Characterization of the deformation behaviour of PCBs under dynamic loading conditions

P. F. Fuchs\textsuperscript{1}, Z. Major\textsuperscript{1,2}, R.W. Lang\textsuperscript{1,3}

1 Polymer Competence Center Leoben GmbH, Leoben, A

2 Institute of Polymer Product Engineering, University of Linz, Linz, A

3 Institute of Materials Science and Testing of Plastics, University of Leoben, Leoben, A

E-mail: fuchs@pccl.at

Abstract. Printed circuit boards (PCBs) are frequently exposed to a complex combination of external and internal thermo-mechanical loads (static, cyclic and impact loads superimposed by local and global temperature effects). In this study, instrumented impact tests of the PCBs were performed and characterized. In addition to the acceleration measurement of the impact, the deformation behaviour was analyzed using a high speed camera and strain gauges. To reduce the testing effort for future PCB design the oscillation behavior of the PCB after impact was simulated using a finite element (FE)-software. Dynamic mechanical analysis experiments were performed and a linear viscoelastic material model was defined. Furthermore, the results of the simulation were compared to the measured values. In spite of the difference in the measured and simulated frequency values over the time, the viscoelastic effects including the damping behaviour were reflected accurately in the simulation.

1. Introduction and Objectives
Printed circuit boards (PCBs) are the heart of all common electronic devices. The area of application of these electronic devices is wide spread. Consequently, the PCBs are exposed to various application dependent complex loads. To meet the increasing demands on the PCBs the build ups and the materials used have to be optimized [1].

In this study the impact loading situation was selected for detailed analysis. Impact is a frequent failure initiator in PCBs and therefore of high practical interest [2] [3]. Due to the load the PCBs are exited to a damped oscillation which was examined and characterized.

To accelerate the optimization process, a finite element (FE) - software was used to simulate the impact. In order to describe the deformation behaviour in the simulation, the material properties had to be determined. Unlike previous studies on the drop test simulation, e.g. [4], which used either elastic or elastic-plastic material models, in this case a viscoelastic material model was chosen. Thus the time dependent damping of the oscillation amplitude and the frequency development could be simulated. Finally the results from the simulation were compared to the experimental results.
The objectives of this paper are to:

- conduct instrumented impact tests on PCBs identifying the loading situation.
- determine the material properties (time dependent modulus values).
- perform a data reduction identifying the parameters for the material model.
- simulate the instrumented impact test.
- compare the simulation with the experiment.

2. Experimental
The specimen characterized was a simplified PCB plate consisting of glass fiber reinforced epoxy layers without intermediate copper layers.

2.1. Instrumented Impact test
Instrumented impact tests were performed using a drop tower and subsequently analyzed. The loading was recorded by an acceleration sensor and the deformation behaviour was characterized by strain gauges applied on the surface of the plates and by a high speed camera (Photron Ultima 512, San Diego, CA, USA). Figure 1 shows the tested plate mounted on the impact fixture with the strain gauges applied. To measure the impact loading the acceleration sensor was fixed at the base plate.

Figure 1. Instrumented impact test with specimen and applied strain gauges and acceleration sensor.

The PCB deformed and the post-impact oscillations measured by the high speed camera are shown in figure 2a. The deformation amplitude is determined at various deformation stages and plotted over the time in figure 2b.

Figure 2. High speed camera image at a deformation stage selected (a) and the oscillogram related to the post-impact oscillations (b).
Due to the limited optical resolution of the high-speed camera, the amplitude decrease could be monitored only during the first 50 ms after the impact. Data from strain gauges was used to cover larger times.

Furthermore, the strain gauges provided information on the local strains. The strain gauges were applied both at the center of the plate and at the half distance between the edge and the mid of the plate. The strain gauge at the center was a biaxial type and additionally to the longitudinal strain the transversal strain was measured.

2.2. Mechanical Analysis
The plate specimen consists of fiber reinforced epoxy resin layers and was therefore supposed to show viscoelastic deformation behavior. To determine an adequate viscoelastic material model for the FE simulation, dynamic mechanical analysis (DMA) experiments were performed under bending load over a wide frequency and temperature range (from 0.01 up to 10 Hz and at the temperatures of -40, -20, 0, 23, 60, 125 °C). The plate was mounted on a 3 point bending fixture and exposed to sinusoidal oscillations by the actuator of the dynamic testing machine (figure 3). An electrodynamic testing machine (BOSE 3450, BOSE Co, MN, USA) was used for these tests.

2.3. Data Reduction
The data obtained from the DMA is the dynamic bending modulus over the frequency for the different temperatures. To get the parameters for the linear viscoelastic material model used in the FE simulation, the following steps were performed:

- Creation of a master-curve using the time (frequency)-temperature shift principle. The master-curve approach is well defined and described in the polymer science literature e.g. [5], [6].
- Calculation of the dynamic tensile modulus from the dynamic bending modulus considering the plate stiffness.
- Usage of the linear elastic equations to determine the dynamic shear modulus from the dynamic tensile modulus assuming a constant bulk modulus and a Poisson’s ratio value from the literature [7].
- Transformation of the frequency basis to a time basis [8].
- Prony series fit for the dynamic shear modulus master-curve. A detailed description on the physical and mathematical background of the Prony series can be found in literature [8].
2.4. Simulation
The deformation behavior during the impact process of the test plate was simulated using commercial FE software Abaqus 6.7.1 (Simulia, Providence, RI; USA). The plate was modelled as a homogenous solid and the boundary conditions were set corresponding to the mounting situation on the impact fixture (see figure 1). The specimen was loaded directly by the acceleration values measured using the acceleration sensor. The material model was assumed as linear viscoelastic and defined by the Prony series parameters calculated from the DMA data. The deformation amplitude as a function of time was determined in the simulation and compared to the experimental results.

