Strength Prediction for MEMS Components Transferring Large Loads

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ABSTRACT

In this paper the authors present a new strength criteria combined with a finite element analysis to predict the strength of MEMS fabricated microridges. The single crystal silicon microridges can be manufactured by various processes that produce different geometries with distinctly different strengths, a topic verified by experiments. A strength criteria based on strain energy concepts is proposed to evaluate the difference observed in component strength. Agreement between test data and model prediction is good with errors less than 25% and usually less than 5%. Therefore, we believe that a wide range of microcomponent strengths can be predicted by performing a limited number of tests.

Keywords: strength prediction, microridge, stress converge.

INTRODUCTION

Simulation and testing of microelectromechanical components is important to the MEMS community. This is because while many applications exist for MEMS systems, the mechanical properties are not readily available. These values can be quite different than those measured for macro-scale structures because of a variety of features including specimen preparation and property measurement. The differences are further complicated by specimen dimensions in the micro-scale that can produce varying results based on amount of defects present [1].

Worthman and Evans calculated the Young's modulus and Poisson's ratio as a function of direction in different orientation planes for silicon and germanium in 1965 [2]. Later Greenwood derived values for Young's modulus and shear modulus for single crystal silicon [3]. Those values are well used in various simulations, and are chosen for use in this paper. However, for measurements of mechanical properties for MEMS materials (i.e. strength), difficulties often arise due to small dimensions of specimens, applied forces, and displacements resulting in low accuracy or repeatability due to poor alignment, weak gluing and/or irreparable mechanical damage inside the specimen [4]. Some material strength tests have been performed on an integrated chip to overcome some of those inherent size obstacles. For example, the chip diminishes effects from other forces and torsion, such as the tensile testing on a chip developed by Sato [4].

In addition to inadequate material properties for MEMS materials, notches and sharp corners often appear as a result of MEMS fabrication process. These sharp geometries, a natural character of MEMS devices, produce advantages associated with electrical applications and function generation, but evaluation of mechanical properties becomes more difficult because of the complex shapes (based on common concepts of mechanical design) and the dubious failure mechanism, unlike the well known properties of the material in its bulk forms.

Many of the investigations recently published for MEMS' mechanical properties emphasize component reliability. Connally and Brown designed a test to study single crystal silicon device for fatigue [5]. Brown, Arsdell and Muhlstein demonstrated failure modes by using resonant fatigue specimens, and indicated that damage was influenced by moisture [6]. For the sharp notches commonly contained in MEMS components, Brown, Povirk and Connally introduced the concept of fracture toughness to evaluate stress concentration at a crack [7]. Suwito, Dunn and Cunningham also applied a critical 90° notch stress intensity for simulating the stress distribution in a T-shaped structure for tensile testing [8]. Wilson and Beck used finite element analysis to obtain the stress distribution in a cantilever beam subjected to a side load in 1996 [9]. While all these studied have provided useful information, most have neglected the influence of fabrication processes on material properties.

In this paper, linear FEM models are used to evaluate the stress distribution in microridges fabricated with different manufacturing processes. For each geometry, models are refined until a converged stress value at a critical radius from the failure location is obtained. This converged stress is used for strength calculation. Our approach to predict component strength is to use strain energy concepts which are formulated under the pretense of simple loading situations. Using the assumption that a linear stress-strain relationship exists, the failure energy can be related to material strength and Young's modulus measured in simple uniaxial tests or an initial test case. The component strength for more complicated loading conditions can be predicted by comparing predicted energy values. In this paper, the finite element models are used to evaluate the stress concentration at sharp corners of the MEMS components coupled with energy concepts to predict strength for different fabrication processes.

5ìm high and 10ìm a pitch. While these dimensions are similar, their profile can vary, depending on the fabrication process. Table 1 shows the different profiles of microridges fabricated by common micromachining techniques produced by Chen [10]. Predicting the observed variation of these four different microridges in strength is the subject of this investigation.

