CARES/*Life* Used for Probabilistic Characterization of MEMS Pressure Sensor Membranes

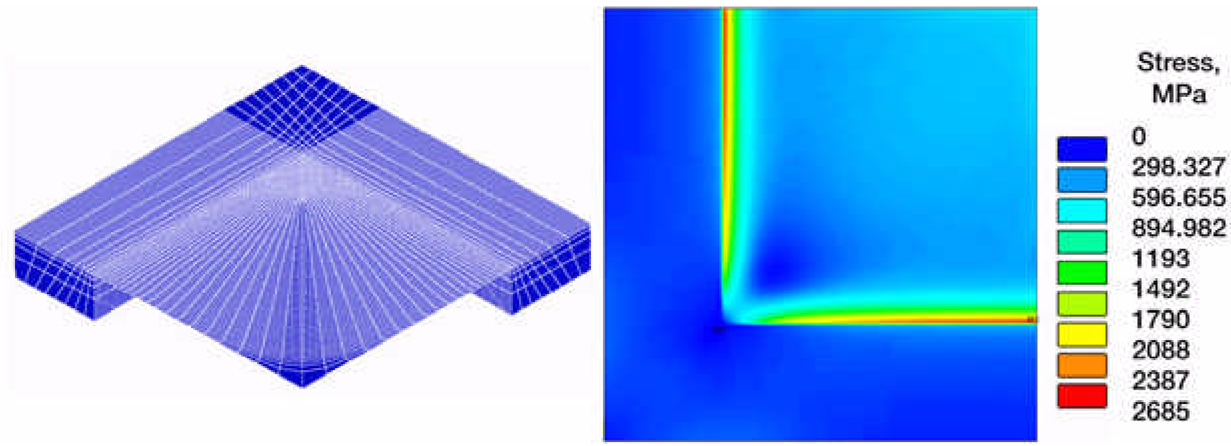
Microelectromechanical systems (MEMS) devices are typically made from brittle materials such as silicon using traditional semiconductor manufacturing techniques. They can be etched (or micromachined) from larger structures or can be built up with material deposition processes. Maintaining dimensional control and consistent mechanical properties is considerably more difficult for MEMS because feature size is on the micrometer scale. Therefore, the application of probabilistic design methodology becomes necessary for MEMS. This was demonstrated at the NASA Glenn Research Center and Case Western Reserve University in an investigation that used the NASA-developed CARES/*Life* brittle material design program to study the probabilistic fracture strength behavior of single-crystal SiC, polycrystalline SiC, and amorphous Si_3N_4 pressurized 1-mm-square thin-film diaphragms. These materials are of interest because of their superior high-temperature characteristics, which are desirable for harsh environment applications such as turbine engine and rocket propulsion system hot sections.

The fracture strength of MEMS devices is known to be affected by the surface defects and surface roughness resulting from the manufacturing process. Such variability can directly impact the failure modes and, in turn, the reliability of the device. In this study, the effect of load and geometric variation (pressure, length, and thickness) from one tested film to the other on the stochastic nature of the strength distribution was accounted for by performing different finite element stress analyses for the various films. Four material combinations were examined (see the table): (1) different suseptor (reaction chambers) on single-crystal silicon carbide--materials 1a and 1b, (2) doubled growth rate on single-crystal silicon carbide--material 2, (3) polycrystalline silicon carbide--Poly SiC, and (4) amorphous silicon nitride--Si_3N_4. The table shows that the device-to-device variation of film thickness was significant.

FILM ISOTROPIC PROPERTIES FOR ELASTIC MODULUS, POISSON'S RATIO, RESIDUAL STRESS, AND MEAN DIMENSIONS
[Standard deviations follow the ± character.]

Material	**Poisson's ratio,** ν	**Elastic modulus,** ***E*****, GPa**	**Residual stress,** σ_R**, MPa**	**Film width, mm**	**Thickness, μm**
1a	359	0.23	254	1.097±0.041	1.60±0.09
1b	363	.23	180	1.040±0.033	1.64±0.09
2	350	.23	120	1.049±0.035	2.69±0.17
Poly SiC	308	.16	75	1.045±0.038	2.86±0.34
Si_3N_4	274	0.27	1200	1.060±0.030	0.20±0.00

