Laser Speckle Photometry (LSP) - Optical Sensor System for Monitoring of Material Condition and Processing

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Abstract. The Fraunhofer IKTS at Dresden-Klotzsche develops innovative methods and testing systems for characterization of material properties and system components, product quality control and monitoring of manufacturing processes. The IKTS owns the extensive know-how of laser-based measurement and testing methods, such as Raman, Fluorescence, Interferometry, Ellipsometry and the Laser Speckle Photometry (LSP). LSP was developed by the Fraunhofer-Gesellschaft completely and has been successfully tested in laboratory. Currently this optical method will be transferred to industrial applications.

The Laser Speckle Photometry is a noncontact nondestructive testing method which bases on detection and analysis of thermal, mechanical or manufacturing process activated characteristic speckle dynamics. The determination of the material conditions state bases on understanding of structural changes on different scaling levels during the excitation of the frequency analysis of time resolved speckle fluctuation. The LSP determined rapid relevant material quality characteristics and detect defects. It allowing a complete online monitoring of production processes. In this work, we perform the LSP to obtain the speckle time response of ceramic material for microcrack detection. Even, it will be present the first results of the development of a sensing system for determination of gold content of contacts manufactured by overlaying welding with the lateral dimensions <100 microns.

Introduction

New non-destructive testing methods and appropriate sensors have been developed in the industry. Both of them are used to detect errors such as porosities or delaminations, as well as for the delamination parameters, material properties or the description of their changes in the manufacturing process. Suitable measuring methods allow the fabrication to adapt the process parameters and avoid waste. During repair work, they provide a valuable aid to the user. In addition, the new sensors should be integrated for the control of inline process in the manufacturing plants.

The characteristics of presented sensors for process monitoring are:
- Using a robust and cost-effective design, which satisfies the requirements of industry.
- The measurement and calculation are performed in-situ and in real time without sampling and analysis.
- The presented measuring system has a modular design of the sensor, electronics and software.
- It is possible to make integration into existing industrial process control easily.
- The measuring system is very accurate and can be calibrated easily. The data output
allows the re-use of the calculation variables such as controlled variables and the creation of a trend.

- Universal measurement method can be adapted and used for monitoring a variety of similar processes.

The foundation of described sensor is the method of Laser-Speckle-Photometry (LSP). It is definitely a quick quality-relevant material characterization and defect detection method, allowing a complete on-line monitoring of the production process. The sensor system is developed comprises the optical and electronic components, algorithms, the hardware and software (Figure 1). The monitoring process is synchronized with machine’s internal control, including the adaption of measuring and evaluating speed to a high manufacturing speed. The extremely short measuring times predestine it for the use of inline in industrial production and for in-situ measurements during maintenance and repair tasks. The approaches to the use of the LSP method for non-destructive process monitoring will be shown in greater details.

1. Laser-Speckle-Photometry

A speckle pattern is generated when an optical rough surface illuminated by a coherent light source [1]. The scattered waves from various points of the illuminated surface interfere on the rough surface. In the observation plane, where they produce the speckle pattern - a spatial structure with randomly distributed intensity minima and maxima. The information of intensity can be detected by a CCD or CMOS chip. A speckle pattern acts as the fingerprint of the 3D information of sample surface [2]. If the examined object is thermally excited, for example excited by a laser, the material characterization can be described by both static and dynamic speckle patterns. Due to the speckle methods and their evaluation for measurements have a wide application, it can be applied to a wide variety of materials.

The time-resolved laser speckle photometry (LSP) as a new optical method, which is mainly based on the evaluation of the temporal change of speckle patterns, opens up the possibility to determine the porosity and surface defects without great effort [3].

![Fig. 1. Schematic structure of the laser speckle photometry. An illumination laser irradiated technically rough surface thereby creating an interference pattern - speckle pattern. The change of 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 conclusions on material parameters.](image-url)
2. Application: Monitoring of welding processes

Nowadays, in the electrical industry, conductive contacts are applied by electroplating, welding or plating. These cost and time-consuming procedures are characterized by a high consumption of material and energy. These processes are accumulating large amounts of environmentally harmful chemicals. Therefore, the development of an alternative additive process with necessary functionality is of high interest. When micro-laser cladding gold is applied in a paste by using a dispenser, it should be dried to remove the binder contents and then remelted with laser radiation for densification and bonding to the substrate. For both the stage of development of new contact-making process and in regard to the subsequent in-process quality control, it offers an inline-capable, laser based and contactless testing method. The time-resolved LSP has been developed and adapted for this application. Figure 2 shows the integrated LSP technique in an appropriate laboratory facility [4].

![Image of LSP technology in gold contact production.](image)

Fig. 2. Integrated LSP technology in the gold contact production; Speckle pattern determines the precious metal content and geometries of the contacts.

The mixing degree of contact with the substrate was determined by the parameter fractal dimension $D_F$ of dynamic speckles in the reflective region. The determination of the calibration curve for the calculation of the noble metal content was carried out with a chemical analysis by the means of EDX of the contact material. The geometric contact measurement was carried out simultaneously to the determination of gold content. The height of contact was determined by calculating the diameter of the inner enveloping circle of the shadow. The internal enveloping circle of the reflective region was used to determine the size of individual contact. The confocal microscopy can be used as a calibration method for the geometric determination of the contact size. Figure 3 shows the resulting curve of calibration, which results from a linear regression of the experimental values measured by LSP technique.

