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Influence of Surface Roughness from Additive Manufacturing on Laser Ultrasonics Measurements

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Abstract. Additive manufacturing (AM) is viewed as a revolutionary technique as it offers numerous appealing capabilities such as complex geometries, functionally graded properties, build-upon-demand, repairs, etc. However, in order to attain the full potential of AM, nondestructive testing for quality assurance of AM parts is essential. Laser ultrasound is of particular interest as a nondestructive technique for AM as it provides a viable means of in-situ process monitoring that could ultimately provide feedback for process control. Rayleigh waves generated by a pulsed laser could interrogate the current layer in the AM build and be received by a laser interferometer. The surface roughness is one challenge that must be overcome if Rayleigh waves are to be used for in-situ monitoring. Surface roughness has detrimental effects on the quality of measurements of laser ultrasonics due to factors such as speckle noise, non-uniform reflectivity of the surface, and wave scattering. In this research, we have studied the effects of surface roughness on generation, ultrasonic wave propagation and reception of laser-generated Rayleigh waves. Further investigations on the effects of surface roughness on nonlinear ultrasonic waves are also being carried out.

INTRODUCTION

Amongst many advantages offered by additive manufacturing (AM), reduction of cost due to low wastage of raw materials as compared to conventional subtractive manufacturing is a crucial advantage. However, cost-effectiveness of additive manufacturing process is only realized when the process yields defect-free parts. This is one of the key challenges that is hindering the proliferation of AM; mainly due to high complexity of the process and lack of in-situ nondestructive evaluation techniques.

In recent years, development of in-situ nondestructive techniques for process monitoring of AM has gained lot of attention in the research community[1-7]. Laser ultrasonics is considered as a suitable technique for in-situ AM inspections due to its many advantages such as non-contact generation and detection of ultrasonic waves, operation in hostile environments, generation and detection over a wide range of frequencies. However, laser ultrasonic measurements are greatly affected by surface roughness and it is well known that AM parts have high surface roughness[8]. Thus, it is crucial to study the effect of surface roughness on laser generation, reception and wave propagation.

In the past few decades, numerous researches have investigated Rayleigh wave propagation along the rough surface of an elastic solid. Maradudin and Mills[9] used a Green's Function method to study the attenuation mechanism by rough surface using Rayleigh waves. Kosachev and Shchegrov[10] developed dispersion equations for a rough surface of an anisotropic medium. Theoretical models correlating the wavelength of the Rayleigh wave and the correlation length of the surface have been developed[11]. Despite the definite progress in theoretical studies of the problem, there are fewer experimental papers validating the theoretical results. Krylov and Smirnova[12] experimentally studied the effect of variation of phase velocity due to two-dimensional and three-dimensionally rough surfaces. Hassan *et al.I*[13] experimentally investigated the dispersion of Rayleigh waves on a randomly rough surface. Ruiz and Nagy[14] measured the dispersion of Rayleigh waves by rough surfaces due to different shot-peened levels.

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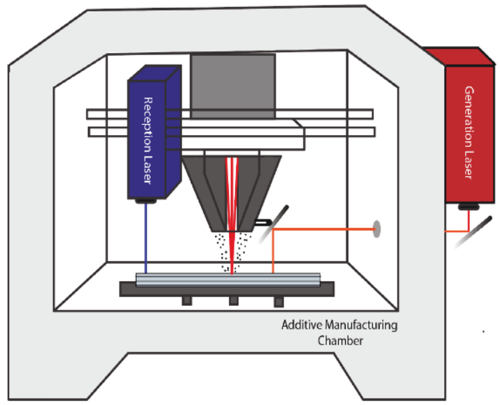

FIGURE 1. Schematic of in-situ layer-wise AM inspection using laser ultrasonics

Typically, in laser ultrasonics, an Nd:YAG pulsed laser is employed for generation of surface waves using the thermo-elastic effect and a laser interferometer is used for wideband reception of surface waves. The received surface waves could be analyzed to obtain information about the material state of the first few layers of AM. Thus, in-situ laser ultrasonic testing provides an opportunity to inspect the AM part as it is processed. We envision an in-situ laser ultrasonic technique for quality assurance of AM with potential to provide a closed-loop process control. A specially designed dual-frequency slit mask would allow narrowband generation of Rayleigh waves using a setup as depicted in Figure 1. Furthermore, the proposed technique could leverage nonlinear wave mixing of laser generated Rayleigh waves for layer-upon-layer inspection. The attenuation and nonlinear features thus obtained could allow assessment of strength through inferences about the microstructure, while wave speed measurements would permit assessment of elastic constants of AM parts.

