Quantifying the effect of porosity on the evolution of deformation and damage in Sn-based solder joints by X-ray microtomography and microstructure-based finite element modeling

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Abstract

The presence of reflow porosity in Sn-based solder alloys is one of the key factors affecting their reliability and mechanical performance. In this study we have used X-ray microtomography to visualize the reflow porosity in a Pb-free solder joint and to reconstruct a three-dimensional model based on the exact geometry of the pores. Interrupted shear tests and subsequent tomography were conducted to image the joint at several stages of deformation. The initial reconstructed microstructure was used as a basis for a finite element (FE) model to simulate damage and predict failure of the single lap shear joint. Sphericity analysis was conducted to verify the accuracy of the FE results. The deformation predicted by the FE simulation incorporating the ductile damage model showed very good agreement with experimental observations. The model was also able to accurately predict the crack nucleation sites and propagation path.

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1. Introduction

The demand for increasingly high functionality and performance of consumer electronics has led to the miniaturization of electronic packaging [1]. As device and interconnect sizes decrease managing microstructural defects becomes increasingly important to ensure reliability. A common cause of premature failure in metallic interconnects is the presence of porosity. Pores are introduced during melting of the alloy in the package, due to entrapment of outgassing flux by the contact pads [2]. Porosity causes weakening of the joint, a loss in ductility due to strain localization around the region of the pores, a reduction in thermal and electrical conductivity, and premature fatigue life failure [3–6]. Several studies have qualitatively described the effect of porosity on thermo-mechanical performance. Lau and Erasmus [7] studied the effect of void size, location, and fraction on the reliability of Sn–Pb solders for bump chip carriers (BCCs) under a thermal cycling load using two-dimensional (2D) finite element (FE) models and crack propagation using fracture mechanics. They concluded that the void size and void location could play important roles in the accumulated inelastic strain of the solder bumps. They stated that joints with a less than 20% void fraction did not affect the reliability of the joint. They also stated that crack propagation could be arrested due to the presence of a void. Gonzalez et al. [3] conducted 2D FE thermal fatigue modeling of voided solder balls including different sizes and positions of the voids inside the joint and the existence of single and multiple voids. They observed that inelastic strain in the case of a single void is not much larger than that of an unvoided joint. However, if several voids were located next to each other the accumulated strain was much larger. Terasaki and Tanie [8] conducted three-dimensional (3D) FE modeling of solder joints with spherical and hemispherical voids.

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Their main conclusion was that the life reduction effect was stronger for hemispherical voids when the void area ratio was higher than 15%. They also conducted 2D FE modeling of the effect of void location on crack propagation. Their calculations revealed that if the void is located at the center of the joint cracks propagate from the joint edge towards the center of the void. An increase in distance between the center of the void and the joint interface resulted in slower crack propagation [8]. Gao et al. [9] and Xu et al. [10] showed similar results based on pore size and location in Al alloys, and Gao et al. also showed that spherical porosity caused enough stress intensification around the pore to debond nearby Si particles from the matrix and significantly reduce the fatigue limit [11]. Li et al. [12] and Shen and Brinson [13] modeled the effect of pores on the strength of Ti. Most of the modeling studies described above incorporate an over-simplified geometry of the microstructure. Hence, the results obtained from these analyses cannot be experimentally verified.

A clear understanding of the influence of pore characteristics, namely size, shape, and distribution within the solder joint, is required to understand the microstructural influence on deformation behavior of these materials. The onset of strain localization due to porosity is a complex function of pore size, pore clustering, pore spacing, and pore shape. Generally, it is known that larger pores have more influence on mechanical behavior, but the effect of smaller pores cannot be neglected, particularly when there is clustering of the pores. Furthermore, pores that are very closely spaced will be highly susceptible to strain localization [14,15]. Thus it is important to have a thorough knowledge of the influence of pore characteristics, and the interplay between them, on the deformation behavior of metallic alloys. More importantly, a concurrent means of quantifying the evolution of microstructure, by experiments and modeling in three dimensions, over time is required.

