

Computational Modeling Demonstrates the Joint Clearance Effect on the Tensile Strength of Solder Joints

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Introduction

Soldered joints can be made with a wide range of base materials and filler metals that allow the assembly to meet its performance and reliability requirements. Structural solder joints have, as their foremost requirement, to provide mechanical attachment between base material structures. The joint is typically subjected to one, or a combination of, three loading configurations: (a) tensile or compressive force, (b) shear force, or (c) peel force. Solder filler metals and in particular, the so-called “soft solders” based on tin (Sn), lead (Pb), and indium (In), generally have a bulk strength that is less than that of the base materials. Therefore, deformation occurs largely in the solder when the joint is subjected to an applied force.

The concentration of deformation in the filler metal causes the *joint clearance* to have a significant effect on the *apparent* strength of the solder joint. This point is illustrated, *qualitatively*, in Figure 1. The schematic diagram shows the deformation of the solder (gray arrows) when the joint is placed under a tensile force, F (light-blue arrows). Two limiting cases are presented of joint clearance (A). At the top, the joint clearance is large relative to the joint area or footprint (x by y). The solder can easily deform in the x and y directions as the tensile force pulls on the joint in the z direction. As a result, the solder joint demonstrates a mechanical strength similar to calculated using the bulk material properties of the filler metal. On the other hand, when the joint clearance is small as illustrated at the bottom of Figure 1, the filler metal is constrained from deforming in the x and y directions, which in turn, restricts its deformation in the z direction. The filler metal and thus, the solder joint, appear to be stronger and less ductile than predicted by the solder alloy bulk properties.

A potential, unwanted consequence of the apparent strength increase is that the failure mode may transition from the filler metal to its interface with the base material. Then, the fracture behavior of the joint becomes dependent upon the mechanical properties of the reaction layer at the interface. Those reaction layers are typically comprised of one or more, brittle intermetallic compounds (IMCs). As a result, the failure mode can potentially become one of a premature catastrophic fracture by the joint.

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A second factor that contributes to an apparent strength enhancement of solder joints is that solder alloys and in particular, the Sn- and In-based filler metals, are very strain rate sensitive. Mechanical properties such as yield strength, strain hardening, and ultimate tensile strength increase rapidly in the filler metal with increased loading rate – e.g., when the solder joint is subjected to a mechanical shock or vibration environment. A similar scenario as described above, can occur whereby the increase of solder strength due to a fast loading rate causes the solder joint failure mode to transition from ductile fracture in the filler metal to a brittle fracture along the IMC layer along the solder/base material interface.

Analysis

A computational modeling study was performed to provide a *quantitative* assessment of joint strength as a function of joint clearance and displacement rate, the latter correlating to loading rate. The modeling approach was selected because an empirical study would be resource-intensive if it were to address even nominal ranges of joint clearances and strain rates. The study considered the 63Sn-37Pb (wt.%, abbreviated Sn-Pb) solder. Calculations, which are not reported here, confirmed that the Sn-Pb solder predictions provide a very good approximation for Sn-based, Pb-free solders such as the Sn-Ag-Cu alloys. The model predicted the engineering stress-strain curves for each of the cylindrical test specimens shown in Figure 2. The base material structures were copper (Cu) cylinders, each measuring 1.27 mm in diameter and 1.27 mm in length. The joint clearances ranged from 0.0254 mm to 0.381 mm, which represent values relevant to most applications. Two displacement rates were evaluated: 0.0508 mm/min and 1.016 mm/min. The model was executed for three temperatures: -55°C, 25°C, and 125°C; however, only the 25°C data will be presented in this report for brevity.

Results

The discussion of modeling results begins with Figure 3, which shows the compilation of engineering stress-strain curves as a function of joint clearance for the slow strain rate of 0.0508 mm/min. The failure criterion was established when the finite element obtained an equivalent plastic strain (EQPS) of 0.80. As additional elements reached the EQPS value of 0.80 and failed, the curve exhibited the drop-off in engineering stress. The model predictions also included the two limiting cases of a pure Cu cylinder, that is, without a solder joint (solid black curve), and a pure Sn-Pb solder cylinder (dashed black curve). The effect of solder joint clearance is significant. The 0.0254 mm joint clearance caused the engineering stress-strain curve to nearly duplicate that of the pure Cu test specimen until failure. In effect, that test specimen performed as though the solder joint was not present. On the other hand, the joint clearance of 0.381 mm caused the engineering stress-strain curve to approach that of the bulk solder (dashed black curve). The test specimen strength became more like that that would be calculated, based upon the mechanical properties of the bulk solder. Nevertheless, a modest strength enhancement was still realized, even with the 0.381 mm joint clearance.

