

## MICROSTRUCTURAL BEHAVIOUR OF SOLDER JOINTS

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**Summary** Mechanical properties of soldered connections, as well as damage initiation and propagation, are strongly influenced by the continuously changing microstructure of the solder. Therefore, in this contribution the microstructure evolution is included in the model by a diffuse interface model that is dependent on a strongly nonlocal parameter. The material behaviour is described by the hyperelasto-viscoplastic Perzyna model. The material parameters are taken to be dependent on the mass fraction.

The model has been implemented within a finite element context. A quantitative comparison has been made between two-dimensional simulations and experiments of the static ageing of a eutectic tin-lead solder. A good agreement was found.

The mechanical response is shown to be sensitive to the coarseness of the microstructure. Furthermore, stress concentrations develop near interfaces, which are known to be crack initiation sites during fatigue failure.

### INTRODUCTION

During their life soldered connections are subjected to thermomechanical loading. In combination with the high temperatures at which they operate, they are susceptible to low cycle fatigue. Solder joints are often tested for their thermo-mechanical fatigue properties by subjecting them to accelerated test methods. However, during these accelerated experiments damage mechanisms might be invoked which do not occur during normal usage. Predictions based on accelerated cycling tests are therefore unreliable. Thermo-mechanical modelling can be used during the design process to simulate the real life conditions of a solder joint, and thus give an accurate prediction of its lifetime, with a reduction in cost and design time when compared to prototype testing.

Solder joints are known to behave differently than the bulk solder material because of their high surface to volume ratio and their small size compared to the microstructure. A joint can thus not be regarded as a homogeneous continuum. Moreover, its microstructure and properties will change over time: the high homologous temperature at which solder materials operate provokes microstructural coarsening, resulting in a markedly different microstructure after only a short time after solidification. This coarsening process is in general not homogeneous. Regions which show increased coarsening are known to be crack nucleation sites during thermal cycling. It is also well-known that thermal cycling leads to faster coarsening rates than static thermal aging, possibly due to the mechanical stresses which arise within the material due to differences in thermal expansion coefficients.

In this contribution the mechanical behaviour of solder joints is investigated while taking the microstructure evolution into account.

### MODELLING

#### A nonlocal diffuse interface model

To describe the microstructural evolution, a diffuse interface theory is used where the free energy is supposed to be dependent on local composition, nonlocal composition and stresses and strains. The model can be seen as an extension of the Cahn-Hilliard model [1, 2]. The total system of equations then reads:

$$\rho \frac{dc}{dt} = \vec{\nabla} \cdot \left[ \rho \mathbf{M} \cdot \left( \frac{\partial F(c, \bar{c}, \boldsymbol{\sigma}, \boldsymbol{\varepsilon})}{\partial c} \right) \right] \quad (1)$$

$$\bar{c} - \ell^2 \vec{\nabla}^2 \bar{c} = c \quad (2)$$

$$\vec{\nabla} \cdot \boldsymbol{\sigma} = 0 \quad (3)$$

where  $\rho$  denotes mass density,  $c$  mass fraction,  $t$  time,  $\mathbf{M}$  mobility,  $F$  free energy,  $\boldsymbol{\sigma}$  Cauchy stress,  $\bar{c}$  nonlocal mass fraction, and  $\boldsymbol{\varepsilon}$  the strain. The internal length parameter  $\ell$  determines the size of the area of influence of an interface.

#### Perzyna hyperelasto-viscoplastic model

Because the elastic energy is an important driving force behind the diffusion process its important that elastic energy is handled correctly in the material model. Therefore a hyperelastic model is used. Furthermore, since the operating temperature of solder alloys is typically close to their melting temperature, the deformation behaviour is governed by high temperature phenomena like creep due to e.g. grain boundary sliding. Therefore the Perzyna viscoplastic material model has been chosen to describe the mechanical behaviour of the solder [3]:

$$\overset{\nabla}{\boldsymbol{\tau}} = \mathbb{H} : (\mathbf{D} - \mathbf{D}_{vp}) \quad \text{with} \quad \mathbf{D}_{vp} = \eta \left( \frac{\tau_{eq} - \tau_y}{\tau_{y0}} \right)^N \mathbf{N} \quad (4)$$

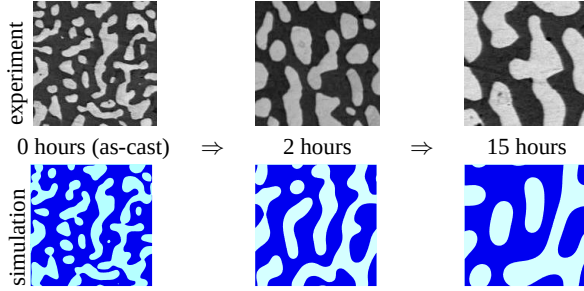
Here  $\overset{\nabla}{\boldsymbol{\tau}}$  is the Truesdell time derivative of the Kirchhoff stress,  $\mathbf{D}$  the strain rate tensor, and  $\mathbb{H}$  is the fourth-order material tensor. The direction of the viscoplastic strain rate  $\mathbf{D}_{vp}$  is  $\mathbf{N}$ , while its magnitude is determined by the fluidity parameter  $\eta$  and the current ( $\tau_y$ ) and initial ( $\tau_{y0}$ ) yield stress of the material.

