

Effects of Surface Induction Hardening on the Torsional Fatigue Performance of Previously Carburized Modified 4121 Steel

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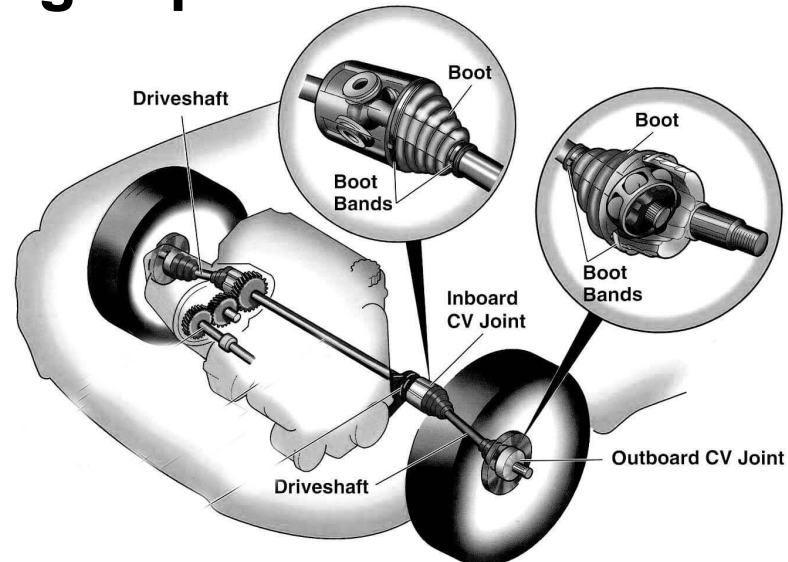
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Outline

- **Introduction**
- **Background**
 - *As-Received Material Composition*
 - *Sample Design*
 - *Heat Treatment Process Overview*
- **Torsional Fatigue Results**
- **Microstructural Characterization**
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 - *NMTP Analysis*
- **Residual Stress Measurements**
- **Fracture Study**
- **Project Conclusions**

Industrial Relevance

- **Torsional fatigue and surface wear resistance are often two of the most important factors to optimize when designing automotive parts subject to cyclical torsional loading, such as CV joints and driveshafts**
- **Observations from industry show that induction hardening previously carburized parts can lead to increased torsional fatigue performance**



As-Received Material

- **SAE 4121 modified with high Cr**
 - *Hereby referred to as 4121m*

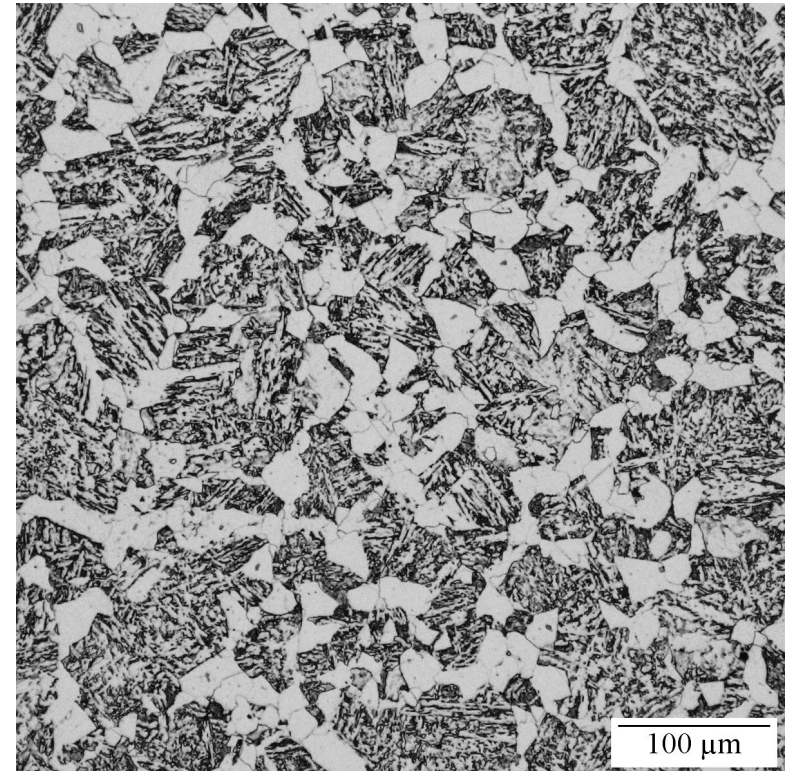
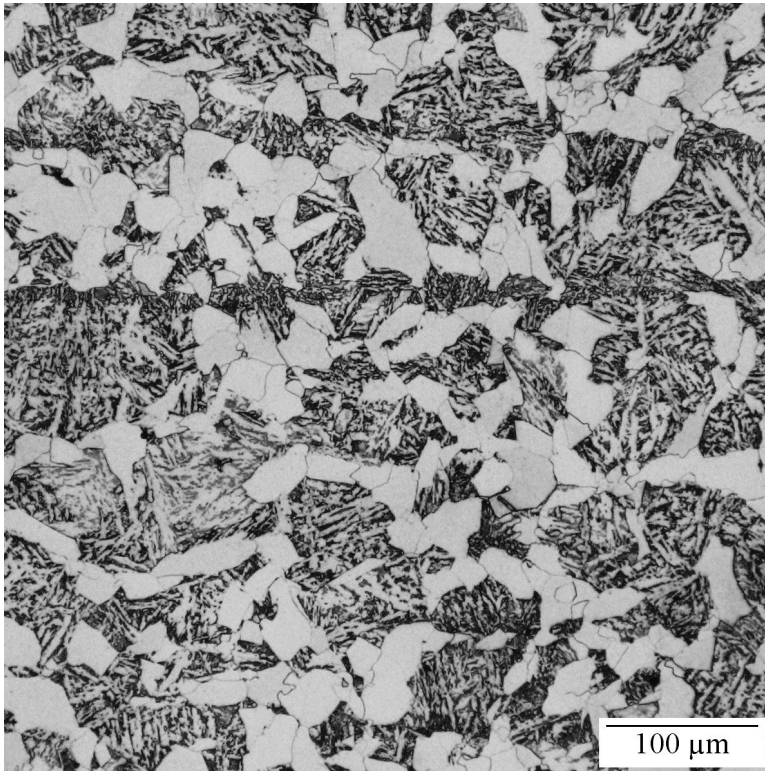
	C	Mn	P	S	Si	Cr	Ni	Mo
wt pct	0.19	0.87	0.009	0.010	0.33	0.84	0.11	0.20

