

Laser speckle photometry – Optical sensor systems for condition and process monitoring

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Article Information

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Material testing and material properties characterization, which guarantee the quality of materials and promote progress in manufacturing, play a significant role in both academic and industrial fields. New non-destructive testing (NDT) methods and appropriate sensors developed in the industry are used for detecting defects such as porosities or delaminations as well as for the characterization of delamination parameters and material properties respectively for the description of their changes in manufacturing processes. Therefore, choosing a suitable measuring method is important for fabrication in terms of adapting process parameters and avoiding waste. In addition, the sensors should be integrated inline as a control in manufacturing plants. In this paper, Laser speckle photometry (LSP), both in theory

and practice, is presented, thus offering an innovative approach to optical NDT and monitoring.

Theoretical approach

Speckle or speckle patterns are interference patterns produced by a scattering coherent light beam. Scientists have investigated this phenomenon since the time of Newton, but it was only after the invention and development of the laser that speckles have finally come into prominence. Until now, numerous speckle related applications have been found. The dynamic speckle is a result of the temporal evolution of a speckle pattern which can be considered as the temporal expression of an interference speckle pattern [1]. It is generated by the incidence of a high-level coherent

Laser speckle photometry (LSP) is an innovative, non-destructive monitoring technique based on the detection and analysis of thermally or mechanically activated speckle dynamics in a non-stationary optical field. With the development of speckle theories, it has been found that speckle patterns carry information about surface characteristics. Therefore, LSP offers a great potential for the characterization of material properties and monitoring of manufacturing processes. In contrast to the speckle interferometry method, LSP is very simple and robust. The sample is illuminated by only one laser beam to generate a speckle pattern on the surface. The signals obtained are directly recorded by a CCD or CMOS camera. By appropriate optical solutions for the beam path, typically, resolutions of less than 10 μm are reached if larger areas are illuminated. LSP is definitely a contactless, quick and quality relevant material characterization and defect detection method, allowing process monitoring in many industrial fields. Examples from online biotechnological monitoring and laser based manufacturing demonstrate further potentials of the method for process monitoring and controlling.

laser beam upon an optically rough surface that results in a boiling grainy image [2]. The theory of speckle or dynamic speckle belongs to the category of statistical optics for which a detailed account of the phenomena is given by Goodman [3], including the mathematical description of speckle properties, for instance the central limit theorem of probability theory and random processes.

Techniques based on laser speckle effects, which can be contactless, non-invasive and remote, have become more and more popular in NDT. One of the earliest techniques was laser speckle photography. Here, speckle patterns are recorded on a photographic emulsion called a photographic negative before and after deformation of an object. By using this negative to re-photograph the fringe pattern through

illumination by a laser beam, quantity information of an object's deformation can be obtained by estimating the diffraction fringes. A laser speckle image encodes phase information and phase differences generated by variations in travel distance which are affected by tiny changes in the surface geometry. If the surface profile is altered by an amount as small as a laser wavelength, the speckle pattern is modified [4]. An algorithm called cross-correlation is established to evaluate the images [5]. It measures the deformation of the object surface by associating patterns with the surface that deforms.

A second important speckle method, laser speckle contrast analysis (LSCAS), is a digital version of the single exposure version of speckle photography which avoids the main disadvantages of the photographic process. LSCAS is a diagnostic technique in which the features of scattered coherent light are explored [6]. At present, it is alternatively called "laser speckle contrast imaging" (LSCI) or "laser speckle imaging" (LSI). These techniques are mainly used in the medical field to detect blood flow and organic tissues whose local speckle contrast varies according to the velocity distribution of the targets [7-9]. The speckle contrast is shown in an equation, which is defined as the ratio between the standard deviation of the speckle pattern and the mean intensity. A formula presenting the relationship between variance of a time-averaged dynamic speckle pattern and the temporal fluctuation statistics is now given [8].

A third well-known speckle-method is laser speckle interferometry. Interferometric techniques are effective tools for visualizing or measuring object deformation. When an object deforms, the phase of scattering light changes which results in a

change in interference fringes. Therefore, the defect of an object makes the fringes look unusual. Speckle interferometry is a well-established optical technique for measuring in-plane displacements [10]. In this section, three kinds of interferometry will be introduced, namely holographic interferometry, electronic speckle pattern interferometry (ESPI) and shearography.

