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An introduction to mechanical-properties-related issues in MEMS structures

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A brief introduction to the issues related to the mechanical properties of MEMS components in terms of their functionality, types of loading and modes of operation is presented. At the microscale, for most cases, some mechanical properties including strength increase. However, surface phenomena such as adhesion/stiction become important as the aspect ratio of the components decreases. Subcritical crack initiation and growth in silicon, as the most common type of material used in MEMS devices under various types of loading is discussed. In addition, fatigue and creep behavior of MEMS components are described. © *2003 Kluwer Academic Publishers*

1. Introduction

MEMS devices, consistent with their definition, have mechanical components that often move or carry load. Reliability and performance of these devices greatly depend on the mechanical properties including fatigue, fracture strength and tribology behavior. MEMS devices are housing more and more moving parts as the need for MEMS devices is rising. The average number of 10 mechanical structures per device of a few years ago has risen significantly with the advent of micromirrors (millions of moving parts) used in electronic industry. From a statistical point of view, with every additional component, chance of failure due to individual components significantly increases. Additionally, in optical routers and optical switches, where communication lines are intertwined, failure of a single device can result in the loss of communication felt by hundreds of users if not more.

With the advent of bioMEMS, reliability of microfluidic devices, such as microfluidic pumps, can have a significant impact on the vitality of patients. Flawless operation of bioMEMS devices that deliver insulin or other types of medicine will save lives. Military use of MEMS such as triggers for weapons, micro-gyros, micro-surety systems, and micro-navigation devices give another dimension to the importance of reliability of these devices. Any accidental triggering may claim many lives and, if in a warehouse, may have a domino effect. Reliability of more complex MEMS devices such as optical routers and micromirrors for projection devices is more challenging since it pushes the limits of performance exponentially to higher levels. MEMS applications in space yet impose more stringent conditions on the performance and reliability. The more stringent requirements are needed in order to assure flawless operation of MEMS devices in satellites or space stations where repairs or replacements are costly if not impossible.

Performance of high aspect ratio surface machined structures for use in various fields including microneedles in bioMEMS, and thermal posts for microheat-exchanges depend on structural integrity, fracture toughness and strength. On the other hand, rotating and sliding structures such as microengines require good surface properties that resist wear and stiction. Reliability of devices such as microswitches and electrostatically driven microactuators that relay on actuation pads that come in contact depend on adhesion properties of contacting surfaces. Components such as micromirrors that have several levels of alignment controls using structural hinges operating at high frequencies suffer from cyclic fatigue damage accumulation and may fail by crack initiation and propagation under cyclic loading. A number of actuators operate by thermal actuation that imposes relatively high temperatures and require resistance against thermal cycling, high temperature fatigue or creep. All these issues necessitate rigorous mechanical tests, on MEMS scale, to examine the effect of various processing parameters, types of loading, service environments and temperatures for different materials and applications. This paper references the work of some investigators on mechanical testing and reliability studies of MEMS structures.

2. Mechanical properties-related issues

2.1. Testing configurations, experimental setups and analytical tools

Most mechanical tests are performed in an ex-situ configuration. However, a number of methods have been developed to test mechanical properties of test structures microfabricated along with other MEMS devices on the same wafer in an in-situ configuration. An example of the on-chip testing of mechanical properties of MEMS devices is a MEMS device developed by Kahn *et al.* [1] for measuring fracture toughness of polysilicon. The advantage of on-chip testing is to include the effect of microstructure on the mechanical properties of the MEMS components. MEMS components made from CVD-deposited polysilicon have nano-sized grains that are affected by deposition parameters and post-deposition heat treatment. Other examples of on-chip testing of mechanical properties include *in situ* friction measurement [2] and *in situ* adhesion measurement [3].

