COMPONENT FAILURE ANALYSIS IN MEMS PACKAGING

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ABSTRACT
A finite element analysis (FEA) method used to determine the limits of package failure criteria is described. The failure criteria for the micro-electro-mechanical system (MEMS) packages presented here include von Mises, Mohr’s theory, and micro-crack phenomena. In addition, we explore the limits of micro-scale failure criteria on brittle MEMS assemblies. The paper describes stress source identification methods and failure mechanisms for packaged assemblies that can guide MEMS package designers to reduce potential failure modes and improve reliability.

Keywords: MEMS, packaging, failure analysis, finite element analysis, reliability

NOMENCLATURE

- $a$: Crack radius
- $g'_{ij}$: Transformation matrix
- $l$: Length of beam
- $t$: Thickness of beam
- $w$: Uniform load
- $E$: Young’s Modulus of Elasticity
- $\overline{G}$: Crack Growth Criteria
- $K_{II}$, $K_{I}$: Stress Intensity Factors (SIF) for Mode I and Mode II
- $K_{Ic}$, $K_{IIc}$: Critical SIFs for Mode I and Mode II
- $\Delta T$: Temperature difference
- $\alpha$: Coefficient of Thermal Expansion (CTE)
- $\beta$: Ration of width and length of beam
- $\theta, \phi$: Transformation angles
- $\nu$: Poisson’s Ratio
- $\sigma$: Stress
- $\sigma_0$: Von Mises Stress
- $\sigma_1$, $\sigma_2$, $\sigma_3$: 1st, 2nd, and 3rd Principal Stress
- $\sigma_c$: Mohr’s max. uniaxial compressive and tensile stress
- $\sigma_{cr}$: Critical stress for crack growth
- $\sigma_b$: Stress tensor
- $\sigma_y$: Yield Strength

INTRODUCTION
Micro-electro-mechanical systems (MEMS) come in various die sizes; many of which are much larger than contemporary integrated circuit (IC) chips. In addition, due to the special functionalities of MEMS, they often require hermetic packaging to achieve long-term reliability and stable operation. Large die size and the requirement for hermetic sealing make the packaging of such MEMS very challenging. Ceramic packages are typically used for the packaging of large, hermetic MEMS devices. Metal seal rings and heat sinks are often soldered to such ceramic packages for hermetic sealing and thermal management, respectively. High melting point solders have to be used for these processes to ensure a suitable solder hierarchy throughout the assembly process. Furthermore, high temperature assembly processes are usually required in hermetic packaging to avoid the outgassing issues common to lower temperature, organic materials. All these high temperature processes add thermo-mechanical stress to the package and the MEMS device. Consequently, typical failure modes found in such devices are of thermo-mechanical nature and include, e.g., substrate and die cracking, die bow, solder fatigue [1-3], and loss of seal integrity. Such failures occur during package build, component mounting, and even after assembly, triggered by environmental temperature changes.

Careful materials selection, package design, and process planning need to be applied to enable the manufacturing of reliable, large die MEMS. Methods for thermal, mechanical, and thermo-mechanical optimization of the package design will be presented. These methods show how finite element analysis (FEA) can be used to optimize the materials, geometry, geometric relations between components, and processes, to minimize the package’s susceptibility to thermo-mechanically induced failure.

Another serious, stress-related concern is micro-crack formation. With micro-crack seeds [4,5], the devices fail at stress levels much lower than the bulk material yield strength. The micro-cracks propagate when stress concentration at the crack tip exceeds a threshold stress much lower than the
material’s bulk strength [6-8]. For this kind of failure, determining the stress level through each step of the assembly process is critical in predicting the effective strength of the component. FEA can predict micro-crack failures by applying strength theory to predict the allowable stress.

After performing the design optimization using FEA [7-10], the devices are built and subjected to physical and environmental testing. Although the ultimate goal for the device is to pass a certain reliability test level, the tests should always be continued until the failure of the devices [11]. Only failed devices reveal the weak points of an assembly and its failure mechanisms. Failure analysis to investigate the failure mechanism for brittle MEMS packaging materials are presented and reliability improvement methods are discussed. Finally, a comparison between the FEA results and laboratory measurements of the same package design are presented.

