# Predicting Remaining Fatigue Life of a Dent with Corrosion Using Advanced Measurements and Modeling

CAAP Presentation
December 1, 2021

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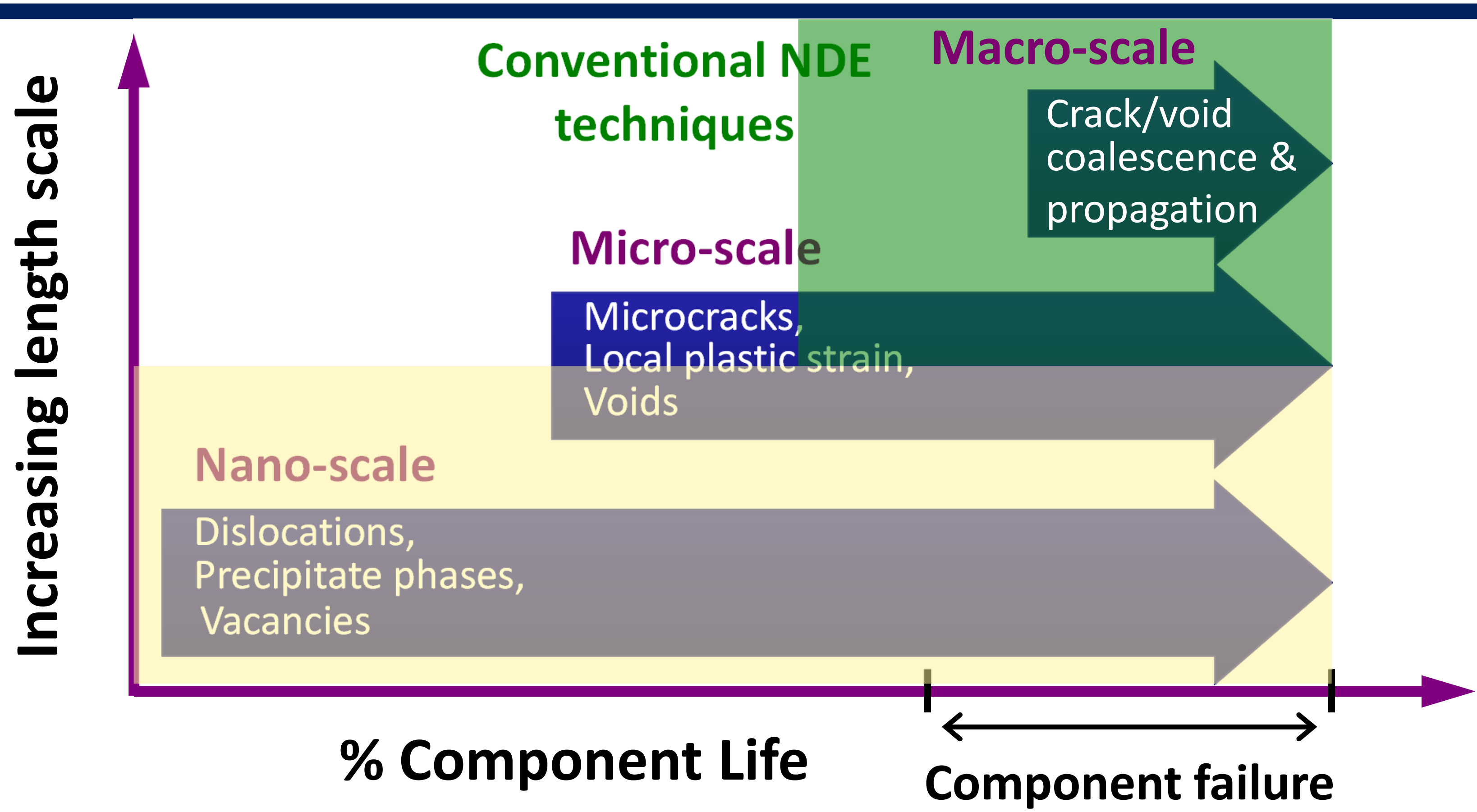
# Acknowledgements

**Thanks to**:
Mark Piazza: *Colonial Pipeline*
Aaron Dinovitzer and Sanjay Tiku: *Fleet BMT*
Zhongquan (ZZ) Zhou, *PHMSA*
Jan Hermann, Christoph Pruell, Simon Walker, Christoph Doerr, Denis Pfeifer and Aurelio Bellotti: *Georgia Tech*

**Supported by**:
US DOT Pipeline and Hazardous Materials Safety Administration (PHMSA)
Contract Number: 693JK31850006CAAP

# Rationale for nonlinear ultrasonics (NLU)




- **Microstructural evolution drives macroscopic damage**
- **How can we monitor features at lower length scales, before critical damage?** → **Nonlinear Ultrasound**

# NLU and microstructure

Equation of motion (1D)

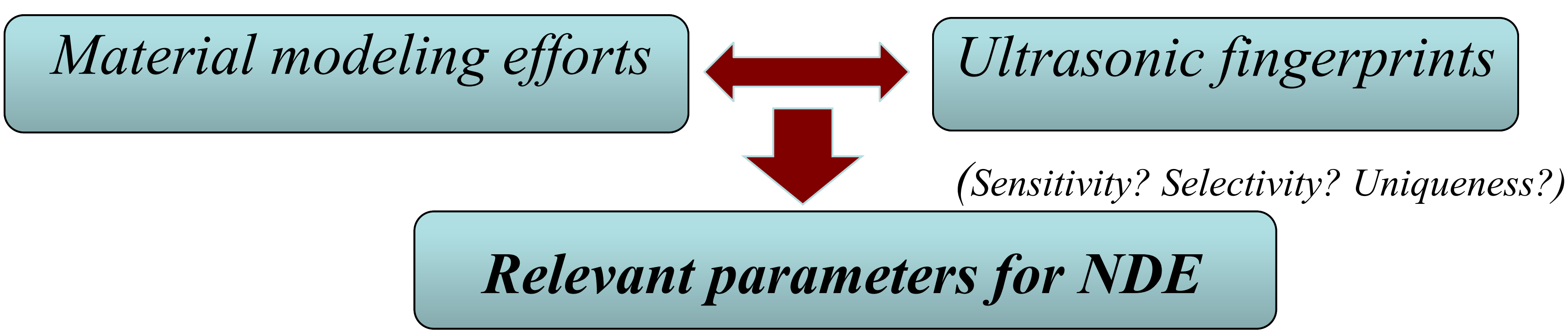
$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x}$$

Nonlinear constitutive relationship

$$\sigma = \varepsilon \cdot E_0 \left[ 1 + \beta\varepsilon + \delta\varepsilon^2 + \alpha\left(\Delta\varepsilon + \varepsilon \cdot \mathrm{sgn}(\dot{\varepsilon})\right) \right]$$