2.1.1. Microtesting systems

There are quite a number of microtesting procedures developed for measurement of mechanical properties of small structures over the last decade. Among these, microtensile and microfatigue testers of Sharpe [4, 5] and Hemker [6] are well developed and will be described briefly here. Microtensile and microfatigue (tension/tension) testing of metallic small structures (ranging from 3–10 mm) are performed using bow-tie shape samples. These can be cut by electrodischarge machining (EDM) of foils of desired thickness [5]. Alternatively, samples can be electrodeposited into PMMA molds by LIGA process followed by a surface polish to desired thickness [7]. To measure the elongation of the gauge length, markers are placed on the sample. These markers have reflective surfaces that are used to reflect laser beam creating laser interferometry patterns. Markers can be in the form of a pair of tabs attached to the samples [7], or in the form of a pair of inverted pyramids created by a microindenter [4, 6, 8]. Fig. 1 shows a typical bow tie sample with tabs and with indent markers.

Microtensile testers consist of a drive or an actuator that provides a linear motion of a platform on which a micro load cell is mounted. The load cell, in turn, is attached to a frictionless air bearing either by a flexible cable [8] or directly by a long screw [9]. Test samples are mounted onto grips which have patterns carved onto them similar to the two ends of the test sample. The depth of these patterns is proportional to the thickness of the sample (e.g., 70–270 microns). One Grip is mounted on the air bearing sliding shaft, while the other one is mounted on a stationary platform. Fig. 2 shows the microtensile testing system.

Measurement of strain is performed using laser interferometry with photodiode arrays that can accommodate 512–4800 diodes linearly. The dark and light bands formed by the two reflected laser beams generate a sinusoidal video signal that can be analyzed by a simple FFT, extracting the spatial frequencies associated with it. This in turn is a measure of the wavelength of the video signal, which is related to the spacing of interferometry bands and ultimately to the spacing of markers on the sample. Local strains are obtained in this manner by following the shift of the FFT peaks of the video signal.

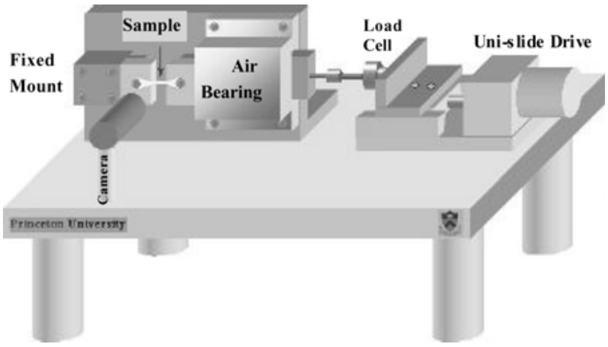

Figure 2 Microtensile testing system.

While this method has a high accuracy at small strains (elastic deformation regime) where reflecting surfaces are unaltered, this is not the case for large strains (e.g., plastic deformation regime). Roughening of the reflecting surfaces for the microindented pyramids in LIGA Ni, and some other materials, diminishes the capabilities of laser interferometry. For this regime, video photography, associated with "on the fly" or "postmortem" image analysis gives more accurate strain measurements [9]. This is due to the fact that it relies on the shape of the landmark rather than the optical quality of the reflecting surfaces. Imaging procedure makes it possible to use landmarks, which do not affect the mechanical properties of the sample (e.g., use sample's surface topography as landmarks). A stress-stain curve obtained by microtensile testing of a sample made by EDM machining of Fe-Cr-Al-Y foil is shown in Fig. 3.

The grips of microtesting systems could be modified to allow testing of foam struts obtained from open cell metallic foams. For this purpose, grips have the shape of the backside of a claw hammer that grips the ends of a foam strut that are nodes with other ligaments cut by EDM. The topography of the surface of the struts are

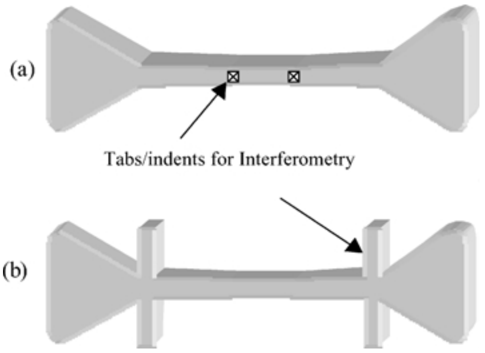

Figure 1 Microtensile/Microfatigue test samples: (a) with inverted pyramid markers and (b) with laser interferometry tabs.

