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# Crack Detection of Ceramics based on Laser Speckle Photometry

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**Abstract**

**Ceramic components subjected to increasingly extreme conditions are being pushed to their performance limits. That is, the critical crack length for alumina is less than 80 µm. Therefore, to guarantee and estimate the quality of ceramics, new advanced nondestructive diagnostics methods with high resolution are required.**

**Laser Speckle Photometry is an innovative optical non-destructive and monitoring technique based on the detection and analysis of thermally or mechanically activated characteristic speckle dynamics in the non-stationary optical field. When an object is excited by an external thermal source, the thermal energy propagation causes a local temperature difference, which generates local thermal expansion. The local thermal expansion excites speckle movement, which can be detected by a fast digital camera. The objective of the paper is to examine the suitability of the LSP technique for the detection of micro-cracks located on the surface of ceramics. Results of measurements with different experimental parameters are presented by means of the imaging LSP method. It shows that LSP is a suitable approach for detecting cracks in ceramics. The results of successful evaluations show that the detectable resolution of the LSP technique at the current research stage is approximately 500 µm in terms of the length of cracks.**

*Keywords: Ceramics, speckles, micro-crack detection, non-destructive optical testing*

## I. Introduction

Cracks are typical defects widely found in materials, which threaten all aspects of a material's life. As a brittle material, ceramic alumina exhibits special mechanical properties in terms of crack propagation. According to linear elastic fracture mechanics, the critical crack length of alumina can be easily estimated from the engineering datasheet [1]. The value of the critical length of alumina is approximately 80 µm under the condition that a double-ended crack is located in an infinite solid [2].

To detect such a small crack and guarantee the quality of materials, non-destructive testing (NDT) techniques are common approaches. In the ceramic industries, different NDT methods including ultrasound, X-ray, and visual inspection can be used for crack detection. Generally speaking, the methods mentioned above are useful for detecting cracks in various materials. However, the disadvantages are obvious. Specifically, the results of visual inspection depend on the competence of the inspectors, which to a certain extent leads to subjective assessment. For ultrasound and X-ray based methods, the high financial cost and time requirement are two crucial aspects and must be optimized in the industrial field. The biggest disadvantage of these methods is the difficulty associated with their integration into a production process to complete in-line inspection. In this case, new advanced nondestructive diagnostic methods are required to satisfy the requirements of the manufacturing process.

The rapid development of hardware and mathematical tools for registration and processing of non-stationary optical fields makes possible the development of new methods for optical measurements. Laser Speckle Photometry (LSP) is an innovative non-contact, optical technique based on the detection and analysis of thermally or mechanically activated characteristic speckle dynamics. It can be used for characterization of a material's defects [3]. Much work has been done with LSP for metallic materials including the characterization of the material properties, damage, hardness, porosity evaluation, etc. [3–5]. Current research focuses on the characterization of ceramics whose thermal and mechanical properties are totally different from those of metallic materials. LSP has been successfully applied for crack detection in ceramic sanitaryware, as shown in Fig. 1. The vertical dark line in Fig. 1b presents information about position and dimension of the existing crack shown in Fig. 1a. In this paper, research on examining the suitability of the LSP technique for the detection of micro-cracks located on the surface of technical ceramics is presented.

## II. Laser Speckle Photometry

A speckle pattern is generated when an optical rough surface is illuminated by a coherent light source [6]. The scattered waves from various points of the illuminated surface interfere on the rough surface in the observation plane, producing the speckle pattern – a spatial structure with randomly distributed intensity minima and maxima. The different luminosities can be detected with a CCD and CMOS chip respectively. The theory of speckle or dynam-

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ic speckle belongs to the category of statistical optics, and a detailed account of the phenomena is given by Goodman [7], including the mathematical description of speckle properties, such as the central limit theorem of probability theory, and random processes. A speckle pattern acts as the fingerprint of the 3D information of sample surface [8]. If the examined object is thermally excited, by a laser for example, the material characterization can be described based on both static and dynamic speckle patterns.