![Graphs showing calibration of gold content and height of contacts.](image)

Fig. 3. (Left) Calibration of gold content measured by EDX vs. that measured by LSP. (Right) Calibration of height of contacts measured by confocal microscopy vs. that measured by LSP.
To assess the accuracy of the results, the tolerance of the two measurements was calculated. The results are summarized in Table 1.

Table 1. Achieved measurement speed and accuracy

<table>
<thead>
<tr>
<th>Measuring speed</th>
<th>To 100 contacts per minute</th>
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<tr>
<td>Tolerance of determination of precious metal content</td>
<td>6.658%</td>
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<tr>
<td>Tolerance of the height measurement</td>
<td>4.026%</td>
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3. Application: Additive Manufacturing

Concrete material parameters such as the porosity can be obtained by LSP based on the evaluation of the temperature curve. This evaluation concept can be implemented for process control of the production of additive manufactured components. Moreover, the errors such as pores and microcracks occurring during the laser-melting process can be detected immediately after their formation by appropriate countermeasures. And these errors can be cleared by remelting of the affected area. As a result, the requirement of downstream, time and cost intensive material testing and rework can be significantly reduced. The sensor system is designed to help reduce the dropout rate of process conclusively so that reduces the energy, material and inert gas consumption significantly in the field of additive manufacturing in terms of metal components. A proposal to build the new LSP sensor is shown in Figure 4. This sensor is integrated directly in the manufactured machine. The communication between the two processes is realized depends on the development of the electronics and algorithms for a regulative approach.

Fig. 4. Schematic principle of the new LSP Sensors for optimizing and controlling additive manufacturing processes.

First investigations were carried out on test specimens (see Figure 5 left). Some of these specimens were prepared with reduced input energy (marked in green) and so primarily have near-surface defects, as well as samples with highly elevated input energy (B2, D3) and corresponding defects or inhomogeneities. In comparison, the reference (line 4) shows the measurements on the samples which were manufactured under optimum conditions. And the references hardly show the flaws. The defects and inhomogeneities in the samples which were produced with reduced and greatly increased input energy can be detected by using LSP technique.

At the same time based on the calculation of the thermal diffusivity of the optical speckle temperature, the so-called speckle diffusivity can be determined. In Figure 6, it can be seen that the calculated speckle diffusivity decreases with increasing porosity of the samples. The thermal diffusivity of the material depends primarily on its density, but also on...
the thermal conductivity. The lower the density and thermal conductivity, as in porous materials, the lower thermal diffusivity they have.

Fig. 5. (Left) The test body for determining errors in the specimens prepared by means of additive methods. Green marked: samples with reduced input energy; B2, D3: samples with highly elevated input energy; Reference parameters: the 4th row. (Right) Result of the LSP: identified flaws are marked with red paint.

Fig.6. (Left) decreasing speckle diffusivity (or thermal conductivity) with increasing porosity. (Right) Pictures to determine the porosity by optical analysis.

4. Application: Crack detection

There is a need for the developing of novel ceramic materials for industrial applications, e.g. aluminum oxide and Na-ß-alumina. These material are used to produce high-temperature, low-cost ceramic batteries. As a widely used engineering material, alumina productions play an important role in nowadays industrial field. Crack as a typical defect widely exists in materials, which threatens all aspects of the life. It was calculated that the critical crack length of alumina is approximately 100 microns. Therefore, to guarantee and estimate the quality state of these ceramics, new kinds of advanced nondestructive diagnostics methods are required. LSP technique being one of those methods is an innovative non-contact, optical technique based on the detection and analysis of thermal or mechanical activated characteristic speckle dynamics, which will be used for characterization of the ceramics’ defects. Figure 7 shows the setup of LSP measurements for crack detection. It contains a laser diode, and a combination of fast CMOS camera and an objective. The angle between laser source and camera is approximately 30°.
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 the means of a resistance wire. For the laser excitation, an extra solid state laser source was applied to excite the sample with different numbers of laser pulses. The speckle movements were recorded by the camera as a video file. Videos of speckle movement were evaluated by an algorithm which is a combination between FFT algorithm of lock-in thermography and difference correlation function. The special difference correlation function was used to make the connection between speckle intensity changes and thermal expansion of object surface caused by the thermal energy propagation. The final result was shown by an imaging method in the frequency domain with the first amplitude of FFT calculation. Figure 8 presents some result of Na-ß-alumina samples with different defects.

5. Summary

In this paper, laser speckle photometry was presented as a new testing method, and it was developed at Fraunhofer IKTS. It is characterized by a simple and very flexible construction
that can be adapted to a variety of problems. Compared with other optical speckle-based methods, LSP provides the ability to determine not only defects, geometric and material parameters such as the porosity and hardness, but also can be used to detect tension changes on the surface. As mentioned above, the process-specific parameters such as gold content of electrical contacts can be inline determined with the parameter "fractal dimension". Development needs becoming apparent in the accuracy of the method. Therefore, it is important to find suitable reference method to evaluate the comparable areas of the material. Currently, the measurement speed is already very high for some applications with 50 frames per second, including measurement and evaluation. Although the picture grabbing rate of high-speed and smart embedded cameras is increased, the results are not only depended on the measuring speed but also the accuracy of measurement. Therefore, for the perspective, the possibility should be found to increase the measuring accuracy.

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