Laser Speckle Photometry for Stress Measuring at Industrial Components

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Abstract

Excessive deformations, cracks or failures occur in industrial practice when components are overloaded. It is therefore desirable to continuously monitor the mechanical stress state of industrial components. Due to their high thermal conductivity, direct copper bonded (DCB) substrates are used in power electronics to meet the high reliability requirements. These DCBs usually carry residual stresses, especially at the edges of the copper layers. The stress concentration can increase under operating conditions or even during the manufacturing process, resulting in cracks and fractures. In order to avoid the critical cracking situation, it is necessary to know the residual stresses. The article presents a possible approach to the measurement of stress states.
A new optical method, the Laser Speckle Photometry (LSP), was used in the laboratory on ceramics exposed to bending stress. Laser Speckle photometry is a fast and contactless method for the measurement of the spatial-temporal dynamics of speckle fields with high temporal resolution after mechanical or thermal excitation. During the experiment laser light illuminates a defined surface region. Due to the optical rough surface of the sample, a so-called speckle pattern is reflected and recorded by a CMOS camera system. The speckle pattern depends on the sample surface condition and the mechanical strain condition. The stress-induced changes in the materials structure lead to changes in the speckle field, which is formed by a probing laser. The shift of speckle-field is analysed by statistical methods, using co-occurrence matrix and correlation functions. Correlations between stress condition and measurement signal were observed and evaluated. This resulting measurement signal was then calibrated using mechanical stresses determined using finite element (FE) simulations.
The authors present the transferability of previous local stress measurements on Al_2O_3 ceramics to LTCC ceramics. It is shown, that laser speckle photometry is a suitable instrument for non-destructive characterization and monitoring of stress states in ceramics.

1. Introduction

Ceramic substrates, for example, are frequently used in power electronics modules to meet heat flow performance requirements due to their excellent thermal and mechanical properties in terms of structural reliability. Typically direct copper bonding (DCB) substrates are applied in electronic applications, which consist of an Al_2O_3-ceramic layer in between two thick copper layers. At the sintered interconnection of copper and ceramic, thermal inducted stresses are generated during the cooling to ambient temperature due to the very high process temperature. The highest stresses occur along the edges of the

copper, where the copper structure has been etched back. These mechanical stresses can cause cracking and even the functional failure of the entire electronic component.
In order to ensure a continuously high quality of the electronic components, it is important to know exactly the stress distribution in order to be able to detect crack initiations or even to avoid them. Currently, there is no technique that allows direct, non-contact and fast determination of mechanical stresses in ceramics. Techniques such as the X-ray diffraction method, the digital speckle pattern interferometry (DSPI), or the ultrasonic scanning microscopy are time consuming, very expensive and sometimes destructive.
The rapid development of hardware and mathematical tools for acquisition and processing of non-stationary optical fields makes it possible to develop new methods for optical measurements. Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) developed an innovative non-contact, optical technique based on the detection and analysis of thermally or mechanically activated characteristic speckle dynamics. This technique is called Laser Speckle Photometry (LSP). Much work has been done with LSP for metallic materials, such as characterization of material properties, damages, hardness, porosity evaluation, etc. [1-3]. Current research focuses on the characterization of ceramics whose thermal and mechanical properties are totally different from those of metallic materials. In this paper, the stress measurement of ceramic substrates based on the so-called LSP technique will be presented.

2. Laser Speckle Photometry

2.1 Principle of Laser Speckle Photometry

The LSP method is based on the analysis of speckle patterns. A speckle pattern is generated when an optical rough surface is illuminated by a coherent light source [4]. The scattered waves from various points of the illuminated surface interfere in the observation plane, producing the speckle pattern – a spatial structure with randomly distributed intensity minima and maxima. The different luminosities can be detected by complementary metal-oxide-semiconductor (CMOS) sensor. For example, if the examined object is thermally excited, the material characterization can be described based on dynamic speckle patterns [2]. This 3D information of sample surface can be used to detect the deformation state of the sample and to determine the resulting stresses afterwards.

