MECHANICAL PROPERTIES OF MEMS STRUCTURES

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ABSTRACT

Mechanical characterization of MEMS (micro electromechanical systems) materials is increasingly important in view of improving reliability and assessing the life time of new miniaturized devices. In this paper first a number of testing methods are described. These methods include tensile, torsion and fatigue testing of specially designed microstructures. Difficulties arise from manufacturing and handling of small structures and the determination of its geometrical dimensions which directly affect the accuracy of material parameters extracted from the experiments. In addition, the measurement of mechanical parameters like small forces and torques or strains poses a challenge. This paper focuses on size effects in rolled copper foils of thickness between 10 and 250 microns as determined from tensile testing. Tensile testing was chosen as a testing method in order to minimize strain gradients.

Depending on the size the copper foils are tested in a classical setup or in a special tensile apparatus which is adapted to the small size of the specimens. The special setup consists of a balance to measure the applied force. The specimens are strained with a lead screw driven translation stage. In order to take care of slip and elasticity in the fixations the strain is measured optically directly on the sample using a least square template matching algorithm. It was found that depending on the thickness of the foils the average fracture strain decreases from about 15% down to .5 % for the 250 and 10 micron specimens, respectively. In order to find a reason for this dramatic change many efforts have been undertaken in order to characterize the specimens more precisely. The microstructure of the samples was determined using various methods including conventional micrographs, hardness measurements and X-ray diffraction.

1 INTRODUCTION

With increasing use of miniaturized systems a strong need arises for the mechanical characterization of the materials used. In particular for polycrystalline materials it is often not possible to use properties obtained from macroscopic experiments, as the microscopic elements have particular grain structures, which are related to the special manufacturing processes used. Also crystalline materials might have special design parameters, because again the manufacturing will influence certain parameters, e.g. by surface roughness. Furthermore, most micromaterials show anisotropy, due to their crystallinity, preferred directions in the growing process or texture related to deformation processes. Therefore, specimens need to be tested in their small configurations in view of measuring the relevant design parameters. The requirements and complexities mentioned make the characterization of MEMS materials quite challenging. In addition testing of small specimens is a window towards exploring the limits of continuum mechanics, which is generally believed to be at the level of several nanometers.

Probably the most widely used technique is nanoindentation. Much research has been done, because of the simplicity with which these instruments can be used. Nevertheless, differences in the resulting parameters often arise for the same materials, in particular when parameters beyond elastic moduli are sought. These differences are due to a variety of reasons like pile up, sink in, substrate effects, anisotropy, loading conditions, etc. (Saha [1], Venkatesh [2]). Another quite widely used technique is tensile testing in a TEM or SEM environment, which is rather cumbersome though.

In this paper an overview of a set of measurement techniques is shown, most of which can be implemented with relative ease and moderate cost. Furthermore, results from tensile testing of rolled copper foils are treated in more detail.

2 MECHANICAL TESTING OF SMALL SPECIMENS

Several methods for the mechanical testing of small specimens of MEMS materials are described which are suitable for testing samples which are fabricated in the same way as MEMS structures.

2.1 Specimens

The specimens used were of single crystal silicon, rolled copper foil or various NiFe LIGA (lithography, galvanic, abformung) alloys, where the first two mentioned are patterned by lithography and wet etching. For better handling the specimens include two relatively large (e.g. 4 mm x 5 mm) end plates connected by the actual testing region (cross-section of e.g. 20 μm x 30 μm, length of 500 μm).

