Ultrasonic Gear Steel Fatigue at NASA

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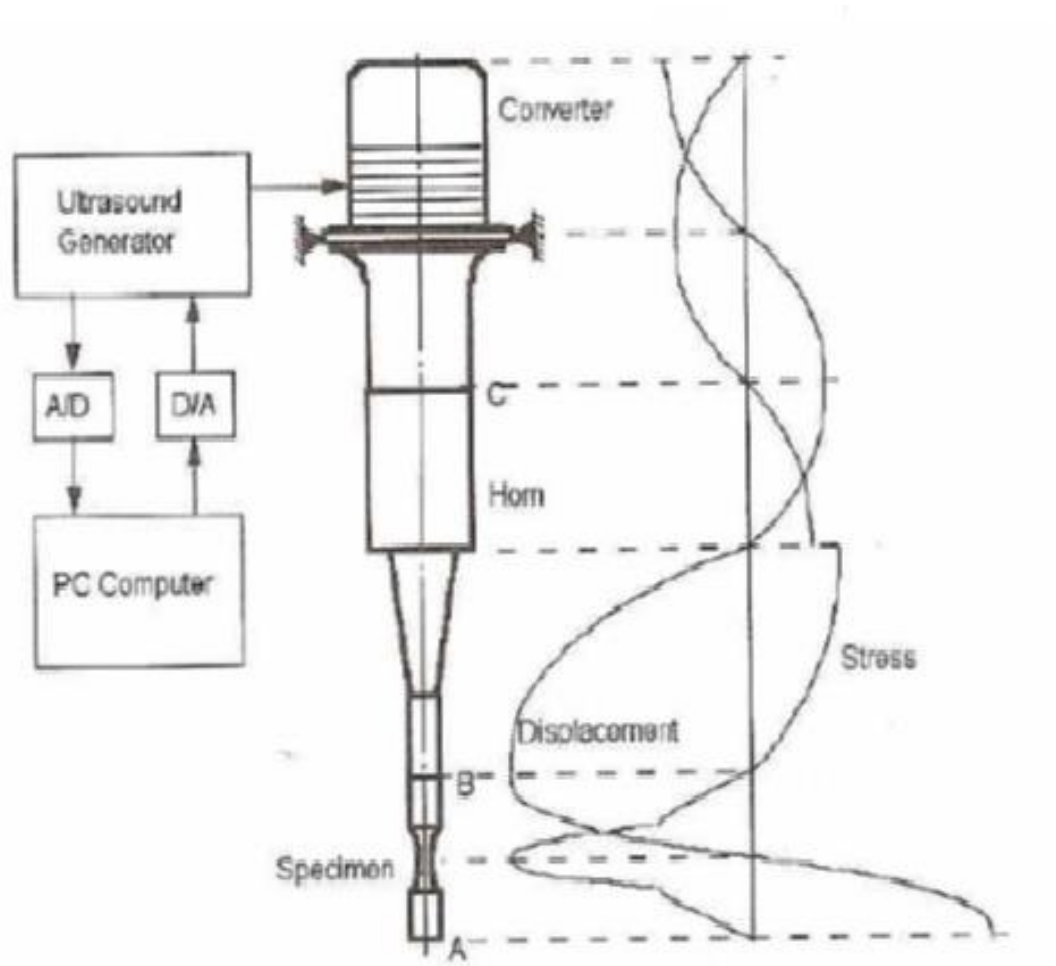
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Outline

1. Background and Motivation
2. Axial Fatigue Testing
   - Specimen Design
   - Dynamic Modulus Testing
   - VAR 9310 fatigue life results
3. Simulated Gear Tooth Testing
   - Issues with 3 point bending
   - Developed New Specimen Design

What is Ultrasonic Fatigue?

- 20 kHz Generator
- Piezo Electric Actuator
- Amplification Horns
- Specimen with 20 kHz natural frequency
- Stress/Strain cycles produced at 20 kHz

