Three-dimensional Deformation Analysis of MEMS/NEMS by means of X-ray Computer-Tomography

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ABSTRACT

Due to their robustness and precision, micro- and nanoelectomechanical systems (MEMS/NEMS) are frequently used for all kind of technological applications. Therefore there is a high demand regarding reliability of these components. Exact knowledge of the deformation behavior of materials, material compounds, components and constructions are the backbone of the reliability evaluation and lifetime prediction under mechanical and thermal loading. Those parameters are usually maintained by means of geometric changes at the surface, independent of the measurement method. The high-resolution computer tomography enables the non-destructive acquisition of loading-dependent variations in the 3D-volume of objects, which can be evaluated quantitative and qualitative by using new developed software.

Keywords: Digital volume correlation, image correlation, computer tomography, reliability, MEMS/NEMS

1 INTRODUCTION

The evaluation of Microsystems components is of major importance, especially during the design-phase. Therefore the digital image correlation (DIC), which is based on the cross-correlation of two images under various loading states, is often used for the analysis of deformations and defects [1]. The technique is commonly used for in-plane and out-of-plane applications, mainly on the surface of the specimen.

High resolution x-ray computertomography (CT) allows the non-destructive 3D-analysis of materials and compounds. Therefore, information of the internal structure of the material or the device becomes available, which are otherwise only gained by destructive analysis.

There is still a high deficit in the analysis of thermal-mechanical caused local variations in the volume, which is especially required for failure analysis or for the evaluation of the deformation behavior of devices. Such variations can be easily analyzed and documented, by means of the high resolution computertomography. Load-specific variations can be qualitatively and quantitatively evaluated and directly compared to unloaded devices. This data is the basis for an essential improvement in numeric models for the evaluation of reliability and durability of materials and compounds. Also the determination of fractures and crack inside of the volume will be enabled and offers completely new possibilities for the experimental evaluation of fracture mechanics.

The metrological acquisition and interpretation of loading caused variations create a new demand on the evaluation of software. Until now, such evaluation possibilities exist only rudimentary. The comparison of geometry changes in equivalent virtual cutting planes between unloaded and loaded devices is the simplest solution for the evaluation of three-dimensional variations in the specimen. Commercially available software for the 3D-reconstruction allows the determination of geometry changes by means of surface comparison, but not any analysis inside the volume. Initial attempts to apply the digital image correlation method onto two-dimensional x-ray transmission images showed that global information of the transmitted sample areas can be gained, but a three-dimensional interpretation would be difficult. For the first time, specially developed software allows the qualitative and quantitative analysis of variations compared to unloaded components. In [2] it has been shown, that the conventional image correlation requires strong improvements for three-dimensional applications and a novel approach became necessary for the analysis of objects deformation. An in-house developed evaluation process allows the possibility of a reliable three-dimensional quantitative and qualitative acquisition of the deformed volumes.

Due safety guidelines regarding X-rays and the technical setup of the CT systems arises a need for special integrated thermal and mechanical loading equipment. A thermal loading system for General Electric's CT system "Nanotom" has been developed and tested for the evaluation of thermal caused deformations of devices. Equipment for defined mechanical loading is under construction and will be presented in the near future.

The functional capability of the thermal loading equipment, a novel approach for the digital volume correlation and first results gained by means of the new evaluation software will be presented in this paper.

2 IN-SITU LOADING EQUIPMENT FOR COMPUTERTOMOGRAPHY

Numerous commercial equipments are available for the evaluation of materials behavior at miniaturized samples [3]. Those solutions are not usable due to the specific conditions of the existing computer tomography system "Nanotom" and due to reasons of applicable components size and weight. Another problem is the required radiography of the entire sample, during the 360° rotation of the image acquisition process.

Therefore a highly specialized and integrated system has been developed to meet the special sample requirements and allow the evaluation of the samples (Figure 1).