The contour plots show the spatial distribution of the EQPS in the solder joint and Cu cylinders for the second-smallest joint clearance and the largest joint clearance of 0.0635 mm and 0.381 mm, respectively. Each starting joint clearance is noted by “A.” The corresponding test points were identified by the red circles and numbers (1), (2), (3), and (4) along the respective engineering stress-strain curve. The case of the small joint clearance, 0.0635 mm (light-green curve) showed deformation and subsequent necking to begin in the solder (1), but then quickly progress into the

Cu base material (2). In effect, the thin solder joint caused the test specimen to have a strength close to that of the pure Cu base material. Note the pure Cu curve (solid black) did not show necking. The solder joint caused necking in the Cu base material because of the stress concentration, which was created by the material discontinuity between the Sn-Pb solder and the Cu base material. On the other hand, the joint clearance of 0.381 mm did not cause significant deformation in the Cu base material. Necking occurred only in the solder at points (3) and (4) and stayed there for the remainder of the engineering stress-strain curve.

The modeling analysis was repeated with the fast displacement rate of 1.016 mm/min. The engineering stress-strain plots and EQPS contour maps are shown in Figure 4. The same increase of apparent joint strength took place with decreasing joint clearance, but having a greater magnitude due to the contribution of strain hardening by the Sn-Pb solder. The test sample curve representing the 0.0635 mm joint clearance remained nearly equivalent to that of the pure Cu test specimen. As expected, necking occurred sooner in the solder at the faster strain rate and as such, more quickly in the Cu base material. The 0.381 mm joint clearance had an engineering stress-strain curve that approached that of pure Sn-Pb solder sample, but to a lesser degree because the faster displacement rate caused a higher work hardening rate by the Sn-Pb solder. Interestingly, despite the more than an order-of-magnitude increase of strain rate, deformation and necking were limited primarily to the solder.

Summary

A computational model was used to predict the engineering stress-strain curves of Cu/Sn-Pb/Cu solder joints to demonstrate the sensitivity of solder joint strength to joint clearance (0.0254 – 0.381 mm) and displacement rate (0.0508 and 1.016 mm/min). As the joint clearance became smaller, the stress-strain curves approach that of a pure Cu cylinder. Effectively, the solder joint had the same strength as the base material. As the joint clearance increased, the apparent test specimen strength decreased towards that of bulk Sn-Pb solder. A faster displacement rate increased the joint strengths across all of the joint clearances. Although a thinner joint clearance offers the benefit of a higher strength, it also risks a transition in the failure mode to the brittle IMC layer that forms along the solder/base material interface.

Figure captions:

