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FEM simulation of the size and constraining effect in lead free solder joints

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Abstract

Due to the ongoing miniaturization in microelectronics, the influence of dimensional constraining effects on the strength of solder joints becomes increasingly important. Detailed investigations show a strong dependence of tensile strength and ductility on solder geometry. This paper focuses on FEM simulations of the thickness effect of Sn-3.5Ag solder gaps under tensile load. Solder joints and copper base material are simulated with an elasto-plastic material model in the framework of von Mises plasticity. Within the solder material a pronounced triaxiality of stress is observed. In consequence, the von Mises stress inside the solder material is considerably smaller than the longitudinal stress along the tensile axis. This leads to increased tensile strength of thin solder joints. However, the increase of strength also depends on the yield stress of the copper base material. The FEM simulations were compared with experimental results of tensile tests and satisfactory coincidence was found. The remaining deviation between experiment and simulation is explained by pressure dependency of the flow stress. In conclusion, a new pressure dependent plasticity model is suggested.

Keywords: von Mises criterion, ductile fracture, solder joints

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1. Introduction

Microelectronic industry is one of the most dynamically developing sectors of industry today. The major requirements for innovative products are higher performance and reliability. From the viewpoint of reliability, there is the necessity to investigate the critical components determining the lifetime of electronic parts. In many cases, solder joints represent the weakest links leading to failure of electronic parts. Due to their low melting point, solder materials exhibit rather low mechanical strength. However, the strength of solder joints may be increased by geometry effects when they connect stronger base materials. Due to constraint effects along the interface to the base material, mechanical deformations introduce a triaxiality of stress within the solder which obstructs plastic deformation. Since this effect depends on the macroscopic dimensions of solder joints, it is in some respect related to mechanical size effects. Nevertheless, it is important to distinguish geometry effects from microstructural size effects which also influence the mechanical properties. Effects of both kinds become increasingly important nowadays, because of the ongoing miniaturization in microelectronics. Therefore, a comprehensive understanding of these phenomena is required to meet the demands of quality control in modern industry.

In the present study, we investigate the tensile strength of lead free Sn-3.5Ag solder joints by Finite Element Analysis. The main part of the experiments has already been published elsewhere [9]. Solder gaps of various thicknesses but identical cross section were connecting pieces

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of copper base material. The experiments revealed a pronounced increase of the ultimate tensile strength with decreasing solder joint thickness. Samples of the same shape and dimensions were now simulated with the FEM code ANSYS. Thereby, elasto-plastic material models were assumed for solder and copper base material. On the whole, satisfactorily agreement between experiments and simulation results was found. The remaining deviation of experiment and theory is analysed in detail whereby similar investigations for Sn-Ag-Cu solder alloys [1, 3, 5] are considered in the discussion. Therefrom, we draw the conclusion that further improvement of the simulations could be achieved by considering a pressure dependency of the yield stress in the material model. This pressure dependency results in a new constitutive equation which is justified on the basis of the Peierls-Nabarro stress [4] necessary to move crystal dislocations.

2. Specimen design and material properties

2.1. Sample geometry

The soldering process was carried out in a commercial reflow furnace. A schematic picture of the sample geometry is depicted in Fig. 1. Solder gaps with cross section of 2×3 mm^2 were connecting dog bone shaped pieces of 99.9 % pure copper base material. In the experiment, the elongation of the sample was measured by a laser speckle extensometer [9]. The locations of the two laser spots used for the optical measurement are indicated in the figure.