**Microstructural contributions to $\beta$:**

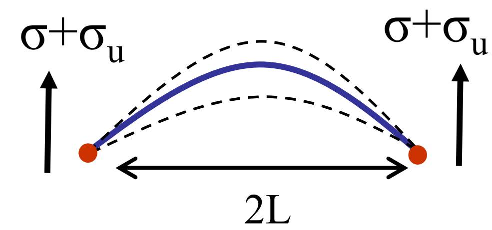
- Lattice anharmonicity and “bowed out” dislocations (Hikata *JAP* 1965)
- Dislocation dipoles (Cantrell & Yost, *IJF* 2001, Cash and Cai, *JAP*, 2012)
- Dislocation Pinning (Cantrell & Zhang, *JAP*, 1998)
- Precipitates (Cantrell & Yost *APL*, 2000)
- Microplasticity (Kim et al, *JNDE,* 2006)




*(Benchmark problems, reliable measurement techniques, standards)*

# Dislocation/precipitate interaction models

Relation[1] to $\beta$: $\Delta\beta \propto \Lambda L^4 |\sigma|$




| Possible Contribution | Stress | Loop length | Relationship |
|---|---|---|---|
| Dislocations only[1] | $\sigma_0$ | $L = L_0$ | $\Delta\beta_{pd} \propto \Lambda L_0^4 \sigma_0$ |
| Precipitate-pinned dislocations[2] | $\sigma_p$<br>$\sigma_0 << \sigma_p$ | $L \approx N_p^{1/3}$ | $\Delta\beta_{ppd} \propto \frac{\Lambda r_p^3 \delta_p}{N_p^{1/3}}$ |
| Vacancy-pinned dislocations[3] | $\sigma_v$<br>$\sigma_v < \sigma_p$ | $L \approx N_v^{1/3}$ | $\Delta\beta_v \propto \frac{\Lambda r_v^3 \delta_v}{N_v^{1/3}}$ |

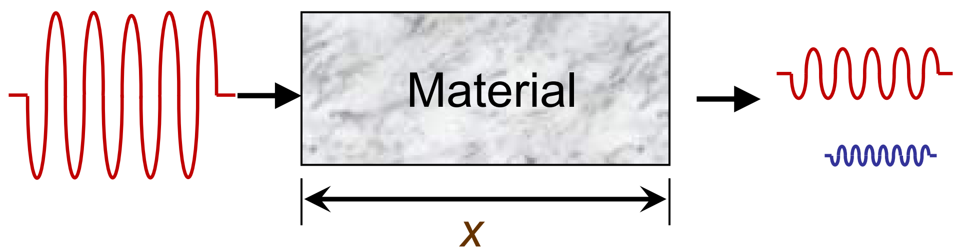
- $\Lambda$ Dislocation density
- $\sigma$ Stress in material
- L Loop length
- N Number density of defect
- r Defect radius

[1]Hikata et al 1965; [2]Cantrell and Zhang 1998; Hurley et al 2000; [3]Cantrell 2006

# Measurement principle: second harmonic generation (SHG)

$u_{in}$ =

$A_o sin(\omega t)$




$u_{out}$ =

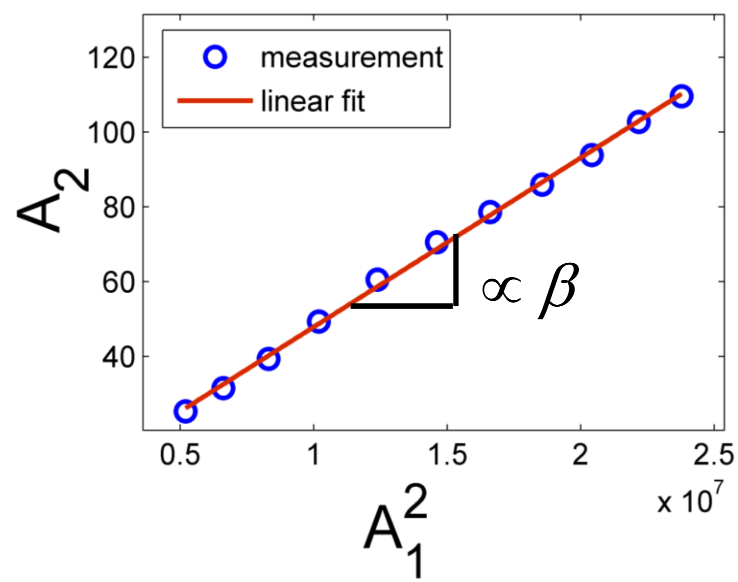
$A_1 sin(\omega t\text{-}kx)$ +

$A_2 sin[2(\omega t\text{-}kx)]$

**Determine $\beta$, the absolute acoustic nonlinearity parameter.**

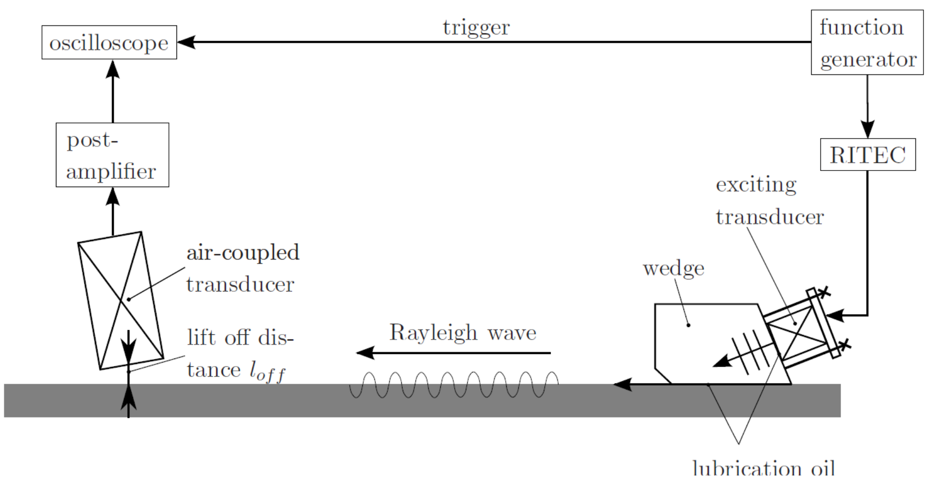
$$A_2 = \frac{\beta A_1^2 x \kappa^2}{8} \Rightarrow \beta = \frac{A_2}{A_1^2}\left(\frac{8}{\kappa^2 x}\right)$$

- Increase input amplitude $A_0$ and make an absolute measurement of $A_1$ and $A_2$