In this research, we study the influence of surface roughness on laser generation, laser reception and Rayleigh wave propagation separately using three different setups. Furthermore, as it is sometimes required to scan the laser in order to receive Rayleigh waves at different propagation distances, two scanning strategies viz. keeping the generation laser fixed and moving the reception laser and vice versa, are studied based on the consistency of data. Firstly, the three experimental methodologies are briefly discussed. Secondly, results and observations are discussed in detail. Finally, the paper ends with the key conclusions.

EXPERIMENTAL METHODOLOGIES

Effect of Surface Roughness on Laser Generation, Laser Reception and Wave Propagation

Figure 2 (A) shows the experimental setup developed to study the influence of surface roughness on laser generation of Rayleigh waves. A 532 nm Nd:YAG pulsed laser (Continuum®, San Jose, CA, USA) is used for generation of Rayleigh waves on a Ti-6Al-4V sample having dimensions 50 × 25 × 6 mm. A slit mask is used for narrowband generation of Rayleigh waves of primary frequency 2.5 MHz. A wedge based broadband transducer of central frequency 5 MHz is used for reception of Rayleigh waves at 17 mm from the laser generation. The surface roughness where the laser irradiates the surface of the sample (under the slit mask), was varied using emery paper of varied grit size – 60 (high roughness), 150 (low roughness), 1500 (smooth).

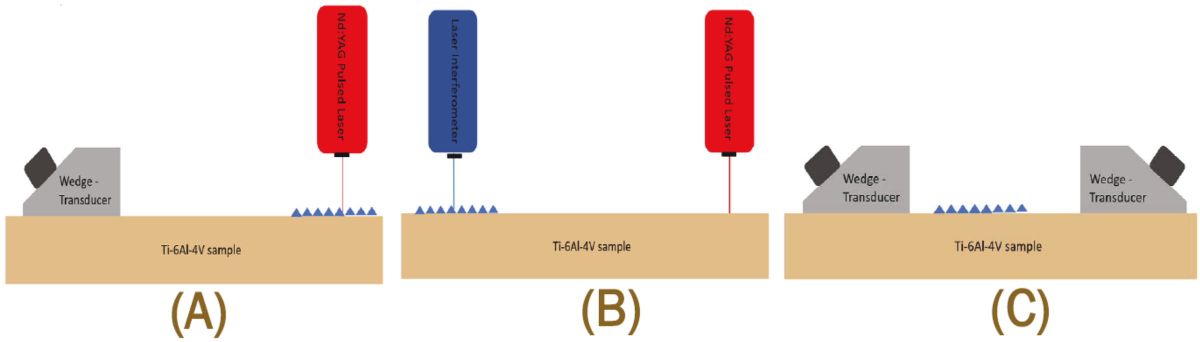

FIGURE 2. Schematic of the experimental setup used to study the effect of surface roughness on (A) laser generation (B) laser reception (C) wave propagation

Figure 2 (B) represents, schematically, the setup used to study the effect of surface roughness on laser ultrasonic reception. Generation of Rayleigh waves by an Nd:YAG laser is carried out as previously descried. A Polytec OFV 505 broadband laser vibrometer (Polytec GmbH, Waldbronn, Germany) is used for reception of Rayleigh waves. The surface roughness of the surface of the sample irradiated by the generation laser is kept smooth, whereas the surface roughness, where the reception laser is focused, is varied using emery paper as previously described. Before the results are discussed in the next section we note that the Polytec laser vibrometer uses a heterodyne interferometer based on Doppler effect, which is highly susceptible to the speckle pattern created by a rough surface. However, other laser interferometers such as Fabry-Perot, two-wave mixing, and multiple quadrature interferometer have better performance for reception from rough surfaces.