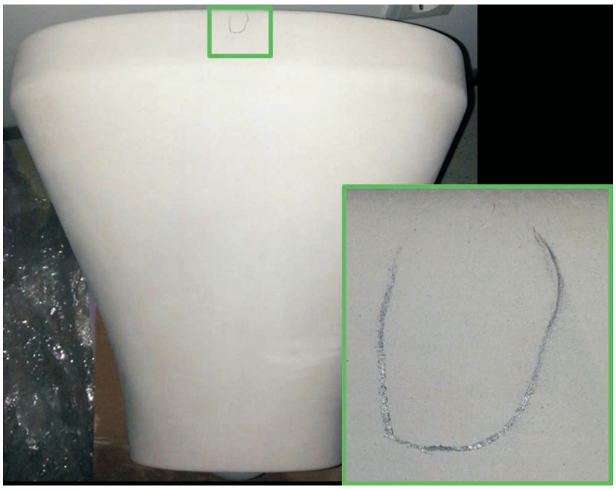

**Fig. 1a:** Optical image of a barely visible crack in the sanitary ceramic.

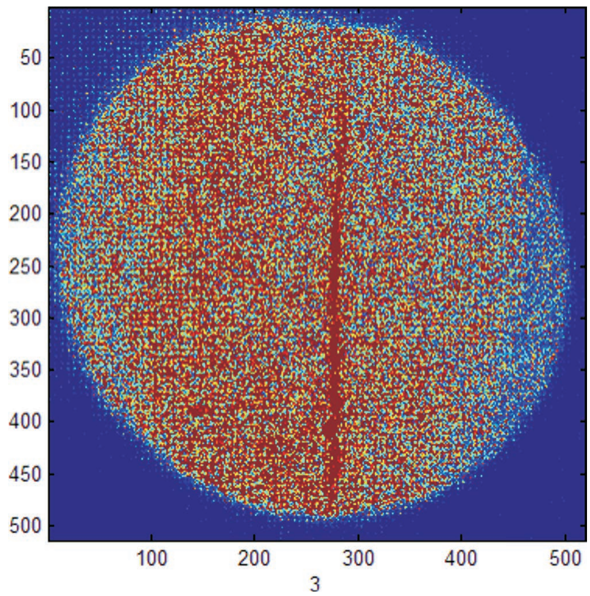



**Fig. 1b:** Resulting speckle image.

Fig. 2 shows the basic experimental setup for LSP measurements. It contains a laser diode as illumination source, and a combination of a fast CMOS camera and an objective as the detector for the speckle movement. In addition, a thermal excitation source intermittently used to change the local temperature of the sample generates the time-dependent speckle movement. Laser excitation, thermal contact and process heat can be treated as good candidate sources for the research. The excitations in all modes are feasibly continuous and pulsed. The thermal energy absorbed by the sample results in the behavior of thermal expansion caused by local temperature differences. And the movements of the speckle pattern caused by the time-dependent thermal expansion are recorded by a fast CMOS camera with the developed software.

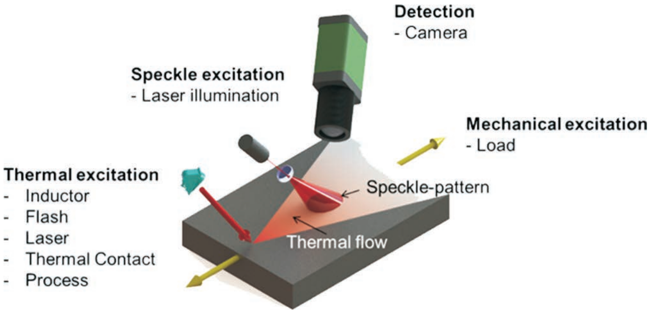



**Fig. 2:** Schematic structure of laser speckle photometry. An illumination laser irradiated technically a rough surface thereby creating an interference pattern – the speckle pattern. The change in the speckle pattern is caused by the thermal or mechanical excitation of the object. The temporal and spatial changes of speckle patterns allow for proper evaluation and conclusions concerning material parameters.

When thermal waves propagate on the sample surface, a spatial temperature gradient is formed. If surface defects exist, the local magnitude of the heat flux will be amplified [9]. This local change of heat distribution results in the thermal energy accumulating around the defect. And the thermal accumulation distorts the normal spatial gradient and leads to a higher level of speckle movement at the edge of defects compared with the surroundings. As a result, a contrast of speckle movement between defective area and background is obtained. On the basis of a special algorithm, speckle movements can be evaluated and analyzed to extract the contrast, which provides possibility for defect detection with the LSP technique.