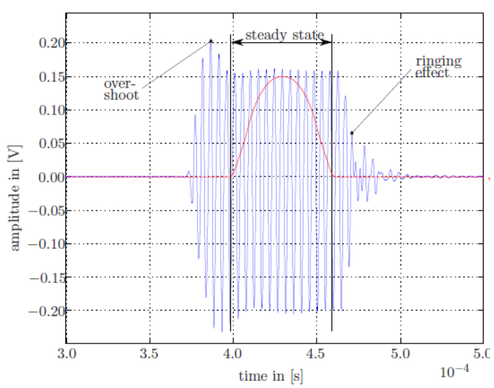


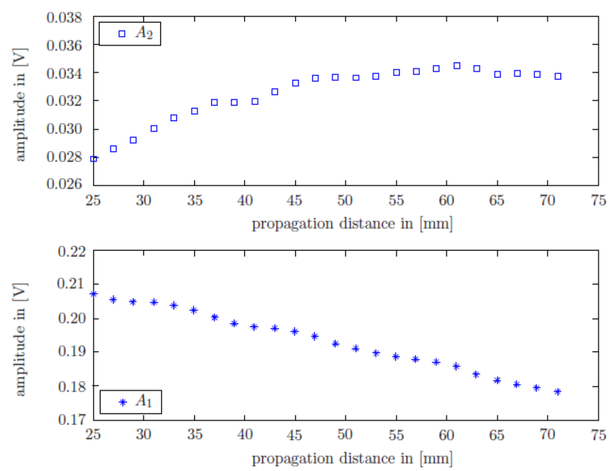
# Nonlinear Rayleigh wave measurements

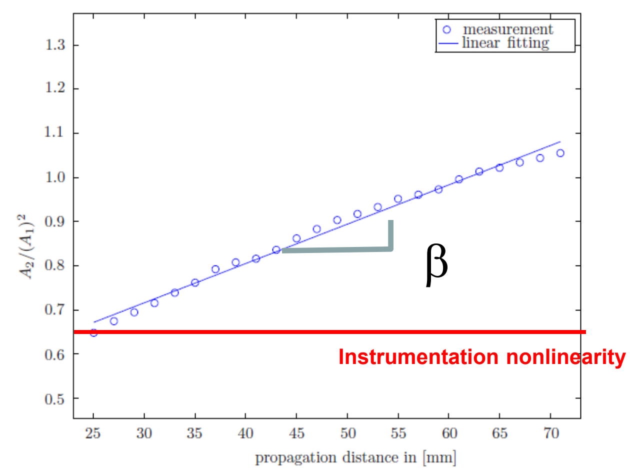
Non-contact detection of Rayleigh surface waves with an air-coupled receiver – material nonlinearity cumulative



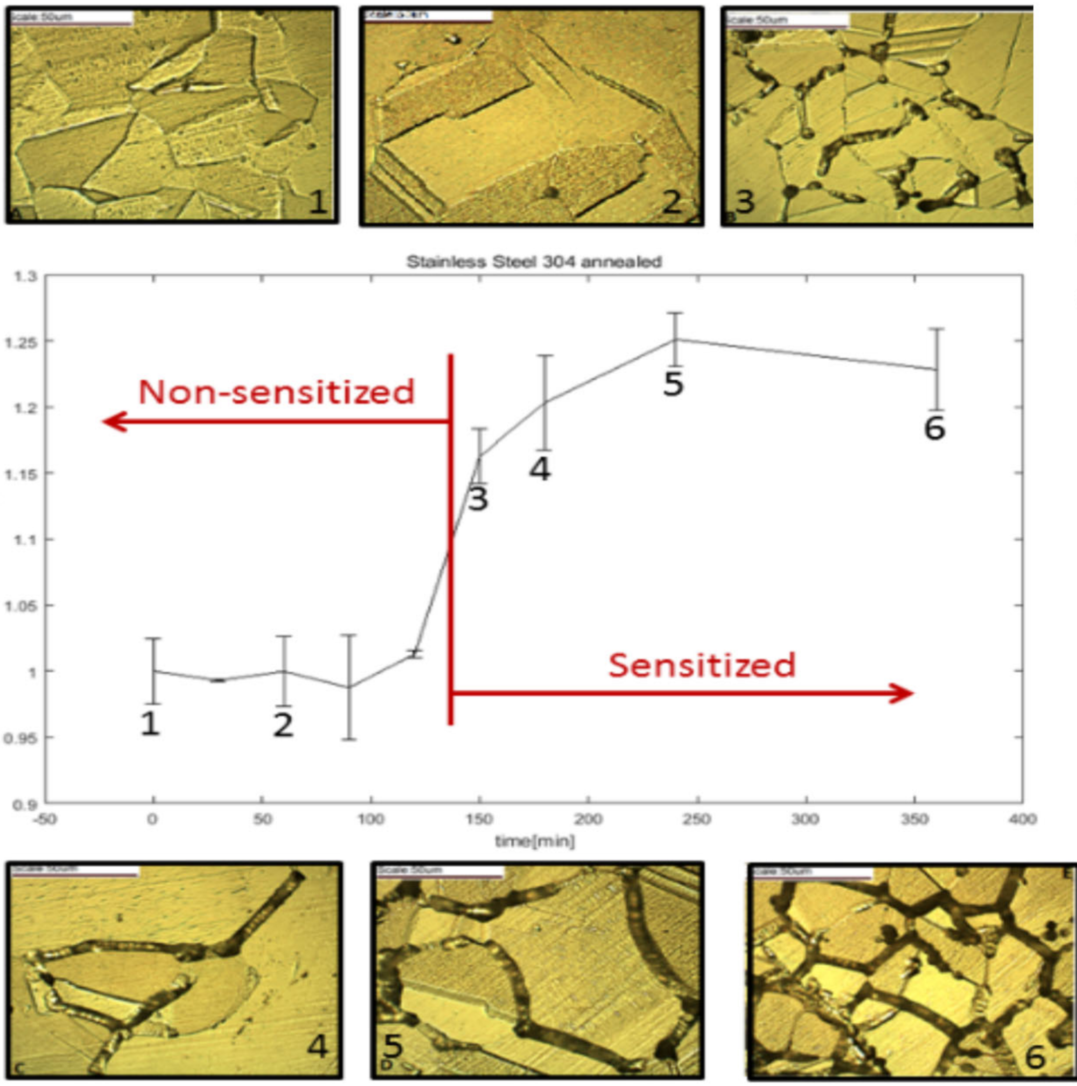

- Isolate *material* nonlinearity from *instrumentation* nonlinearity
- Relative value of β
- $(A_2 / A_1^2) \propto \beta x$