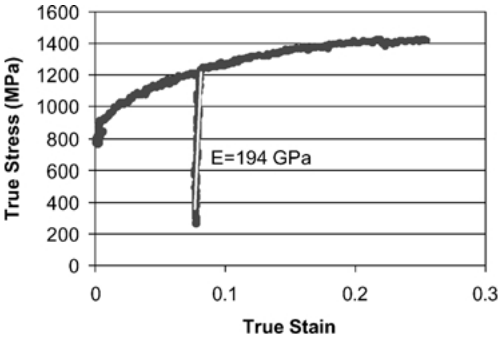

Figure 3 Strees-strain curve for a microtensile specimen obtained by EDM machining of Fe-Cr-Al-Y foil.

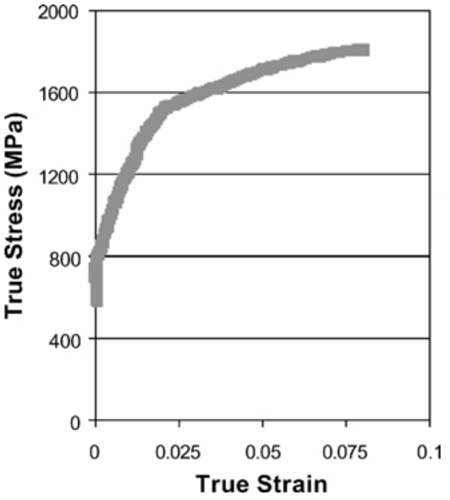

Figure 4 Stress-strain curve for a foam strut obtained by EDM machining of Fe-Cr-Al-Y foam.

used for image analysis-based strain measurement. A typical stress-strain curve of Fe-Cr-Al-Y foam is shown in Fig. 4.

Microfatigue testing of metallic samples prepared by EDM machining or by LIGA process, similar to those of Fig. 1, is performed by a microfatigue system elucidated in Fig. 5. A piezoelectric actuator capable of frequencies up to 1000 Hz, and stroke lengths of up to 180 microns is utilized. Grips are connected to the x-y-rotational stage and to the load cell. Load cell, in turn is attached to the piezoelectric actuator. A mounted microscope allows precise alignment of the grips using the x-y movement and the rotation of the lower grip attached to the lower stage.

Microtesting systems developed for brittle materials like Si, come in different varieties. One system developed by Sharpe *et al.* [10] resembles the microtensile system presented above, but with different grip mechanisms. Silicon tensile samples tested by this system have large paddle like ends that are either electrostatically attached to a charged grip or glued to a rod that is in turn attached to a grip. In a different system, [11] a micro-cantilever beam made from materials such as amorphous diamond is externally actuated by a flat tipped diamond in a nanoindenter. Actuation can be used for monotonic or cyclic loading of the cantilever.

Load control actuation is achieved by continuous adjustment of that amplitude and offset of actuation using LabView®. A program written in LabView®, uses the load cell feedback signal to modify the actuation waveform. The displacement signal comes from a sensor built in the actuator. The significance of load control adjustments becomes evident in the light of the fact that most metallic samples work harden (or work soften in some instances) during fatigue tests. Both load and displacement are displayed and recorded along with time and actuation cycles. Fig. 6 presents a fatigue S-N curve for 70-micron thick LIGA Ni samples tested under a load ration of 0.1 and a frequency of 10 Hz.

There are a number of on-the-chip testing methods for characterization of mechanical properties of MEMS structures. These usually use electrostatic or capacitive forces to actuate cantilevers or membranes. The most widely used system employs capacitively driven resonant structures that are actuated by application of an AC voltage across their interdigitating combs. One such structure developed by Van Arsdell *et al.* is shown in Fig. 7.