Holography is a technique which can record both amplitude and phase information from a light beam reflecting off objects. In interferometry a laser beam is split into two beams, one, called a "reference beam", is used as a reference, the other, the "object beam", is used to illuminate the object in question. ESPI and shearography use two different optical setups for speckle interferometry. ESPI is based on the same principles as holographic interferometry but it electronically records and processes speckle interference patterns [11]. The visualization is achieved in the form of fringes which approximately represent a displacement of half a wavelength of the laser beam. The sensitivity of in-plane displacement equals the value of half a wavelength. The features of shearography include sensitivity to out-of-plane deformation and the capability to directly measure strain data in real time but not the displacement of objects because rigid body movement produces displacement as well. Shearography was used to detect large cracks in reinforced concrete and the intrados of bridges [12]. Micro-cracks in a glass-fiber reinforced plastic tube stressed by a 0.04 MPa internal pressure can be detected by shearography as well [13].

A novel speckle method for NDT is laser speckle photometry (LSP) [14, 15] which is based on the detection and analysis of thermally or mechanically activated speckle dynamics in non-stationary optical fields.

Relying on high speed cameras and easier configurations compared with the experimental setups presented above, LSP can also be used in real time monitoring, and it has a high sensitivity to both out-of-plane and in-plane displacement. Deviating from other techniques based on speckle phenomena which concentrate on the distortion of a whole speckle pattern or fringes, LSP is based on measuring the spatial-temporal dynamics of laser speckles which focuses on the intensity change of each single pixel of a camera sensor. Through a specific correlation function (difference autocorrelation), the connection between speckle dynamics and quality states of the samples can be established [14-16]. The basic algorithm of LSP includes the calculation of thermal diffusivity by applying the thermal transfer equation [14-18] and active thermography for crack detection [15]. The algorithms will be introduced in the next section. In recent years, LSP technique has been successfully used for the hardness calibration of steel samples, the evaluation of material porosity of cellular metals and ceramics, damage fatigue states and stress change during welding processes.

LSP represents a promising foundation for new NDT methods and appropriate sensors to be developed by industry to characterize material properties or describe their changes in the manufacturing process. It is definitely a fast quality relevant material characterization and defect detection method, allowing for the monitoring of production processes completely in-line. The sensor system developed comprises the optical and electronic components, algorithms, the hardware and software. The monitoring process is synchronized with the machine's internal control, including the adaption of measuring and evaluating speed for high manufacturing performance. The short measuring times predetermine it for use in in-line monitoring in industrial production and for in-situ measurements during maintenance and repair tasks.

Laser speckle photometry

A speckle pattern is generated when an optical rough surface is illuminated by a coherent light beam. The waves scattered from various points of the illuminated surface interfere on the rough surface on the observation plane where they produce a speckle pattern – a spatial structure with randomly distributed intensity minima and

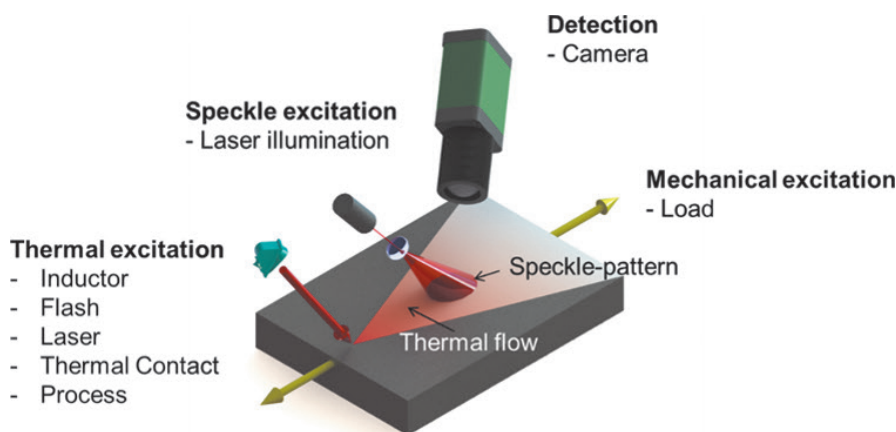


Figure 1: Schematic structure of laser speckle photometry

maxima. The varied luminosities can be detected by a CCD or a CMOS chip, respectively. A speckle pattern resembles the fingerprint of the 3d information of a sample surface [15]. If the examined object is thermally excited, for example by a laser, the material can be characterized by both static and dynamic speckle patterns.