	Cu	Al	Ca	H (ppm)	N	O	Pb	–
wt pct	0.22	0.028	0.0008	1.1	0.0181	0.0012	0.0010	–

- **21 cylindrical bars from a single production heat**
 - *Length: 101.6 cm (40 in)*
 - *Width: 6.43 cm (2.53 in)*

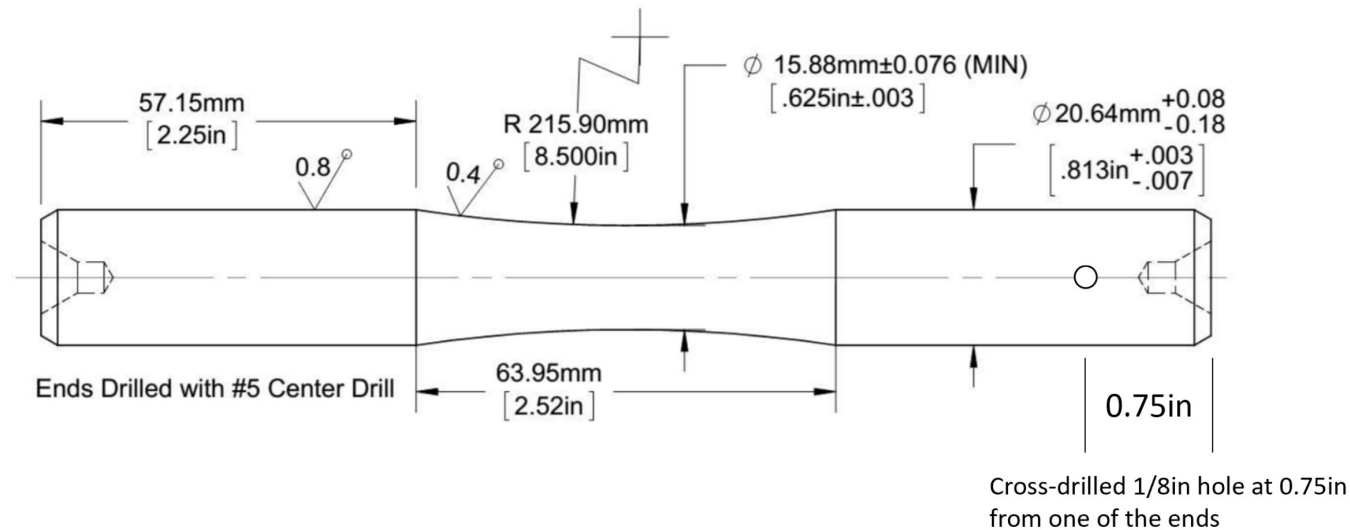
Light Optical Micrographs of the As-Received 4121m

- **Rolling direction,
2 pct nital etch**
- **Transverse direction,
2 pct nital etch**



Sample Design

- Designed by Dr. Lee Rothleutner for his PhD project
- Designed to be easily induction hardened while fitting the physical and test constraints of the torsional fatigue equipment at CSM
- Added a cross-drilled hole at 0.75 in (1.9 cm) from the end to allow for by-wire hanging during carburizing



Heat Treatments – Carburizing

- **Carburizing performed at Nexteer Automotive**
- **Case depths of 1.0 and 1.5 mm**
 - *Depth to 50 HRC*
 - *Post-quench temper at 182°C for 1.5 hr*

