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Non-destructive thermal-wave-radar imaging of manufactured green powder metallurgy compact flaws (cracks)

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ABSTRACT

Thermal wave radar imaging (TWRI) was developed to detect manufacturing cracks in automotive powder metallurgy components (transmission sprockets) in their green (unsintered) state. The crack detection capability of the TWRI phase was validated by two sets of cracked/crack-free green and sintered sprockets which were sectioned after TWRI measurements. An automatic defect recognition (ADR) TWR image processing method was also developed to differentiate cracks from local defects. Measurement results demonstrated that TWRI is superior to conventional lock-in thermography imaging (LITI) in both flaw detection resolution and speed, and thus is a viable green-sprocket manufacturing flaw imaging technology.

1. Introduction

Automotive industry utilization of powder metallurgy (PM) technology is increasing in popularity due to requirements for intricate and dimensionally accurate neat-shaped components which can be produced at competitive cost. The manufactured components, such as sprockets (for automatic transmissions and transfer cases), clutch plates (for automatic transmissions) clutch hubs (for transfer cases), synchronizer hubs (for manual transmissions) and other parts usually operate under high loads. Failure of any of the above mentioned components may cause transmission or transfer-case failure, hence loss of functionality for the vehicle. Therefore, quality and integrity requirements are high. A most important defect type in these manufactured parts is the possibility of incipient (surface breaking or subsurface) cracks present in high-stress areas such as at angles and steps [1]. PM components are formed by multi-ton pressing on the metal powder-lubricant compound. Crack appearance in a green part is related both to the powder materials and problems with the adjustment of the press equipment. Once created during the forming process, the cracks remain (often unchanged in size) after sintering. These cracks can cause component fracture in-application, possibly resulting in loss of vehicle driving power.

The PM automotive parts manufacturing industry uses various non-destructive testing (NDT) methods (acoustic, magnetic, fluorescent liquid penetrants, microscopy) to diagnose defective elements not in the "green" state but only after sintering. Nowadays, with the dramatic increase in global energy prices, international economic upheavals, and the recent serious downturn in the North American automotive industry, it is ill-afforded and expensive for the industry to dispose of, and effectively waste, defective sintered components. A highly desirable alternative solution to this problem would be the detection of the presence of cracks in automotive parts in the green state. Then, the identified defective parts can be easily reduced to metal powder which can be recycled by the manufacturer and produce new components. However, to the best of our knowledge, until now there exist no effective NDT techniques which can detect cracks in the un-sintered manufactured state. Infrared imaging has often been used as a NDT technique to detect cracks. Two crack detection mechanisms behind the technique have been identified by Bodnar et al. [2,3] and further investigated by Burrows et al. [4]: (1) rise in temperature near the crack edges due to crack-blocked lateral heat flow when the laser spot is incident on the side of crack; (2) crack-induced strong laser absorption and therefore high temperature rise when the laser spot is on the crack. In both situations the net result is enhanced thermal infrared photon (Planck) emission compared to non-cracked regions which defines the image contrast. In recent years, the technique of infrared thermographic imaging has been applied to manufactured automotive parts inspection. A dynamic frequency-domain form of this imaging method, lock-in thermography (LIT), has been developed [5–8], and used by Böhm et al. [9] to inspect adhesively bonded parts. Netzelmann used flying-spot (moving laser beam) lock-in thermography to detect cracks in steel [10]. Those researchers estimated the attainable depth of flaw

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detection to be ca. 3 mm in plastics, 6 mm in fiber reinforced plastics and 12 mm in metals. However, this range of depths does not easily apply to hairline (~20–100 μm wide) cracks and powder metallic compacts because of the diffusive nature of thermal waves (poor spatial and axial resolution) and the relatively poor thermal properties and rough surfaces of these materials. Early on it was recognized that LIT (more generally: photothermal) phase imaging is superior to amplitude imaging for NDT applications [11] as it yields pure thermal-wave images based only on thermophysical property contrast and higher depth resolution; it is less affected by non-uniform heating, surface emissivity variations and optical reflectivity [12,13]. Other thermal and thermally-mediated non-destructive imaging (NDI) methodologies have been developed (pulsed thermography (PT), step thermography (ST) and vibrothermography (VT), to name the most popular) [14].

The first - and, to our best knowledge, the only- attempts to apply infrared thermography to green PM compacts have been reported by Benzerrouk and Ludwig [15]. These authors made an extensive comparative study of most available NDT methods which could potentially be used for green PM compact inspection (Eddy current, ultrasound, acoustic resonance, x-rays, resistivity and thermography) [16,17]. They came to the conclusion that infrared imaging was the only method capable of testing green state compacts under realistic industrial conditions and under the desired inspection speed conditions. Their thermographic method consists of electrically resistive (Joule) heating of a green part and detection of the temperature rise by means of a mid-infrared camera which captures Planck emissions from the heated surface. The electro-thermally generated steady-state temperature field is calculated analytically or through a finite-element formulation and defects (cracks) are identified through the perturbation they cause to the (known or theoretically expected) temperature field of intact samples. The method can also be extended to dynamic electro-thermography through the use of pulsed electric fields [15]. The major problems with this arrangement are a) the cumbersome requirement for contacting electric power-generating caps to which the geometry of the inspected parts must conform: It appears that cylindrical sample geometries are best for this method; b) the very low subsurface defect contrast due to the diffusive dc thermal field which limits the detection depth range to < 20 μm, essentially confining the technique to ultrashallow surface-breaking crack detection; c) imposition of electrical conductivity value-range requirements so as to induce adequate electrical heating for thermographic imaging; and d) the lack of depth profilometry, a feature that can be attained only with frequency-scanned thermal waves or with dynamic transient thermography, provided there is effective time slicing leading to adequate axial resolution, a non-trivial condition in diffusive fields.