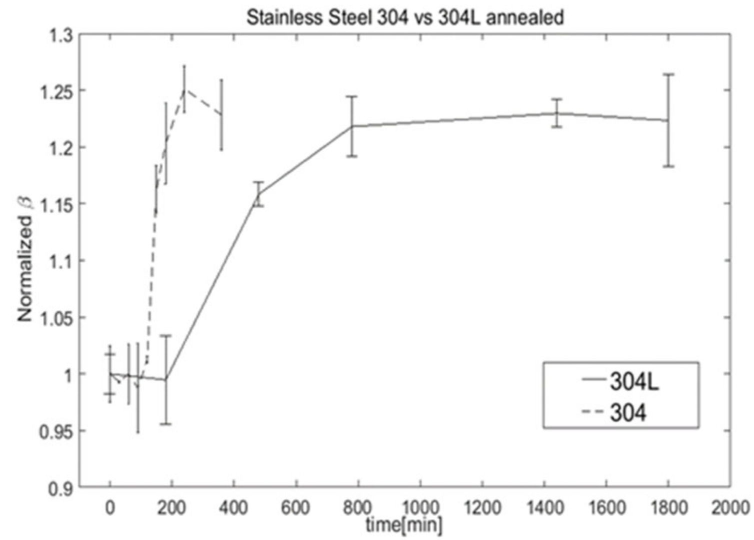


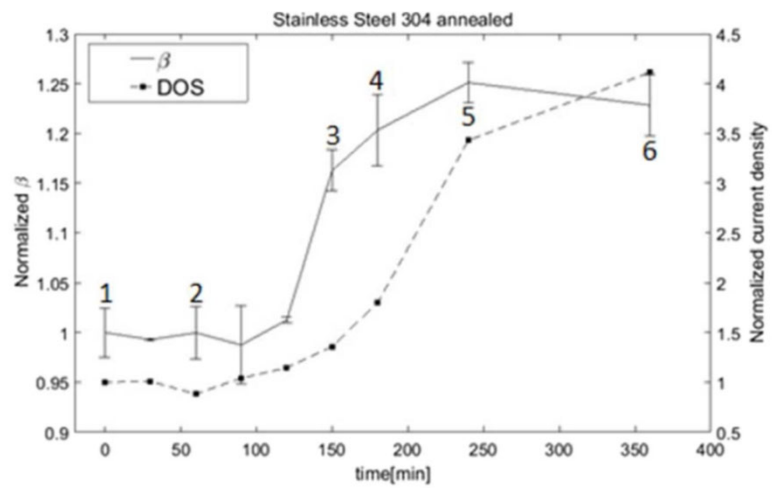



# Sensitivity: Sensitization 304 SS



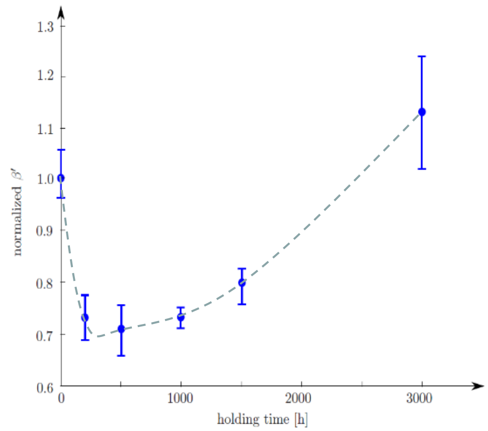



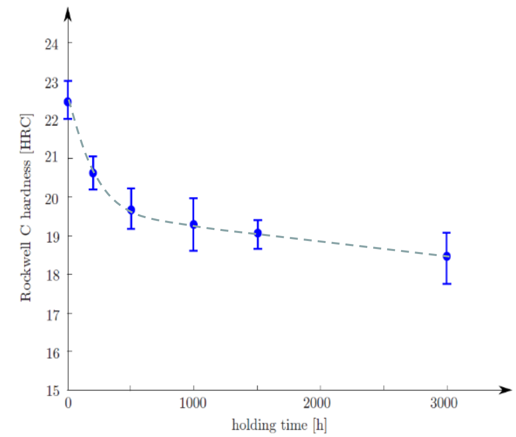

Doerr et al *NDT&E (2017)*

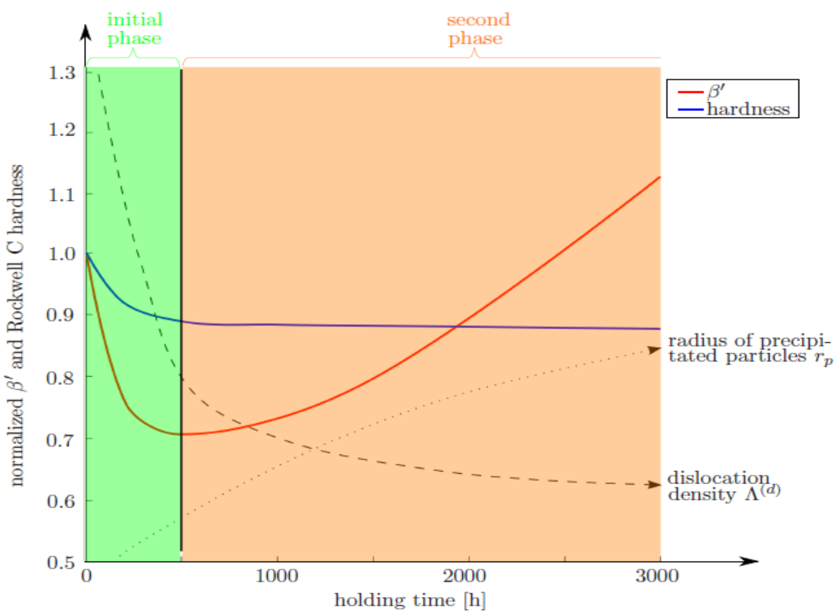
# Interaction of dislocations, precipitates and intermetallics

## Thermal degradation (650°C) in tempered 9% Cr steel

- Precipitation hardening is the major strengthening mechanism
- High-density dislocations in martensite Laves phase and precipitates of various types would be the major players