Figure 1 shows the basic experimental setup of LSP measurements. It contains a laser diode as illumination source and a speckle signal detector as a combination of a fast CMOS camera and an objective. The angle between laser source and camera amounts to approximately 30°. In addition, a thermal excitation source is periodically used to change the local temperature of the sample and generate the time-dependent speckle movement. For example, the thermal excitation laser, thermal contact and process heat are applicable. The excitations in both modes are feasibly continuous and pulsed. The thermal energy absorbed by the sample results in the thermal expansion behavior are caused by a local temperature difference. The speckle movements caused by time-dependent thermal expansion are recorded by a fast CMOS camera and the software developed.

Digital algorithms

The approaches of LSP pattern evaluation are shown in Figure 2a and Figure 2b, respectively. Static analysis is based on single images wherein the initial speckle intensity of each pixel depends on a group of pixels around it (e.g. the 3-by-3 neighborhood). The value of the core pixel can be obtained after calculating the neighboring pixels. Repeating this procedure for every pixel of the image, a contrast image is gained. Dynamic evaluation is based on one pixel in a time sequence rather than on multiple pixels in one image. The method for computing speckle contrast is presented in [19], calculation of the fractality of speckle signals is described in [14]. This paper will explain the evaluation steps of frequency analysis.

The time-varying intensity can be related to the spatial gradient by the correlation function. The thermal energy causes a temperature change and leads to the thermal expansion on the surface of the sample. This correlation function is given by:

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

with n_{\max} : number of video frames which provide the time dependence, τ : time shift or

the number of frame intervals and $S(n, x, y)$: intensity of the pixel whose location is determined by the coordinates x and y in the n -th frame.

This correlation function comes from the so-called semi-variogram, which is a geostatistical tool for studying the relationship between the collected data in the function of distance and direction [20]. Applying this correlation function at each time shift shows the accumulation of intensity differences of frame couples having this time shift. However, for crack detection, it focuses on the difference between the first frame and other frames depending on the time shift rather than on the details of the frame couples mentioned above. Therefore, a slight modification was made on Equation (1), where n becomes a fixed value, $n = 1$. The new correlation function is given by:

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

with n : number of the frame.

The highest shift in the speckle images leads to the maximum of this correlation function [16]. As is known, images can be digitally processed as matrices. Therefore, based on this correlation function, a three-dimensional matrix indicating the changes between each frame and the first frame for each single pixel was created. 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 can be determined by the number of frames which were used to calculate the FFT. This number was determined by the interval be-

tween the start and saturation point of the correlation function. Information contained in the intensity change of each single pixel was re-distributed depending on the energy at different frequencies in the frequency domain. M two-dimensional matrices can be obtained, and the value of each element in the same matrix presents the energy of each pixel at an exact frequency. In this case, the intensity changes of time-varying speckle patterns were converted to the frequency domain for the further analysis of different applications.

Applications

Monitoring of welding processes. Presently, in the electrical industry, conductive contacts are applied by electroplating and welding. These cost and time-consuming procedures are characterized by a high consumption of material and energy. These processes accumulate 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 re-melted via laser radiation for densification and bonding to the substrate.

An example of gold contact is shown in Figure 3a. A contact has a diameter of approximately 80 μm . For both the stage of development of the new contact-making process and the subsequent in-process quality control, it offers an inline-capable, laser based and contactless testing method. The time-resolved LSP has been developed

