Autofrettage: Measuring Residual Stress in High Performance Fuel Systems

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Cummins Fuel Systems produces high pressure common fuel rail systems for diesel engines. The rails must withstand high cyclic pressures during operation. To increase fatigue resistance, Cummins uses autofrettage (AF) to induce compressive residual stresses in the rails. Cummins wants to reduce the costs associated with common fuel rail systems by determining a cheaper and faster method to assess fuel rail reliability. Four test methods were developed to measure residual stresses in the rails: Vicker's hardness, XRD, residual stress estimation by cutting, and eddy current measurements. The test methods were evaluated by comparing results to expected residual stress values and finite element analysis results to determine feasibility.

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Project Background

Problem Statement

Cummins fuel rails are autofrettaged (AF) to create residual compressive stresses which strengthen the inner surface and lengthen the fatigue life of the rails.

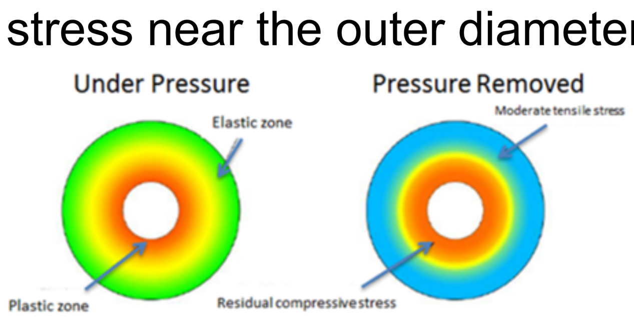
Goal

Determine a faster, cheaper, and preferably non-destructive method to measure residual stresses in fuel rails due to AF

Autofrettage (AF)

Photograph of Cummins fuel rail

AF is a strengthening technique in which internal pressure is applied to plastically deform the inner surface of a cylinder, inducing compressive residual stresses near the inner diameter and tensile residual stress near the outer diameter. Finite element analysis (FEA) modeling provided an estimate of depth and peak residual stress within AF fuel rails.



Schematic of residual stresses due to AF[1]

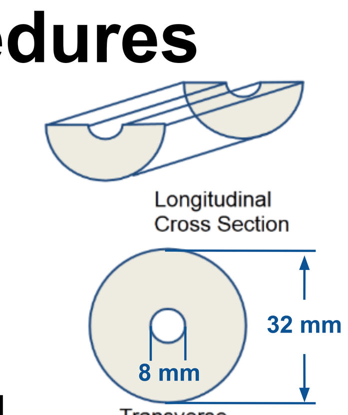
Sample Compositions

Mini fuel rails composed of 4 steel alloys

1. 38MnSiVS5 (38Mn)
2. Metasco MC 25MnCrSiVB6 (25Mn)
3. AISI 4140 (4140)
4. AISI 1045 (1045)

Experimental Procedures

Sectioning and Sample Preparation

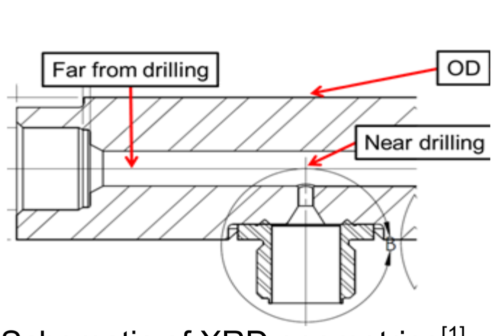


Rails cross sectioned transversely using a water-cooled LECO CM24 abrasive saw.

Residual Stress Measurement by Vickers Hardness (ASTM E384-11)[2]

Transverse cross sections polished to 600 grit
Compared AF/NAF samples of alloys
20 indents from inner diameter (ID) moving outward

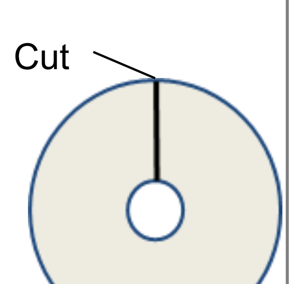
Residual Stress Measurement by XRD



Schematic of XRD geometries[1]

Measured using $\sin^2\psi$ method[3] at Cummins Fuel Systems
Tests at outer diameter (OD) (unsectioned), near and far from drilling (sectioned longitudinally)

Residual Stress Estimation by Cutting (ASTM E1928-13)[4]



Transverse cross sections cut through thickness as shown.
Compared AF/NAF samples of alloys
Surface stress (σ) calculated by Equation 1[4]
where E=elastic modulus, D=diameter (before or after cut), μ=Poisson's ratio

