Application of Ultrasonic Guided Waves for Surface Roughness Measurement

Jahanbin, M., Santhanam, S., Ihn, J.B. and McMillan, A

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Authors: Mark Jahanbin
Sridhar Santhanam
Jeong-Beom Ihn
Alison McMillan

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ABSTRACT

Surface roughness is inherently a product of manufacturing process and is often undesirable. In surface metrology, the term “roughness” is typically applied to the high-frequency and short-wavelength parameters of a finished surface. In practical applications, the surface roughness is directly associated with the quality of the manufacturing. This study proposes the use of ultrasonic surface guided waves to characterize the surface roughness amplitude and frequency during the manufacturing process. Finite element modeling (FEM) of acoustic wave propagation along a rough surface has revealed that there is a cut-off threshold for Rayleigh wave propagation, which is indicative of the surface roughness description. This cut-off occurs for a particular ratio of the spatial surface waviness and the acoustic wavelength, and the detection of the resulting wave attenuation and decay characterizes the surface roughness. If such a measurement system can be used in-line with the production process then it could signal adjustment of the material deposition rate when needed to achieve the required product quality.

INTRODUCTION

Roughness is often a good predictor for the performance of mechanical components in both subtractive and additive manufacturing processes. Typically the irregularities on the surface finish may form nucleation sites for cracks and corrosion. Fatigue is a surface phenomenon and high surface roughness increases the crack growth initiation possibility. Also roughness plays an important role in material interaction with the environment such as corrosion. The surface roughness is also a particular challenge in manufacturing of 3D printed parts. The majority of additive manufacturing methods are constructing the parts geometry by layered deposition of the material. The quality of final product after post processing depends on surface roughness which is a drawback in some application such as high fatigue cycle components.

Mark Jahanbin, Villanova University, 800 E. Lancaster Avenue Villanova, PA 19085, USA
Sridhar Santhanam, Villanova University, 800 E. Lancaster Avenue Villanova, PA 19085, USA
Jeong-Beom Ihn, Boeing Research & Technology 9725 Marginal Way Tukwila, WA 98108 USA

Alison McMillan, Wrexham Glyndwr University, Mold Road, Wrexham, LL11 2AW, UK

This study proposes a novel in-line ultrasonic inspection technique using high frequency ultrasonic Rayleigh waves to characterize the surface roughness parameters during AM component manufacture.

Eguiluz and Maradudin used mathematical model on the basis of Rayleigh's method and the effect of surface roughness on the dispersion relation of a Rayleigh wave on an isotropic medium has been studied [1]. Other researchers have explored experimental approaches to investigate wave propagation problem over rough surfaces. Krylov and Smirnova perform experimental study of the attenuation and dispersion of a Rayleigh wave on a rough surface [2]. The shortcoming of such an experimental approach is that it is practicable create sufficient test specimens to investigate the attenuation and dispersion for a wide range of roughness parameters. In the present study a computational approach to investigate the influence of surface roughness parameters on Rayleigh wave propagation. The method uses surface wave energy loss and attenuation to characterize surfaces roughness. Other wave parameters such as the rate of wave speed changes can also be used to measure surface roughness profile.

SURFACE ROUGHNESS PARAMETERS

The quality of machined surface is characterized by the precision of its manufacture with respect to the dimensions, tolerances and other characteristics specified by the designer. Every manufacturing operation leaves characteristic evidence on the surface. For example, in machining this evidence appears in the form of finely spaced micro irregularities left by the cutting tool.

Roughness consists of surface irregularities which result from the various manufacturing processes. These irregularities combine to form surface texture and are illustrated in Figure 1. The roughness width ($\lambda_{surface}$) is the distance parallel to the nominal surface between the successive peaks or ridges constituting the predominant roughness pattern roughness. The roughness height, also known as the height of unevenness, is the height of the irregularities with respect to a reference mean-line.