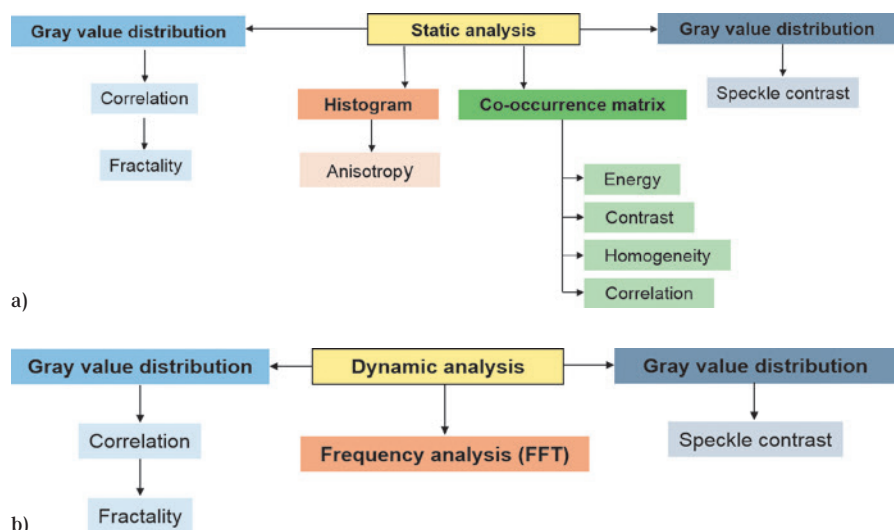


Figure 2: Schematic overview of the possibilities for evaluating the speckle signals by a) static analysis, b) dynamic analysis

and adapted for this application. Figure 3b shows the integrated LSP technique in an appropriate laboratory facility [21].

The mixing degree of contact with the substrate was determined by the parameter fractal dimension D_F [14] of the dynamic speckles in the reflective region. The determination of the calibration curve for the calculation of the metal content was carried out by means of a chemical analysis of the contact material, energy-dispersive X-ray spectroscopy (EDX). The geometric contact measurement was carried out simultaneously with the determination of the gold content. The contact height 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 the indi-

vidual contact. Confocal microscopy can be used as a calibration method for the geometric determination of contact size.

Figure 4 shows the resulting curve of calibration which was calculated from a linear regression of the experimental values measured by the LSP technique.

The accuracy of the results at a measuring speed of 100 contacts per minute can be summarized as 6.7 vol.-% of tolerance of the determination of the precious metal content and 4.0 vol.-% of tolerance of the height measurement. Measurement precision is dependent on the accuracy of the reference method for calibration. The EDX used is a local method in comparison to LSP resolution. Therefore, the real Au-fraction in the complete contact can be varied to the result of the EDX. Hence, the differ-

ence in the calibration process can be minimized, which decreases the tolerance of the measurement.

Monitoring of biological processes. Modern biotechnological production processes for the manufacture of hosiery and additives, e. g., for pharmaceutical, cosmetic or food using vegetable cells, tissue cultures (e. g. hairy roots) and heterogeneous microorganisms (e. g. filamentous mushrooms), are increasingly in the focus of research and development. Currently, there are several research projects focusing on the development of economic production processes for crop secondary metabolites (pharmaceutical and nutritionally potent substances with hairy root cultures) for the extraction of enzymes [22]. The economic management of the cultivation of biotechnological processes for active extraction requires the determination of the biomass and the determination of their growth kinetics. Established methods cannot be used to meet the requirements of the cultivation of hairy roots due to the inhomogeneous distribution of the root segments. In order to shorten the optimization period, a quantitative and preferably direct measurement method for determining the current biomass concentration is required. Therefore, the development of a fully automated, non-invasive sensor for determining the biomass concentration and morphology parameters in different heterogeneous biotechnological systems is of great interest.

The basic structure for the evaluation of temporal change in the biomass by LSP is shown in Figure 5. To evaluate current biomass concentration, scale properties of the speckle pattern are evaluated. The parameter fractal dimension D_F [14] describes how "rugged" the examined object is at any given time due to an absolute value. To the same proportion, the given dynamic parameter can describe the growth state of the examined object. Additionally, static changes in the object are well suited for the characterization of its growth stage. For this approach, the evaluation of the co-occurrence matrix and parameters like entropy can be used. The correlated reference measurement is foreseen for future research.

In Figure 6, it can be seen that the fractal dimension increases with the duration of cultivation in four independent samples. To evaluate the root activity, one method is based on the calculation of speckle contrast. The presentation of time-resolved contrast values shows that the areas of higher growth and change are always characterized by low contrast. In Figure 7, for example, root areas growth is visualized