Lastly, a wedge-transducer arrangement is used to study the effect of surface roughness on wave propagation of Rayleigh waves and its higher harmonic components with the setup shown in Figure 2 (C). Rayleigh wave generation was obtained using a 2.25 MHz nominal frequency narrowband transducer excited at 2.5 MHz. A 5 MHz central frequency broadband transducer was used to receive the primary Rayleigh waves (2.5 MHz) as well as its second (5 MHz) and third (7.5 MHz) harmonic components. The distance between the generation and reception wedges was kept constant at 20 mm. The surface roughness of the sample between the two wedges was varied from coarse to mirror-like using emery paper of decreasing grit size – 60, 150, 400, 800, 1500 and mirror-like. The results are discussed in the following section.

Effect of Surface Roughness on Laser Scanning

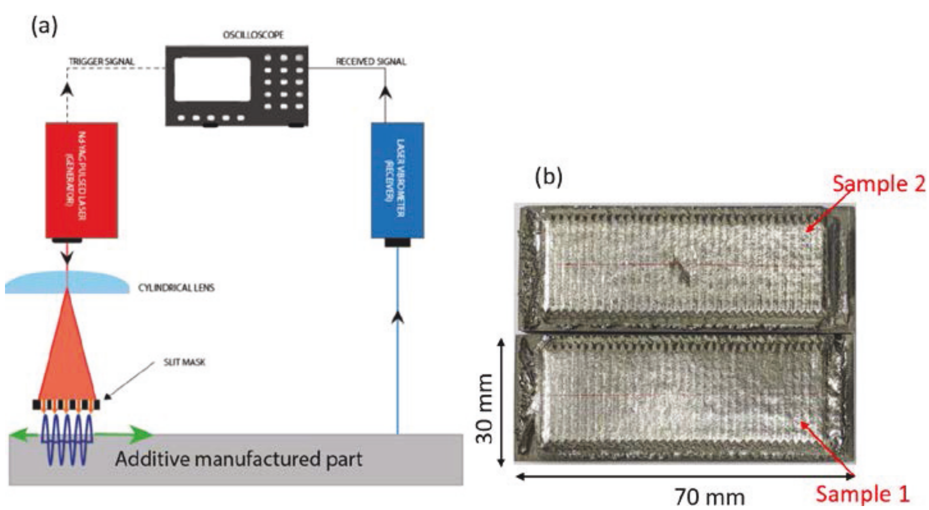

FIGURE 3. (a) Schematic of the experimental setup for laser-based narrowband Rayleigh wave generation using slit mask and out-of-plane laser reception (b) Photo of Ti-6Al-4V samples manufactured by direct energy deposition additive manufacturing process

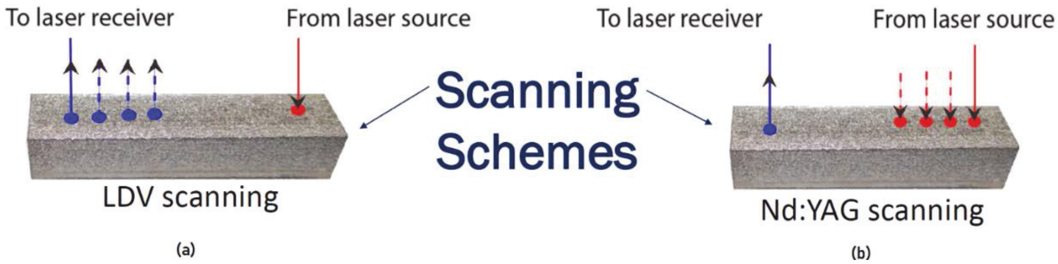

FIGURE 4. (a) Linear scanning scheme with LDV moving and Nd:YAG fixed, (b) Linear scanning scheme with Nd:YAG moving and LDV fixed

