FATIGUE DESIGN AND BEHAVIOUR OF CARBURIZED STEEL

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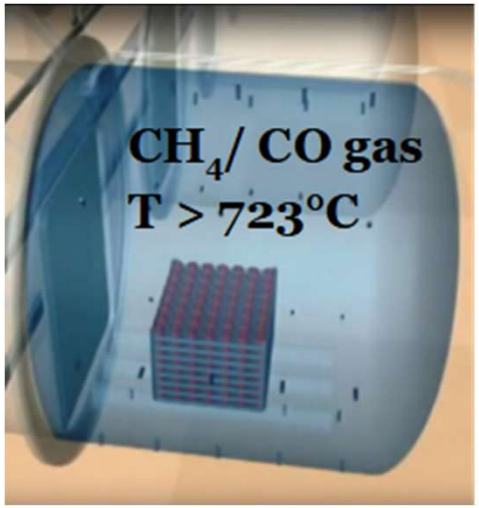
Overview

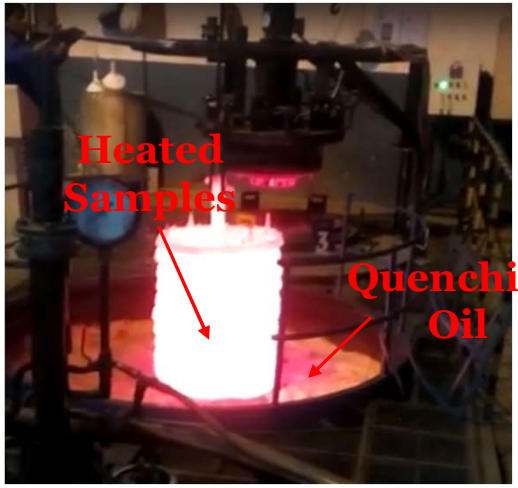
1. **Background**
2. **Material Properties**
3. **Retained Austenite and Residual Stress Estimates**
4. **Fatigue Analysis**
5. **Conclusions and Recommendations**

BACKGROUND

Background: Carburization Procedure

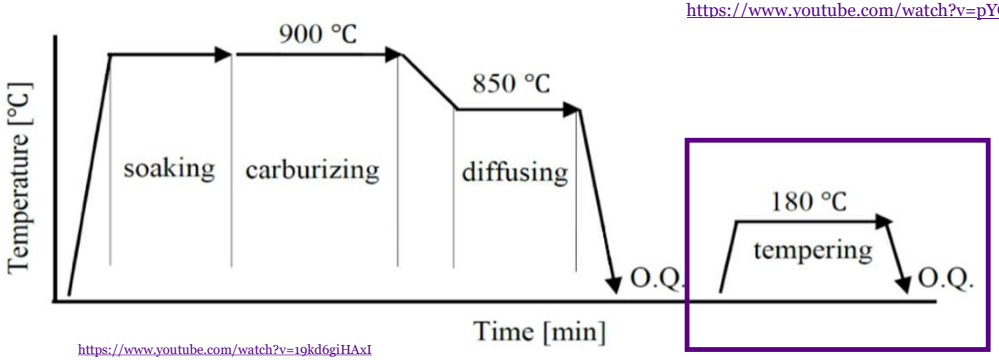
https://www.google.com/url?sa=i&url=https%3A%2F%2Fkhkgears.net%2Fnew%2Fgear_manufacturing.html&psig=AOvVaw38cWxfuNMfL2gglV0RRQfe&ust=1648327024954000&source=images&cd=vfe&ved=0CAsQjRxqFwoTCMiz3umO4vYCFQAAAAAdAAAAABAf





Quenching

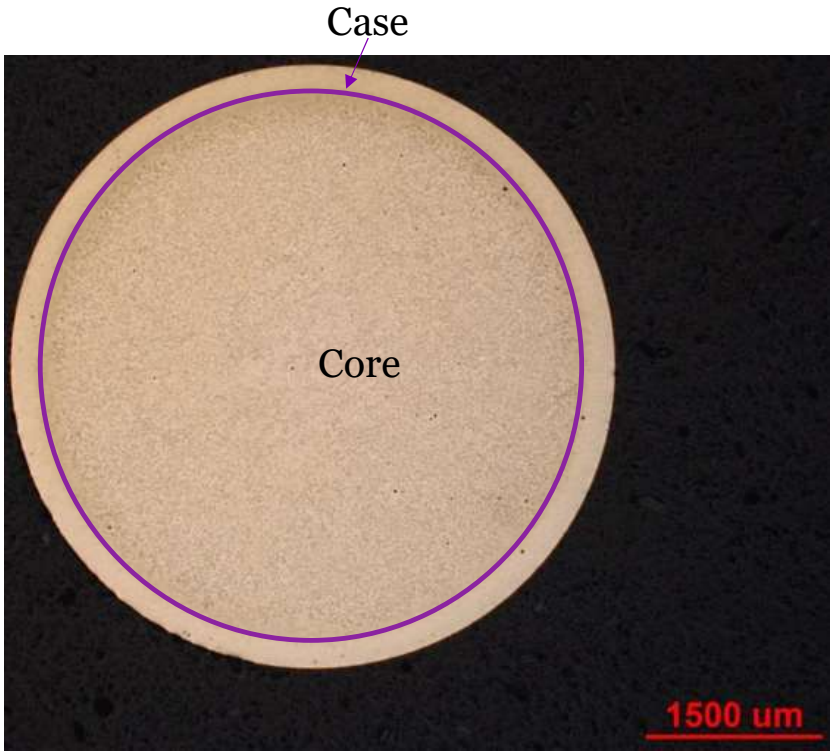
https://www.youtube.com/watch?v=pYQuqNFG2ro&t=35s



https://www.youtube.com/watch?v=19kd6giHAxI

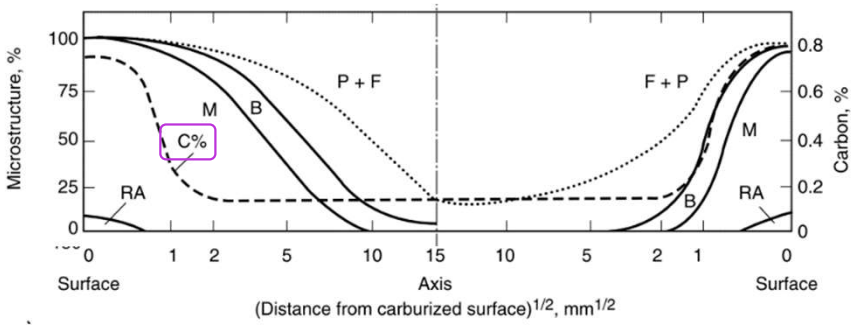
Background: Steel Carburization

- Two layers:
  - Case: high carbon content, high strength, brittle
  - Core: high toughness
- Benefits:
  - Better wear resistant surface
  - Increased surface hardness
  - Compressive residual stress on the surface

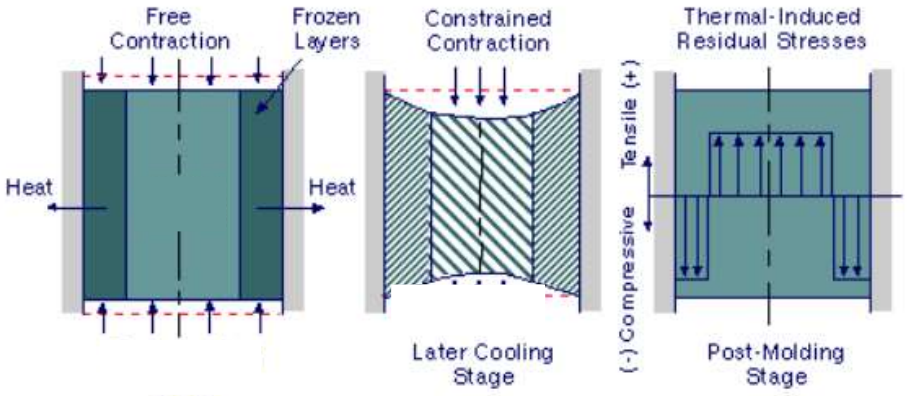


Background: Residual Stress Sources

- Volume change from phase transformation:
  - Case: Austenite -> Martensite
  - Core: Austenite -> Ferrite
- Different thermal expansion coefficients in the case and the core during quenching

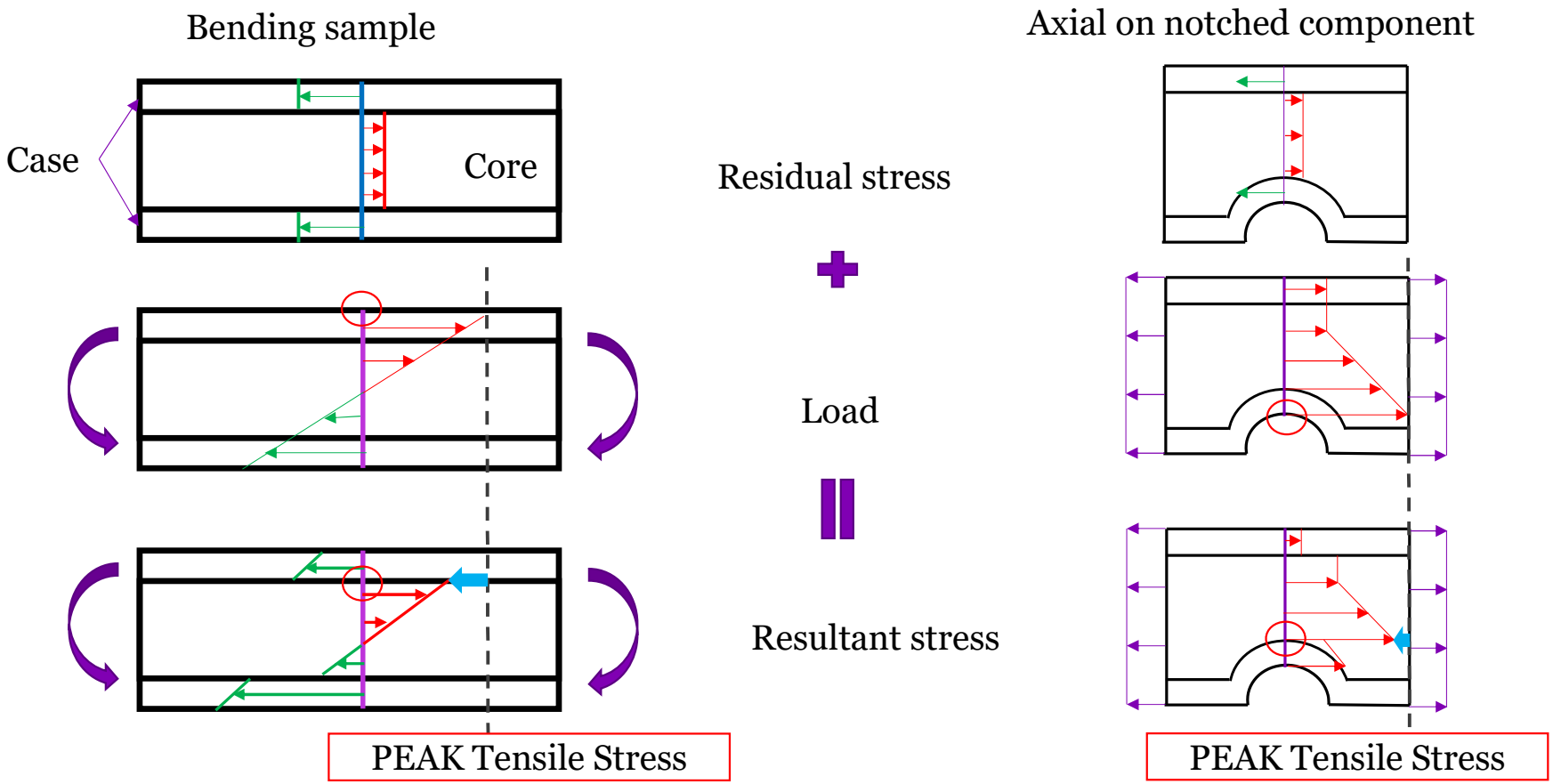


Microstructure of carburized steel [4]



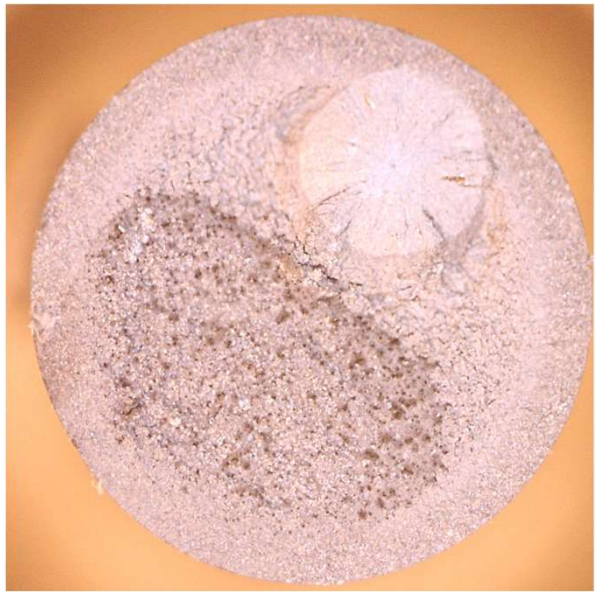
Development of residual thermal stress during cooling
http://www.dc.engr.scu.edu/cmdoc/dg_doc/develop/process/physics/b3400001.htm