Laser speckle photometry works without a reference beam, unlike other speckle-based processes. This allows a simple and robust construction, which can be easily integrated into a process control system. Measurement and calculation of the obtained data are performed in real time.

## III. Experiments

The experimental setup is shown in Fig. 3a. The laser diode with the wavelength of 635 nm, power of less than 1 mW, was used to generate the speckle pattern on the sample surface. The speckle movements were recorded by the monochromatic camera as video files. The optical paths are revealed in Fig. 3b, and the angle between the laser source and camera was approximately 30°.

There were two different samples in the measurements, one was $Al_2O_3$ plate and the other was Na-β-alumina plate. The diameter of the plates was 33 mm as shown in Fig. 3a, the thickness of the $Al_2O_3$ plate was 0.24 mm and that of the Na-β-alumina plate 1.5 mm. Cracks were introduced into samples by means of a Vickers hardness indenter. The applied force of the indenter was 10 N, and the indentation lasted 10 s. Fig. 4a and Fig. 4b show the introduced cracks ranging from 200 μm to 1500 μm in the samples. In Fig. 4c, an air pore whose diameter was approximately 200 μm exists on the surface of the Na-β-alumina plate, which was also an important defect detected by LSP in our research.

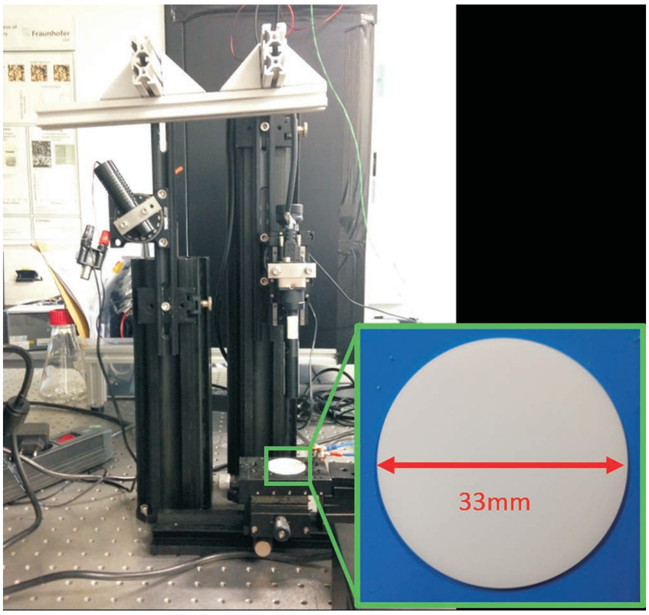


**Fig. 3a:** Experimental LSP setup for crack detection.

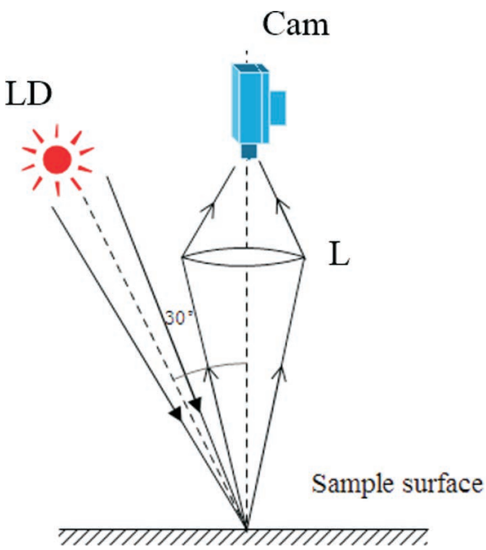


**Fig. 3b:** Schematic of optical paths in the setup.

Two thermal excitation methods were chosen to generate the speckle dynamics, one was thermal contact and the other was laser excitation. For the thermal contact method, a power supplier was used to generate the output electrical pulse signal and then the electrical energy was converted to thermal energy by means of a resistance wire. For the laser excitation, an extra solid-state laser source was applied to excite the sample with one single laser pulse. The excitation time was approximately 0.5 s, and recording of the camera was started synchronously with the excitation process.