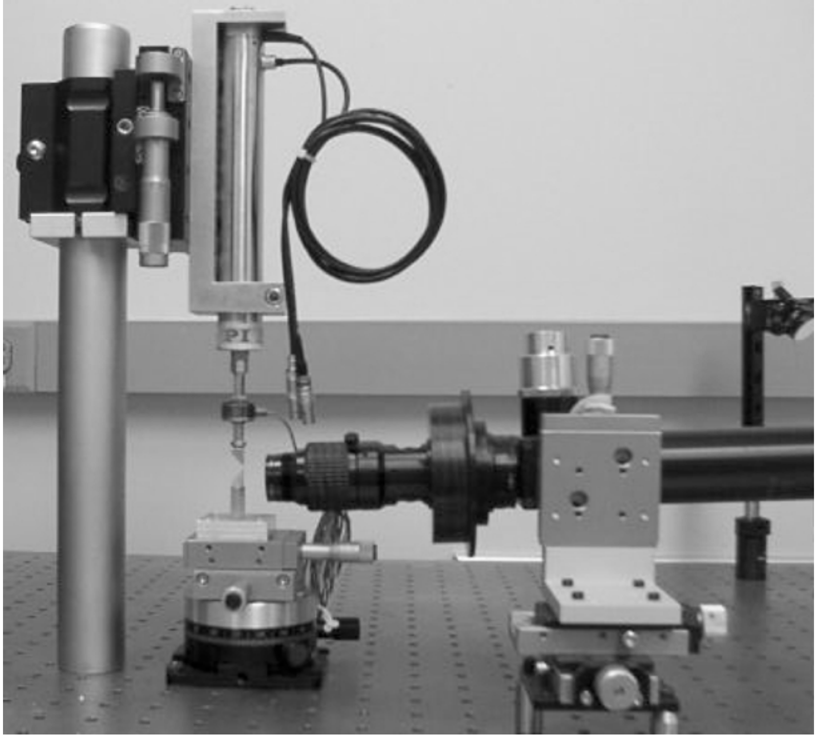

Figure 5 Microfatigue system comprising a piezoelectric actuator, an x-y-rotational stage, a loadcell, and a z-stage mounted on a post. A mounted microscope allows precise alignment of test sample grips.

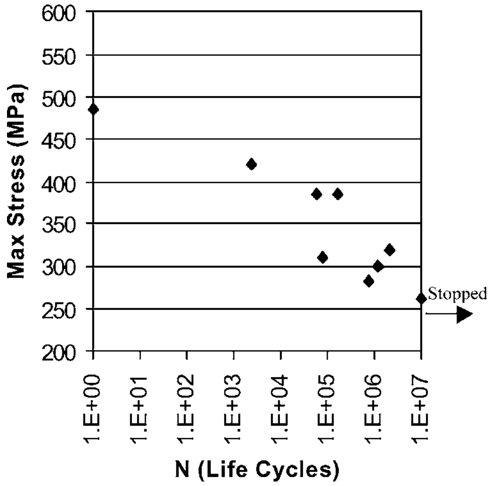

Figure 6 S-N Curve for 70 micron thick LIGA Ni foil.

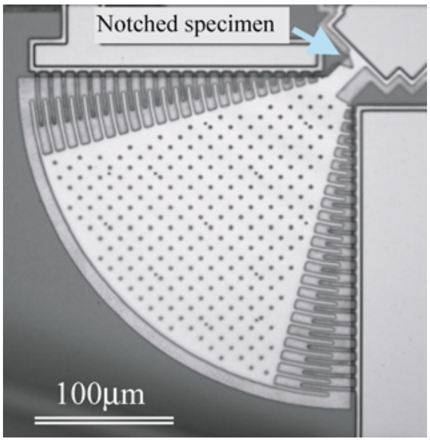

Figure 7 Capacitively driven comb drive test.

2.1.2. Analytical tools

While experimental work is of utmost importance in determination of mechanical properties of MEMS materials, modeling is frequently needed to properly interpret experimental results. This is particularly true for results of mechanical testing of multicomponent samples such as multilayered structures subjected to mechanical loads. Models required for the determination of mechanical (e.g., elastic) properties of MEMS-structures such as thin films can be developed using finite element method. However, analytical solutions to specific problems such as load-deflection of thin films are desirable for their simplicity. As an example, a newer solution for the load-deflection of square membranes has been presented by Maier-Schneider *et al.* [12]. Another use of analytical tools is in the reliability design rules. Tanner *et al.* have developed a predictive reliability model for wear of rubbing surfaces in microengines [13].

