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Economic Method for the Collection of Complex Materials Data for the Design of Microsystems

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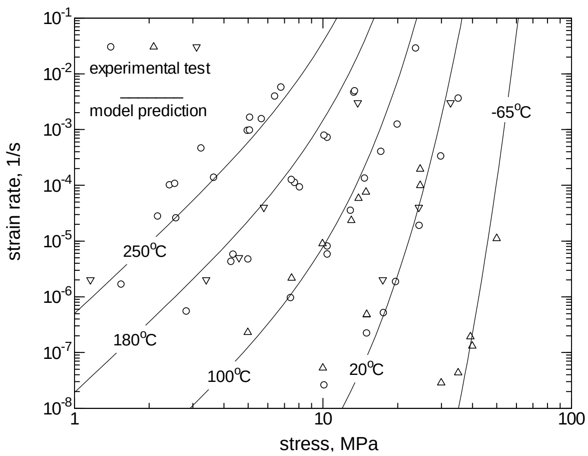
Abstract

In this paper a method is described to utilize microhardness testing for the determination of the mechanical properties of small volumes of material. The concept comprises the hardware for testing as well as the software for the data extraction. Basis of the hardware is a modified commercial indentation hardness tester. For temperature control of the specimen a special hot chuck was designed which allows precise heating or cooling without thermo-mechanical reaction of the sample. Stress-strain data extraction is accomplished by a special data fitting procedure of measured and simulated deflection-load-time curves. Using the data extraction method in combination with the modified indentation tester it was possible to characterize a number of different materials like conductive adhesives or lead-free solders including their elastic, visco-plastic and visco-elastic properties over a wide temperature range.



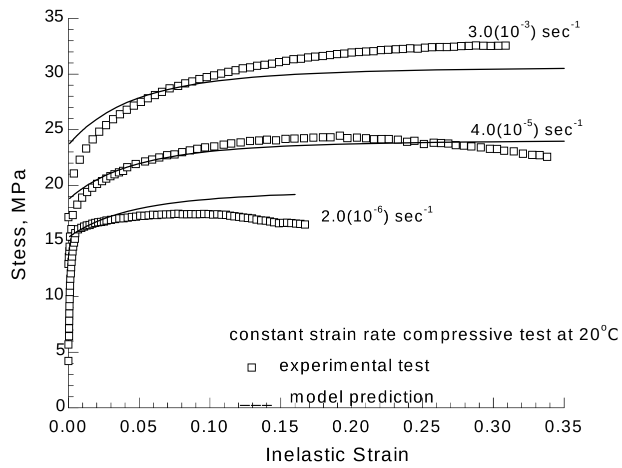


Figure 1a and b: Plastic deformation and creep properties of the solder alloy Pb92.5 Sn5 Ag2.5: measured data and multi-variant regression curves to the viscoplastic Anand model /1/.

Introduction

Mechanical design of microsystems is in many cases performed with finite-elements software tools /2/. A realistic simulation requires that the materials properties are implemented physically correct and with sufficient precision. This is an indispensable prerequisite for materials like polymers or solder alloys which exhibit strong non-linearity as well as temperature dependence and time dependence. As the material is an important degree of freedom in design optimization a set of thermo-mechanical properties must be is available in the design software. Unfortunately materials suppliers do not have all of the required information available while measurements require excessively high efforts for each individual material. Therefore it was the aim of our work to provide a solution for the rapid and economic determination of thermo-mechanical materials data in the relevant temperature range from –55 to 150 °C. Indentation testing seems to be a very efficient method to characterize small volumes of material. Although several attempts have been reported earlier to utilize micro-hardness testing for the measurement of the mechanical properties of micro-materials, two principal shortcomings could not be overcome satisfactory: One is the required temperature range and the second is the generation of stress and strain data from the load-deflection curves provided by such a tester.

Materials Data in Electronic Packaging

The principal deformation property of materials which describes the dependency between stress and strain is the elastic modulus. A well-established test method is DMTA (dynamic mechanical thermal analysis) where the elastic modulus is computed from the bending vibration of a test bar. When a material is stressed over the yield point, it will deform irreversibly. In metals science the dependency between stress and irreversible strain is described as plasticity which is considered to be independent of the rate of deformation and hence independent of time. Typically solders and also adhesives exhibit such plasticity. In Figure 1b the dependency between stress and plastic strain is demonstrated for a solder material. Plastic strain will lead to lower stresses than in the case of pure elastic deformation. It is obvious that plasticity is a property which is strongly affected by the operating temperature.