## IV. Digital Algorithm

The digital algorithm for the evaluation of recorded speckle-video is based on a time-resolved image analysis shown in Fig. 5. In this algorithm, the intensity of each pixel, the most important parameter, is processed in the time domain. During the movement of speckle patterns, the time-varied intensity can be related to the spatial gradient with a special correlation function. It says that the value of the correlation function is proportional to the local temperature in terms of a certain region of interest, which is given by the work of Kazak [10]. In our research, an alternative correlation function was used. It is given by:

$$C(\tau) = \sum_{n=1}^{n_{max}} \langle S(n+\tau,x,y) - S(n,x,y)\rangle^2 \qquad (1)$$

where max n is the frame numbers of the video which can provide the time dependence, $\tau$ is the time shift or the number of frame intervals, S(n, x, y) is the intensity of pixel whose location is determined by the coordinates x and y in the n-th frame. This correlation function comes from the so-called semivariogram, which is a geostatistical tool for studying the relationship between collected data as a function of distance and direction [11]. The result of this correlation function at each time shift shows the accumulation of the intensity difference of frame couples having this time shift. However, in the work of crack detection, it does focus 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 to Eq. (1), where n becomes a fixed value, n=1. The new correlation function is given by:

$$C(\tau) = \sum_{n=1}^{n_{max}} \langle S(1+\tau,x,y) - S(1,x,y)\rangle^2 \qquad (2)$$