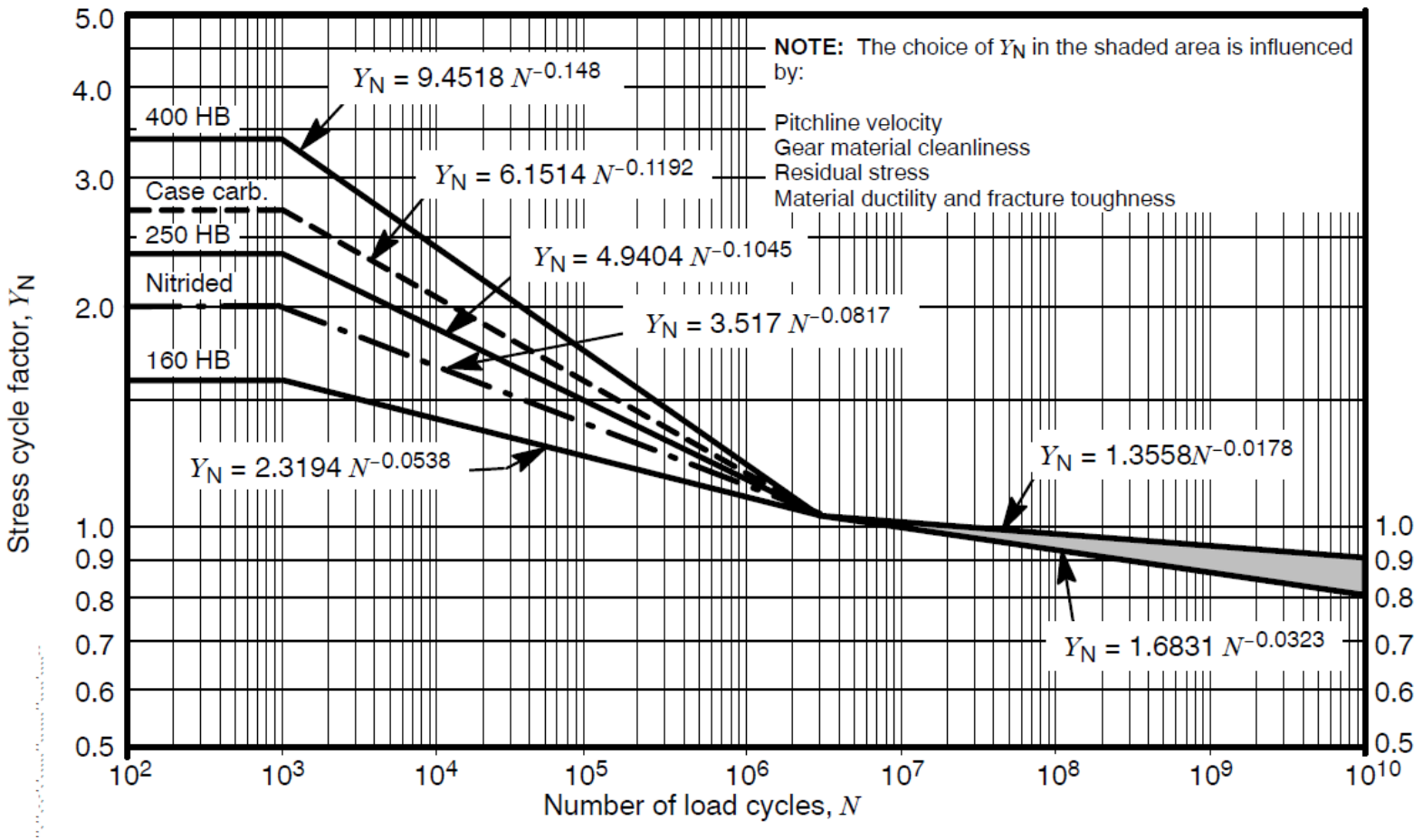


Schematic of Ultrasonic Fatigue Testing

Aerospace Transmission Bending Fatigue Cycles

Gear Box Input Speed (RPM)	Gear Tooth Fatigue Cycle Estimate at Flight Hours		
	1000 Hours	6000 Hours	10000 Hours
6000	3.6E+08	2.2E+09	3.6E+09
12000	7.2E+08	4.3E+09	7.2E+09
18000	1.1E+09	6.5E+09	1.1E+10
24000	1.4E+09	8.6E+09	1.4E+10
30000	1.8E+09	1.1E+10	1.8E+10

Current AGMA Method



$$\sigma_{wt} = \sigma_{f_{10^7}} \cdot Y_N$$

Ref: “Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth” ANSI/AGMA 2001-D04, American Gear Manufacturers Association, 2010

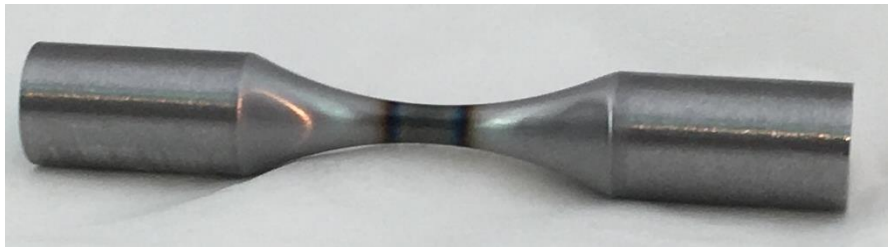
Comparison of Testing Times

GRC Material and Gear Tooth Fatigue Capabilities Times To Very High Cycle Fatigue Lives					
Test Method	Speed (Hz)	Time to 10^7	Time to 10^8	Time to 10^9	Time to 10^10
Standard Material Fatigue Testing	20	5.78 Days	57.9 Days	1.58 Years	15.8 Years
High Speed Gear Fatigue Rig	166.67	16.7 Hours	6.94 Days	69.4 Days	1.9 Years
Hydraulic Single Tooth Bending Rig	1000	2.77 Hours	1.15 Days	11.6 Days	116 Days
Ultrasonic Fatigue Rig	20000	8.33 Min	1.38 Hours	13.9 Hours	5.78 Days