Moreover, due to the high homologous temperatures, solder alloys tend to creep, i. e. to deform continuously under mechanical stress. The creep rate $\dot{\varepsilon}_c = d\varepsilon_c / dt$ is sensitive to variations of stress level and temperature, Figure 1a. Results of both types of mechanical tests on solder alloys have been fitted to a visco-plastic deformation law, combining plasticity and creep in an unified physical model /3/. A kinetic equation defines a dependency between viscoplastic strain rate $\dot{\varepsilon}_v = d\varepsilon_v / dt$ stress σ and temperature T.

$$\dot{\varepsilon}_{\mathrm{v}} = A \cdot e^{-\frac{Q}{RT}} \left[\sinh(\xi \cdot \frac{\sigma}{s}) \right]^{\frac{1}{m}} \qquad (1)$$

s is a variable which models strain hardening or strain softening. A further set of equations defines the evolution of $\dot{s}$.

$$\dot{s} = \left\{ h_0(|B|)^a \cdot \frac{B}{|B|} \right\} \cdot \dot{\varepsilon}_{\mathrm{v}} \,; a > 1 \qquad \mathrm{B} = (1 - \frac{\mathrm{s}}{\mathrm{s}^*}) \qquad s^* = \hat{s} \cdot \left[\frac{\dot{\varepsilon}_{\mathrm{v}}}{A} e^{\frac{Q}{RT}} \right]^n \qquad (2, 3, 4)$$

The parameters of this model like a, B, h_o, A, Q, $\hat{s}$ and m are materials constants which must be implemented into a FEM software tool like ANSYS. Typically, the effort for experimental characterization of a single material is extremely high with respect to labor capacity (about a person-year) and equipment.

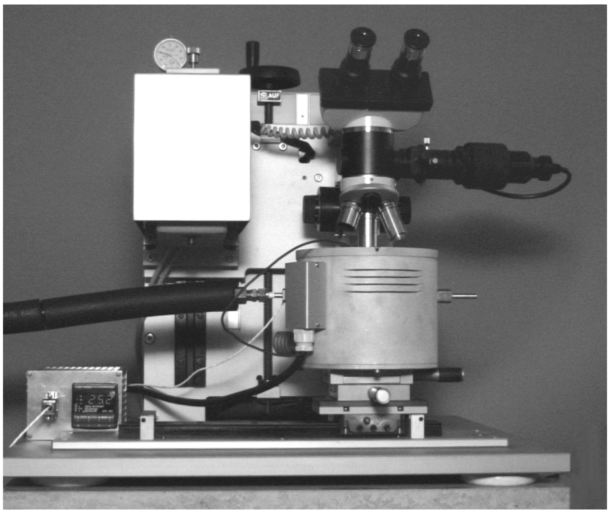


Figure 2: Indentation tester with modifications for tests at high and low temperatures.

Figure 3: Metallographic specimen mounted into the indentation tester. Tester is in microscope position.

Hardware Concept

Indentation testing has been reported earlier as a method to analyze the mechanical behavior of micromaterials /4/. One advantage is the possibility to test small volumes in the region from 1000 µm³ to 0.1 mm³. Furthermore the test is performed just on a single metallographic specimen rather than on many costly test samples which have to be machined to shape. Up to now the main disadvantages have been the limitation to room temperature testing and the lack of an efficient method to extract material parameters. The aim of our development was a method for the characterization of new materials over a temperature range from –40 to 150 ° C within less than one week.

