In-situ analysis of an industrial material compound package by means of X-ray micro tomography and digital volume correlation

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Abstract
The characterization of the thermo-mechanical deformation behavior and failure mechanism plays a central role in reliability evaluations of packaging technology for power electronics. This paper demonstrates the potential of laboratory X-ray micro-computed tomography (X-CT) to characterize the thermo-mechanical behavior of industrial packages through in-situ experiments. A specific thermal loading device offers the possibility to capture deformations and damages of material compounds in a temperature range up to 300°C. Digital volume correlation (DVC) and a novel method based on digital image correlation (DIC) are applied to estimate the deformation field within the specimen at each loaded state as well as the thermal expansion of a specific layer.

Keywords: in-situ, X-ray tomography, material compound, volume correlation, thermal expansion

1 Introduction
Important design parameters for electronic power components are an extended functionality by integration of logic elements, miniaturization, energy efficiency, and cost reduction. Due to that, operating temperatures up to 300°C have been claimed recently for electronic power components as used for instance in electronic vehicles. Obviously, there is a high demand on the reliability of those components. Thus, for the design, development and qualification of new material systems and packaging technologies, precise reliability evaluations and lifetime predictions are of major importance. For that, an exact knowledge of the deformation behavior of materials, material compounds, and components under mechanical and thermal stress is essential [6,7].

High resolution X-ray micro-computed tomography (X-CT) enables the non-destructive acquisition of stress-dependent variations in the interior of an object. Compared to conventional methods using any kind of preparation, this provides greater insight into the real deformation processes of complex components.

However, there is still a high deficit in the analysis of thermal-mechanical caused failure mechanisms with respect to characteristic deformation processes inside micro-electronic compound packages. Special in-situ heating equipment is required for thermal loading of the respective specimens inside the X-CT chamber. Temperature-specific variations can then be evaluated by comparison of the unloaded and the stressed specimen.

The simplest approach to examine deformations between different states is to compare equivalent sectional images using a digital image correlation method. It directly provides in-plane displacements and strains and thus may give first information about critical regions but does not provide any convincing three-dimensional information.

Commercially available software for the visualization and analysis of CT data mostly offers the determination of geometry changes by means of surface comparison. Thus, the global three-dimensional behavior of the specimen can be judged, but the deformation inside the object cannot be measured.
In recent years, numerous variants of digital volume correlation (DVC) methods for the measurement of full three-dimensional deformations based on X-ray computed tomography (X-CT) have been proposed [1, 11]. Nevertheless, the applicability of the technique is limited to a narrow class of materials [12]. Yet, DVC applications have only been published for materials that have a good contrasting microstructure, as for instance wood-based fiberboards [14], wood [5], scaffold [8], metallic foam [13], poly-granular graphite [9], and epoxy resin filled with metallic particles [2]. Especially the analysis of specimens with varyingly radio-opaque components is still a challenging problem. However, electronic packages are always assembled from components with very distinct radiation absorbing properties. Thus, artifacts due to the image acquisition and reconstruction have potentially a more dramatic effect than noise on the computed displacement field [12], particularly for such specimens. Hence, we propose a straightforward and robust DVC method based on modified sub-volume (template) matching.

First of all we present a custom-built heating stage for the integration in General Electric’s CT system nanotom® in Sec 2. In Sec. 3 we propose a generalized approach for the comparison of equivalent sectional images using digital image correlation. This approach handles the information of several neighboring sectional images and thus provides a fast and robust method to get a first idea about potential critical regions within the object under investigation. The proposed DVC method is described in Sec. 4. Experimental in-situ measurements and the respective results are discussed in Sec. 5.

2 In-Situ Heating Equipment

There are numerous requirements on the load test device, if one wants to stress a sample thermally inside the nanotom®. Firstly, there are narrow limits regarding the component size and weight. Besides, for high resolution CT image acquisition it is necessary to place the sample as close as possible to the X-ray source. Another challenge is the required stability of the sample during the 360° rotation within the image acquisition process.

![Figure 1: Left: Thermal load test device (heater) installed inside the X-ray chamber of the CT-system nanotom®. Right: Schematic illustration of the functional principle of the heater.](image)

To meet all the requirements, we developed a highly specialized and integrated heater (Fig. 1). The heater is based on sample heating caused by hot air flow and is designed for specimen up to
20 mm in diameter. A temperature range from room temperature up to 300 °C is feasible with this system.

Air is carried from the outside into the load test device where it passes a heating element and absorbs heat during its turbulent flow before it is lead along the inner walls of the ‘chimney’ to the sample (Fig. 1, on the right). Temperature control is carried out by a thermocouple which is placed close to the sample. Due to that, a measurement uncertainty of approximately 1 K is achieved. This value can be reduced by an adequate heating time. A system calibration directly at the sample position and prior to the actual CT measurement is possible as well. 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. Furthermore, the X-ray tube is cooled actively. For a more detailed description of the heater we refer to [6, 7].