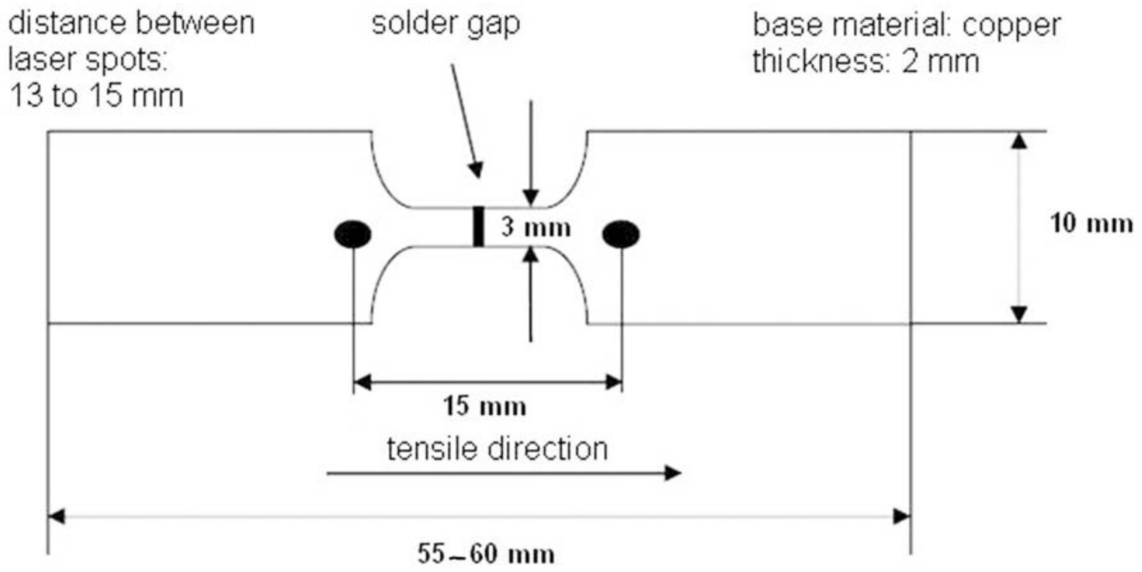

Fig. 1. Schematic picture of the specimen geometry used for tensile tests

The thickness of the solder gap along the tensile direction was varied in the range from 64 to 900 μm. The sample dimensions considered in the FEM model were the same as in the experiment.

2.2. Material properties

Two different types of heat treatment were applied to solder joints: In a first series, the samples were thermally treated at $80\,^{\circ}$C for 3 hours. In the second series, the heat treatment was carried out at $170\,^{\circ}$C for 500 hours. In order to compare the effect of heat treatment on the base material, tensile tests were also conducted with copper specimens exposed to the same thermal treatments [8]. Extensive heat treatment at 170 °C leads to thermal recovery of copper and reduces its yield strength. On the other hand, the effect of heat treatment on the solder material is more complex. The long heat treatment leads to growth of intermetallic compounds in the vicinity of the interface between solder and copper. An increase of volume fraction of the IMC should in principle increase the solder joint strength. But a heat treatment of 500 hours reduces the quality of the IMC and therefore increases the probability of brittle fracture.

In the simulation, copper and solder material were both modelled elasto-plastically following the assumption of von Mises plasticity. The uniaxial stress-strain curves of technically pure copper were obtained by comparison with experiments and are depicted below. The uniaxial stress-strain curve of Sn-3.5Ag bulk solder was taken from literature [6], whereby the same material model was used for either thermal treatment.

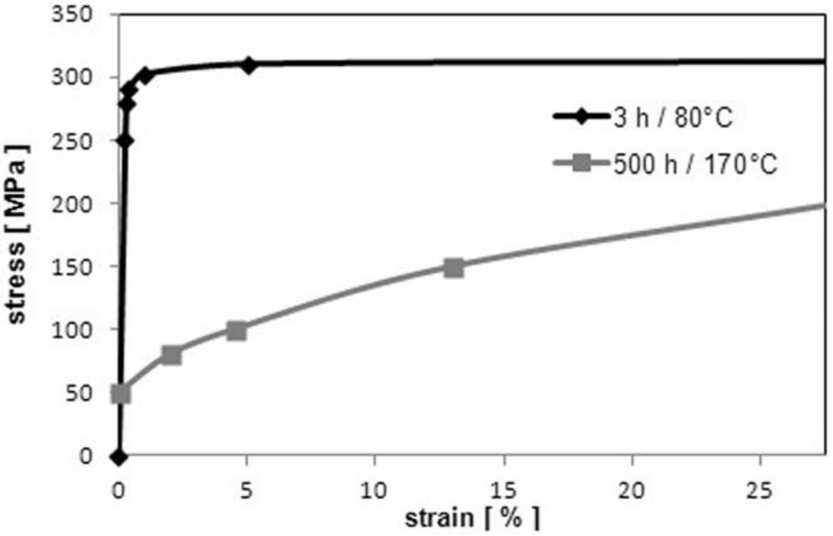

Fig. 2. Engineering stress — strain curves of the elasto-plastic material models for copper after two different heat treatments