A fundamental understanding of porosity in metallic alloys requires a means of visualizing and quantifying the pores in three dimensions. Furthermore, a means of visualizing the changes in the microstructure under an applied stimulus, e.g. mechanical load, as a function of time gives us a fourth dimension. Several techniques have been developed to visualize microstructural features in three dimensions. Two of the most widely used techniques are serial sectioning combined with optical microscopy [16,17] and focused ion beam milling [18,19], with image reconstruction to visualize the microstructure in three dimensions. This allows limited microstructural evolution analysis [20], and the destructive nature of serial sectioning precludes any true four-dimensional (4D) analysis. X-ray computed tomography (CT) is an excellent technique to quantify microstructures non-destructively. X-ray microtomography imaging tools with resolution limits of around 1 μm have been developed with synchrotron [21–24] as well as laboratory scale X-ray sources [25,26]. The non-destructive nature of this technique enables us to study the evolution of damage in the material, giving a better understanding of how microstructural features control the damage process.

X-ray tomography has been used as a basis for obtaining microstructurally realistic FE models. The detrimental effects of porosity have been examined in several metallic systems. Nicoletto et al. [27] simulated the stress concentration around individual casting pores in Al-Si, improving on previous spherical pore approximation models. Vanderesse et al. [28] incorporated realistic casting pore microstructures into an elastic FE model to predict stress fields around pores. Weck et al. [29] looked at the plasticity and coalescence of artificially created voids in copper using in situ tensile testing in a tomography set-up, and compared the results with a number of void growth models. Li et al. [30] conducted a 4D study in which a cast Al specimen was imaged by tomography before and after fatigue cycling. Using an elastic–plastic model that incorporated the casting porosity they showed that an area of initially high stress localization due to porosity eventually develops a fatigue crack after cycling. Similarly, Youssef et al. [31] gave qualitative comparisons of pore shape changes in a metallic foam, determined by X-ray tomography experiments and FE simulations.

A systematic, thorough, side-by-side comparison of the evolution of damage due to porosity by X-ray tomography coupled with a microstructure-based FE model of simulation has yet to be conducted. Furthermore, FE models are required that predict the onset and evolution of damage caused during deformation and simulate porosity-induced failure. Indeed, X-ray tomography is an excellent tool for this analysis because not only does it provide a microstructurally realistic input to modeling [32], but it allows validation of those models by being able to measure actual 3D deformation over time.

In this work the effect of reflow porosity on the deformation behavior of a single lap shear joint composed of Sn–3.9Ag–0.7Cu solder reflowed between copper bars was studied. A laboratory scale XRAdia Micro XCT was utilized to image the pores in the joint as a function of strain. Our previous work [33] has shown that numerical models incorporating only a simplified geometry of the microstructural features do not accurately reproduce the macroscopic stresses and strains. Indeed, the stress and strain state can only be represented accurately using models that incorporate the true geometry of the microstructural features. Hence, a 3D reconstruction of the exact microstructure was incorporated into an FE model to predict the onset and propagation of a crack in the joint using a ductile damage model. Our approach is shown schematically in Fig. 1. Interrupted lap shear tests combined with X-ray tomography were conducted at different strain levels to visualize damage evolution within the joint. It will be shown that the FE model predictions are in good agreement with the X-ray tomographic observations. Thus the combined approach of tomography and numerical modeling can be used as an effective means of predicting failure of a solder joint.
2. Materials and experimental procedure

A single lap shear joint of Sn–3.9Ag–0.7Cu alloy was reflowed between two copper bars. To prepare the joint a 1 × 1 mm square was cut from a 0.5 mm thick sheet of the alloy. The high purity oxygen-free copper bars (approximately 1 × 1 × 10 mm) were mechanically polished to a 0.05 µm colloidal silica finish, and masked with graphite, leaving a 1 × 1 mm area for the solder to bond. The unmasked region of each copper bar was coated with a thin layer of mildly activated rosin flux in order to optimize wetting. The copper bars and solder were then fixed in place using a jig to maintain the alignment of the joint, and reflowed on a hotplate. The joint was heated to a peak temperature of 275 °C and held above the melting point of the Sn–3.9Ag–0.7Cu alloy for 100 s. The joint was then air cooled on an Al block that cooled at a reproducible rate of 1.7 °C s⁻¹. More details of the reflow processes for these joints can be found elsewhere [34].

To track the evolution of the Sn alloy microstructure during shear deformation the lap shear joint was first imaged using X-ray microtomography in the as-reflowed state, and then loaded in shear using a microforce testing system (Tytron 250, MTS Systems, Minneapolis, MN). The joint was sheared at a constant strain rate of 10⁻³ s⁻¹. More details of the reflow processes for these joints can be found elsewhere [34].