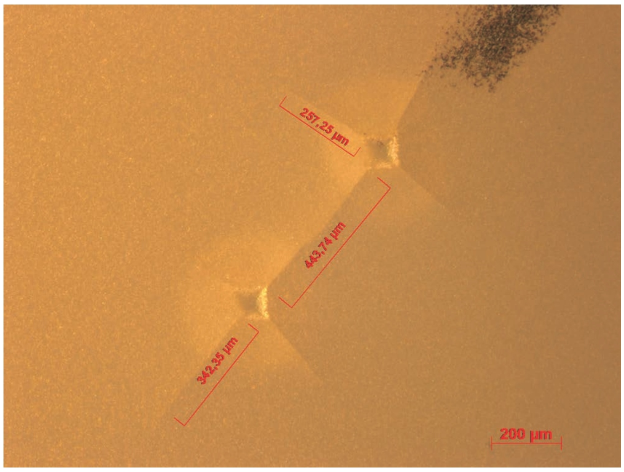


**Fig. 4a:** Introduced cracks in the sample.

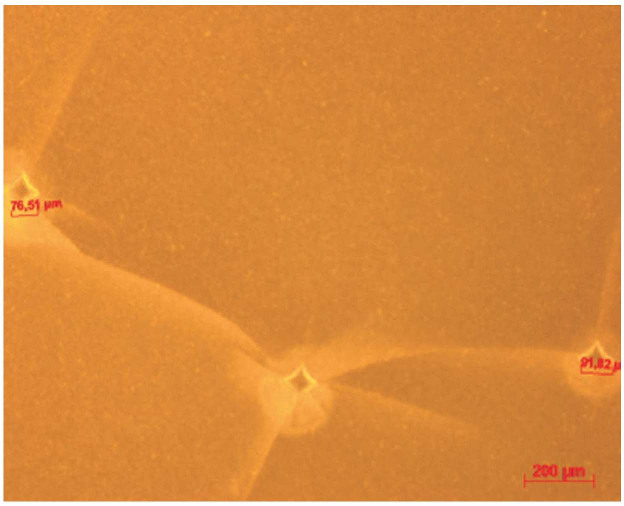


**Fig. 4b:** Introduced cracks in the sample.

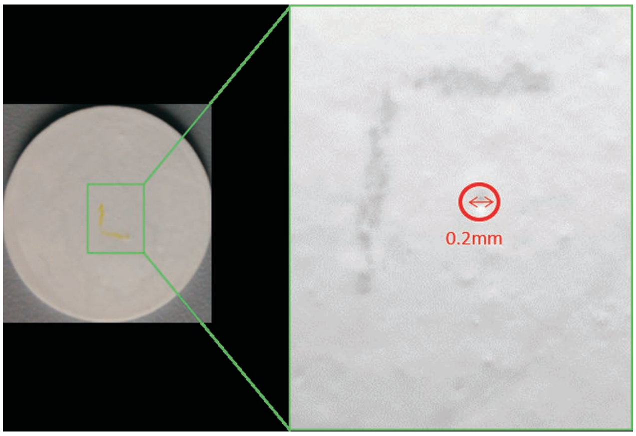


**Fig. 4c:** An existing air pore in the Na-β-alumina plate.

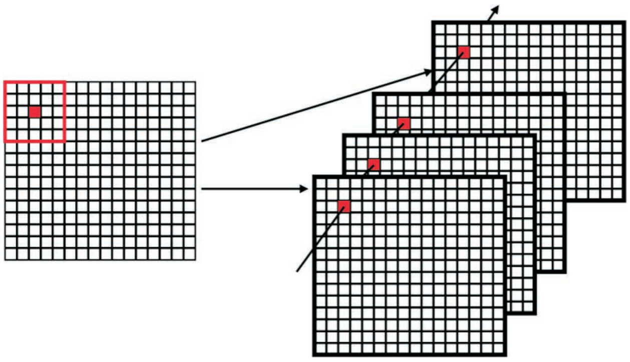

**Fig. 5:** Schematic of the time-resolved image analysis.

It has been proven that the highest shift in the speckle-images leads to the maxima of the correlation function [12]. The relationship between the correlation function and the change of local temperature is shown in Fig. 6. The numerical value of the calculated correlation function was divided by 25 to be observed at the same magnitude of the curve of local temperature. From the diagram, it can be concluded that before saturation point the correlation function exhibits similar behavior to that of the local temperature, which is entirely consistent with the conclusion of Kazak as mentioned above. As known in the digital imaging processing, every image can be demonstrated by a two-dimensional matrix. Therefore, in the data evaluation procedure, a new three-dimensional matrix showing the changes between each frame and the first frame for each single pixel was created after the calculation based on the correlation function. In terms of this change of each single pixel in the time domain, an M-point Fast Fourier Transformation (FFT) was applied to convert it into frequency domain, and M was a constant determined by the number of frames that were used to calculate FFT. This number was given by the interval between the start and saturation point of the correlation function. For example, in Fig. 6, the similar behavior between the correlation function and local temperature was constrained within the first 15 frames. In order to ensure a strict connection between the speckle signal and thermal behavior of sample, the constant M could be valued by 15 in this case. Information on this intensity change of each single pixel was re-distributed depending on the energy of different frequencies in the frequency domain. M two-dimensional matrices can be achieved and the value of each element in the same matrix presented the energy of each pixel at an exact frequency. Results of the measurement were shown in scaled images in accordance with amplitude information of the first matrix, which means the DC component of FFT.

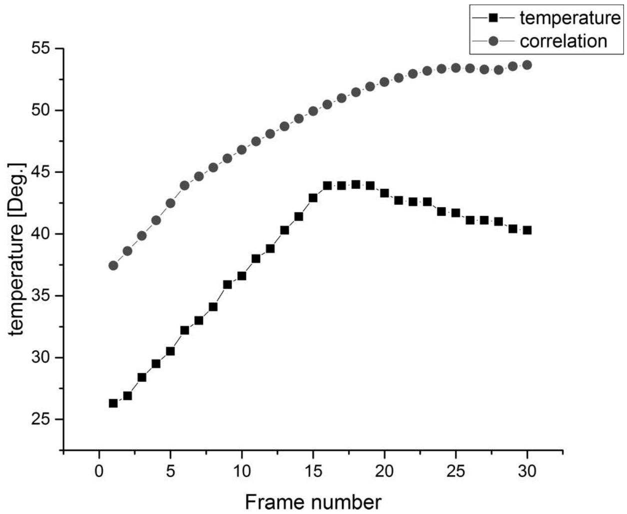


**Fig. 6:** Relationship between the correlation function and local temperature.

## V. Results and Discussion

Fig. 7a shows the result of pore detection for the sample Na-β-alumina plate. The left part of Fig. 7a is an optical image showing the relative position between a 0.2-mm air pore and a 0.4 -mm resistance wire which acts as the thermal source. The result of the speckle image is shown in the right part of Fig. 7a. Specifically, the colors represent different amplitudes of pixel after FFT calculation. The red part indicates the existence of the defect possessing a greater amplitude than the blue part. Besides, one of the results for crack detection of aluminum oxide is presented in Fig. 7b. The existing crack in the optical image is indicated by a dark red trace consisting of concentrated red dots in the resulting image. However, there is a large number of red dots scattered around the indication. Such noise blurs the image, and the indication is more difficult to extract from the background owing to the decreasing signal to noise ratio. This especially influences the quality of results for crack detection on micro scale.

