Nonlinear Ultrasonic Techniques for the Quantification of Dislocations and Residual Stress Fields in Additive Materials

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Motivation

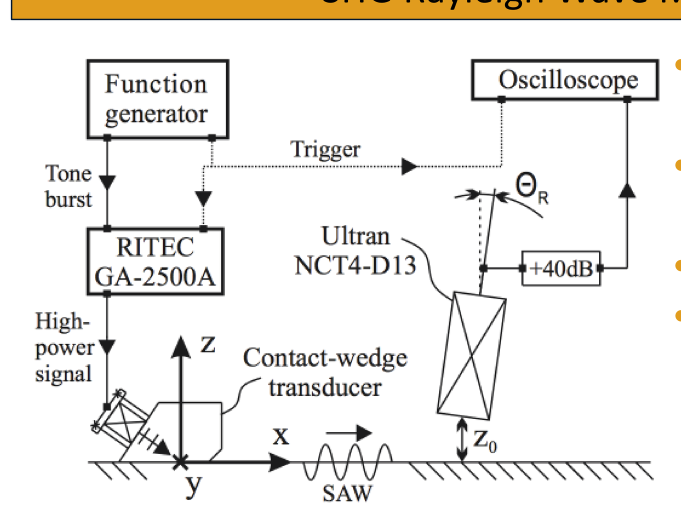
- Microstructure/material properties of **additive manufactured (AM)** parts strongly depend on:
  - Print rate
  - Cooling rate
  - Bulk material properties
  - Manufacturing method
- **Residual stress** in AM parts is often high **compared to wrought** manufactured materials because of large temperature gradients
  - Can unintentionally contribute to inhomogeneity of material performance in a part
- Dislocations provide a mechanism for plastic deformation
  - Higher **dislocation density** corresponds to harder metals
- **Non-linear ultrasonic** (NLU) techniques may help decide to reject a printed part or apply post-manufacturing heat treatments
- **Second harmonic generation** (SHG) technique will be used to measure the acoustic nonlinearity parameter β which is sensitive to microstructural characteristics
- Due to relatively large grain size, ultrasonic **attenuation measurements** are expected to be an important means to quantify grain-size variations.

Objectives

- Investigate the applicability of NLU for quantifying dislocation density and residual stress fields in AM metals
- Perform a parametric study of the correlation of process variables and microstructure
- Measure **attenuation** and investigate grain-size variations from AM
- Isolate nonlinear effects of dislocations by reducing residual stress with **stress-relief annealing**
- Relate microstructure detected by NLU to macroscopic properties

Setup

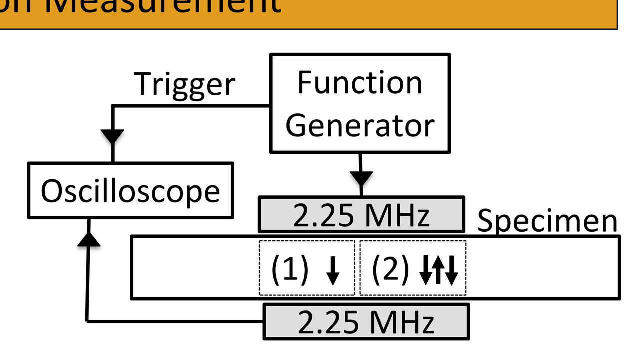
SHG Rayleigh Wave Measurement



- Function Generator: **2.1 MHz, 20 cycles** Tone Burst
- RITEC 2500GA: Gated High Power Amplification **710Vpp**
- Source : Parametrics V106
- Receiver: Ultran NCT4-D13 **air-coupled** transducer to detect Rayleigh waves

Relative Attenuation Measurement

- Function Generator: **8-20 MHz**, 20 cycles, Tone Burst
- Pulser/Receiver : CTS Valpey DR202 - 20 MHz
- Based on amplitude decrease between (1) and (2)



