);
SACm122=min(SAC122_x_short);
SAC122_x_short=SAC122_x_short-SACm122;
SAC123_x_short=SAC123_x(as123:bs123);
SAC123_y_short=SAC123_y(as123:bs123);
SACm123=min(SAC123_x_short);
SAC123_x_short=SAC123_x_short-SACm123;
SAC124_x_short=SAC124_x(as124:bs124);
SAC124_y_short=SAC124_y(as124:bs124);
SACm124=min(SAC124_x_short);
SAC124_x_short=SAC124_x_short-SACm124;
SAC125_x_short=SAC125_x(as125:bs125);
SAC125_y_short=SAC125_y(as125:bs125);
SACm125=min(SAC125_x_short);
SAC125_x_short=SAC125_x_short-SACm125;
SAC126_x_short=SAC126_x(as126:bs126);
SAC126_y_short=SAC126_y(as126:bs126);

```

```

SACm126=min(SAC126_x_short);
SAC126_x_short=SAC126_x_short-SACm126;
SAC211_x_short=SAC211_x(as211:bs211);
SAC211_y_short=SAC211_y(as211:bs211);
SACm211=min(SAC211_x_short);
SAC211_x_short=SAC211_x_short-SACm211;
SAC212_x_short=SAC212_x(as212:bs212);
SAC212_y_short=SAC212_y(as212:bs212);
SACm212=min(SAC212_x_short);
SAC212_x_short=SAC212_x_short-SACm212;
SAC213_x_short=SAC213_x(as213:bs213);
SAC213_y_short=SAC213_y(as213:bs213);
SACm213=min(SAC213_x_short);
SAC213_x_short=SAC213_x_short-SACm213;
SAC214_x_short=SAC214_x(as214:bs214);
SAC214_y_short=SAC214_y(as214:bs214);
SACm214=min(SAC214_x_short);
SAC214_x_short=SAC214_x_short-SACm214;
SAC215_x_short=SAC215_x(as215:bs215);
SAC215_y_short=SAC215_y(as215:bs215);
SACm215=min(SAC215_x_short);
SAC215_x_short=SAC215_x_short-SACm215;
SAC216_x_short=SAC216_x(as216:bs216);
SAC216_y_short=SAC216_y(as216:bs216);
SACm216=min(SAC216_x_short);
SAC216_x_short=SAC216_x_short-SACm216;
SAC221_x_short=SAC221_x(as221:bs221);
SAC221_y_short=SAC221_y(as221:bs221);
SACm221=min(SAC221_x_short);
SAC221_x_short=SAC221_x_short-SACm221;
SAC222_x_short=SAC222_x(as222:bs222);
SAC222_y_short=SAC222_y(as222:bs222);
SACm222=min(SAC222_x_short);
SAC222_x_short=SAC222_x_short-SACm222;
SAC223_x_short=SAC223_x(as223:bs223);
SAC223_y_short=SAC223_y(as223:bs223);
SACm223=min(SAC223_x_short);
SAC223_x_short=SAC223_x_short-SACm223;
SAC224_x_short=SAC224_x(as224:bs224);
SAC224_y_short=SAC224_y(as224:bs224);
SACm224=min(SAC224_x_short);
SAC224_x_short=SAC224_x_short-SACm224;
SAC225_x_short=SAC225_x(as225:bs225);
SAC225_y_short=SAC225_y(as225:bs225);
SACm225=min(SAC225_x_short);
SAC225_x_short=SAC225_x_short-SACm225;
SAC226_x_short=SAC226_x(as226:bs226);
SAC226_y_short=SAC226_y(as226:bs226);
SACm226=min(SAC226_x_short);
SAC226_x_short=SAC226_x_short-SACm226;
SAC311_x_short=SAC311_x(as311:bs311);
SAC311_y_short=SAC311_y(as311:bs311);
SACm311=min(SAC311_x_short);
SAC311_x_short=SAC311_x_short-SACm311;
SAC312_x_short=SAC312_x(as312:bs312);
SAC312_y_short=SAC312_y(as312:bs312);
SACm312=min(SAC312_x_short);

```



```

SAC312_x_short=SAC312_x_short-SACm312;
SAC313_x_short=SAC313_x(as313:bs313);
SAC313_y_short=SAC313_y(as313:bs313);
SACm313=min(SAC313_x_short);
SAC313_x_short=SAC313_x_short-SACm313;
SAC314_x_short=SAC314_x(as314:bs314);
SAC314_y_short=SAC314_y(as314:bs314);
SACm314=min(SAC314_x_short);
SAC314_x_short=SAC314_x_short-SACm314;
SAC315_x_short=SAC315_x(as315:bs315);
SAC315_y_short=SAC315_y(as315:bs315);
SACm315=min(SAC315_x_short);
SAC315_x_short=SAC315_x_short-SACm315;
SAC316_x_short=SAC316_x(as316:bs316);
SAC316_y_short=SAC316_y(as316:bs316);
SACm316=min(SAC316_x_short);
SAC316_x_short=SAC316_x_short-SACm316;
SAC321_x_short=SAC321_x(as321:bs321);
SAC321_y_short=SAC321_y(as321:bs321);
SACm321=min(SAC321_x_short);
SAC321_x_short=SAC321_x_short-SACm321;
SAC322_x_short=SAC322_x(as322:bs322);
SAC322_y_short=SAC322_y(as322:bs322);
SACm322=min(SAC322_x_short);
SAC322_x_short=SAC322_x_short-SACm322;
SAC323_x_short=SAC323_x(as323:bs323);
SAC323_y_short=SAC323_y(as323:bs323);
SACm323=min(SAC323_x_short);
SAC323_x_short=SAC323_x_short-SACm323;
SAC324_x_short=SAC324_x(as324:bs324);
SAC324_y_short=SAC324_y(as324:bs324);
SACm324=min(SAC324_x_short);
SAC324_x_short=SAC324_x_short-SACm324;
SAC325_x_short=SAC325_x(as325:bs325);
SAC325_y_short=SAC325_y(as325:bs325);
SACm325=min(SAC325_x_short);
SAC325_x_short=SAC325_x_short-SACm325;
SAC326_x_short=SAC326_x(as326:bs326);
SAC326_y_short=SAC326_y(as326:bs326);
SACm326=min(SAC326_x_short);
SAC326_x_short=SAC326_x_short-SACm326;

```