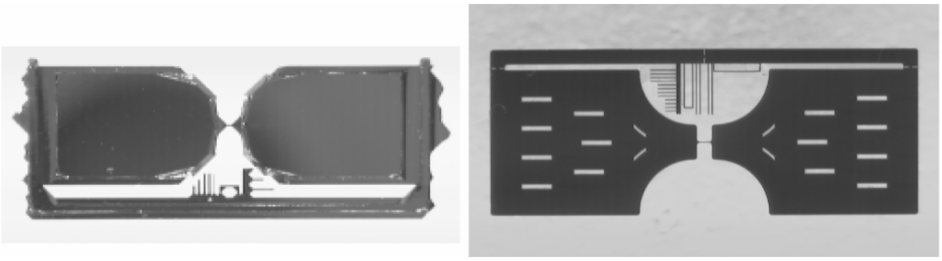

Figure 1: Microstructure specimens (left: Silicon, right: metallic LIGA) used in order to determine material parameters. The small testing region between the large plates has a length of about 300 μm. The additional small structures are used for detecting intrinsic stresses.

2.2 Testing Methods

2.2.1 Torsion Testing

Relatively little work has been done on torsional testing. In Schiltges [3] a torsional testing set-up is described: The torque is determined from the rotation of a bar, which is supported with a calibrated torsional spring. The rotation of the bar is measured with a two point optical fiber interferometer. The specimens (Figure 1) are attached with one plate to the bar and with the other plate to a rotational stage. The actual rotation angle is measured with a linear diode detector. The torque resolution is about 0.05 μNm. While the silicon specimens show a brittle behavior in a torsion test, the LIGA Ni and NiFe specimens show large deformations including plastic behavior.

2.2.2 Fatigue Testing

When fatigue testing is concerned, a resonance technique turns out to be the most suitable (Connally [4], Schlums [5]). It is based on the fact that upon crack propagation the resonance frequency of a structure in bending decreases in a monotonous way with increasing crack length. By using a phase-locked feedback loop, the resonance frequency can be tracked, such that frequency vs. time curves result. Using simple fracture mechanics, the resonance frequency of a beam can be related to the crack length, using a compliance matrix based on stress intensity factors. The specimens used are similar to the ones shown in Figure 1 with the difference that the testing region contains a notch. They are vibrated in their plane using a stacked piezo element. The vibrations are measured with a laser optic displacement sensor in order to close the feedback loop.

2.2.3 Tensile Testing

In order to determine critical stresses for microstructures, specimens with a design similar to Figure 1 were subjected to a tensile test. A tensile test apparatus was designed for testing small specimens: The force acting on the specimen is determined using a high resolution balance, while the strain is determined using a video camera and a least square template matching algorithm (LSM) which yields a super resolution in the specimen extension around 10nm under an optical microscope (Mazza [6] and Mazza [7]). The LSM algorithm matches the six parameters that characterize a homogeneous deformation by adaptive least squares correlation. The LSM results agree very well with results of vibration measurements and the Young's modulus typically used for Silicon in the <100> direction (Hull [8]). Critical stresses as computed from force and cross-sectional area in the middle of the testing region amounted to 586 MPa with a standard deviation of ± 3%. Of course all the specimens broke at their ends because of stress singularities. In fact, with the anisotropic etching a nearly perfect notch was produced there. As fracture starts at the atomic level, such a tensile test can therefore be used as a window towards molecular dynamics. Continuum mechanics can be matched with atomistic theories.

3 SIZE EFFECTS OF THIN COPPER FOILS IN TENSILE TESTING

The influence of the size of a specimen on its mechanical behavior is an object of current research. An overview of possible size effects is given in Arzt [9]. Many size effects are explained based on a theory developed by Fleck [10] who explained size effects in copper wires in torsion using a strain gradient plasticity theory.

While elastic properties do not seem to vary with the size of the specimen, for other quantities large discrepancies might arise. When testing Ni specimens made with the LIGA technology it was found, that the ultimate strength was considerably higher than for macroscopic specimens (Mazza [11]). Klein [12] reported a decrease of the fracture strain with smaller sample size and a more complicated influence of the size on the ultimate tensile strength when testing copper wires and stripes. The thickness of the tested specimens varied between 9 and 200 μm.