THERMO-MECHANICAL STRESS

Thermo-mechanically induced stress is a primary cause of failure in MEMS packages. The packages typically consist of materials with different coefficients of thermal expansion (CTE). Changes in temperature may induce thermo-mechanical stress between attached components and within a single component as a result of thermal mismatch (e.g., CTE mismatch, thermal gradients). The magnitude of the stress is a function of the temperature difference, \( \Delta T \) [12]. For a single component or a component attached to a much stiffer counterpart, the stress \( \sigma \) if given by:

\[
\sigma = \frac{E \alpha \Delta T}{(1 - \nu)},
\]

where \( E \) is Young’s modulus of elasticity, \( \alpha \) is the coefficient of thermal expansion, and \( \nu \) is Poisson’s ratio. Meanwhile, bending stress is generated as components are warped under the thermo-mechanical stress. The bending stress is defined as:

\[
\sigma = \beta \frac{w l^2}{t^2},
\]

where \( w \) is uniform load, \( l \) and \( t \) are length and thickness of the component being bent, respectively. \( \beta \) is a constant determined by the ratio of lengths and width of the component.

Material strength theory can be used to predict the acceptable stress levels for a MEMS package design. Typically a design safety factor of two is used for brittle materials. This would allow a maximum stress of roughly 50% less than the selected failure mode criteria.

FAILURE CRITERIA

The combination of different loads acting on a packaged MEMS device will mechanically damage, e.g., break or crack the package and MEMS die if critical values are exceeded. Failure criteria are used to define such critical values. For mechanical failures, the critical value is usually expressed in the form of a stress. Different failure criteria have been developed to predict the point of failure for any generic three-dimensional stress field based on material properties like, e.g., yield strength, ultimate tensile strength, and stress intensity factor. These material properties are obtainable by simple, standardized mechanical testing. Different failure criteria are applied depending on how the part fails, i.e., brittle or ductile. For ductile materials, von Mises criterion can be used, whereas for brittle materials, Mohr’s theory can be applied. To estimate the influence of micro-cracks in brittle materials a micro-crack criterion can be used.

**Von Mises Criterion**

The von Mises criterion is also known as the maximum distortion energy criterion, octahedral shear stress theory, or Maxwell-Huber-Hencky-von Mises theory. It is often used to estimate the yield of ductile materials.

The von Mises criterion states that a material will yield if the distortion (strain) energy reaches a critical value, e.g., the yield strain energy found in uniaxial tension [13]. It can be shown that for pure elastic materials, the strain energy is proportional to the von Mises stress as defined in Eq. 3:

\[
\sigma_0 = \sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2} / 2,
\]

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the principle stress. The von Mises criterion states that a structure will behave elastically when:

\[
\sigma_0 < \sigma_y,
\]

where \( \sigma_y \) is the yield strength of the material.

Most FEA tools provide direct output of von Mises stress, thus it is commonly used to investigate stress distribution in finite element simulations.

**Mohr’s Theory**

The Mohr Theory of Failure is also known as the Coulomb-Mohr criterion, or internal-friction theory. Mohr’s theory is used to predict failure of brittle materials under two-dimensional stress.

Mohr’s theory is based on Mohr’s Circle [14]. It predicts that a part fails if the Mohr’s Circle for any point of the body crosses the envelope created by the two Mohr’s Circles for uniaxial tensile strength and uniaxial compressive strength, respectively. The criterion can be defined as four different cases, as shown in Table 1. Each of the cases defines the maximum allowable values for the two principle stress \( \sigma_1 \) and \( \sigma_2 \) of a planar stress condition.

**Table 1: Mohr’s theory to predict failure of brittle materials.** \( \sigma_1 \) and \( \sigma_2 \) are the maximum uniaxial tensile and compressive stress, respectively.

<table>
<thead>
<tr>
<th>Case</th>
<th>Principle Stress ( \sigma_1, \sigma_2 )</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Both in tension ( \sigma_1, \sigma_2 )</td>
<td>( \sigma_1 = \sigma_2 = \sigma_l )</td>
</tr>
<tr>
<td>2</td>
<td>Both in compression ( \sigma_1, \sigma_2 )</td>
<td>( \sigma_1 = -\sigma_c, \sigma_2 = -\sigma_c )</td>
</tr>
<tr>
<td>3</td>
<td>( \sigma_1 ) in tension, ( \sigma_2 ) in compression ( \sigma_1, \sigma_2 )</td>
<td>( \frac{\sigma_1 + \sigma_2}{\sigma_1 - \sigma_c} = 1 )</td>
</tr>
<tr>
<td>4</td>
<td>( \sigma_1 ) in compression, ( \sigma_2 ) in tension ( \sigma_1, \sigma_2 )</td>
<td>( \frac{\sigma_1 + \sigma_2}{-\sigma_c - \sigma_l} = 1 )</td>
</tr>
</tbody>
</table>
**Micro-Crack Criterion**

MEMS component failures sometimes occur under stress levels that are much lower than the bulk material strength or than the failure criteria prediction. This indicates that the failures may be caused by micro-cracks, which propagate under a stress concentration at the crack tip.