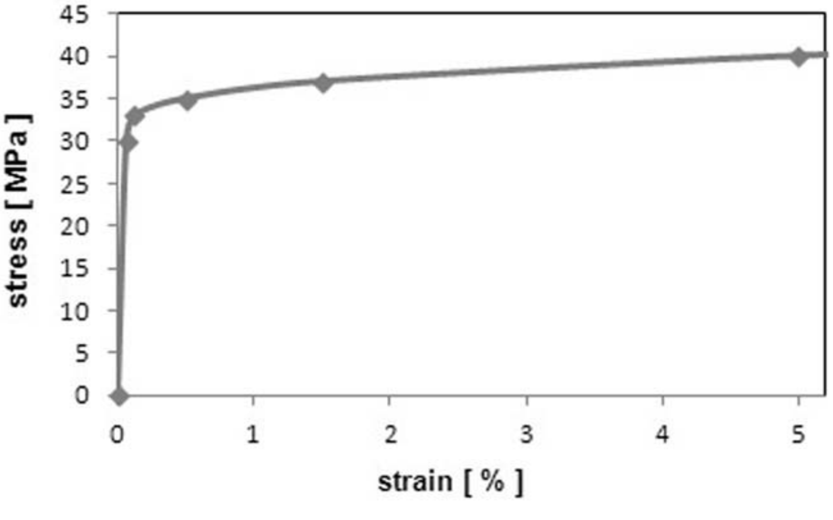

Fig. 3. Engineering stress — strain curve of the elasto-plastic material model for Sn-3.5 Ag

3. FEM simulation of tensile tests

FEM simulations were performed with ANSYS 11 classic using element type solid 186. The solder gap thicknesses considered in the simulations were 64 μm, 110 μm, 150 μm, 300 μm, 550 μm and 900 μm. The mesh of the sample with gap size of 300 μm is depicted in Fig. 4.

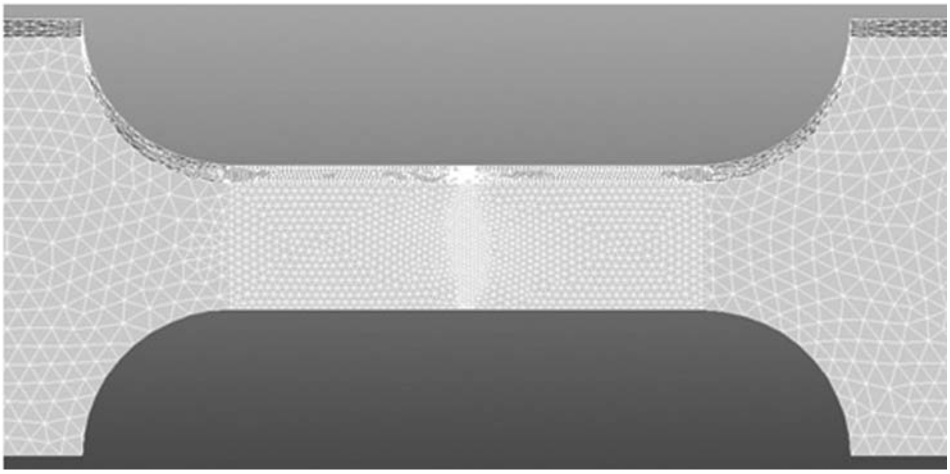

Fig. 4. Mesh of the sample with gap size of 300 μm. Tetrahedral shaped elements of type solid 186 were used

The simulations showed a pronounced increase of tensile strength with decreasing solder gap thickness. Since there is conservation of volume during plastic deformation, plastic elongation of the specimen is always accompanied by cross contraction. However, cross contraction of the solder joint is obstructed by the stronger base material. Therefore, the constraints along the interface impose a triaxiality of stress. Hence, the von Mises stress inside the solder material is smaller than the longitudinal stress component along the tensile axis, as can be seen in Fig. 5. In consequence, solder joints can carry higher loads compared to bulk solder material. This effect increases with decreasing solder gap thickness.

