FRACTURE AND FATIGUE BEHAVIOUR OF MEMS RELATED MICRO MATERIALS

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1 ABSTRACT

Micro-Electro-Mechanical Systems (MEMS) stand for the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. MEMS-materials can be used for a large number of components. These materials show a complex material behaviour due to different mechanical and thermal properties throughout the sandwich, which can influence the mechanical and thermal reliability as well as the life time of it. Filled epoxy resin and electrodeposited metallic thin films are frequently used as MEMS-related materials. However, their mechanical characteristics, which are especially important for Finite Element Analysis (FEA), vary over a wide range. Therefore, for small-dimension samples the theory for bulk materials is oftentimes inaccurate. In this paper, a test method has been developed to determine the fracture toughness of filled epoxy resin with miniature CT-specimens (1" x 1"). The investigation of fracture using small specimens is based on analysing crack resistance against stable and unstable crack growth behaviour of standard specimens under quasi-static loading conditions by means of experimental fracture mechanics. The experimentally obtained fracture mechanics parameters will be geometry independent, if they fulfil the geometry criterion of minimal specimen thickness. The critical minimum specimen thickness of epoxy was determined to be 4 mm. Furthermore, a new test methodology will be presented for the determination of the fatigue behaviour of thin copper and nickel films, which is based on bi-material bending. The tests were accompanied by FEA to calculate the cyclic plastic strain of the bending experiments.

Keywords

MEMS, Fracture Behaviour, Toughness, Fatigue Behaviour, Filled Epoxy Resin, Films, Copper, Nickel

2 INTRODUCTION

A large number of MEMS-materials can be used for a large variety of components. These materials show a complex material behaviour due to different mechanical and thermal properties throughout the sandwich which can have on influence on the mechanical and thermal reliability as well as the life time. Filled epoxy resin, as thermoset and electrodeposited metallic thin films are frequently used as MEMS-related materials. At room temperature crosslinked epoxies typically exhibit a high modulus and a nearly elastic stress-strain behaviour, but they have poor resistance to fracture. A complex material behaviour can often be observed due to different mechanical and thermal properties of filler-bonded components which can influence the overall thermomechanical reliability strongly. The methods of fracture mechanics have an increasing significance regarding the assessment of failure behaviour. In the future, the use of miniature specimens for the determination of fracture mechanics parameters should become practicable so that an efficient toughness evaluation of newly-developed materials can be performed [1],[2]. Furthermore, the evaluation of the mechanical characteristics of thin films is a complicated task. Important properties to be measured are CTE, Young's modulus, the plastic yield limit, fracture stress or – strain as well as internal stresses caused by processing. All these properties are subject to temperature. For them all, miniaturization, too, can have a significant effect on the material properties. To define dependencies between the microstructure of materials and their mechanical properties is a continuously ongoing research task, becoming even more important with the current developments in nano-materials. Low-cycle fatigue is the most frequently observed kind of failure with metallic films, mostly caused by thermal mismatch related straining. The results of the test were accompanied by Finite Element – Analysis as input data from microscale test methods.

3 EXPERIMENTAL METHODS AND PROCEDURE

3.1 Fracture toughness of thermoset

The test material that was chosen for all investigations was highly filled epoxy resin. The fracture mechanics values of the cured resins were measured by miniature compact-tension (CT)-specimens with the dimensions length L = 25.4 mm, width W = 20.4 mm, and thickness B = 1 - 10 mm. For all specimens the ratio of the initial crack length to the width a/W was 0.55. Additionally, to realize a sharpened crack tip, the specimens were notched with an industrial razor blade [1],[3]. All tests were performed on an INSTRON universal testing machine. The load-line displacement was measured by means of a laser-double scanner. This System is favoured for experimental fracture mechanics examinations and works in transmission mode with two parallel laser beams. With these two beams, the load-line displacement and crack mouth opening displacement could be determined by contactless measurements for the shown specimens (Fig. 1) [4].

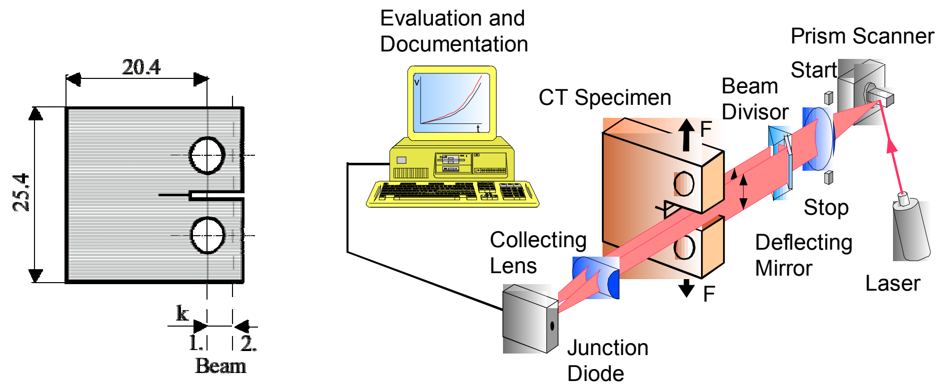
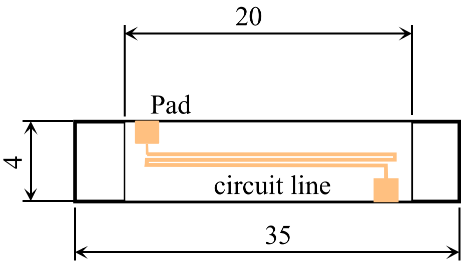