2.2. Mechanical properties of MEMS materials

Mechanical properties of MEMS structures have been studied by a number of researchers. It is obvious that some mechanical properties such as Young Modulus are not size dependant. However, their dependence on crystal orientation will be pronounced for the case of MEMS-scale structures where size of the structure may be of the order of grain size. Most mechanical properties depend on the microstructure, which is much finer for MEMS structures. Structures made from bulk by etching processes, maintain the microstructure and mechanical properties of the bulk to a great extent (e.g., resonant cantilevers made by machining single crystalline Si wafers). However, most additive processes used for fabrication of MEMS structures have nano-size grains and refined microstructures. This simply arises from the fabrication techniques such as thin film deposition, and lithography based electrodeposition. In the following sections, some of the mechanical properties that are affected by size reduction or refinement of microstructure are discussed.

2.2.1. Fracture strength

As the most important mechanical design property, fracture strength of MEMS, has been investigated for various materials used in MEMS [14]. Loading types include monotonic [15, 16] and cyclic [17, 18]. Aspects of fracture studied include orientation dependence [16] and toughness [19]. Materials studied in terms of fracture are mostly silicon single and polycrystals [10, 16, 18–32], brittle materials [33–35], and metallic films [8, 36]. Fracture test structures have been developed that are configured in modes such as tensile [37], bending [18] or a combination of tensile and bending [38]. Actuation can be either by a piezo actuator (e.g., by a pin actuated from outside) or electrostatically, as an integral part of the structure [38]. Typical principal stresses that can be achieved by electrostatic actuation are reported to be 1 GPa [38] in tensile mode and 2.7 GPa [18] in bending.

Etch holes are necessary for the release of large microstructures during fabrication process. Mechanical properties of these structures are shown to degrade by the imposition of these holes. According to Sharpe *et al.*, tensile strength of phosphorous-doped polysilicon is 50% lower compared to a similar structure without etch holes. Similarly, a reduction of 18% is observed in Young's modulus [39].

2.2.2. Fatigue

Cyclic loading tests of single crystal Si under uniaxial tensile conditions have been attempted by Ando *et al.* [40]. These authors showed a significant reduction in the fatigue life for test specimens exposed to strains over 3.5%. They reported Young's moduli of 122, 140 and 111 GPa for orientations of (100), (110) and (111) respectively. As will be discussed later, fatigue induced fracture is not a leading factor in the failure of moving components [41], rather, sticking of the sliding surfaces causes microdevices to fail. Fatigue tests by Maekawa *et al.* on unnotched Ni-P amorphous alloy cantilevers prepared by FIB showed that fatigue strength is about one-third of the static bending strength [42]. Striations observed on the fracture surfaces of notched specimens lead the authors to conclude that crack propagation occurs by cyclic plastic deformation at the crack tip. Surface topography evolution during cyclic actuation of polysilicon resonating structures has been demonstrated by Allameh *et al.* [18, 43–45]. The results show evolution of large perturbations at locations where stress level was highest (e.g., at the notch root) [18, 44, 45]. Also deepening of the grooves occur with a rate proportional to the stress levels [43]. Similar polysilicon resonant structures tested by Muhlstein *et al.* show cyclic failure under cyclic stresses, some 50% of the single crystal fracture strength. They related cyclic damage accumulation during crack initiation to surface oxidation cracking [46–48].

2.2.3. Creep

The creep properties of materials and their variabilities are critical to the structural reliability of MEMS devices. Reliability of MEMS devices will greatly be affected by creep of components that operate at high temperatures. The reliability will also suffer when MEMS components are made of materials, which creep at room temperature. Electrothermal microactuatuors, considered as the driver components for micromotors, are examples of structures prone to creep deformation upon actuation. Additionally, components made of polymers, such as polyimides [49], will undergo creep at room temperature. Creep behavior of materials exposed to thermal cycling, including solders [50] used for joining MEMS components is important to performance of MEMS devices.

2.2.4. Internal stresses

Residual stresses developed during fabrication of most deposited MEMS structures are usually relieved by annealing at an appropriate temperature. For some structures, the as-deposited state of stress is compressive due to implantation of various species, which upon annealing at high temperatures changes into tensile. Stress-free films of a hydrogenated amorphous silicon carbide (a-SiC:H) has been fabricated using a 550°C anneal after deposition [51]. One of the methods to fabricate stress free films is to deposit alternate layers of polysilicon at different temperatures. The resulting layers will have residual stresses that can alternate in sign (tensile for one layer, and compressive for the next). By carefully tailoring the thickness and number of these layers, it is possible to make stress free multilayered films. Stress-free as-deposited LPCVD polysilicon films with nine alternating columnar and equiaxed layers have been fabricated by Yang *et al.* [52].

