A SURFACE WAVE MEDIATOR TECHNIQUE FOR CRACK DETECTION IN GREEN PARTS

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ABSTRACT

A surface wave mediator technique has been explored for crack detection in a variety of green parts ranging from small, thin specimens such as gears to large, thick parts such as components for heavy construction equipment. The surface wave mediator is constructed by placing a normal beam longitudinal wave transducer on a Plexiglas wedge at the third critical angle, which generates Rayleigh surface waves in a steel mediator. The ultrasonic wave travels along the mediator and is imposed onto a specimen through a small contact area at a knife-edge tip. Measurements are made by a through transmission setup. Upon the comparison of potential cracked areas and defect free areas of specimens, the cracked areas are detected through a decrease in amplitude and increase in arrival time of the wave packets of the received RF signal. Component scans such as circumferential amplitude profiles can be generated on circular objects such as gears to show the location and often severity of the defect area. Surface wave propagation theory will be reviewed. Several sample problems will be presented to demonstrate the success of this technique. Quick and effective implementation techniques will also be discussed.

INTRODUCTION

The structural quality of a sintered powder metal part can be compromised by the presence of cracks within the part. The cracks in green parts form because either interparticle bonds are not formed or the interparticle bonds become broken [1]. Small cracks located within a part can close together during sintering but surface breaking cracks exposed to the sintering atmosphere have the potential to become larger as shrinkage occurs during sintering. Sintering green compacts with structural defects adds to the cost of production. To date, visual inspection is the only somewhat reliable process used to find defects in green compacts before sintering. This paper presents a novel ultrasonic Nondestructive Evaluation (NDE) technique that requires minimal contact with a green part employing Rayleigh surface waves to detect surface breaking cracks.
Ultrasonic NDE testing can be performed through multiple contact methods and non-contact methods to find defects in a variety of materials and structures. Contact methods use a coupling medium other than air or direct contact with the part being inspected. The coupling medium allows for the transmission of ultrasonic energy between transducer and the part being inspected. Residues remaining from coupling media used on green parts can contaminate the part during the sintering process producing impurities and defects. These impurities can affect final part properties such as strength and ductility and change part appearance by altering surface finish by creating bubbling, cracks, and surface corrosion. Ultrasonic immersion techniques performed in a water tank can result in the corrosion of ferrous metals or in residual moisture content affecting the sintering process. Gel and oil based couplants and adhesive tape layers applied before using gel and oil based couplants can leave residues on a part. Dry coupling techniques using rubber like material with low loss have the potential to be used on green parts. Hertzian contact through points and lines use minimal contact area to induce ultrasonic waves into a part for defect detection. Laser based ultrasound can cause surface ablation and localized, uncontrolled sintering in the production of thermal based stress waves. Air coupled transducers have high signal attenuation due to air coupling. Electromagnetic Acoustic Transducers (EMAT) can induce waves in conductive materials but have the potential to pull compacted powders apart due the strong magnetic forces produced by EMATs.

Two different types of ultrasonic techniques can be used to detect cracks and other defects in green parts: Ultrasonic Guided Wave Techniques and Acoustic Signature and Ultrasonic Resonance Techniques. The surface wave mediator technique is an example of an ultrasonic guided wave technique. This technique is good for inspecting parts with simple geometries and parts with case histories of cracks at specific locations. Acoustic signature and ultrasonic resonance techniques use normal beam bulk wave methods to determine the wave resonance of a part. Deviations in wave resonance from a standard “good” part will indicate the presence or cracks other defects. This technique is good for the inspection of small parts with odd shapes and parts with no case history of flaws. Acoustic signature and ultrasonic resonance techniques can indicate the presence of defects, but guided wave techniques have the potential to locate and size a defect thus giving the ability to fully characterize a defect within a part.

SURFACE WAVE MEDIATOR PROBE THEORY

The surface wave mediator technique uses mediator probes to induce Rayleigh surface wave in the specimen being tested. The procedure for making wave velocity measurements of a material using surface wave mediators is shown in Appendix E in [2]. Rayleigh wave theory and formulas are presented in [2]. The surface wave mediator technique has been used for composite materials characterization [3] and density gradient measurements in green powder compacts [4]. The mediator probes, as shown in Figure 1, are constructed of an ultrasonic normal beam longitudinal transducer, a Plexiglas wedge, and a steel mediator. The ultrasonic transducer generates an ultrasonic wave that propagates into the Plexiglas wedge. At the interface of the Plexiglas wedge and the steel mediator, the ultrasonic wave is refracted and mode conversion occurs. Surface waves travel at a 90° incident angle with the normal to the interface. The third critical angle, \( \theta \), between Plexiglas and steel can be found using Snell’s Law as shown in Equation 1 knowing longitudinal wave velocity of Plexiglas, \( C_{L,\text{Plexiglas}} \) (2730 m/sec), and the Rayleigh surface wave velocity of steel \( C_{R,\text{steel}} \) (2990 m/sec).