```

%% SnCu Alloy

```

```

% Using Area of IMC to convert the load to a stress (F/A)
SnCu111_y=SnCu111_yo/0.017030308; % BLOWOUT, average IMC
size was used
SnCu112_y=SnCu112_yo/0.023000441;
SnCu113_y=SnCu113_yo/0.018829603;
SnCu114_y=SnCu114_yo/0.016628874;
SnCu115_y=SnCu115_yo/0.026538041;
SnCu116_y=SnCu116_yo/0.021521410;
SnCu121_y=SnCu121_yo/0.023634311;
SnCu122_y=SnCu122_yo/0.016969616;
SnCu123_y=SnCu123_yo/0.018738417;

```

```

SnCu124_y=SnCu124_yo/0.014078496;
SnCu125_y=SnCu125_yo/0.022873667;
SnCu126_y=SnCu126_yo/0.016716286;
SnCu211_y=SnCu211_yo/0.017030308; % BLOWOUT, average IMC
size was used
SnCu212_y=SnCu212_yo/0.017060169;
SnCu213_y=SnCu213_yo/0.017030308; % BLOWOUT, average IMC
size was used
SnCu214_y=SnCu214_yo/0.017621259;
SnCu215_y=SnCu215_yo/0.017642510;
SnCu216_y=SnCu216_yo/0.014808420;
SnCu221_y=SnCu221_yo/0.014932050;
SnCu222_y=SnCu222_yo/0.014868828; % Used manual measurment
SnCu223_y=SnCu223_yo/0.018225694; % Used manual measurment
SnCu224_y=SnCu224_yo/0.013003399;
SnCu225_y=SnCu225_yo/0.017456718;
SnCu226_y=SnCu226_yo/0.010697318;

```

```

% Determine maxiMCM value of the data sets, this will be useful
later.
%MC()=max(SnCu111_y); % BLOWOUT % disp(['The MaxiMum value is: ',
num2str(SnCu111)])
MC(1)=max(SnCu112_y);
MC(2)=max(SnCu113_y);
MC(3)=max(SnCu114_y);
MC(3)=max(SnCu115_y);
MC(4)=max(SnCu116_y);
MC(5)=max(SnCu121_y);
MC(6)=max(SnCu122_y);
MC(7)=max(SnCu123_y);
MC(8)=max(SnCu124_y);
MC(9)=max(SnCu125_y);
MC(10)=max(SnCu126_y);
%MC()=max(SnCu211_y); % BLOWOUT
MC(11)=max(SnCu212_y);
%MC()=max(SnCu213_y); % BLOWOUT
MC(12)=max(SnCu214_y);
MC(13)=max(SnCu215_y);
MC(14)=max(SnCu216_y);
MC(15)=max(SnCu221_y);
MC(16)=max(SnCu222_y);
MC(17)=max(SnCu223_y);
MC(18)=max(SnCu224_y);
MC(19)=max(SnCu225_y);
MC(20)=max(SnCu226_y);

```

```

% Establishing shifting values for data set using C
ac111=find(SnCu111_y>c,1); % disp(['The first time the value
exceeds 1 is: ', num2str(SnCu111)])

```

```

bc111=find(SnCu111_y>c,1,'last'); % disp(['The last time the value
exceeds 1 is: ', num2str(b111)])
ac112=find(SnCu112_y>c,1);
bc112=find(SnCu112_y>c,1,'last');
ac113=find(SnCu113_y>c,1);
bc113=find(SnCu113_y>c,1,'last');
ac114=find(SnCu114_y>c,1);
bc114=find(SnCu114_y>c,1,'last');
ac115=find(SnCu115_y>c,1);
bc115=find(SnCu115_y>c,1,'last');
ac116=find(SnCu116_y>c,1);
bc116=find(SnCu116_y>c,1,'last');
ac121=find(SnCu121_y>c,1);
bc121=find(SnCu121_y>c,1,'last');
ac122=find(SnCu122_y>c,1);
bc122=find(SnCu122_y>c,1,'last');
ac123=find(SnCu123_y>c,1);
bc123=find(SnCu123_y>c,1,'last');
ac124=find(SnCu124_y>c,1);
bc124=find(SnCu124_y>c,1,'last');
ac125=find(SnCu125_y>c,1);
bc125=find(SnCu125_y>c,1,'last');
ac126=find(SnCu126_y>c,1);
bc126=find(SnCu126_y>c,1,'last');
ac211=find(SnCu211_y>c,1);
bc211=find(SnCu211_y>c,1,'last');
ac212=find(SnCu212_y>c,1);
bc212=find(SnCu212_y>c,1,'last');
ac213=find(SnCu213_y>c,1);
bc213=find(SnCu213_y>c,1,'last');
ac214=find(SnCu214_y>c,1);
bc214=find(SnCu214_y>c,1,'last');
ac215=find(SnCu215_y>c,1);
bc215=find(SnCu215_y>c,1,'last');
ac216=find(SnCu216_y>c,1);
bc216=find(SnCu216_y>c,1,'last');
ac221=find(SnCu221_y>c,1);
bc221=find(SnCu221_y>c,1,'last');
ac222=find(SnCu222_y>c,1);
bc222=find(SnCu222_y>c,1,'last');
ac223=find(SnCu223_y>c,1);
bc223=find(SnCu223_y>c,1,'last');
ac224=find(SnCu224_y>c,1);
bc224=find(SnCu224_y>c,1,'last');
ac225=find(SnCu225_y>c,1);
bc225=find(SnCu225_y>c,1,'last');
ac226=find(SnCu226_y>c,1);
bc226=find(SnCu226_y>c,1,'last');

```