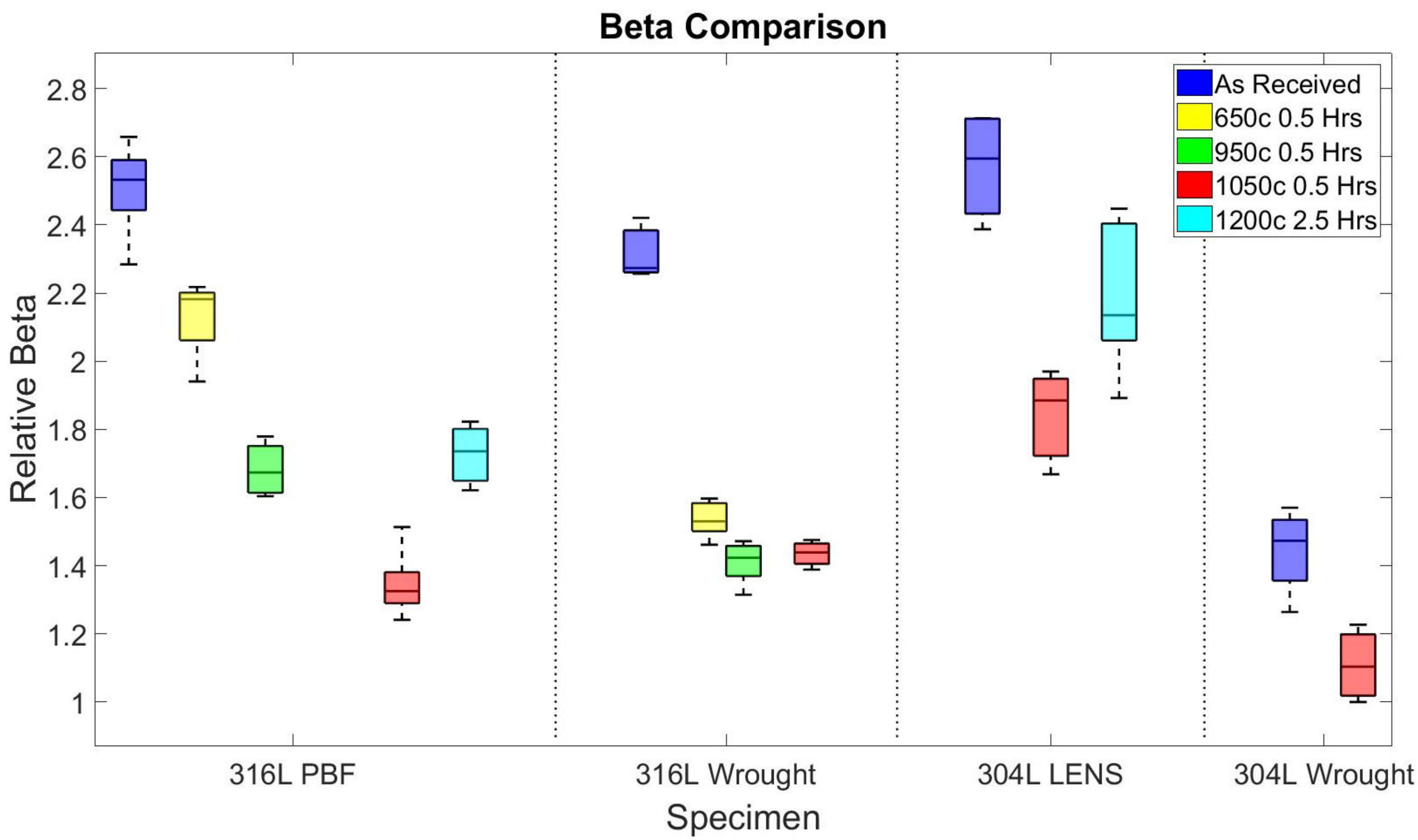




| Changes | Hardness | β |
|---|---|---|
| Dislocation density ↓ | ↓ | ↓ |
| Coarsening of M23C6, MX (precipitates) | ↓ | ↓ |
| Growth of Laves phase | ↑ | ↑ ? |

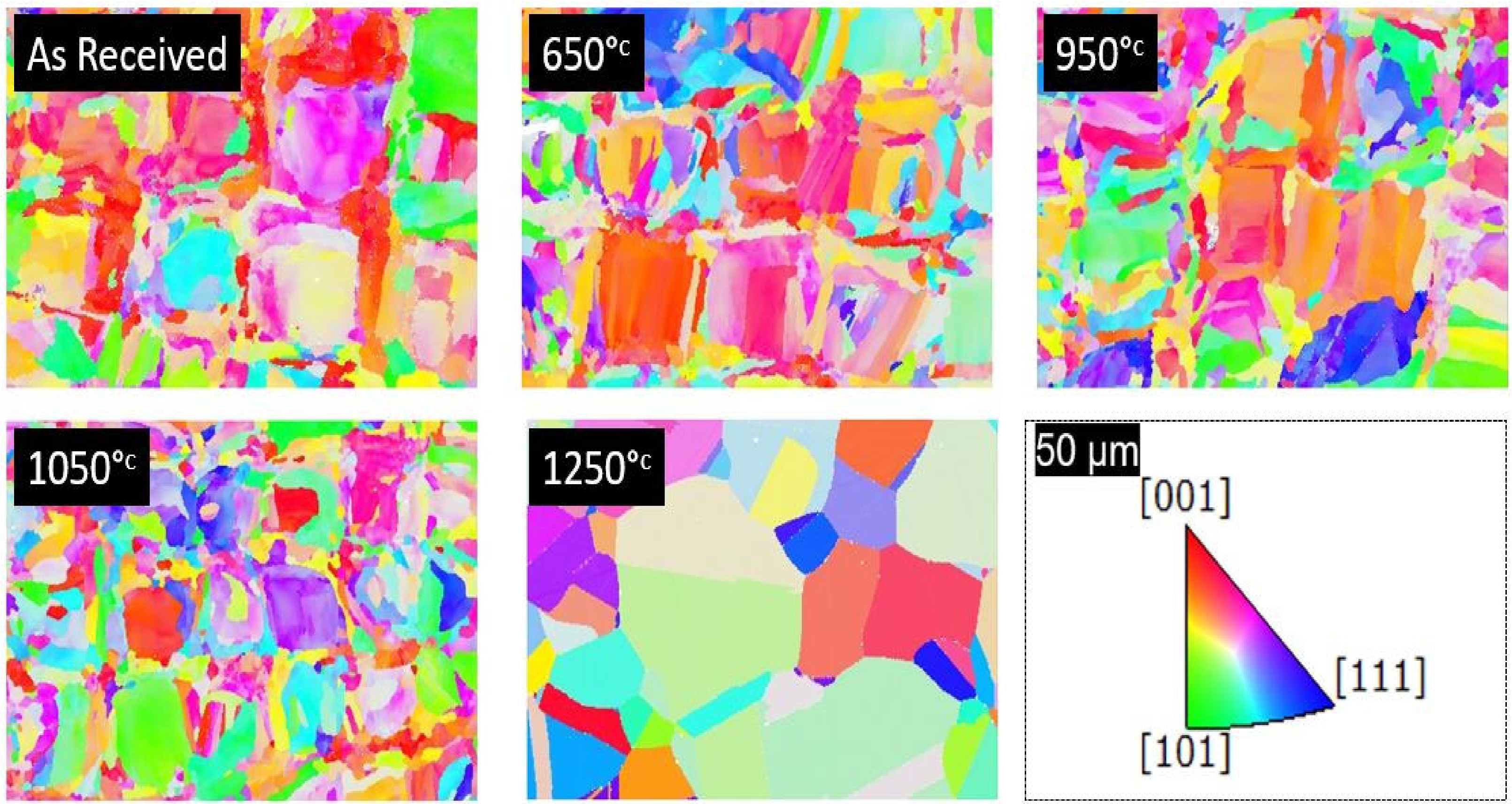
Marino et al, NDT&E Intl (2016)

# Wrought vs Additive 316 and 304 SS




Bellotti et al *JASA* (2021)

