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IMPROVED LASER ULTRASONIC INSPECTION FOR ADDITIVE MANUFACTURING BY INCORPORATING SURFACE PROFILING

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ABSTRACT

Inline inspection of additive manufactured components for subsurface defects using laser ultrasonics (LU) is still technically challenging due to various complicating factors including material microstructure, anisotropy, and surface topography. A new method for determining surface topography during LU inspection is presented that does not require any additional equipment or measurements. The ultrasonic generation laser beam is positioned at an oblique angle to the test surface, while the detection laser beam is normal to the surface. This geometry causes the path length of the ultrasonic head (skimming) and Rayleigh waves, which follow along the surface, to vary with surface profile. Therefore, the variation in wave arrival time can be used to infer the surface profile. The inferred profile can then be compensated for during inline LU data processing to yield greater accuracy in imaging subsurface defects. The method is demonstrated using numerically modelled data as well as experimental measurements.

Keywords: additive manufacturing, laser ultrasonics, surface topography

NOMENCLATURE

AM	additive manufactured
B-scan	LU data of detection amplitude vs t and x
LU	laser ultrasonics
t	time since ultrasonic pulse generation
x	1D position along LU scan
z	height of surface profile or depth of subsurface defect from nominal surface plane

1. INTRODUCTION

Laser ultrasonics (LU) used for inline inspection of additive manufactured (AM) components offers key benefits in being sensitive and non-contact, so that it can inspect components *in situ* during fabrication at high temperature and evaluating at process speeds by LU imaging. LU data are collected in real time by scanning the surface with two laser beams, for ultrasonic generation and detection, separated at the surface by an offset of a few millimeters [1]. The data are then processed, again in real time, to form an image of the material several millimeters below the surface that shows the depth, position and size of localized defects. This type of inspection is preferably carried out on a layer-by-layer basis during fabrication to provide immediate results that can be used in guiding the AM process to ensure that completed components are qualified as free of critical defects.

LU inspection is still technically challenging due to various complicating factors, including material microstructure, anisotropy, and surface topography. In this paper we focus on how surface topography impacts detection and characterization of subsurface pore defects. The height of the surface may vary on the order of one to several millimeters along the path of inspection. Given the high ultrasonic frequencies, and hence high spatial resolution, used in LU inspection, this surface profile needs to be compensated for to avoid significant degradation of the LU image.

2. SURFACE PROFILE ESTIMATION METHOD

It is possible to estimate the profile of a surface undergoing LU inspection directly from the LU data without any additional equipment or measurements, provided the proper laser beam geometry is used. The generation beam is positioned at an oblique angle (typically 45°) to the surface, while the detection beam is normal to the surface, as shown in FIGURE 1. Variation in surface height then causes variation in the distance between the two spots produced by the two beams on the surface. The path length of the ultrasonic head (skimming) and Rayleigh waves, which follow along the surface, thus varies with surface profile. Therefore, the variation in wave arrival time can be used to infer the surface profile. Note that it is not possible to infer the profile if both beams are normal to the surface.

To estimate the surface profile, the arrival time of the head wave pulse is extracted from the LU data, which consists of an ultrasound "B-scan" of LU detector amplitude vs time after pulse generation and 1D position (x) along the scan. The surface profile is parameterized and interpolated to match the arrival times as illustrated in FIGURE **4**1 and described as follows: The intersection of the laser beams with the surface is computed first. Next the wave path length and travel time along the surface are calculated. The travel time difference between calculation and

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measurement is minimized using the least squares method. Using the resulting travel times and numerically inverting the calculations yields the surface topography and the actual positions of ultrasonic generation and detection on the surface. This information is used in an imaging algorithm assuming a homogeneous isotropic medium, but with surface topography.

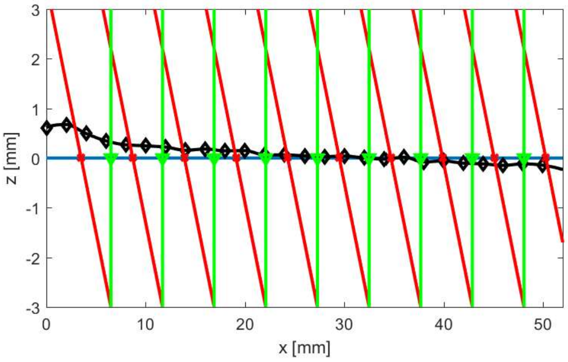

FIGURE 1 ILLUSTRATION OF SURFACE PROFILE PARAMETERIZATION AND INTERPOLATION (AT DIAMOND MARKERS), FOR INTERSECTIONS OF NOMINAL SURFACE PLANE (Z=0) WITH GENERATION BEAM (RED LINE AND "×") AT 45° AND DETECTION BEAM (GREEN LINE AND TRIANGLES) AT NORMAL INCIDENCE.

