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Quantitative characterization of porosity and determination of elastic modulus for sintered micro-silver joints

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ABSTRACT

High resolution serial block-face scanning electron microscopy has been performed on sintered micro-silver pastes that are used as lead replacement joints for die bonding. The size and spatial distributions of the porosity before and after ageing were determined by quantification of the segmented 3D images. The elastic modulus was determined by an image-based finite element model and validated by results obtained from a dynamical resonance method. In agreement with contemporary analytical models on the elastic behaviour of porous materials, the elastic modulus was found to be a function of pore fraction only. Ageing the specimens does not alter the density or Young's modulus.

1. Introduction

Sintered micro-silver pastes are good candidates to replace lead-based alloys for die bonding of power electronics due to their excellent electrical properties and high melting temperature as described by Li et al. (2013) who investigated the creep properties of these materials. Other mechanical properties of sintered micro-silver pastes can be found in the literature where Siow (2012) has provided a review of the work done in determining elastic modulus, strength and factors affecting the bonding strength of such joints. However, very few give a relationship between mechanical properties and porosity. Furthermore, no work has been done on the impact of ageing the material. With respect to the elastic behaviour, Panin et al. (2005) concluded that an increase in grain size due to annealing had no effect on the elastic properties as determined by nano-indentation.

Lifetime prediction of the entire system requires quantifying the evolution of the porous structure during thermal ageing in order to understand the modification of mechanical properties dominated by the porous structure of the joint material. The effect of the pore distribution on the elastic properties of sintered micro-silver pastes during ageing is one of the key parameters for modelling the elastic behaviour of the entire electronic system in the operating conditions. This study represents a first step towards addressing this issue by using imaging to determine the porous structures of both as-sintered material and aged material and relating it to the elastic properties.

Several analytical models have been proposed that link porosity with the elastic moduli of porous materials. Mackenzie (1950) states that the Young's modulus, E, as a function of the pore fraction, P, is of the form

$$E = E_0(1 - aP + bP^2) \qquad (1)$$

where E_0 is the Young's modulus of the solid material and a & b depend on the shape of the pores, although the exact form of this dependence is unknown. The work of Ashby et al. (2000) on foams takes into account how E scales with P:

$$E = cE_0(1 - P)^n \qquad (2)$$

where $0.1 \le c \le 4$ and $n \approx 2$.

Ramakrishnan and Arunachalam (1990) provided a model consistent with Eq. (2), but further demonstrated that it is possible to predict the Young's modulus of a porous solid as a function of pore

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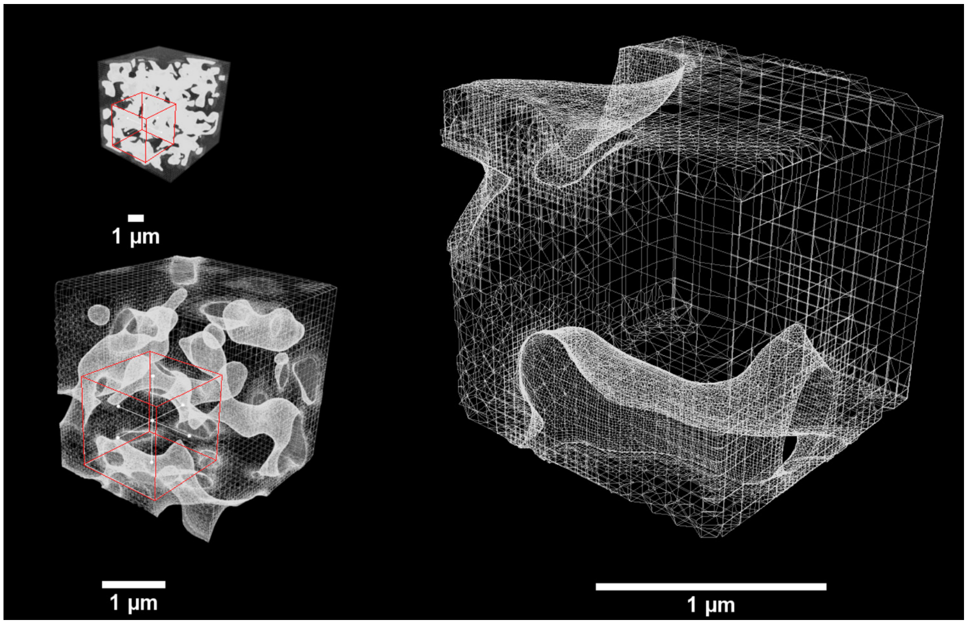