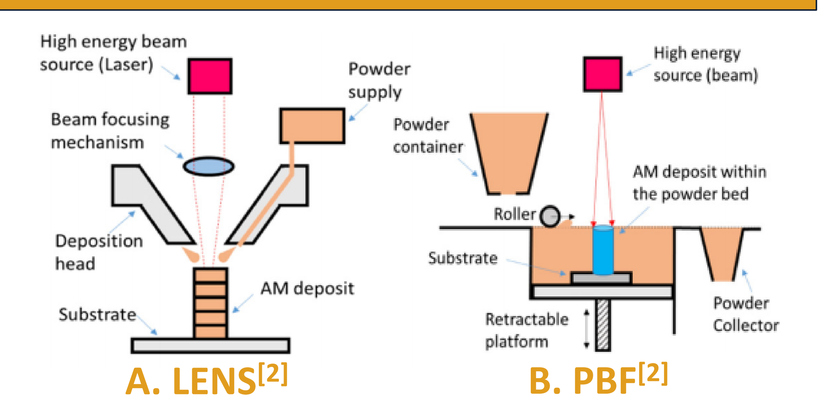
Specimen Preparation

Specimen Set

- Four samples:

	316L	304L
AM	316L PBF	304L LENS
Wrought	304L Wrought	304L Wrought

- Two stainless steel variants:
  - 304: 18% chromium, 8% nickel
  - 316: 16% chromium, 10% nickel, 2% molybdenum
  - L indicates low carbon content (<0.03%)
- Two additive manufacturing methods
  A. **Laser Engineered NetShaping** (LENS) is a directed Energy Deposition technology which applies thermal energy as the material is being laid onto a surface
  B. **Powder Bed Fusion** (PBF) applies thermal energy through either lasers or compression to a spread layer of the powdered bulk material



Annealing Plan

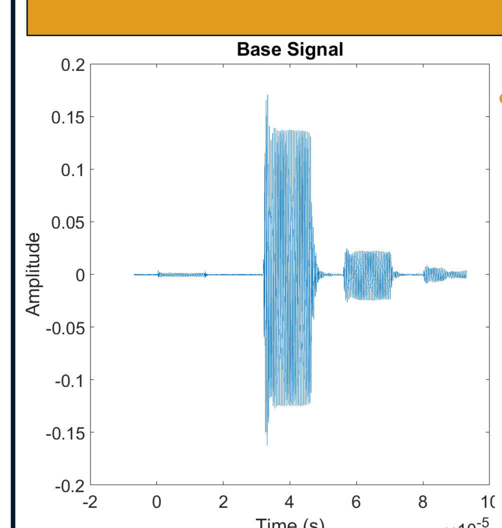
- Annealing removes residual stresses formed in manufacturing and rehabilitates some dislocations
- Inert atmospheric ovens and near-vacuum stainless steel bags prevent oxidization. Parts are air quenched.

Specimen	HT 1	HT 2	HT 3	HT 4
304L LENS	1323 K for 0.5 hr	1473 K for 2.5 hr	N/A	N/A
316L PBF	923 K for 0.5 hr	1223 K for 0.5 hr	1323 K for 0.5 hr	1473 K for 2.5 hr
316L Wrought	923 K for 0.5 hr	1223 K for 0.5 hr	1323 K for 0.5 hr	1474 K for hr
304L Wrought	1323 K for 0.5 hr	1473 K for 2.5 hr	N/A	N/A

- Measurement set made after each heat treatment and a subsequent 1000 grit surface polish
- Gradual annealing allows for finer gradation on microstructure changes in relation to β measurements
- Final heat treatment for each specimen intends for **complete recrystallization** to see if any lingering differences between AM and Wrought manufacturing techniques can be detected