Background: Benefits of Residual Stress



Background: Failure Location

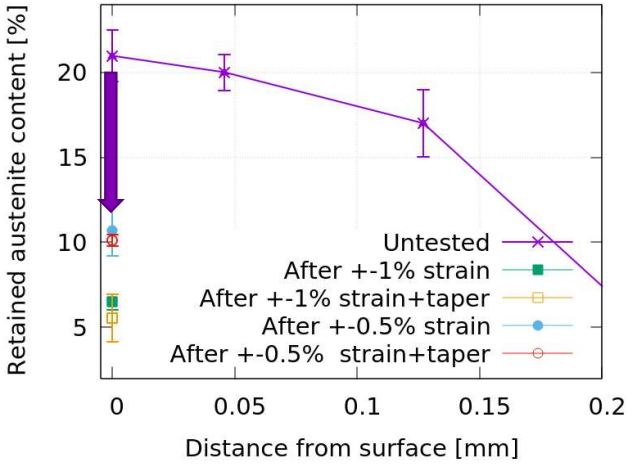
Axial sample with surface failure



Axial sample with fisheye failure

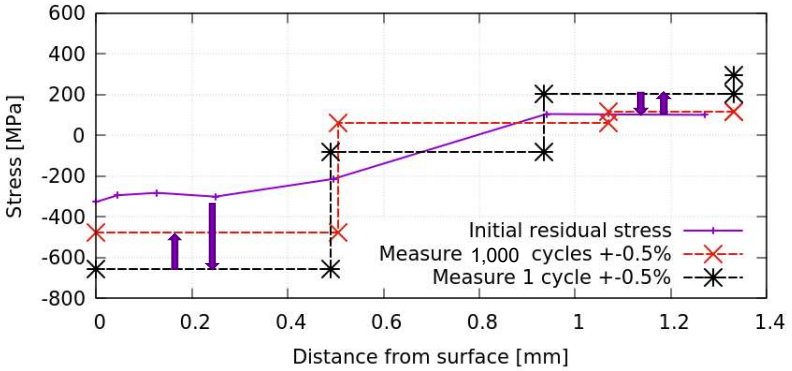
Background: Change in Residual Stress During Cyclic Loading

- Retained austenite transformation during loading causes volume change



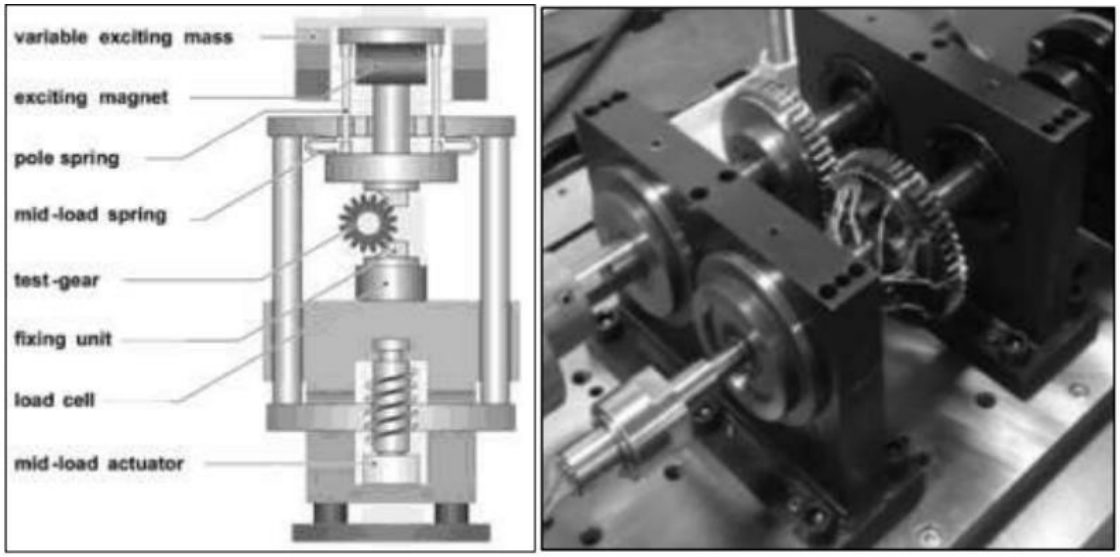
RA content before and after loading

- Residual stress relaxation during cyclic loading



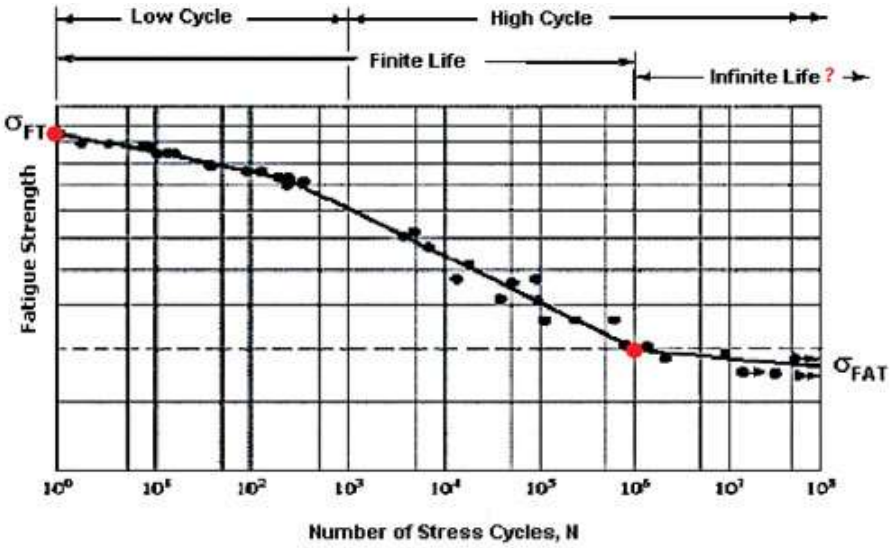
Residual stress relaxation under cyclic loading

Background: Current Design Approach



Gear test rig and gear box for measurement of root stress

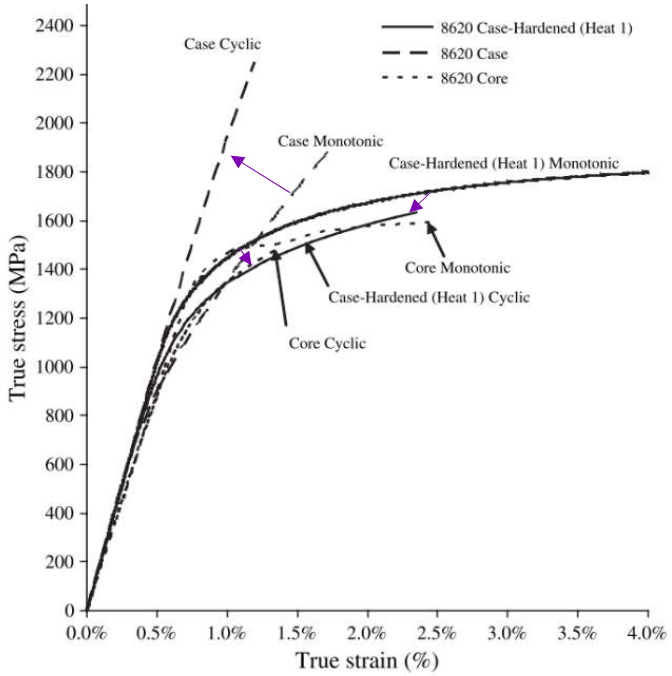
https://www.matec-conferences.org/articles/matecconf/pdf/2017/04/matecconf_aigev2017_01037.pdf



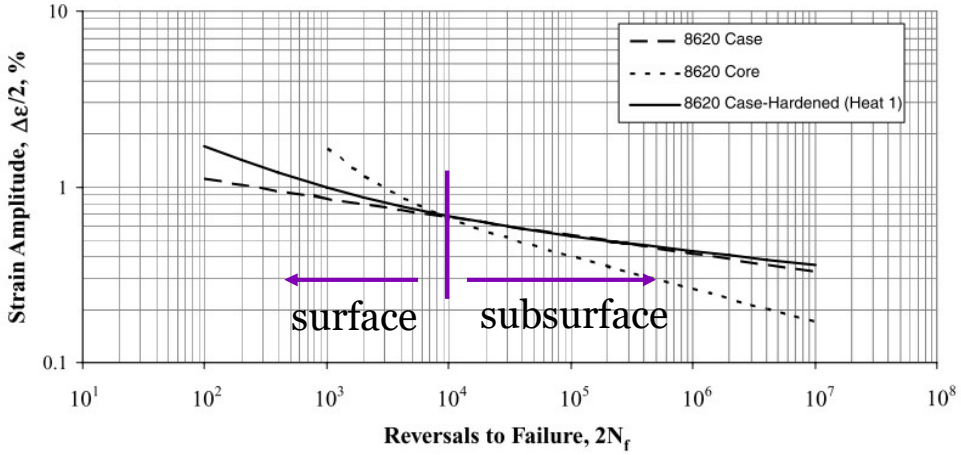
Stress-life curve of a gear

http://gearsolutions.com/features/estimating-gear-fatigue-life/

Background: Current Stage of Research

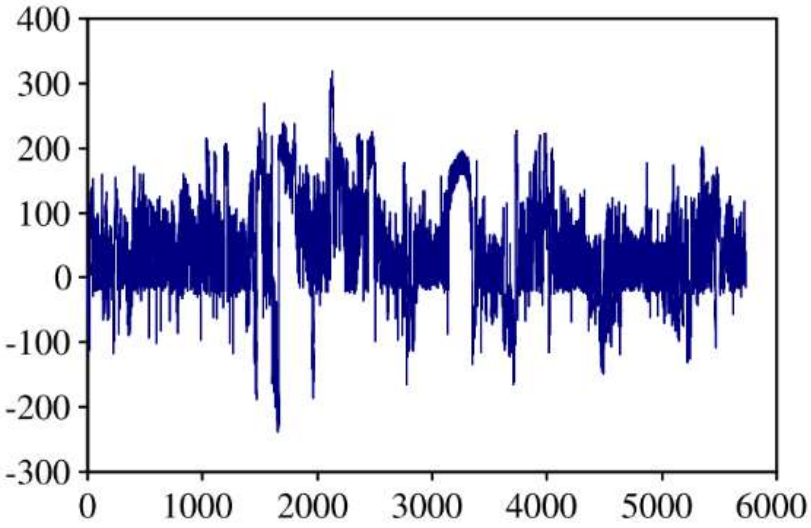


Stress-strain behaviours of the case, core and case-hardened materials [2]

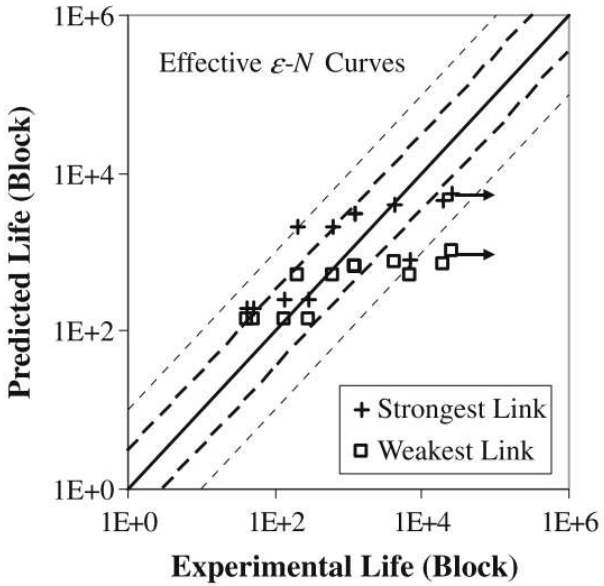


Strain-life curves of simulated case, through core and carburized steels [3]

Background: Current Stage of Research



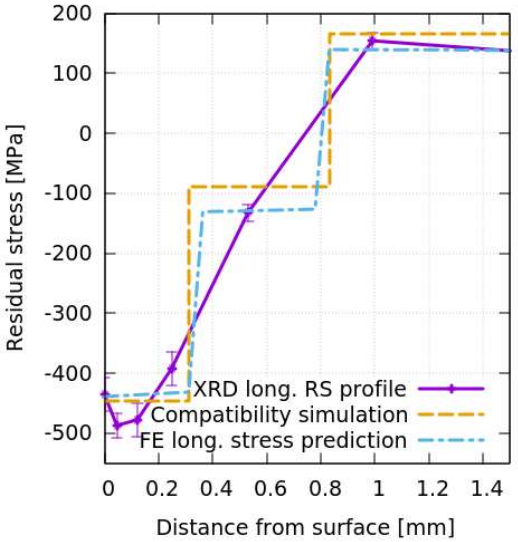
Variable amplitude (VA) load history [1]



Correlations between predicted and experimental fatigue lives for case-hardened specimens under VA load history [1]

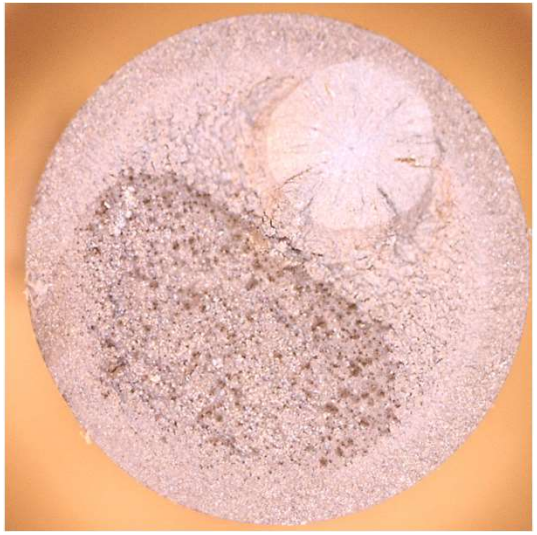
Background: Objectives

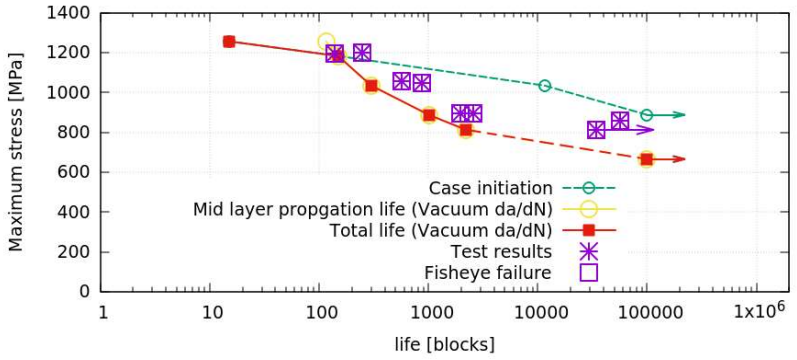
- To estimate the residual stresses generated from carburization
- To model the residual stress change during cyclic loading
- To predict the fatigue initiation site and total fatigue life of carburized components