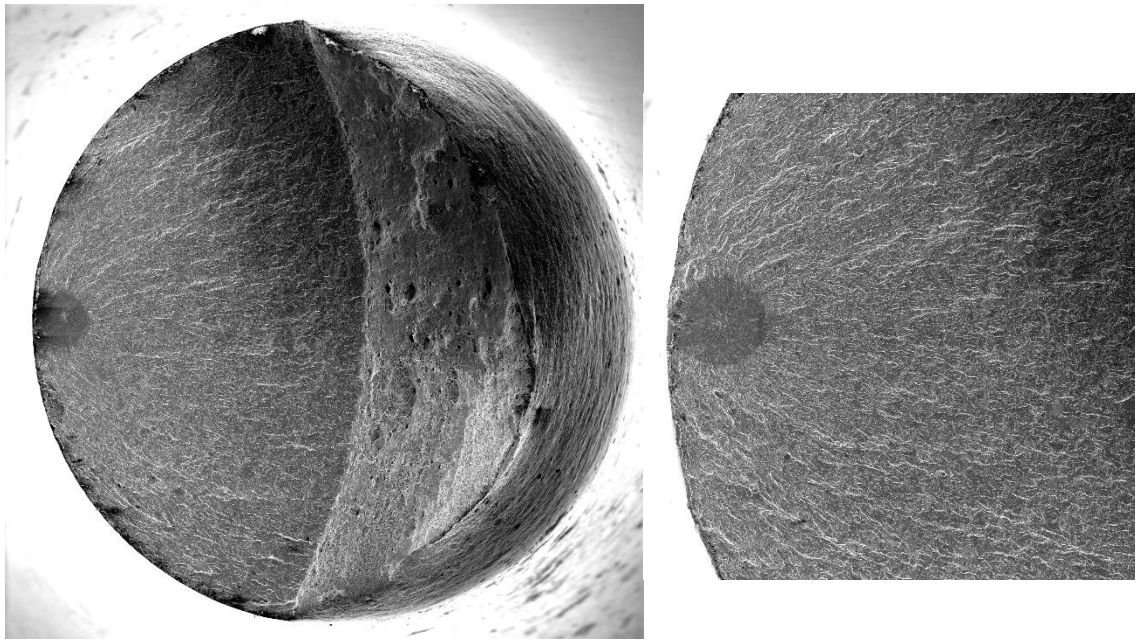
Ultrasonic Fatigue Drawbacks

- Heat Generation
  - Low cycle fatigue not possible due to heat
  - High cycle fatigue requires cooling
- Over Predicts Fatigue Strengths
  - Strain Rate Effects
  - Stressed Volume Effects
  - Internal Damping Effects
- Research Question: Relating 20 KHz fatigue testing to gear tooth bending fatigue
- Ultrasonic fatigue does find the “characteristic defect”
- Comparison of:
  - Heat treatment
  - Steels

Results of Ultrasonic Fatigue at <10^6 cycles:

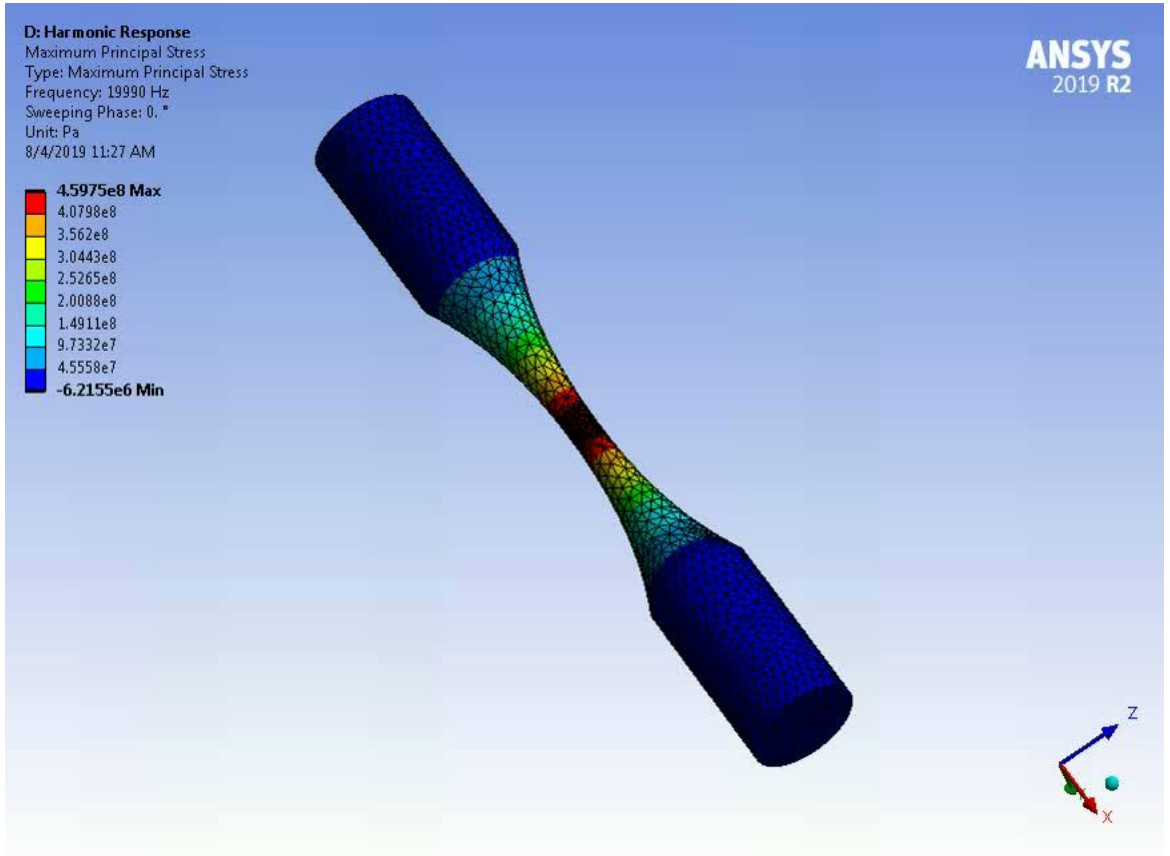


Fracture surface above 10^7 cycles:



Specimen Design for Ultrasonic Fatigue

- Natural Frequency of 20 kHz
  - +/- 200 Hz
- Analytical wave equations
  - $\frac{\partial^2 u(x,t)}{\partial t^2} = \sqrt{\frac{E_d}{\rho}}\left(\frac{A'(x)}{A(x)}\frac{\partial u(x,t)}{\partial x} + \frac{\partial^2 u(x,t)}{\partial x^2}\right)$
  - E_d= Dynamic Young's Modulus
    - » Accounts for internal damping
- Finite Element Modal Analysis
  - Free Vibration
    - » No Boundary Conditions
  - E_d also required