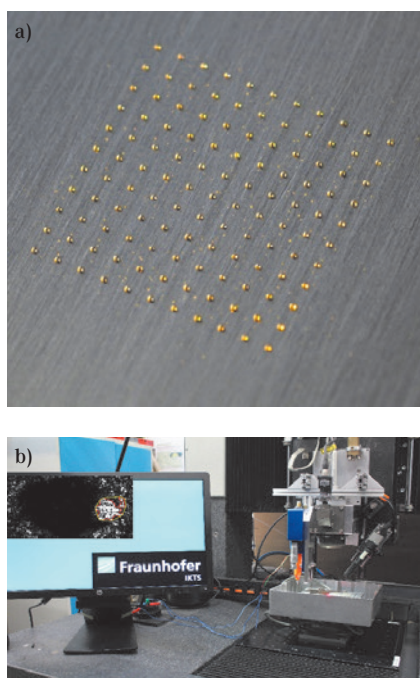


Figure 3: a) Gold contacts at Nickel-Alloy Inconel 625, b) integrated LSP technology in the gold contact production, speckle pattern determines the precious metal content and geometries of the contacts

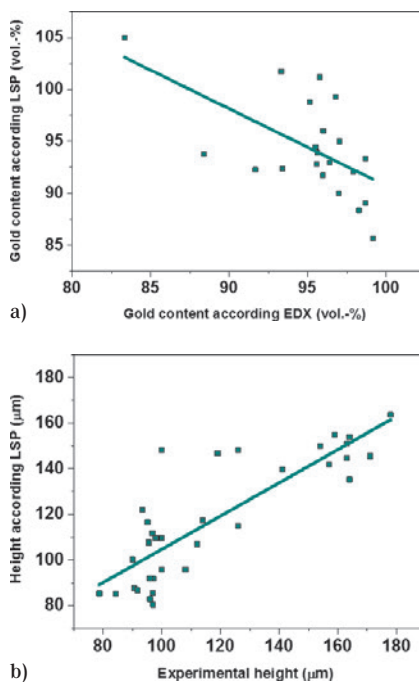


Figure 4: a) Calibration of gold content measured by EDX vs. that measured by LSP, b) calibration of height of contacts measured by confocal microscopy vs. that measured by LSP

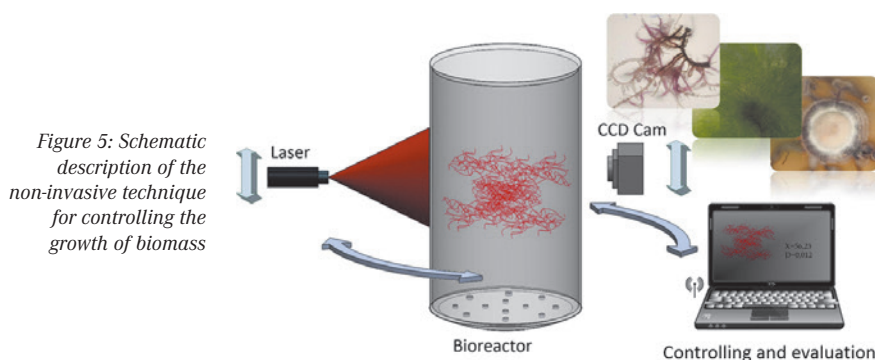


Figure 5: Schematic description of the non-invasive technique for controlling the growth of biomass

almost in white. During the following days, branches formed at these locations.

Additive manufacturing. Material parameters such as porosity can be obtained by LSP based on an evaluation of the temperature line. This evaluation concept can be implemented for process control in the production of additive manufactured components. Moreover, defects such as pores and micro-cracks occurring during the laser-melting process can be detected immediately after their formation to enable appropriate countermeasures. In addition, these defects can be cleared by re-melting the affected area. As a result, the requirement of downstream, time and cost intensive material testing and rework can be significantly reduced. An LSP sensor system is designed to help reduce the drop-out rate in the process so that energy, material and inert gas consumption can be reduced significantly in the additive manufacturing of metal components. The LSP sensor is integrated directly into the manufactured machine. The communication between the two processes is realized – depending on the development of the electronics and algorithms – for a regulative approach.

First investigations were carried out on test specimens (see Figure 8a). Some of these specimens were prepared by reduced input energy (marked in green) and so primarily have near-surface defects, as well as samples by highly elevated input energy (B2, D3) and corresponding defects/inhomogeneities. In comparison, the reference (row 4) shows the measurements on the samples manufactured under optimum conditions. The references hardly show the flaws. The defects and inhomogeneities in the samples 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, so-called speckle diffusivity can be determined. In Figure 8b, it can be seen that the speckle diffusivity calculated decreases with the 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 their thermal diffusivity.

Conclusions

Compared with other optical speckle-based methods, LSP provides an opportunity for determining defects, geometric and material parameters such as porosity, and for evaluating biological growth processes.