3 A Novel Method for the Correlation of Sectional Images

Conventional digital image correlation (DIC) directly provides full-field displacements and strains by comparing the digital images of the specimen in the un-deformed (or reference) and deformed states respectively [10, 3]. As a simple approach to evaluate deformations within the interior of an object, one could compare sectional images of 3d CT images. However, for DIC it is essential that the whole considered specimen region remains in the same plane parallel to the optical sensor during loading, i.e. it is mapped in exactly one sectional image respectively. An out-of-plane motion of local regions leads to a mapping to different sectional images. Hence, the DIC method fails.

Nevertheless, for electronic packages, one is often interested in the thermal response of a specific (thin) layer as we will discuss in Sec. 5. Moreover, due to the layer composition of those packages, out-of-plane displacements can be almost excluded. Thus, local deformations due to thermal stress will be mapped to only a few neighboring sectional images.

We therefore generate a highly textured image containing the most contrasty patterns of several neighboring sectional images. The resulting pattern enhanced image then contains all the information regarding the local deformations within the considered layer and a conventional DIC can be performed to determine the in-plane deformation and the thermal strain subsequently (comparing pattern enhanced images of different states). This method will be referred to as pattern enhanced DIC (PE-DIC) in the sequel.

Figure 2: Several sectional images are used to generate a synthetic, highly textured image which contains in-plane deformation information of all the sectional images. Left: Five sectional images of the specimen discussed in Sec. 5. Due to a curvature of the imaged layer, large regions of a single sectional image are influenced by surrounding materials and thus appear blurred. Right: Synthetic image composed of highly textured regions of the several sectional images. Thus, the whole considered layer is mapped onto a single image.

Obviously, since we map 3d deformations to a single synthetic image, this yields to additional in-plane displacement measurements. However, keeping in mind that the PE-DIC measurement may contain a certain error, this approach leads to a simple and computational efficient method for an initial analysis
of CT images of different sample states. Thus we quickly get a good idea about the deformation processes and a first indication about potentially critical regions within the considered layer.

4 Wavelet-Based Digital Volume Correlation

Digital Volume Correlation (DVC) provides the measurement of full three-dimensional stress dependent deformations based on high-resolution X-ray computed tomography. Basically, DVC is a straightforward volume extension of 2D DIC technique but allows the measurement of displacements and strains within the interior of the sample. To stress the specimen, a specific load test device is needed for in-situ measurements inside the CT chamber. A custom-built heating stage for the integration in the CT system nanotom® has been described in Sec 2.

The essential parts of DVC are the following:
1. Experimental set-up: specimen preparation (if necessary), mounting of the loading device, sensor initialization
2. Volume data acquisition for each stress stage
3. Tomographic volume reconstruction
4. Calculation of 3D displacements by means of correlation between each stress state (sub-volume tracking)

The DVC algorithm has to satisfy some challenging requirements: Firstly, image correlation has to be very robust against noise due to image reconstruction artifacts. Secondly, as for 2D DIC, displacement measurement has to be more accurate than voxel level.

Generally, due to the comparison of (at least) two 3D CT images the motion of predefined measuring points is computed. To estimate the displacement of a point P, a reference subset centered at P, from the reference image (local surrounding environment of P) is used to estimate its corresponding position in the deformed image. As a similarity measure between the grey scale intensity patterns of the reference subset and the target subset a cross-correlation criterion is used. The peak position of the distribution of similarity values indicates the relative shift of the reference pattern and hence the displacement vector at point P. In a second step the displacement measurement accuracy can be approved using a sub-voxel registration algorithm. To obtain an area-measured analysis of the deformation behavior the calculation is done for a multitude of local points.

Most correlation methods apply the cross-correlation coefficient as a similarity measure to compare grey scale intensity patterns. There, artifacts due to image acquisition and reconstruction often yield to artifacts.
incorrect evaluations. To reduce such miscalculations we propose a new approach we refer to as wavelet-based digital volume correlation (wDVC) [4].
In case of wDVC, we do not compare local grey scale intensity patterns but wavelet decomposition thereof. We therefore compute the approximation coefficients and details coefficients (horizontal, vertical, and diagonal), obtained by wavelet decomposition of the input sub-volumes with respect to Haar wavelets, performing multi-level decomposition (see Fig. 3 for an illustration in the two-dimensional case). We use the Haar wavelet family for decomposition, since these basis functions are well-suited for piecewise constant functions (and hence especially for digital images) and the decomposition can be computed efficiently.
The essential benefit of wDVC is that the wavelet coefficients represent local, high-frequent phenomena as well as global properties of the sub-volume images. This multi-scale representation contains obviously more information about the image subsets than the spatial domain representation. Noise is partially suppressed and a robustness of the approach is achieved.