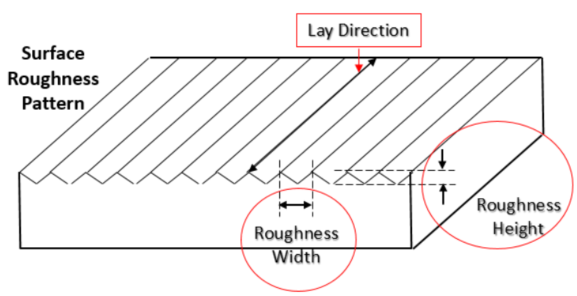

Figure 1: surface characteristics

The "Lay" represents the direction of predominant surface pattern produced and it reflects the manufacturing operation used to produce it. "Waviness" refers to widely spaced irregularities outside the roughness width cut off values, and which may be the result of work piece or tool deflection during machining, vibration or tool run-out.

Waviness height is the peak to valley distance of the surface profile, measured in millimeters.

Any surface irregularities and welling up and down due to manufacturing has different roughness definition such as waviness, wrinkle and kink for fiber composites. Regardless a uniform form of roughness is used in this study and the modeling technique explained in the next section.

ROUGHNESS COMPUTATIONAL MODELING AND SIMULATION

The explicit dynamic solver of Abaqus 2016 is used to mode the propagation of US acoustic waves through a work piece with a surface for which the roughness has been modelled.

The surface roughness can be described as fractal down to a limiting length scale which for practical purposes can either be considered a FEA mesh scale cut-off or a limit to the resolution of surface scan metrology [3]. A representative FE model is constructed of a rough surface with a series of uniform deviations are defined from the normal surface in 2D to model roughness.

Then a numerical study has been performed with finite element simulation of guided wave propagation on surfaces with different roughness parameters. Series of FE model with Dynamic Explicit solver of Abaqus software has been used to demonstrate the wave behavior based on the surface roughness.

In the propose roughness, the distance between successive peaks assumed to be in x and height of unevenness in z direction, demonstrated in figure 2. The geometrical algorithm in which the surface metrology is defined, are regular surface corrugations.

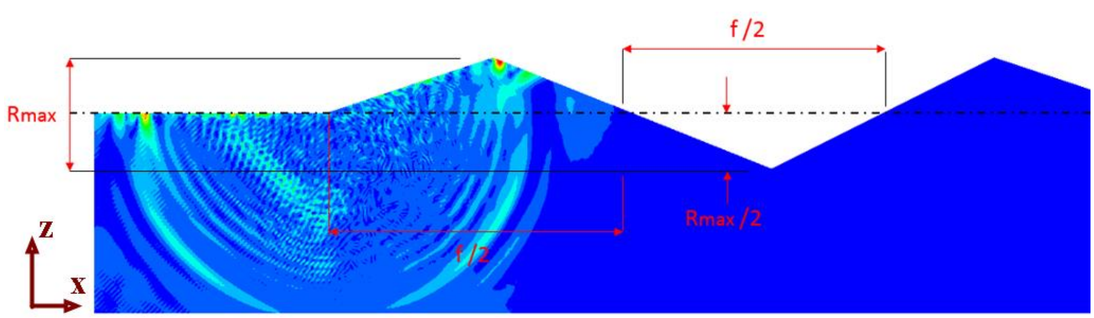

Figure 2: Rayleigh wave propagation on rough surface

Several FEM model have been constructed with different surface roughness factors. The Rayleigh wave frequency in all models is the same as incident pulse wave on figure 3 with 1MHz frequency. The vertical size of roughness irregularities are identical in all model where Rmax = λwave = 0.254 mm.

The initial incident wave pulse used in this study is formed by taking a Hanning window of one micro second (μs) time period and applying it to a sinusoidal wave with a frequency of 1 MHz. Then time history domain amplitude of the incident wave is changed to produce different surface wave at different wavelength.