Initial residual stress profile after carburization

Fracture surface of axial composite sample





VA life prediction for axial composite sample

MATERIAL PROPERTIES

Material Properties: Chemistry and Heat Treatment

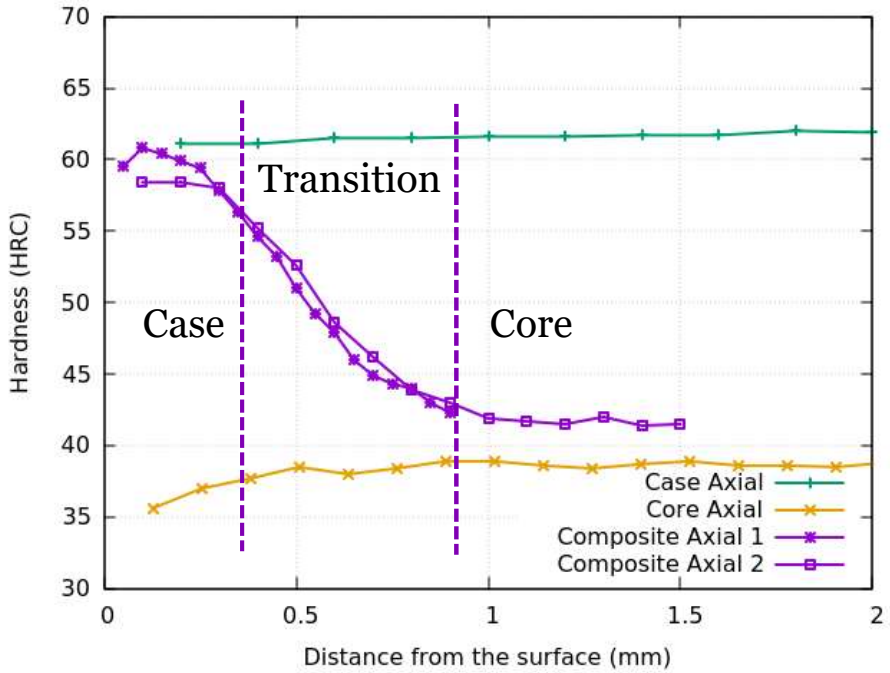
Chemical Composition of 16MnCr5

C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Al
0.14%	1.23%	0.011%	0.035%	0.21%	1.04%	0.21%	0.06%	0.19%	0.021%
V	**Cb**	**Ti**	**Zr**	**Co**	**Sn**	**B**	**Pb**	**Ca**	**W**
0.028%	0.01%	ND	ND	0.01%	0.01%	0.0019%	ND	0.003%	0.01%

Carburizing Procedure

Sample	Carburization Temperature	Carburizing Time	Carbon Potential	Quench Oil Temperature	Tempering
Case-Hardened Composite	927˚C	90 minutes	0.85%	66˚C	177˚C for 90min
Case	927˚C	1800 minutes	0.85%	66˚C	177˚C for 90min
Core	927˚C	90 minutes	0	66˚C	177˚C for 90min

Material Properties: Hardness



Hardness profile of the case, the core and the case-hardened samples

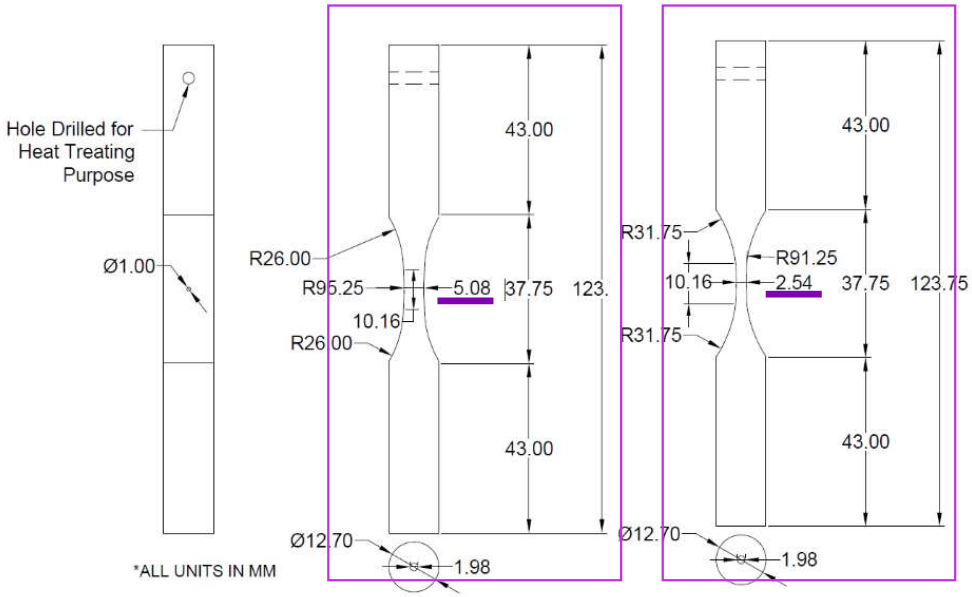
Material Properties: Sample Geometry

Plate (2 thicknesses)

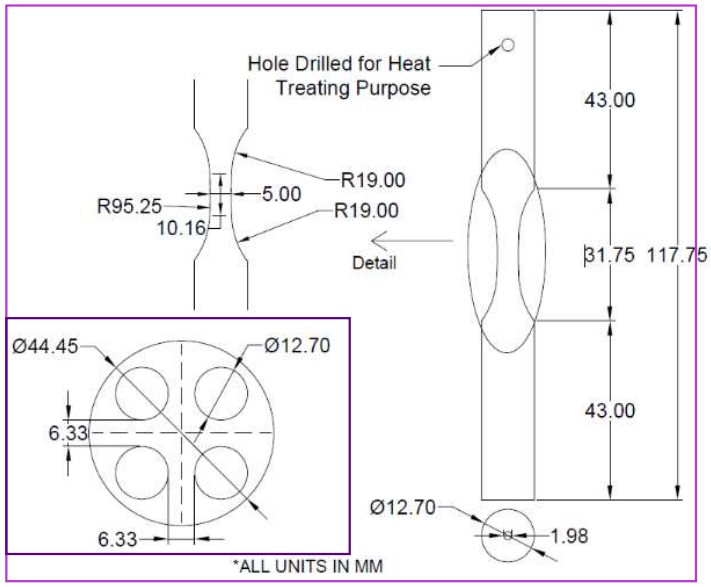
Case

Composite

Core



- Axial samples
  - Case
  - Core
  - Composite

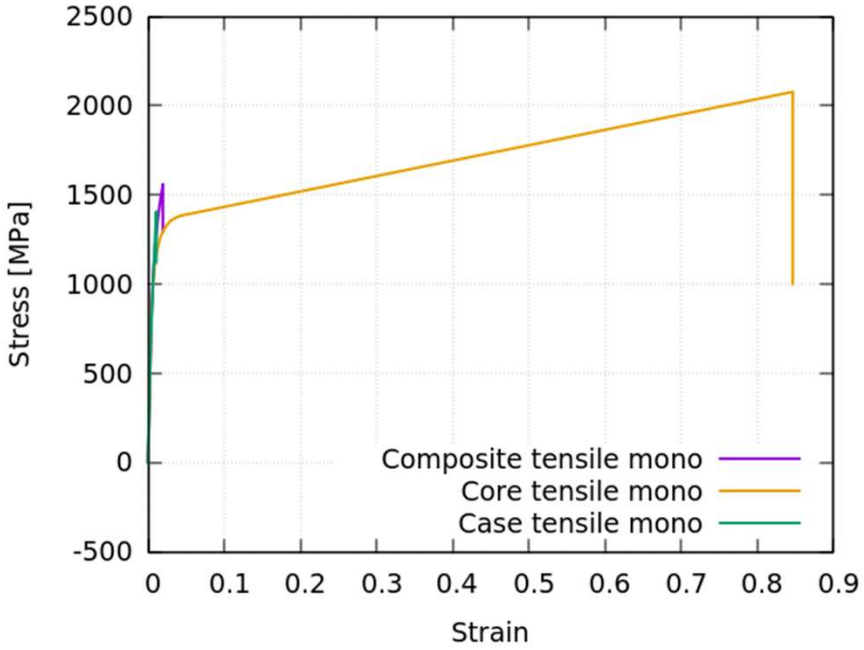


Material Properties: Test Pictures

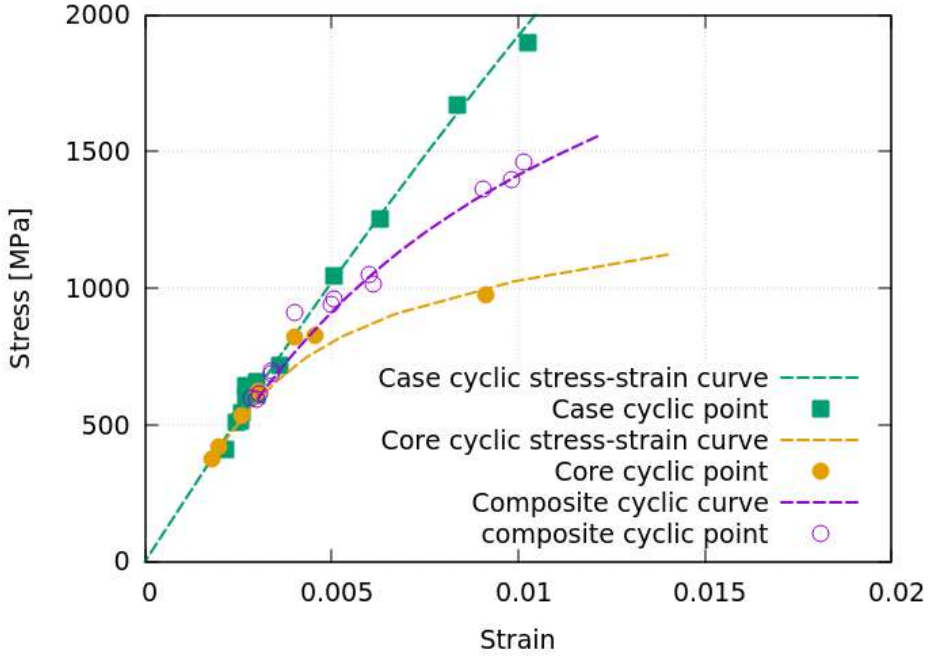
Notched plate tests

Axial sample tests

Material Properties: Monotonic and Cyclic Stress-Strain Curves

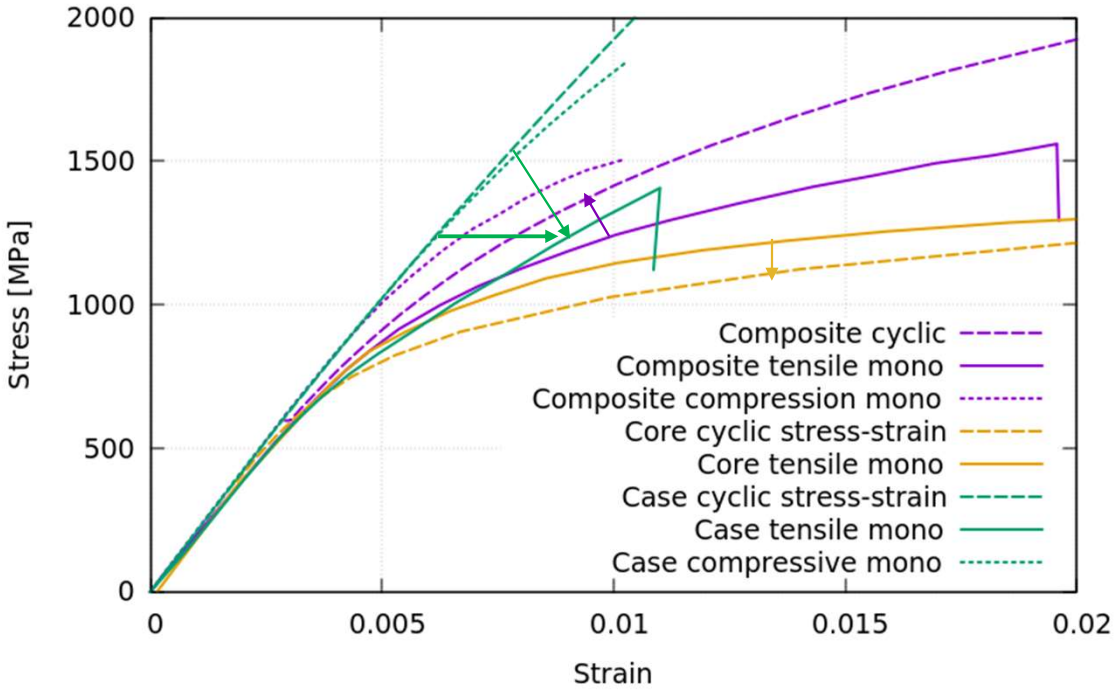


Monotonic stress-strain curves



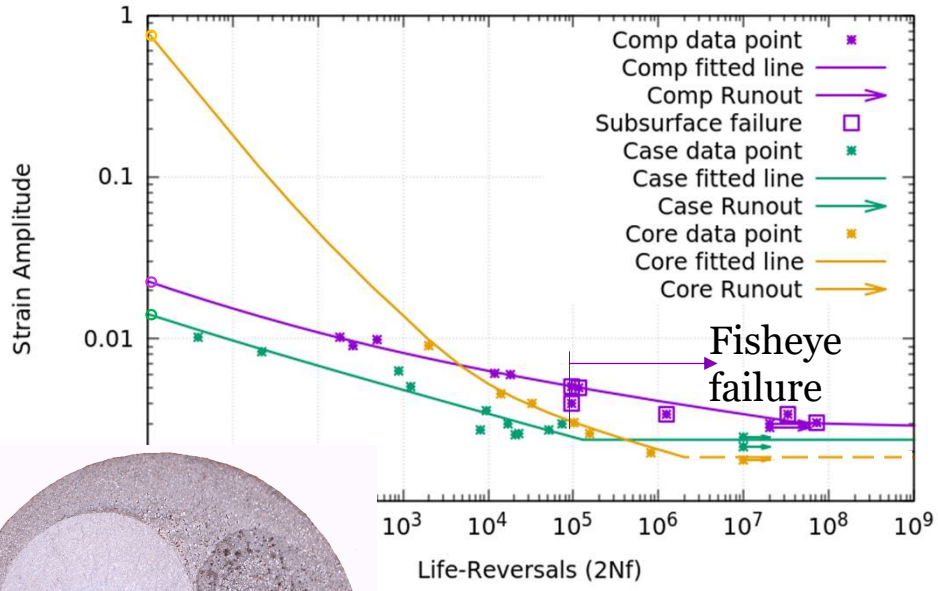
Cyclic stress-strain curves fitted to data points