Figure 1: Thermal loading equipment for the computer tomography with power supply and temperature controller

This loading system is based on sample heating caused by hot air flow and is designed for specimen up to 20 mm in diameter. Air is carried from the outside into the heating chamber installed inside of the "Nanotom" CT system and passes across a flat heater panel. The air causes a turbulent flow along planar sidewalls and absorbs heat while flowing until it is lead, along the inner walls of the "chimney", to the sample. The design was constructed according to the following simplified thermodynamic considerations (1). A simplification is necessary due to the undefined geometric assembly inside of the setup.

$$\Delta T_{air} = \frac{5{,}8 + 4 * \dot{V}}{c * V * \rho} * \frac{A * \Delta T_{WL} * \Delta t}{\frac{\pi}{4} * D^2 - d^2} \qquad (1)$$

ΔT_{air} is the increase of the temperature inside of the heater system. It is calculated by the heat transfer coefficient α ($\dot{V}$ - volume flow, V - air volume, ρ - density) and the conditions of the heater (A - heater area, ΔT_{WL} - heater temperature, Δt - dwell time) divided by the geometry of the "chimney" (D - diameter of the outer wall, d - diameter of the inner wall).

Inert gas can be used alternatively for the air flow, to avoid chemical reactions or oxidation of the sample at high temperatures. Temperatures in the minus range can be achieved by the evaporation of liquid nitrogen. Hence, a range from -80 °C up to 200 °C is feasible with this equipment. Higher temperatures can be achieved by surface enlargement or better isolation of the system. The equipment installed in the computer tomography system "Nanotom" is shown in figure 2.

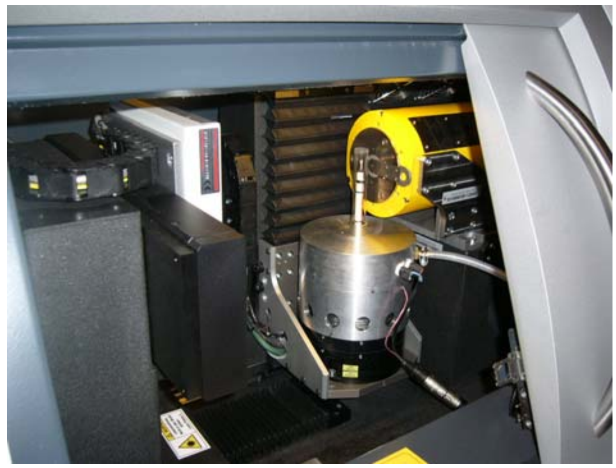

Figure 2: Thermal loading equipment installed in the computer tomography system "Nanotom"

The system is mounted on a sample holder frame; so that the air bedded sample chuck (max. 2 kg loading) is not exposed to additional loading. The sample itself is mounted at a sample rod, which is lead through the thermal isolation. The hot air flows in the area between the inner thermal isolation tube and the outer glass cylinder. Temperate controlling is carried out by a thermocouple, which is placed close to the sample. A measurement uncertainty of approx. 1 K is possible due to the lack of temperature measurement directly at the sample. This value can be reduced by an adequate heating time. A system calibration directly at the sample and prior to the actual CT-measurement is also possible. The heating rate is adjusted by the air flow and the electrical parameter of the heater. The emergent hot air is drawn off from the sealed x-ray chamber, to avoid thermal instability of the CT system.

Mechanical loading equipment is under construction. It will be used for tensile or compression loading of samples to evaluate the fracture behavior or for crack propagation.

3 DIGITAL VOLUME CORRELATION

Today available 3D reconstruction software, e.g. VG studio, offers a function for the ISO-surface comparison of various loadings of one sample, which works only at clearly separately structures. Due to the lack of information of the behavior inside the volume, software on the basis of digital image grayscale correlation analysis has been developed, which spatially evaluates all the grey values in a CT-volume-image-acquisition [4].

