Laser photothermal non-destructive metrology of cracks in un-sintered powder metallurgy manufactured automotive transmission sprockets

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Abstract. A non-contact and non-intrusive method of revealing crack presence in un-sintered (green) automotive transmission parts (sprockets), manufactured by means of a powder metallurgy technology based on analysis of photo-thermal radiometric (PTR) signals and their statistical analysis was developed. The inspection methodology relies on the interaction of a modulated laser generated thermal wave with the potential crack and the resulting change in amplitude and phase of the detected signal [1-5]. The crack existence at points in high stress regions of a group of green (unsintered) sprockets was evaluated through frequency scans. The results were validated by independent destructive cross-sectioning of the sprockets following sintering and polishing. Examination of the sectioned sprockets under a microscope at the locations where signal changes was used for correlation with the PTR signals. Statistical analysis confirmed the capabilities of the method to detect the presence of hairline cracks (~5 – 10 µm size) with excellent sensitivity (91%) and good accuracy (78%) and specificity (61%). This measurement technique and the associated statistical analysis can be used as a simple and reliable on-line inspection methodology of industrial powder metallurgy manufactured steel products for non-destructive quality and feedback control of the parts forming process.

1. Introduction

Automotive components produced from powder metallurgy technologies operate under high strain. The most significant defects are micro-cracks near regions of high stress concentration such as corners and steps. They can appear during the forming process in the green (un-sintered) state, remain after sintering, and may cause serious damage. Nowadays, industry uses various non-destructive testing methods [5], but only after sintering. A highly desirable solution of this problem would be the detection of crack presence in the green state, resulting in reduction of the identified defective parts to a metal powder for recycling and reuse. However, until now there exists no non-destructive testing (NDT) technique capable of detecting cracks in the green state. In past years several photothermal techniques were proposed for monitoring cracks in solids [1] including a microphone-cell photoacoustic setup [2], a laser pump-probe photothermal beam displacement method (Mirage effect) [3] and a photopyroelectric needle probe method [4]. Promising experimental studies [5] have been performed with a mid-IR camera for detection of the thermal radiation emitted after the industrial part forming process or produced after direct external heating of the PM components.
The photothermal radiometric (PTR) technique developed in the present work exploits thermal-wave sensitivity to material discontinuities and interfaces in the form of delaminations, which is what an air gap (crack) effectively is. The crack presence changes the amplitude and phase of the detected signal (blackbody, Planck radiation), emitted by the sample upon heating with an intensity-modulated laser beam, following conduction of the thermal wave to the (sub) surface region of the crack and thermal interaction with it. These changes depend on the difference between the thermal parameters of the green powder material and those of the crack, its position, and geometry. The thermal wavelength is invariably large compared to crack thickness. However, thermal-wave fields are very sensitive to interface properties such as the thermal interface interaction (“reflection”) coefficient, especially when the properties of the two sides of the interface (powder material and air gap) are very different.

2. Experimental set-up and methodology
An outline of the experimental system is shown in Fig. 1. A modulated laser beam of 532 nm was focused on the sample surface using a gradium lens and a micro-mirror. The laser beam spot size on the sample surface was 20 µm. The thus generated thermal infrared radiation was directed to an infrared mercury-cadmium-telluride (MCT) photo-detector through two reflecting objectives. There, the radiative flux was transformed into an electrical signal that was processed by a lock-in amplifier and computer. The thermal signal consists of the amplitude and phase, which are functions of laser-intensity-modulation frequency at a fixed spot or as a function of location during a line scan at a fixed frequency. Typically, low frequencies correspond to long pathlengths in the interrogated material (~mm) while high frequencies probe shorter distances (~µm). Positioning of the circular sprocket samples for line and frequency scans at 45° to the laser beam were performed with the aid of a motorized sample holder stage.

**Figure 1.** Schematic of experimental system for photothermal radiometry of hairline manufacturing cracks.

In the first phase of the project, a preliminary large volume of data (not shown in this paper) was obtained from line scans across selected known cracks. The results showed PTR amplitude and phase variations at the crack area even when its size was a few µm. The same measurements were performed on industrial green PM parts (automotive transmission sprockets) across and along interior steps with subsurface cracks. However, it was not possible to correlate the crack presence with the behavior of the line scan PTR signal as it was dominated by the step discontinuities presence and surface roughness, rather than the presence of cracks. In order to enhance the crack contribution in the PTR
signal generation a group of frequency scans was performed in the immediate vicinity of cracks under the step. The use of multiple frequencies allows probing of the PTR signal in the form of spherical thermal waves at various subsurface depths and increases the probability of interaction between the probing thermal waves and neighboring cracks. The thermal wave-length is proportional of the thermal diffusion length, \( \mu(f) = \frac{\alpha_s}{\pi f} \), where \( \alpha_s \) - the thermal diffusivity of the layer and \( f \) - the modulation frequency.