3. RESULTS AND DISCUSSION

3.1 Numerical simulation

2D numerical finite difference simulations were performed to evaluate the presented concept. The model used is for stainless steel with a randomly varying surface profile and four side-drilled holes with diameter of 0.5 mm at varying depth to simulate subsurface defects, as shown in FIGURE . The surface also includes random roughness to make the model more realistic. An LU measurement scan is simulated by moving the detection spot and generation beam spot, shown in green, along the surface from x = 1 mm to x = 29 mm with an increment of 0.125 mm. The vertical component of the surface velocity is recorded at each increment.

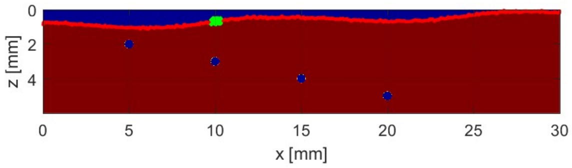

FIGURE 2 SIMULATION MODEL

The recording models are filtered in the wavenumber-frequency domain to remove the Rayleigh wave because for AM applications this is usually considered to be noise. The modelled data are shown in FIGURE 3, which plots a record of ultrasonic pulse arrival time vs mid-point position between the two laser beams. The head wave arrival time is extracted from these data.

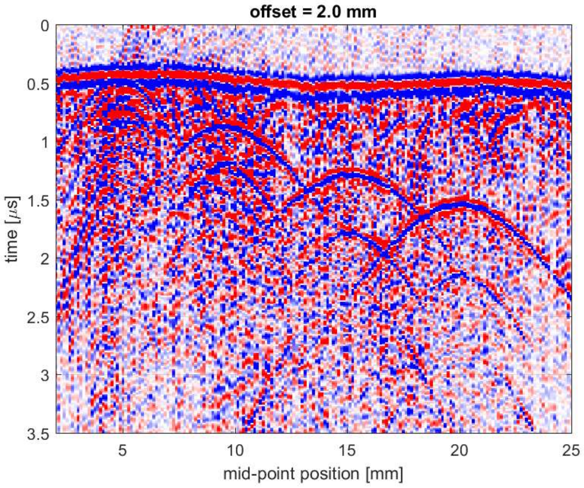

FIGURE 3 MODELLED RECORD SHOWING THE HEAD WAVE (WAVY LINES) AND DIFFRACTIONS FROM THE SIDE-DRILLED HOLES (DOWNWARD HYPERBOLAS).

Using an inversion approach, the time difference between the head wave arrival time from the simulation and the calculated arrival time is minimized. The estimated surface profile is shown plotted onto the model in FIGURE 4. A very good match is seen between the actual surface profile and the reconstructed profile. The numerical modelling results thus confirm the accuracy of the reconstruction of the surface profile.

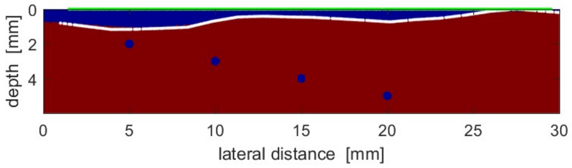

FIGURE 4 ESTIMATED SURFACE PROFILE (WHITE MARKERS) PLOTTED ONTO THE SIMULATION MODEL

In order to evaluate how the surface topography affects the imaging of the defects, the data for a nominal beam offset of 2 mm is shown imaged with and without compensating for the surface tomography in FIGURE . Imaging of the side-drilled holes is seen in FIGURE (a) to be degraded by surface tomography, particularly in the regions where the profile slopes upward. The second hole from the left is imaged as being highly elongated, even though all holes are in fact circular. Moreover, the resolution with which the third and fourth holes from the left are imaged is clearly degraded compared to the case where the topography compensated for FIGURE (b). Compensating for surface topography reduces noise in the image and increase the amplitude of the defect indications, and also improves spatial resolution.