```

% Shift the data sets based on the values found above
SnCu111_x_short=SnCu111_x(ac111:bc111); % Create shifted values
of extension based on miniMCM load
SnCu111_y_short=SnCu111_y(ac111:bc111); % Create shifted values
of load to then correspond to the shifted extension MSnCutrix

```

```

SnCum111=min(SnCu111_x_short); % Find starting
displacement for timmed data set
SnCu111_x_short=SnCu111_x_short-SnCum111; % Using this
displacement, set new displacement zero value, decrease all extension
values to correspond to this
SnCu112_x_short=SnCu112_x(ac112:bc112);
SnCu112_y_short=SnCu112_y(ac112:bc112);
SnCum112=min(SnCu112_x_short);
SnCu112_x_short=SnCu112_x_short-SnCum112;
SnCu113_x_short=SnCu113_x(ac113:bc113);
SnCu113_y_short=SnCu113_y(ac113:bc113);
SnCum113=min(SnCu113_x_short);
SnCu113_x_short=SnCu113_x_short-SnCum113;
SnCu114_x_short=SnCu114_x(ac114:bc114);
SnCu114_y_short=SnCu114_y(ac114:bc114);
SnCum114=min(SnCu114_x_short);
SnCu114_x_short=SnCu114_x_short-SnCum114;
SnCu115_x_short=SnCu115_x(ac115:bc115);
SnCu115_y_short=SnCu115_y(ac115:bc115);
SnCum115=min(SnCu115_x_short);
SnCu115_x_short=SnCu115_x_short-SnCum115;
SnCu116_x_short=SnCu116_x(ac116:bc116);
SnCu116_y_short=SnCu116_y(ac116:bc116);
SnCum116=min(SnCu116_x_short);
SnCu116_x_short=SnCu116_x_short-SnCum116;
SnCu121_x_short=SnCu121_x(ac121:bc121);
SnCu121_y_short=SnCu121_y(ac121:bc121);
SnCum121=min(SnCu121_x_short);
SnCu121_x_short=SnCu121_x_short-SnCum121;
SnCu122_x_short=SnCu122_x(ac122:bc122);
SnCu122_y_short=SnCu122_y(ac122:bc122);
SnCum122=min(SnCu122_x_short);
SnCu122_x_short=SnCu122_x_short-SnCum122;
SnCu123_x_short=SnCu123_x(ac123:bc123);
SnCu123_y_short=SnCu123_y(ac123:bc123);
SnCum123=min(SnCu123_x_short);
SnCu123_x_short=SnCu123_x_short-SnCum123;
SnCu124_x_short=SnCu124_x(ac124:bc124);
SnCu124_y_short=SnCu124_y(ac124:bc124);
SnCum124=min(SnCu124_x_short);
SnCu124_x_short=SnCu124_x_short-SnCum124;
SnCu125_x_short=SnCu125_x(ac125:bc125);
SnCu125_y_short=SnCu125_y(ac125:bc125);
SnCum125=min(SnCu125_x_short);
SnCu125_x_short=SnCu125_x_short-SnCum125;
SnCu126_x_short=SnCu126_x(ac126:bc126);
SnCu126_y_short=SnCu126_y(ac126:bc126);
SnCum126=min(SnCu126_x_short);
SnCu126_x_short=SnCu126_x_short-SnCum126;
SnCu211_x_short=SnCu211_x(ac211:bc211);
SnCu211_y_short=SnCu211_y(ac211:bc211);
SnCum211=min(SnCu211_x_short);
SnCu211_x_short=SnCu211_x_short-SnCum211;
SnCu212_x_short=SnCu212_x(ac212:bc212);
SnCu212_y_short=SnCu212_y(ac212:bc212);
SnCum212=min(SnCu212_x_short);
SnCu212_x_short=SnCu212_x_short-SnCum212;

```

```

SnCu213_x_short=SnCu213_x(ac213:bc213);
SnCu213_y_short=SnCu213_y(ac213:bc213);
SnCum213=min(SnCu213_x_short);
SnCu213_x_short=SnCu213_x_short-SnCum213;
SnCu214_x_short=SnCu214_x(ac214:bc214);
SnCu214_y_short=SnCu214_y(ac214:bc214);
SnCum214=min(SnCu214_x_short);
SnCu214_x_short=SnCu214_x_short-SnCum214;
SnCu215_x_short=SnCu215_x(ac215:bc215);
SnCu215_y_short=SnCu215_y(ac215:bc215);
SnCum215=min(SnCu215_x_short);
SnCu215_x_short=SnCu215_x_short-SnCum215;
SnCu216_x_short=SnCu216_x(ac216:bc216);
SnCu216_y_short=SnCu216_y(ac216:bc216);
SnCum216=min(SnCu216_x_short);
SnCu216_x_short=SnCu216_x_short-SnCum216;
SnCu221_x_short=SnCu221_x(ac221:bc221);
SnCu221_y_short=SnCu221_y(ac221:bc221);
SnCum221=min(SnCu221_x_short);
SnCu221_x_short=SnCu221_x_short-SnCum221;
SnCu222_x_short=SnCu222_x(ac222:bc222);
SnCu222_y_short=SnCu222_y(ac222:bc222);
SnCum222=min(SnCu222_x_short);
SnCu222_x_short=SnCu222_x_short-SnCum222;
SnCu223_x_short=SnCu223_x(ac223:bc223);
SnCu223_y_short=SnCu223_y(ac223:bc223);
SnCum223=min(SnCu223_x_short);
SnCu223_x_short=SnCu223_x_short-SnCum223;
SnCu224_x_short=SnCu224_x(ac224:bc224);
SnCu224_y_short=SnCu224_y(ac224:bc224);
SnCum224=min(SnCu224_x_short);
SnCu224_x_short=SnCu224_x_short-SnCum224;
SnCu225_x_short=SnCu225_x(ac225:bc225);
SnCu225_y_short=SnCu225_y(ac225:bc225);
SnCum225=min(SnCu225_x_short);
SnCu225_x_short=SnCu225_x_short-SnCum225;
SnCu226_x_short=SnCu226_x(ac226:bc226);
SnCu226_y_short=SnCu226_y(ac226:bc226);
SnCum226=min(SnCu226_x_short);
SnCu226_x_short=SnCu226_x_short-SnCum226;