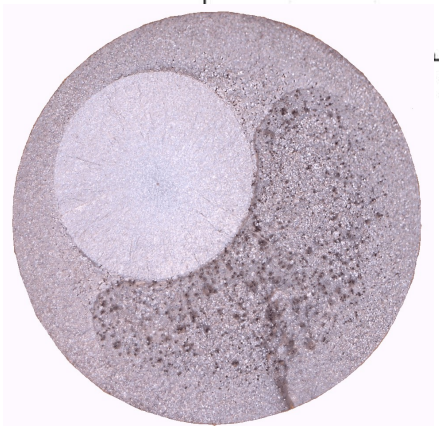
Material Properties: Stress-Strain Properties



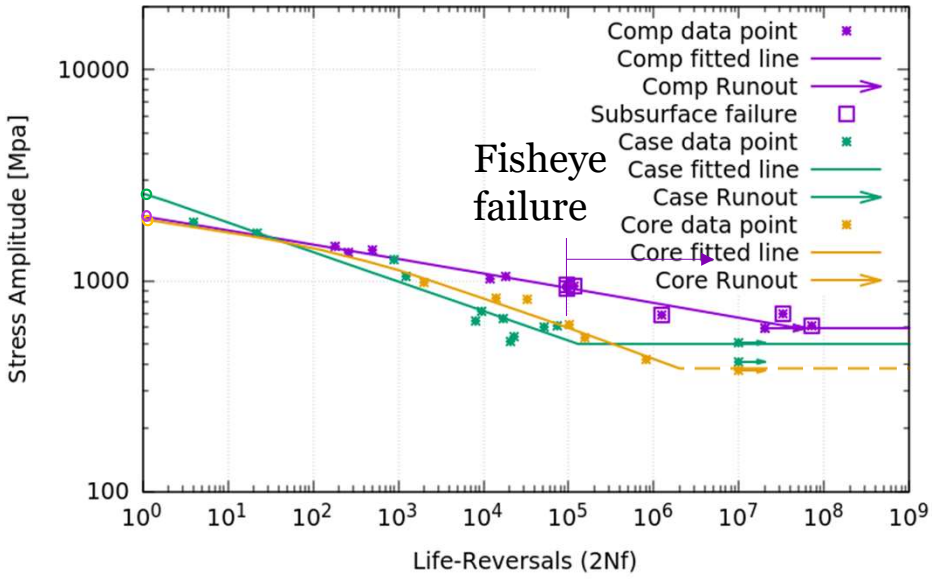
Tensile, compressive and cyclic stress-strain curves

Material Properties: CA Fatigue Properties





Strain-life data



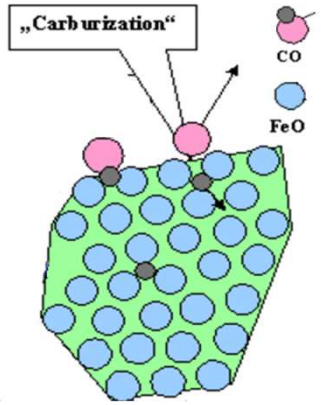
Stress-life data

RETAINED AUSTENITE AND RESIDUAL STRESS ESTIMATES

RA and RS Estimate: Carburization Induced Residual Stress

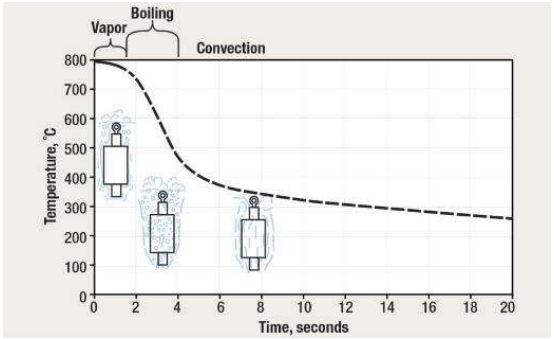
Steps for preliminary estimation of residual stress:

1. Carbon diffusion profile during carburizing



Carbon Atoms diffuses into steel part
https://www.tf.uni-kiel.de/matwis/amat/iss/kap_a/backbone/ra_2_3.html

2. Temperature field during quenching

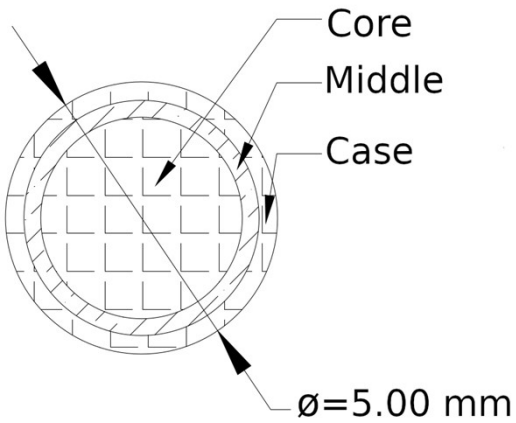


Oil-quench cooling profile
https://www.industrialheating.com/articles/92639-vacuum-oil-quenching-applications-and-unique-properties

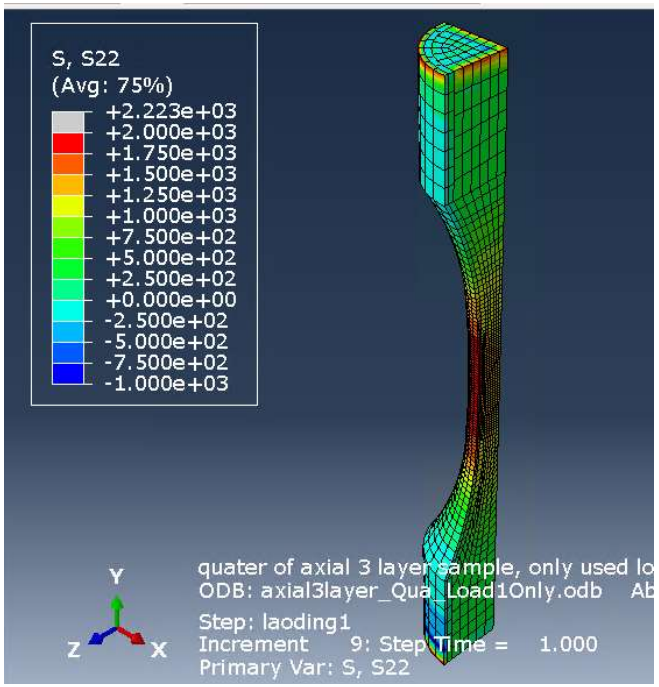
3. Volume change in each layer due to phase transformation

4. Mechanical response and residual stress during quenching.

RA and RS Estimate: Initial Residual Stress



Cross-sectional area



Finite element model

$$\sum F = E_1 A_1 \varepsilon_1 + E_2 A_2 \varepsilon_2 + E_3 A_3 \varepsilon_3$$

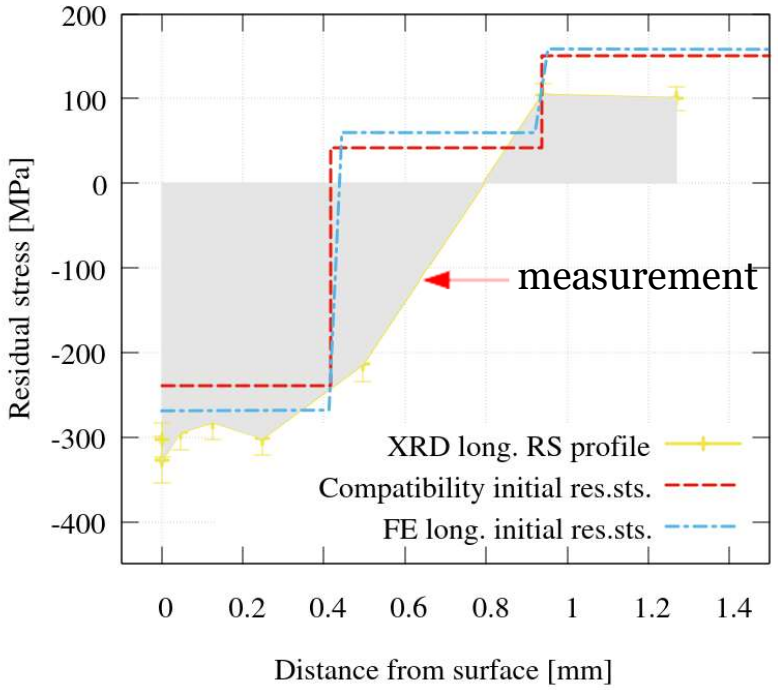
$$\varepsilon_i = \varepsilon_f - \varepsilon_i^Q$$

$$\sigma_i = E_i(\varepsilon_f - \varepsilon_i^Q)$$

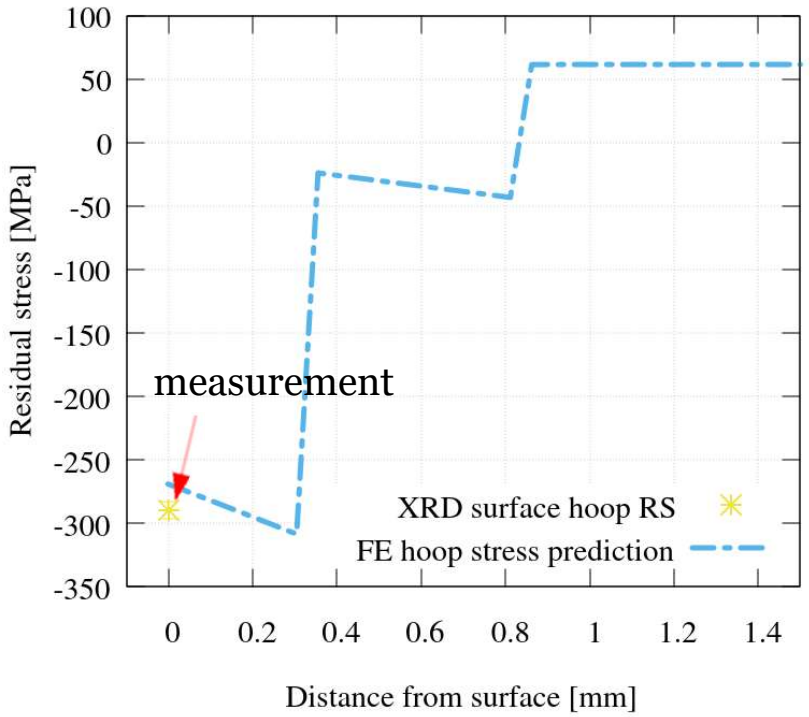
ε_i^Q(C, T, RA%)

