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NANOMATERIAL BEHAVIOUR OF A GOLD MICROCANTILEVER SUBJECTED TO PLASTIC DEFORMATIONS

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The nanomechanical material behaviour of a gold microcantilever subjected to plastic deformations is presented in this paper. Using an atomic force microscope, experimental investigations are performed in order to determine the dependence between bending deflections of sample versus applied forces and to estimate the maximum stress in the beam structure. During testing, the force has successive positions on microcantilever, starting from the beam free-end and moving toward to the anchor. The plastic deformation of microcantilever occurs when the force is applied close to the beam anchor and performed large deflections. Finite element analysis is used to visualize the deflection of microcantilever and to estimate the maximum stress.

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1. Introduction

Determination of the failure mechanisms of micro/nano-components is the key to the design of reliable products. Issues on micro/nano-systems reliability are seeking to discover methods and new technologies to increase their lifetime. The slow movement of atoms under mechanical stress is expected to be one of the major problems especially for radio frequency (RF) microswitches when the flexible plate deflects complete to substrate in the actuated state and performed a direct metal-to-metal contact [1, 2]. There exists two forms of RF microswitches: the metal-to-metal contact microswitch (ohmic) and the capacitive microswitch. RF microswitches can be used in a variety of RF applications including cellular phones, phase shifters, smart antennas, multiplexers for data acquisition, and more. The specific ohmic switches essentially use cantilever microbeams that deflects under an applied force. The stress distribution in a microcantilever when it is deflected to substrate depends by the contact area between flexible plate and substrate [3]. If the contact area between flexible plate and substrate increases, the maximum stress increases..

Ductile materials are generally defined by means of the *yield strength*- which is the stress corresponding to the point on the stress-strain characteristic where the linear behaviour ends, and the *ultimate strength* – the stress where failure occur [4]. In this paper, the microcantilever behaviour under large deformations is analyzed and the yield strength is predicted based on the experimental force-displacement AFM curve. Under large deformation, the materials no longer obey the linear relationship and the microcantilever is subjected in additional to shear stress. It is generally accepted that Timoshenko beam theory taking shear deformation into account is more accurate than Euler-Bernoulli beam theory for described the deformation behaviour of beam [3, 4].

2. Theoretical formulas

2.1 Dependence between force versus deflection and stiffness of a microcantilever under bending and shearing deformations

Stiffness is a fundamental criterion of elastically-deformable mechanical flexible microcomponents whose static, modal or dynamic responses need to be evaluated [4, 5].

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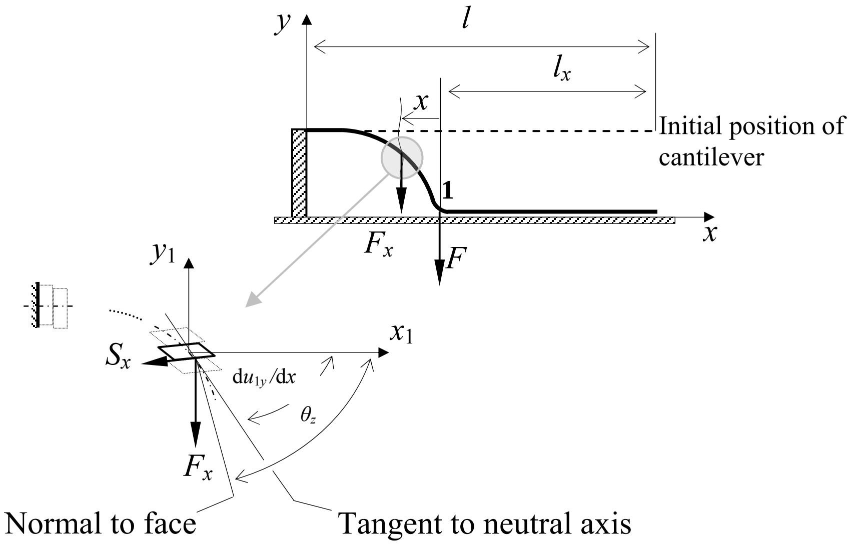


Fig.1. Microcantilever under bending and shearing deformations.