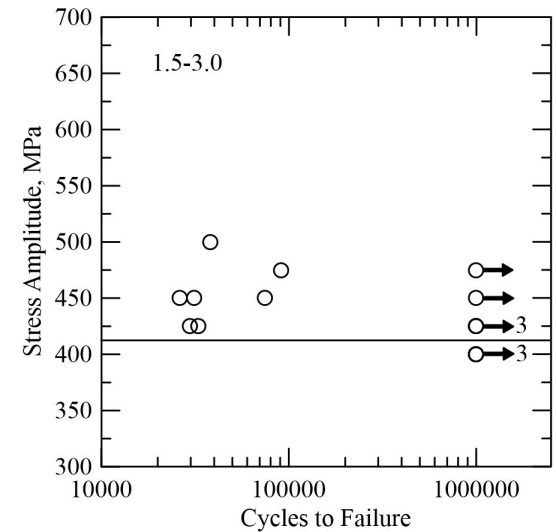
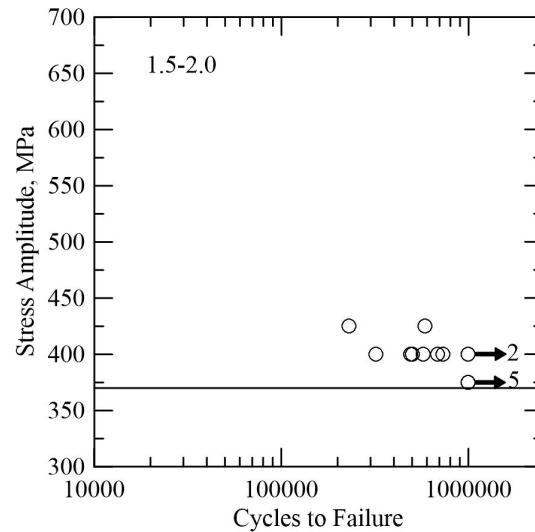
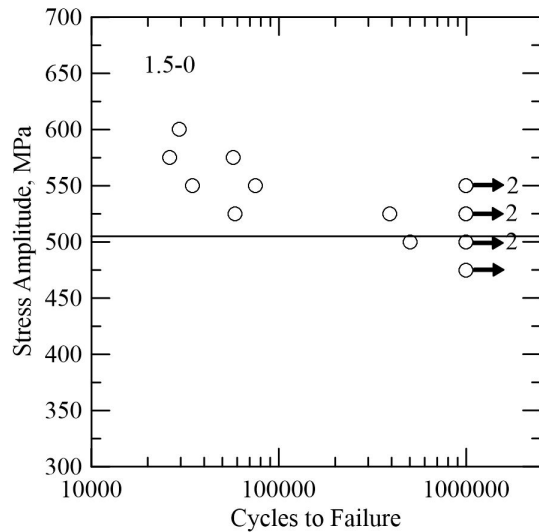
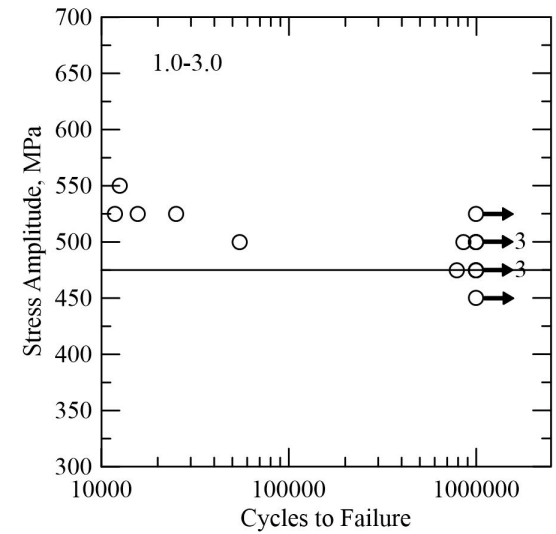
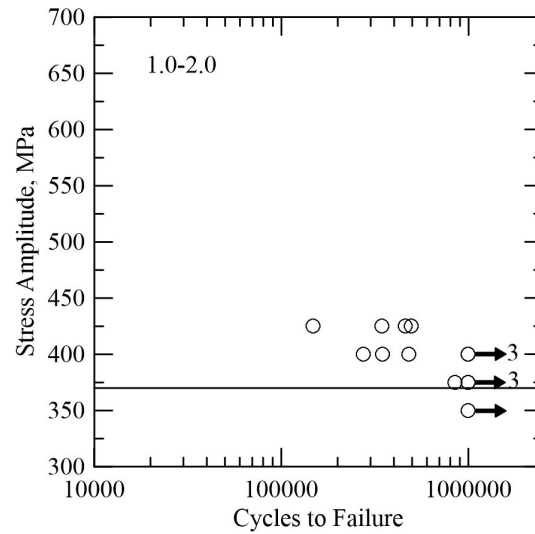
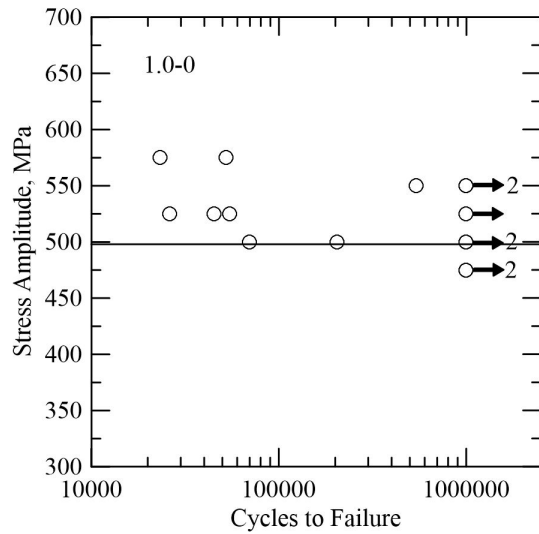
Process Step	1.0 mm	1.5 mm
Boost Cycle Temperature, °C	927	927
Boost Cycle Time, h	4.25	9
Boost Cycle Carbon Potential, wt pct C	0.9	0.9
Diffuse Cycle Temperature, °C	843	843
Diffuse Cycle Time, h	2	2.5
Diffuse Cycle Carbon Potential, wt pct C	0.8	0.8
Quench Medium	Hot Oil	Hot Oil
Quench Temperature, °C	121	121

Heat Treatments – Induction Hardening

- Induction hardening performed at InductoHeat
- Case depths of 0, 2.0, and 3.0 mm
 - Depth to 40 HRC
 - Post-quench temper at 182°C for 1.5 hr
- Heat treatments performed post-carburizing
- Sample group labels are a combination of carburized and induction hardened case depth
 - Example: samples carburized to **1.5 mm** and induction hardened to **3.0 mm** are labeled **1.5-3.0**

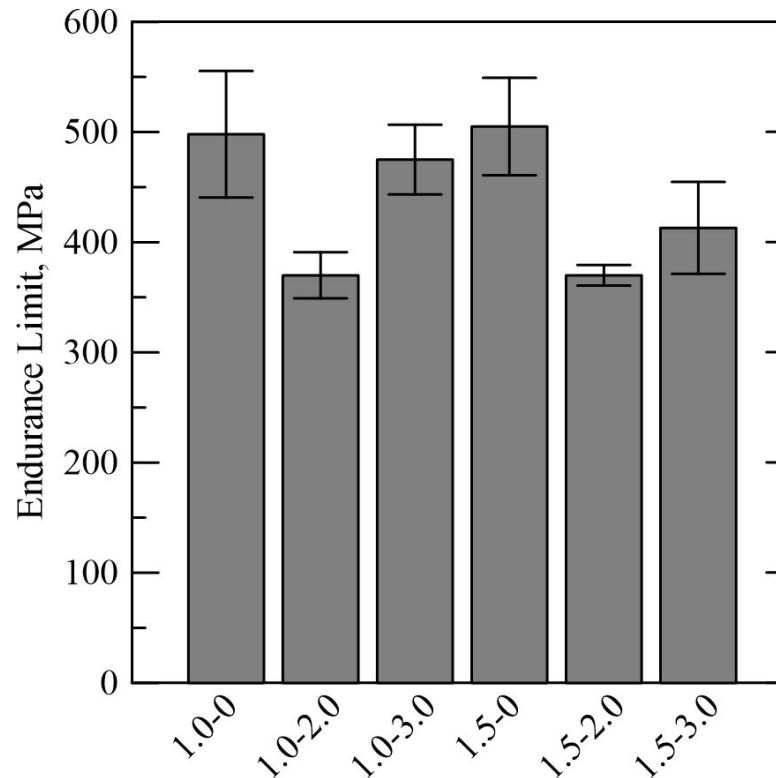
Process Step	2.0 mm	3.0 mm
Power, kW	114	84
Nominal Peak Temperature, °C	975	975
Time at Peak Temperature, s	1.49	2.63
Frequency, kHz	29.2	22.4
Quench Medium	6% Polymer Solution	6% Polymer Solution
Quench Temperature, °C	32	32