Micro-crack failure criterion is a suitable prediction method for acceptable stress levels in a ceramic package. This paper uses a micro-crack criterion, as developed in [4,6], and summarized below, to estimate failure stress in a MEMS package.

A typical stress-strain curve of a brittle material includes several stages, i.e., linear elasticity, pre-peak non-linear hardening, rapid stress drop, and strain softening. For the failure of brittle materials, the unstable crack growth during the third stage, i.e., the stage of rapid stress drop is the determining factor. The growth criterion for such crack growth takes the form:

$$
\overline{G} = \left( \frac{K_I}{K_{Icc}} \right)^2 + \left( \frac{K_{II}}{K_{IIcc}} \right)^2 = 1,
$$

(5)

where $K_I$ and $K_{II}$, and $K_{Icc}$ and $K_{IIcc}$ are the mode I and mode II stress intensity factors (SIFs) and their critical values, respectively. The SIFs are defined as:

$$
K_I = \sqrt{ \frac{2}{\pi} } a \sigma_{Ii},
$$

(6)

$$
K_{II} = \frac{4}{2 - \nu} \sqrt{ \frac{2}{\pi} } \left[ (\sigma_{21})^2 + (\sigma_{23})^2 \right]^{1/2},
$$

(7)

where $a$ is the radius of the micro-crack and

$$
\sigma_{ij}(\theta, \phi) = g_{ij}^I(\theta, \phi) g_{ij}^II(\theta, \phi) \sigma_{kl}.
$$

(8)

The transformation matrix $g_{ij}$ is defined as

$$
g_{ij} = \begin{bmatrix}
\cos \theta \cos \phi & \sin \theta & -\cos \theta \sin \phi \\
-\sin \theta \cos \phi & \cos \theta & \sin \theta \sin \phi \\
\sin \phi & 0 & \cos \phi
\end{bmatrix},
$$

(9)

where $\sigma_{ij}$ and $\sigma_{kl}$ are the stress tensors in the global and local coordinate systems, respectively. A local coordinate system has been defined which is simply rotated about the global coordinate system through angles $\theta$ and $\phi$. For simplicity, the global coordinate system is consistent with the principle stress coordinate system of the general three dimensional stress.

By substituting equations (6) and (7) into (5), $\overline{G}$ can be expressed by only the principle stress $\sigma_1$, $\sigma_2$, and $\sigma_3$, $\theta$, $\phi$, $a$, $K_{Icc}$ and $K_{IIcc}$. Additionally, it is assumed that $\sigma_2$ is the maximum principle stress. Provided that

$$
K_{Icc} \leq \frac{2 - \nu}{\sqrt{2}} K_{IIcc},
$$

(10)

it has been shown that, $\overline{G}$ reaches a maximum value $G_{max}$ for $\theta = 0$, given by

$$
G_{max} = \frac{4a \sigma_2^2}{\pi K_{Icc}^2}.
$$

(11)

With the growth criteria defined as $\overline{G} = 1$ (see Eq. (5)) and a typical crack radius $a_o$ the critical stress $\sigma_{cc}$ is given as:

$$
\sigma_{cc} = \frac{K_{Icc}}{2 \sqrt{a_o}}.
$$

(12)

**DESIGN OPTIMIZATION AND FAILURE ANALYSIS**

A systematic design approach using a combination of FEA, micro-crack theory, and test results [3,15,16] can aid in the development of optimal device design and assembly processes. Inputs to the design optimization should include the design concept, all functional and reliability requirements of the system, material properties, and device geometry.

Figure 1 shows a design process flowchart, which can be used to iteratively improve a package design using the methodology presented in this paper. First, a package design concept is generated, which is then analyzed using FEA including all relevant material properties. The results of the FEA will indicate the sources of stress and likely failure points. The FEA results are then compared to the failure mode criteria presented earlier. If they do not meet safety factor requirements for the device, the FEA may be used to evaluate different strategies to improve the package design or assembly process.