To enhance the signal to noise ratio of the resulting images, a 3 by 3 harmonic mean filter was used as a post image processing tool. Fig. 8a and Fig. 8b show the results before and after filtering respectively, and the referential optical image is shown in Fig. 8c. After being processed by the spatial filter, the image is smoother than the one without filtering, which makes the indication easier to recognize among the background. Different thermal excitation energies were applied to the same sample shown in Fig. 8c to investigate influences caused by the thermal source. Figs. 9a, b, and c show the results of the identical sample excited by multiple energies. The output voltages of the power supplier were 3, 6, and 9 V respectively. Within the same region of interest, embedded in the white frames as shown in the images, the indication is more and more recognizable with increasing thermal excitation energy.

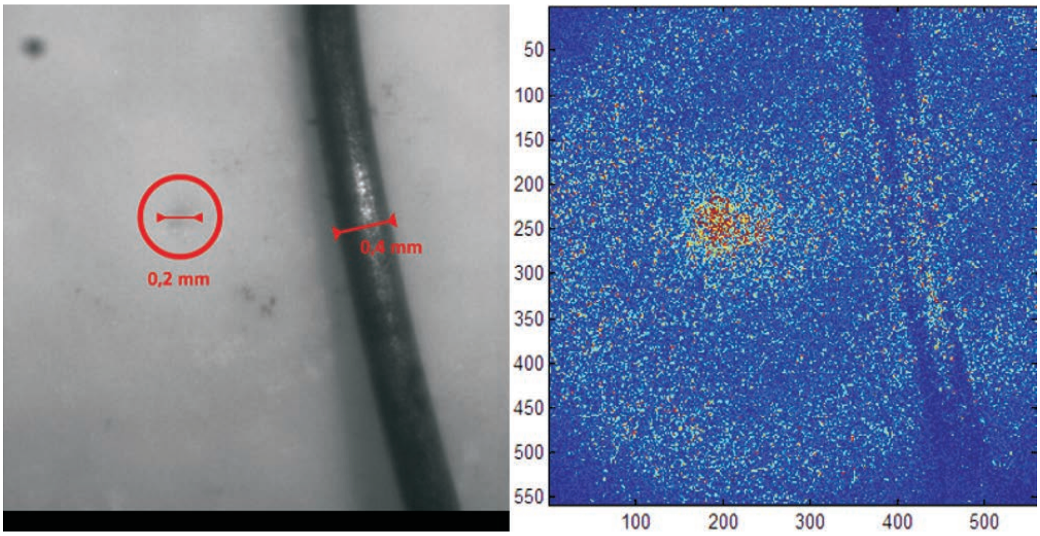