%% STATS

% Delete values from arrays that are below the cut-off value, b
% MA (MA<b) = [];
% [ma,na] = size(MA);
% xA = ones(ma,na);

MSAC (MSAC<b) = [];
[mSAC,nSAC] = size(MSAC);
xSAC = ones(mSAC,nSAC)*2;

MC (MC<b) = [];
[mC,nC] = size(MC);
xC = ones(mC,nC)*3;

```

```

SEM_A = std(MA)/sqrt(length(MA)); % Standard Error
% ts_A = tinv([0.025 0.975],length(MA)-1); % T-Score
% CI_A = mean(MA) + ts_A*SEM_A; % Confidence
Intervals
ts_Al = tinv(0.025,length(MA)-1); % T-Score
ts_Au = tinv(0.975,length(MA)-1);
CI_Al = mean(MA) + ts_Al*SEM_A;
CI_Au = mean(MA) + ts_Au*SEM_A;

SEM_SAC = std(MSAC)/sqrt(length(MSAC)); % Standard Error
% ts_SAC = tinv([0.025 0.975],length(MC)-1); % T-Score
% CI_SAC = mean(MC) + ts_SAC*SEM_SAC; % Confidence
Intervals
ts_SACl = tinv(0.025,length(MSAC)-1); % T-Score
ts_SACu = tinv(0.975,length(MSAC)-1);
CI_SACl = mean(MSAC) + ts_SACl*SEM_SAC; % Confidence
Intervals
CI_SACu = mean(MSAC) + ts_SACu*SEM_SAC;

SEM_C = std(MC)/sqrt(length(MC)); % Standard Error
% ts_C = tinv([0.025 0.975],length(MC)-1); % T-Score
% CI_C = mean(MC) + ts_C*SEM_C; % Confidence
Intervals
ts_Cl = tinv(0.025,length(MC)-1); % T-Score
ts_Cu = tinv(0.975,length(MC)-1);
CI_Cl = mean(MC) + ts_Cl*SEM_C; % Confidence
Intervals
CI_Cu = mean(MC) + ts_Cu*SEM_C;

avg = [mean(MA), mean(MSAC), mean(MC)];
stan = [std(MA), std(MSAC), std(MC)];
CIl = [CI_Al, CI_SACl, CI_Cl];
CIu = [CI_Au, CI_SACu, CI_Cu];

% % % Newest Stats
avg_all_SnAg = [max(A111_y); max(A112_y); max(A113_y);
max(A114_y); max(A115_y); max(A116_y); max(A121_y); max(A122_y);
max(A123_y); max(A124_y); max(A125_y); max(A126_y); max(A211_y);
max(A212_y); max(A213_y); max(A214_y);
max(A215_y); max(A216_y); max(A221_y); max(A222_y); max(A223_y); max(A224_
y); max(A225_y); max(A226_y)];
avg_all_SAC =
[max(SAC111_y); max(SAC112_y); max(SAC113_y); max(SAC114_y); max(SAC115_y
); max(SAC116_y); max(SAC121_y); max(SAC122_y); max(SAC123_y); max(SAC124_
y); max(SAC125_y); max(SAC126_y); max(SAC211_y); max(SAC212_y); max(SAC213_
y); max(SAC214_y); max(SAC215_y); max(SAC216_y); max(SAC221_y); max(SAC22
2_y); max(SAC223_y); max(SAC224_y); max(SAC225_y); max(SAC226_y); max(SAC3
11_y); max(SAC312_y); max(SAC313_y); max(SAC314_y); max(SAC315_y); max(SAC

```

```

316_y);max(SAC321_y);max(SAC322_y);max(SAC323_y);max(SAC324_y);max(SA
C325_y);max(SAC326_y)];
avg_all_SnCu = [max(SnCu111_y);
max(SnCu112_y);max(SnCu113_y);max(SnCu114_y);max(SnCu115_y);max(SnCu1
16_y);max(SnCu121_y);max(SnCu122_y);max(SnCu123_y);max(SnCu124_y);max
(SnCu125_y);max(SnCu126_y);max(SnCu211_y);max(SnCu212_y);max(SnCu213_
y);max(SnCu214_y);max(SnCu215_y);max(SnCu216_y);max(SnCu221_y);max(Sn
Cu222_y);max(SnCu223_y);max(SnCu224_y);max(SnCu225_y);max(SnCu226_y)]
;
mean_all_SnAg =mean(avg_all_SnAg);
mean_all_SAC =mean(avg_all_SAC);
mean_all_SnCu =mean(avg_all_SnCu);

```