Figure 3 (a) is a schematic of the experimental setup developed to study whether scanning of the generation or reception laser produces more consistent results. For this purpose, in the first case, the generation laser was kept fixed and the reception laser was scanned in the direction of Rayleigh waves propagation as shown in Figure 4 (a). In the second case, the reception laser is kept fixed while the generation laser was scanned in the direction of propagation of Rayleigh waves, refer Figure 4 (b). The out-of-plane displacements were obtained from 15 mm to 30 mm away with 5 mm increments from the generation. The experiments were conducted on direct energy deposition additive manufactured Ti-6Al-4V samples shown in Figure 3 (b).

RESULTS AND DISCUSSION

Results for the experimental setup shown in Figure 2 (A) are discussed first. The results are averaged over four experimental trials. Figure 5 shows three A-scans of the out-of-plane displacement of Rayleigh waves generated by a pulsed laser incident separately on surfaces with three different surface roughness. It can be observed that the high surface roughness results in higher amplitude Rayleigh wave generation, whereas, the smooth surface results in lower amplitude.

When a pulsed laser is incident on the surface of material, thermal energy is absorbed at the surface. Absorption of thermal energy causes the small volume of the material near the surface to expand and contract rapidly, which leads to ultrasonic wave generation. The increase in amplitude for rough surfaces can be attributed to higher absorption of thermal energy due to multiple reflections. This observation is consistent with the previously established result that higher surface roughness leads to higher absorption of thermal energy[15].

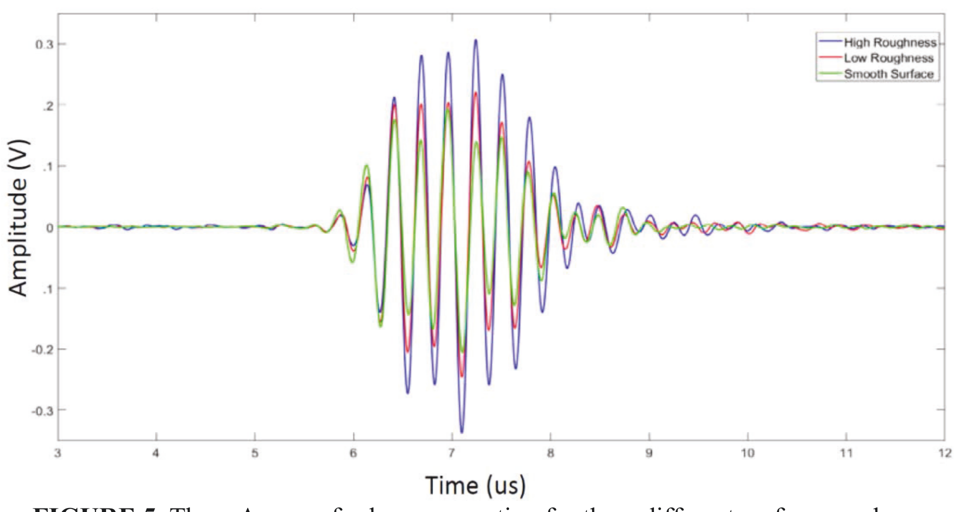

FIGURE 5. Three A-scans for laser generation for three different surface roughness

Figure 6 shows the results for the experimental setup studying the effect of surface roughness on laser reception of Rayleigh waves; refer to Figure 2 (B). Figure 6 represents three A-scans for laser reception on surface with high roughness, low roughness and smooth surface respectively. Note that the A-scans for low roughness and smooth surface are displaced by -0.02V and -0.04V in amplitude in order to represent them in the same plot. The calculated values of the SNR were 2.4, 4.33, and 8 for the high roughness, the low roughness and the smooth surface respectively. The SNR was calculated as the ratio of peak to peak amplitude of the signal and the noise. It can be observed that the A-scan with high surface roughness has lowest signal-to-noise ratio (SNR) and high noise level, whereas the A-scan for smooth surface has higher SNR and lower noise level. This is because the surface with higher roughness induces higher speckle noise in the signal received by the reception laser. Moreover, focusing of reception laser is difficult on a rough surface, which causes reduction in signal amplitude and increase in noise level.