To substantially improve the disadvantages of LIT, our group has developed a novel imaging extension of the photothermal radiometry (PTR) method: the thermal-wave radar (TWR). In this paper we report the detection of the presence of subsurface cracks in green automotive parts with a camera-based Thermal-Wave Radar Imager (TWRI) and the specifications for fast in-line inspection.

2. The principle of TWRI flaw (crack) detection

Thermal wave imaging is an infrared non-destructive extension of PTR. Its crack detection ability in manufactured solids is based on probing subsurface and surface-breaking cracks at high-stress regions of automotive parts using laser-induced thermal waves in the vicinity of the crack (within one thermal diffusion length, μ, see definition below) by means of harmonic heat source modulation which generates periodic heat conduction ("thermal wave"), reaching the subsurface crack location by varying the modulation frequency of the source (usually a laser beam). The presence of a crack amounts to a thermal boundary impedance and is sensed through confinement (accumulation) of the thermal wave at the crack. Sensitivity is highest when the thermal wavelength is on the order of the crack size (width). Interaction with the flaw changes the amplitude and phase of the detected signal. The detected thermal wave is "depth integrated", a depth integral extending from the surface down to approx. one thermal diffusion length, μ, defined by the laser intensity modulation frequency f: $\mu(f) = (\alpha/\pi f)^{1/2}$, where α is the thermal diffusivity [cm^2/s] of the medium. Signal changes carry information about the subsurface crack region which affects thermal-wave propagation, and depend on differences between the thermal parameters (diffusivity, effusivity) of the surrounding material and those of the crack, as well as on the position, orientation and geometry of the crack [18]. Major factors limiting detectivity of near-subsurface narrow manufacturing-induced cracks (a few microns wide) using harmonic thermal waves are: a) the depth-integrated and depthwise exponentially damped nature of the signals [19,20]; b) their highly dispersive nature which results in very poor axial resolution; c) the low signal-to-noise ratio (SNR); d) the unknown depth of cracks which can be easily missed with single frequency dynamic thermography that fixes the probe depth approximately to the value of the thermal diffusion length and may miss deep flaws located directly below the laser probe; and e) the long duration of PTR frequency scans (15 – 20 min). To overcome these adverse factors, the concept of the linear frequency modulated (LFM) continuous-wave (CW) radar was combined with frequency domain photothermal physics, thereby introducing *the thermal-wave radar (TWR),*Fig. 1 [21]. The presence of subsurface discontinuities can be enhanced considerably through signal generation and processing techniques similar to the ultrasonic radar [22]. In this mode, a linear frequency sweep *("chirp")* modulates the source (e.g. laser intensity) and a cross-correlation (CC) processing algorithm with a *"matched filter"* generates CC signal peaks, Fig. 1 (bottom trace), resulting in high axial resolution and depth range superior to LIT inside a sample. Higher frequencies correspond to earlier signal capture times (and shallower depths), and vice versa through a Fourier transformation. The earliest reports on LFM of thermal waves and use of radar signal (cross-correlation) processing methods appeared in a series of 1986 articles by our group using photothermal beam deflection [23–25]. Subsequently, Mulaveesala *et al.*[26] presented a similar approach using infrared thermography. The algorithm shown in Fig. 1(a) can be used to obtain depth-resolved photothermal information instead of the conventional depth-integrated LIT response by progressively delaying the matched filter and registering signals coherent to it. This can be done through CC, extensively used for signal detection in CW radars, between a judiciously delayed replica of the incident wave controlled by the operator and the generated signal [27–29]. The CC can be tuned to a particular signal arrival delay time, τ_p, corresponding to a fixed depth below the interrogated surface, while efficiently zeroing or greatly minimizing contributions from arrivals at earlier and later times which tend to dominate and mask contributions from the given depth due to the axial superposition of signal-generating sources in depth-integrating LIT. In Fig. 1 the schematic CC signal peak delay time and phase plots show the responses of thermal-wave accumulation/depletion due to discontinuities near (solid line) and farther below (dashed line) the interrogated surface. *Pulse compression* can make the width of the peak narrower (better axial resolution) and its height larger (better SNR). To meet fast industrial inline inspection requirements, a camera-based TWRI is developed for manufactured component crack detection in green sprockets.

3. Materials and methods

3.1. Powder metallurgy samples

The samples under investigation are typical products of the automotive industry, that is, sprockets with a circular geometry, Fig. 2(a), and five main regions (hub, web, spline, flange and counterbore), Fig. 2(b). Flaws (cracks) usually appear at the high-stress intersections of two perpendicular regions, or corners (web-counterbore, web-spline