5 Experimental In-Situ Measurements and Discussion of the Results
We studied the thermal response of a regular industrial package with a pre-existing damage due to a bending test (crack in the adhesive layer). The package is composed of a silicon chip bonded on a copper lead frame using a silver conductive adhesive (mixture of resin and silver particles). Figure 4 gives a schematic representation of the package.

![Schematic representation of the observed industrial package.](image)

Eight temperature states have been performed using the in-situ heating device described in Sec. 2. Therefore, the sample was heated up to the specific temperature state and (after an appropriate dwell time) the CT image acquisition was performed at constant temperature in each case (eight states from 27°C to 180°C).
The radiation intensity of the X-ray source was adjusted to image the conductive adhesive layer between the copper lead frame and the silicon chip clearly and we analyzed the deformation and thermal strain in this layer. However, the adhesive layer is imaged only in few sectional images within the entire volume image. Moreover, due to the prior bending test, the whole package is slightly curved.

![Horizontal displacement field for the adhesive layer on either side of the crack due to heating from 27°C to 180°C.](image)

Figure 5: Horizontal displacement field for the adhesive layer on either side of the crack due to heating from 27°C to 180°C. Left: Results for DIC using a single sectional image. Middle: Results for the proposed PE-DIC approach using a synthetic image fused from five neighboured sectional images. Right: Results for the full 3d displacement field obtained using the proposed wDVC approach. We remark that the difference in the colour display is present due to the use of different visualization tools. However, the colour scale is the same for all three figures.
Consequently, in each of the sectional images, the adhesive layer is represented only in a small range clearly. In other words, only small regions of each sectional image show the adhesive highly textured due to the influence of the neighboured materials during radiography.

Moreover, due to the layout of the electronic package we do not assume relevant displacements directed towards the silicon chip and the copper layer, respectively. Hence, the proposed PE-DIC approach may lead to quite good results. We therefore generate a highly textured image containing the best contrasting patterns of five sectional images.

Figure 5 shows the horizontal displacement field for the adhesive layer due to heating from 27°C to 180°C comparing the three methods. The left image in Fig. 5 shows the results for DIC using a single sectional image from each of the two temperature states. Compared to the results of the other approaches, it becomes obvious that the lack of information within the sectional image leads to miscomputations in several regions. The middle image in Fig. 5 shows the results for the PE-DIC approach. The synthetic image contains information of several sectional images and hence the in-plane deformation for the whole adhesive layer can be measured. The results are quite similar to the results for wDVC, depicted on the right side in Fig. 5. However, wDVC provides a full 3d displacement field for the whole conductive layer, whereas for PE-DIC potential out-of-plane displacements yield to additional in-plane measurements. Anyway, the displacement fields for PE-DIC and wDVC are quite similar in all regions which mutually corroboratives the results.

Consequently, we applied the computational efficient PE-DIC approach for the following investigations. As we are interested in the thermal expansion of the adhesive layer under constrains within the package, we calculated the thermal strain for all temperature states. Figure 6 (left) shows the vertical displacements for a restricted region on the right side of the crack which was used for the estimation of the thermal expansion. The estimated mean thermal expansion for the adhesive layer is 18–20 ppm/K which is close to the CTE of silver stated in the literature. Again, we explicitly remark that the expansion is substantially affected by the surrounding materials since the adhesive layer expands together with the silicon chip and the copper lead frame.

![Figure 6](image)

**Figure 6**: Left: Vertical displacements for a restricted region (on the right side of the crack) for the estimation of the thermal expansion (using PE-DIC), Right: Linear thermal expansion of the adhesive layer.

### 6 Conclusions

In this paper we introduced a highly robust DVC method based on wavelet decomposition. Due to that it is possible to use small and cuboid-shaped sub-volumes of arbitrary edge lengths for sub-volume matching and the influence of artifacts due to image acquisition and reconstruction is diminished. Moreover, we proposed a simple and computational efficient method based on DIC. The fusion of several neighbored sectional images leads to a pattern-enhanced synthetic image. Thus, small out-of-plane displacements do not lead to failure comparing suitable synthetic images of different stress states using conventional DIC.
A specific thermal load test device was used to heat an industrial package with a pre-existing crack within the adhesive layer due to a bending test. We calculated the displacements within the adhesive layer between two temperature states. We compared the results for conventional DIC, PE-DIC, and wDVC using a single sectional image, a synthetic image assembled from five sectional images, and the full 3d CT data, respectively. We demonstrated that the PE-DIC may provide a computational efficient alternative to full 3d DVC for specific applications.

The proposed methods have a great potential for an improved characterization of the thermo-mechanical deformation behaviour of electronic packages. In-situ experiments with X-ray tomography allow non-destructive reliability evaluations. In combination with the proposed correlation methods we can analyse the specific deformation behaviour of a single layer affected by the surrounding components in composite materials. This allows precise reliability evaluations and lifetime predictions for micro-electronic compound packages.

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References