Compatibility model

RA and RS Estimate: Initial Residual Stress

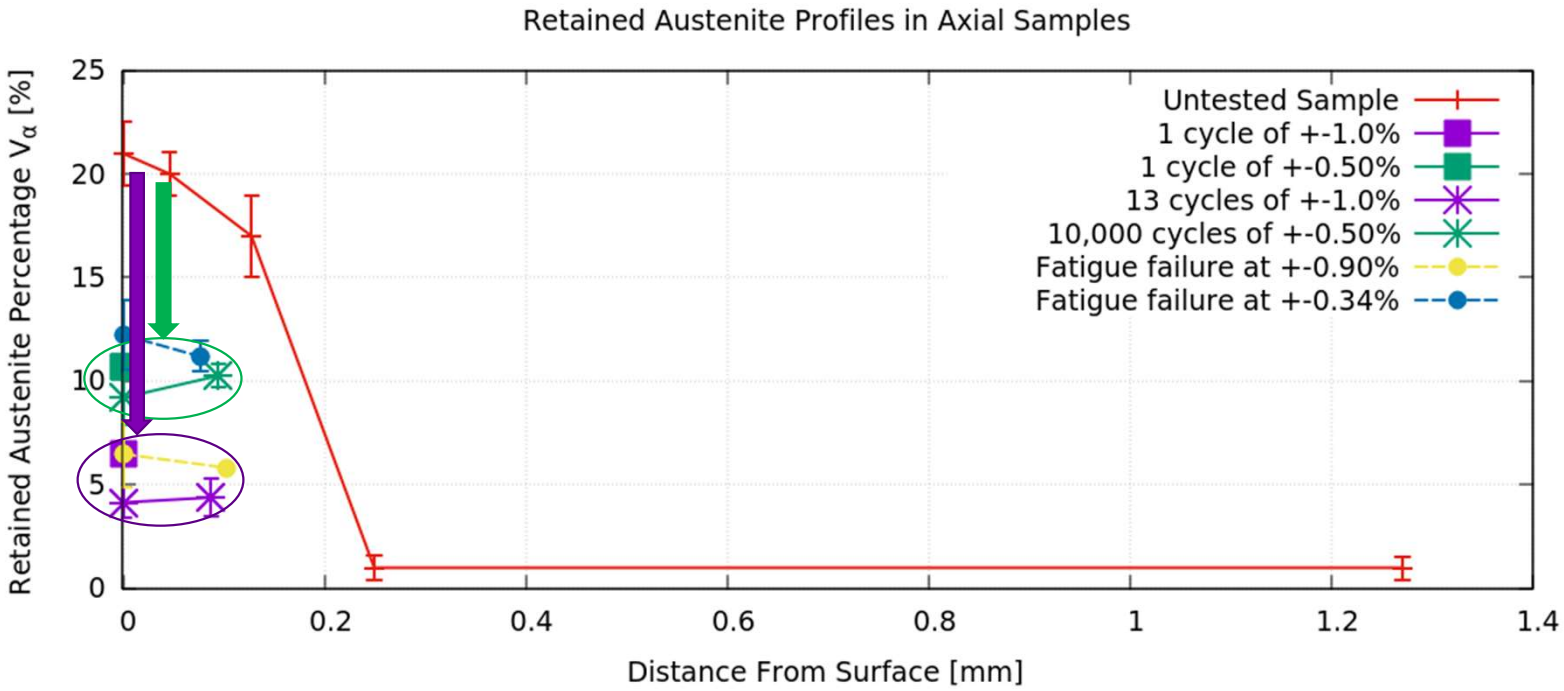


Longitudinal residual stress profiles



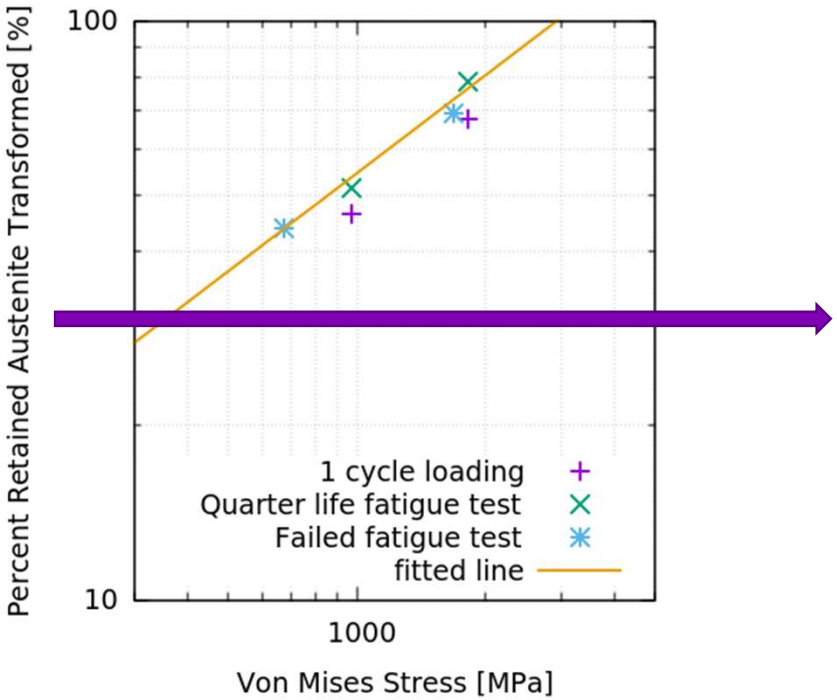
Hoop residual stress profiles

RA and RS Estimate: RA Transformation

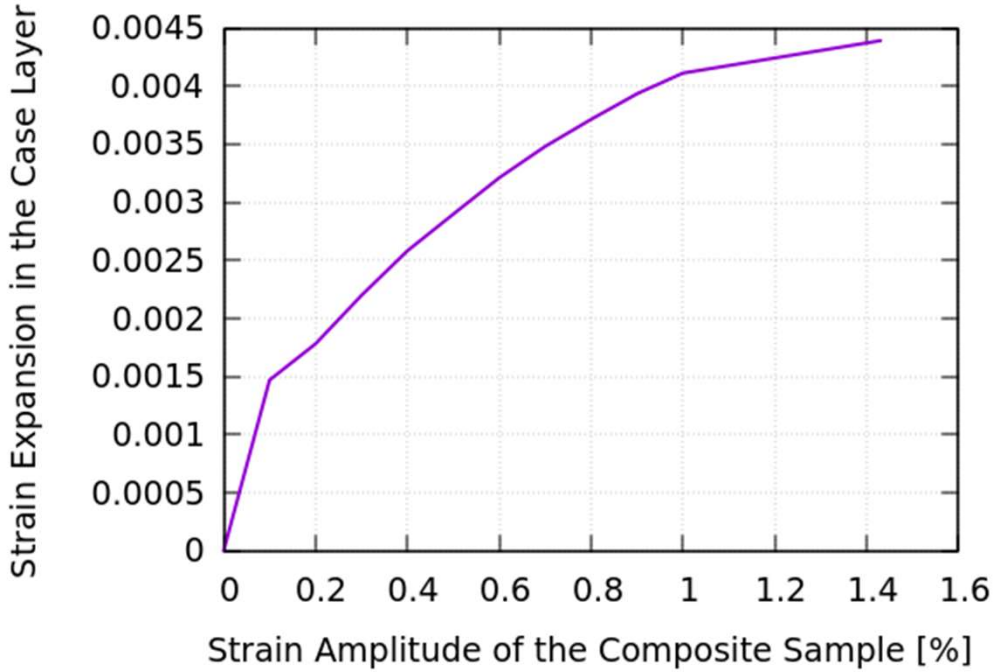


Leftover retained austenite content after different loading

RA and RS Estimate: RA Transformation

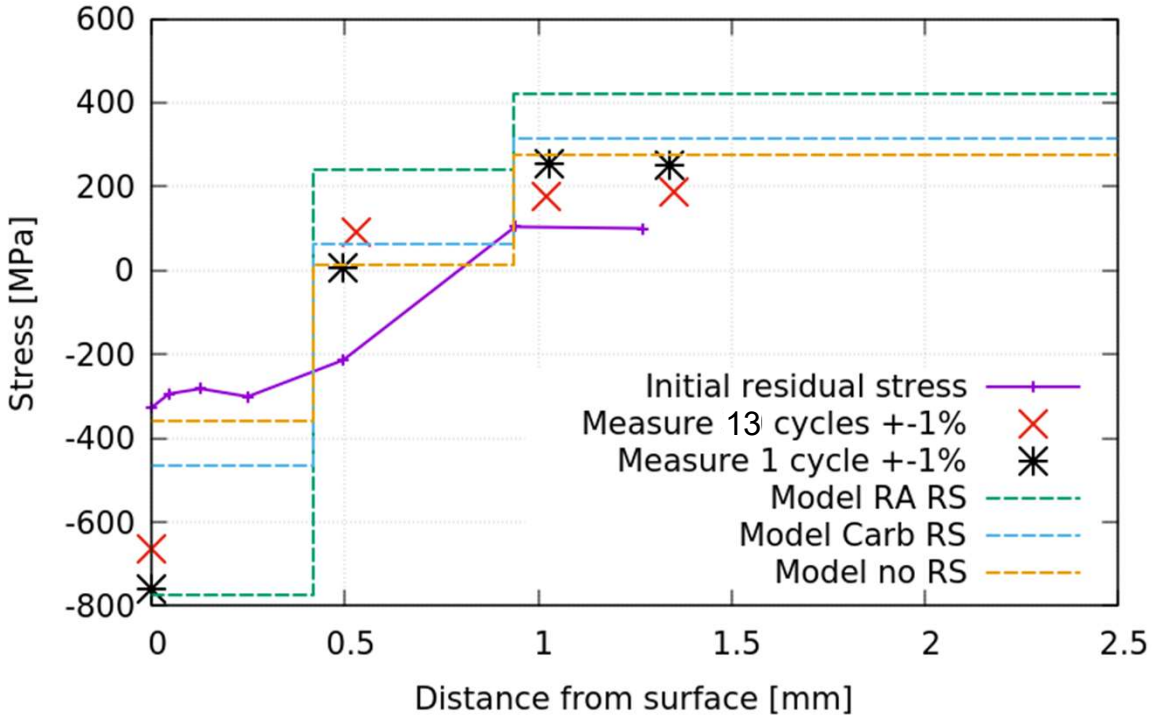


RA% transformation vs. Von Mises stress



Strain expansion in the case layer vs. applied strain amplitude

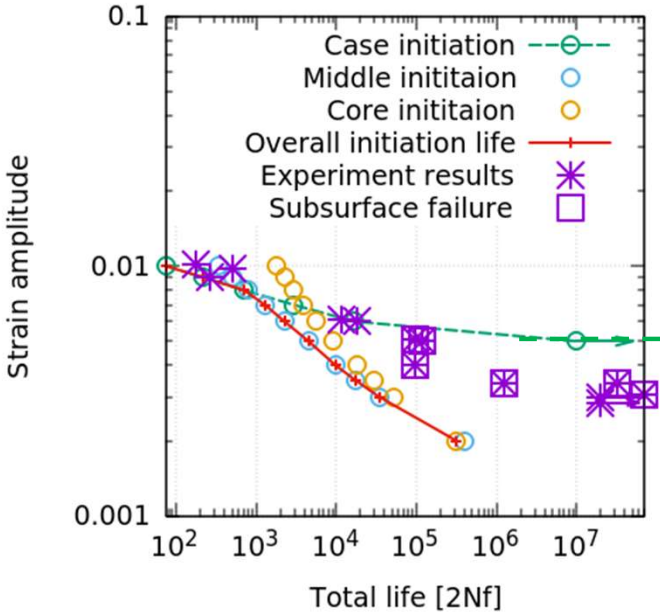
RA and RS Estimate: Residual Stress Change During Cyclic Loading



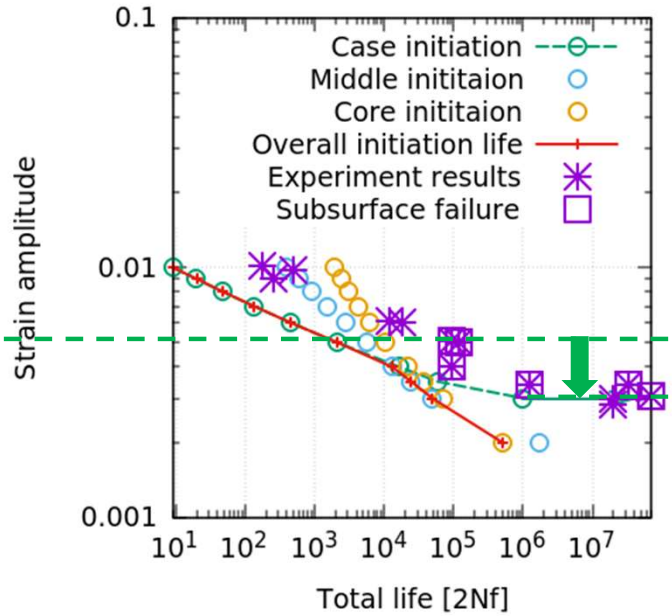
Residual stress profile after cyclic loading

FATIGUE ANALYSIS

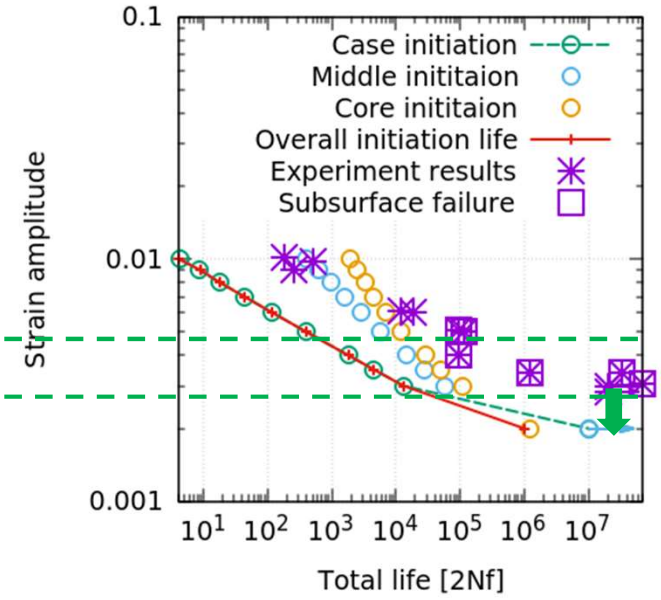
Fatigue Analysis: CA Axial Sample Initiation Predictions