2.2.5. Young's modulus (E)

Dynamic characteristics of MEMS-structures are influenced by internal stresses, which are, in turn, affected by dopants such as boron [53]. This trend was seen by Sharpe *et al.* in one of the two sets of samples tested by their microtensile system. The second set did not show a significant drop in the Young's modulus [8]. Quantification of structural nonidealities in MEMS has been addressed by Jenson *et al.* [54]. These authors integrated results of interferometry of microcantilevers with numerical finite difference modeling [54]. This is in addition to the values of Young modulus (164.3 ± 3.2 GPa) obtained from electrostatically actuated polysilicon cantilevers. Extraction of mechanical properties such as Young's modulus is also possible from dynamic characteristics such as resonant frequencies of microcantilevers [53, 55]. A study of Young's modulus of LIGA Ni, performed by the analysis of vibration frequencies of microcantilevers, showed an average value of 195 GPa, which is lower than that of bulk Ni (206 MPa) [55]. Microtensile testing of LIGA Ni using interferometry technique for strain measurement show a modulus of 160 GPa [7]. A static beam bending approach used by Stephens *et al.* [56], however, show a significantly lower modulus (93 GPa). In both studies (Buchheit and Stephens *et al.*) LIGA Ni was produced using sulfamate bath. It is well known that composition of the salt bath and current density affect mechanical properties significantly [7, 56].

Nanoindentation of metallic and ceramic films has been performed to obtain mechanical properties including Young's modulus [57, 58]. Li and Bhushan [57] examined doped (100) Si, doped and undoped polysilicon and SiC films used for MEMS applications and found the Young's modulus to be 168, 175, 95 and 395 GPa respectively. They reported corresponding fracture toughness values to be 0.75, 0.11, 0.89 and 0.78 $\mathrm{MPa}\sqrt{\mathrm{m}}$ [57]. Along with these, hardness and coefficient of frictions of these materials were obtained in nanoindentation and microscratch tests [57]. The results of these researchers showed that SiC had higher values of hardness and Young's modulus, better scratch resistance, as well as lower friction compared to silicon [57].

2.3. Size scale effect

Size of the polysilicon MEMS structures does not seem to affect the Young's modulus; however, smaller structures show a higher tensile strength. This has been attributed to the lower number of flaws present in the smaller structures [59]. Mechanical properties of thin films may differ from bulk materials. This is particularly true when the thickness is reduced to the degree that the contribution from surfaces becomes significant. Additionally, there is another size-dependant contribution that affects mechanical property measurements: strain gradient plasticity [58, 60–62]. Mechanical measurements that are affected by strain gradient plasticity are mainly microbending, microtorsion and nanoindentation. For LIGA Ni, the size effect on mechanical properties was investigated by Shrotriya *et al.* [60]. They determined a composite length-scale parameter ($L_c = 4.7 \pm 0.3\ \mu\mathrm{m}$) with stretch (4.6–4.8 μm) and rotation components. Size effect is especially important for MEMS devices, which contain thin metallic structures (e.g., LIGA processed Ni and Cu cantilevers and rack and pinions).

2.4. Failure analysis

Failure analysis (FA) of MEMS devices is assuming an important role in the design, fabrication, performance and reliability of microstructures. Some of the FA techniques developed for integrated circuits have been applied to MEMS devices. These techniques include optical and electron microscopy, focused ion beam techniques (FIB), atomic force microscopy (AFM), acoustic microscopy (to resolve contacts between sticking parts) and scanning laser microscopy (SLM). For moving parts experiencing wear, fatigue and fracture of the components are not the major sources of failure. Instead, sticking of the sliding contacts [41] leads to failure. The sticking occurs due to changes in the surface topography of the sliding surfaces, which accelerate with an increase in the applied forces. One of the major challenges in failure analysis of MEMS structures has been the inability to duplicate failures [63]. Failure of some MEMS components like microengines has been reported to be due largely to a single dominant failure mode (e.g., sticking of microengine gears to the substrates or to the hubs) [63]. For microengines, this has been verified by the unimodal failure of microengines tested for FA purposes [63]. Surface roughening can also cause failure of MEMS structures. According to Miller *et al.* [41], surface roughening due to overetching of polysilicon in ammonium hydroxide, leads to the shearing of pin joints in microengines.