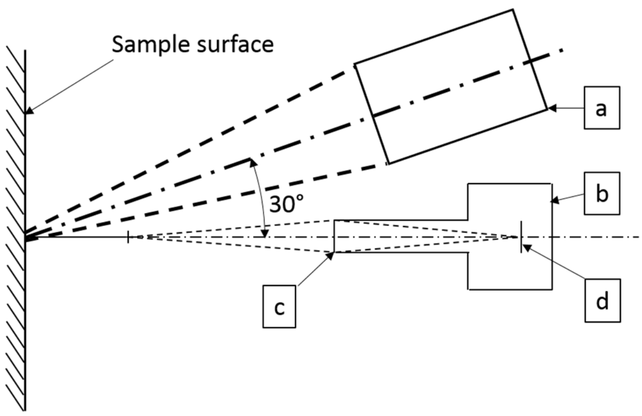

Figure 1. Schematic structure of the laser speckle photometry setup: (a) – Laser Diode (LD), (b) – camera system, (c) – optics and (d) –sensor from [7]

Figure 1 demonstrates the basic setup for LSP measurements. The speckle pattern is generated on sample surface by a laser diode (a), and the speckle signal will be recorded by a detecting system (b), which is containing optics (c) and a sensor (d). The illumination of the sample is performed by the irradiation of the surface with coherent light from a laser diode at a 30° and lesser angle. In the work of this paper, the dynamic speckle signal is stimulated by a changing mechanical strain, which is caused by mechanical bending. A rough surface responds to this stimulation with changing the position of surface reflectors respectively scattering points and converting the variations into changes of the speckle pattern recorded by the camera system.

2.2 Evaluation algorithm of Laser Speckle Photometry

The recorded Speckle signal can be analysed with different algorithms depending on the specific situation. The evaluation algorithms used in this paper for determining mechanical stresses can be divided into two groups – algorithms for static and dynamic analyses, respectively. The static evaluation focuses on the image scale, wherein the initial speckle intensity of each pixel is depending on a group of pixels around it (e.g. the 3-by-3 neighborhood), which after the computation have the parameter value of the central pixel. This process is repeated for each pixel of the image. The interested parameters of image can be classified into intensity, histogram and grey-level co-occurrence matrix (GLCM) based on texture analysis. Instead, the dynamic analysis calculates the grey value distribution of a single pixel in time sequence rather than based on multiple pixels in one image and is called in this paper dynamic speckle change value (DSCV) evaluation. The investigated algorithms of LSP evaluation are shown in Figure 2.

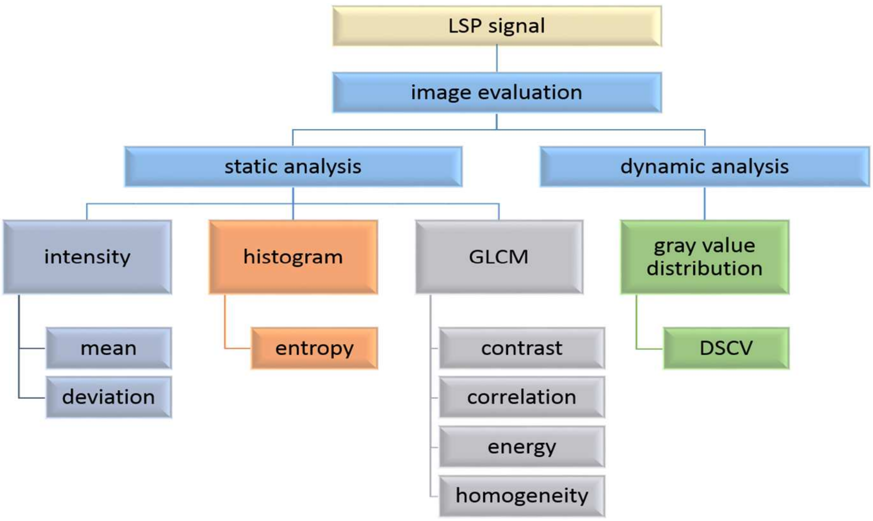

Figure 2. Schematic overview of the possibilities to evaluate the speckle signals by static and dynamic analysis from [7]