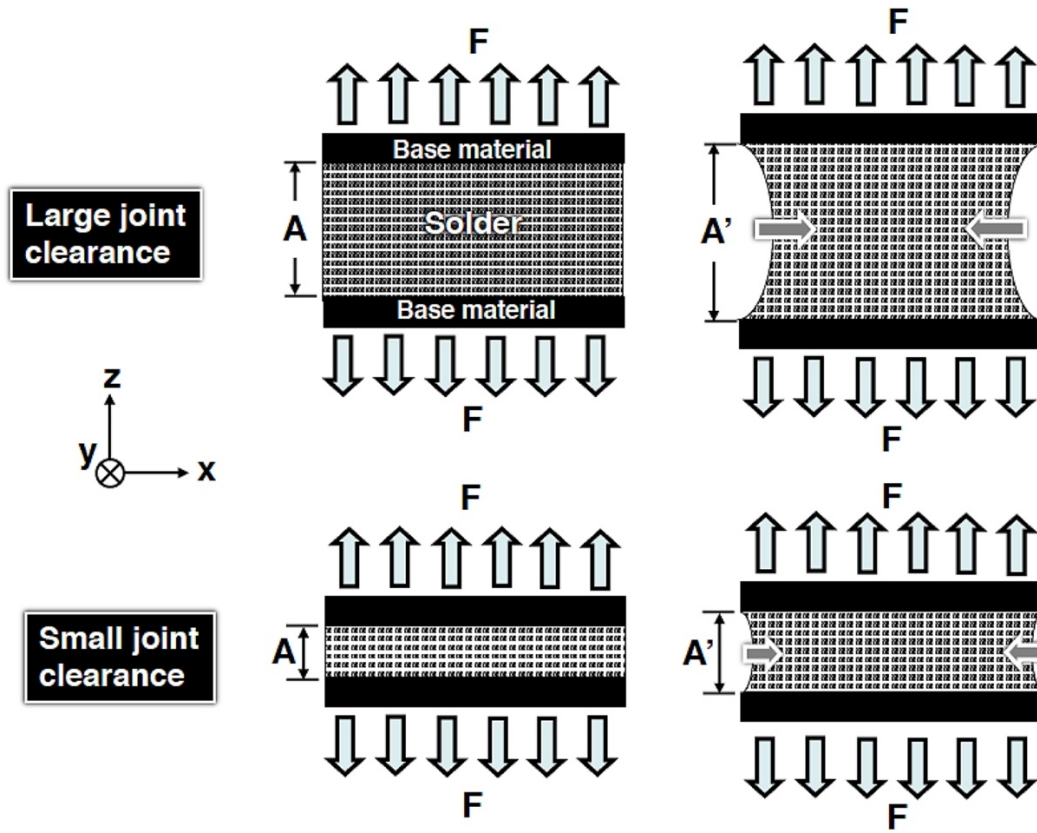


Figure 1 Schematic diagrams illustrate the deformation (gray arrows) that occurs in the solder filler metal under a tensile force, F , (light-blue arrows) as a function of joint clearance.

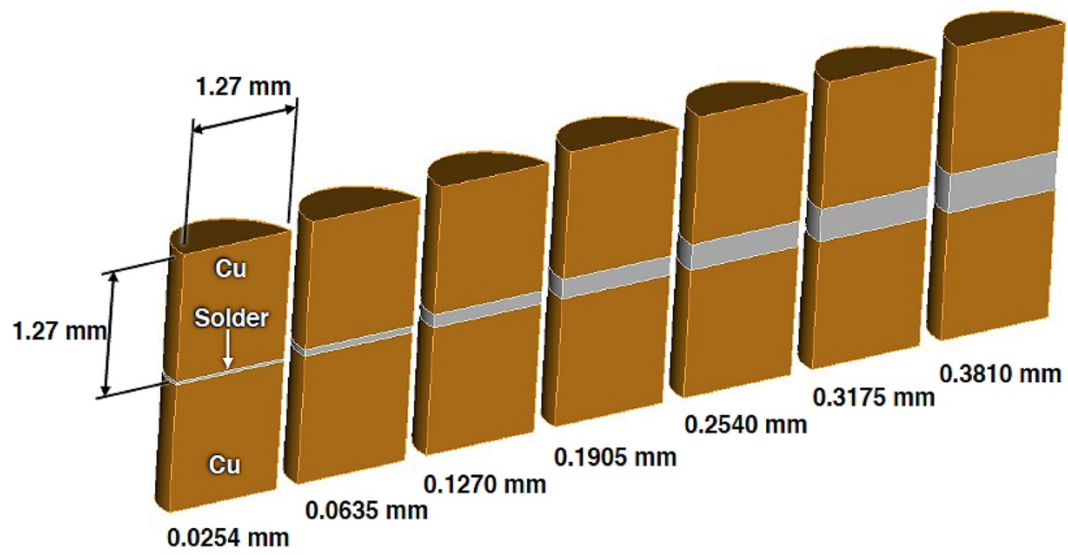


Figure 2 Solid models show the geometries of the test specimens as a function of joint clearance that were evaluated by the computational model.