Basis of the hardware design was a commercial micro-indentation tester (Fischerscope H 100 V-B) which is capable of loading in the range from 10 mN to 1000 mN and which has a nominal deformation resolution of 2 nm. An indenter exerts a controlled force on the sample while its movement towards the sample is measured. Thus it is possible to perform indentation tests at a pre-determined loading rate which is necessary to characterize plasticity. Subsequently time-dependent creep tests at constant load are performed with test times up to 30 min. The main effort of the hardware development was a temperature chuck which is heated electrically and cooled with cold nitrogen gas. In the indentation tests it is of great importance to avoid movement of the sample towards the indenter which would lead to erroneous deformation measurement. By a special design high thermo-mechanical stability in test cycles was achieved, Figure 2 and 3. The choice of the indenter has a significant influence on the data extraction. For viscoplastic materials the Vickers pyramid, Rockwell cones, or Brinell balls are suitable. After initial tests we chose a ball made of hard metal with a diameter of 0.4 mm. Typically an indentation depth up to 20 µm can be achieved for forces up to 1000 mN. Another important factor for the selection of the ball was it's rotational symmetry. As it was planed to calibrate the measurements by means of finite elements simulations, a simple geometry of the assembly was desired. In the case of the ball FE models can be reduced to half of a two-dimensional model with rotational symmetry. With such a reduction much shorter computational times are achieved.

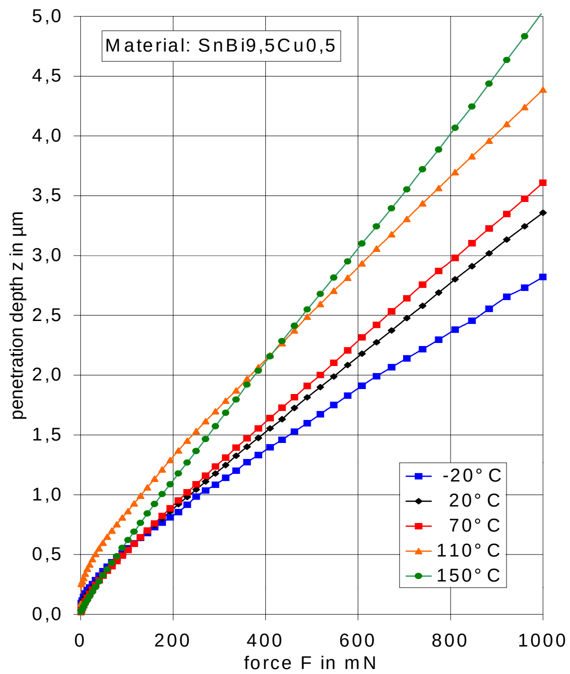


Figure 4: Indentation depth of a solder materials in the temperature range from –20 to 150 ° C. Plasticity tests at a constant loading rate.

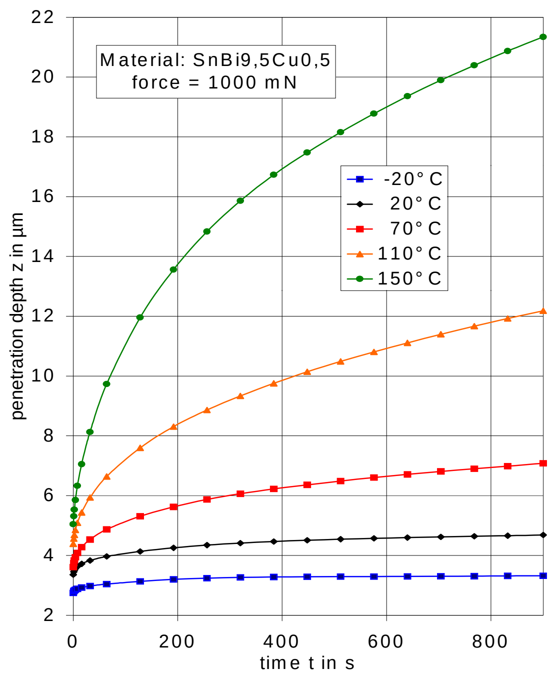


Figure 5:. Indentation depth of a solder materials in the temperature range from –20 to 150 ° C. Creep tests at constant load.

Results and Concept for the Extraction of Materials Data

The described test equipment was used to evaluate a number of solder materials. Presently, due to legislative requirements lead-free solder alloys are of special interest. In Figures 4 and 5 plasticity and creep behavior of a solder material SnBi9.5Cu0.5 were characterized. First, the force is increased continuously within 25 seconds resulting in an almost linear increase of deformation with load. The temperature dependence of the material is demonstrated clearly over the temperature range from –20 to 150 ° C. At a load of 1000 mN indentation depths between 2.7 and 5 µm are reached. In the successive phase of the test the force was held constant over a time of 15 min. Further continuous deformation is observed as a result of creep processes. Apparently the creep deformation rate is significantly reduced for higher deformations.