Fig. 5. Plot of the von Mises stress [Pa] at a tensile stress of 100 MPa. Solder gap size: 300 μm

The distribution of plastic equivalent strain in the solder joint is depicted in Figs. 6, 7 and 8. The maximum strain is found at the surface in the vicinity to the interface. In order to obtain

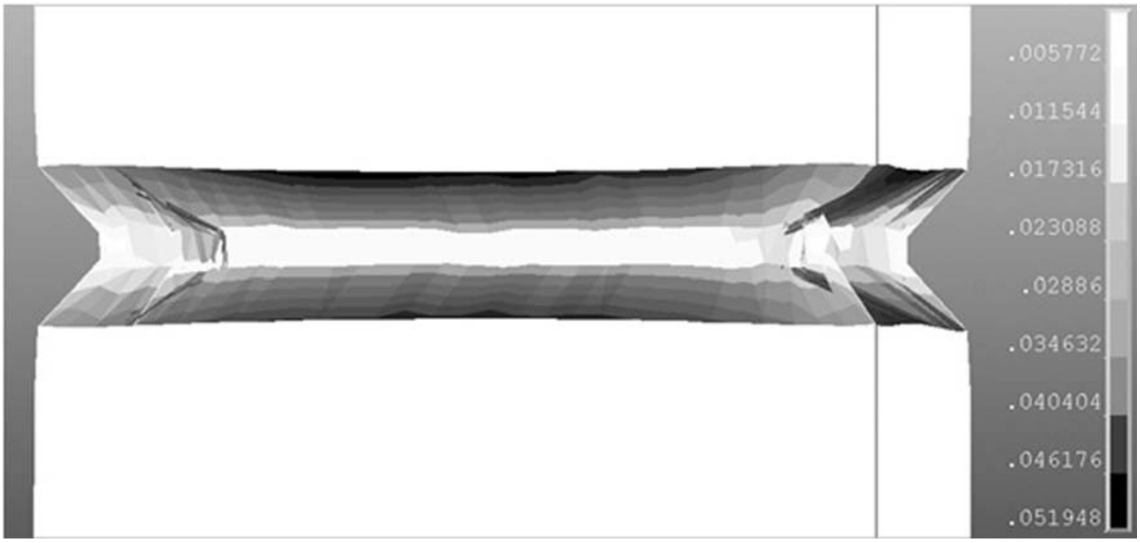

Fig. 6. Plot of plastic equivalent strain at a tensile stress of 100 MPa. Solder gap size: 300 μm

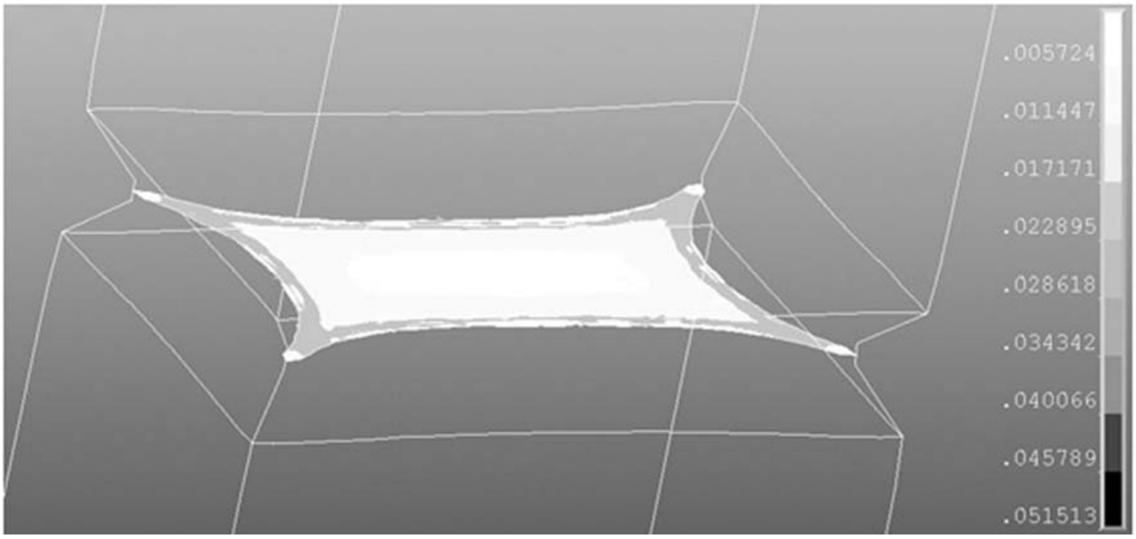

Fig. 7. Cut through the plot of plastic equivalent strain at a tensile stress of 100 MPa. Solder gap size: 300 μm