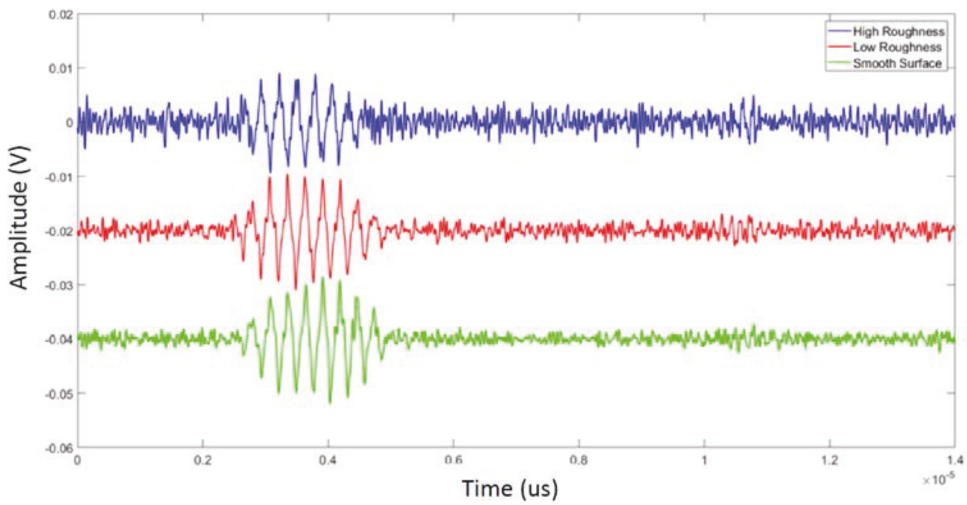

FIGURE 6. A-scans showing higher noise level for higher surface roughness for reception of surface waves using laser

Figure 7 shows the results of the experiments performed to study the effect of surface roughness on Rayleigh wave propagation, refer Figure 2 (C). Figure 7 shows the frequency domain amplitudes for the fundamental (2.5 MHz) Rayleigh wave, and its second (5 MHz) and third (7.5 MHz) harmonic components for different roughness levels obtained by fast Fourier transform of windowed wave packets in the A-scans. The amplitudes are normalized with respect to the amplitudes obtained for the mirror-like surface finish.

It can be observed that the amplitude of the fundamental and higher harmonics initially increases to a peak value and then decreases with the increasing surface roughness. This behavior can be related to the theoretical results in[10,11]. The theoretical models developed in[10,11] predict an overall decrease in amplitude with increase in the surface roughness, but a peak amplitude is also anticipated at frequencies where the Rayleigh wavelength is comparable to the correlation length of the surface. However, further experiments need to be conducted to conclude the observations.

