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Solder Joint Aging Characteristics
from the MC2918 Firing Set
of a B61 Accelerated Aging Unit (AAU)¹

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ABSTRACT

The B61 accelerated aging unit (AAU) provided a unique opportunity to document the effects of a controlled, long-term thermal cycling environment on the aging of materials used in the device. This experiment was of particular interest to solder technologists because thermal cycling environments are a predominant source of solder joint failures in electronic assemblies. Observations of through-hole solder joints in the MC2918 Firing Set from the B61 AAU did not reveal signs of catastrophic failure. Quantitative analyses of the microstructural metrics of intermetallic compound layer thickness and Pb-rich phase particle distributions indicated solder joint aging that was commensurate with the accelerated aging environment. The effects of stress-enhanced coarsening of the Pb-rich phase were also documented.

1. Introduction

A B61 (6,8) weapon (minus the pit) was subjected to a thermal cycling environment at Los Alamos National Laboratory, for a period of time beginning December 12, 1989 and completed in January-February 1996 time frame, as part of an accelerated aging unit (AAU) program. The unit was exposed to a two-week long cycle, comprised of the following segments:

0 - 160 hours:	5 cycles	50°C to 70°C
160 - 220 hours:	1 cycle	70°C to -18°C
220 - 336 hours:	1 cycle	hold at 60°C
		return to 50°C

repeat ...

An unplanned excursion occurred in the course of the testing in which the unit was exposed to a temperature of 130°C for 18-24 hours. Although this particular "mod" of the B61 did not reach production status, its systems and components are widely used in the enduring stockpile.

Thermal cycling environments have the potential to cause significant degradation to solder joints in weapon system electronics. The temperature variations induce mechanical fatigue damage in the joints as a consequence of the thermal expansion mismatch between the various materials which comprise the joint. Clearly, the electronics packages in the accelerated aging B61 unit provided a unique opportunity to document the effects of thermal cycling on solder joint reliability. Moreover, such data provide a means to validate models currently being developed to describe the evolution of solder joint microstructures under these and similar, environmental conditions.

This report describes a microstructural analysis of the solder joints taken from electronic circuit boards that were part of the MC2918 Firing Set component in the B61 AAU unit. A qualitative

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examination of the solder joints for large-scale damage was followed by the quantitative assessment. The two quantitative metrics used to describe solder joint aging were: (1) the thickness of the intermetallic compound (IMC) layer that formed at the interface between the 63Sn-37Pb solder and the Cu conductor features and (2) the Pb-rich phase particle size distribution as it existed within the Sn-rich matrix. The reader is referred to Reference [1] for a more detailed description of the data acquisition techniques.

The IMC layer forms initially at the time of solder joint manufacture (Fig. 1). The layer is comprised of the line (or ordered)

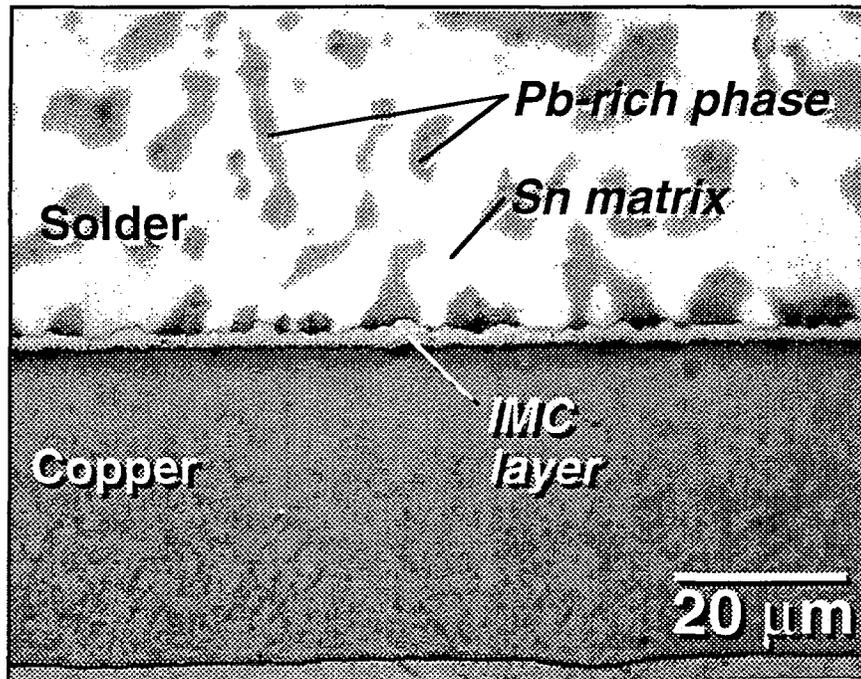


Fig. 1 Optical micrograph of the intermetallic compound (IMC) layer and Pb-rich phase particles for the 63Sn-37Pb solder/Cu solder joint from the MC2918 firing set of the B61 AAU.