Although it is known that the microstructure of a polycrystalline sample affects its mechanical behavior to a large extent this fact was often neglected in many studies concerning size effects in small structures. Here, results of a study are presented which tries to close this gap for thin rolled copper foils: Thin rolled copper foils of varying thickness (10 – 250 μm) were tested in tension in order to minimize effects of external strain gradients. Larger specimens (copper foils thicker than 20 μm) are tested with a commercial tensile test machine (Zwick 1445) with a 10 N and 200 N load cell and a specially designed clamping apparatus to allow clamping free of initial tension. Smaller samples are tested with the apparatus explained in Section 2.2.3. The specimens were made of 99.9% pure copper foils (Goodfellow) and had ratios of thickness to width to gauge length of 1 to 20 to 200, which was kept constant when downscaling (further details in Villain [13]). The specimens were manufactured by photolithography and wet etching and had the longitudinal axis in the rolling direction. The strain rate was in the order of 10^{-4} 1/s - 10^{-5} 1/s. Additionally, a detailed characterization of the microstructure was performed prior and after the test including X-ray diffraction, hardness tests and metallography.

3.1 Microstructure

The microstructure of the foils has a strong (100)[001] cube texture and weak deformation texture resulting from the rolling process. Figure 2 shows a sketch of the grain structure: It is dominated by large grains which have approximately a cylindrical shape with a flat ellipse as a cross section normal to the rolling direction where the major diameter (D) is in the range of a few microns and is approximately 5 times the minor diameter. The length of these grains (L) is 5-10 times the major diameter (D). Furthermore, there are some small grains which are situated in between the larger grains.

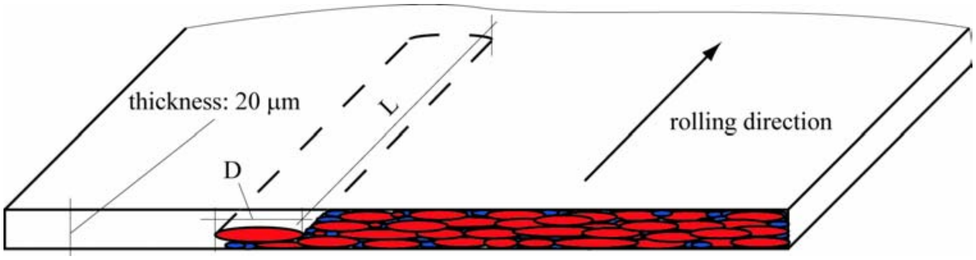

Figure 2: Sketch of the grain structure of the copper foils: Large cylindrical grains (diameter D and length L) are accompanied by small grains.

3.2 Results of Tensile Tests

In Figure 3 on the left the results of a tensile test for a 10 and 34 μm thick foil are presented. The 34 μm thick foil shows a typical stress strain relationship for ductile materials, whereas the 10 μm thick foil has a stress strain behavior which is typical for brittle materials (nearly only elastic part). The right graph of Figure 3 displays the relationship between foil thickness and fracture strain (circle, left vertical axis) and ultimate strength (dot, right vertical axis). The results of the tensile tests indicate a moderate increase of the tensile strength (except for the 10 μm foil) and a strong decrease of the fracture strain with decreasing thickness of the copper foils. In terms of fracture strain, when going from 250 μm to 10 μm thickness, the fracture strain is reduced dramatically from 20% to 0.2-0.5% (scatter of fracture strain values). For the interpretation of the strain results it has to be stressed that the strain measured is the average strain of the whole sample in tensile direction (“macroscopic strain”). Figure 4 shows a comparison of the tensile results of copper foils and wires from the literature (Klein [12]) with results from this study. Thinner specimens show a lower fracture strain for both wires and foils. The situation is more complicated for the tensile strength. The results suggest that when both dimensions of the cross-section are scaled (wires of Klein [12] and foils of this study) the tensile strength increases with decreasing size. When only one dimension is scaled (stripes in Klein [12]) the trend is opposite.