```

avg_bl_SnAg = [max(A111_y); max(A112_y);max(A113_y);
max(A114_y);max(A115_y);max(A116_y);max(A121_y);max(A122_y);
max(A123_y); max(A124_y);max(A125_y);max(A126_y); max(A211_y);
max(A212_y);max(A214_y); max(A215_y);max(A216_y);
max(A221_y);max(A222_y);max(A223_y);max(A224_y);max(A225_y);max(A226_
y)];
avg_bl_SAC =
[max(SAC111_y);max(SAC112_y);max(SAC113_y);max(SAC115_y);max(SAC116_y
);max(SAC121_y);max(SAC122_y);max(SAC123_y);max(SAC124_y);max(SAC125_
y);max(SAC126_y);max(SAC211_y);max(SAC212_y);max(SAC213_y);max(SAC214_
y);max(SAC215_y);max(SAC216_y);max(SAC221_y);max(SAC222_y);max(SAC22
3_y);max(SAC224_y);max(SAC225_y);max(SAC226_y);max(SAC311_y);max(SAC3
12_y);max(SAC313_y);max(SAC314_y);max(SAC315_y);max(SAC316_y);max(SAC
321_y);max(SAC322_y);max(SAC323_y);max(SAC324_y);max(SAC325_y);max(SA
C326_y)];
avg_bl_SnCu =
[max(SnCu112_y);max(SnCu113_y);max(SnCu114_y);max(SnCu115_y);max(SnCu
116_y);max(SnCu121_y);max(SnCu122_y);max(SnCu123_y);max(SnCu124_y);ma
x(SnCu125_y);max(SnCu126_y);max(SnCu212_y);max(SnCu214_y);max(SnCu215_
y);max(SnCu216_y);max(SnCu221_y);max(SnCu222_y);max(SnCu223_y);max(S
nCu224_y);max(SnCu225_y);max(SnCu226_y)];
mean_bl_SnAg =mean(avg_bl_SnAg);
mean_bl_SAC = mean(avg_bl_SAC);
mean_bl_SnCu = mean(avg_bl_SnCu);

```

```

avg_thomp_SnAg = [max(A111_y); max(A112_y);
max(A114_y);max(A115_y);max(A116_y);max(A121_y);max(A122_y);
max(A124_y);max(A125_y);max(A211_y); max(A212_y);max(A214_y);
max(A215_y);max(A216_y);max(A221_y);max(A222_y);max(A224_y);max(A225_
y);max(A226_y)];
avg_thomp_SAC =
[max(SAC111_y);max(SAC116_y);max(SAC121_y);max(SAC122_y);max(SAC123_y
);max(SAC126_y);max(SAC216_y);max(SAC221_y);max(SAC222_y);max(SAC224_
y);max(SAC311_y);max(SAC312_y);max(SAC314_y);max(SAC315_y);max(SAC321_
y);max(SAC322_y);max(SAC324_y);max(SAC326_y)];
avg_thomp_SnCu =
[max(SnCu112_y);max(SnCu113_y);max(SnCu114_y);max(SnCu122_y);max(SnCu

```

```

123_y);max(SnCu124_y);max(SnCu125_y);max(SnCu126_y);max(SnCu212_y);ma
x(SnCu214_y);max(SnCu215_y);max(SnCu216_y);max(SnCu221_y);max(SnCu222
_y);max(SnCu223_y);max(SnCu224_y);max(SnCu225_y);max(SnCu226_y)];
mean_thomp_SnAg = mean(avg_thomp_SnAg);
mean_thomp_SAC = mean(avg_thomp_SAC);
mean_thomp_SnCu = mean(avg_thomp_SnCu);

```

```

%% PLOTS

```

```

% Original Data

```

```

figure('Name','Original Data','NumberTitle','off')
hold on
subplot(1,3,1)
plot(A111_x, A111_y, A112_x, A112_y, A113_x, A113_y, A114_x, A114_y,
A115_x, A115_y, A116_x, A116_y, A121_x, A121_y, A122_x, A122_y,
A123_x, A123_y, A124_x, A124_y, A125_x, A125_y, A126_x, A126_y,
A211_x, A211_y, A212_x, A212_y, A213_x, A213_y, A214_x, A214_y,
A215_x, A215_y, A216_x, A216_y, A221_x, A221_y, A222_x, A222_y,
A223_x, A223_y, A224_x, A224_y, A225_x, A225_y, A226_x, A226_y)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'),
title('Original Data for SnAg')
subplot(1,3,2)
plot(SAC111_x, SAC111_y, SAC112_x, SAC112_y, SAC113_x, SAC113_y,
SAC114_x, SAC114_y, SAC115_x, SAC115_y, SAC116_x, SAC116_y, SAC121_x,
SAC121_y, SAC122_x, SAC122_y, SAC123_x, SAC123_y, SAC124_x, SAC124_y,
SAC125_x, SAC125_y, SAC126_x, SAC126_y, SAC211_x, SAC211_y, SAC212_x,
SAC212_y, SAC213_x, SAC213_y, SAC214_x, SAC214_y, SAC215_x, SAC215_y,
SAC216_x, SAC216_y, SAC221_x, SAC221_y, SAC222_x, SAC222_y, SAC223_x,
SAC223_y, SAC224_x, SAC224_y, SAC225_x, SAC225_y, SAC226_x, SAC226_y,
SAC311_x, SAC311_y, SAC312_x, SAC312_y, SAC313_x, SAC313_y, SAC314_x,
SAC314_y, SAC315_x, SAC315_y, SAC316_x, SAC316_y, SAC321_x, SAC321_y,
SAC322_x, SAC322_y, SAC323_x, SAC323_y, SAC324_x, SAC324_y, SAC325_x,
SAC325_y, SAC326_x, SAC326_y)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'),
title('Original Data for SAC')
subplot(1,3,3)
plot(SnCu111_x, SnCu111_y, SnCu112_x, SnCu112_y, SnCu113_x,
SnCu113_y, SnCu114_x, SnCu114_y, SnCu115_x, SnCu115_y, SnCu116_x,
SnCu116_y, SnCu121_x, SnCu121_y, SnCu122_x, SnCu122_y, SnCu123_x,
SnCu123_y, SnCu124_x, SnCu124_y, SnCu125_x, SnCu125_y, SnCu126_x,
SnCu126_y, SnCu211_x, SnCu211_y, SnCu212_x, SnCu212_y, SnCu213_x,
SnCu213_y, SnCu214_x, SnCu214_y, SnCu215_x, SnCu215_y, SnCu216_x,
SnCu216_y, SnCu221_x, SnCu221_y, SnCu222_x, SnCu222_y, SnCu223_x,
SnCu223_y, SnCu224_x, SnCu224_y, SnCu225_x, SnCu225_y, SnCu226_x,
SnCu226_y)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'),
title('Original Data for SnCu')
hold off

```