The parameters used for the Perzyna model are taken to be dependent on the mass fraction field calculated with the microstructure evolution model. In this way the influence of the size and shape of the microstructure is accounted for. The system of equations is solved using the finite element method in a large deformation framework.

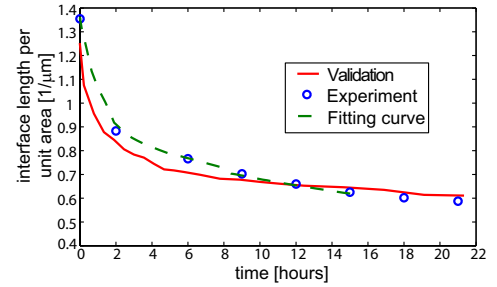
## RESULTS

Figure 1 shows the microstructure during static ageing of a eutectic tin-lead solder at 150°C for both an experiment and a simulation. This coarsening process has been quantified, the result of which can be seen in figure 2.

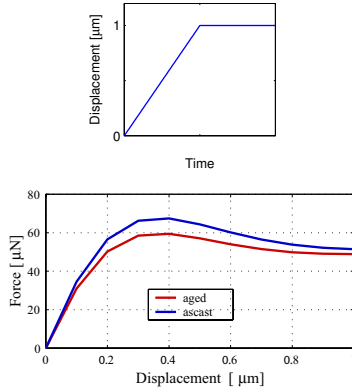
Figures 3 and 4 show the mechanical response of an as-cast and an aged microstructure of tin-lead solder under uniaxial tension.



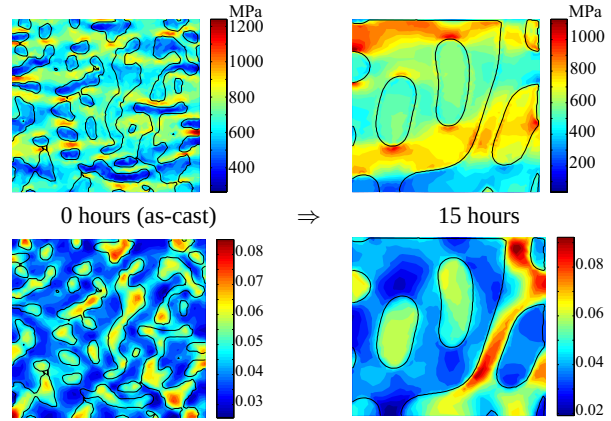
**Figure 1.** Ageing of tin-lead, size  $10 \times 10 \mu\text{m}$



**Figure 2.** Development of interface area.



**Figure 3.** Loading and force-displacement curve.



**Figure 4.** Stress (top) and strain (bottom) distributions at 3% strain.

## CONCLUSIONS

An extension of the Cahn-Hilliard model is used to describe the microstructure evolution of tin-lead solder. The free energy density is taken to be a function of the local and a strongly nonlocal mass fraction which in this case is calculated by solving a Helmholtz partial differential equation. The difference between the nonlocal and the local mass fraction is associated with the surface energy. The variation with respect to local mass fraction of this energy acts as a driving force for the coarsening process. Incorporation of additional driving forces into the free energy is straightforward. In this way the effect of stresses on diffusion is also accounted for through the addition of the elastically stored energy.

The numerical implementation of the nonlocal diffuse interface theory is done within the framework of the finite element method in a large deformation setting, which allows for arbitrary geometries to be modelled. The results are found to be in a good quantitative agreement with experimental data.

The mechanical behaviour of the material is described with the hyperelasto-viscoplastic Perzyna model. The material parameters are taken dependent on the mass fraction of the components calculated with the diffusion part of the model. In this way the microstructure is accounted for. The mechanical behaviour is shown to be dependent on the microstructure. Stress concentrations arise within the harder phase and near interfaces. Strains tend to localise in the softer phase.

## References

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- [3] Perzyna, P.: Fundamental problems in visco-plasticity. In: *Recent Advances in Applied Mechanics*. Academic Press, New York, 1966.