FINITE ELEMENT MODELS

An FEM model containing a single pitch with proper boundary conditions and applied loads is established to reproduce the behavior of the structure shown in Fig.2 and Table 1. These models were refined and are discussed in detail by Chen [10]. ANSYS is the program used for stress analysis and calculations. A PLANE82 2-D 8-Node Structural Solid Element, for 2-dimentional modeling in the x-y plane (see Table 1) and has a homogeneous character in the z-direction, is used for the simulation [11]. Plain strain (i.e., the z-strain $\varepsilon_z = 0$) is assumed since the length in the z-direction of the ridges is relatively large. That is, the length is on the order of mm while in-plane dimensions are on the order of microns. Anisotropic single crystal silicon material properties are used in the model. This is important because the ridge structures have different crystal orientations [2, 3], for example, compare No. 1 to No. 4 in Table 1.

To avoid the singularity at sharp corners, we evaluate the converged stress value at a critical distance from the corner in each model. Fig.3 demonstrates this concept, and the converged stress (or other terms) is calculated by averaging outputs of the nodes lying on the critical converged radius. By using this concept, we are able to accurately define the stress state in the vicinity of the sharp geometry.

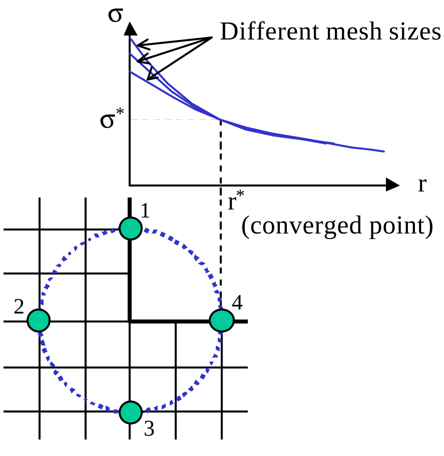

Figure 3: Concept of converged stress

A small fine-mesh area with a dense element distribution is used to calculate accurate nodal properties without unnecessarily occupying computer resorses. During the modeling process, mesh refinements are required until the stress state is obtained for each ridge profile. The final model contains a circular fine-mesh area with a radius of 0.05ìm, and the converged stress is obtained at 0.005ìm from the sharp geometry. The model for the U-groove microridges is shown in Fig. 4.

STRENGTH CALCULATION

"Component strength" is a concept that is related to both the stress concentration (i.e., geometric load) and ultimate strength (i.e., material load). One approach to predict component strength is to use strain energy (U) concepts which are formulated under the pretense of simple loading situations. Using the assumption that a linear stress-strain relationship exists, the failure energy U_f of the material can be related to material strength (S) and Young's modulus (E) as

$$U_f = \int_0^{e\ failure} s \cdot de = S^2 / 2E \qquad (1)$$

The "S" above, indicating the strength of the material, is a mechanical property. However, the stress concentration in our structures influences the strength value so additional information is required.

In this paper, a uniform load is applied on each model to predict the stress concentration for different ridge shapes. The ratio of the material failure energy to the strain energy generated for a specific geometry can be used as an index of component strength for a ridge profile. A term "strength

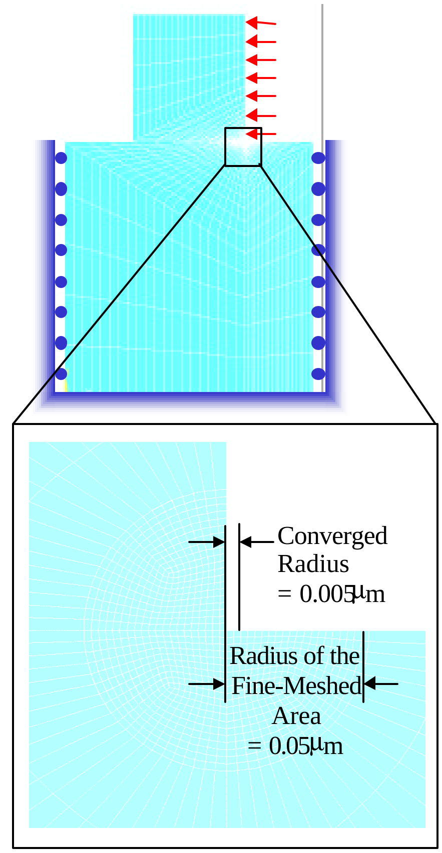

Figure 4: FEM model for U-groove ridges

factor", marked as "SF",is defined to represent component strength. Similar to Eq. (1), a relationship between the failure energy U_f, the strain energy U_i calculated under a uniform load condition and the strength factor SF_i for the i^{th} profile can be reasonably derived as