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After a given strain was applied the sample was removed from the test fixture and imaged again using X-ray tomography. X-ray microtomography using a commercial X-ray tomography system (MicroCT-200, XRadia, Concord, CA) was used to image the solder joint after reflow and as a function of strain. A series of 745 images, taken at angular increments of 0.25°, was acquired at a specimen–source distance of 35 mm, a specimen–detector distance of 8 mm, and an accelerating voltage of 150 kV. These settings resulted in a resolution of approximately 2 µm. These images were reconstructed using the XRadia Reconstructor software into a 3D model of the microstructure which was subsequently sliced into a stack of parallel cross-sections. Each virtual cross-section was spaced 2.16 µm apart and saved as a tagged image file (TIFF) image with square pixels of 2.16 µm. Each cubic element (voxel) of the resulting stack represented the absorption contrast of a 10 µm³ volume. This process was repeated several times, producing tomographic datasets at 0, 0.05, 0.12, 0.18, and 0.44 shear strain. Details of image segmentation and reconstruction for quantitative analysis and incorporation into the FE analysis is provided in the next section.

3. Results and discussion

3.1. Experimental 3D visualization and quantification of damage

The image datasets were segmented using commercial tomographic reconstruction software (Mimics 13.1, Materialise, Ann Arbor, MI). Segmentation was done by dividing the dataset into masks (corresponding to solder, pores, and the “background”). Simple thresholding was inadequate for separating solder and pores, due to the relatively low contrast. This was especially true for smaller pores (<20 µm). We used a Livewire algorithm, implemented in three dimensions in the Mimics software, to segment the pores. Working on a virtual cross-section of the joint, the operator selects a starting point for segmentation along
the edge of a feature of interest. The software then generates in real time a livewire connecting the starting point with the current location of the cursor. The livewire line strongly tends to follow edges, and is guided by the user completely around the feature in a loop by the selection of additional points. The result is a quickly defined, accurate boundary contour that delineates the feature from the rest of the image. To complete segmentation of the feature in three dimensions a second contour is drawn on an orthogonal plane, at which point the software automatically contours the feature on the third orthogonal plane, creating a 3D mask of the object. Simple high contrast geometries can be segmented with as little as one contour in each of the two manually defined directions, while complicated shapes often require several contours.

The Livewire tool is able to follow edges by assigning a “cost” to every possible path between the starting point and cursor. Paths that have the characteristics of an edge will be given lower costs through the use of a local cost function. The cost function in Mimics gives the cost of travel from a pixel \( p \) to an adjacent pixel \( q \) as:

\[
l(q) = \omega_G \cdot f_G(q) + \omega_Z \cdot f_Z(q)
\]

where \( \omega \) are weight terms that are added to unity, \( f_G \) corresponds to the gradient magnitude, and \( f_Z \) to the Laplacian zero crossing. The gradient magnitude term assigns a low cost to pixels with a high 2D color gradient, a common feature of interfaces or edges in images. The Laplacian zero crossing term uses local maxima in a gradient to identify edge pixels, assigning them a low cost. The path calculation also considers an “attraction parameter” that determines whether small cavities in the boundary of an object are followed closely or bridged. Both the weight factor and the attraction parameter can be modified by the user \([35–39]\) (D. Beski, personal correspondence).

While the Livewire technique is more time consuming than the simpler thresholding segmentation technique, an accurate, repeatable representation of each of the pores in the joint is critical to correctly simulating the joint behavior in four dimensions, and the Livewire semi-automatic approach better captures the pore boundaries than user-defined threshold limits. After segmentation the body of the solder and each of the included pores were reconstructed in three dimensions in Mimics. This was accomplished by applying a surface mesh to each mask, with a smoothing algorithm applied to remove surface artifacts from the reconstruction process. The smoothing parameters used were 2 iterations of smoothing with factor 1.0, 10 iterations of advanced edge triangle reduction with angle 60°, and a \( 2 \times 2 \) matrix reduction. These settings consistently produced smooth 3D models suitable for FE meshing.