3. Results and Discussion
First, the data measured in the DMA experiments for the generation of the material model is presented. The frequency dependence of the dynamic bending modulus values for three different temperatures over the frequency range investigated (from 0.01 up to 10Hz) are shown in figure 4.

As the experimentally determinable frequency range is limited, to obtain dynamic modulus values for higher frequency ranges, a reference temperature was selected (in this case it was the room temperature, 23 °C) and a master-curve was created.

The master-curve was generated by shifting the dynamic modulus measured at higher temperatures to lower frequencies and the dynamic modulus measured at lower temperatures to higher frequencies. The concept is based on the physical effect, that the influence on the material behavior is similar regarding a change of the loading time and a change of the temperature.

The time-dependent dynamic shear modulus was calculated from the frequency-dependent dynamic bending modulus. The resulting master-curve was shown in figure 5. A Prony series measured was fitted to the data and the relaxation time values and the modulus values were calculated.

![Figure 4](image1.png)

*Figure 4. The frequency dependence of the dynamic bending modulus for three different temperatures (-40°C, 23°C and 125°C).*

![Figure 5](image2.png)

*Figure 5. Master-curve of the dynamic shear modulus with the Prony series fit.*
The envelop curves of both the measured deformation amplitudes and the simulated deformation amplitudes at the center of the plate over the time were shown in figure 6.

The deformation amplitude was calculated from the longitudinal strain measured by the strain gauge applied at the center of the specimen. The maximum value of the deformation measured by the high speed camera to the maximum value of the longitudinal strain was taken as proportionality factor. The second curve shows the results of the FE simulation. Over the measured time range of 0.25s, the experimental and the simulated envelop curves reveal only small, nearly negligible differences. It is concluded that the damping behaviour of the material in terms of amplitude decay is accurately described by the Prony series and by the master curves generated using the DMA experiments.

![Figure 6. Deformation amplitude development of the post impact oscillation.](image1)

The frequency of the damped oscillation was found to decrease with increasing time both in the experiments and in the simulation. For comparison the results are shown in figure 7. Along with the amplitude, the loading rate is also decreasing over the time. Due to the viscoelastic properties of the epoxy matrix, the decline of the loading rate leads to a lower stiffness. As the frequency of the oscillation depends on the specimen stiffness [9], this effect could possibly explain the sinking frequency.

However, the experimental results reveal significantly smaller values over the entire time range than the simulation (the initial values are at about 300 Hz and 500 Hz respectively). No plausible reason for this discrepancy was found up to now. One reason of the difference between the experiments and the simulation could be measurement errors due to the very small forces at the dynamic bending test which were difficult to record. To address this problem, further experiments will be performed and theoretical considerations regarding the viscoelastic model used will be done.

![Figure 7. Frequency development over the time of the post impact oscillation.](image2)
4. Summary and Conclusion

Instrumented impact tests were performed on PCB plates and the subsequent oscillations were recorded by optical devices and by strain gauges over a wide time range.

To characterize the material behavior and to determine material parameters for FE simulation dynamic mechanical analysis (DMA) tests were carried out. A linear viscoelastic material model was defined by the parameters of a Prony series and applied.

FE simulations were performed on PCB plates using the viscoelastic material models and the results of the simulation in terms of amplitude and frequency were compared.

While the results of the simulation reveal a good correlation to the experimental results regarding the amplitude of the deformation behavior, significant difference was found between the measured and the calculated frequency range for the damped oscillations.

To gain more insight into the frequency change during the damped oscillations, both further experiments will be performed and theoretical considerations regarding the viscoelastic material model and the FE model used will be done.

References
[1] Ehrler S 2002 Properties of new printed circuit board base materials Circuit World 28/4 38
[2] Jeng S T, Sheu H S, Yeh C L, Lai Y S, Wu J D 2007 High G drop impact response and failure analysis of a chip packaged printed circuit board International journal of impact engineering 34 1655
[3] Liu F, Meng G, Zhao M 2007 Viscoelastic influence on dynamic properties of PCBs under drop impact Journal of electronic packaging 129 266
[4] Wang Y, Low K H, Pang H L J, Hoon K H, Che F X, Yong Y S 2006 Modeling and simulation for a drop-impact analysis of multi-layered printed circuit boards Microelectronics Reliability 46 558
[5] Wineman A S, Rajagopal K R 2000 Mechanical Response of Polymers An Introduction (Cambridge:University Press)
[6] Schwarzl F R 1990 Polymermechanik (Berlin: Springer)
[7] Walter H 2003 Morphologie-Zähigkeitskorrelation von modifizierten Epoxidharzsystemen mittels bruchmechanischer Prüfmethoden an Miniaturprüfkörpern (Halle-Wittenberg: Martin-Luther-Universität)
[8] Tschoegel N W 1989 The Phenomenological Theory of Linear Viscoelastic Behavior (Berlin: Springer)
[9] Pilkey W K 1994 Formulas for Stress, Strain, and structural Matrices (New York: Wiley–Interscience)