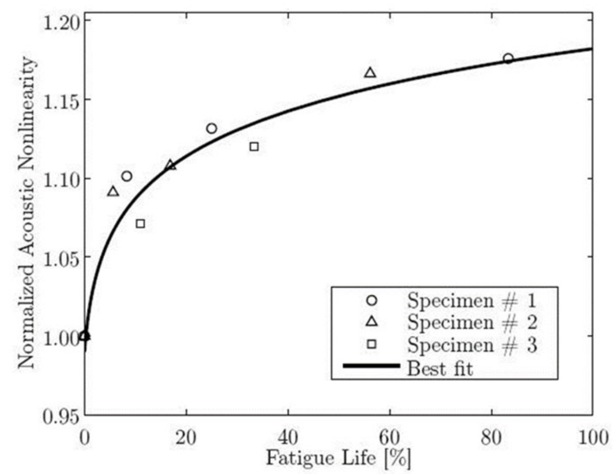
# 316 L- PBF EBSD Microstructure

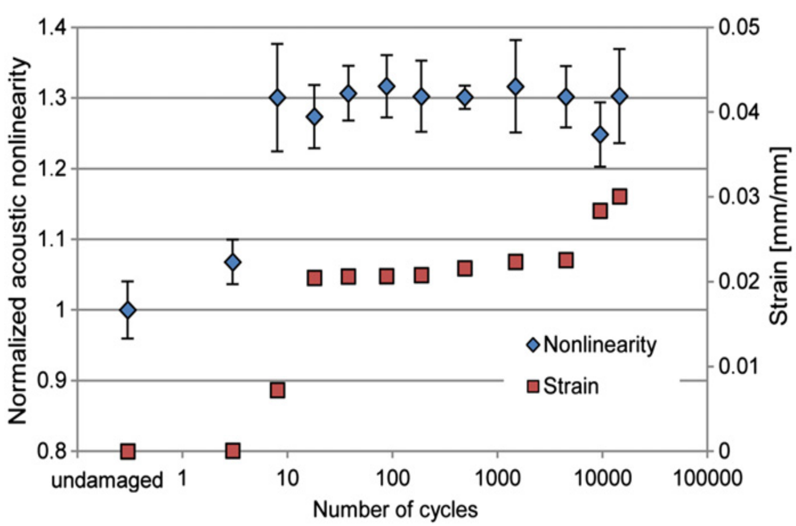


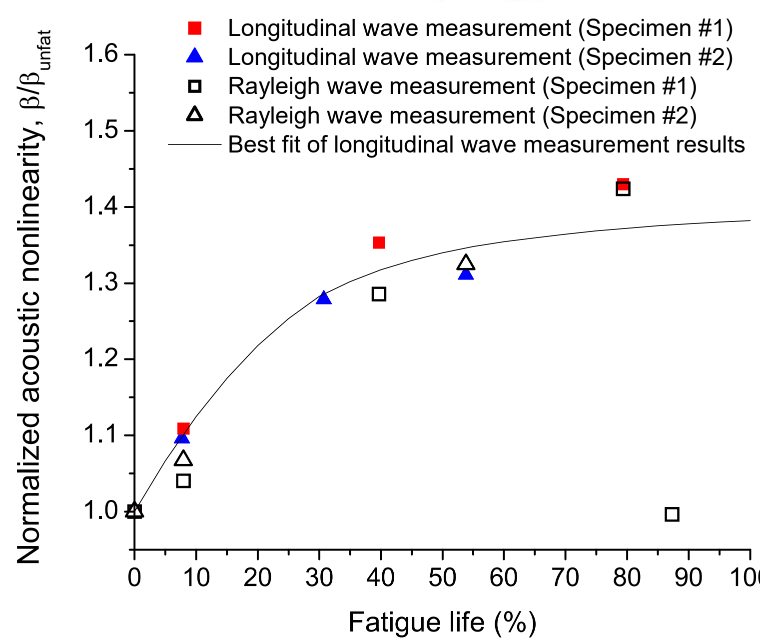
# Sensitivity: Dislocation driven fatigue damage

*Fatigue on A36 steel, Ni Superalloy and Aluminum, bulk and guided waves*

Characterization of early stage fatigue damage (before the formation of microcracks) requires the ability to track the densities of dislocation monopoles and dipoles, plus the evolution of persistent slip bands (PSBs).

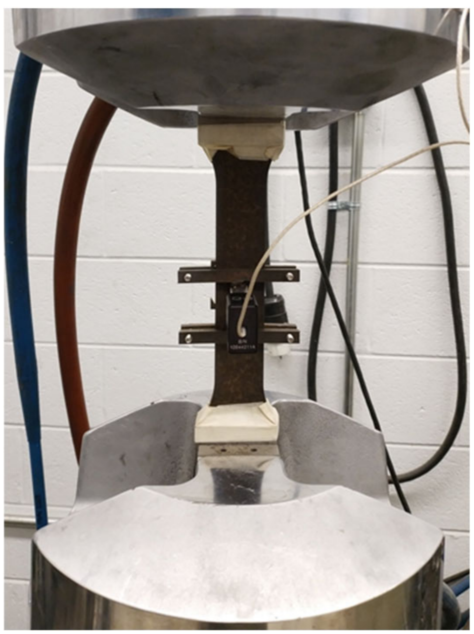


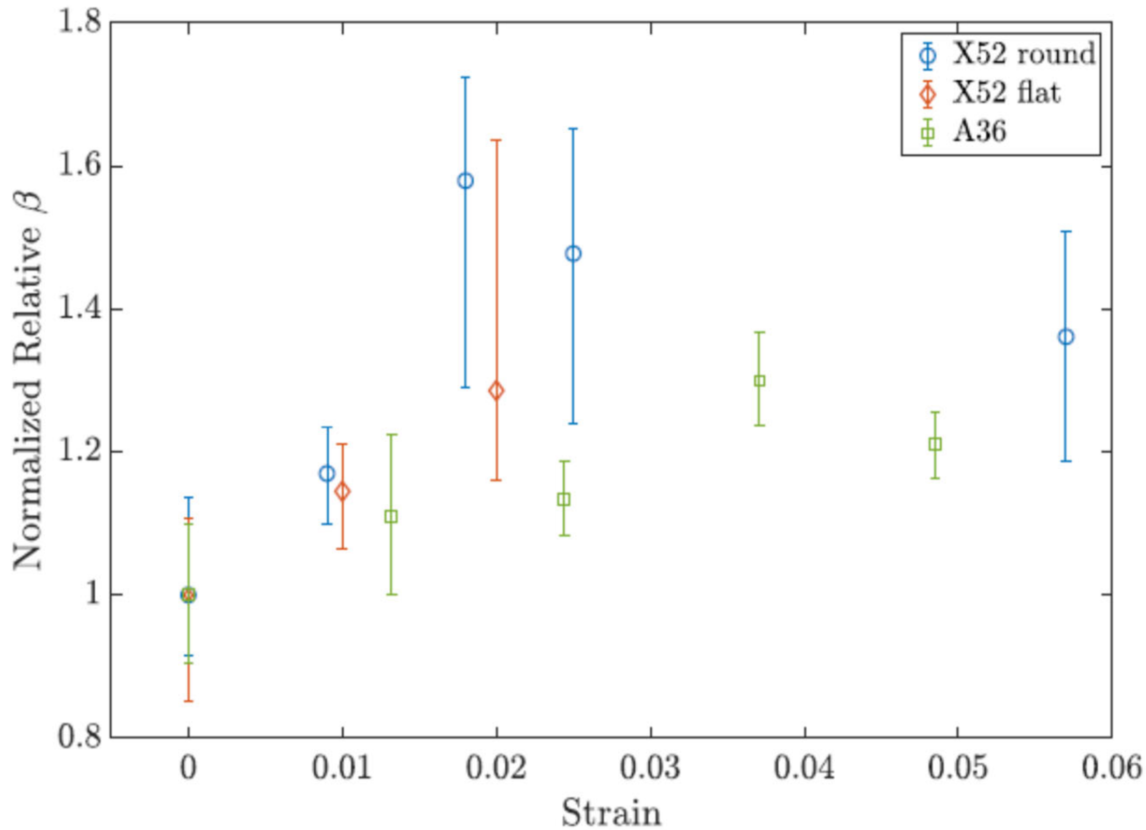




Herrmann et al, JAP (2006)
Pruell et al, SMS (2009)
Walker et al, *NDT&E Int* (2011)