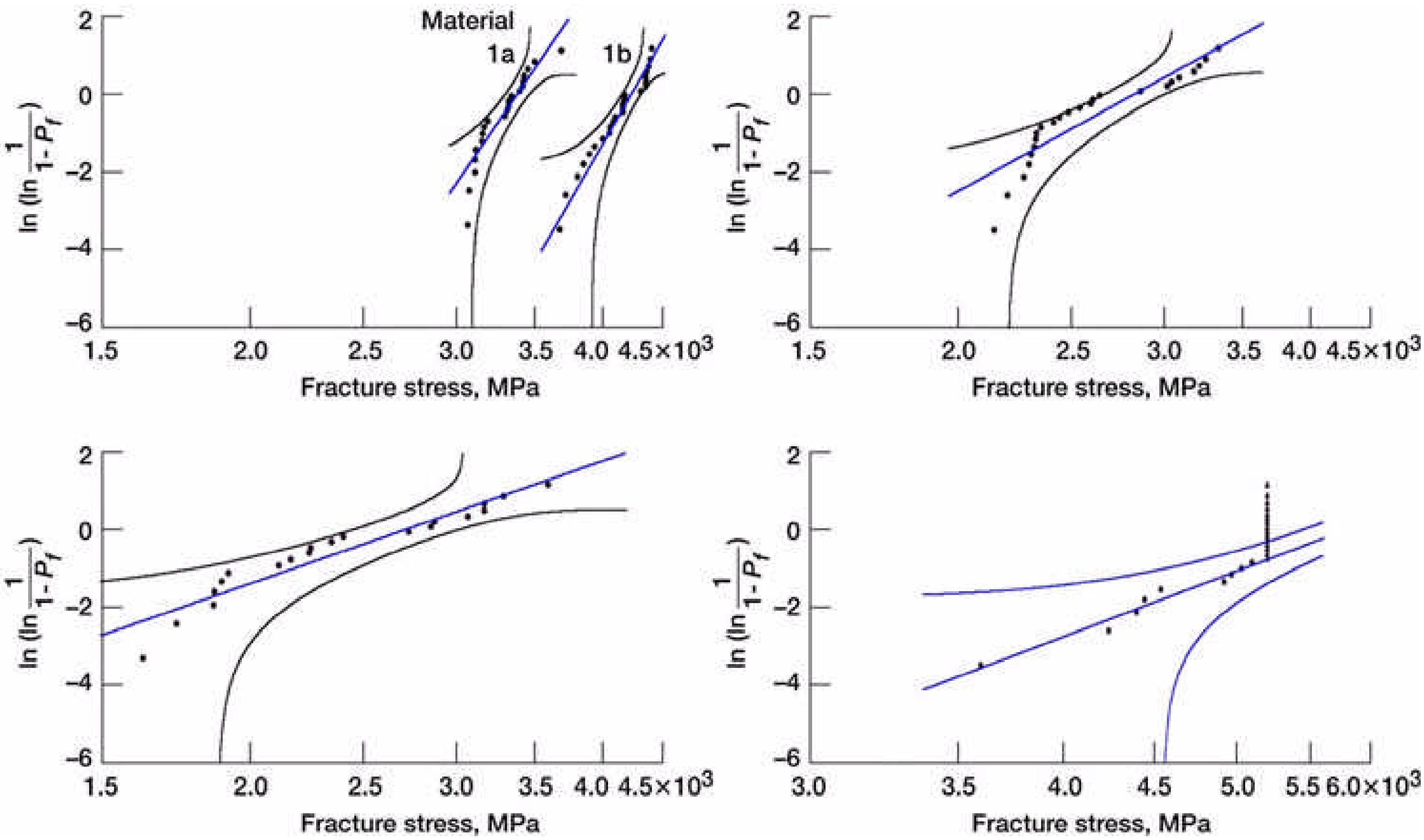
Finite element stress modeling was carried out for 113 membranes that were burst under pressure loading conditions. Residual stress in the film, burst pressure, and film thickness were all taken into account. The finite element analysis yielded the unique fracture strength value for each of the burst films from the recorded burst pressure. The strength values for each material set were statistically analyzed using CARES/*Life*. The CARES/*Life* program was further used to characterize the probabilistic fracture strength of these materials on a per-unit-area basis by using fracture-mechanics-based multiaxial failure criteria and the results from the finite element analysis of the stress distribution throughout the film. For the single-crystal silicon carbide material, a three-dimensional reliability model based on anisotropic fracture toughness was used. These models allow experimental data to be extrapolated to other conditions of loading, stress state, and device geometry; in other words, they enable a device to be designed for optimum reliability. Such a simulation and reliability prediction approach is important to reduce product development time and to minimize the potential for costly failures during service life.



Left: Quarter model of the finite element analysis mesh for the pressure membrane and silicon substrate. The film is nominally 1 mm square and is 2 mm thick. Right: First principal stress distribution in the MEMS pressure membrane due to both the residual (thermal) and pressure loadings being applied simultaneously. The diaphragm center is at the upper right corner of the figure. This view is of the polished (externally pressurized) surface.

The figure on the left shows a finite element mesh of a film. Nominal dimensions were a side length of 1 mm and a thickness of 2 µm. The films were pressurized externally or outside the cavity.

The figure on the right shows a typical first principal stress distribution in the film. Stresses are highest at the edge because of the small thickness-to-length ratio. Average residual stresses were accounted for in the analysis, but device-to-device variations in residual stresses were not. Finite element analysis was performed for each tested film--accounting for the individual dimensional variations. This enabled associating a device fracture pressure with the strength of the film. The two-parameter Weibull distribution was used to characterize the film strength distribution for the materials as shown in the following graphs. This characterization yielded the Weibull parameters for these MEMS materials.



Top:Weibull plots; P_f, probability of failure. Left: Single-crystal SiC films (materials 1a and 1b). Right: Single-crystal SiC films (material 2). Bottom: Weibull plots; P_f, probability of failure. Left: Amorphous Si_3N_4 films. Right: Polycrystalline SiC films. Unbroken films are denoted with triangular points (stacked on the right).

This study showed how thin-film strength varies from device to device. It was also shown that device-to-device film thickness variations and suseptor-to-suseptor (manufacturing) variations were significant and must be considered in any analysis. Furthermore, this work illustrates the need for probabilistic-based design practices for MEMS structures and the need for probabilistic-based life-prediction tools such as the NASA-developed CARES/*Life* computer program.

Find out more about this research http://www.grc.nasa.gov/WWW/LPB/cares/

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