Fig. 1. A wire-frame display of the mesh produced by snappyHexMesh at increasingly higher magnifications to illustrate the refinement of the mesh.

fraction knowing only the Young's modulus and Poisson ratio of the solid material, i.e. E_0 and ν_0 respectively, by

$$c = \frac{1}{1 + (2 - 3\nu_0)P} \quad (3)$$

where ν_0 is the Poisson ratio of the solid material. Ramakrishnan and Arunachalam (1990) verified this analytical model using idealized 2D finite element (FE) models.

Following advancements in computing power, synthetic 3D FE meshes based on statistical models of porous solids were simulated. Roberts and Garboczi (2000) used such an approach to model the elasticity of porous ceramics and showed their results to be consistent with the analytical model proposed by Bert (1985) who developed another empirical model that is very close in form to Eq. (2) for spherical pore geometries. Advancements in 3D imaging have allowed the replacement of such synthetic meshes with real image-based meshes, which fully describe the complicated geometry of porous solids. Knackstedt et al. (2006) and Hardin and Beckermann (2007) used image-based 3D FE models of foams obtained by X-ray tomography (XRT) and used the analytical model proposed by Bert (1985) to fit their results.

Serial block-face scanning electron microscopy (SBFSEM) is a relatively new, destructive, high resolution 3D imaging technique, first used in a materials science context by Zankel et al. (2009), that is capable of achieving significantly higher spatial resolutions compared with XRT. The authors use SBFSEM datasets to produce FE models of the sintered pastes that are validated against experimentally determined values for Young's modulus using a dynamic resonance method (DRM) as described by Gadaud et al. (2009) who derived a formalism for interpreting the torsional vibrations to determine elastic and shear moduli.

2. Materials and methods

Heraeus LTS 043 04P2® Ag paste was sintered using an alternative processing route as described by Caccuri et al. (2014), which includes a final sintering step at 240 °C for 3 min under 10 MPa. This allows production of the bulk specimen with the same microstructure as the real joint material. Ageing was performed at 125 °C for 1500 h in air. The density of the specimens prior to and after ageing was obtained from the weight to volume ratio using a high precision Sartorius MZ1 balance (accuracy better than 10 mg) and a micrometer (accuracy better than 1 µm).

Sectioning for the SBFSEM was performed at a nominal thickness of 75 nm, and an accelerating voltage of 2 kV in high vacuum mode was used to obtain backscattered electron micrographs of the block-face in the SEM. Magnification settings on the SEM give a pixel size of 37.5 nm.

Pore fractions were obtained from the segmented binary image. The quantification of size and spatial distributions considers pores unconnected to the large singular porous network. Images were segmented by an automatic thresholding algorithm developed by Otsu (1979) who used image histograms to determine threshold values for the segmentation. Volumes and barycentres were calculated following connected component labelling as described by Suzuki et al. (2003) using a 6 voxel neighbourhood. A clustering ratio is defined as the ratio of the expected nearest neighbour distance given a random distribution with the measured mean nearest neighbour distance. Chandrasekhar (1943) provides a derivation of the mean nearest neighbour distance for a distribution of random particles.

Segmented sub-volumes of the tomographic datasets acquired from the SBFSEM data were used to produce FE models such that each sub-volume provides a single datapoint for the pore fraction and corresponding Young's modulus. This is achieved by forming a stereolithography surface at the pore/matrix interface of the binarized image and utilizing the 'snappyHexMesh' utility bundled with OpenFOAM. A refinement level of 5 was used to produce a volume mesh of the matrix composed of hexahedra and split hexahedra as shown in Fig. 1. For the boundary conditions, a uniform stress of 10 Pa was applied normally to the face of the mesh and the adjacent face was kept at a fixed displacement. Known physical parameters for pure silver (density: 10.490 g cm^{-3}, Poisson ratio: 0.37 & Young's modulus: 83 GPa) were used in the simulation. The simulation was run using the 'solidDisplacementFoam' solver bundled with OpenFOAM; convergence criteria were set such that the global residual does not exceed 10^{-10}. The Young's modulus was obtained from the simulation by using the known applied stress and the calculated global strain, determined by the average displacement field of the pressurized face.