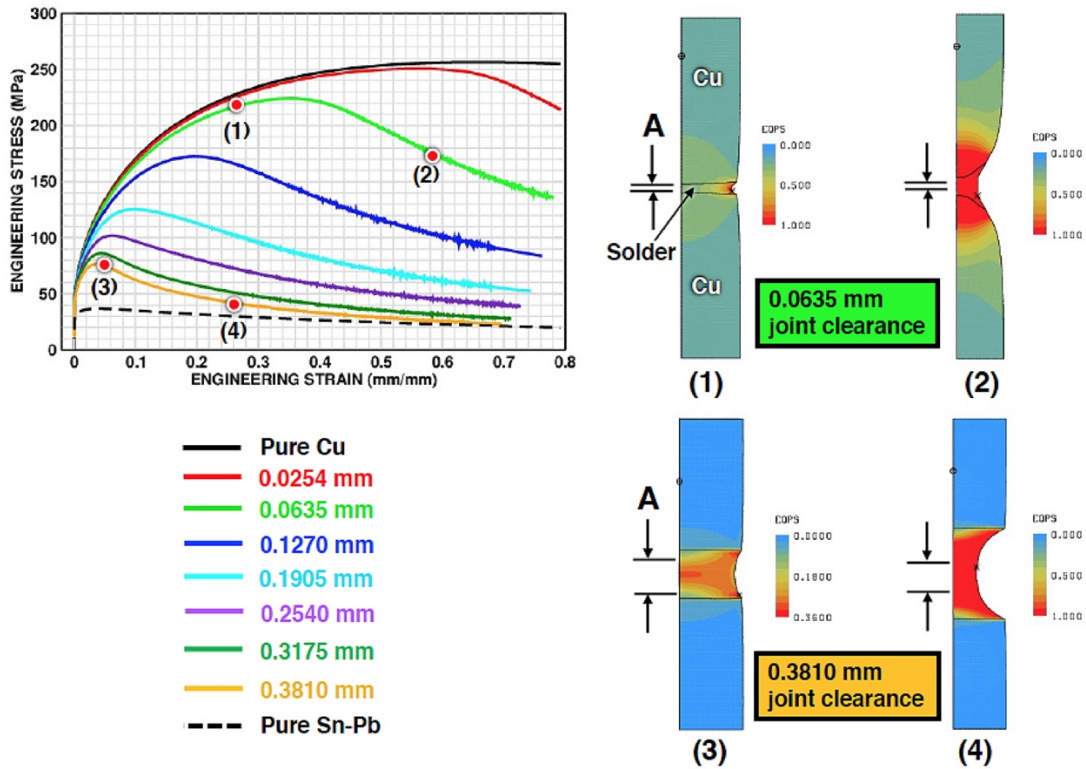


Figure 3 Engineering stress-strain curves show the deformation of the test specimens as a function of joint clearance for the model conditions of 25°C and displacement rate of 0.0508 mm/min. The contour diagrams are provided of the equivalent plastic strain (EQPS) for the 0.0635 mm and 0.3810 mm joint clearances at the engineering strain points in the curve identified by the red circles and corresponding numbers (1), (2), (3), and (4). The initial joint clearance is noted by “A.”

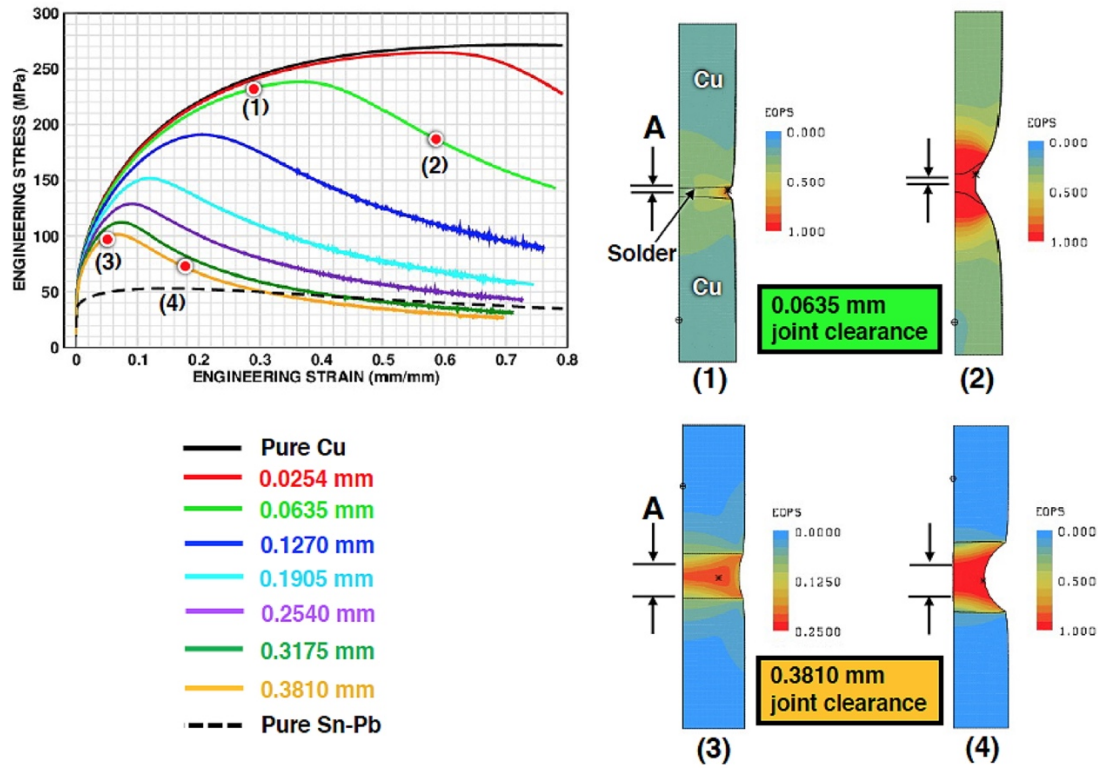


Figure 4 Engineering stress-strain curves show the deformation of the test specimens as a function of joint clearance for the model conditions of 25°C and displacement rate of 1.016 mm/min. The contour diagrams are provided of the equivalent plastic strain (EQPS) for the 0.0635 mm and 0.3810 mm joint clearances at the engineering strain points in the curve identified by the red circles and corresponding numbers (1), (2), (3), and (4). The initial joint clearance is noted by “A.”