3.1 Conventional 2D image correlation

Conventional grayscale correlation can determine the field of the in-plane deformations under various loading conditions based on digital images. The analysis is performed by calculation of a similarity proportion of any displacement of a reference pattern from the first image, within a search area in the second image. The two-dimensional cross correlation delivers a discrete correlation field, whose maximum describes the relative displacement of the reference pattern. The accuracy of the displacement measurement can be increased by means of a sub-pixel algorithm. Field-like information about objects behavior can be gained by performing the calculation at multiple measurement point. Quantitative and qualitative conclusions of deformation procedures can be gained, as well as information about various physical values like e.g. strain, internal stresses, and adhesion and material properties. Reliability predictions can be derived from these values.

A common technique for the acquisition of information about the inner structure of an object is the x-ray transmission. It suggests itself to use 2D-shadow projections for the deformation analysis. Test with thermal and mechanical loaded samples showed, that the evaluation of shadow projections is possible with the in house software UNIDAC. In [5] has been shown, that this 2D technique can be used for the survey of the global deformation of samples, but easily reaches technology given limitations for the evaluation of inner structures (especially for compound materials and complex components).

3.2 Pattern enhanced volume correlation

Increasing complexity of the material structures enhance the desire for information of the deformation behavior inside of objects. Also for the analysis of fractures it is very helpful to know the local spatial deformation of objects. Three-dimensional (3D) image sequences of the object under investigation are the foundation of the 3D volume correlation.

The basic principle of the digital volume correlation is based on the two-dimensional (2D) approach. Three dimensional images (volumetric structures) of the object are acquired by means of the computer tomography - initially in the unloaded state and then under loading.

A spatial reference patterns similarity is calculated in a spatial search field volume pattern. In [2] it has been shown that the conventional method delivers unsatisfying results under certain circumstances, i.e. deformations results are unreliable and sometime defective due to low contrasts and lacking structuring of x-ray volumetric images. That's why; a so called Pattern Enhanced Technology (PET) correlation algorithm was developed and implemented as a novel approach for the modeling of objects deformation. In opposite to the classical algorithm (use of the correlation coefficient between two gray scale matrices or use of FFT) the topological association of pattern regions with similar "grayness „ is taken into account to determine the spatial displacements.

Proofs of concept measurements have been performed on a glass rod, covered with epoxy resin and aluminum foil. Thermal loading has been performed with the presented loading equipment in a temperature range from 21 °C up to 60 °C. A homogenous deformation field has been expected, due to the epoxy extension directed to the outside.

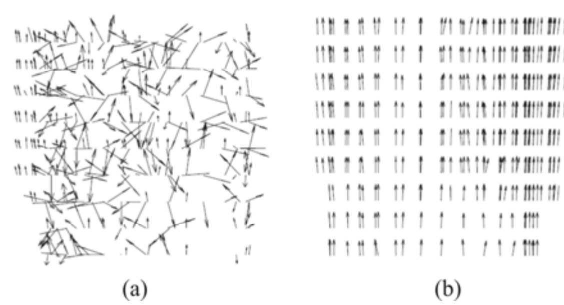

Figure 3: Result field of a thermal deformation: (a) conventional 3D-image correlation, (b) pattern enhanced volume correlation

Figure 3 (a) shows the result field of the conventional grayscale correlation algorithm in 3D generalization. The displacement field is diffuse and only hardly allows any conclusions regarding the actual deformation. In contrast the pattern enhanced volume correlation algorithm provides a uniform displacement field, which enables a qualitative and quantitative interpretation of the actual deformation.

3.3 Volume correlation on thermal loaded ball grid arrays (BGA)

The algorithm has been implemented into the software VG Studio from Volume graphics to benefit from the excellent 3D-visualisation features of a volume graphics code. The functionality of the volume correlation has been successfully demonstrated with the help of "artificial" and real samples, like it will be demonstrated by means of the following results. Figure 5 shows the global displacements between two loading states of a heated BGA sample, presented by means of spatial vectors. The sample has been loaded in-situ by thermal heating from room temperature up to 120 °C. The pitch between the vectors is user-definable, but has been chosen in a reasonable interval for visualization. The vectors shown in figure 4 represent the deformation of the solder ball, including the experimentally caused rigid body motion of the entire sample under thermal loading.