values for the ultimate tensile strength, it is necessary to define a fracture criterion. In fact, literature data for the ductility of Sn-3.5Ag bulk solder show considerable scattering when data of different authors are compared. The main reason seems to be that in this material little or no work hardening is observed at strain values above 5 %. This leads to necking at the position where the samples cross section takes its minimum. Thus, small differences of sample design or inhomogeneities of cross sections may lead to different experimental values of fracture strain. It may therefore be assumed that fracture occurs when plastic equivalent strain somewhere exceeds a critical value. In the present study, the critical value for plastic equivalent strain was estimated to be 50 %.

It should be mentioned here that the fracture criterion of a critical value for plastic equivalent strain automatically leads to a reduction of the macroscopically measured value for the ductility of thin solder joints. Indeed, thin solder joints appear almost brittle on a macroscopic level, because the local strain in the vicinity to the interface is much higher than the average value.

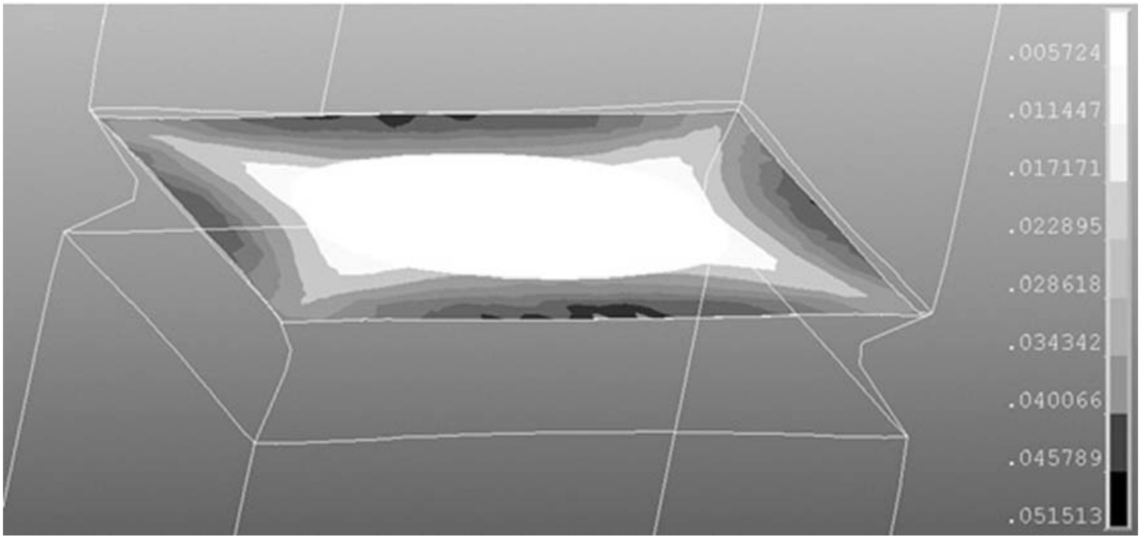

Fig. 8. Plastic equivalent strain in the vicinity of the interface (tensile stress: 100 MPa, gap size: 300 μm)