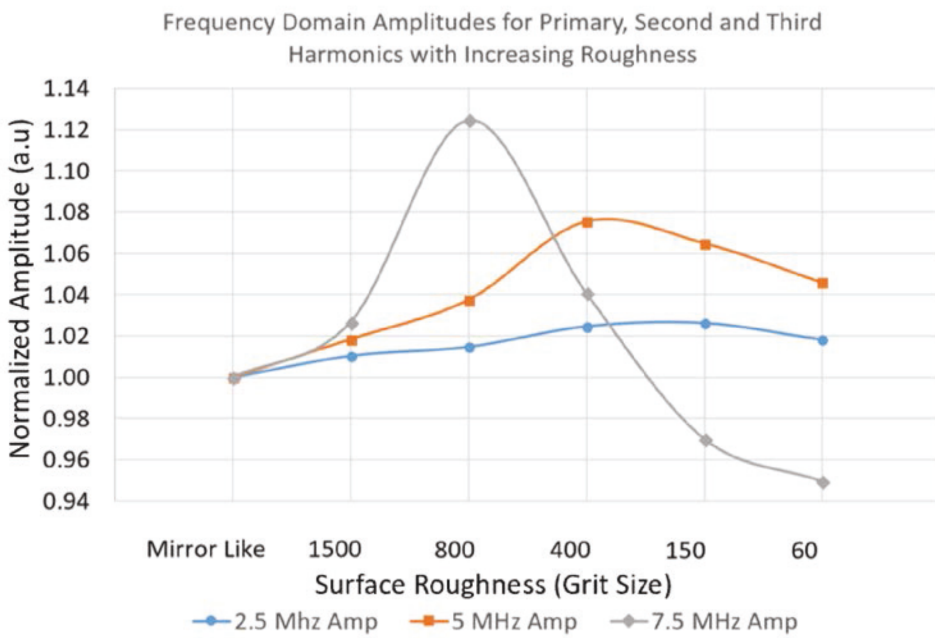

FIGURE 7. Plot of normalized frequency domain amplitude for fundamental (2.5 MHz), second harmonic (5 MHz) and third harmonic (7.5 MHz) wave at different surface roughness levels

The evaluation of scanning schemes based on the consistency of obtaining data is carried out. Variability from the trendline plotted for the decrease in amplitude with respect to the increase in propagation distance and variability in the SNR are used as the deciding factors for checking the consistency of the scanning scheme. The results obtained for the two samples manufactured by direct energy deposition additive manufacturing technique are shown in Figure 3 (b). Figure 8 and Figure 9 show the plots of frequency domain amplitude of the laser generated narrowband Rayleigh waves at 2.5 MHz frequency versus propagation distance. The results are obtained by linear scanning along the direction of propagation of the Rayleigh waves.

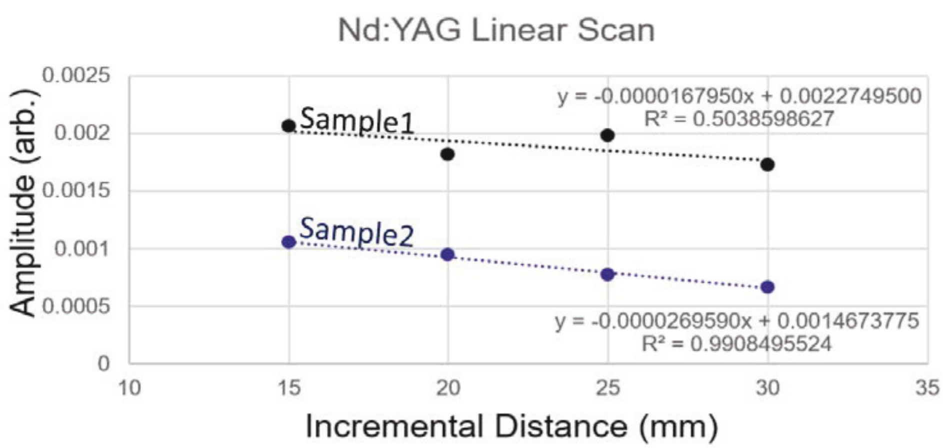

FIGURE 8. Plot of Frequency domain amplitude versus propagation distance for Nd:YAG (generation laser) scanning

Firstly, the decrease in amplitude with increasing propagation distance can be observed for both the samples for Nd:YAG scanning as well as LDV scanning cases. This is due to the loss of energy due to attenuation and scattering. Furthermore, it can be observed that in both Figures 8 and 9, the amplitudes obtained for Sample 2 are lower than Sample 1. This is due to the presence of a visible defect on the surface of Sample 2, refer to Figure 3 (b). This demonstrates the capability of the laser-based non-contact setup for detection of surface defects on AM sample. Also, it can be observed that the R^2 values for the linear scan using Nd:YAG laser (LDV is kept fixed) are more than the

R^2 values for the linear scan using LDV laser (Nd:YAG is kept fixed). Additionally, signal-to-noise ratio was calculated for the Nd:YAG scanning and LDV scanning cases. Results are provided in Figure 10. Note that the signal to noise ratio was calculated as the ratio of area under the bandwidth 2.4 MHz to 2.6 MHz and area under the noise level i.e. 0 MHz to 2 MHz and 3 MHz to 4 MHz in the frequency domain plot. Although the averaged SNR for both - Nd:YAG scanning and LDV scanning cases - are similar, the error bars indicate that the variability of SNR is higher in the case of LDV scanning. Thus, the aforementioned results indicate that Nd:YAG scanning yields more consistent data as compared to the LDV scanning.