# Legacy X52 pipeline material

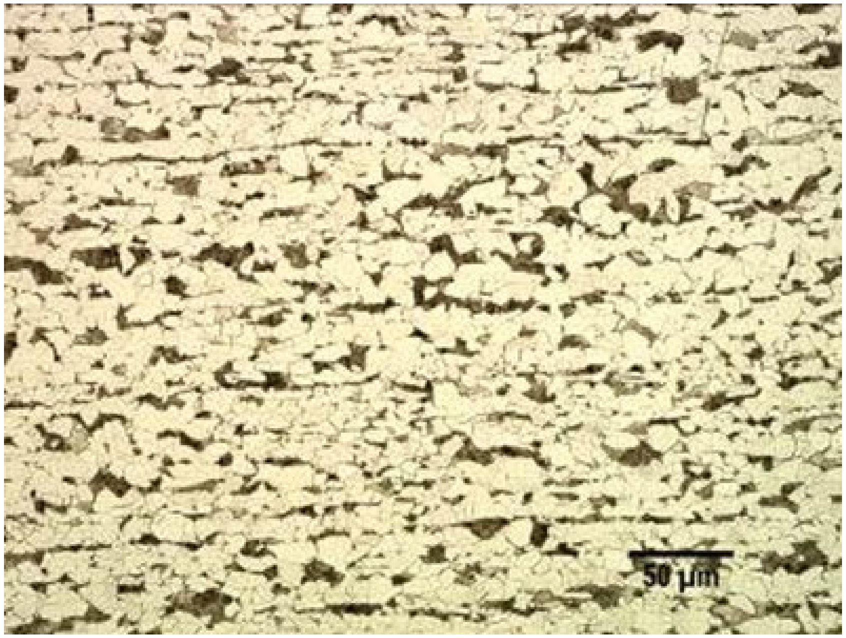





Pfeifer et al *MSSP* (2020)

# Microstructure Comparison – Close to OD surface

Grade X-52



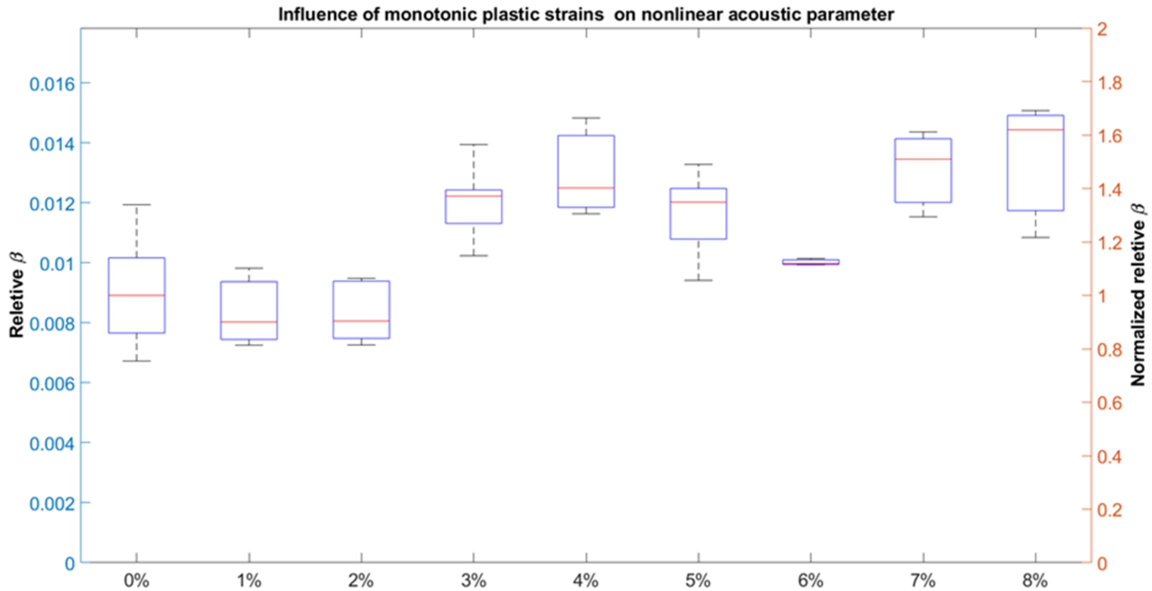

Grade X-70

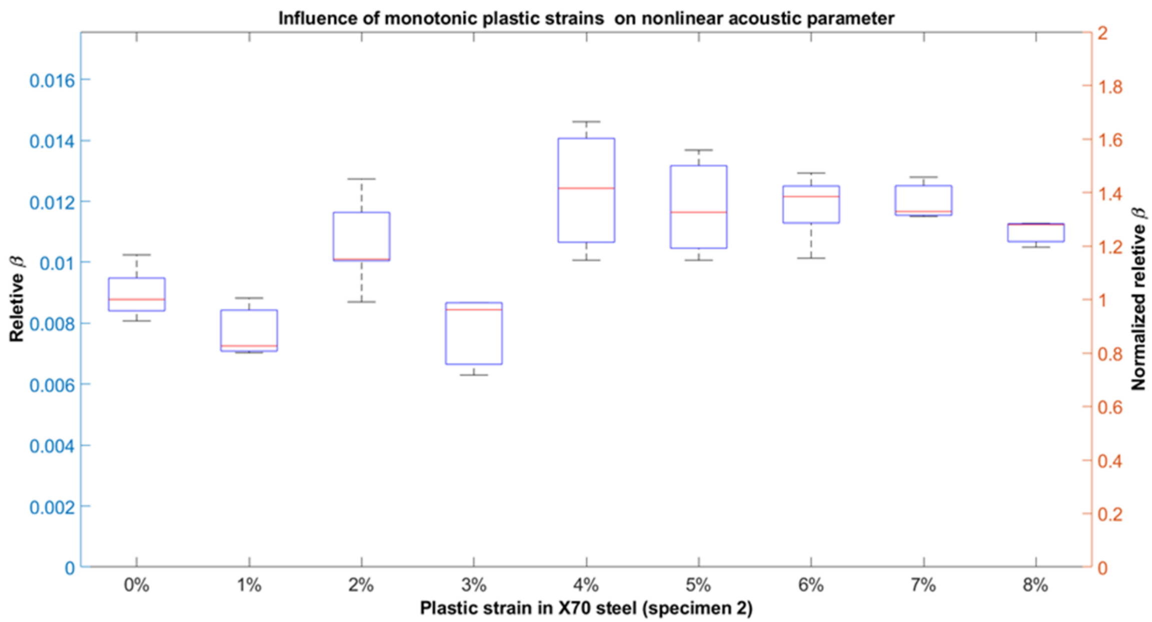
# Monotonic vs. Fatigue loading X70

*<u>Group 1: Repeated monotonic loads on 3 or 4 tensile specimens</u>*. First make baseline nonlinear ultrasound (NLU) on each specimen. Apply monotonic strains in steps from minimum to maximum (e.g. 1% -8%) bringing it back to zero and then make NLU measurements. Repeat the same procedure on all 3 (or 4) specimens. The objective of these Group 1 experiments is to compare the effect of different magnitude of strains on one specimen (Baseline specimen is the same). Comparing different specimens allows for the evaluation of the effect of strain cycle on measurements, if any as well as variability in measurements.