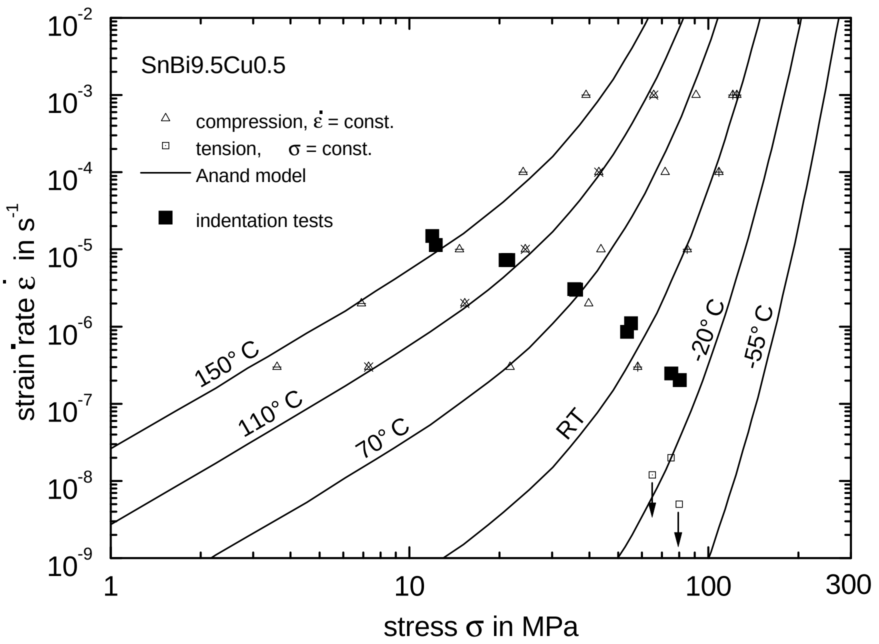


Figure 6: Creep rate of the a solder material SnBi9.5Cu0.5 s as a function of stress in the temperature range from –55 to 150 ° C. Comparison of mechanical standard tests and indentation tests.

The main reasons for this are the increase of the indentation area and the strain hardening of the solder. From the following data extraction process of these raw data two principal results are expected. The first are stress-strain-time curves computed from the measured force-indentation depth-time data. An approximation can be made using a model published in /4/. The representative stress σ_r is computed from the load F and the true contact radius of the indenter r according to:

$$\sigma_r = \frac{F}{\pi \cdot r^2} \cdot \Psi^{-1} \qquad (5)$$

Ψ is a function which describes the dependency between the average contact pressure and the representative stress /4/. For steels, Ψ typically is about 3. The representative strain ε_r in the z-direction is calculated from the true contact radius r and the ball Radius R according to:

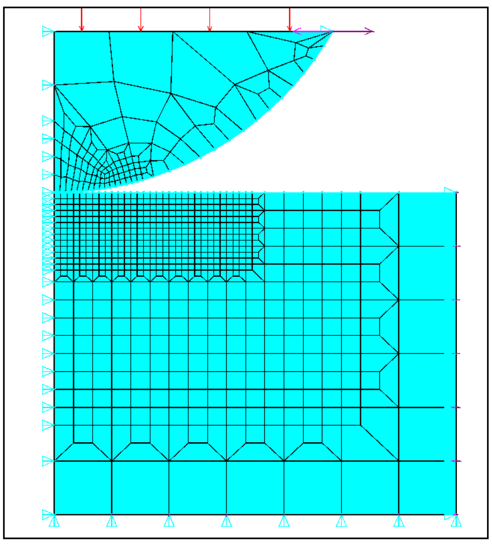


Figure 7a: Finite-Elements Model of the indentation hardness test.