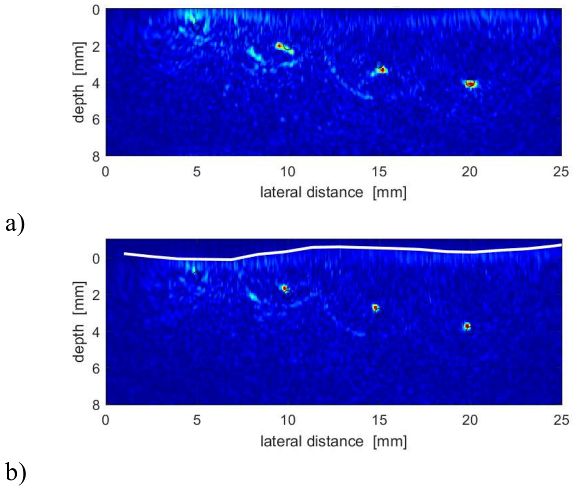

FIGURE 5 IMAGING RESULTS WITHOUT (a) AND WITH (b) COMPENSATION FOR SURFACE TOPOGRAPHY. PARTICULARLY THE DEFECTS BELOW THE SLOPE ARE MUCH BETTER IMAGED.

3.2 Experimental data

Measurements have been performed on an Inconel sample with a number of artificially produced defects. The B-scan data are shown in FIGURE 6. The varying arrival time of the head wave shows that on the left side of the sample there is a significant surface topography. The presented approach is applied to these data. The fitted head wave travel time is shown in FIGURE . The time differences between measurement and model fit are typically on the order of 10 ns. The estimated surface profile is then compensated for in imaging the data in FIGURE **8**8(b). For reference, the image without using any surface topography compensation is shown as well in FIGURE **8**8(a). The imaging of the first defect from the left is seen to be clearly improved. This is the defect that is most affected by the presence of surface topography. Compensating for surface topography is seen again to reduce noise in the image and increase the amplitude of the defect indications, and also improves spatial resolution.

4. CONCLUSION

An LU AM inspection approach has been presented where the test surface topography is estimated from the LU data, without any additional equipment or measurements, and then compensated for in data processing. The concept has been demonstrated using numerically modelled simulation and experimental measurements.

The subsurface image quality is clearly improved by applying this approach. It reduces noise in the image, boosts the amplitude of defect indications, and improves spatial resolution. This makes the image more reliable for detecting and characterizing subsurface defects inline during AM fabrication, thus improving the capability of laser ultrasonic inspection to ensure that completed components are qualified to be free of critical defects.

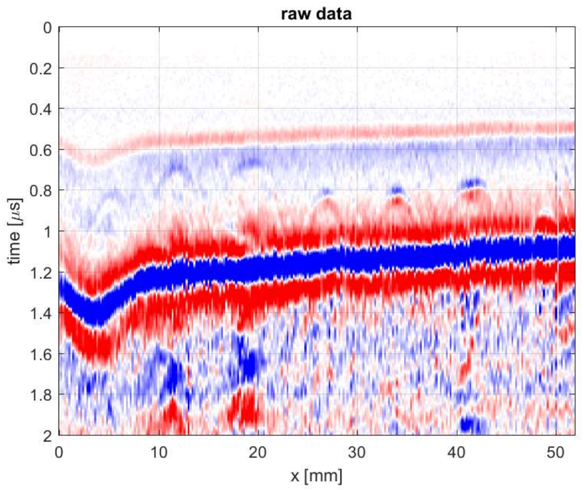

FIGURE 6 RAW LASER ULTRASONIC DATA.

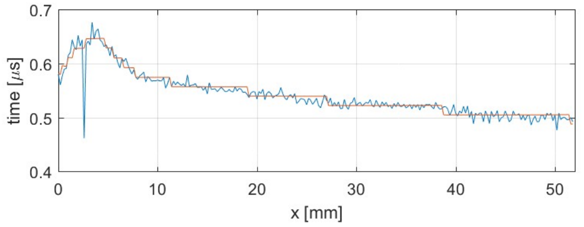

FIGURE 7 FITTED TRAVEL TIME OF THE HEAD WAVE.

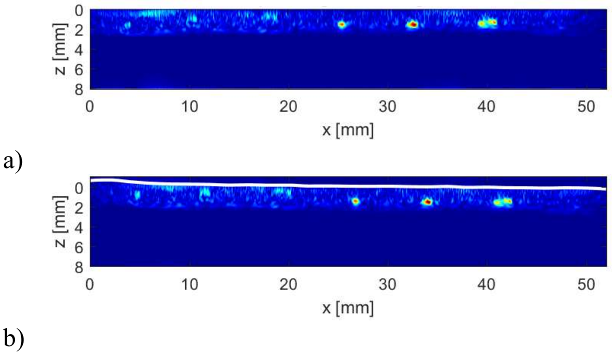

FIGURE 8 IMAGING RESULT WITHOUT (a) AND WITH (b) SURFACE TOPOGRAPHY COMPENSATION

REFERENCE

[1] M. Klein and J. Sears, "Laser Ultrasonic Inspection of Laser Cladded 316L SS and TI-6-4", Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics (2004).