*<u>Group 2: Single monotonic loads on 10 tensile specimens</u>*. Make baseline measurements, subject each individual specimen to a single monotonic strain level (0% -8%) only, and then make the NLU measurements. These results will determine the effect of magnitude of one monotonic strain level. Comparison with Group level 1 specimens (of similar strain magnitude) to examine effect of strain cycle.

# Group 1: Repeated monotonic loads X70



# TMCP Strategy

- X70 is manufactured with thermo-mechanical controlled processing (TMCP)

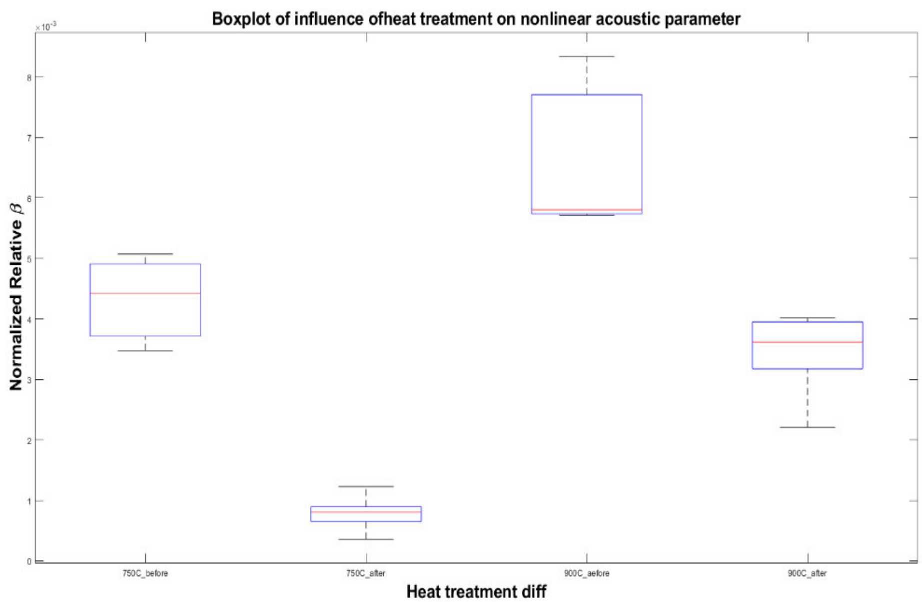
- This TMCP procedure first heats the rough steel section (slab) to a temperature regularly used for hot working operations (about 1200°C). The initial hot working ('roughing') is carried out in a normal fashion, but the final hot work reduction or “finishing pass” is carried out at a lower temperature than would be used for older processes.

# TMCP Strategy

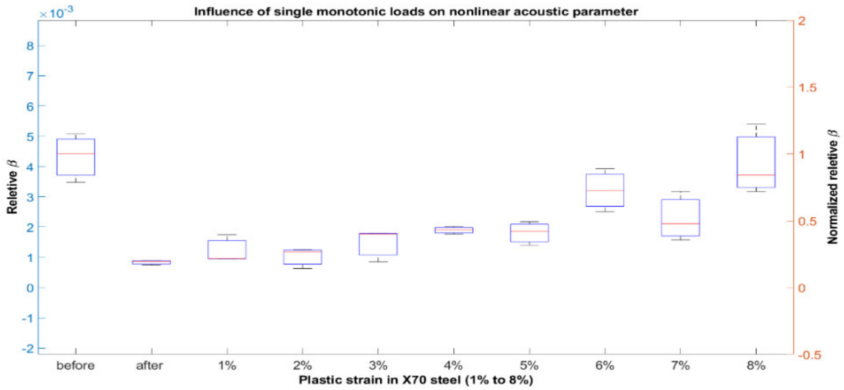
- Plastic deformation at this lower temperature promotes fine grain sizes and retards precipitation. This procedure is different from the X52 material previously considered, which is a more traditional processing. The TMCP processing creates a dislocation structure thermally instead of mechanically.

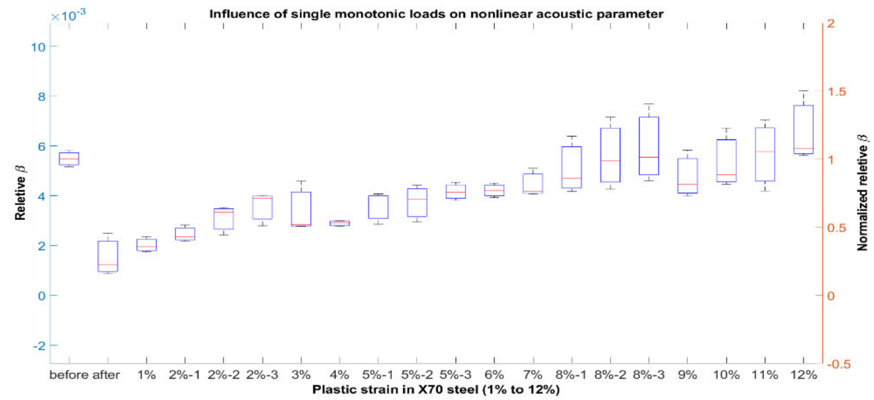
- This means that the additional mechanical load on the X70 material changes the microstructure in a different fashion than the X52 material.

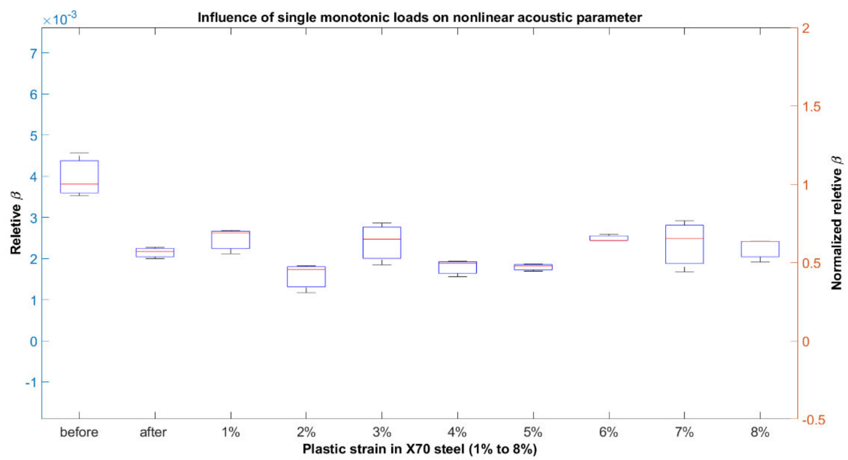
# Analysis of heat treatment on $\beta$ in X70



# Repeated monotonic loads on HT X70



# Conclusions

- *Sensitivity:* NLU sensitive to dislocation and precipitate driven damage and material state
  - NLU is sensitive to changes in the X52 and X70
  - Trends between $\beta$ versus plastic strain are encouraging but high variability in results
  - Combine Machine Learning (ML) algorithm with simple physics-based model for interpretation
- *Selectivity:* NLU measures single parameter, $\beta$ that is sensitive to multiple material state features
- Prognostics requires integration of multi-physics measurements and physics-based, materials models
- Field acceptance requires development of benchmark problems, reliable measurement techniques and standards

# Questions

Thank You. Questions?