![Fig. 1: Package design flowchart using FEA-Failure Criteria Analysis methodology](image-url)

Once the design has progressed to a point, where it satisfies the requirements, samples will be built. Depending on the complexity of the design and the cost of prototyping, it may be preferable to build design verification test (DVT) samples first. DVT samples are simplified parts that adequately represent the design feature to be tested. These samples are subsequently subjected to different tests to validate the FEA results. If failures occur, they are analytically evaluated to determine the root cause. FEA is then applied to simulate the failure conditions. The results of FEA simulation are compared to the initial failure criterion. Based on this analysis, the model can be refined by adapting the parameters, e.g., typical crack radius $a_o$, to increase the accuracy of the model. The improved model can be reapplied to the iterative design process to develop a MEMS device that meets the requirements.

**Failure Analysis Using FEA**

FEA was used to determine thermally induced stress within a MEMS package design. Figure 2 (a) shows a schematic of the packaged MEMS device. The analysis used a quarter model with symmetric boundary conditions, as shown in Fig. 2 (b). The functional dependence of material properties
was included in the nonlinear thermal analysis to evaluate the heat dissipation and thermo-mechanical behavior of the system. Analysis assumptions include thermal management conventions, the surface temperature and heat convection coefficients. Other assumptions include:

1. The primary heat source is from the ambient environment. Internally generated heat is much less than ambient heat.
2. The heat flux from the die due to power dissipation is fixed at a constant value. This value is based on nominal device power output and efficiency. The package body is maintained under thermal management [17] with a constant surface temperature.
3. The adhesion layer is modeled as a visco-elastic material, governed by the Maxwell model [7,18-20].

A separate analysis was performed for each step of the assembly process. The analyses were performed in the same order as the assembly process intended for the design. Each consecutive analysis carried over residual stress from the preceding process steps. This methodology is particularly applicable to micro-cracks, which are more sensitive to stress than the bulk material.

The results of the FEA indicate that the largest thermal resistance would occur along the longest dimension of the package. Figure 3 shows FEA results of the die warping along the long edge of the MEMS die for a temperature variation ($\Delta T$) of 65°C. Figure 4 shows the stress contours of the quarter symmetry FEA model for the intrinsic package stress.

Fracture Analysis
Fracture analysis is a useful tool for verifying FEA results. Fracture analysis can be performed on failed parts, or on test specimens that are representative of the materials and geometry to be used in the package design [3,12,21].

A more detailed description of fracture analysis is given in [12]. Analysis of micro-crack induced failures begins by making a crack map. Figure 5 shows an example of such a crack map for a failed package. The first step in preparing a crack map is to collect all broken pieces and re-assemble, forming the crack profile. The crack propagation direction can be identified by observation of the Wallner lines or Hackle Marks. Following the crack against the direction of crack propagation will lead to the origin of the breakage. Often, the type of stress causing the fracture can also be identified by visual inspection of, e.g., the fracture surface. Finally, all information is compiled and combined with the process information to identify the source of the crack.
The result of the fracture analysis is then compared to the stress field predicted by FEA. If the location of the crack matches the stress field, the root cause for the cracking is material overload. Further analysis is required to define the cause of the stress overload, e.g., micro-cracking, intrinsic stress, or initial material quality. If the location of the crack does not match expectation, special conditions could be responsible for the failure. Such special conditions might be damages caused by tooling, equipment, or processes.

**Design and Process Optimization**

The purpose of optimizing the package design and assembly process is to increase reliability and performance of the component by reducing deformation and stress levels in the system. The optimization may be achieved by changing the package dimensions, package materials, or by selecting low stress processes. For example, reducing the process temperature as shown in Fig. 6, significantly reduces von Mises stress and resulting die warpage.

![Fig. 6: Process temperature influence on the stress and warpage of the MEMS die.](image)

Figure 7 demonstrates the improvement from increasing the ceramic board thickness (and, in effect, the stiffness and strength). The stress level in the MEMS die was reduced and the warpage was less than half the initial value.

![Fig. 7: Effect of the shape ratio [9,18] on the stress and warpage of the MEMS package](image)

**CONCLUSION**

FEA can be used to define critical stress data for a MEMS package design to meet its functionality and reliability requirements. The work described in this paper indicates that micro-crack failure criterion is more conservative and accurate than von Mises criteria or Mohr’s theory for predicting failures in brittle MEMS packages.

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**REFERENCES**


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