Torsional Fatigue Results



Torsional Fatigue Results

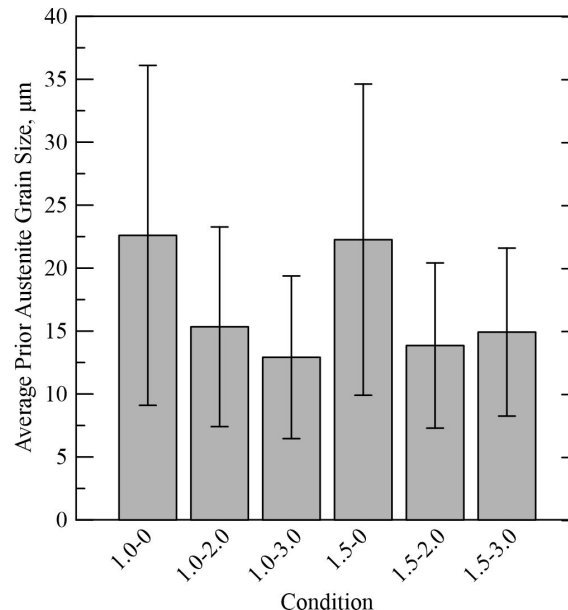
- **As-carburized conditions exhibited better fatigue performance than the carburized plus induction hardened conditions**



What Factors are Most Affecting Fatigue Performance?

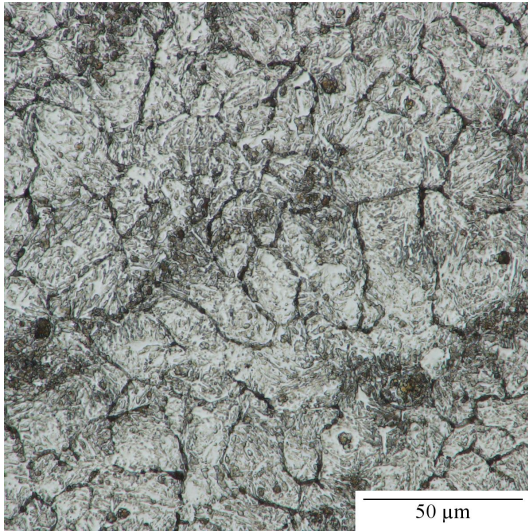
Prior Austenite Grain Size (PAGS)

- Analyzed between 500 and 550 grains
100-400 μm from surface
- As-carburized conditions are nearly identical
- Carburized plus induction hardened conditions are similar and smaller than the as-carburized conditions