$$\frac{U_f}{U_i} = SF_i^{\,2} / 2E \qquad (2)$$

Since all the microridges are fabricated from the same material, the strength between the two components can be compared as below

$$\frac{SF_2}{SF_1} = \frac{\sqrt{2E \cdot (U_f / U_2)}}{\sqrt{2E \cdot (U_f / U_1)}} = \frac{1/\sqrt{U_2}}{1/\sqrt{U_1}} \qquad (3)$$

A complete comparison of component strength between each ridge profile can be obtained by using Eq. (3). In this paper we nornalize the strength factor to the experimental values measured for U-groove ridges (Table1, ridge profile 1). The strength of other ridges with different profiles is predicted, based on the strength factor obtained from the U-groove. Therefore, one would expect exact agreement for the U profile.

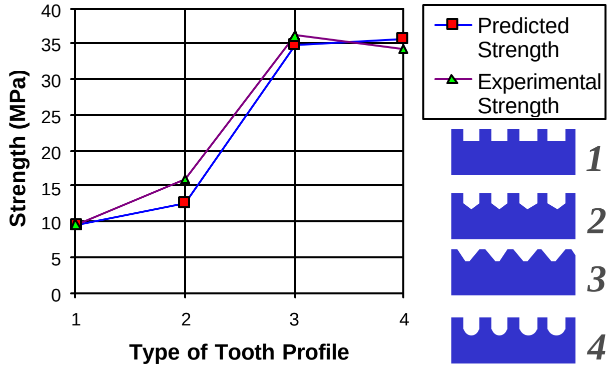

Figure 5: Comparison of predicted and experimental strength for different ridge profiles

RESULTS AND DISCUSSION

The comparison between the normalized component strength and the experimental result for each microridge geonetry is shown in Fig.5. The agreements between the simulation and experiment error by 22.2% for V-groove ridges (Profile 2), 3.1% for the trapezoid ridges (Profile 3) and 4.6% for round-groove ones (Profile 4). The largest disagreement is an under-prediction for the V-groove ridges. In the model, a sharp V-notch is simulated rather than a smoother V-notch one finds in the actual structure. Therefore, one would expect the prediction to the be on underestimate.

Similarly for round-groove ridges, a perfect semicircular groove is employed without any stress concentrations and so that the model overpredicts the strength slightly. The actual structure fabricated with deep reactive ion etching (DRIE) process makes smooth sidewalls and grooves, but it still has a small stress concentration along the cruved sidewalls and potentially lower the component strength. Therefore, one would expect the model to overpredict strength for ridge profile 4.

Since the criteria developed is comparing the strength ratio between each geometry, the normalization to one experimental datum is necessary. In this paper, the U-groove ridge is the selected profile to be normalized only because it is the first ridge profile modeled. Normalization at a different data point, or different geoemetry, alters the agreement slightly. When another geometry is normalized, the relationship of strength between each geometry (i.e., the predicted strength line in Fig.5) is proportionally shifted. Therefore, the accuracy of the model does not change appreciably. By using this simulation criteria, the strength of each component can be predicted in reasonable accuracy as long as any one of them is tested by experiments first.

CONCLUSIONS

The proposed strength criteria produces predicted values that have good agreements with experimental data for different ridge profiles. The component strength of microstructures is found to be strongly influenced by fabrication processes. By using this strength criteria, mechanical simulation for MEMS components with stress concentration can be feasible and accurate as long as limited experimental data is provided. Component strength fabricated with different materials can likely be developed based on the relationship of materials' ultimate strength.

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