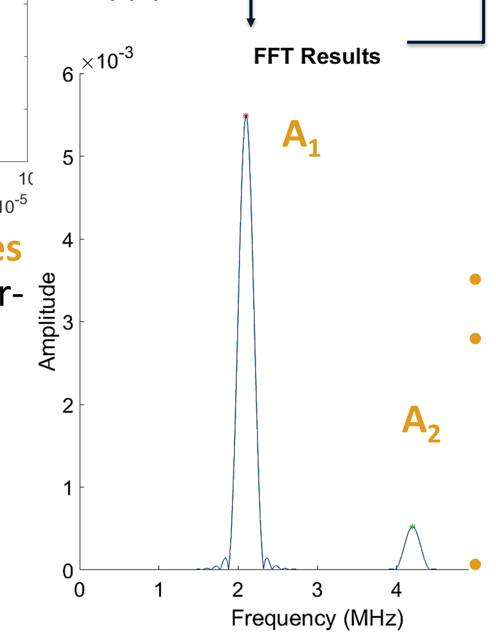
Analysis and Results

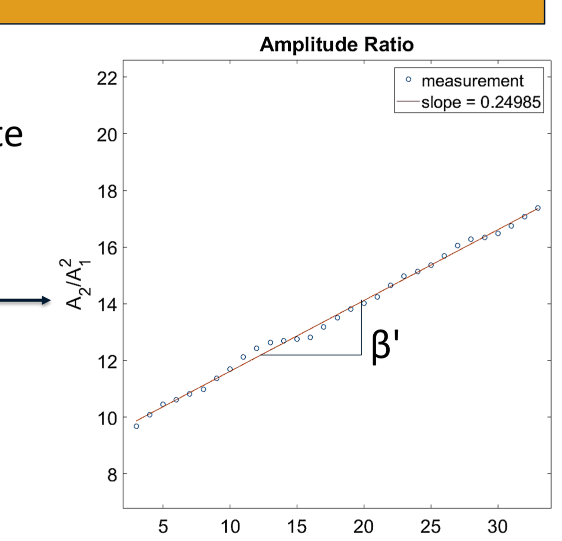
Nonlinearity Data Analysis



- A **Fast Fourier transform** (FFT) is applied to separate the fundamental (A_1) and second harmonic (A_2)

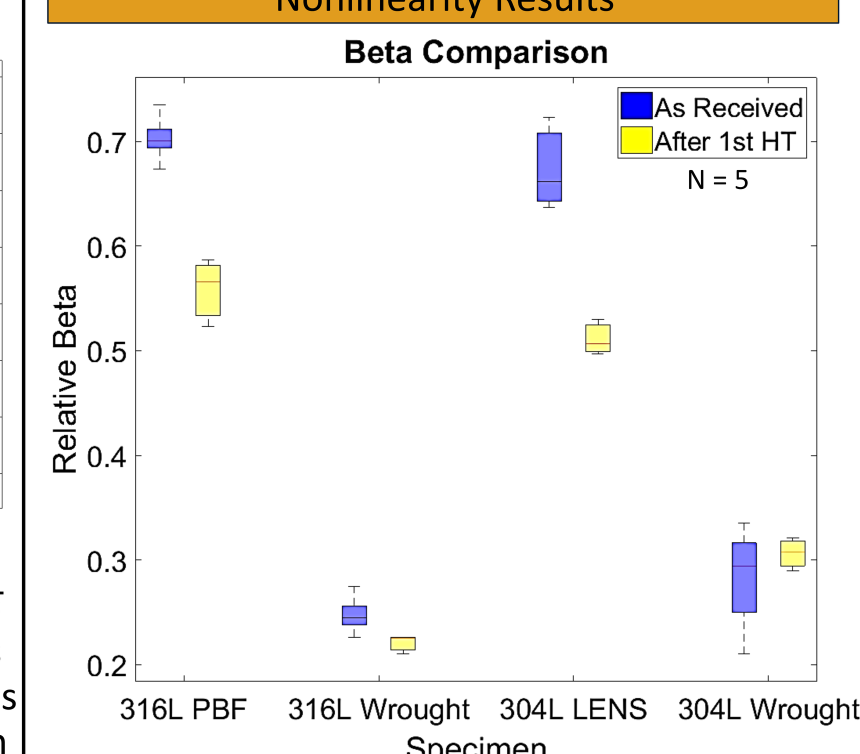
FFT





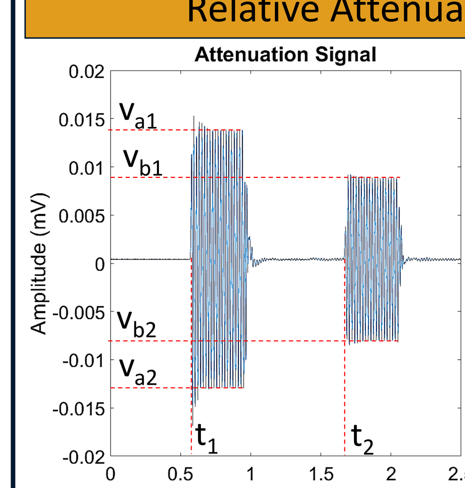
- **Leaked Rayleigh waves** are detected by the air-coupled transducer, amplified, and time-averaged to increase SNR.
- A **Hann window** is applied to reduce transient effects
- **Relative nonlinearity**: $\beta' = \frac{A_2}{x A_1^2}$
- A_2 increases with propagation as each material nonlinearity causes the further distortion of Rayleigh wave into fundamental and second harmonic (cumulative)
- A_1 decreases due to spread and boundary loss of fundamental