In this paper, two static evaluation parameters are chosen to represent speckle signal for the stress measurement on ceramic substrates. The first parameter is the *standard deviation* σ_I of the intensity. It can be computed by:

$$\sigma_I = \sqrt{\frac{1}{N_p}\sum_{p=1}^{N_p}[g(p)-\mu]^2}\ , \quad (1)$$

where N_p is the total pixel number of an image or region of interest (ROI), $g(p)$ is the grey value of a pixel, and μ is the mean value of intensity of the ROI . The other parameter is *contrast* C_G, defined as a measure of the local variations. It is a conventional parameter of texture analysis based on the GLCM, which is detailed demonstrated in the paper of Haralick [5] including the definitions and generation of the matrix. The *contrast* C_G is calculated by the equation:

$$C_G = \sum_{i,j=0}^{Q-1}(i-j)^2 C_{i,j}, \quad (2)$$

where $C_{i,j}$ is the value of element of GLCM at position i and j, and Q is the width of GLCM.

The dynamic parameter in Figure 2 is calculated based on grey value distribution with time dependent grey value changes of a single pixel. Furthermore the time-varied intensity of pixel can be related to the spatial gradient by the correlation function already presented in [7]:

$$C(\tau,x,y) = \sum_{n=1}^{N_n}\frac{[g(n+\tau,x,y)-g(n,x,y)]^2}{N_n}, \quad (3)$$

where $g(n+\tau,x,y)$ is the grey value of the pixel whose location is determined by the coordinates x and y in the n^{th} frame of the recorded video file. τ is the time shift in form of frames and N_n is the maximal number of frames in the video.

This correlation function is based on the semivariogram, which is a geostatistical tool for studying the relationship between collected data in function of distance and direction [6]. The result of the function at each time shift shows the accumulation of intensity difference of frame couples having this time shift. However, in the work of stress detection, it focuses on the difference between the first frame and other frames depending on the time shift rather than the details of frame couples mentioned above. Therefore, a slight modification was made on equation (3), where n becomes a fixed value of 1, so the summation is dropped out, and the exponent was set to 1 to track the direction changes of stress. The new correlation function is given by [7]:

$$C(\tau,x,y) = \frac{1}{N_n}[g(1+\tau,x,y)-g(1,x,y)]. \quad (4)$$

Based on this function, a three dimensional matrix showing the changes between each time shift and the initial time for each single pixel is created. Then the dynamic speckle change value (DSCV) is calculated as the spatial average of intensity changes at a specific time step via equation (5) [7].

$$DSCV(\tau) = \frac{1}{x_{max}y_{max}}\sum_{x=1}^{x_{max}}\sum_{y=1}^{y_{max}} C(\tau,x,y) \quad (5)$$

3. Calibration method of LSP signals for stress determination

To determine mechanical stress of ceramic substrates of DCB directly from LSP signals, a calibration method was developed which describes the correlation between both variables [7]. The process of the time-resolved speckle position and brightness changes is caused by changes of the local strain field of the surface during the deformation or heating of the material. The behavior between mechanical stress and strain can be described in the elastic range and for small stretches with the Hooke's law. Therefore, in our research the strain $\varepsilon(t)$ at the measurement position and at the time t can be given by:

$$\varepsilon(t) = \frac{\sigma(t)}{E} + \alpha(T(t) - T_0). \tag{6}$$

In the equation, $\sigma(t)$ is the mechanical stress, and E is Young's modulus. In the second term, it shows the relative length change of the sample caused by thermal expansion over the temperature range $\Delta T = T(t) - T_0$ multiplied by the coefficient of thermal expansion α. Because of a constant specimen temperature in the experiment, the term regarding thermal expansion is dropped out. Due to the LSP signal is dependent on the surface strain of the sample, therefore, the strain in equation (6) is replaced by the speckle signal $S_{LSP}(t)$, and also the calibration parameters a and b are introduced:

$$S_{LSP}(t) = a \cdot \frac{\sigma(t)}{E} + b. \tag{7}$$

For stress calculation, equation (7) is converted into a suitable form:

$$\sigma(t) = P_1 \cdot S_{LSP}(t) + P_2, \tag{8}$$

where the new parameters P_1 and P_2 need to be determined by the experimental calibration test. Since the unloaded condition of sample is defined to be stressless, the parameter P_2 is set to zero. The calibration parameter is estimated by linear fitting of the mechanical stress σ computed by the finite element method (FEM) simulation from the calibration measurement which will be introduced in the next section and the LSP signal$S_{LSP}(t)$. The fitting is obeyed the least-squares fitting method. If calibration parameter P_1 is determined, the real stress condition of sample $\sigma(t)$ can be calculated directly from the detected LSP signal by the calibration function (8) [7].

4. Experiment

The experimental setup consists of the optical setup and the mechanical configuration, shown in Figure 3. The ceramic samples were fixed in a 3-point-bending clamp mounted on the dynamic mechanical analyzer (DMA) Q800 from TA Instruments, which was used to apply precisely defined loading on ceramic samples to introduce corresponding strain. The experimental setup was already described in [7]. The distance between the outer clamps is 41.2 mm. Note that the clamping jaws have not been fastened deliberately. This way, the specimen was not clamped at the ends and could move freely. Equilibrated at room temperature of 25 $°C$ and preloaded by a force of 0.01 N the specimens were systematically loaded in steps of 0.04 N to a specimen dependent force, shown in Table 1. Meanwhile, the speckle pattern was generated on the sample surface by a single mode laser diode of type DD650-16-3 (14x45) with a wavelength of 650 nm from

PICOTRONIC GmbH. The diameter of total illumination area on sample surface was approximately 12 *mm*. The dynamic speckle signal changing with different loading force steps was recorded by a digital camera UI-3360CP-M-GL (IDS) with a COMS chip. The full resolution of the chip was 2048x1088 pixels. A macro length LINOS 8x whose working distance was 70 *mm* away from the sample surface, was mounted on the camera. The dynamic speckle signal of whole experiment procedure was recorded in a video file with the framerate 6 *fps*.

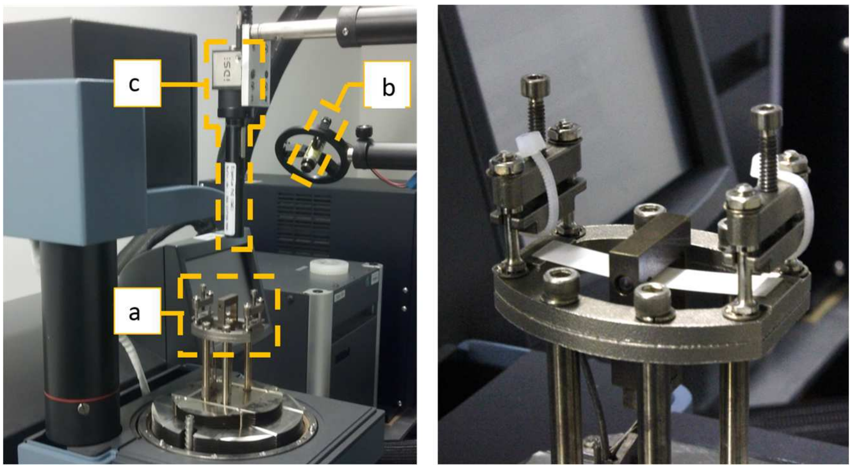

Figure 3. Calibration experimental setup combined a mechanical part with the LSP system, (a) 3-point-bending clamp, (b) laser diode, (c) digital camera from [7]

To correlate the dynamic speckle signal and real stress of sample at the measuring position, the images corresponding to different stress states of the samples were sorted out based on intensity from the recorded videos. These images were regarded as the input of the subsequent analysis procedures. The parameters *standard deviation*, *contrast* were calculated for each sorted image according to equation (1) and (2) respectively in C++. The difference correlation function is calculated by means of the software MATLAB®. Intensity changes of each pixel were stored at an identical position in a three dimensional matrix compared with the original images equation (4). This matrix is defined by dimensions of input images and number of frame intervals. The $DSCV$ is than calculated using equation (5).