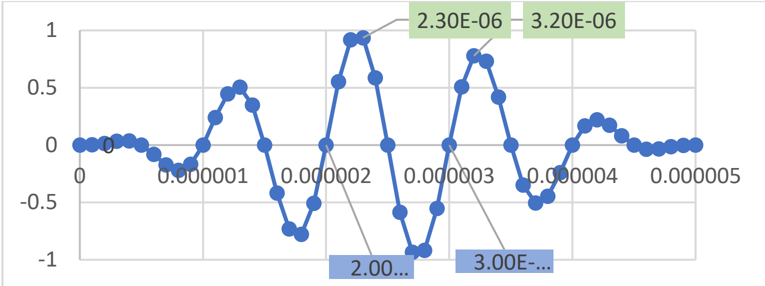

Figure 3: Hanning windowed incident wave signal at T = 1 μs → f = 1 MHz.

WAVE PROPAGATION ON ROUGH SURFACE

The surface wave partial attenuation and the rate of the wave front energy loss is measured by the data extracted from Displacement – Time curve. For example in figure 4, the point a is located on the rough surface and the displacement – time curve shows the surface wave front reaches at this point 13.9 μs post incident wave signal initiation. This curve can be used to measure the time of flight for any point on the surface and monitor the displacement magnitude to measure the partial or total surface wave attenuation. Typically the time-of-flight, or the time the wave front propagate the rough surface is higher than Rayleigh wave propagation on the smooth surface with no irregularities. The increase in time of flight can be interpreted as the increase in the propagation path and wave refraction along the surface roughness profile.

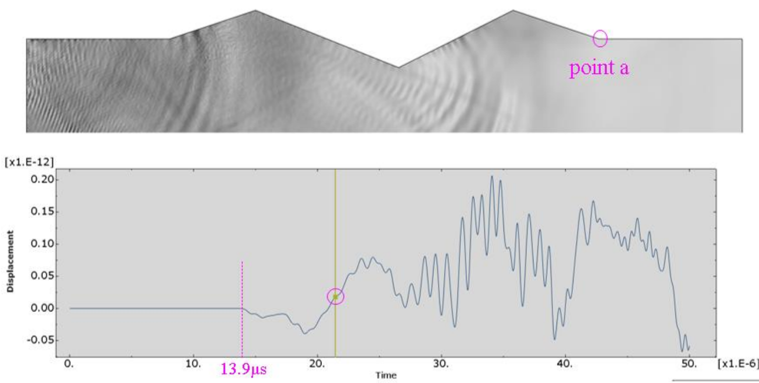

Figure 4: surface wave displacement (in) – time (μs) curve

The Rayleigh wave propagates over the surface of solid media and gradually loses its energy due to roughness profile while there is no discernable energy loss on the smooth surface. Figure 5 shows the attenuation of surface wave relative to the surface profile parameters. The wave packet on the rough surface decay by interfering the roughness pattern. The roughness profile and the magnitude of R_{max} and feed can cause immediate or partial attenuation of the wave. If the height distance of R_{max} / 2 is higher than Rayleigh wavelength, then the surface wave will not form at all and wave front reflect immediately. But for the frequency spectrum ranging less than one wavelength where $R_{max} < \lambda_{surface}$, the surface wave forms and propagate but eventually damped at certain distance along the rough surface.

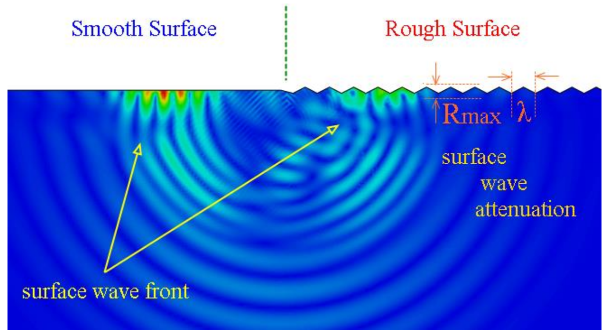

Figure 5: Rayleigh wave propagation on smooth surface vs. rough surface

There is a cut-off wavelength that can be described as a ratio between surface wavelengths over incident wavelength, λsurface / λwave at which the Rayleigh wave does not form. The surface waves attenuate at any point beyond this cut off wavelength value. The higher the magnitude of the surface wavelength, λsurface, the greater the wave attenuation. In general observation of the results there is total attenuation if the ratio is 0.1 and no attenuation if the ratio is 1. The partial attenuation of the Rayleigh wave in the range of 0.1 < λsurface / λwave < 1 has been investigated in results section.