Fig. 1 Laser-double scanner system and specimen geometry [4]

3.2 Fatigue behaviour of thin films

The new test methodology to determine the low-cycle fatigue properties of the films is based on the bi-material bending of metallic films (4 –5 µm thickness) on a substrate [5]. The beam-like test specimens are made of polymeric substrates, which are plated with a pattern of thin metallic lines, arranged to form a meandering structure. The geometry of the test specimens is shown in Fig. 2. The substrate has to be selected so that it allows easy processing and reversed bending with an appropriate bending deflection for a high cycle number without showing signs of damage. These composite beams are subjected to cyclic three-point or four-point bending. The plastic strain amplitudes in the metallic lines can be controlled by the bending deflection of the beam. Failure of the metallic line can easily be monitored in-situ during cycling. For this purpose, an electrical current is applied to the meandering metallic line and fatigue failure is detected when an electrical open occurs. (more details for the test set up in [5])



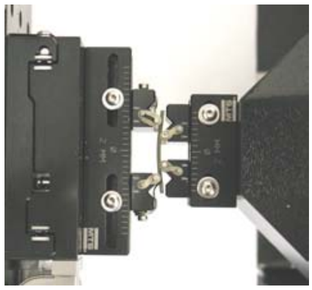
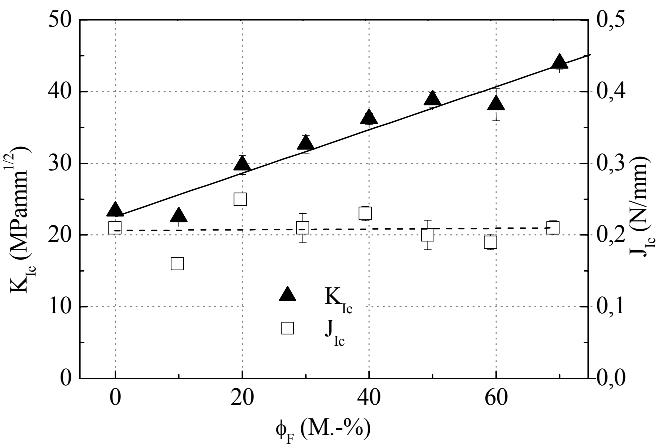


Fig. 2 Geometry of the bending samples 100 µm line width- four-point testing machine

4 RESULTS AND DISCUSSION

The filled thermosets are brittle and show an instable crack propagation over a wide temperature range. For this specimen's -CT-geometry the critical minimum specimens thickness was determined to be 4 mm. Thereby the fracture mechanics parameters can express the influence of material structure and test conditions. The fracture toughness value is dependent on many factors - e.g.. loading rate, and test temperature filler content ϕ_F [1],[2]. The addition of anorganic particles with high modulus is a further possibility for modifying the fracture toughness. These micro particles in epoxy formulation can improve absorption of energy clearly and therefore improve the toughness as well as the mechanical behaviour and reduce the cost of the whole material composition. The main cause of improvement of fracture toughness is the debonding process of particles of the polymer. This behaviour is based on the mechanism of crack length deflection. The deformation behaviour is clearly load and stress determined, because the deformation behaviour of the thermoset formulation is strictly dependent on filler and content. Opposite, the evaluation of fracture behaviour with energy determined J-integral showed that the deformation obstruction also increases if the content of filler increased.



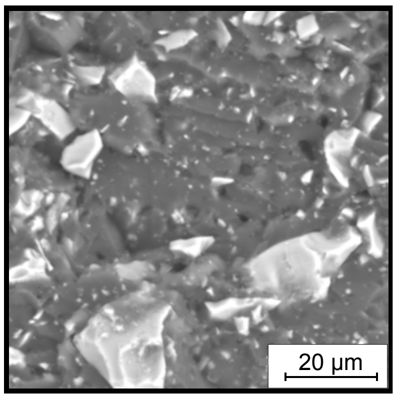


Fig. 3 Fracture toughness and J-integral with glass powder filled epoxy resin as a function of filler content – SEM image of geometry of particles

