Detection of cracks in green products of powder metallurgy by means of laser vibrometry

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Abstract. Cracking of green parts in powder metallurgy (PM) is a big concern in PM industry. Detection of cracks in green parts before sintering can prevent recycling of already sintered parts or production of defective ones. As opposed to sintered parts, where the presence of cracks is well revealed by impact spectroscopy, it is challenging for green parts. The reason is an extremely low mechanical quality factor of these parts composed of compacted but non-sintered metal powder particles. Low mechanical integrity of particles causes the absence of pronounced resonances of the parts. The aim of the study was to test a possibility to discerning healthy and cracked green parts using spectral characteristics of signals obtained by laser vibrometry. Four similar green PM gear wheels made of steel powder were obtained from a PM manufacturing company, two of them were healthy and two with simulated cracks that appeared in the area of stress concentration between the hub and the disc. The experimental setup included a Polytec PSV-500 scanning laser vibrometer and a Brüel & Kjær vibration stand type 4824. Integrated spectrograms in the frequency range 50 – 3500 Hz were recorded upon a 95-point network on the gear surface at different vibration intensities proportionally graded in the range from 1 to 5. Comparison of the 3D (frequency-intensity-amplitude) vibration spectrograms showed that the defected specimens with cracks differed from the healthy ones in the following features: resonance frequency shift and/or splitting of resonances when the load changes. The study confirmed the principal possibility of cracks detection in green PM parts using laser vibrometry regardless the crack location in the part. The aim of further studies is to determine the sensitivity limit in terms of crack size. Keywords: non-destructive testing, powder metallurgy, green parts, cracks, laser vibrometry.

1. Introduction
Powder metallurgy (PM) makes it possible to obtain products with unique physical and mechanical properties, increasing the utilization rate of metal and reducing the mechanical processing of products to a minimum [1]. PM products are used to operate in responsible units of machines and structures under a wide range of extreme mechanical loads, thus, a strong defect-free requirement applies to these parts. One of the most dangerous causes of destruction is the formation of cracks that can appear at the stage of pressing the product, i.e. at the green or unsintered state, followed by their growth during sintering and finishing operations. The main causes of green-state cracks can be summarized into four basic categories: improper material composition such as a lack or excess of lubricant and the presence of impurities; particles side shifting with an improper compacting technology; improper elastic strain release in the presence of plastic deformations; and high tensile/shear stresses imposed by external or
internal factors during manufacturing [2]. It is desirable to detect cracks even at the early green state that can prevent the production of defective parts. In this case, there is no need of labor-intensive and energy-intensive operations of re-processing of defective sintered products. Although the problem of cracking diagnostics of sintered parts has been more or less solved by impact resonance spectroscopy, including in-line commercial installations [3], cracks detection in green parts still remains challenging. This is due to two reasons: firstly, the inapplicability of impact to green parts that can damage them, and secondly, an extremely low mechanical quality factor of these parts composed of compacted but non-sintered metal powder particles with weak bonds between them. Despite considerable efforts, traditional non-destructive testing (NDT) methods have been largely unsuccessful at defects detecting in green PM parts or showed a limited applicability in real production environment. Electrical resistivity method was realized by the voltage distribution measurements on the surface by an array of spring-loaded needle contacts [4]. The surface wave mediator technique used point contact to induce and receive Rayleigh acoustic surface waves in a megahertz frequency range that was sensitive to surface breaking cracks [5]. Another tested option was realized in the same work by ultrasonic electromagnetic acoustic transducers inducing shear horizontal waves and torsional waves. Increased attenuation of high frequency acoustic waves in green PM parts forced to switch to lower frequencies than traditionally used in ultrasonic NDT of metal objects [6]. Enhanced image processing techniques applied to digital radiographic images allowed recognition of a crack in a green PM compact that was virtually invisible in the original digital x-ray picture [7]. Summarizing the said approaches, it can be concluded that despite the demonstrated positive effects, NTD of green PM parts is still complicated by one or a few of the following reasons: a lack of sensitivity; measurement only in a local accessible plot; impermissible impact or contact action; huge and slow operating equipment and/or inability to adapt the equipment to in-line testing.

The purpose of this study was to assess the possibility of detecting cracks in green PM products by the spectral characteristics of signals obtained by laser vibrometry. The laser Doppler vibrometry [8] was chosen taking into account such its advantages as remote sensing that avoids the necessity of a direct contact with a PM part and a gentle vibration effect on the test object. Besides, it is adaptable to objects of different size and complicated shape. Despite the relatively high cost of laser vibrometry equipment, it can be quite well built into in-line testing and can pay off in bulk mass production.

2. Materials and methods

2.1. Examined PM parts.

![Figure 1](image1.png)

**Figure 1.** Examined PM gears: A – product general view; B, C – simulated cracks in gears’ bodies denoted by arrows.

The examined PM parts were four similar green PM gear wheels made of steel powder with a diameter of 80 mm. The specimens were obtained from a large PM manufacturing company, Miba Sinter Slovakia, S.R.O. Two specimens were healthy and other two ones were artificially damaged with simulated cracks. The cracks were induced by a moderately light blow and appeared in the area of stress concentration on the disc by the trajectory connecting a hole between the hub and the disc (Figure 1).
2.2. Laser vibrometry.
The experimental laser vibrometry equipment consisted of a single-channel laser vibrometer and a vibrometer stand depicted in Figure 2.