With RS including RA transformation and Carburization RS

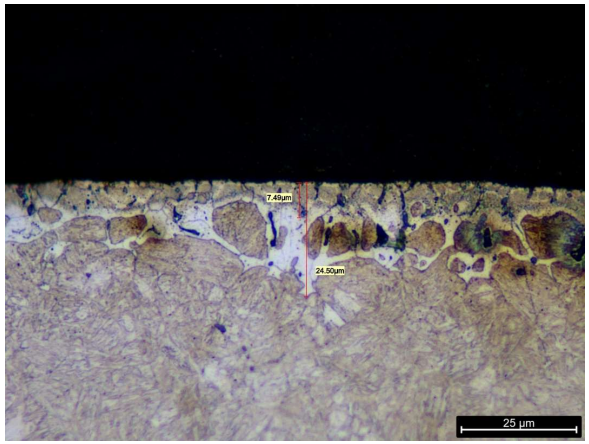


With RS including Carburization RS only

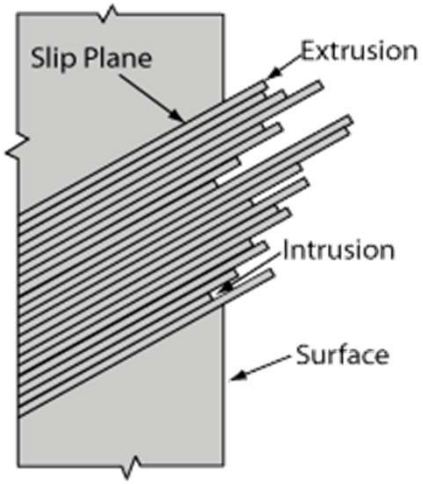


Without RS

Fatigue Analysis: Core Axial Sample vs Core Layer Prediction

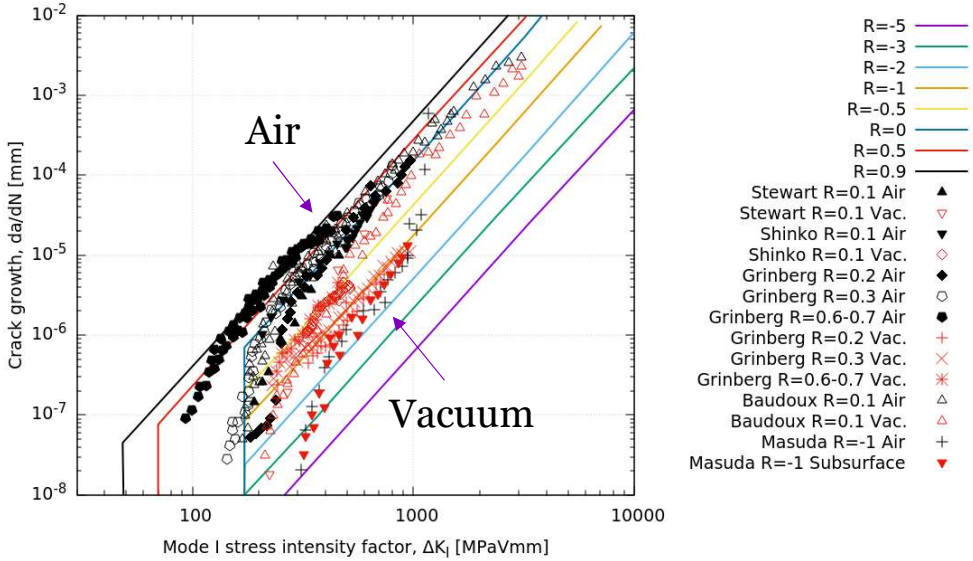


Surface of the core axial sample



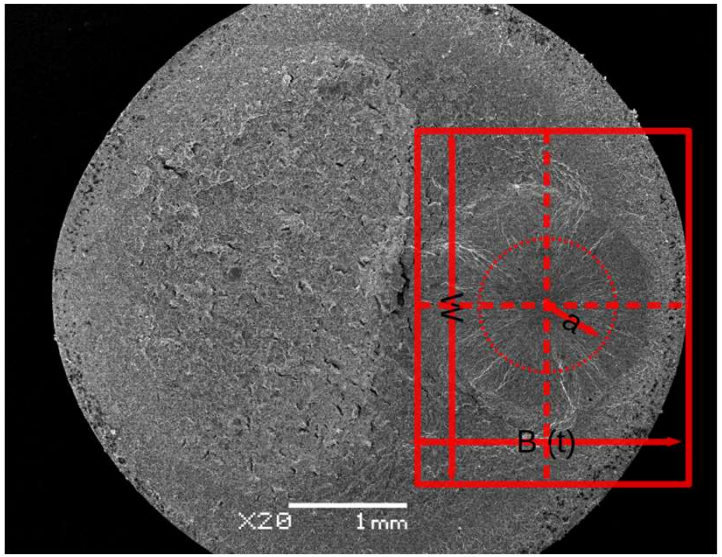
Fatigue crack initiation on the surface

https://www.nde-ed.org/Physics/Materials/Structure/fatigue.xhtml

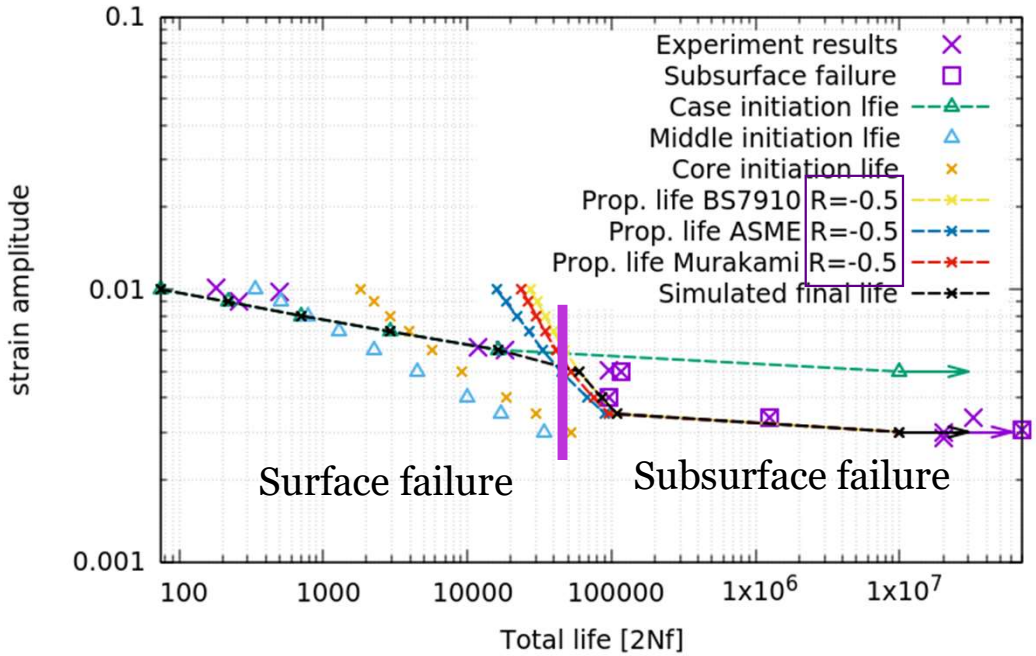


Vacuum and air crack growth data

Fatigue Analysis: Subsurface Crack Propagation Model Comparison Under CA for Axial Sample



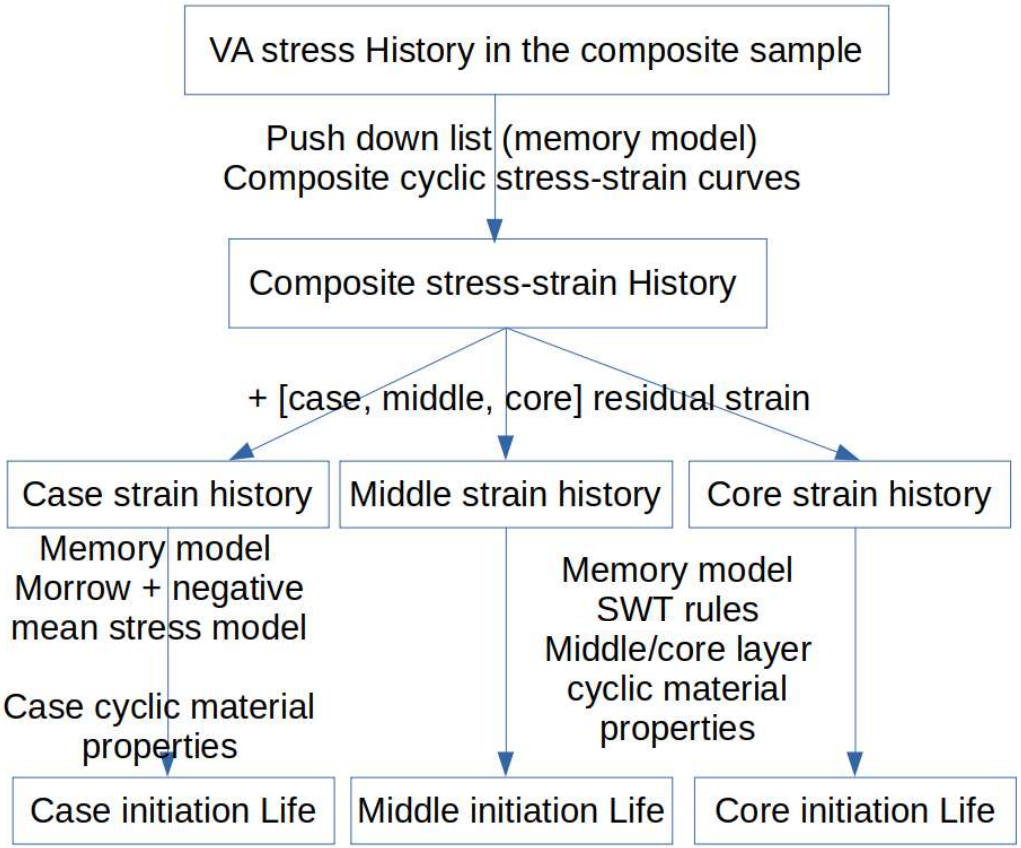
Axial sample fracture surface with subsurface elliptical crack on a plate



CA fatigue life predictions for axial samples using BS7910, ASME and Murakami's elliptical crack growth model

Final life = min(case initiation, subsurface propagation)

Fatigue Analysis: Methodology for Fatigue Analysis under VA Load

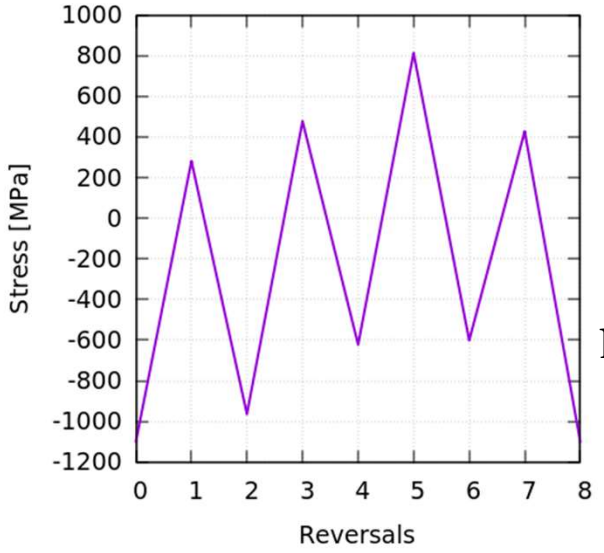


Fatigue Analysis: Methodology for Fatigue Analysis under VA Load

VA stress History in the composite sample

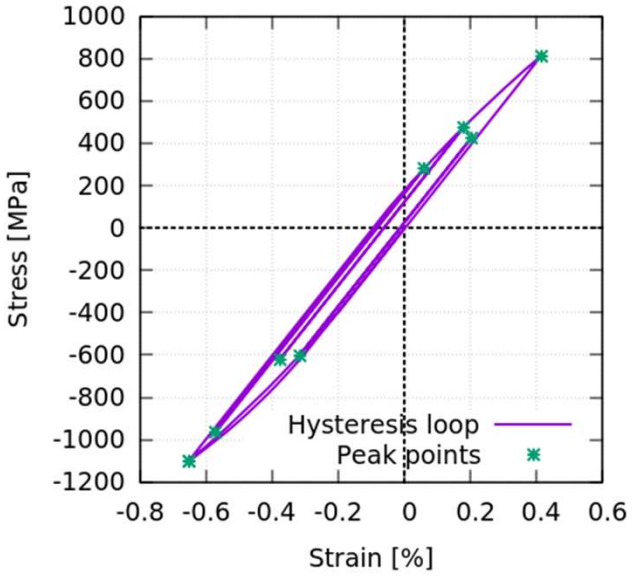
Push down list (memory model)
Composite cyclic stress-strain curves

Composite strain History

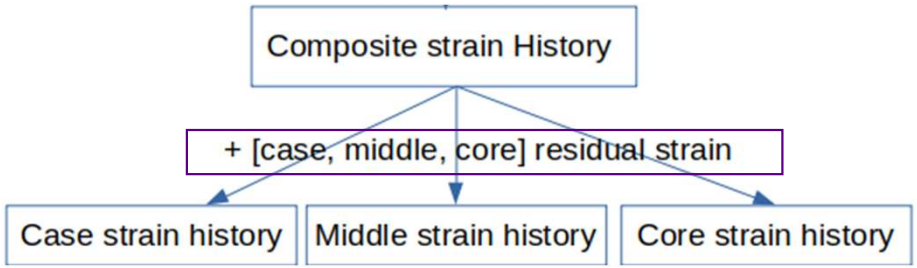


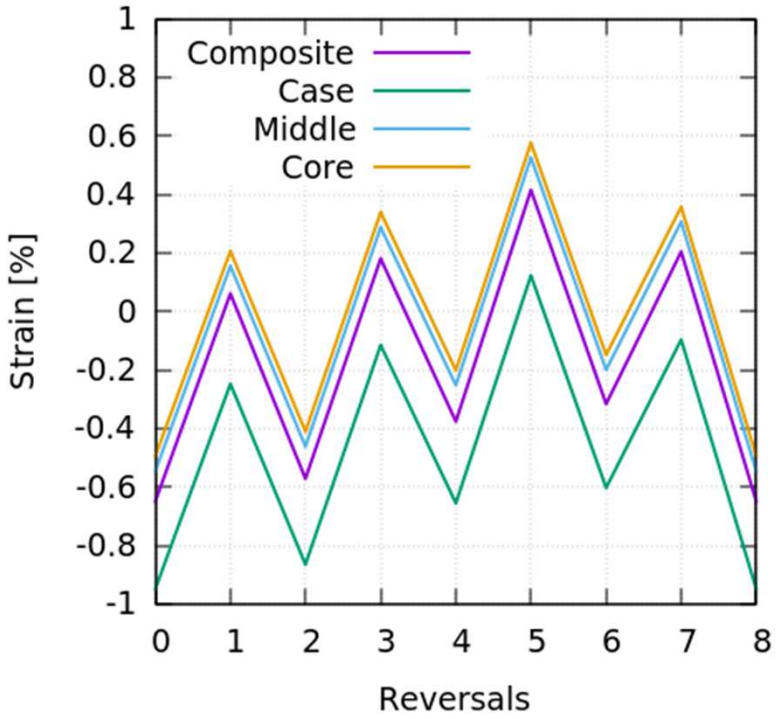
Stress history

Stress-strain history



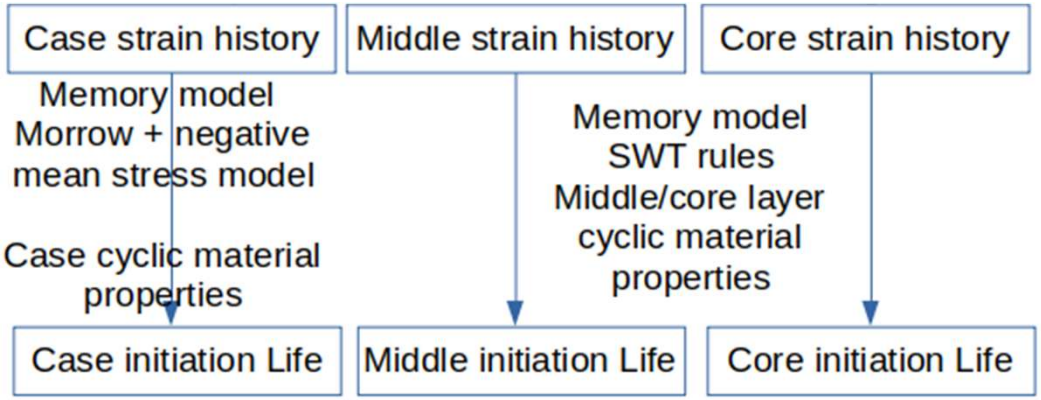
Fatigue Analysis: Methodology for VA Loading Prediction