2.5. Environmental effects

Presence of an aggressive environment such as water vapor for Si MEMS can affect the mechanical performance of MEMS devices such as micromachines. While the presence of water as lubricant on polysilicon sliding surfaces is desirable [64, 65], its effect on cyclic damage accumulation of actuated structures has been shown to be detrimental [18, 66–68]. There are a few models that account for the formation of grooves and their evolution into sharp cracks in stressed solids that are exposed to aggressive environments [18, 69–71]. One possible mechanism cited in literature is stress-assisted dissolution of topical silica leading to evolution of perturbations and deepening of grooves with a rate proportional to the state of local stresses. Other mechanisms suggested include formation and thickening of native silica layer at loci of highest stress levels and cracking of such oxide layer [46].

The effect of temperature on microengines in the range of -55°C to $+200^{\circ}$C was investigated by Tanner *et al.* who reported no detrimental effect on the operation of Sandia microengines [13]. This is true considering the fact that higher temperatures only cause expansion of polysilicon. The susceptibility of MEMS-based microengines to shocks has also been reported by the same authors. They imposed shock pulses of 1 to 0.2 ms in the range from 500 g to 40 kg. Devices that were not powered up during the shock test were found to have survived the shock at most shock levels. However, at levels of 4 kg, shorts in actuators were observed due to debris from die edges. At 20 kg, structural damage to thin flexures and thin small diameter pin joints were observed [72]. These microengines exposed to vibrations of a peak acceleration of 120 g and a total number of 5×10^5 oscillations showed only a 10% failure rate. The microengines were not powered during the vibration test. Failures were reported to be largely due to adhesion after rubbing caused by vibration [73].

2.6. Reliability

The link between mechanical properties and reliability of MEMS structures has been explored extensively in the past few years [50, 74–81]. Characterization tools developed for the study of reliability include tools for electrical actuation of surface machined actuators, tools for *in situ* visual inspection of components in operation, tools for acquiring test data, and tools for extraction of performance characteristics [82]. Lifetime studies of MEMS devices can be performed in parallel on a large number of devices to produce statistically significant reliability data [13]. The first quantitative and predictive model for MEMS actuator reliability was presented by Tanner *et al.* [13, 63, 65, 72–74, 83–85]. Factors that affect the reliability such as frequency [84], shock [72, 86], stiction [74], mechanical wear [65], fracture [15], fatigue [87], vibration [73] and environment [88] have been investigated. Reliability issues have been addressed for a number of applications including microengines [84, 89], microactuators [82, 90], aerospace [91–93], microrelays [94], telecommunications [95–97], thin films [98–100], resonating structures [66, 67], interfacial properties [101], size effect [102], packaging [103, 104], and structural applications [105].

Fatigue life projection of MEMS components can provide insights into the correct selection of materials and processing parameters for manufacturing reliable MEMS devices [106]. Data obtained from reliability tests of 41 microengines were analyzed by Tanner *et al.* who fit the test data to various distribution models. For Weibull distribution, they obtained a straight line fit that resulted in an estimate for characteristic life of 66 million cycles (66% of devices are expected to fail at characteristic life). Similar results were obtained by fitting their data to lognormal distribution model, which resulted in an estimate of a median lifetime of 7.8 million cycles (50% of devices are expected to fail at this life). Data fit in both Weibull and lognormal distributions indicate a unimodal failure distribution for the microengines [63].

3. Conclusions

A brief introduction to the challenging issues in the characterization and optimization of mechanical properties of MEMS structures was presented. Bulk of the efforts made in the characterization of mechanical properties of MEMS structures address a few issues. The more important issue is the reliability of structures used under various loading conditions in different environments. Other issues in the performance of MEMS components include tribology behavior, adhesion and friction, fatigue and creep, environmental effects and residual stresses.

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