![Figure 2. Illustrations of experiment: A – tested gear on the vibrator’s platform; B – general view of equipment, C – gear with imposed grid of measurement points; D – gear with imposed virtual oscillation pattern at a resonance.](image)

The laser vibrometer was a Polytec Scanning Vibrometer PSV-500 in 1D optical configuration providing fully automated vibration measurements in the range from DC to 100 kHz. The Polytec vibrometer system is a laser Doppler vibrometer determining the vibration velocity and displacement at a point by sensing the frequency shift and phase variation of back scattered laser light from a moving surface. The scanning head with a high precision scanner and HD video camera helped recording of vibration spectra upon a 95-point network on the gear surface (Figure 2C), and presenting the integral spectrum upon all 95 points as a result. The vibrometer was a Bruel&Kjer electrodynamic Modal Exciter Type 4824 (Figure 2A) intended for modal testing in structural dynamics investigations. It operates in a frequency range from DC to 5 kHz providing sine force rating up to 100N. The selected frequency range was from DC to 4000 Hz since the resonances of natural vibrations of the tested specimens were exactly in this range. The frequency step of the spectra acquisition was 1 Hz. As a result, an integral spectrum was presented for all 95 points of the measurement network on the gear surface. To assess the dependence of the spectral characteristics on the intensity of vibration, the spectra were taken at 5 power levels set by the gradually increased excitation voltage of the vibrator from 1 to 5 V with a step of 1 V.

![Figure 3. Vibration spectra of empty platform (A) and the platform loaded by a PM gear (B) at 5 levels of vibration intensity controlled by excitation grades from 1 V to 5 V.](image)
Figure 3 represents examples of integral vibration spectra of the unloaded vibrator with empty platform (A) and the same platform loaded with a PM gear specimen from the group. The amplitudes of obtained spectra are proportional to 5 gradually increasing levels of vibration intensity.

3. Results and discussion
The main results are visually presented in Figure 4. It shows the integral spectra of the empty platform and the platform loaded by healthy (H1, H2) and damaged (D1, D2) specimens in the frequency range from 500 to 3500 Hz. The spectra are presented as B-scans, where brightness decodes the spectrum amplitude. One line corresponds to the step of vibration intensity, at which the spectrum was obtained. The spectra are normalized by the peak amplitude. Areas denoted as quadrangles A and B in two-dimensional frequency-intensity patterns outline regions-of-interest, where differences between healthy and damaged specimens are the most expressed.

The differences between healthy (H1, H2) and damaged (D1, D2) specimens are clearly identified in the presented frequency-intensity patterns in Figure 4. There are two main manifestations that separate groups H and D. The first one is the frequency shift towards lower frequency values in damaged specimens with cracks that is shown by appearance of bright plots in quadrangles A and B, the most expressed in the case of D1. The second one is the splitting of spectral peaks and appearance of additional resonances as shown in the case D2, quadrangle A.

In both cases of healthy and damaged samples, changes in the spectra are observed depending on the vibration intensity. An exception is the case with the empty platform, which is stiffly connected with the vibrator. It has a strong resonance at about 2750 Hz, which is invariant with respect to the vibration intensity. Obviously, the main source of nonlinearity in our experiment is the absence of a rigid coupling between the PM specimen and the platform. Nevertheless, this circumstance does not interfere with the identification of differences between healthy and damaged specimens. At the same time, the frequency shift as a function of vibration intensity imposes demands on taking this factor into account when planning testing.

Two-dimensional frequency-intensity patterns formed by vibration spectra at gradually increased levels of vibration intensity demonstrated a good opportunity to use it as a source material for diagnosing
the state of PM of parts using the principles of pattern recognition and machine learning. Regions-of-interest in such patterns can be predetermined using a database for a specific type of PM product, obtained in notoriously known healthy and damaged specimens.

With regard to the applicability of the method in production, the key success criterion is the speed of testing products and the rejection of defective ones causing minimal impact. Despite the fact that a complete scanning of the object surface in the current experiment on a multipoint grid took a few minutes, the vibrometry test using the integral spectrum of the object can be reduced to a few (5-6) seconds allowing in-line quality assurance in mass production. Further industrial studies are necessary to determine the ability of the method to detect small inner cracks at different location and orientation within the object on the background of random deviation of spectra in a series of similar healthy objects of different size and shape.

4. Conclusion
The study confirmed the principal possibility of cracks detection in green PM parts using laser vibrometry regardless the crack location in the part and using integral vibration spectra upon a PM part as a function of vibration intensity. Two-dimensional frequency-intensity patterns formed by vibration spectra at gradually increased levels of vibration intensity can serve as a source material for diagnosing the state of PM of parts using pattern recognition. The aim of further studies is to determine the sensitivity limit of the approach in terms of crack size and location, as well as the ability of the method to test objects of complex structure.

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