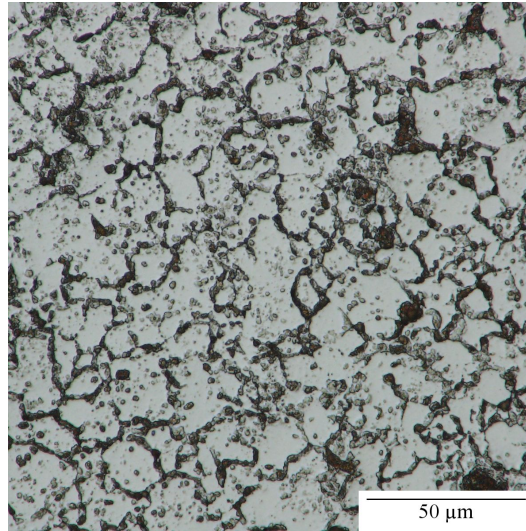


PAGS Micrographs

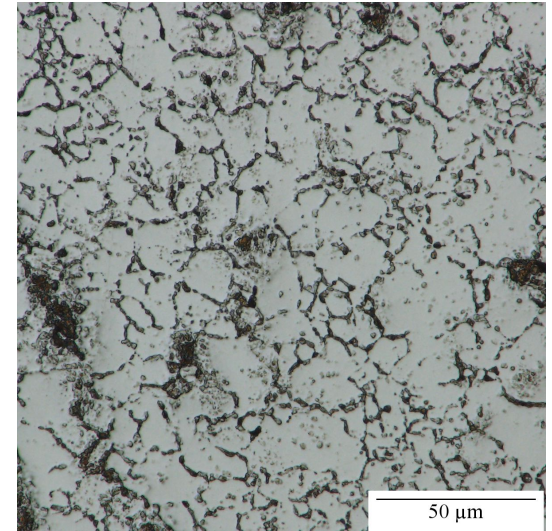
1.0-0



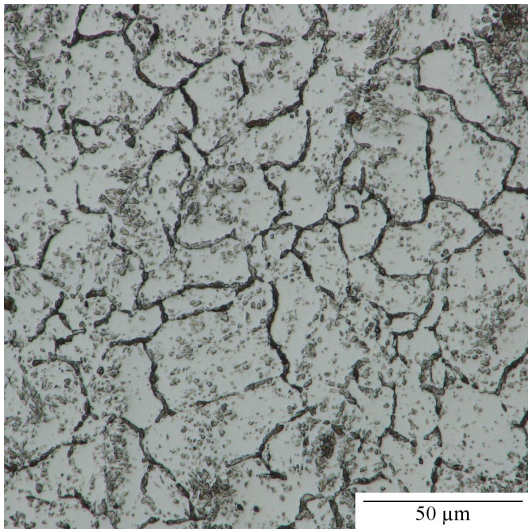
1.0-2.0



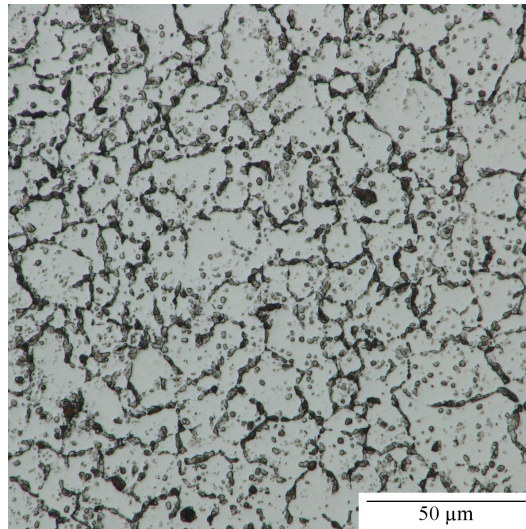
1.0-3.0



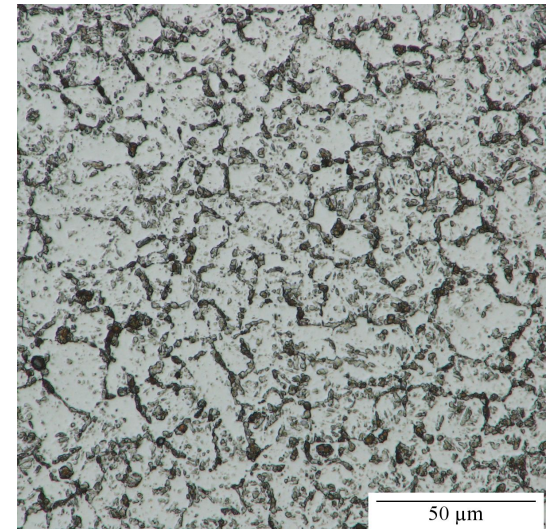
1.5-0



1.5-2.0



1.5-3.0

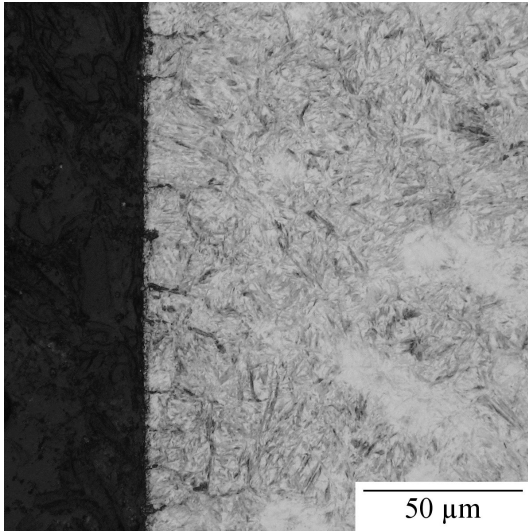


NMTP Analysis – LOM

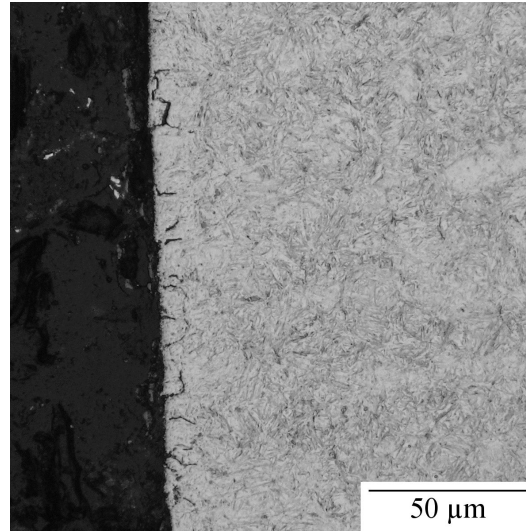
- **Analysis performed using LOM and a light 2 pct nital etch**
- **Minor evidence of NMTP in as-carburized samples and no visible evidence in carburized plus induction hardened conditions**