Dynamic Modulus Testing

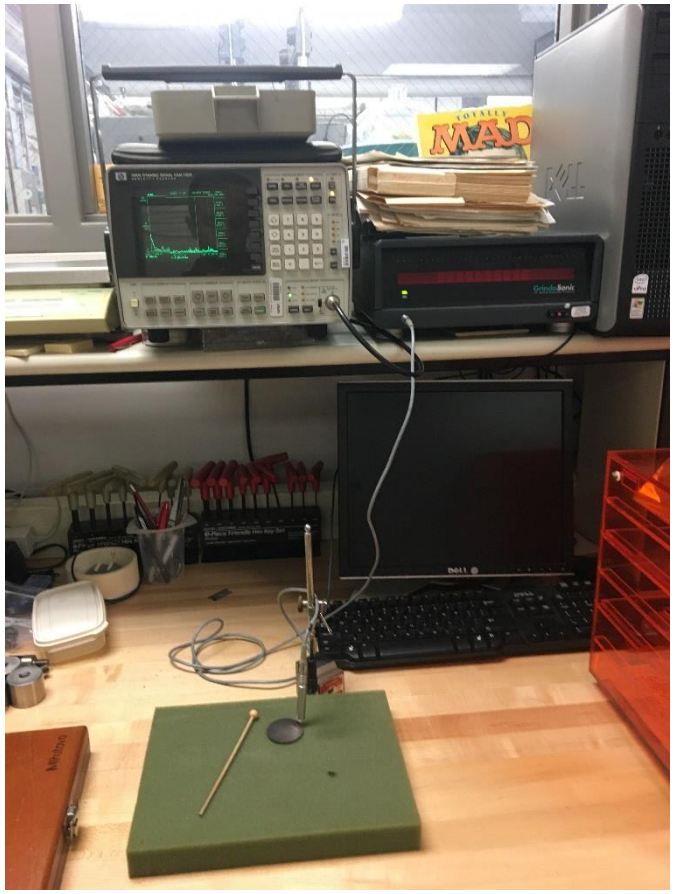
Ultrasonic Excitation

Ed=202.414 GPa



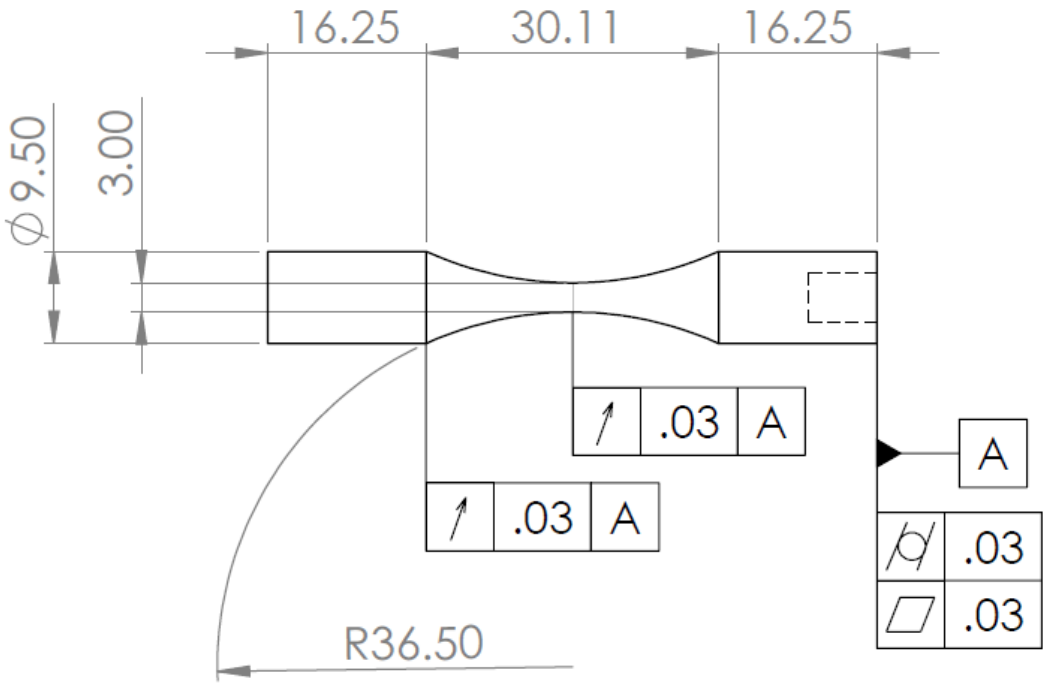
Impulse Excitation (ASTM C1259 – 08)

Ed=202.396 GPa



VAR 9310 Specimen Geometry

- 3 mm Gage Section
  - Recommended by supplier
- .01 um Displacement Control
  - +/- 2 MPa of control
- ~.04 um of noise
  - +/- 8 MPa of noise
- Increased gage needed

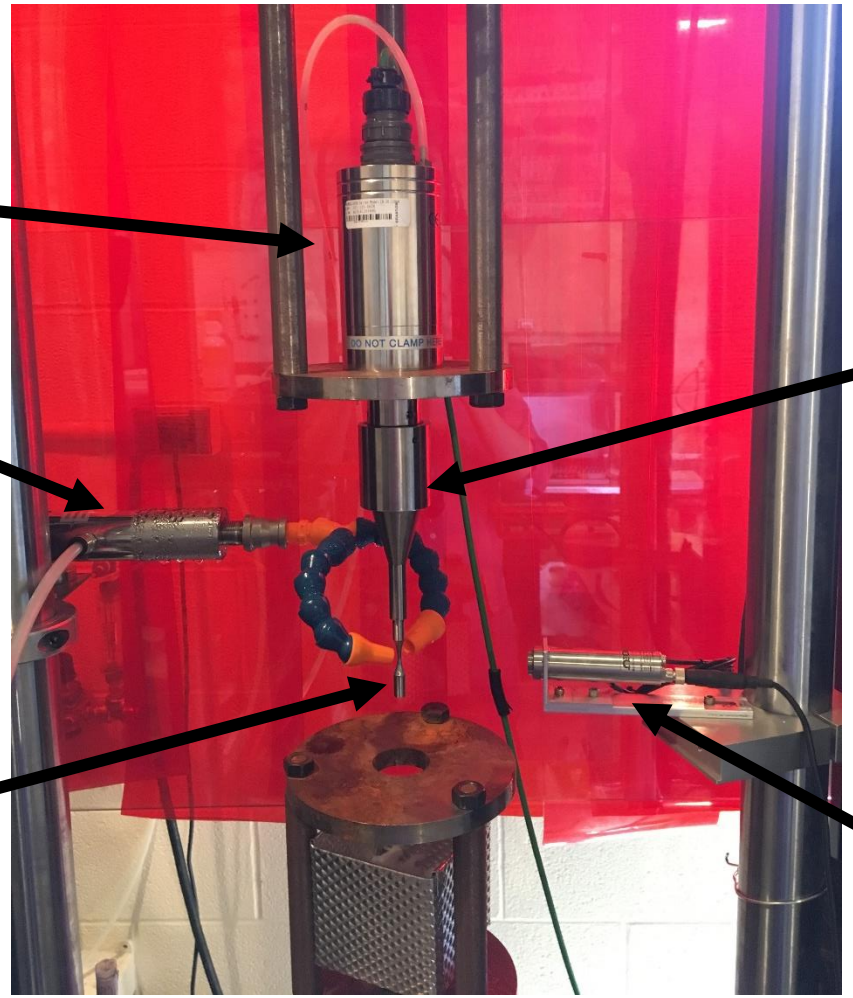


Manufacturing Process

1. Machine Rough Geometry
2. Heat Treat to Core Hardness
    1. Mock Carburize 927 C for 8 hours
    2. Cool to RT
    3. Reheat to 787 C
    4. Oil Quench
    5. Temper 148 C for 2 hours
3. Low Stress Grind Gage Section
4. Cut Specimen To Length