The interrupted shear stress–shear strain curves from each step are plotted in Fig. 2, showing good agreement with the curve produced by uninterrupted shear loading of a comparable joint. The shear strain was measured using two different techniques. The first consisted of measuring the displacement using a displacement gage attached to the loading arm of the microforce testing system, and dividing by the thickness of the joint. The second method corresponded to measuring the displacement of the solder from the images obtained by X-ray tomography. Both measurements show good correlation at all of the strains measured. Representative 2D images of the joint at different stages are shown in Fig. 3a. After acquisition the joints were segmented using the Livewire algorithm and reconstructed in three dimensions (Fig. 3b). Note that due to the time required for segmentation and the difficulty in segmenting cracked/coalesced pores only a fraction of the pores are shown in the deformed models in Fig. 3b. The deformed tomography images show that most of the strain was localized in the lower half of the joint. At intermediate strain (\( \gamma = 0.18 \)) no cracking is observed, but the pores in the lower half of the joint elongate while the pores in the upper half remain relatively unchanged. After the onset of fracture (\( \gamma = 0.44 \)) cracks are seen propagating through the pores near the lower solder/Cu interface, and the few pores that are not split by a crack show very large elongation. Using X-ray tomography to image the joint at intermediate stages of strain allows the progression of deformation to be compared with the FE model (Fig. 3c). These results are presented in the next section.

3.2. Microstructure-based finite element modeling

FE modeling was used to model the deformation of the solder joint and to predict the initiation and propagation of cracks by incorporating a progressive ductile damage model \([40,41]\). The reconstructed model was imported into commercial meshing software (Hypermesh v. 9.0, Altair Engineering Inc., Troy, MI) to generate a volume mesh. The meshing was conducted using linear tetrahedral elements (C3D4) in such a way that there was a highly refined mesh around the region of all the pores, as shown in Fig. 4a. The mesh was allowed to grow gradually into
the matrix so that the total number of elements in the final model did not significantly increase the computation time. The final meshed model has 1728,106 elements. The meshed model was exported to Abaqus v. 6.10 (Dassault Systems Simulia Corp., Providence, RI) for further analysis.

The 3D computational model used for the analysis is shown in Fig. 4b. The solder joint is attached to copper bars at the top and bottom of the joint as in the physical joint. The copper bar at the bottom is fixed in all three translational directions while the copper bar on the top is fixed in the y and z directions and displaced in the x direction.

Fig. 3. (a) Cross-sections of a plane though the solder joint at the indicated shear strains. (b) 3D reconstructions of tomography data showing solder (yellow) and reflow pores (red). At 18% and 44% strain only those pores with significant deformation are shown to assist in visualization of the shape changes of the pores. (c) Deformed FE models produced by simulating shear deformation for 0% reconstruction, showing good agreement with the experimental results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. (a) Meshed model showing the pores. A cross-section along the thickness of the joint shows the refined mesh around the pores and a relatively coarser mesh in the matrix. (b) 3D model for FE analysis. The copper bar on the bottom was fixed in all three translational directions while the copper bar on the top was fixed in the y and z directions and displaced in the x direction.
the $x$ direction to obtain shear deformation of the solder joint up to a nominal strain of 0.9.

In the model the copper bars are modeled as linear elastic with a Young's modulus of 114 GPa, Poisson ratio of 0.31, and density of 8.92 g cm$^{-3}$. The Sn–3.9Ag–0.7Cu solder was modeled as an elastic–plastic solid with a Young's modulus of 48 GPa, Poisson ratio of 0.33, and density of 7.29 g cm$^{-3}$. The plastic properties of solder used for the model were obtained from tensile stress–strain data for Sn–3.9Ag–0.7Cu solder. The ultimate tensile strength (UTS) of the joint was about 38 MPa at a plastic strain of 0.1252, beyond which perfectly plastic behavior was assumed.

Initially a basic elastic–plastic simulation was conducted to obtain insight into the stress–strain behavior of the joint and to determine the regions of strain localization which are the most likely sites for crack nucleation. Next we incorporated a damage model capable of simulating failure of the joint. The progressive ductile damage model available in Abaqus was used to simulate ductile failure of the solder joint. A schematic of the ductile damage response of a material is represented in terms of the stress–strain curve shown in Fig. 5. The initial response of the material is linear elastic and is represented by region 1–2 in the plot. This is followed by plastic yielding of the material in region 2–3. Beyond point 3 there is a reduction in stress carrying capacity of the material with further straining until rupture at point 4. In the absence of damage the stress in the material would increase with increasing strain beyond point 3, as shown in the region 3–4 of the curve. Point 3 corresponds to the material state at which damage initiates and point 4 is the point at which the material fails completely and has no stress carrying capacity. The region 3–4 of the curve represents the damage evolution path of the material during which gradual degradation of the material stiffness takes place. The damage process is defined in terms of a scalar damage parameter $D$ such that:

$$\sigma = (1 - D)\sigma$$

(2)

where $\sigma$ is the stress tensor in the current increment and $\sigma$ is the flow stress in the absence of damage. Thus, at the onset of damage $D = 0$ and at material failure $D = 1$. Once a finite element reaches the material failure point it is removed and a crack is developed in the model. As the material is strained more elements reach the failure criterion and eventual cracking of the model takes place by the linkage of pores. Thus the ductile damage response of a material is specified in three parts: damage initiation point, damage evolution path, and failure point.