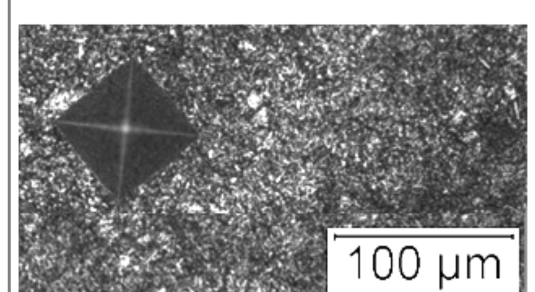
$$\sigma = \frac{Et(D_{after} - D_{before})}{2D_{before}D_{after}(1-\mu^2)} \quad (1)$$

Eddy Current Test

Eddy Current Tester: ZETEC MIZ - 10A
Probe: ID probe from GE with 6.8mm diameter
Impedance change reflects thickness variation in the rail walls, which is affected by residual stresses.
Data points at equal spacings from rail end to end

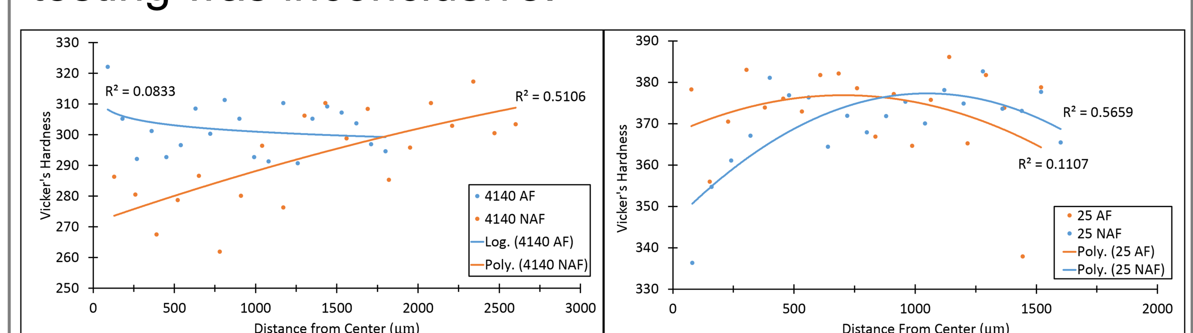
Results

Microhardness Test



Optical image of Vicker's indent

Student T test determined that hardness values of AF and NAF alloys were not significantly different. The best fit of the average hardness values at each indent (pictured below) indicated microhardness testing was inconclusive.



Best fit lines of average Vicker's Hardness values measured on 4140 AF and NAF, and 25MnCrSiVB6 AF and NAF samples.

Residual Stress Measurement by XRD

Measurements showed tensile stresses at outer diameter and compressive stress at inner diameter. The measurements (tabulated below) were reasonable compared to the expected compressive residual stress = -690 MPa.

Table 1. Residual Stress Measurements of AF samples by XRD

Alloy	Outer Diameter Stress (MPa)	Far drilling Stress (MPa)	Near drilling Stress (MPa)
38Mn	364.6 ± 10.0	-447.3 ± 10.0	-351.6 ± 7.6
25Mn	218.8 ± 18.1	-552.5 ± 12.8	-351.3 ± 8.3
4140	315.1 ± 8.6	-423.2 ± 7.8	-437.0 ± 7.8
1045	739.3 ± 9.0	-337.8 ± 9.3	-360.8 ± 7.1

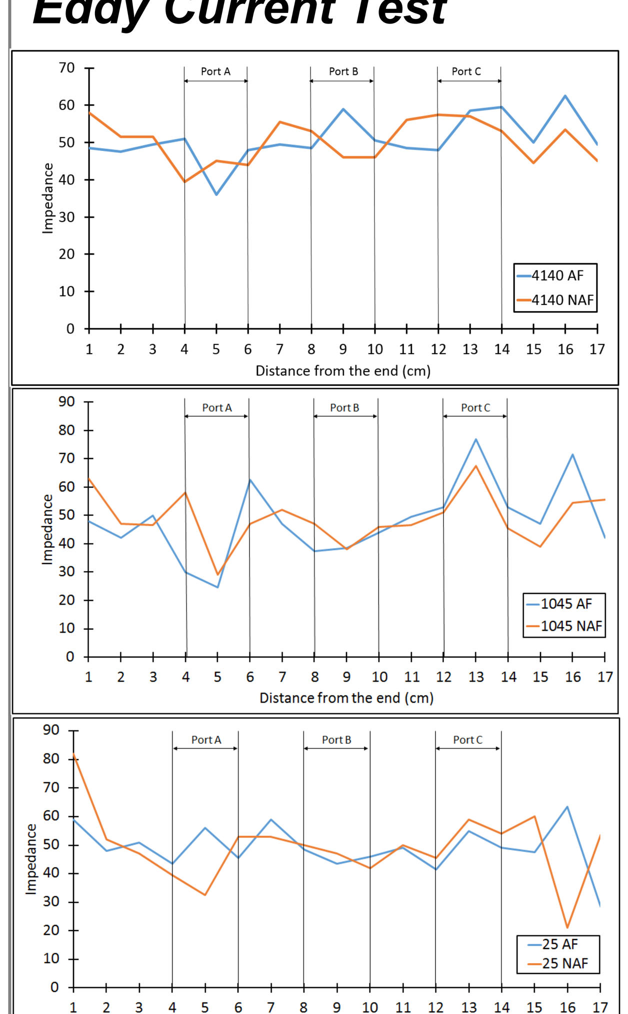
Residual Stress Estimation by Cutting

AF samples increased in diameter after cutting indicating maximum tensile stress located at outer diameter. NAF samples showed residual stresses <10 MPa, much lower than the stresses for AF samples.