Table 1. Specimen dimensions and maximum applied force

Specimen	Material	Length [mm]	Width [mm]	Thickness [mm]	Force [N]
1	Al_2O_3	50.0	10.0	0.62	18.00
2	Al_2O_3 with C-vapor deposition layer	50.0	10.0	0.62	18.00
3	LTCC	50.0	10.0	0.67	5.00

In [7], the results and the method validation of three different Al2O3 specimens with different width but same thickness was presented in detail. To map the stress conditions on real DCB substrates, the calibration measurements were carried out on the Al_2O_3 samples whose thickness were the same as provided DCB substrates. One of them was normal Al_2O_3 sample, and the other was Al_2O_3 with carbon-vapor deposition layer on the surface. The details of the samples are shown in Table 1 including dimensions and maximum applied static force of DMA machine. Furthermore, the calibration experiment was repeated on a so-called low temperature co-fired ceramic (LTCC) to check the suitability of the method in stress detection for different kinds of ceramic substrates. The information of LTCC sample is also shown in Table 1. The calibration experiment was repeated two times on each specimen in direct succession.

5. Results

The experimental values measured by LSP technique of sample 1 and 2 plotted against the mechanical forces given from the DMA are shown by *standard deviation*, *contrast* and *DSCV* in Figure 4. From the diagram it can be observed that all the speckle parameters have a linear relationship with the mechanical force, which is proportional to the stress, applied by DMA. That means with the compressive stress on the sample surface the LSP-parameter decrease. Since the LSP measurements were initially performed during the bending tests in the elastic region by load and unload forces, and constant temperature as well. The speckle parameters change the direction while the loading turns into unloading. That means the elongation process according to upward and downward force is reflected in the parameter change. Comparing to the results of thinner Al_2O_3 samples shown in [7], the absolute values of the speckle parameters in Figure 4 (a) are decreasing. The possible reason is different intensity distributions of speckle pattern on sample surface. With the increasing thickness of the sample, the detector records more scattering and reflecting signal from the inner part of the sample resulting in brighter and more homogeneous recorded speckle images. The speckle pattern generated on thicker sample is not as sharp as that on thinner sample in terms of Al_2O_3. Therefore, the absolute value of resulting speckle pattern is decreasing.
The resulting diagram of the sample with C-vapor deposition layer is shown in Figure 4 (b), the dynamic range of the speckle parameters are almost the same as that shown in Figure 4 (a). Due to the very thin carbon layer, reflectors are introduced into the sample surface, therefore, the surface condition of sample is modulated. On the layered samples the sharpness of the speckle pattern is increased, which leads to the parameter *standard deviation* and *contrast* becoming more sensitive to the mechanical force. In other words, the coating of sample surface can improve the detectability of stress on Al_2O_3 samples based on the technique of LSP in some extent.