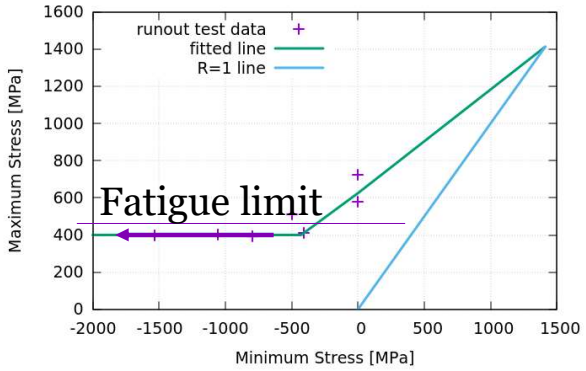


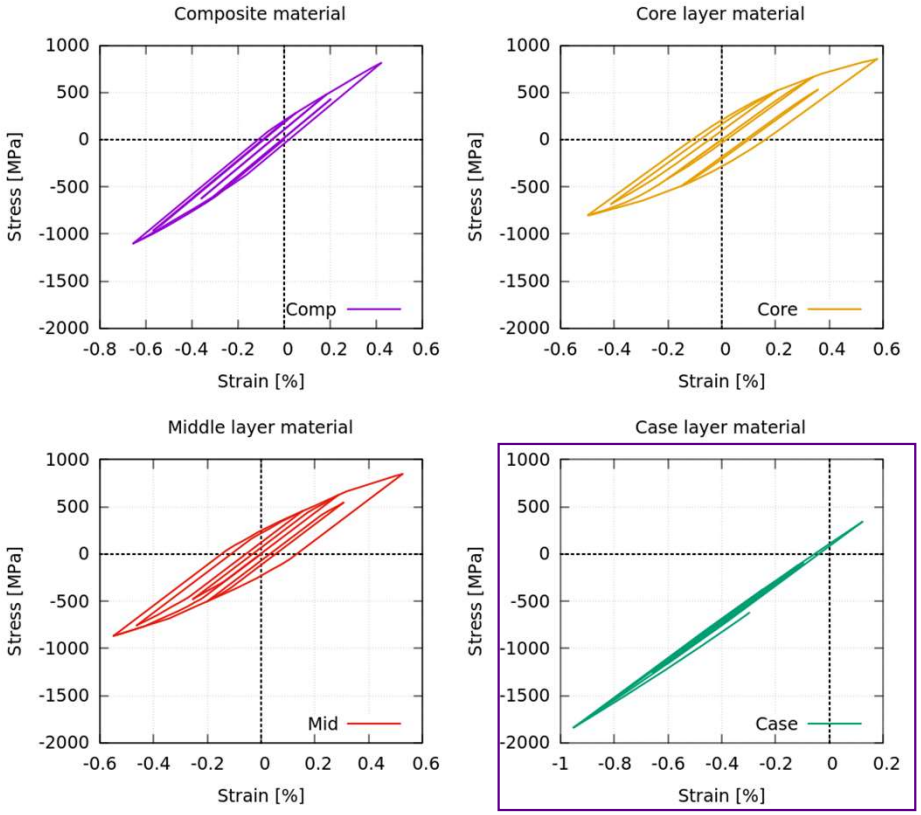
Strain history of each layer

Fatigue Analysis: Methodology for VA Loading Prediction



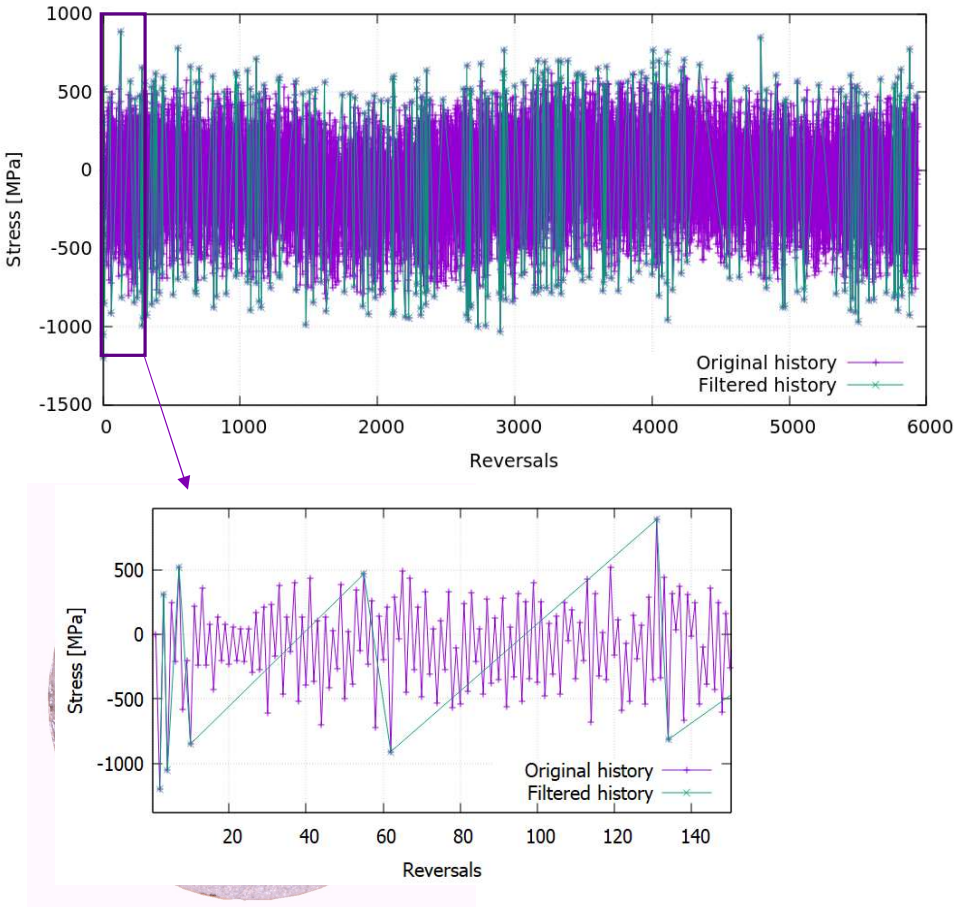
Negative mean stress rule

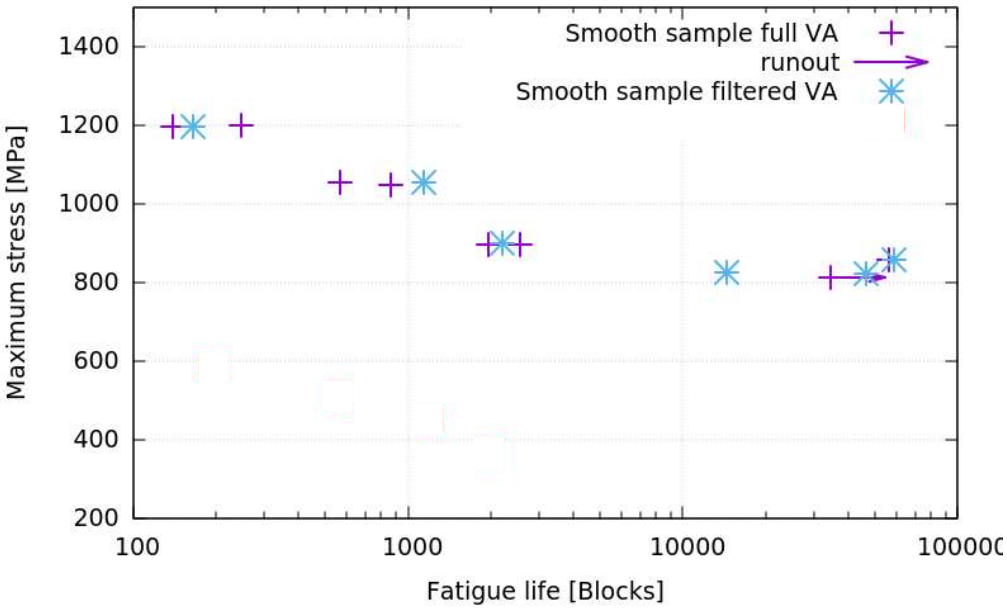




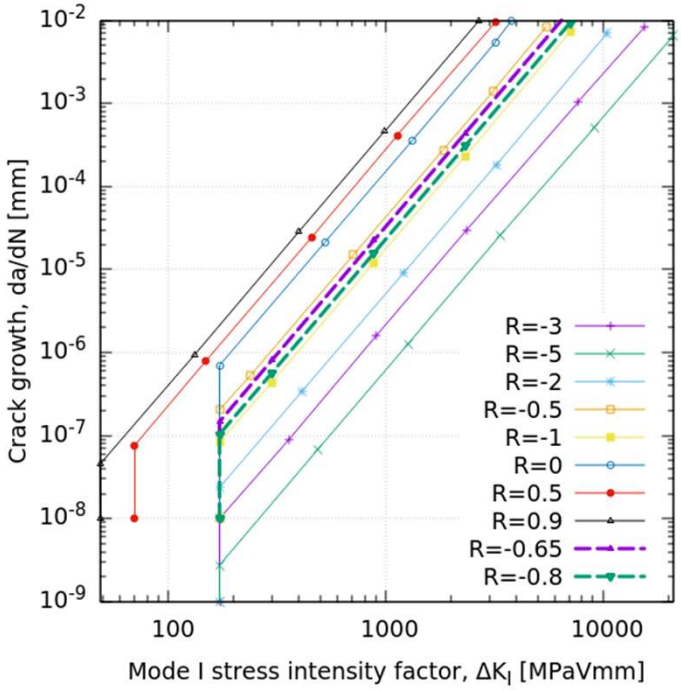
Hysteresis loops of the local stress and strain in each layer

Fatigue Analysis: Test Result for Axial Composite Sample under VA Load

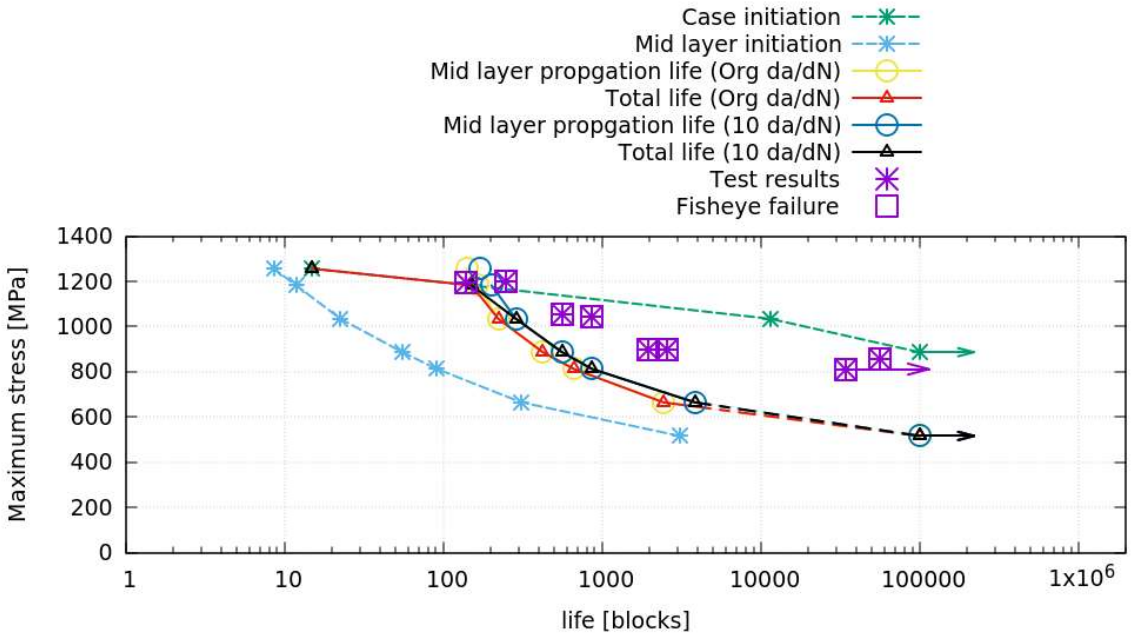




Fatigue analysis: Subsurface Crack Propagation Prediction under VA using BS7910 for Axial Sample

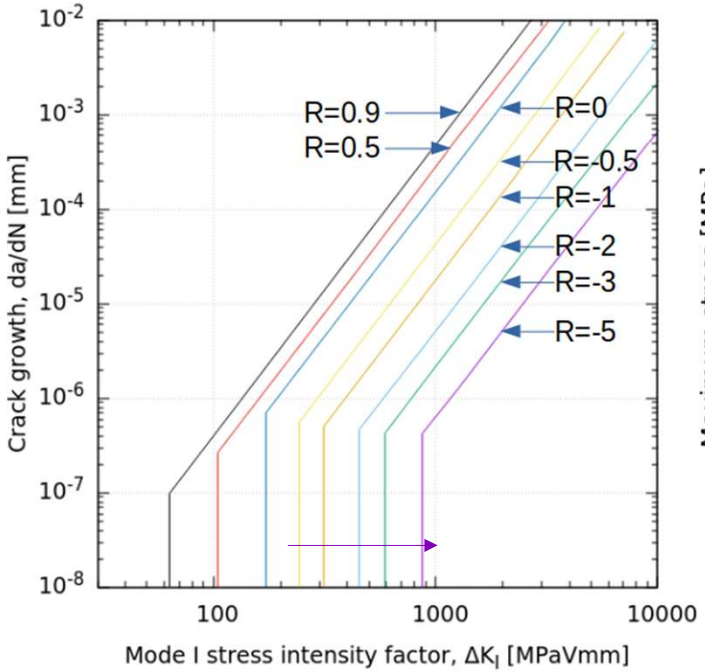


Hasegawa1 da/dN curves

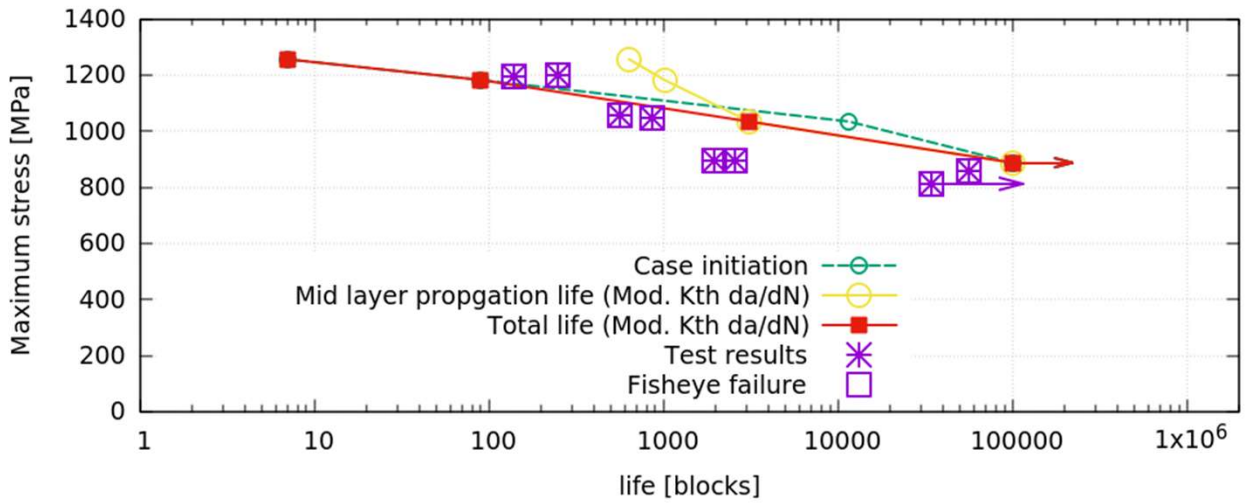


VA fatigue life prediction for axial samples

Fatigue analysis: Subsurface Crack Propagation Prediction under VA using BS7910 for Axial Sample