NMTP Micrographs – LOM

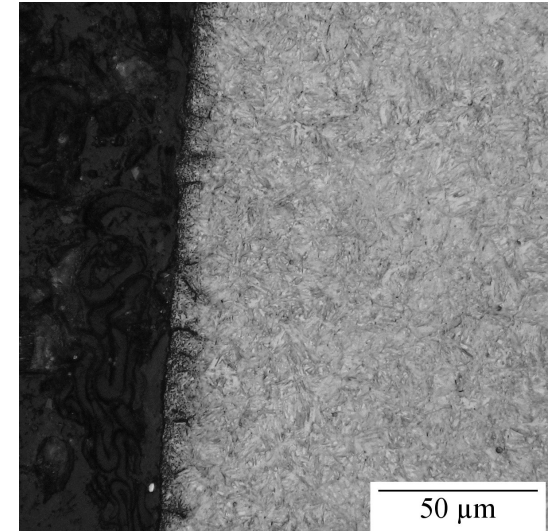
1.0-0



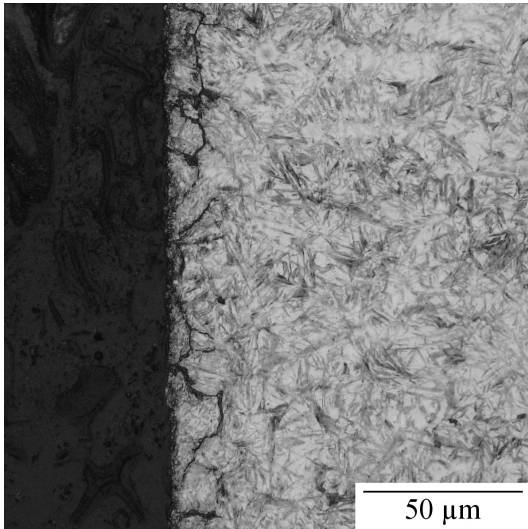
1.0-2.0



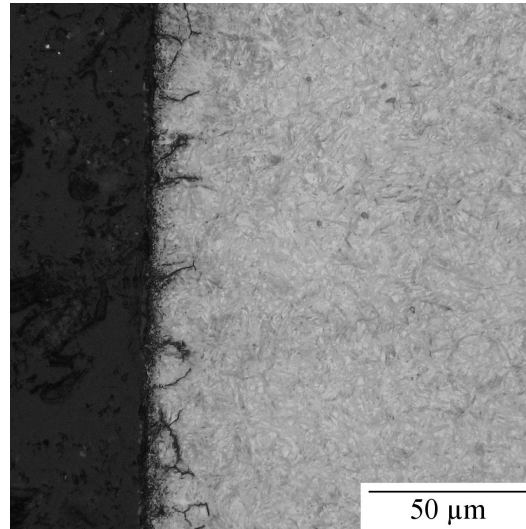
1.0-3.0



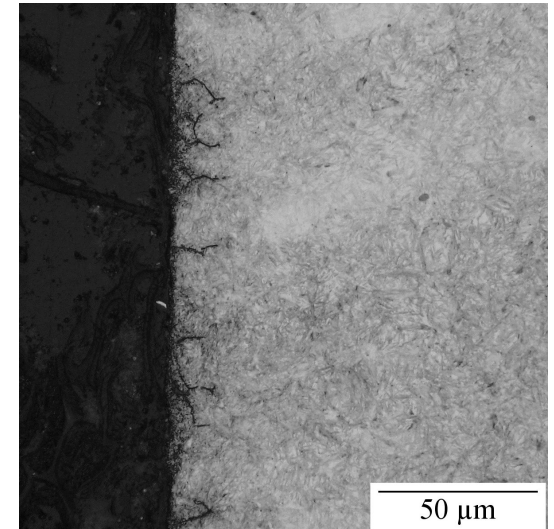
1.5-0



1.5-2.0



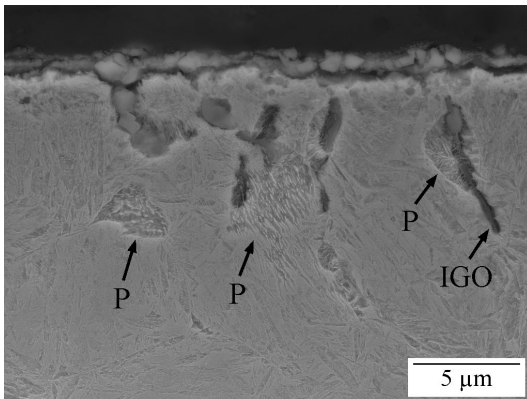
1.5-3.0



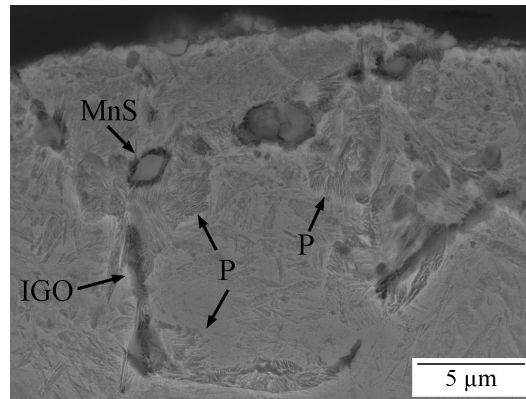
NMTP Analysis – SEM

- **SEM revealed small fractions of pearlite near or directly adjacent to IGO in as-carburized conditions**
- **No NMTP observed in carburized plus induction hardened conditions**

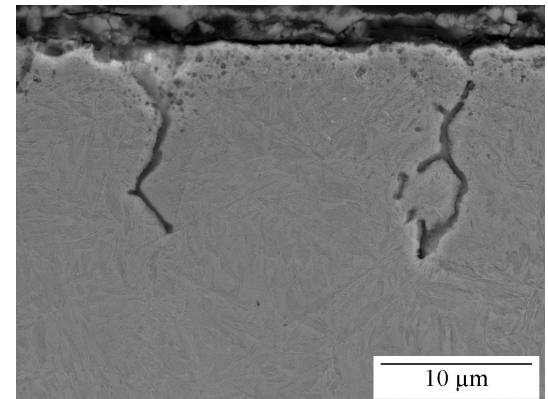
1.0-0



1.5-0

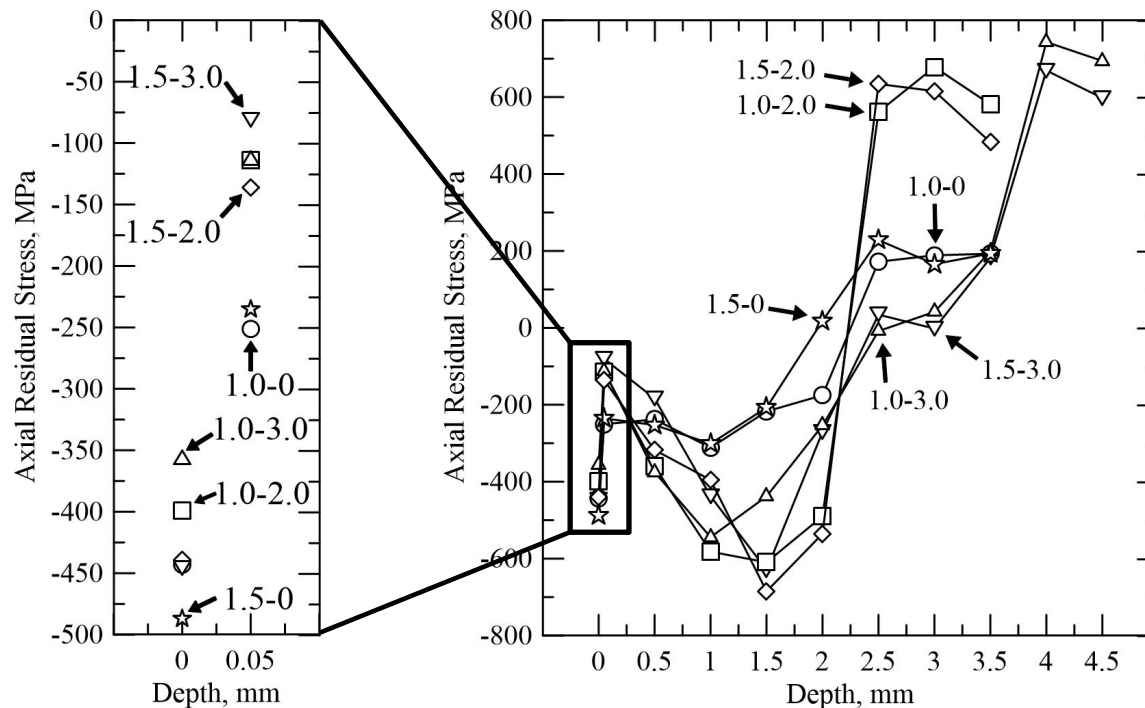


1.5-2.0



XRD Residual Stress Analysis

- **Performed at Caterpillar**
- **As-carburized conditions exhibit higher surface and near-surface axial residual stresses than the carburized plus induction hardened conditions**