```

figure('Name','Data Above Low Load Threshold
Value','NumberTitle','off')

```



```

hold on
subplot(1,3,1)
plot(A111_x_short, A111_y_short, A112_x_short, A112_y_short,
A113_x_short, A113_y_short, A114_x_short, A114_y_short, A115_x_short,
A115_y_short, A116_x_short, A116_y_short, A121_x_short, A121_y_short,
A122_x_short, A122_y_short, A123_x_short, A123_y_short, A124_x_short,
A124_y_short, A125_x_short, A125_y_short, A126_x_short, A126_y_short,
A211_x_short, A211_y_short, A212_x_short, A212_y_short, A213_x_short,
A213_y_short, A214_x_short, A214_y_short, A215_x_short, A215_y_short,
A216_x_short, A216_y_short, A221_x_short, A221_y_short, A222_x_short,
A222_y_short, A223_x_short, A223_y_short, A224_x_short, A224_y_short,
A225_x_short, A225_y_short, A226_x_short, A226_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnAg')
subplot(1,3,2)
plot(SAC111_x_short, SAC111_y_short, SAC112_x_short, SAC112_y_short,
SAC113_x_short, SAC113_y_short, SAC114_x_short, SAC114_y_short,
SAC115_x_short, SAC115_y_short, SAC116_x_short, SAC116_y_short,
SAC121_x_short, SAC121_y_short, SAC122_x_short, SAC122_y_short,
SAC123_x_short, SAC123_y_short, SAC124_x_short, SAC124_y_short,
SAC125_x_short, SAC125_y_short, SAC126_x_short, SAC126_y_short,
SAC211_x_short, SAC211_y_short, SAC212_x_short, SAC212_y_short,
SAC213_x_short, SAC213_y_short, SAC214_x_short, SAC214_y_short,
SAC215_x_short, SAC215_y_short, SAC216_x_short, SAC216_y_short,
SAC221_x_short, SAC221_y_short, SAC222_x_short, SAC222_y_short,
SAC223_x_short, SAC223_y_short, SAC224_x_short, SAC224_y_short,
SAC225_x_short, SAC225_y_short, SAC226_x_short, SAC226_y_short,
SAC311_x_short, SAC311_y_short, SAC312_x_short, SAC312_y_short,
SAC313_x_short, SAC313_y_short, SAC314_x_short, SAC314_y_short,
SAC315_x_short, SAC315_y_short, SAC316_x_short, SAC316_y_short,
SAC321_x_short, SAC321_y_short, SAC322_x_short, SAC322_y_short,
SAC323_x_short, SAC323_y_short, SAC324_x_short, SAC324_y_short,
SAC325_x_short, SAC325_y_short, SAC326_x_short, SAC326_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)')
ylabel('Stress (lbf/in^2)')
title('Load Bearing Data for SAC')
subplot(1,3,3)
plot(SnCu111_x_short, SnCu111_y_short, SnCu112_x_short,
SnCu112_y_short, SnCu113_x_short, SnCu113_y_short, SnCu114_x_short,
SnCu114_y_short, SnCu115_x_short, SnCu115_y_short, SnCu116_x_short,
SnCu116_y_short, SnCu121_x_short, SnCu121_y_short, SnCu122_x_short,
SnCu122_y_short, SnCu123_x_short, SnCu123_y_short, SnCu124_x_short,
SnCu124_y_short, SnCu125_x_short, SnCu125_y_short, SnCu126_x_short,
SnCu126_y_short, SnCu211_x_short, SnCu211_y_short, SnCu212_x_short,
SnCu212_y_short, SnCu213_x_short, SnCu213_y_short, SnCu214_x_short,
SnCu214_y_short, SnCu215_x_short, SnCu215_y_short, SnCu216_x_short,
SnCu216_y_short, SnCu221_x_short, SnCu221_y_short, SnCu222_x_short,
SnCu222_y_short, SnCu223_x_short, SnCu223_y_short, SnCu224_x_short,
SnCu224_y_short, SnCu225_x_short, SnCu225_y_short, SnCu226_x_short,
SnCu226_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnCu')
hold off

```

```

figure('Name','SnCu Pulloff Tests Original','NumberTitle','off')
plot(SnCu111_x, SnCu111_y, SnCu112_x, SnCu112_y, SnCu113_x,
SnCu113_y, SnCu114_x, SnCu114_y, SnCu115_x, SnCu115_y, SnCu116_x,
SnCu116_y, SnCu121_x, SnCu121_y, SnCu122_x, SnCu122_y, SnCu123_x,
SnCu123_y, SnCu124_x, SnCu124_y, SnCu125_x, SnCu125_y, SnCu126_x,
SnCu126_y, SnCu211_x, SnCu211_y, SnCu212_x, SnCu212_y, SnCu213_x,
SnCu213_y, SnCu214_x, SnCu214_y, SnCu215_x, SnCu215_y, SnCu216_x,
SnCu216_y, SnCu221_x, SnCu221_y, SnCu222_x, SnCu222_y, SnCu223_x,
SnCu223_y, SnCu224_x, SnCu224_y, SnCu225_x, SnCu225_y, SnCu226_x,
SnCu226_y)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'),
title('Original Data for SnCu')

figure('Name','SnCu Pulloff Tests above
threshold','NumberTitle','off')
plot(SnCu111_x_short, SnCu111_y_short, SnCu112_x_short,
SnCu112_y_short, SnCu113_x_short, SnCu113_y_short, SnCu114_x_short,
SnCu114_y_short, SnCu115_x_short, SnCu115_y_short, SnCu116_x_short,
SnCu116_y_short, SnCu121_x_short, SnCu121_y_short, SnCu122_x_short,
SnCu122_y_short, SnCu123_x_short, SnCu123_y_short, SnCu124_x_short,
SnCu124_y_short, SnCu125_x_short, SnCu125_y_short, SnCu126_x_short,
SnCu126_y_short, SnCu211_x_short, SnCu211_y_short, SnCu212_x_short,
SnCu212_y_short, SnCu213_x_short, SnCu213_y_short, SnCu214_x_short,
SnCu214_y_short, SnCu215_x_short, SnCu215_y_short, SnCu216_x_short,
SnCu216_y_short, SnCu221_x_short, SnCu221_y_short, SnCu222_x_short,
SnCu222_y_short, SnCu223_x_short, SnCu223_y_short, SnCu224_x_short,
SnCu224_y_short, SnCu225_x_short, SnCu225_y_short, SnCu226_x_short,
SnCu226_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnCu')

figure('Name','SnCu Pulloff Test - Blowout','NumberTitle','off')
plot(SnCu221_x_short, SnCu221_y_short)
axis([0 .035 0 3700])
rawr = trapz(SnCu221_x_short, SnCu221_y_short)
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnCu')