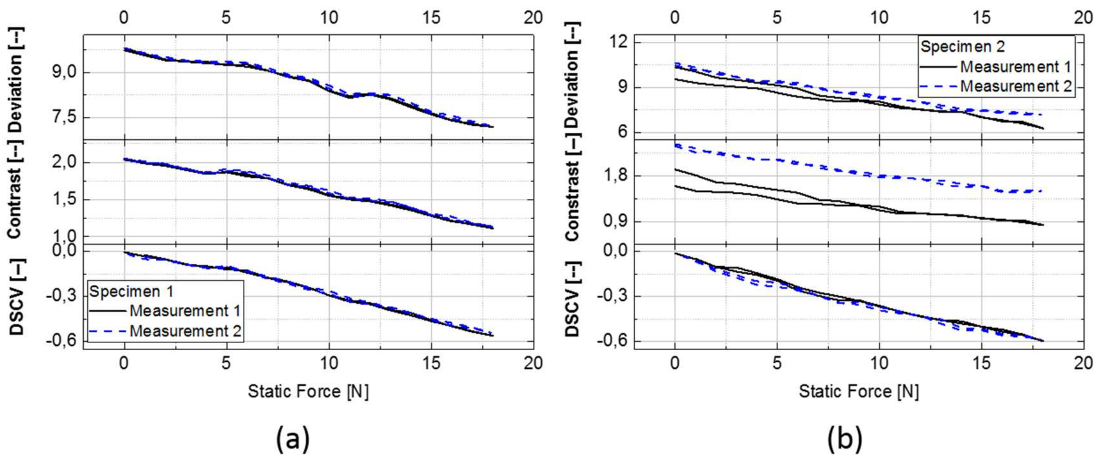

Figure 4. Dependency of the LSP signals from the applied force on the specimen. (a) Al_2O_3, (b) Al_2O_3 with C-vapor deposition layer

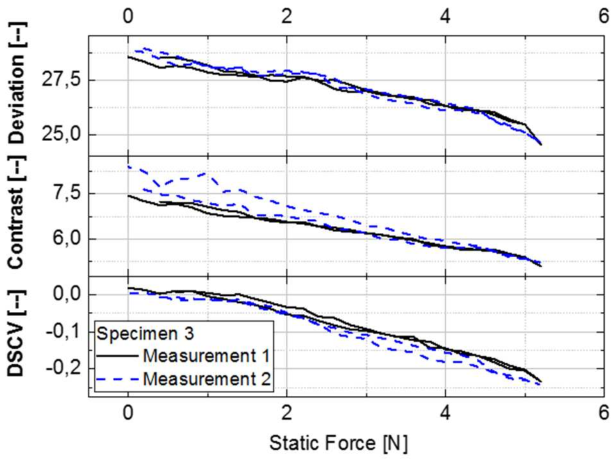

Figure 5. Dependency of the LSP signals from the applied force on the LTCC sample

Figure 5 shows the resulting curve between speckle parameters and static force applied by DMA machine of the sample LTCC. The diagram shows, that the linear tendency of the change during the linear loading of the sample is obvious. Therefore, the LSP method can also be used to detect stress condition on LTCC. Meanwhile, the speckle parameters, especially *standard deviation* and *contrast*, measured on LTCC is more sensitive to mechanical force compared to those measured on Al_2O_3 samples with the same dimension, due to the surface condition, e.g. roughness of LTCC. The LTCC sample shows that it has a better reflective property than normal Al_2O_3 samples in terms of the laser diode used in the experiment.

Currently, by repeating tests and evaluations, the technical spatial resolution of the method is 100 pixel, approximately 70 µm, limited by pixel dimension of camera chip and the algorithms of speckle evaluation. That means, the stress can be detected if the object surface is large than 70*70 µm^2.

6. Conclusions

This paper presents an optical based measurement method to determine mechanical stresses inside of DCB ceramic substrates especially Al_2O_3 and LTCC. The paper shows the possibility for the measurement of the stress condition on the surface the ceramic sheet by use of the speckle specific values evaluated by the equation for *standard deviation*, *contrast* and *DSCV*. For this approach the calibration was done under very controlled mechanical condition using 3-point bending loads. General conclusion were made:

- The application of LSP measurements was successfully established to quantify mechanical stresses on Al_2O_3 and LTCC ceramics.
- The proposed measurement setup is well suited for nondestructive contact-less characterization of stresses in ceramics.
- The calibration concept was developed and successfully tested in the bending test on three different samples.
- The results obtained by the LSP method generally dependent on the reflection and scattering properties of the tested material.
- In the sample inner generated speckle induce perturbing noise in the LSP signal.

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