Table 2. Residual Stress of AF samples by Cutting

Sample Name	Estimated Residual Stress (MPa)
38Mn	40
25Mn	605
4140	13
1045	125

Eddy Current Test



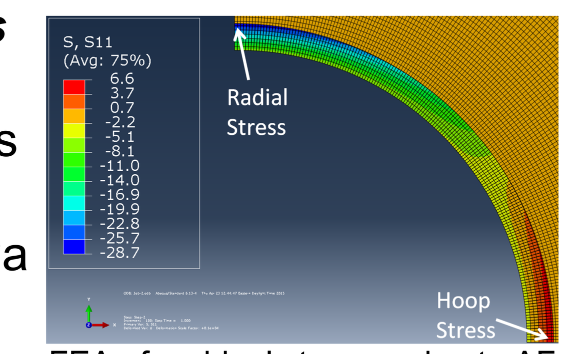
Eddy current impedance versus rail position for 4140, 1045, and 25Mn AF rails (blue) and NAF (red)

Larger impedance values are expected for thinner materials. As seen in the plots, the results are unstable and impedance peaks occur at port positions, which are indicated by vertical lines. AF rails generally showed more points with higher impedance values than NAF rails, but the impedance values were randomly distributed across the rail and too similar to be conclusive.

Discussion

Finite Element Analysis

- FEA model estimated depth of residual stress of 90 µm and peak radial stress of -29 MPa for a 4140 rail



FEA of residual stresses due to AF

Microhardness Test

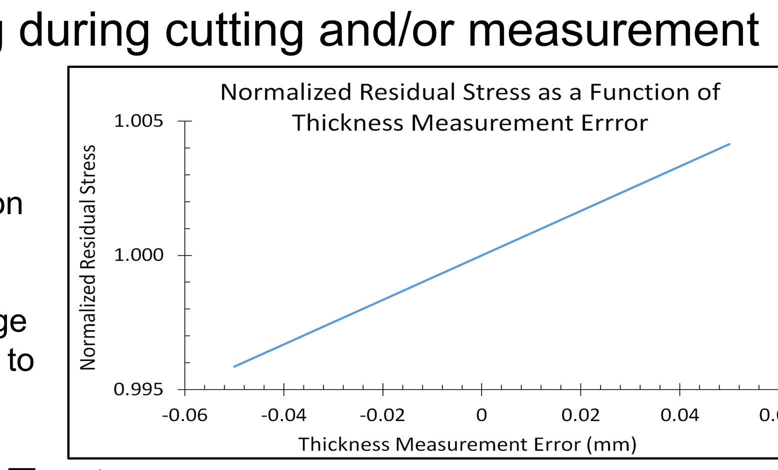
- Expected hardness gradient increasing from ID to OD not observed
- High standard deviations for each indent led to statistically insignificant results
- The plastically stressed region was approximately equivalent to indent spacing

Residual Stress Measurement by XRD

- Nondestructive if tensile stresses at OD correlated to compressive stresses at ID
- Results near drilling are less accurate due to increased surface roughness.
- Different amounts of residual stresses in each alloy due to differences in yield stress.

Cutting Test

- Indicated presence of residual stresses
- Calculation based on thin tube geometry and linear stress profile gave qualitative results.
- Inaccurate residual stress calculations may occur from heating during cutting and/or measurement errors.



Effect of thickness measurement error on calculated residual stress. Note the relatively small change in residual stress due to errors.

Eddy Current Test

- No conclusive pattern was observed in the distribution of results, although results do show thinning for AF rails.
- Rail geometry greatly affects the test results. The ports, welds, and intersection between the ports all have an effect on the recorded impedance values.

Recommendations

Of the developed techniques, XRD and Estimation by Cutting provided the most useful results. XRD is ideal for providing quantitative measurements nondestructively. Estimation by Cutting provides a rapid, qualitative indication of the presence of residual stresses.

Acknowledgements

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References:

[1] Information/photos received from Cummins Fuel Systems Inc.
[2] ASTM Std. E384, 2011e1, "Standard Test Method for Knoop and Vickers Hardness of Materials," ASTM Int'l.
[3] *Determination of Residual Stresses by X-ray Diffraction-Issue 2*, NPL, 2005.
[4] ASTM Std. E1928, 2013, "Standard Practice for Estimating the Approximate Residual Circumferential Stress in Straight Thin-walled Tubing," ASTM Int'l.