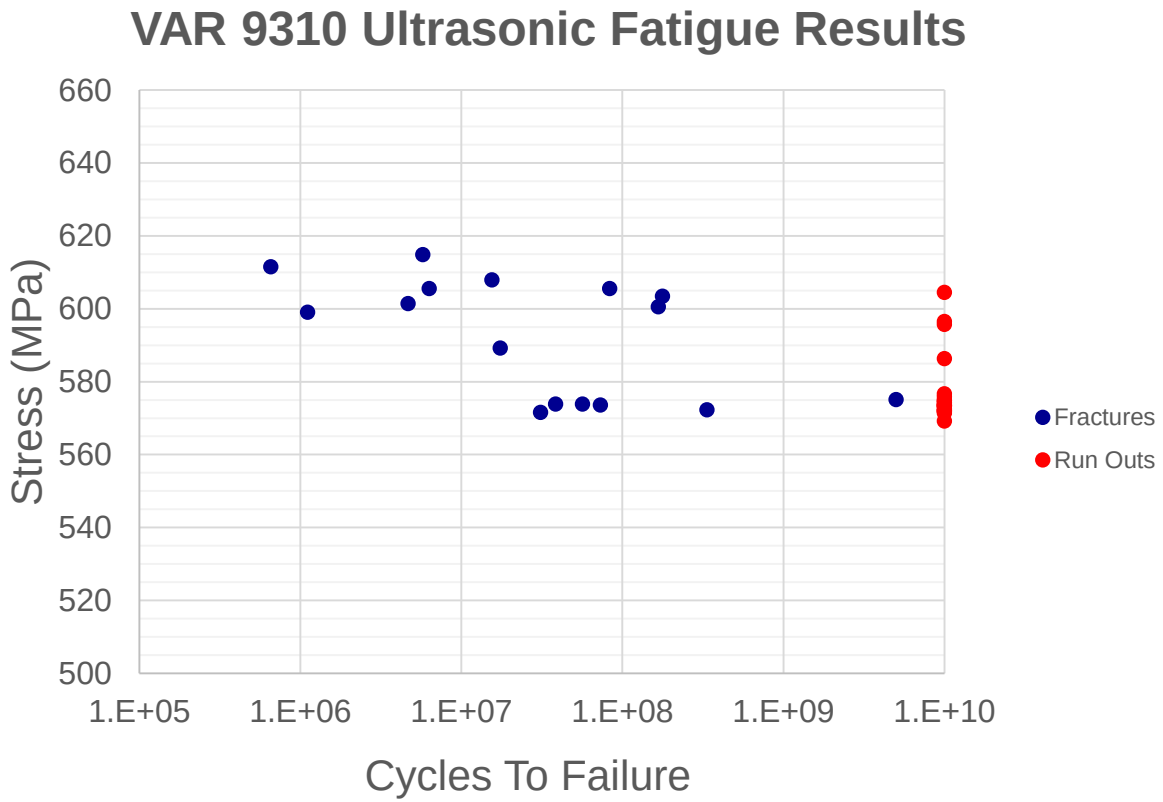
Vickers Hardness Testing	
Specimen #	Vickers Hardness (Hv)
1	394
2	394
3	396
4	398
5	396
Average	395 (41 HRC)