\[
\frac{C_{L,\text{Plexiglas}}}{\sin \theta} = \frac{C_{R,\text{steel}}}{\sin 90°}
\]  

Equation 1

The calculated third critical angle where longitudinal waves in Plexiglas are converted into Rayleigh waves in steel is 66°, as shown in Figure 2. The surface waves travel across the mediator and are transmitted to the green part through a line of Hertzian contact stress thus allowing the Rayleigh surface waves to be induced on both curved and flat surfaces of a part to be tested. Rayleigh surface waves have
the ability to travel along complex geometries and are sensitive to cracks and defects at the surface/subsurface level.

![Ultrasonic transducer, Plexiglas wedge, Steel mediator](image1)

Figure 1. The components of the mediator probes.

![The third critical angle for the generation of Rayleigh surface waves in steel](image2)

Figure 2. The third critical angle for the generation of Rayleigh surface waves in steel is shown referenced to the wedge/mediator interface.

**EXPERIMENTAL SETUP AND FIXTURING**

The mediator probes are used in a through transmission setup as shown in Figure 3. The amount of wave energy transferred to a part can be varied by adjusting the angle between the mediator probes upper face and the part surface. The mediator probes can either be affixed at an optimal angle determined by experimentation for receiving the maximum signal, Figure 4, or can be affixed at an angle of near normal incidence with the part surface in order to be used on parts with complex geometries, Figure 5. The attenuation of wave energy due to cracks and defects yields a decrease in the amplitude and an added time delay of the received wave when compared to a defect free section.

![Through transmission setup for crack detection](image3)

Figure 3. Through transmission setup for crack detection.

A MATEC tone burst system is used to pulse the transducers and record the waveform signal. This system allows ultrasonic transducers with high bandwidth to be driven at frequencies other than their natural frequency. The transducers used had a natural frequency of 500 kHz.
TEST SPECIMENS

Test specimens for this study were provided by industry members of the Center for Innovative Sintering Products (CISP) at the Pennsylvania State University.

The first test specimen is a part for a track roller assembly for large-scale excavation equipment. This part is approximately 170 mm long, 66 mm high, and 75 mm wide, see Figure 6. The track roller assembly part had a case history of cracking in the in the thinnest sections of the through hole walls in the part, see Figure 7.

The second test specimen is a 30 tooth green gear with the following dimensions: 33mm outer diameter, 21.4 mm inner diameter, and 6.35 mm thick, see Figure 8. The gear was divided into 15 testing sections in the circumferential direction, see Figure 9.
EXPERIMENT RESULTS

Testing performed on cracked and defect free through wall sections of the track roller assembly part show how cracks attenuate ultrasonic energy. Figure 10 shows the difference in the waveforms between the cracked and defect free section. The cracked section has a significant amplitude reduction and time delay associated with its received wave packet. The signals were acquired at the same gain to visualize the attenuation effect.

The potential exists to be able to measure the crack depth in the through hole wall by using time delay and wave velocity measurements assuming the crack is in area of the part containing no variation in density gradients.
Surface wave testing was completed on each section of a sample green gear as shown in Figure 11.

![Figure 11. Mediator probes at a near incident angle on a gear section.](image)

The wave packet of interest for crack detection in a green gear section is shown in Figure 12. The cracked section has a significant decrease in amplitude in the gated area of the waveform as compared to the defect free section.

![Figure 12. Wave forms of defect free and cracked sections of a green gear.](image)

Plotting the magnitude versus section position of the collected waveforms for each section around the green gear show the location and often severity of the defect area. Figure 13 shows the collected waveforms for the 15 green gear section and the respective magnitudes of the gated waveforms plotted on a normalized circumferential amplitude profile. Sections 3 and 7 of the green gear analyzed contained cracks. The circumferential amplitude profile in Figure 13 shows a significant amplitude reduction in these sections.
Figure 13. Collected waveforms for green gear sections are used to produce a circumferential amplitude profile. Note: Defective regions occur at sections 3 and 7 of the gear.

CONCLUSIONS AND FUTURE RESEARCH DIRECTION

Testing of green parts using the Surface Wave Mediator technique has the ability to detect cracks through amplitude and arrival time changes of wave packets collected using this ultrasonic technique. Defect detection and variations in green part properties can be shown through plot comparing sections of a part with each other such as the circumferential amplitude profile presented for the green gear. Automating the testing process will allow for the quality control of a part’s structural integrity can be completed during the manufacturing process. The development of a single test fixture for a part containing multiple sensors can allow for part inspection in one contact pass. Possible reduction in surface wave mediator probe size could be achieved by using comb transducers made of piezocomposites or PVDF films instead of a piezoelectric transducer and Plexiglas wedge.

REFERENCES