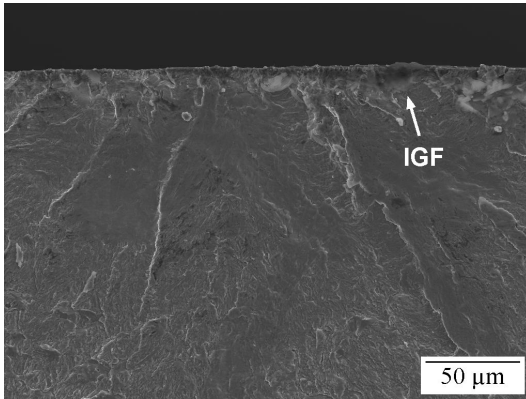


Fracture Study – Fatigue Crack Initiation

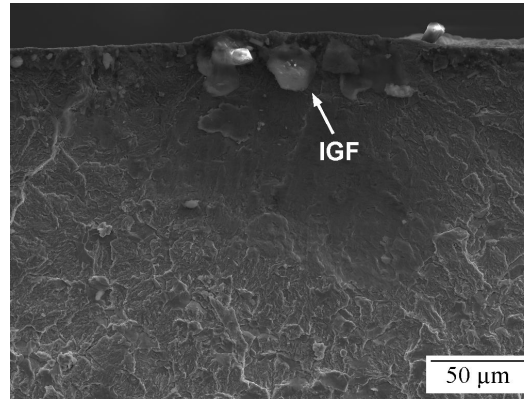
- **All conditions appear to exhibit “initiation zones” rather than a single initiation site**
 - *i.e. multiple cracks initiate simultaneously and coalesce into one*
- **No obvious favored initiation mechanism**
 - *Inclusions and areas of apparent intergranular fracture observed within initiation zones for all conditions at different stress amplitudes*

Fracture Study – Fatigue Crack Initiation

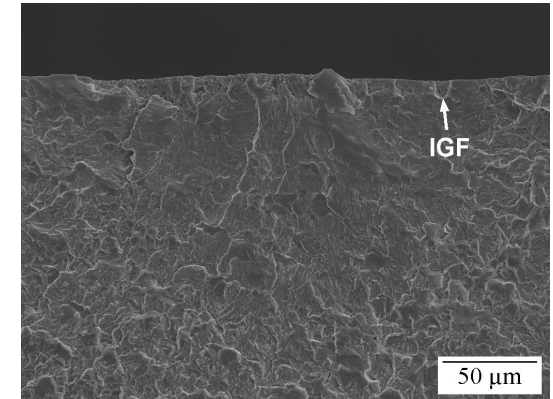
1.0-0, 525 MPa, 26,200 cycles



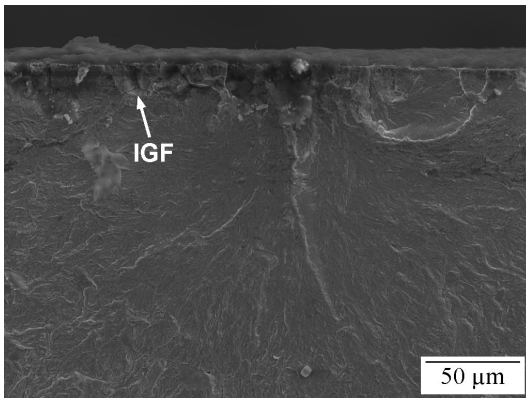
1.0-2.0, 425 MPa, 147,600 cycles



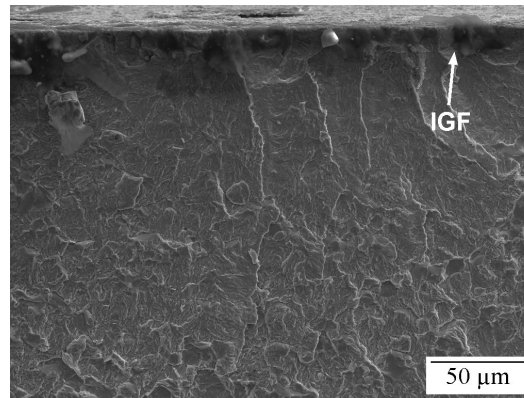
1.0-3.0, 525 MPa, 15,600 cycles



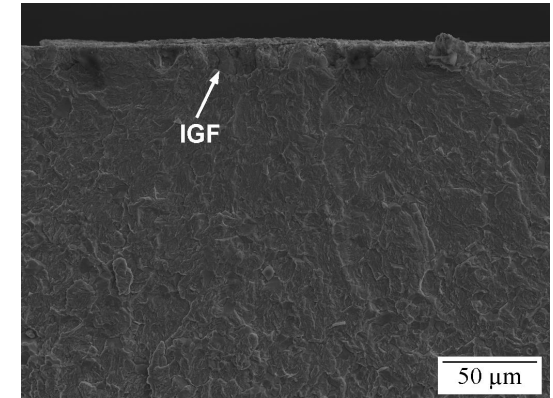
1.5-0, 525 MPa, 390,800 cycles



1.5-2.0, 425 MPa, 229,400 cycles



1.5-3.0, 500 MPa, 38,100 cycles

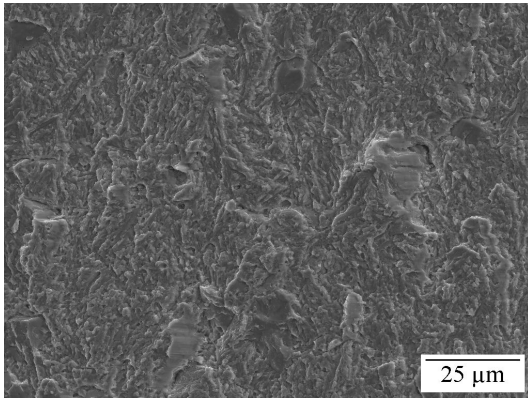


Fracture Study – Overload Failure

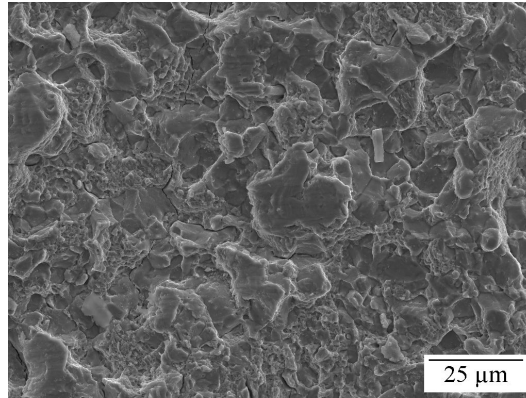
- **Area examined was below the deepest point of the stable fatigue crack zone just beyond the transition to overload failure**
- **Preferred fracture modes in this region:**
 - *1.0-0: transgranular*
 - *1.5-0: primarily transgranular with fraction of intergranular*
 - *Carburized plus induction hardened conditions: almost exclusively intergranular*
 - *Possible grain boundary embrittlement*