VAR 9310 Fatigue Test Set Up



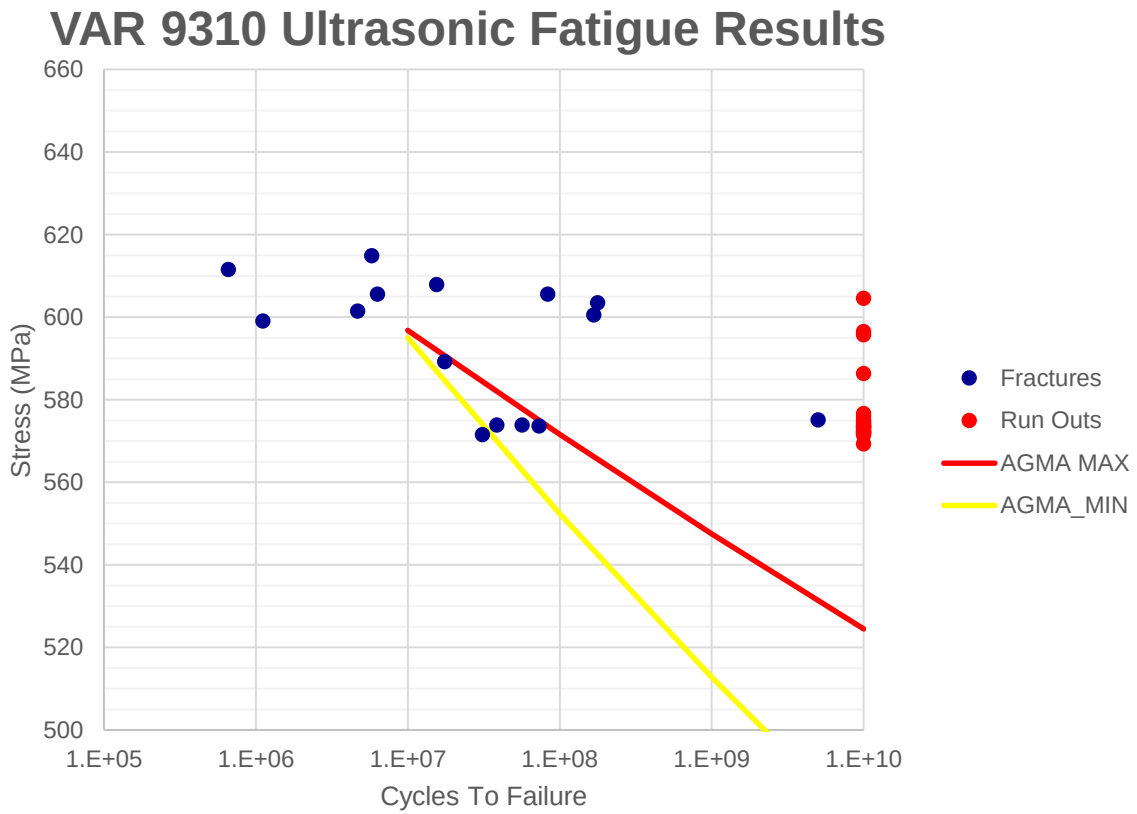
VAR 9310 Ultrasonic Fatigue Testing Results

- Load Ratio of -1
- Room Temperature (<100 F)
- 40 Test Specimens
- Run out = 10^10 cycles
- Estimated 10^10 Fatigue Strength of 570 MPa
- AGMA predicts steeper reduction in Fatigue Strength



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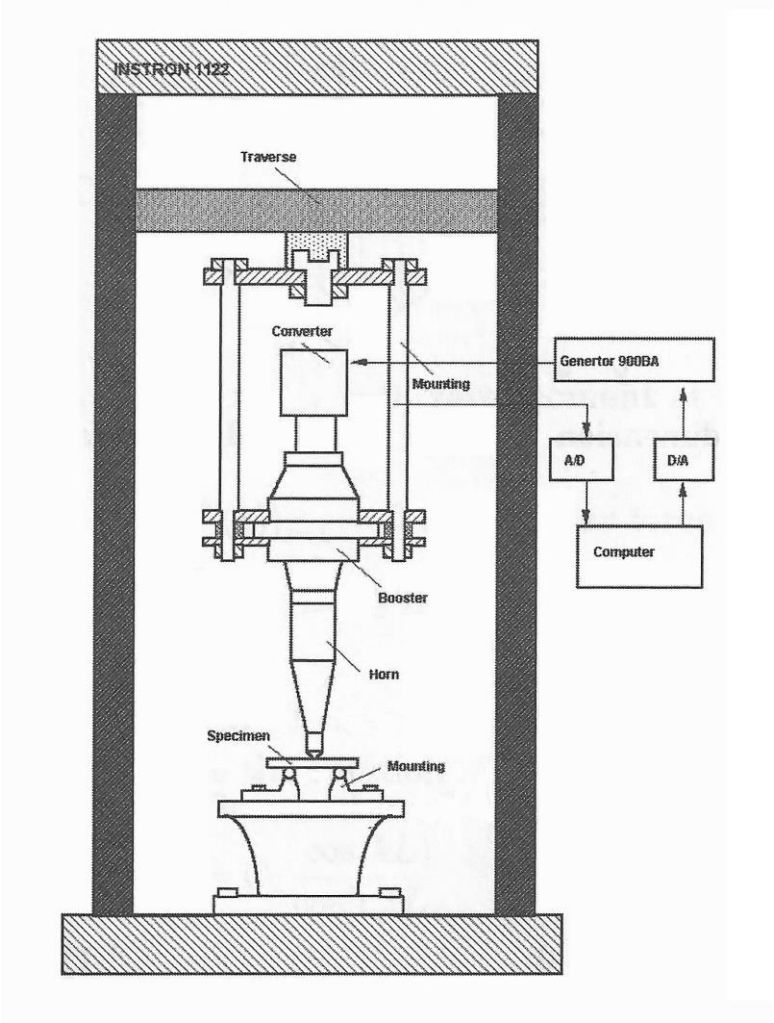