RESULTS

The effect of ratio of surface roughness wavelength to the Rayleigh wavelength is summarized. If the value of $R_{max} / 2$ is higher than Rayleigh wavelength, the surface waves reflect and shall not propagate on the rough surface. The other factor for total or partial wave attenuation due to roughness is the ratio of λsurface / λwave. Simultaneously the surface waves decay and propagate relatively slower on the rough surfaces. The rate in which the time of flight (TOF), or the measured time when wave form travels on the surface, depends on roughness profile.

Several models are constructed to verify surface wave propagation on rough surfaces. The incident wave frequency and corresponding wavelength is identical for all the models and described in figure 3. The typical numerical value for the material used for this FEM simulation is shown in Equation 1 where λ_R is wavelength, f is the frequency, V_R and V_T are Rayleigh and transverse wave velocity respectively.

Equation 1: incident wavelength

$$\lambda_R = \frac{V_R}{f} = \frac{V_T\left(\frac{0.87 + 1.12\nu}{1+\nu}\right)}{f} = \frac{\sqrt{\frac{G}{\rho}}\left(\frac{0.87 + 1.12\nu}{1+\nu}\right)}{f} = \frac{\sqrt{\frac{26.5 \times 10^9}{2.7 \times 10^3}}\left(\frac{0.87 + 1.12 \times 0.3}{1 + 0.3}\right)}{1000000} = 2.91 \text{ mm}$$

Where:

E = 68.9E+9 Pa   G = 26.5E+9 Pa

ρ = 2.70E+03 kg/m3 $\nu = 0.30$

The only changing geometrical parameter in the modeling is the roughness profile by changing the irregularities peek to peek distance or λsurface, where λsurface = 0 represents the surface with no roughness (smooth surface). For simplicity the ratio of λsurface / λwave has been used to measure the amplitude lost at specific time (decay) and decay over time scale of the models (attenuation). Figure 6 shows the wave form when λsurface / λwave = 1 and figure 7 is demonstrating the ratio for λsurface / λwave = 0.5

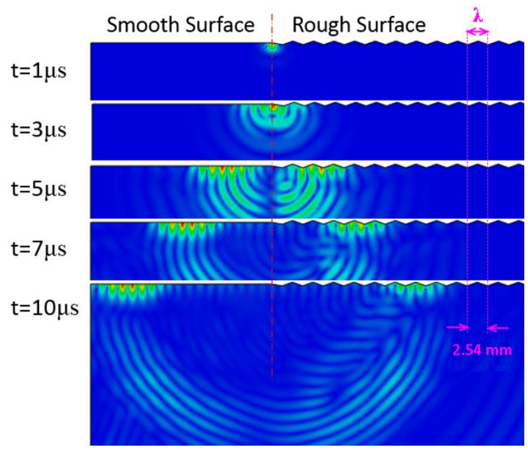

Figure 6: surface wave propagation where λsurface / λwave = 1

For example in case of λsurface / λwave =1 where λsurface = λwave = 2.54 mm the surface is considered to be relatively smooth. The attenuation in this case is negligible because the surface wave propagates with no discernable reflection and very small refraction shown in figure 5. While the ratio of λsurface / λwave decreases, the surface is becoming rougher and surface wave form is gradually changing.