**Fig. 7a:** Result of pore detection, left: optical image, right: result of speckle image.

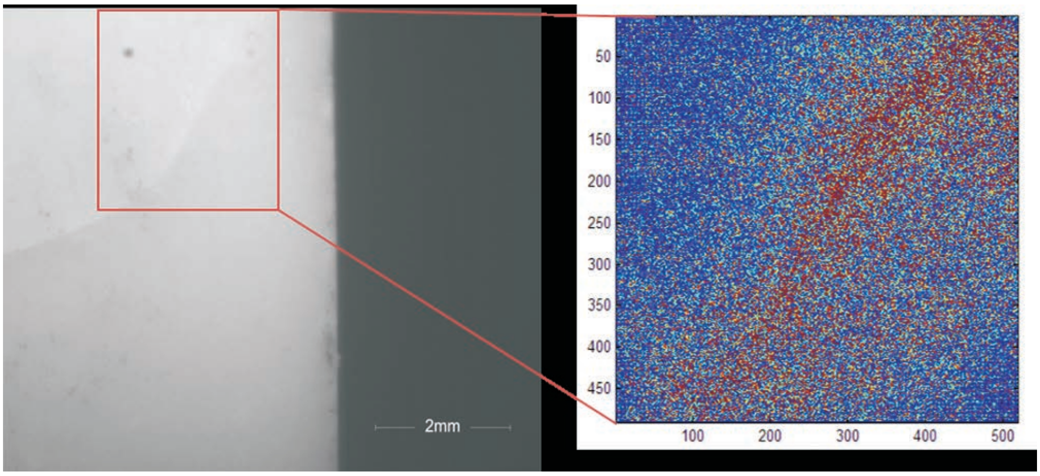


**Fig. 7b:** Result of crack detection, left: optical image, right: result of speckle image.

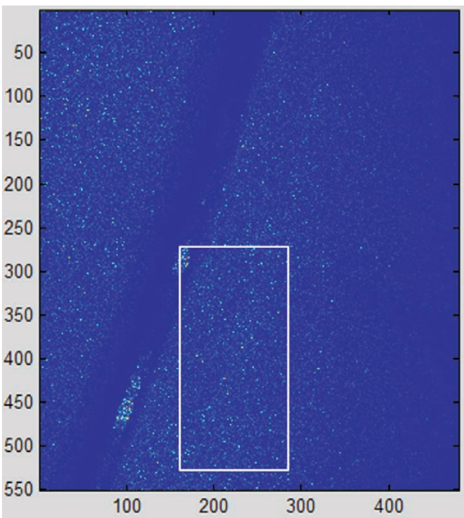


**Fig. 8a:** Result without filtering.

Indications in the resulting images qualitatively reveal the existence of defects on sample surfaces. It can be regarded as an incipient criterion to determine whether products are acceptable during the ceramic manufacturing process. By means of inline LSP inspection, defects could be detected at an early stage (up to sintering) of the production process. As a result, resources e.g. materials and energies could be saved, and the productivity of ceramic products benefiting from the technique of LSP improved.

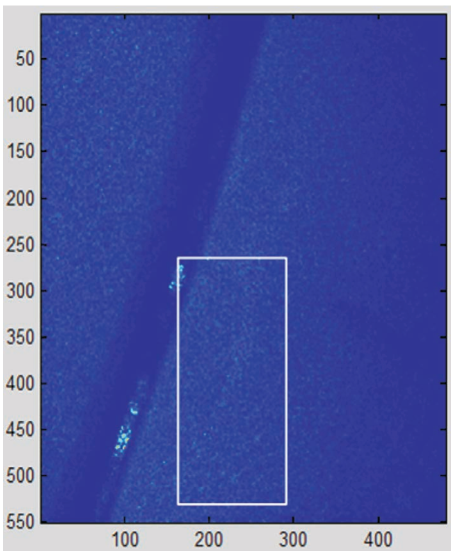


**Fig. 8b:** Result with filtering.

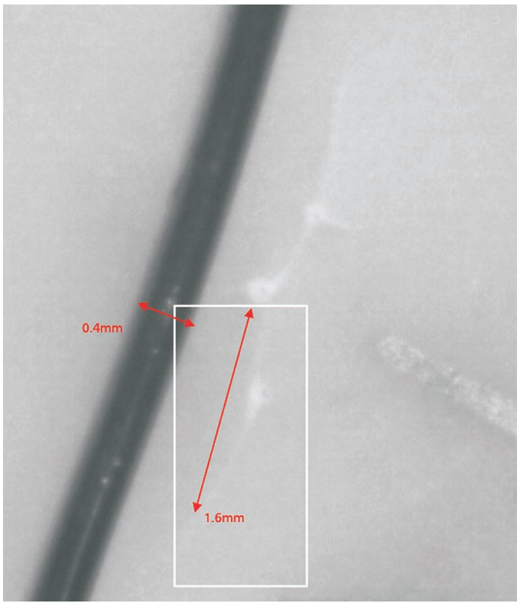


Fig. 8c: Referential optical image.