In a RF-microswitch the microcantilever deflects to substrate as it is presented in Fig.1. The contact area between the flexible plate of beam and substrate increases if the load is moved toward to the anchor [3, 6]. If this contact area is large and the force is applied close to the anchor, searing effects became important, and the regular bending deformations are augmented by additional of shearing deformations, according to the Timoshenko beam model. In this case, the cross-sections are no longer perpendicular to the neutral axis in the deformed state and the total strain energy is [4]

$$U_b = \frac{\int_l \frac{M_b^2}{I_z} \mathrm{d}x}{2E} + \frac{\kappa \int_l \frac{S^2}{A} \mathrm{d}x}{2G} \tag{1}$$

where M_b is the bending moment, S is the shear force, A is the cross-sectional area, I_z is the cross-sectional moment of inertia, E is the Young's modulus, G is the shear modulus, and κ is a coefficient accounting for the cross-sectional shape and it is $\kappa = 5/6$ for a rectangular cross-section.

Based on the relation (1) and considering the bending moment given by the force F and the l - l_x distance (Fig.1), after performed the necessary calculations, the dependence between deflection of a microcantilever and the acting force can be computed as

$$u_{1y} = F(l - l_x)\left[\frac{(l - l_x)^2}{3EI_z} + \frac{\kappa}{GA}\right] \tag{2}$$

The shearing – dependent stiffness can be written in the form of

$$k_{b(sh)} = \frac{3EGI_z A}{(l - l_x)\left[GA(l - l_x)^2 + 3\kappa EI_z\right]} \tag{3}$$

2.2 Equivalent stress of a microcantilever under combined loading

In the case of a microcantilever if the force is applied close to the anchor, the normal stress is affected by the searing effects. Corresponding to this situation, the tangent to the neutral axis is not perpendicular to the beam frontal face (Fig.1) as to the pure bending deformation. This is due to the fact that shearing effects become important, and produces the additional angular deformation

$$\theta_z(x) - \frac{\mathrm{d}u_{1y}(x)}{\mathrm{d}x}$$

The equations combined effects of shearing and bending, according to the Timoshenko beam model, and applied of the case presented in Fig. 1 are [3]

$$\begin{cases} M_z(x) = E \cdot I_z \dfrac{\mathrm{d}\theta_z(x)}{\mathrm{d}x} \\ \theta_z(x) - \dfrac{\mathrm{d}u_{1y}(x)}{\mathrm{d}x} = \dfrac{\kappa \cdot S(x)}{A \cdot G} \end{cases} \tag{4}$$

By taking into account the bending moment at the section x of beam (Fig. 1)

$$M_b(x) = F(l - l_x - x) \tag{5}$$

the angle $\theta_z(x)$ can be computed by integrating the first of Eqs. (4) considering that $\theta_z(l - l_x) = 0$, as

$$\theta_z(x) = \frac{F\left[(l - l_x)^2 - x^2\right]}{2EI_z} \tag{6}$$

Considering a cross-sectional element at the x- distance about the point 1 (Fig.1) and a force F_x acting on this section, the shear stress is

$$\tau(x) = \kappa \frac{S_x}{A} = \kappa \frac{F_x \cos\left[\theta_z(x) - \dfrac{\mathrm{d}u_{1y}(x)}{\mathrm{d}x}\right]}{wt} \tag{7}$$

as well as the bending stress

$$\sigma_b(x) = \frac{6F_x(l - l_x - x)}{wt^2} \tag{8}$$

Failure in micro/nano-systems, as the situation where a microcomponent does no longer perform as design, can occur in the form of yielding for ductile materials where the stresses exceed the yield limit [3, 4]. Failure in RF microswitches can occur in the form of excessive deformations, either elastic and/or plastic - when the flexible plate does not regain its original shape after loading is relieved.