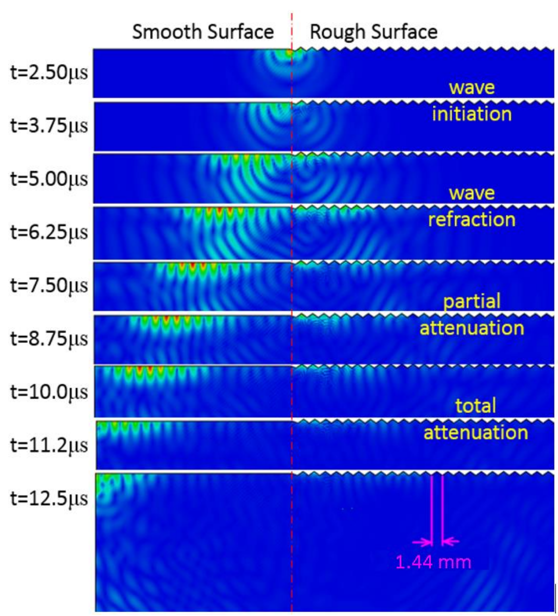

Figure 7: surface wave attenuation where λsurface / λwave = 0.5

The attenuation of surface wave starts at a certain wavelength cut-off ratio. The threshold for 1MHz incident wave appears to be at the ratio of 0.5, i.e. λsurface / λwave = 0.5. If the wavelengths ratio lower than 0.5 threshold, the wave forms won't form on the rough surface. On the other hand for the ratio higher than 0.5 the wave front propagate to certain distance and then surface waves disappears. The distance between roughness irregularities or λsurface at the cut-off ratio of 0.5 is 1.44 mm.

CONCLUSIONS

The propagation of Rayleigh wave on series of rough surfaces have been modeled and studied by finite element simulation. The surface wave propagation attenuation and decaying rate has been used to determine the cut-off ratio where the wave forms do not form due to roughness intensity. The cut-off ratio appears to be at a threshold when λsurface / λwave = 0.5. The results of this study can be used to define a quality method to inspect the roughness requirements for manufacturing applications. The cut-off wavelength and effective frequency of inspection can be customized for different roughness profile. This is particularly an effective approach to measure the quality of 3D printed components with different present and future additive manufacturing technologies.

REFERENCES

1. 'Frequency shift and attenuation length of a Rayleigh wave due to surface roughness' A. G. Eguiluz and A. A. Maradudin, Phys. Rev. B 28, 728 – Published 15 July 1983
2. 'Experimental investigation of Rayleigh wave dispersion on a rough surface' Victor V. Krylov Z.A. Smirnova, Soviet Physics Acoustics 36(6):583-585 November 1990
3. 'A computational study of the influence of surface roughness on material strength' Alison McMillan, Rhys Jones, Daren Peng & Gregory A. Chechkin - An International Journal of Theoretical and Applied Mechanics AIMETA. ISSN 0025-6455 – "Meccanica" VOL 53 2018
4. Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS) 'Interface Waves in Hybrid Metal-Composite Structures', ASME 2016 Stowe, Vermont SMASIS2016-9007 Vol1, pp. V001T05A002; Jahanbin, Santhanam, Ihn
5. SPIE Smart Structures + Nondestructive Evaluation 'Application of Interface Waves for near surface damage detection in hybrid structures' SPIE Portland, OR 2017 1016996_ProcSPIE_SS17- SSN08-35 Jahanbin, Santhanam, Ihn, Bossi, Cox
6. International Committee on Aeronautical Fatigue and Structural Integrity ICAF 'Application of Interface Guided Waves for Structural Health Monitoring of Hybrid Bonded Joints', International Committee on Aeronautical Fatigue and Structural Integrity (ICAF2017 – Nagoya Japan) Jahanbin, Santhanam, and Ihn. BTJ
7. International Workshop of Structural Health Monitoring System - IWSHM 'Application of Interface Waves for Damage Detection in Laminated Composite Bends' International Workshop of Structural Health Monitoring (IWSHM2017) Stanford, CA , Jahanbin, Santhanam, Ihn and Desai.
8. Additive Manufacturing Certificate Program, Boeing - Massachusetts Institute of Technology (MITxPro 2017)

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