The ductile damage initiation ($D = 0$) point is specified in terms of equivalent plastic strain at the onset of damage $\varepsilon_{pl}^D$, which is a function of stress triaxiality $\eta$ and the strain rate $\dot{\varepsilon}_{pl}$. In the present study $\varepsilon_{pl}^D$ is assumed to be independent of the stress triaxiality, for the sake of simplicity and due to lack of experimental data to define the functional form [42]. Once damage sets in material softening and strain localization take place, which display a strong mesh dependency. Hence, the effective plastic displacement $u_{pl}$ is defined by the evolution equation:

$$u_{pl} = L\varepsilon_{pl}$$

(3)

where $L$ is the characteristic length of an element and is defined as the cube root of the integration volume for tetrahedral elements. A linear evolution of damage was assumed so that when the equivalent plastic displacement reaches the failure point $u_{pl}^f$, the damage parameter $D$ becomes unity. The evolution of damage can then be written in terms of the damage parameter as:

$$D = \frac{u_{pl}}{u_{pl}^f}$$

(4)

Thus the ductile damage response is completely specified in terms of two parameters, $\varepsilon_{pl}^D$ and $u_{pl}^f$ [43]. In this study the damage was assumed to initiate at the UTS of the material and $\varepsilon_{pl}^D$ was chosen to be 0.1252, which is the strain at UTS. The characteristic length of the elements varied greatly in the whole model, as shown in Fig. 4a. Such variability in

![Fig. 5. Schematic representation of the ductile damage model [43].](image)

![Fig. 6. Plastic equivalent strain plots at (a) $\varepsilon = 0.37$; (b) $\varepsilon = 0.4$. Higher strain localization is seen at the bottom interface around the vicinity of the two large pores.](image)
element lengths was inevitable to limit the total number of elements in the final model. Since the range of element lengths was quite wide it was not possible to define an average failure displacement value for all the elements in the model. This would have resulted in the failure of elements with characteristic lengths much greater than the average length at a failure strain much lower than the actual failure strain. Thus, to make all the elements in the model fail at approximately the same strain the model was divided into sub-groups based on the element length and appropriate failure displacements were applied to these groups. The different sub-groups and their failure criteria are listed in Appendix A Table A1. The failure displacements correspond to a failure strain of 0.5944.

Fig. 6a illustrates the plastic equivalent strain developed in the model at a nominal shear strain of 0.37. The two large pores near the bottom interface of the joint act as strain localization sites where the highest strain in the model is observed. As the model is deformed the plastic equivalent strain (PEEQ) around each of the two large pores increases significantly, as shown in Fig 6b. Also, the bottom interface has a higher strain than the top interface. This can be attributed primarily to the fact that the bottom interface has a smaller cross-sectional area in the actual joint than the top interface, as discussed below.

With the incorporation of the damage model in the FE analysis the stress–strain behavior exhibits similar work hardening behavior as that observed in the elastic–plastic analysis. Once the damage criterion is met at the ultimate shear strength the stress in the model decreases with further shearing and a crack is introduced into the FE analysis results by the removal of an element. The overall stress–strain response of the entire solder model is illustrated in Fig. 7. The stress in the ductile damage model deviates from the elastic–plastic model at a strain of 0.35 and starts decreasing significantly.

Fig. 3b and c shows the deformation of pores observed experimentally and as predicted by the FE model. The FE results show very good correlation with the experimental results. In both cases more pronounced deformation is seen in pores in the lower half of the sample, located near the solder/copper interface. Two large pores (about 200 and 290 µm in diameter) are also observed near that interface.