Nonlinearity Results



- Differentiable between manufacturing techniques
- First annealing heat treatment causes decrease in β'

Relative Attenuation Data Analysis



- 1st packet transverses 1x
- 2nd packet transverses 3x

z	Thickness
λ	Wavelength
x	Distance traveled
b	Transducer radius
J	Bessel Function

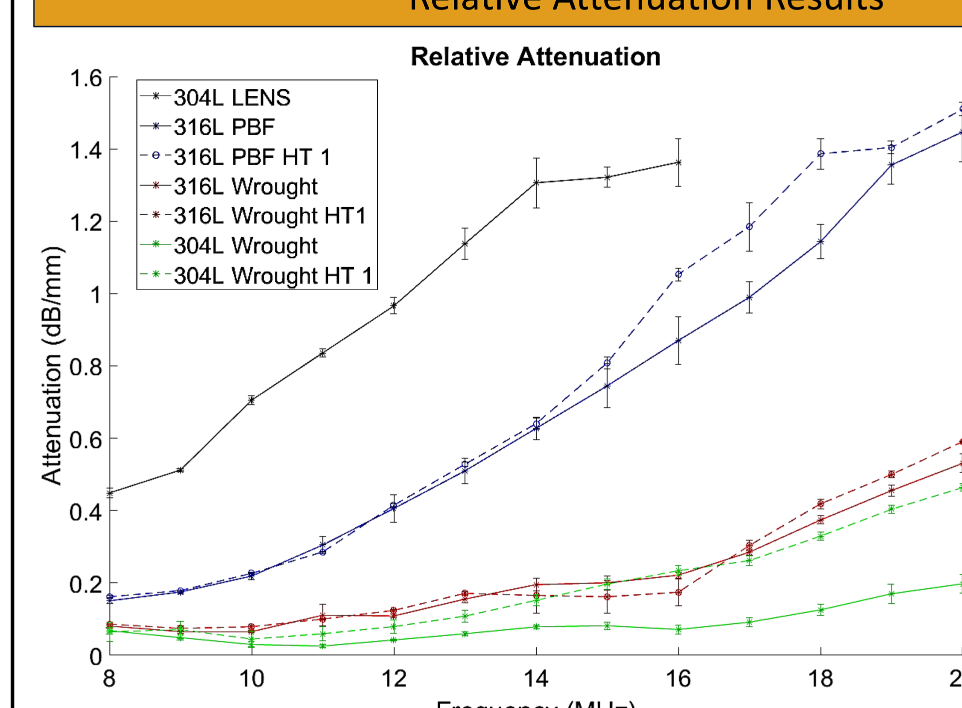
$$c = \frac{2 \times z}{t_2 - t_1}$$

$$s(f) = \frac{\lambda \times \Delta x}{b^2}$$

$$D(s) = 1 - e^{-i\frac{2\pi}{s}}\left[J_o\left(\frac{2\pi}{s}\right) + iJ_1\left(\frac{2\pi}{s}\right)\right]$$

$$\alpha(f) = \frac{1}{2z}\left[\ln\left(\left|\frac{s_1(f)}{s_2(f)}\right|\right) - \ln\left(\left|\frac{D(s_1)}{D(s_2)}\right|\right)\right]$$

Relative Attenuation Results



- At high frequencies, good differentiation between materials
- AM parts have significantly higher attenuation due to more complex microstructure
- Annealing leads to higher relative attenuation due to increase in grain size

Conclusions

- The acoustic nonlinearity parameter is sensitive to the microstructural differences between AM and Wrought metals
  - The measurements following the reduction of residual stress indicate β's potential sensitivity to differences in dislocation density in AM metals
- Relative attenuation acts as a viable material identification parameter
- Heat treatment grain size increase corresponds with attenuation increases

Future Work

- Complete cycle of heat treatments and measurements
- **Microscopy** at each state of heat treatment to investigate microstructural changes and its relation to β
  - Provides a visual microstructural baseline for measurements
- **Hardness measurements** of samples cut at each stage of HT cycle to correspond with dislocation density
- Measure absolute attenuation
- **Statistical analysis** to validate differentiability between materials

References

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[2] S.M. Thompson, L. Bian, N. Shamsaei, A. Yadollahi, An overview of direct laser deposition for additive manufacturing; part I: transport phenomena, modeling and diagnostics, Additive Manufacturing 8 (2015) 36–62.

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