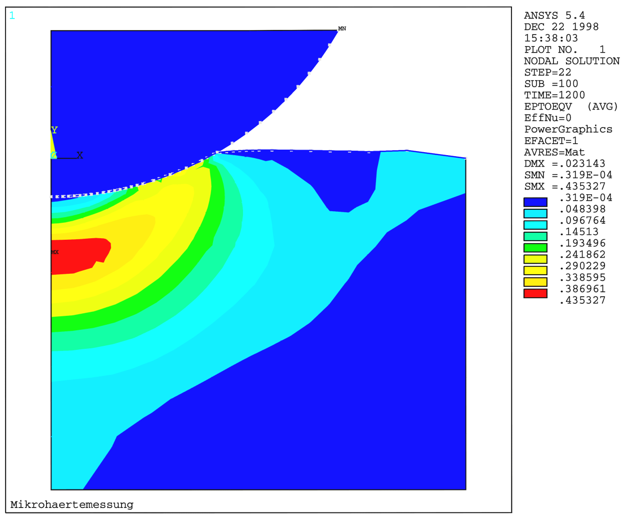


Figure 7b:. Results of the FE-calculation of the indentation test. Distribution of viscoplastic strains

$$\varepsilon_r = \frac{\alpha \cdot r}{\sqrt{1-(r/R)^2} \cdot R} \qquad (6)$$

α is a constant. The true contact radius r can be computed from the indentation depth applying elementary geometric calculations in combination with a correction for the pile-up of material around the indentation.

In Figure 6, the results of indentation tests are exhibited in the case of the steady-state deformation at the end of the holding time. Apparently, it is possible to achieve similar results compared to standard materials testing with tensile tests or compression tests. It should be noted, that the steady-state of creep has possibly not yet been fully accomplished within the short time of the indentation test and therefore the strain rates somewhat too high. Furthermore, the simple analytic calculation provides only average values of stress and strain. In order to analyze their distribution, FE analysis is helpful, Figure 7a and b. It becomes clear that the strains are not evenly distributed below the indentation ball. Hence one FE analysis should contain all of the stress-strain-time information for a constant temperature.

Using a complete set of measured data the parameters of Anand's model can be extracted analytically by multi-variant non-linear regression to a model which combines creep and plasticity. If the precision of these data is not sufficient, further refinement is possible. Here the regression results are starting values for a subsequent calibration using the finite elements method. For FE models similar to those in Figure 7 the creep curves and the plastic deformation curves are computed. Using an optimization algorithm, the parameters of the materials model are varied until differences between experiment and minimized, Figure 8. Presently, we are working on the improvement of this method.

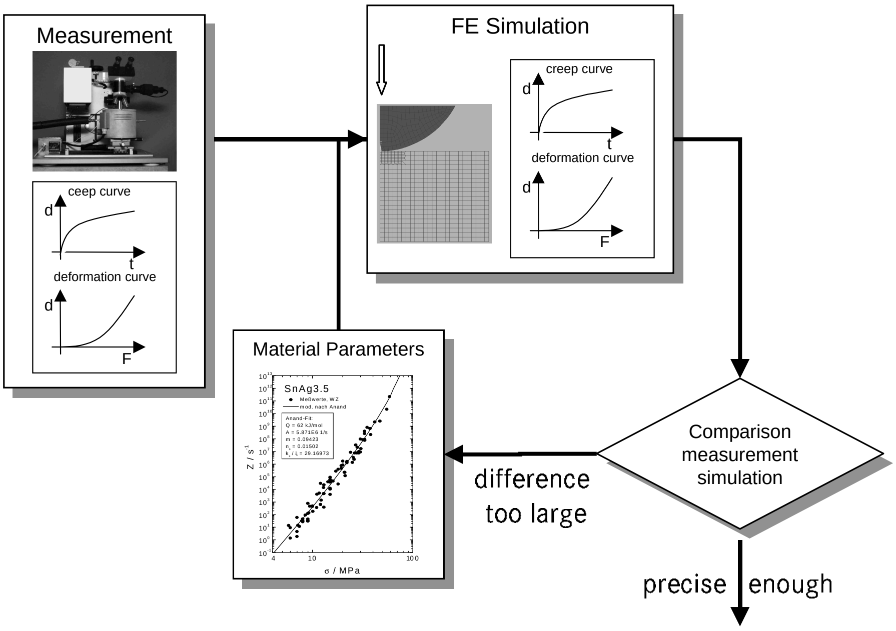


Figure 8:. Concept for the extraction of materials data

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