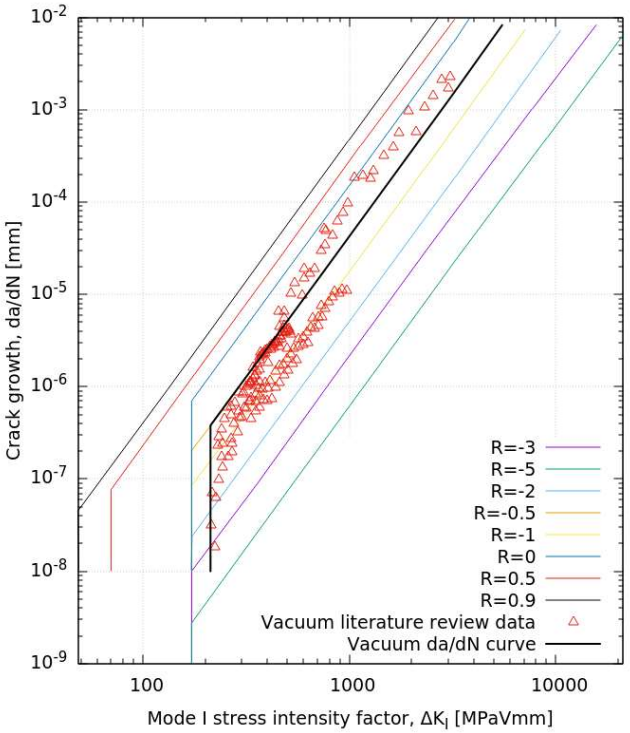


Hasegawa2 da/dN curves

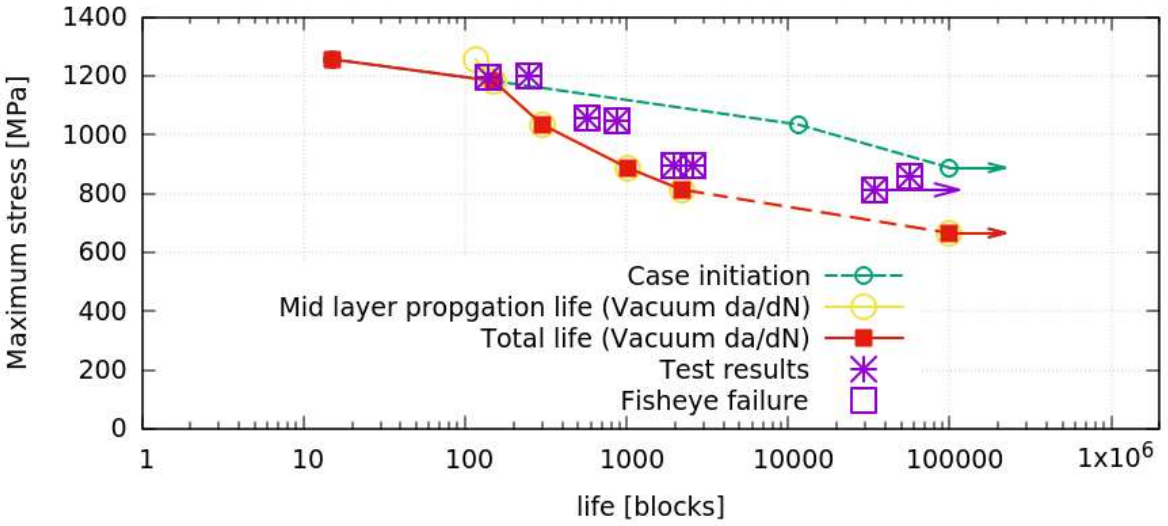


VA fatigue life prediction for axial samples

Fatigue analysis: Subsurface Crack Propagation Prediction under VA using BS7910 for Axial Sample

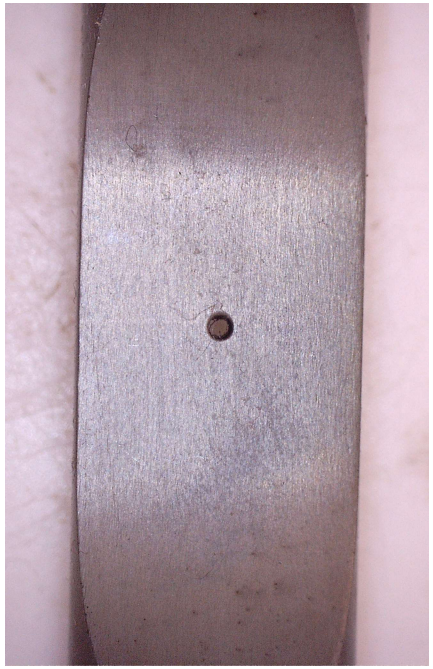


Vacuum da/dN curve

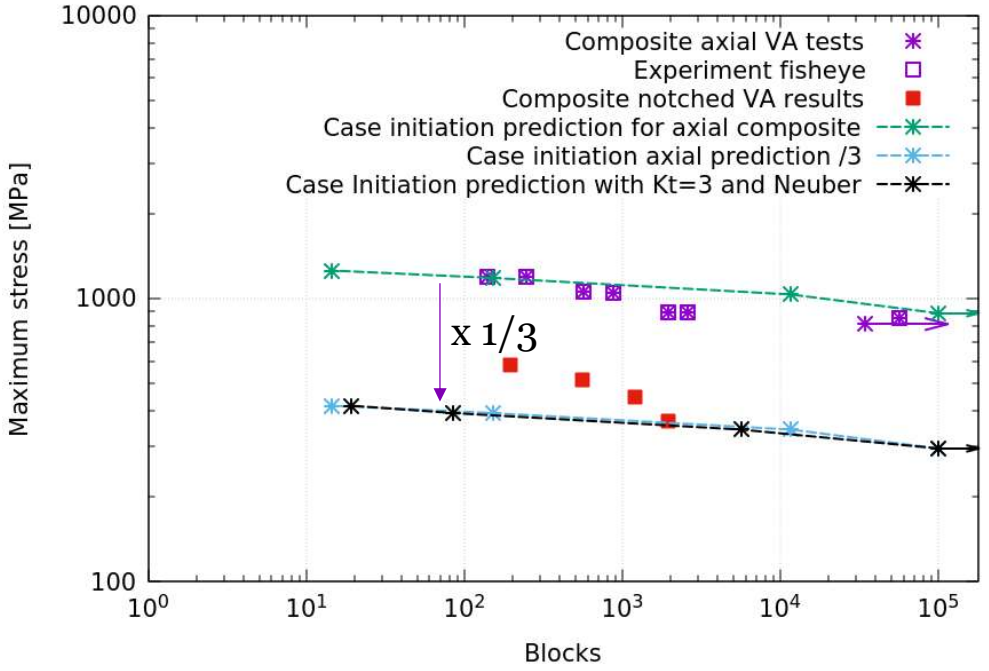


VA fatigue life prediction for axial samples

Fatigue Analysis: Initiation Life Prediction for Notched Sample



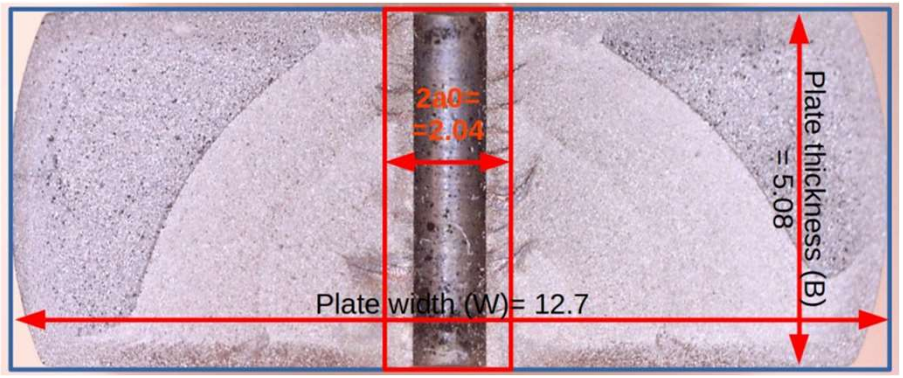
Notched plate sample



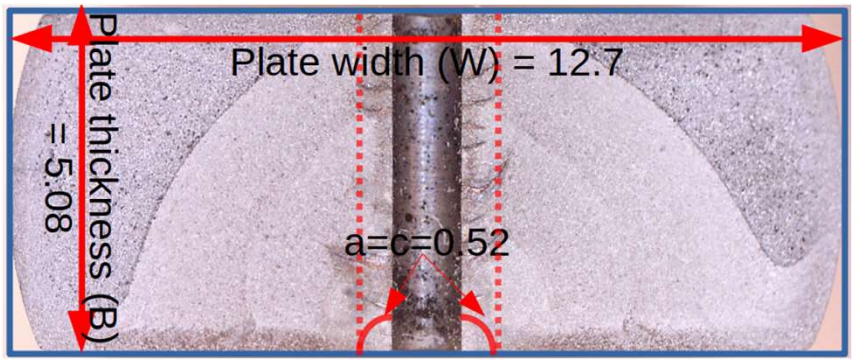
Case initiation of the notched and axial composite sample under VA loading

Final life = case initiation + subsurface propagation

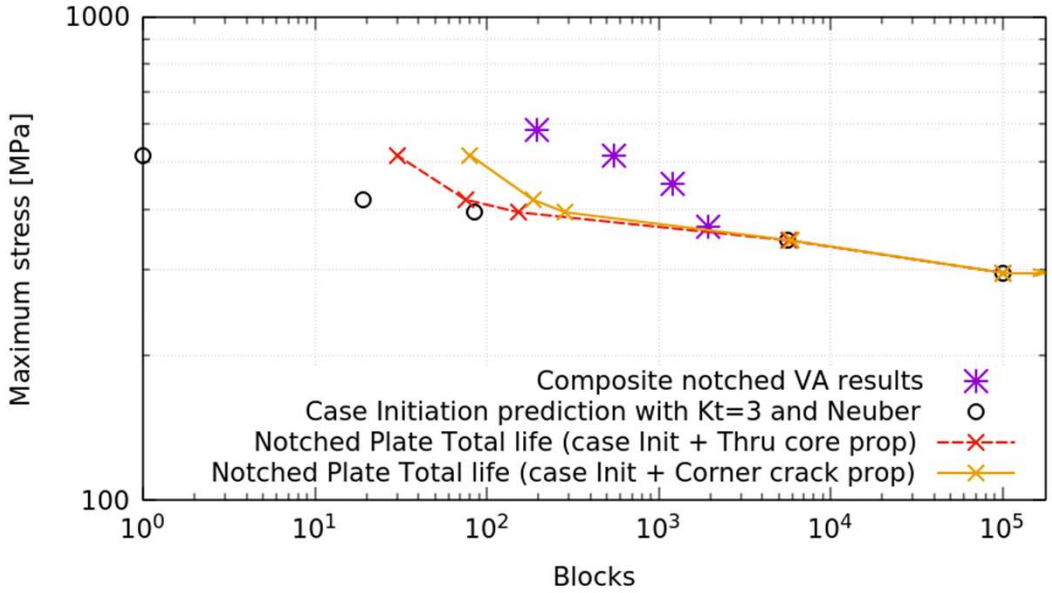
Fatigue Analysis: Through-Crack Model for Notched Sample



Through-crack parameter



Corner crack at a hole parameter



VA fatigue life prediction for notched samples

CONCLUSIONS & RECOMMENDATION

Conclusions

- Causes of RS change:
  - RA transformation
  - RS relaxation
- Axial composite sample fatigue prediction:
  - Total life = shorter (case initiation life, subsurface crack propagation life)
  - Subsurface crack growth life estimated using subsurface elliptical crack propagation
- Notched plate sample fatigue prediction:
  - Total life = case initiation + core layer propagation
  - Through-crack and corner crack models for subsurface layer crack propagation

Contributions

- Fatigue life prediction in carburized steel
  - Consider RA transformation and RS relaxation
  - Modeled the effect of RA transformation on RS
  - Employed surface and subsurface crack propagation models

Recommendation for Future Studies

- Collect more data for RA transformation vs. cyclic loading
- Collect more data for subsurface crack growth at different R-ratios
- Observe residual stress relaxation under cyclic loading

List of Relevant Publications and Presentations

- Journal papers:
  - **Liang W**, Pineault J, Albrecht Conle F, Topper TH. Retained Austenite Transformation-Induced Residual Stress Change in Carburized 16MnCr5 Steel. Journal of testing and evaluation. 2022;50(3):1-16. doi:10.1520/JTE20210457
  - Da Silva DG, Lockwood JT, **Liang W**, Topper TH. Mean stress effect in stress-life for hard steels. International Journal of Fatigue. 2021 May 1;146:106101.
  - **Liang W**, Conle FA, Topper TH, Walbridge S. A review of effective-strain based and multi R-ratio crack propagation models and a comparison of simulated results using the two approaches. International Journal of Fatigue. 2021 Jan 1;142:105920.
- Presentations:
  - Liang W, FEA Simulation of 4-pt Bending Tests on Carburized Steel for AISI Iteration IT184/185, AISI Bar Fatigue Committee, South Field, MI, USA, 2018 Jan 17.
  - Liang W, Residual Stress Relaxation Models of Carburized Axial Sample, FD&E Residual Stress Committee Meeting, Online meeting, 2020 Oct 6.
  - Liang W, Comparison of Effective-strain Based and Multi R-ratio Crack Propagation Models, Fall 2020 SAE FD&E meeting, Online meeting, 2020 Oct 28.
  - Liang W, Retained Austenite Transformation Induced Residual Stress Change in Carburized 16MnCr5 Steel, ASM International - Residual Stress Technical Committee, Online meeting, 2021 Dec 16

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PROTO

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Reference

1. Yin, F. , Fatemi, A., & Bonnen, J. (2010). Variable amplitude fatigue behavior and life predictions of case hardened steels. International Journal of Fatigue, 32(7), 1126–1135. doi:10.1016/j.ijfatigue.2009.12.009
2. Yin, F., & Fatemi, A. (2011). Monotonic and cyclic deformations of case-hardened steels including residual stress effects. Strain, 47 (SUPPL. 1), 74–83. doi:10.1111/j.1475-1305.2008.00504.x
3. Yin, F. & Fatemi, A. (2009). Fatigue behaviour and life predictions of case-hardened steels. Fatigue and Fracture of Engineering Materials and Structures, 32 (3), 197–213. doi:10.1111/j.1460-2695.2009.01326.x
4. Reti, T. (2002). Residual stresses in carburized, carbonitrided, and case-hardened components. Handbook of residual stress and deformation of steel, 189–208.