Fig. 4 shows the measured cycle numbers in dependence on the cycling bending deflection of metallic metallization. Copper (batch 1) has a clearly higher fatigue resistance than nickel. For the electrodeposited Cu and Ni lines with 4-5 µm thickness, fatigue cracks were observed at locations within the constant strain region, between the inner pivots. The cracks typically went through the whole cross section of the metallic lines, nearly perpendicular to the bending direction. Furthermore, it can be observed, that Cu and Ni lines show a similar kind of cracking. The elastic-plastic properties of electrodeposited thin Cu and Ni films differ to a great extent from bulk values and are highly process dependent. In cases when significant initial flaws could be detected to be responsible for the failure initiation, the cycle results were rejected. The test were accompanied by Finite-Elemente-Analysis to calculate the cyclic plastic strain of the bending experiments. Modelling assumptions are required concerning both the geometric representation of the test and the constitutive behaviour of the materials. These plastic strains can serve as the basis for an empirical low-cycle fatigue hypothesis, the Manson-Coffin equation. The fatigue behaviour of metallic thin films, especially copper films, has already been shown to obey a Manson-Coffin type relation [6] for the critical cycle number N_f ,

$$N_f = \left(\frac{\Delta\sigma}{\sigma_0}\right)^{-b} + \left(\frac{\Delta\varepsilon_{pl}}{\varepsilon_f}\right)^{-c} \qquad (1)$$

where the first term describes high cycle fatigue, i.e. fatigue caused by cyclic straining in the elastic deformation range, measured by the cyclic stress amplitude $\Delta\sigma$ in relation to a characteristic stress σ_0, and the second term describes low cycle fatigue, where the damage stored in each cycle is related to the cyclic plastic strain amplitude $\Delta\varepsilon_{pl}$ divided by a constant ε_f . Sometimes this constant can be related to the static fracture strain. It was shown that the elastic-plastic material behaviour strongly depends on microstructure of the deposited layer.

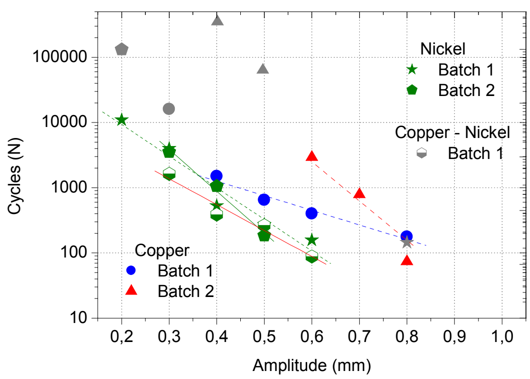
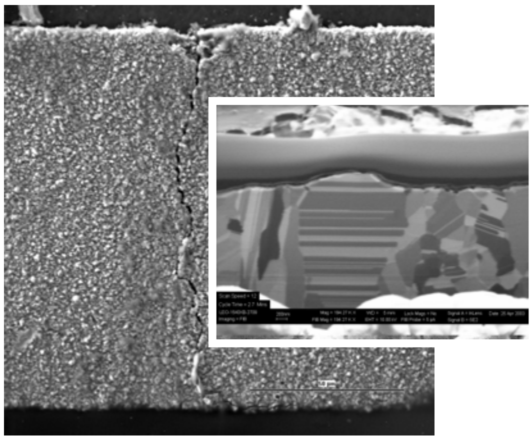


Fig. 4 Measured cycles to failure in dependence of a the cyclic bending amplitude for metallic metallization. four-point bending test



SEM micrograph of a cracked Cu line after 400 cycles with bending deflection 0.6 mm – focus ion-beam (FIB) image of Cu microstructure

5 SUMMARY

The aim of this work is the evaluation of specific toughness behaviours of thermosets with miniature compact tension specimens using a laser-extensometry. In the case of filled materials, the fracture toughness is better if irregular particles such as powder are used. The Application of fracture mechanics concepts makes it a possible to obtain a lot of information to characterise the fracture toughness of newly developed or modified materials, e.g. MEMS, using miniature specimens. For the characterisation of low cycle fatigue behaviour, the proposed method using a bi-material bending specimens, has several advantages compared to the standard reversed bending procedure, using a mandrel arrangement. For example, a testing machine, which allows cyclic bending loading, requires no additional experimental set-up. Arbitrary thin metallic layers can be investigated, without any need for the preparation of free standing samples. Strain amplitudes can easily be varied, ranging from purely elastic to elastic-plastic straining with different plastic strain amplitudes within the lines. The Manson-Coffin hypothesis seems to be still applicable, at least to give an estimate of mean cycles to failure. FE-simulation is an important tool to complement the experiment, since they it provide physical information about the modes of failure. Insight into failure mechanisms and structural performance can be obtained by the methodology presented here. Future work will address structural reliability issues in MEMS. The first testing results show that also for the thin metallic films with thicknesses in the range of 5 µm the Manson-Coffin hypothesis is applicable. Mean cycles to failure obey a power-law relationship in dependence on plastic strain amplitudes. Since a slight change in electroplating parameters has shown a significant effect on the fatigue-failure behaviour for copper, the investigations are still ongoing.

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