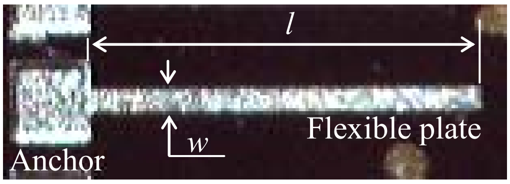
One way to characterize the deformable limit of a flexible component is the yielding criteria. In essence, if the bending load is affected by the searing effects, the compounds stress with normal and tangential components, need to be less then a limit value in order for the microcomponents to operate reliable. The von Mises criterion is one of the common criteria that predict the yield response of flexible components under combined stresses. The stress based on the von Mises criterion is

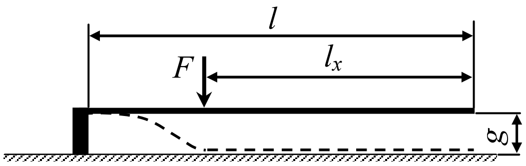
$$\sigma_{ech} = \sqrt{\sigma_b(x)^2 + 3\tau(x)^2} \tag{9}$$

If the yields stress σ_y for a material is known, it is possible to perform the verification of the yielding criteria $\sigma_{ech} \leq \sigma_y$ and the calculation of the dimensions of sample with respect the yielding criteria [5, 6].

3. Experimental investigation

The material used to fabricate of microcantilever is gold (electroplated + about 40 nm evaporated Au). The structure (Fig.2a) is fabricated in ten lithography and deposition steps using silicon as substrate. The dimensions of microcantilever are the length l = 345μm, the width w = 50μm and the thickness t = 3μm. The gap between flexible plate and substrate is g = 3μm.





a. b.

Fig.2. Microcantilever for experimental investigations (a), and an instantaneous position of the load on microcantilever (b)

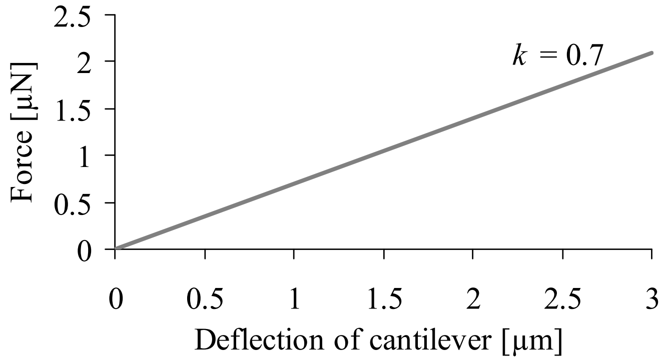


Fig.3. Force versus deflection of a microcantilever (the force is applied at the free-end of sample)

Experimental investigations are performed using an atomic force microscope (AFM). During testing, a mechanical force is applied at different positions on the investigated microcantilever (Fig.2b) and deflects the sample to substrate. The AFM dates are use to estimate the experimental behaviour of microcantilever during deflections. The deflection of AFM probe and its real stiffness give the acting force. In the AFM tests, the difference between displacement of AFM piezo-table and the detected deflection of AFM probe gives the displacement of sample [5, 7]. Using these AFM dates, the experimental dependence between force and the deflection of sample is computed. Figure 3 present the experimental dependence between force and bending deflection of sample when the force is applied at the free-end of microcantilever. The slope of experimental force-deflection curve gives the sample stiffness (0.7 N/m). In the other case, when the force is applied at a distance of 30μm from the beam anchor, a nonlinear behaviour of microcantilever deflection was experimental monitored (Fig.4).