Future Plans: Bending Fatigue

- Goal: Bending fatigue of a case carburized specimen representative of a gear tooth
- Initial Plan: 3 Point Bending

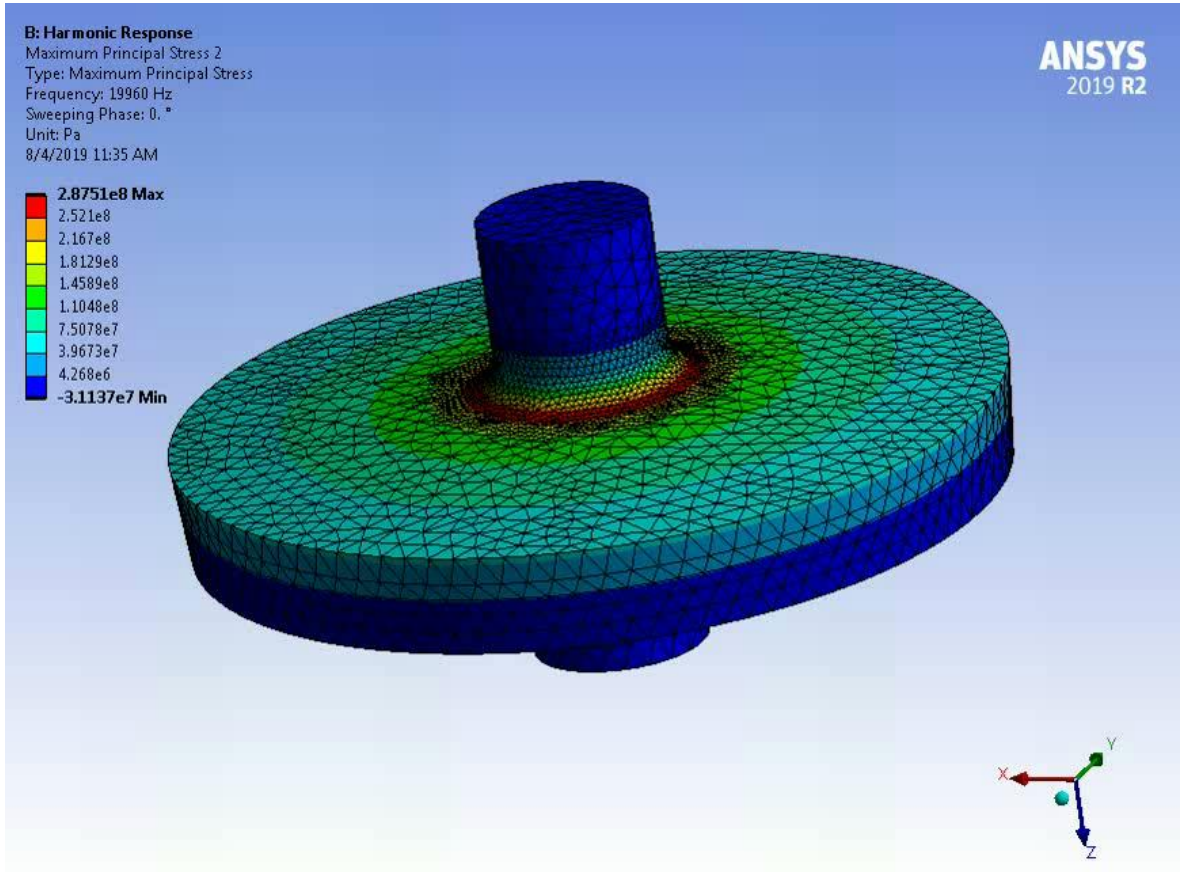
  Issues with:

  - » Stiffness
  - » Frictions
  - » Alignment



New 20 kHz Simulated Tooth Fatigue Specimen

- Fully Reversible bending Fatigue at 20kHz
- Representative of NASA's standard test gear
- In process of validating design



Summary

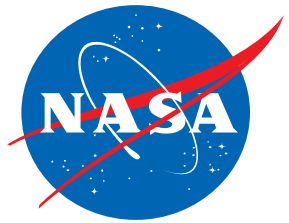
- Ultrasonic fatigue enables fatigue testing at cycles >10^7
- Goal: Improve on current empirical methods for predicting gear tooth fatigue at >10^7 cycles
- Preliminary VAR 9310 fatigue results presented
- Future plans for simulated gear tooth fatigue.

Acknowledgments

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QUESTIONS ?


Glenn Research Center
Lewis Field
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Example Initiation Site