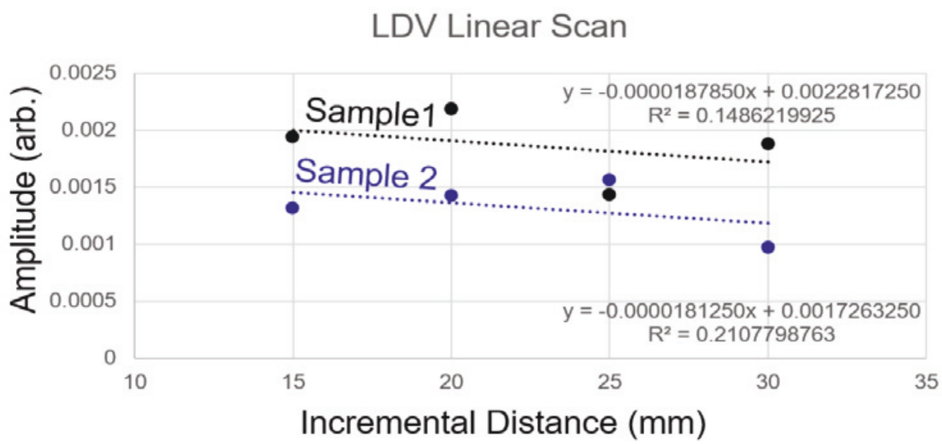

FIGURE 9. Plot of Frequency domain amplitude versus propagation distance for LDV (reception laser) scanning

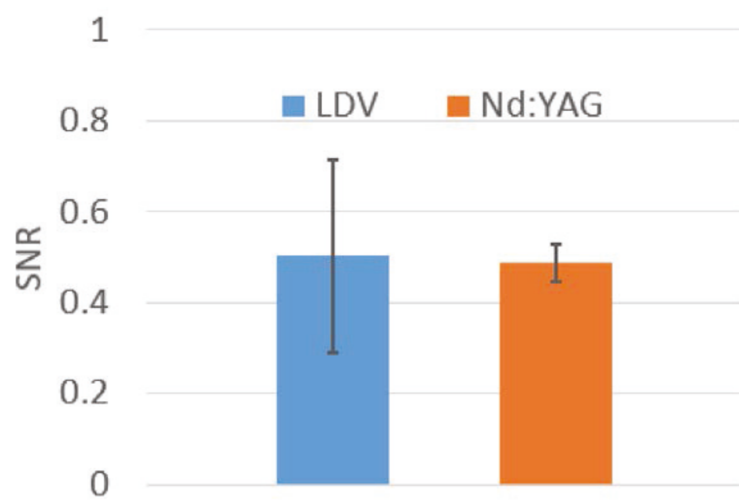

FIGURE 10. SNR for LDV scanning and Nd:YAG scanning schemes

CONCLUSIONS

This work demonstrates the effect of surface roughness on laser generation, laser reception, and wave propagation. The crucial insights obtained in this research include increase in signal amplitude of laser generated Rayleigh waves with increase in roughness level, increase in noise level and reduction in SNR with increase in roughness level for laser reception of out-of-plane displacement of Rayleigh waves, and effect of surface roughness on fundamental and higher harmonic waves. Moreover, it is typically required to perform linear scans along the direction of propagation of Rayleigh surface waves to observe the behavior of fundamental and harmonic components and measurement of material nonlinearity. In this regard, the performed experiments indicate higher consistency and reliability of obtaining data with Nd:YAG scanning as compared to the LDV scanning. These insights are of particular importance for in-situ implementation of laser based nondestructive evaluation of additive manufacturing.

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