% Blow-out plots
figure('Name','Blowout Plots','NumberTitle','off')
hold on
subplot(1,3,1)
plot(A213_x_short, A213_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnAg')
subplot(1,3,2)
plot(SAC114_x_short, SAC114_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SAC')
subplot(1,3,3)

```

```

plot(SnCu111_x_short, SnCu111_y_short, SnCu211_x_short,
SnCu211_y_short, SnCu213_x_short, SnCu213_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnCu')
hold off

% Adjusted Plots - No Blowouts
figure('Name','Adjusted Plots - No Blowouts','NumberTitle','off')
hold on
subplot(1,3,1)
plot(A111_x_short, A111_y_short, A112_x_short, A112_y_short,
A113_x_short, A113_y_short, A114_x_short, A114_y_short, A115_x_short,
A115_y_short, A116_x_short, A116_y_short, A121_x_short, A121_y_short,
A122_x_short, A122_y_short, A123_x_short, A123_y_short, A124_x_short,
A124_y_short, A125_x_short, A125_y_short, A126_x_short, A126_y_short,
A211_x_short, A211_y_short, A212_x_short, A212_y_short, A214_x_short,
A214_y_short, A215_x_short, A215_y_short, A216_x_short, A216_y_short,
A221_x_short, A221_y_short, A222_x_short, A222_y_short, A223_x_short,
A223_y_short, A224_x_short, A224_y_short, A225_x_short, A225_y_short,
A226_x_short, A226_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnAg')
subplot(1,3,2)
plot(SAC111_x_short, SAC111_y_short, SAC112_x_short, SAC112_y_short,
SAC113_x_short, SAC113_y_short, SAC115_x_short, SAC115_y_short,
SAC116_x_short, SAC116_y_short, SAC121_x_short, SAC121_y_short,
SAC122_x_short, SAC122_y_short, SAC123_x_short, SAC123_y_short,
SAC124_x_short, SAC124_y_short, SAC125_x_short, SAC125_y_short,
SAC126_x_short, SAC126_y_short, SAC211_x_short, SAC211_y_short,
SAC212_x_short, SAC212_y_short, SAC213_x_short, SAC213_y_short,
SAC215_x_short, SAC215_y_short, SAC216_x_short, SAC216_y_short,
SAC221_x_short, SAC221_y_short, SAC222_x_short, SAC222_y_short,
SAC223_x_short, SAC223_y_short, SAC224_x_short, SAC224_y_short,
SAC225_x_short, SAC225_y_short, SAC226_x_short, SAC226_y_short,
SAC311_x_short, SAC311_y_short, SAC312_x_short, SAC312_y_short,
SAC313_x_short, SAC313_y_short, SAC314_x_short, SAC314_y_short,
SAC315_x_short, SAC315_y_short, SAC321_x_short, SAC321_y_short,
SAC322_x_short, SAC322_y_short, SAC323_x_short, SAC323_y_short,
SAC324_x_short, SAC324_y_short, SAC325_x_short, SAC325_y_short,
SAC326_x_short, SAC326_y_short)
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SAC')
subplot(1,3,3)
plot(SnCu112_x_short, SnCu112_y_short, SnCu113_x_short,
SnCu113_y_short, SnCu114_x_short, SnCu114_y_short, SnCu115_x_short,
SnCu115_y_short, SnCu116_x_short, SnCu116_y_short, SnCu121_x_short,
SnCu121_y_short, SnCu122_x_short, SnCu122_y_short, SnCu123_x_short,
SnCu123_y_short, SnCu124_x_short, SnCu124_y_short, SnCu125_x_short,
SnCu125_y_short, SnCu126_x_short, SnCu126_y_short, SnCu212_x_short,
SnCu212_y_short, SnCu214_x_short, SnCu214_y_short, SnCu215_x_short,
SnCu215_y_short, SnCu216_x_short, SnCu216_y_short, SnCu221_x_short,
SnCu221_y_short, SnCu222_x_short, SnCu222_y_short, SnCu223_x_short,
SnCu223_y_short, SnCu224_x_short, SnCu224_y_short, SnCu225_x_short,
SnCu225_y_short, SnCu226_x_short, SnCu226_y_short)

```

```
axis([0 .07 0 3700])
xlabel('Displacement (in)'), ylabel('Stress (lbf/in^2)'), title('Load
Bearing Data for SnCu')
hold off
```

```
%
figure()
M = [MA MSAC MC];
%x = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3];
x = [xA xSAC xC];
boxplot(M,x)
```

6.2 IMC Size Analysis MATLAB Code

```
% Dot Image Processing
clear all
%% Read image and convert to binary image
close all
% imgNum = 8;
% p = zeros(imgNum,6); BWdist = zeros(imgNum,2); SGdist =
zeros(imgNum,2);

G=(imread('SAC_216.jpg'));
% G(:, :, 2)=0;
% G(:, :, 3)=0;