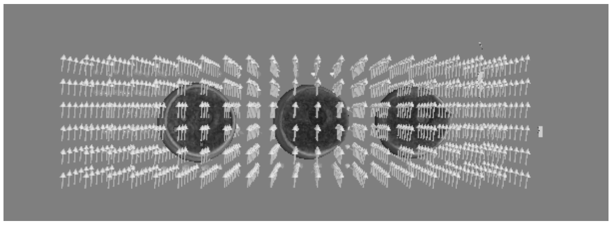

Figure 4: Vector visualization of the spatial deformation between RT and 120 °C according to the BGAs solder ball sample, including the rigid body motion

The local deformations are gained by subtraction of the rigid body motion (figure 5)

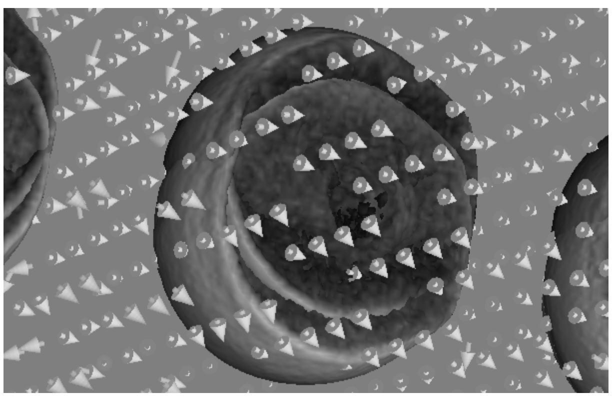

Figure 5: Vector visualization of the spatial displacement field inside the volume without the rigid body motion

The vectors now describe not only the geometry changes at the contours of the surface, but extra at any arbitrary position inside the volume. The direction of the displacement is indicated by the arrow heads of the vector. The local differences in the material behavior of the solder ball and in its surrounding become obvious.

4 CONCLUSION

Computer tomography enables non-destructive and high-resolution analysis inside the volume of materials, material compounds and components. By using adequate loading equipment, the deformation behavior of samples under thermal and mechanical loading becomes directly visible. Special thermal loading equipment has been designed regarding the special requirements of the "Nanotom" system and has been constructed and tested successfully.

The characterization of the deformation behavior occurs generally by comparison of various sample loading states. That means that for every loading state a complete CT-acquisition with subsequent volume reconstruction has to been carried out.

The two-dimensional DIC analysis is applicable to x-ray transmission images, under certain conditions. This technology allows a fast survey of the global deformation behavior of a sample.

An innovative software algorithm taking into account topological relations between pattern regions with similar gray values (speckles) called Pattern Enhancement Technology (PET) approach has been developed for the exact description of the local deformation behavior. This volume correlation software allows the qualitative and quantitative analysis of the displacements at any spatial point. Initial results of the three dimensional evaluation had been shown.

REFERENCES

[1] Dost, M.; Seiler, B.: uniDAC - Image Analysis System for Motion Analysis and Measurement of Shift and Deformation Processes, Fachtagung MicroCar, Leipzig 27. 02. 2008

[2] S. Haase. Mathematische Modellierung von Objektverformungen anhand von 2d und 3d Bildsequenzen, Diploma Thesis, University of Applied Sciences Mittweida, Dep. Of Mathematics, Natural & Computer Sciences, Germany, 2009

[3] Walter, H. et al.: Determination of Poisson's ratio of electronic packaging materials dependent on temperature by means of UNIDAC-method, 1st Int. Congress on MicroNanoReliability, Berlin, Sept. 2.-5. 2007

[4] Faust, W. et al: B.: Deformation analysisby means of CT, High Resolution X-ray CT-Symposium Dresden 2010, 31. August- 2.September 2010

[5] Hammacher, J., Faust, W., Scheiter, L., Erb, R., Michel, B.:Digital volume correlation by means of X-ray computer tomography, Applikations-workshop Digitale Bildkorrelation, Chemnitz 24.10.2010