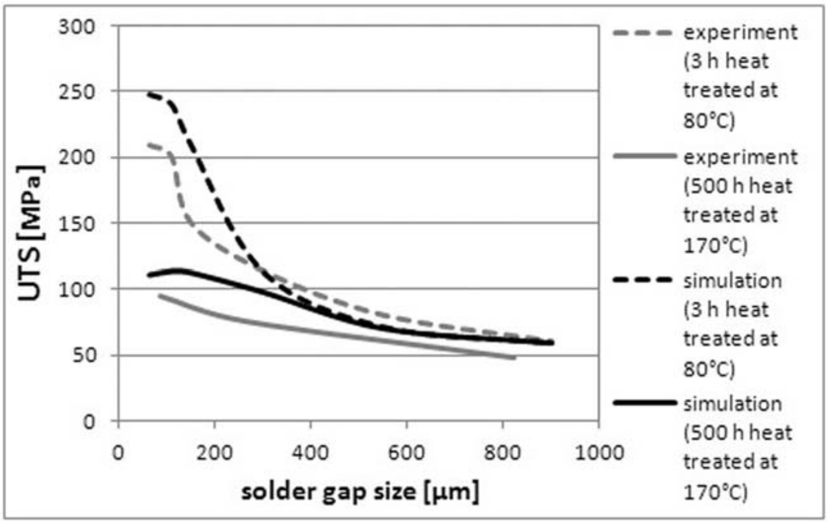

Fig. 9. Comparison for the UTS of experiment and simulation

4. Results and discussion

A comparison for the ultimate tensile strengths of experiment and simulation is shown in Fig. 9. The simulations confirm the experimental results. In the case of a heat treatment of 3 hours at $80\,^{\circ}$C, a remarkable thickness effect on the tensile properties was found. On the other hand, the thickness effect was much less pronounced after heat treatment at $170\,^{\circ}$C for 500 hours. If the yield strength of the copper base material is reduced by heat treatment, the constraining effect decreases accordingly.

In spite of qualitative agreement between experiment and simulation, we will here investigate the reasons for remaining deviations: After heat treatment at $170\,^{\circ}$C for 500 hours, the mechanical properties of the solder seem to have deteriorated. During heat treatment the volume fraction of intermetallic compounds (such as Cu_3Sn and Cu_6Sn_5) at the interface increases, but defects emerge. Aging at elevated temperature leads to Kirkendall voids. In consequence, the solder joints become brittle and premature rupture of specimens may occur. A similar effect was reported by Wu et al. [5]. They have aged Sn-3.5Ag-0.5Cu and Sn-3.5Ag solder alloys connecting copper bars which were at the ends plated with Ni and Au. Aging at $150\,^{\circ}\mathrm{C}$ for 120 or 200 hours lead to an increase of the IMCs layer. Thus, the shear strength of the aged samples decreased due to brittleness. This argumentation may also be applied to the present investigation. It explains the reduced values for the ultimate tensile strength of aged samples compared to the simulation results.

In the case of a short thermal treatment at $80\,^{\circ}\mathrm{C}$, however, defects like Kirkendall voids are not expected. So there should be a different reason why the theoretical values overestimate the strength of thin solder gaps. A similar behaviour was found by Cugnoni et al. [1] for lead free Sn-4.0Ag-0.5Cu solder joints. They attributed the reduced experimental strength of the thinnest solder joints to some residual porosity caused by the manufacturing process. But problems of this kind were avoided in the present investigation by controlling the temperature profile of soldering by use of a reflow process. A subsequent SEM investigation did not show noteworthy defects of the solder material. Therefore, we claim that the remaining discrepancy between experiment and theory is caused by pressure dependency of the yield point which is neglected in the framework of von Mises plasticity.

A pressure dependency of flow stress in metals is generally accepted in the theory of severe plastic deformation [7]. An increase of hydrostatic pressure usually raises the value of flow stress. Hence, a negative hydrostatic pressure as consequence of triaxial tension should reduce its value. Therefrom, one can expect that the accordance of experiment and simulation results depicted in Fig. 9 could be further improved by considering pressure dependency in the material model.

In order to be complete, further contributions to the thickness effect are briefly discussed: Aside from the geometry effect simulated here, effects of microstructure can occur. Since thinner solder gaps may lead to finer microstructure [3], a further increase in tensile strength of thin joints is possible. Moreover, strain rate effects can also increase the strength of thin joints: When the tensile deformation of specimens is carried out with constant cross head speed, thinner joints are exposed to higher strain rates and are therefore expected to show higher strength. However, the detailed consideration of such effects in the simulation would rather increase the discrepancy between experiment and simulation results. It should therefore be stressed once again that an improvement of the simulation may be achieved through a pressure dependent plasticity model.