I=rgb2gray(G);
figure(), imshow(I), title('Grey-scale Image')
% Increase Contrast of gray-scale image
d = imadjust(I, [.55; .6], [0; 1]);
figure(), imshow(d), title('Increased Contrast')
% x=I(2500,:,1);plot(x)
BW= imcomplement(im2bw(d)); % imcomplement
figure(), imshow(BW), title('Inverted Image')

% figure(3), imhist(BW);title('Grayscale Histogram')

bw2 = imfill(BW, 'holes'); % Get rid of islands inside of IMC
figure(), imshow(bw2), title('Islands removed from inside IMC')

bw3=bwmorph(bw2, 'majority',3); % Get rid of isolated white pixels
figure(), imshow(bw3);
```

```

L=bwlabel(bw3);
s = regionprops(L, 'Centroid');
imshow(bw3)
hold on
for k = 1:numel(s)
    c = s(k).Centroid;
    text(c(1), c(2), sprintf('%d', k), ...
        'HorizontalAlignment', 'center', ...
        'VerticalAlignment', 'middle');
end
hold off

```

6.3 SEM-EDS Raw Data

URI ESEM Laboratory

Spectrum Report

Friday, June 19, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 13:50:39

Live Time:	29.99	Count Rate:	4856	Dead Time:	38.81 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

Element	Wt%	At%	ChiSquared	Z Corr	A Corr	F Corr
Cu	39.85	55.30	3.50	0.925	1.041	1.000
Sn	60.15	44.70	12.03	1.060	1.018	1.000
Total	100.00	100.00	3.01			

URI ESEM Laboratory
Spectrum Report
Friday, June 19, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 14:12:58

Live Time: 30.00 Count Rate: 5166 Dead Time: 39.73 %
Beam 20.00 Beam 1.00 Takeoff 45.00
Voltage: Current: Angle:

Element	Wt%	At%	ChiSquared	Z Corr	A Corr	F Corr
C	0.00	0.00	395.88	0.677	2.582	1.000
Sn	80.16	68.38	18.94	1.030	1.009	1.000
Cu	19.84	31.62	2.89	0.900	1.054	1.000
Total	100.00	100.00	3.48

URI ESEM Laboratory
Spectrum Report
Friday, June 19, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 13:50:39

Live Time:	29.99	Count Rate:	4856	Dead Time:	38.81 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_250x_bei_SEI.bmp
Collected: June 17, 2015 11:04:48

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 11:06:25

Live Time:	30.00	Count Rate:	5833	Dead Time:	42.76 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 11:07:19

Live Time:	30.00	Count Rate:	7380	Dead Time:	49.58 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 11:08:20

Live Time:	30.00	Count Rate:	4156	Dead Time:	35.80 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_bump_250x_bei_SEI.bmp
Collected: June 17, 2015 11:28:54

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_bump_250x_bei_SEI_T001.pgt
Collected: June 17, 2015 11:29:44

Live Time:	30.00	Count Rate:	222	Dead Time:	9.04 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_bump_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 11:30:19

Live Time:	30.00	Count Rate:	1470	Dead Time:	19.09 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_bump_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 11:30:57

Live Time:	30.00	Count Rate:	4500	Dead Time:	37.20 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAg_bump_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 11:31:47

Live Time:	30.00	Count Rate:	158	Dead Time:	8.48 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_sub_250x_bei_SEI.bmp
Collected: June 17, 2015 11:48:38

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_sub_250x_bei_SEI_T001.pgt
Collected: June 17, 2015 11:49:38

Live Time:	30.00	Count Rate:	5873	Dead Time:	42.26 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_sub_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 11:50:32

Live Time:	29.99	Count Rate:	2517	Dead Time:	26.06 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_sub_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 11:51:14

Live Time:	30.00	Count Rate:	8006	Dead Time:	51.62 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_sub_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 11:52:17

Live Time:	30.00	Count Rate:	3464	Dead Time:	31.71 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_bump_250x_bei_SEI.bmp
Collected: June 17, 2015 13:25:40

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_bump_250x_bei_SEI_T001.pgt
Collected: June 17, 2015 13:26:35

Live Time:	30.00	Count Rate:	3786	Dead Time:	32.69 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_bump_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 13:27:21

Live Time:	30.00	Count Rate:	4217	Dead Time:	35.08 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_bump_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 13:28:08

Live Time:	30.00	Count Rate:	2321	Dead Time:	23.74 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnAgCu_bump_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 13:28:49

Live Time:	30.00	Count Rate:	3791	Dead Time:	32.51 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI.bmp
Collected: June 17, 2015 13:47:07

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T001.pgt
Collected: June 17, 2015 13:48:00

Live Time:	30.00	Count Rate:	5795	Dead Time:	42.11 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 13:48:53

Live Time:	30.00	Count Rate:	5347	Dead Time:	40.31 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 13:49:45

Live Time:	30.00	Count Rate:	6025	Dead Time:	42.92 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_sub_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 13:50:39

Live Time:	29.99	Count Rate:	4856	Dead Time:	38.81 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Image Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI.bmp
Collected: June 17, 2015 14:11:01

Width(μm): 526.98 Height(μm): 395.24 $\mu\text{m}/\text{pixel}$: 0.515

Scope magnification: 250X

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI_T001.pgt
Collected: June 17, 2015 14:12:07

Live Time:	30.00	Count Rate:	5231	Dead Time:	40.19 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI_T002.pgt
Collected: June 17, 2015 14:12:58

Live Time:	30.00	Count Rate:	5166	Dead Time:	39.73 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI_T003.pgt
Collected: June 17, 2015 14:13:49

Live Time:	30.00	Count Rate:	4904	Dead Time:	38.60 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

URI ESEM Laboratory
Spectrum Report
Wednesday, June 17, 2015

File: C:\URI Data\Brown\Greg\61715\SnCu_bump_250x_bei_SEI_T004.pgt
Collected: June 17, 2015 14:14:40

Live Time:	30.00	Count Rate:	6095	Dead Time:	43.97 %
Beam	20.00	Beam	1.00	Takeoff	45.00
Voltage:		Current:		Angle:

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