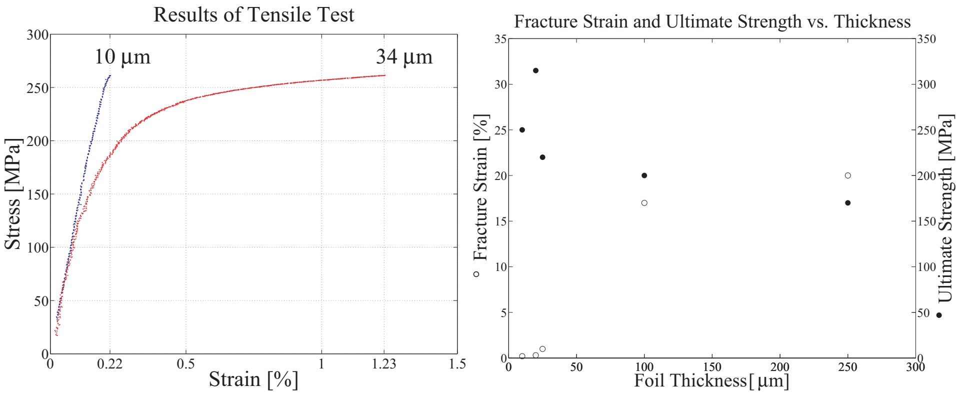

Figure 3: Tensile test results (strain rate 2.5*10^{-5} 1/s): Stress-strain curve for a 10 and 34 µm thick foil (left image) and fracture strain (circle, left vertical axis) and ultimate strength (dot, right vertical axis) vs. foil thickness (right image).

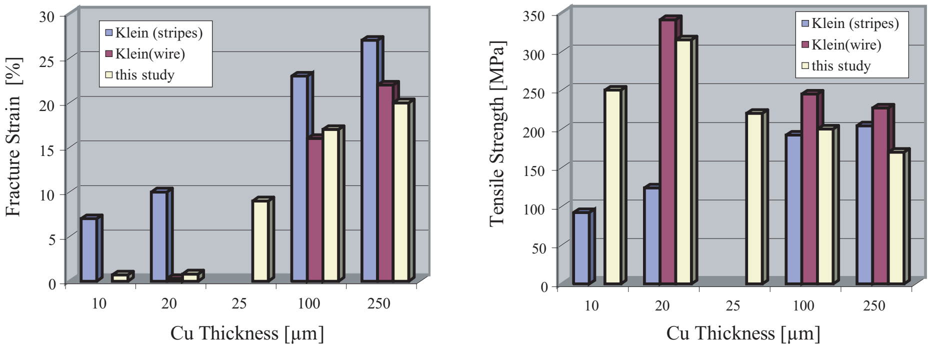

Figure 4: Comparison of the tensile test results of copper foils and wires from Klein [12] and this study.

The reason for the strong decrease in fracture strain is unclear at the moment. Considerable efforts are currently made to characterize the specimens used in terms of surface roughness, grain shapes, orientations, size, dislocation densities, etc. Because of the small size this turns out to be quite difficult though. Furthermore, the effect of additional heat treatments is studied. First tests on annealed samples (300°C for 2h) indicate a strong increase in the fracture strain and decrease of the ultimate tensile strength which is expected as the amount of strain hardened material is reduced due to recrystallisation. Nevertheless, thinner foils still display a smaller fracture strain than thicker foils.

4 SUMMARY

In addition to the well-known nanoindentation technique a number of other methods exist to determine the mechanical properties of MEMS materials, which have not been used to their full potential so far. They offer insight into many interesting phenomena like size effects (micro tensile and torsion tests) or resonance fatigue testing with extremely high resolutions. Together with elaborate manufacturing possibilities and well characterized materials like Si as known from MEMS and IC fabrication, they offer possibilities of probing material behavior in the nm range. While elastic properties do not seem to vary with the size of the specimen, the ductility seems to decrease with smaller testing volumes.

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