Fracture Study – Overload Failure

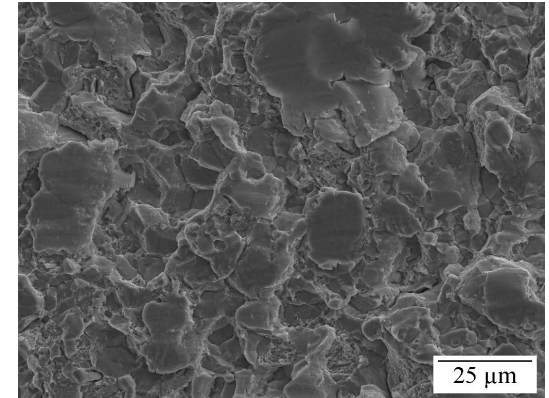
1.0-0, 525 MPa, 26,200 cycles



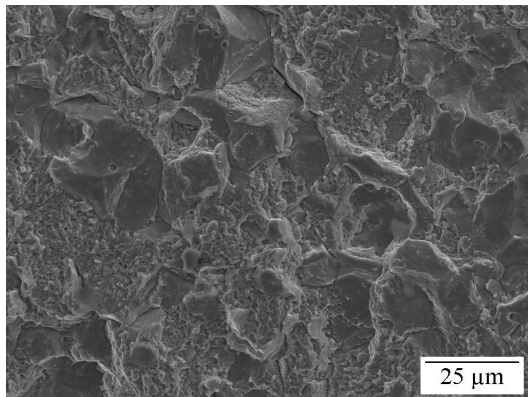
1.0-2.0, 425 MPa, 147,600 cycles



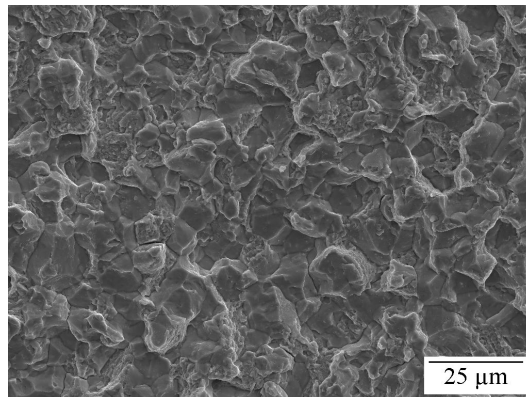
1.0-3.0, 525 MPa, 15,600 cycles



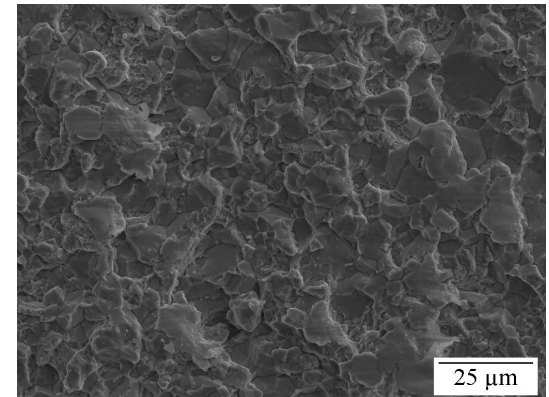
1.5-0, 525 MPa, 390,800 cycles



1.5-2.0, 425 MPa, 229,400 cycles



1.5-3.0, 500 MPa, 38,100 cycles



Relative Effects of Examined Features on Fatigue Performance

- **PAGS**: as-carburized conditions with larger **PAGS** exhibited better fatigue performance
 - *Opposite of what is observed in literature*
- **NMTP**: as-carburized conditions were the only conditions that exhibited any NMTP, yet these conditions also exhibited better fatigue performance
 - *Opposite of what is observed in literature*

Relative Effects of Examined Features on Fatigue Performance

- **Residual Stress**: as-carburized conditions with higher compressive surface residual stresses exhibited better fatigue performance
 - *Matches literature*
- **Fracture Study**: carburized plus induction hardened conditions exhibited worse fatigue performance, and these conditions also exhibited intergranular fracture in the overload failure zone

Relative Effects of Examined Features on Fatigue Performance

- Residual Stress: as-carburized conditions with higher compressive surface residual stresses exhibited better fatigue performance

The residual stress profiles and the potential grain boundary embrittlement of the carburized plus induction hardened conditions are likely the primary factors causing the reduced fatigue performance of these conditions.

failure zone

- *Intergranular fracture is less tough compared to transgranular fracture*

Project Summary and Conclusions

- **Project Goals:** evaluate the relationship between carburizing and induction hardening as it relates to torsional fatigue performance with the goal of providing recommendations to industry
- **Methods:**
 - *Torsional Fatigue Testing*
 - *Microstructural Characterization using LOM and SEM*
 - *PAGS Analysis*
 - *NMTP Analysis*
 - *Residual Stress vs Depth Profiles Using XRD*
 - *Fracture Study (Fractography and Fracture Toughness)*

Project Summary and Conclusions

- 1. The as-carburized conditions exhibited better fatigue performance despite having larger average PAGS and being the only conditions to exhibit any NMTP**
- 2. Two factors are likely responsible for the reduced fatigue performance of the carburized plus induction hardened conditions**
 - Reduced compressive surface residual stresses*
 - Potential grain boundary embrittlement and associated intergranular fracture during overload failure*
- 3. The results of this project highlight the importance of process optimization, as shown through the grain boundary embrittlement resulting from induction hardening**

Thank You!

Any questions?
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