5. Conclusions

In conclusion of the preceding analysis, a new pressure dependent constitutive model is suggested. The physical basis for the model is provided by a pressure dependency of the Peierls-Nabarro stress which is necessary to move a mobile dislocation [4]. If the crystal lattice is stretched elastically due to triaxial tension, then the interplanar spacing between lattice planes is increased. This leads to a reduced value of yield stress

$$\sigma_{\text{flow}}(p) = \sigma_0 \cdot \exp\{\alpha \cdot p\}, \tag{1}$$

where p is the hydrostatic pressure, σ_0 is the yield stress at zero pressure and α is a material parameter. The yield surface in principal stress coordinates corresponding to Eq. (1) is depicted in Fig. 10.

In order to achieve conservation of volume during plastic deformation, the flow rule of the proposed model shall be defined in analogy to von Mises plasticity. This means, the direction of plastic flow is parallel to the deviatoric stress, but the onset of plastic yielding is shifted to a

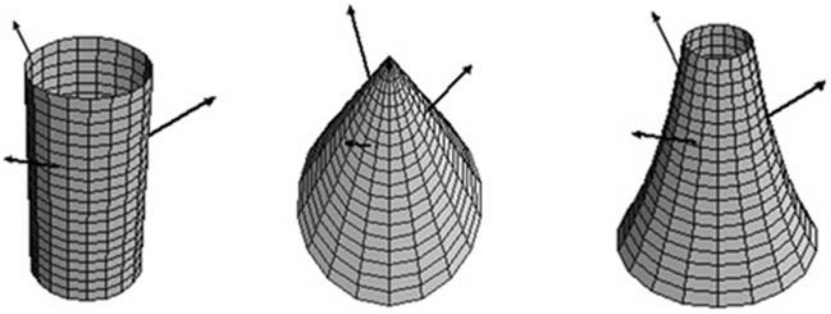

Fig. 10. Comparison of yield surfaces in principal stress coordinates. From left to right: von Mises plasticity, Drucker Prager model, new constitutive model

pressure dependent level. In this respect, the proposed model differs from the Drucker-Prager model [2] for granular materials which predicts a considerable volume change during plastic deformation.

In summary, the Finite Element simulations presented here can satisfactorily explain the thickness effect on tensile strength of solder joints. The main reason for the increase in strength with decreasing solder gap thickness is a triaxiality of stress introduced by constraints along the interface to the base material. Further improvement of accordance between experiment and theory may be achieved with use of a pressure dependent plasticity model.

Acknowledgements

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References

[1] Cugnoni, J., Botsis, J., Janczak-Rusch, J., Size and constraining effects in lead-free solder joints, Advanced Engineering Materials 8 (3) (2006) 184–191.

[2] Drucker, D. C., Prager, W., Soil mechanics and plastic analysis or limit design, Quarterly of Applied Mathematics, 2 (10) (1952) 157–165.

[3] Hedge, P., Whalley, D. C., Silberschmidt, V. V., Size and microstructure effects on the stress-strain behaviour of lead-free solder joints, European Microelectronics and Packaging Conference, EMPC 2009, 1–9, 2009.

[4] Nabarro, F. R. N., Fifty-year study of the Peierls-Nabarro stress, Materials Science and Engineering A234–236 (1997) 67–76.

[5] Wu, F., He, M., Wu, Y., An, B., Zhang, W., Effect of interfacial IMCs proportion on the reliability of miniature lead free solder joint, 7th International Conference on Electronic Packaging Technology, 2006.

[6] Xu Chen, Gang Chen, Sakane M., Modified Anand constitutive model for lead-free solder Sn-3.5Ag, Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM ’04, Vol. 2, 2004, 447–452.

[7] Zehetbauer, M. J., Stüwe, H. P., Vorhauer, A., Schafler, E., Kohout, J., The role of hydrostatic pressure in severe plastic deformation, Advanced Engineering Materials 5 (5) (2003) 330–337.

[8] Ziering, A., current diploma thesis, University of Vienna

[9] Zimprich, P., Betwar-Kotas, A., Khatibi, G., Weiss, B., Ipser, H., Size effects in small scaled lead-free solder joints, Journal of Materials Science: Materials in Electronics 19 (2008) 383–388.