Fig. 8. 2D sections across the thickness of the joint showing a comparison of crack propagation observed experimentally (grayscale image) and that predicted by FE analysis. The crack propagation path predicted by the FE model correlates well with the actual crack propagation path.
The numerical model developed should not only correctly predict deformation of the pores but also accurately represent failure of the joint. Fig. 8 shows a comparison of the crack propagation path predicted by the FE model and observed experimentally. Two 2D cross-sections across the thickness of the joint depicting the crack in the sample are shown in the figure. The first cross-section shown on the left in Fig. 8 shows a crack around the pore located near the bottom left corner of the joint as observed in the simulation results and tomographic images. The crack is seen to nucleate around the large pore and propagates towards the interface in both cases. The second cross-section on the right shows the crack around the other large pore located at the bottom right corner of the joint. The FE model predicts crack nucleation in the same location where failure of the pore wall is observed experimentally. Comparison of the FE with the experimental results clearly demonstrated the capability of the numerical damage model to accurately simulate the deformation as well as failure of the solder joint.

3.3. Sphericity

In addition to correctly predicting the crack nucleation sites in the joint, the predictive damage model should correctly capture the strain localization that occurs around the reflow pores. The ability of a model to correctly predict strain localization can be measured by comparing the predicted pore shape change with experimental observations. To quantify the change in shape of pores in three dimensions the sphericity of the pores was tracked as a function of strain. The sphericity ($\Psi$) of a pore is given by the ratio of the surface area of a sphere (with a volume equal to the pore volume) to that of the pore:

$$\Psi = \frac{A_s}{A_p} = \frac{\pi^{1/3}(6V_p)^{2/3}}{A_p}$$

where $A_s$ and $A_p$ refer to the surface area of the sphere and pore, respectively, and $V_p$ is the pore volume. The surface area ratio can be reduced to a function of the pore surface area and volume, which are easily measured from a 3D reconstruction. Sphericity measures the departure of a shape from perfectly spherical ($\Psi = 1$) and measures the extent of deformation for a given pore. To measure the accuracy of the ductile damage model in predicting deformation of individual pores the sphericity change for selected pores in the joint was simulated at several strain values by exporting the displacement values of nodes on the surface of the pore from the model and reconstructing the pore in three dimensions using the same parameters as for the experimental data.

To give a basis of comparison for the ability of the FE model to predict deformation a simplified model was constructed to look at deformation of a single pore. A basic characterization of deformation in the lap joint would be to assume that the body of the solder deforms homogeneously in simple shear. This result would ignore any strain localization in the joint, and emphasize the necessity of its incorporation. To simulate simple shear deformation the segmented 3D masks of as-reflowed pores were exported to MATLAB where a shear transformation was applied in the loading direction. The sheared masks were then imported into the Mimics software and reconstructed as with the FE and experimental masks.

Once the pores were reconstructed from the experimental imaging and the FE model and simple shear simulations a surface wrap algorithm was applied to each reconstruction to remove any artifacts. The sphericity of each reconstruction was then calculated from its volume and surface area. The sphericity measurements of representative pores from the top and bottom interfaces are plotted as a function of strain in Fig. 9. For the bottom pore at low
strain values all three curves show a gradual decrease in sphericity, with a drop-off occurring in the experimental and FE data around a strain of 0.35. This drop-off coincides with a higher degree of strain localization occurring in the joint at high strain. Accordingly, the simple shear deformation model does not predict this acceleration in deformation. In the top pore plot the sphericity is seen to decrease very little as the joint is deformed. Again, the FE ductile damage model was able to simulate the experimental behavior much more accurately than the simple shear model, showing that the ductile damage model is good at capturing both the true local deformation of the joint and its macroscopic failure.

4. Conclusions

X-ray microtomography was used to quantify the evolution of pore microstructure in a Sn-based alloy as a function of strain. In particular, the size, shape, and distribution of reflow porosity on damage evolution was studied. An interrupted test combined with tomography enabled progressive visualization of damage in the model. Cracks initiated at the two large pores and propagated along the interface, indicating the influence of pore size on failure of the joint. The 3D reconstruction of the tomographic data was incorporated in a FE model to predict failure of the joint using a ductile damage model. The local deformation, crack initiation, and failure predicted by the ductile damage model were in good agreement with the experimental observations. Sphericity analysis also successfully verified the ability of the model to predict local deformation. The results clearly demonstrated the accuracy of the numerical damage model, using the actual microstructure as a basis, in simulating damage occurring in the Sn-based alloy due to the presence of reflow porosity.

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Appendix A

See Table A1.

References