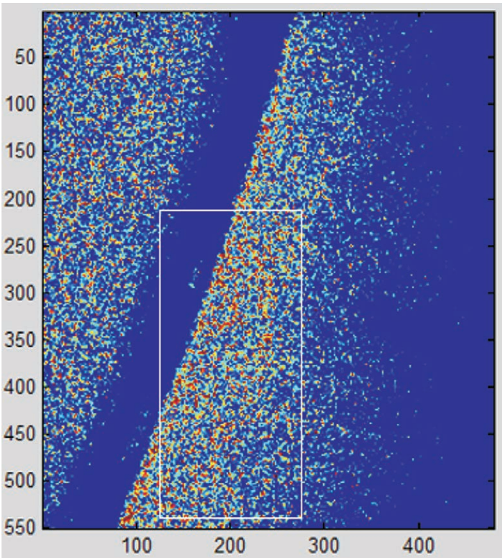


Fig. 9a: Result of sample excited with a 3V output voltage.

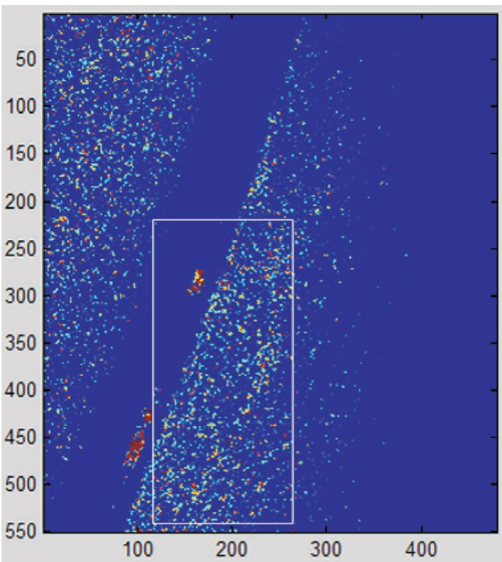


Fig. 9b: Result of sample excited with a 6V output voltage.

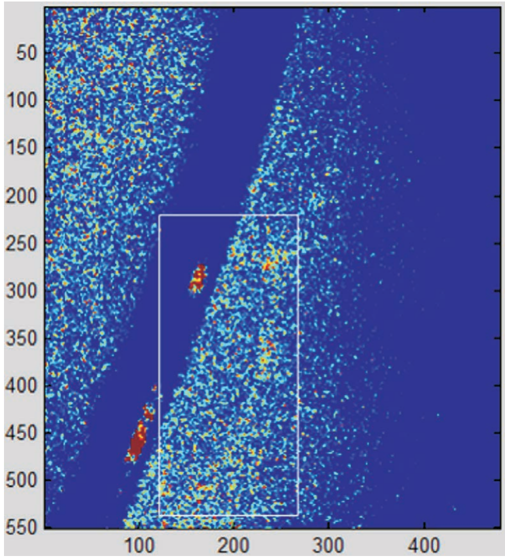


Fig. 9c: Result of sample excited with a 9V output voltage.

The summarized crack detectability of LSP in ceramics is approximately 500 µm after repeating the measurements with a variety of cracked samples in the present research. In reality, the ideal detectability of LSP is mainly determined by the sensor size of the digital camera, since the sensor size is far greater than the wavelength of laser source. Nevertheless, a great deal of noise was produced during the measurements, influencing detection, for instance, vibration and slight displacement of samples owing to the impact of thermal excitation, and inhomogeneous heat propagation on sample surface caused by the thermal source. Noise generated by the measuring system cannot be ignored, such as noise introduced by the camera itself, vibration of experimental setup caused by ambient influence, and some tiny contamination on sample surface and objective. These technological limitations affect the detectability and should be optimized in future research.

## VI. Conclusions

As an innovative, non-invasive optical NDT technique, LSP is suitable for the detection of microcracks in ceramics. At the current research stage, detectability is approximately 500 µm in length. According to the results shown in Fig. 9, an assumption could be proposed that crack size and optimal thermal excitation energy can be related. No matter how big the crack is, an optimal corresponding excitation energy can be found to obtain the best indication. Moreover, LSP has a simple but robust design, reducing cost compared with other conventional NDT methods, and depending on its working principle, it can be integrated into an inline manufacturing process, e.g. additive processes, coating and biotechnological processes, to complete the inspection tasks in real time. The modular design of the test method can be adapted to a variety of problems. And, this new method has already proven itself in the laboratory and is now being transferred to industrial application. Last but not least, there is huge potential for the LSP technique to be applied in the whole field of ceramic production.

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