3. Experiments and statistical analysis of the PTR data
Experiments were performed on five green sprockets, including two “good” samples (1 and 2) with no cracks and “bad” samples (3, 4 and 5) with known crack presence under the step. The step positions were specified with radial scans completed across the inner step at eight radial directions a, b…h (Fig. 2a). The frequency scans were performed at the location of the step-generated amplitude peak of the corresponding a, b…h line scans and at a reference point TF located on the flat part of the sample surfaces (Fig. 2a). According to the manufacturer, in this area the expectation of crack presence was null. Our experiments showed that the frequency scan amplitudes depend strongly on surface irregularities and give misleading information about the crack presence. Graphs of the frequency scan phases at points TF are presented in Fig. 3a. The phase variance from sample to sample in the two known uncracked sprockets 1 and 2 is very small and the remaining phase curves from the otherwise cracked sprockets tend to be close to these two reference samples up to ~ 300 Hz beyond which they diverge. After the PTR measurements, these samples were sent back to the manufacturer for sintering and cross sectioning, which included the radial lines scanned with PTR. Slices were obtained and polished on both sectioned surfaces, and microscope pictures were taken of the crack on both sides as shown in Fig. 2b. The presence or absence of a crack in the sliced sprocket surfaces shown in photos taken at all radial directions were chosen as the golden standard validating the PTR phase frequency scan results from cracked and non-cracked samples. The mean values and standard deviations of phases all frequency scans at the eight directions (a, b…h) on the “good” samples (16 points in all) were used to generate a reference phase frequency band corresponding to non-cracked green samples. In Figure 3b we present plots of the frequency scan phases performed at directions b and f on samples 4 and 5, respectively. Curves in both graphs lie outside and above the non-cracked reference band. The corresponding photos of the sliced surfaces showed the presence of a crack under the step. Conversely, as an example of non-cracked behavior, the curves in the phase graphs presented in Fig. 3c remain within the non-cracked reference band. Nevertheless, the small size of the cracks and the uncertainties
in crack-laser beam relative positioning has led to some false signals. In Fig. 3d, we demonstrate the graphs of phase frequency scans from directions d and e on samples 3 and 4, respectively. Despite the obvious crack presence on the picture of direction e on sample 4, the phase remains within the reference band. On the other hand, the phase graph of direction d on sample 3 rises almost entirely outside the reference band despite the absence of a crack in its photos.

These anomalies are shaping PTR crack detection technology as a statistical inspection method or hairline cracks. All phase frequency scan data were divided into four categories: true positive (TP) – at least one of the two-side photos shows a crack is present and the phase frequency scan also shows the crack presence lying outside the reference band; true negative (TN) – the photos show no crack is present and the phase frequency scan graph also shows the absence of a crack by entirely lying inside the reference band; false positive (FP) – the photos show no crack is present, but the phase graph position shows a crack is present by lying outside the reference band; false negative (FN) – at least one of the two-side photos shows a crack is present, but the phase graph position shows the absence of a

| Sprocket number | Scan directions a, b...h |
|-----------------|--------------------------|
| 1               | FP TN TN TN FP TN TN TN |
| 2               | TN TN FP FP TN TN FP TN |
| 3               | TP TP FN FP TP TP TP FP |
| 4               | TP TP TP TP FN TP TP TP |
| 5               | TP TP TP TP TP TP TP TP |

Table 1. Crack presence statistics.

Figure 1. Frequency scan phase performed at: (a) – TF points on samples 1, 2, 3, 4, and 5; (b) – directions b and f on samples 4 and 5; (c) – directions g and b on samples 1 and 2; (d) – directions d and e on samples 3 and 4.
crack by entirely lying inside the reference band. The results from a statistical analysis of the experimental data from all green sprockets vs. the validation golden standard are presented in Table 1 and summarized in Table 2. The statistical analysis shows that the sensitivity of the technique is excellent – 91% probability that the positive PTR reading is the result of a true crack. The specificity is not as good – 61% probability that a negative PTR reading is the result of the absence of crack. The

| Inspection Method | Sensitivity | Specificity | Accuracy | Points |
|-------------------|-------------|-------------|----------|--------|
| PTR Frequency Scan Phase | 0.91(20/22) | 0.61(11/18) | 0.78 | 40 |

*in parentheses: TP / (TP + FN); in parentheses: TH / (TH + FP); in parentheses: (TP + TN) / (TP + FN + TN + FP)

accuracy is significantly higher at 78%. We now discuss in some more detail the eight test measurements in terms of statistical results for each of the five sprockets (Table 1): Sprocket #3 – five instances of crack presence were confirmed, one location gave false negative information, and two locations gave false positive information. At 63% true crack positives, sprocket #3 would have been labeled “cracked” under non-destructive PTR interrogation alone; Sprocket #4 – seven instances of crack presence were confirmed and one test result was false negative. At 88% true crack positives, sprocket #4 would have been labeled “cracked” under non-destructive PTR interrogation alone; Sprocket #5 – all eight test results confirmed the presence of crack along the various radial directions. At 100% true crack positives, sprocket #5 would have been labeled “cracked under non-destructive PTR interrogation alone. Indeed the sprockets #3, #4, and #5 had been labeled “cracked” by the manufacturer before being subjected to PTR crack analysis; Sprocket #1 – six test results confirmed the absence of subsurface cracks while two test results gave false positive indication. At 75% true crack negatives, this sprocket would have been labeled crack-free under non-destructive PTR interrogation alone; Sprocket #2 – five test results confirmed the absence of subsurface cracks while three test results give false positive indications. At 63% true crack negatives, this sprocket could have been labeled crack-free under non-destructive PTR interrogation alone. Indeed, sprockets #1 and #2 had been labeled “crack-free” by the manufacturer before being subjected to PTR crack analysis.

4. Conclusion
It has been shown that PTR can be a valuable NDT technique for monitoring the presence of hairline cracks created during the forming process of green parts. The use of modulated laser beam as a heat-generating source allows the use of the frequency scanned technique that eliminates the influence of surface texture, roughness, and cleanliness. A statistical analysis of the PTR frequency scan phase data performed at eight points on the surface of five green sprockets was presented. The lower specificity and accuracy of the PTR technique compared to its sensitivity may be explained by the variance in inner step shapes and by fluctuations in thermophysical properties of green samples as well as with the limited possibilities of the current experimental setup.

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