The process-specific parameters such as the gold content of electrical contacts or the biomass content in the reactor can be inline determined by the parameter “fractal dimension”. Further development is needed to increase the accuracy of the method. Here it is important to find suitable reference methods to evaluate comparable areas of the material. Currently, measurement speed is already very high for some applications at 50 frames per second, including measurement and evaluation. Depending on the region of interest (ROI) the following applies: the smaller the ROI, the higher the frame rate. But the results are not only dependent on the measuring speed but also on the accuracy of measurement.

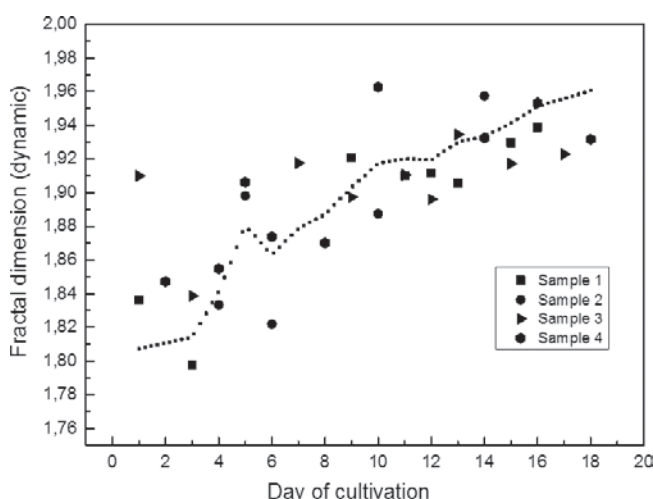


Figure 6: Parameter of the fractal dimension with the length of cultivation during the increase of biomass growth

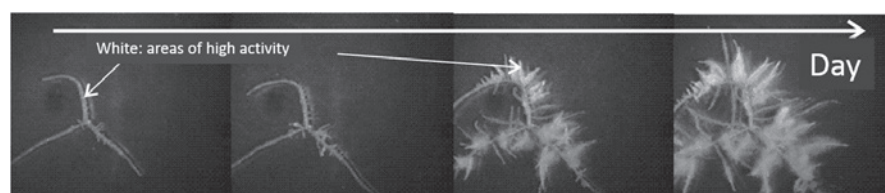


Figure 7: The contrast in the illustrated temporal speckle pattern changes during the cultivation of hairy roots. The brighter area of the plant is shown, the higher the growth activity in the area

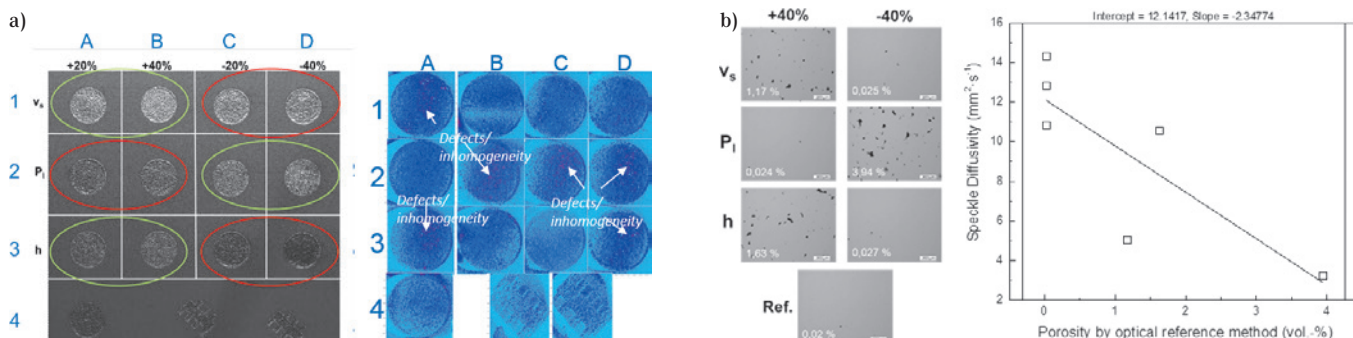


Figure 8: a) test sample of additive manufacturing, b) results of speckle signal presented by speckle diffusivity. The percentage shows the ratio between real input energy and optimal energy. V_s , P_i and h present the speed, fill in power and hatch distance of process, respectively

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