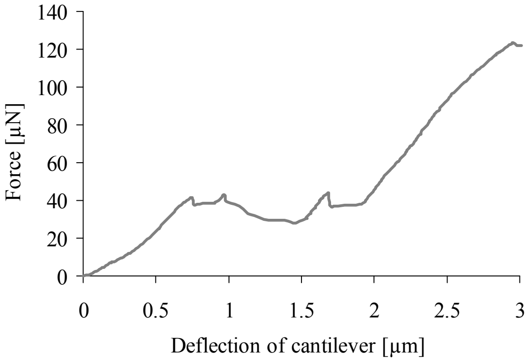


Fig.4. Nonlinear dependence between force and deflection of a microcantilever (the force is applied close to the beam anchor)

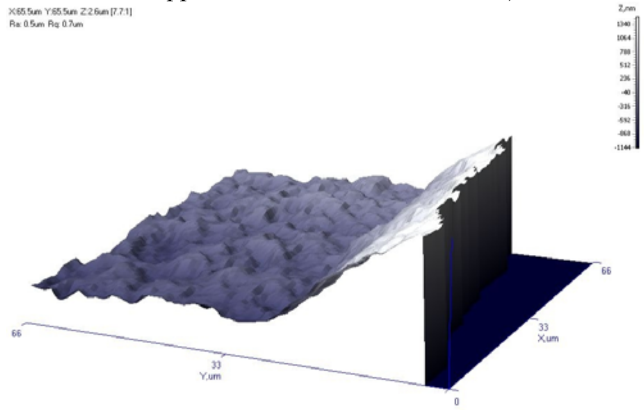


Fig.5. Inelastic deformation of a microcantilever when the force is applied close to the beam anchor.

After unloading, the scanning of sample was performed and the obtained 3D image (Fig. 5) confirms that: during loading with a force applied at the distance of 30µm from the beam anchor, the plastic deformation appears and the flexible plate does not completely regain its original shape after unloading. At a deflection of sample of 0.76 µm an inelastic deformation occurs. The force corresponding to this deflected position is obtained based on the bending deflection of AFM probe and its real stiffness (48N/m). This force is 41.22µN and it is applied at a distance of 30µm from the anchor.

4. Finite element analysis

The scopes of finite element analysis (FEA) are useful to estimate the stress distribution in the investigated microcantilever when the beam deflects to substrate. The forces used in the FEA are the forces coming from the experimental investigations given by the AFM probe. The modeling and FEA were performed using Oofelie::Multiphysics Software.

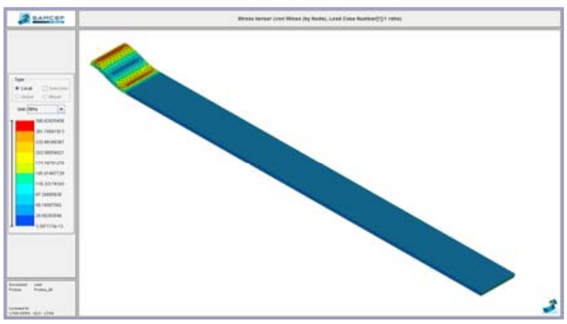


Fig. 6. Stress distribution in the investigated microcantilever subjected to plastic deformations

Fig. 6 shows the stress distribution of the investigated microcantilever when the beam is deflected with 0.76 μm (as in the experiment, Fig.4) and a plastic deformation occurs. The force is applied at a distance of 30μm from the beam anchor and the maximum equivalent stress is computed. The yield strength - which corresponds to the point where the linear behaviour ends, is 290.82 MPa. The high value of this maximum stress confirms the plastic behaviour of the microcantilever material.

5. Conclusions

This paper presents the analytical formulas and the experimental investigations of a microcantilever subjected to a mechanical force which bends the flexible plate to substrate. The studies were made for a microcantilever with known geometrical dimensions, manufactured from gold. During experimental tests, a linear dependence between force and deflection of a microcantilever were experimental monitored when the force was applied at a distance 5 times larger than the width of sample (Fig.1). Relatively short components are generally prone to inelastic deformation, as part of their cross-section is already in the non-linear portion of the stress-strain dependence. This type of deformation is inelastic, so the microcomponent does not completely regain its original shape. The experimental works developed and presented in this paper confirm that, an inelastic behaviour of a microcantilever occurs if the acting force is applied at a distance from the beam anchor, 5 times less than the width of sample.

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