compound Cu_6Sn_5 . The thickness of the IMC layer at the time of manufacture was extrapolated from baseline measurements performed on test vehicles assembled by operators at the Kansas City plant. The layer can thicken further after formation of the joint by thermally activated, solid-state diffusion processes. The Arrhenius expression models the IMC layer thickness (x) to an isothermal aging time (t) and aging temperature (T) via the equation:

$$x - x_0 = A t^n \exp(-\Delta H / RT) \quad (1)$$

where x_0 is the initial layer thickness ($0.714 \pm 0.269 \mu\text{m}$); A is the pre-exponential constant; ΔH is the apparent activation energy; and R is the universal gas constant. The solid-state growth kinetics of the total IMC layer were determined from isothermal aging experiments on 63Sn-37Pb solder/Cu diffusion couples. The equation, expressed in MKS units, is:

$$x - 0.71 \times 10^{-6} = 3.265 \times 10^{-3} t^{0.58} \exp(-6282 / T) \quad (2)$$

The second quantitative metric of the solder joint structure is the size distribution of the Pb-rich phase particles located in the solder microstructure (Fig. 1). Under thermally activated, solid-state diffusion processes, the Pb-rich phase particles will coarsen with time; the rate of coarsening being a function of the temperature conditions and time duration. The coarsening kinetics of the microstructure were determined from aging experiments performed on 63Sn-37Pb solder/Cu couples

under similar conditions. An Arrhenius equation, based upon MKS units, with the exception being that the particle size is represented in mm^2 is:

$$x - 4.17 \times 10^{-6} = 1.47 \times 10^{-3} t^{0.32} \exp(-3728 / T) \quad (3)$$

Solder joints were examined from circuit boards contained in the MC2918 Firing Set of the AAU. Those data were statistically analyzed; the results were introduced into Equations (2) and (3), respectively. Assuming a time duration of *six (6) years*, an effective (isothermal) aging temperature was computed for each of the two metrics. Those results are discussed below.

2. Results and Discussion

The IMC layer thickness and Pb-rich phase particle size analyses were conducted on four pairs of through-hole solder joints (total of eight solder joints) from the oscillator circuit board of the MC2918 firing set. Two separate regions were examined for a total of 16 data points per either the IMC layer thickness or mean particle size parameters. The mean IMC thickness value was determined to be $1.96 \mu m$. Putting this value into equation (2) and using a time value of 6 years (1.89×10^8 s), an effective, isothermal aging temperature was determined to be: $59^\circ C$. Similarly, a mean Pb-rich phase particle size was computed from the solder joint data; that value was $2.44 \times 10^{-5} mm^2$. Introducing the mean particle size into equation (3) resulted in an effective, isothermal aging temperature of $85^\circ C$.

It is noted that the effective aging temperature calculated by the two parameters were significantly different. It was hypothesized that the difference arose from the fact that, unlike IMC layer development, the Pb-rich phase particle size is also sensitive to mechanical stresses that are present in the joint. Such stresses arise from temperature cycling, coupled with the thermal expansion mismatch between the pins, the solder, and the circuit board laminate. The stresses accelerate the coarsening of the particle size distribution[2]. In order to confirm this hypothesis, the Pb-rich phase particle sizes from lug joints on a neighboring circuit board were similarly analyzed. The lug geometry exposed the solder to a considerably reduced level of residual stresses. The mean particle size from the lug joints was determined to be $1.21 \times 10^{-5} mm^2$, corresponding to an effective, isothermal aging temperature of $56^\circ C$. This effective temperature corroborates that which was calculated from the IMC data.

3. Conclusions

A model which predicts the thermally activated, solid-state growth of the IMC layer and that which describes coarsening of the Pb-rich phase particles were evaluated with the solder joint microstructures from the electronic firing set component in a B61 AAU. An effective, isothermal aging temperature of $59^\circ C$ was computed from IMC layer growth. Analysis of the Pb-rich particles in the same joints resulted in a significantly higher effective temperature, $85^\circ C$. The discrepancy was observed to have been caused by the role of mechanical stress which accelerates the coarsening mechanism of the Pb-rich phase particles beyond that arising from the solely elevated temperature environment.

These illustrate the capability of the Arrhenius, isothermal models to predict IMC layer growth and Pb-rich phase particle coarsening caused by elevated temperature environments. These models have been introduced into a computer algorithm which explicitly accounts for non-isothermal (time-dependent) temperature histories, giving a more accurate correlation between the respective microstructural metrics and the aging time and temperature.

4. References

- [1] P. Vianco and J. Rejent, "A Microstructural Analysis of Solder Joints from The Electronic Assemblies of Dismantled Nuclear Weapons." *Sandia Report SAND97-0991*. Sandia National Laboratories, Albuquerque, NM.
- [2] D. Frear, "Thermomechanical Fatigue in Solder Materials," *Solder Mechanics: A State of the Art Assessment* ed. D. Frear, W. Jones, and K. Kinsman (TMS, Warrendale, PA), pp. 191-237.