PROBABILISTIC APPROACHES FOR FRACTURE AND RELIABILITY ESTIMATIONS OF MICROSYSTEMS

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ABSTRACT

A comparatively large scatter of both local material properties and random geometrical imperfections can often be observed within the material compounds of microsystems. Recently, much progress has been made in modeling, FE-simulation and experimental verification of fracture and lifetime behaviour of MEMS based on deterministic assumptions. But until now there is a lack in consideration of the scatter or uncertainty of certain characteristics. For example, the partial randomness of certain input parameters creates considerable uncertainties in the Finite Element determination of mechanical quantities which are provided for thermo-mechanical reliability optimization and lifetime prediction. Furthermore, deviations in failure driving characteristics may lead to a changeover in the ranking of competing failure mechanisms.

The paper covers several approaches for taking into consideration randomness or uncertainty in failure and reliability estimation of microsystems. After structuring the various kinds and corresponding reasons of unavoidable scatter in parameters, the following problems are treated: (i) scatter in underlying materials structure – application of homogenization techniques, (ii) scatter in fracture mechanics parameters – randomization of primarily deterministic relations, (iii) scatter of geometry parameters – probabilistic FE analyses using Monte Carlo simulation techniques or response surface methods, (iv) variation of loading – rainflow methods, point processes and other methods of mathematical probability theory.

1 INTRODUCTION

Microsystems, microelectronic packages, thin electronics devices, or functional micromaterials like layered or dispersed structures, are typically compounds of materials with varying geometry and material properties, as well. Although much progress has been made in modelling, FE-simulation and experimental verification of fracture and lifetime behaviour of MEMS based on deterministic assumptions, there is a lack in the consideration of the scatter or uncertainty of certain characteristics [1-4].

There are several reasons for random scatter which may influence the fracture behaviour of microsystems in different ways. The different kinds of scatter arise at different levels of the material/component and involve different probabilistic approaches. For an overview of the quite different approaches, the following structure has been used, facilitating contrast and comparison:

(i) scatter in underlying materials structure – application of homogenization techniques,
(ii) scatter in fracture mechanics parameters – randomization of primarily deterministic relations,
(iii) scatter of geometric parameters – probabilistic FE analyses using Monte Carlo simulation techniques or response surface methods,
(iv) variation of loading – rainflow methods, point processes and other methods of mathematical probability theory.

2 SCATTER IN UNDERLYING MATERIALS STRUCTURE

Variations in materials structures are an outstanding characteristic of micromaterials. Typical examples include dislocations, intermetallic phases, porous media, polycrystalline materials and composites. Due to the very small dimension of the microcomponent itself, most of the materials have to be treated as heterogeneous. Another reason is the comparatively large ratio of the material's surface compared to the bulk material. The (possibly evolving) size, shape, orientation, physical properties and spatial distribution of the microstructural constituents largely determine the macroscopic, overall behaviour of these multi-phase materials. To predict the macroscopic behaviour of heterogeneous materials various homogenization techniques are typically used. Recently, existing first-order computational homogenization schemes which fit entirely into a standard local continuum mechanics framework have been generalized to second-order schemes to predict effects related to second-order variations of certain quantities [5]. Nevertheless, less progress has been made in practical applications by considering the resulting macroscopic behaviour as a random process (field) instead of a mean quantity.

A quite different stochastic approach for damage evolution is based on the following assumptions: Weak spots of the material form a random structure, e.g. a random spatial mosaic (tessalation). Microcrack growth preferably occurs along such paths [6]. Consequently, microcrack growth and coalescence lead to irregular crack patterns which can be described using tools of stochastic geometry [7-9]. Reversely, the evolution of the damage can be simulated using the stochastic model of weak spots within the material [10].

3 SCATTER IN MATERIALS AND FRACTURE MECHANICS PARAMETERS

Commonly used analytical models for both lifetime estimation and accelerated life testing are purely deterministic equations [11]. On the other hand, experimental life testing of electronic equipment shows an obvious random scatter which is modelled in many cases by a Weibull distribution with a Weibull modulus commonly resulting in the range between 2 and 4. To fit the results of numerical lifetime simulations to experimental results the numerically determined value is interpreted as the mean of a certain probability distribution. The link from the random character at material or component level to the kind of global lifetime distribution is still missing. In principle, the random scatter in material parameters leads to a randomization of formerly deterministic lifetime equations which can then be solved by the framework of probability theory (integral equations). This has been done, for example, in the context of Coffin-Manson lifetime equations in spite of uncertain equation parameters. The assumed type of probability distribution of the parameter plainly determines that of the failure distribution. It must be stated that much more effort is needed to correlate the failure mechanisms to physically understandable failure distributions which has been done, for example, using the weakest link model for brittle fracture. The problem is the very complex character of microsystem failure with numerous superpositioning failure mechanisms which are modelled by the so-called "physics-of-failure approach" (e.g. [12]).

4 SCATTER OF GEOMETRIC PARAMETERS

The geometry of microcomponents can only be manufactured within certain tolerances. To strive for perfection is neither physically possible nor financially feasible. Therefore, the deterministic Finite-Element analysis has to be supplemented by a probabilistic one. This means more than a deterministic worst case analysis or a FE-mesh generation from cross sections of real components. The variation of several parameters has to be taken into account. This leads to the problem of efficiently performing numerous FE computations and to compose the single results to a stochastic

one. The two techniques commonly used are Monte-Carlo simulation and response surface methods, respectively [13-14].
A probabilistic analysis provides information that cannot be discovered otherwise. Especially interesting are the questions: How large is the scatter in the global reliability characteristics ? What are the most important input parameters that need to be addressed in order to achieve a reliable design ? Here, a probabilistic FE analysis helps the user to a better understanding of the behaviour of the microcomponent under real-life conditions and of how to efficiently derive measures for design optimization, quality improvement and cost reduction [12, 15-16].

5 VARIATIONS IN LOADING

In contrast to the well-defined test conditions for microcomponents, the field conditions are characterized by high levels of complexity, uncertainty, and nonrepeatability.
The statistically based approach covers the modelling the occurrence frequency, intensity and duration of random loading events by various stochastic models, like rainflow methods or point processes. In this way, the random load history can be subsumed to a few statistical characteristics.
A second, more empirical approach is based on continuous component monitoring which will becomes possible with increasing miniaturization and system integration. Special data recorders and malfunction indicators are integrated into selected reliability-relevant electronic devices. These react to damage accumulation during the operational life as well as to unusual events, such as extreme acceleration during accidents or dangerously high temperatures. If a suitable lifetime model for the component is applied, the lifetime consumption during the operational life can be determined and the remaining lifetime can be estimated. To fit the theoretically determined "equivalent age" of a real component to its actual condition, certain parameters describing the level of damage are necessary. Currently, much effort is spent to qualify such concepts of "health monitoring". One possible approach is to observe changes or drifts in the response of the component to certain, well defined excitations, the other lies in observing changes in the topology of the structure [18].

6 SUMMARY

The damage and fracture behaviour of microsystems cannot be modelled purely deterministically since it is influenced by a certain measurement of random scatter. Different kinds of randomness or uncertainty arise at different levels of the material/component and involve different probabilistic approaches. Probabilistic analyses provide information that cannot be discovered otherwise. They help us to a better understanding of the behaviour of the microcomponent under real-life conditions and of how to efficiently derive measures for design optimization, quality improvement and cost reduction.

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