Effect of Sulfur on the Durability of SAE4140 Steel Forgings

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April 2008

OUTLINE

- Motivation and Objectives
- Experimental Program
- Experimental Observations
- Correlations and Predictions
- Conclusions

MOTIVATION

- A common inclusion in steels is sulfides, such as MnS.
- Up to a certain low level, MnS inclusions are desirable as they improve the machinability.
- Metal working processes such as rolling and forging result in anisotropic microstructure.
- Fatigue failures are the most common type of failures governed by crack nucleation and growth.
- Understanding the effects of S and S inclusions on fatigue behavior is of considerable interest.

OBJECTIVES

- To evaluate the effects of sulfur content and sulfide inclusions on tensile properties, impact toughness, and fatigue resistance.
- To compare the effects of sulfur content and sulfide inclusions between the longitudinal and transverse loading directions.
- To develop a predictive model as a function of S to represent fatigue behavior for loading in the transverse direction.

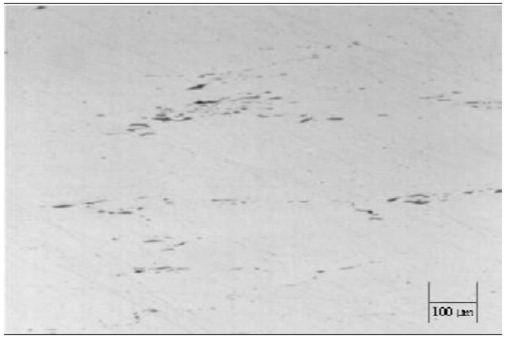
MATERIALS

- SAE 4140 steel at 3 Sulfur Levels
- Continuously Cast into 150 mm Square Billets
- Transverse Tests
  - *Cast Billets Hot Forged into 64 mm Square Bars, Normalized, and Quenched & Tempered to 43 HRC and 52 HRC*
- Longitudinal Tests
  - *Cast Billets Hot Rolled into 29.8 mm Round bars, Normalized, and Quench & Tempered to 42 HRC*

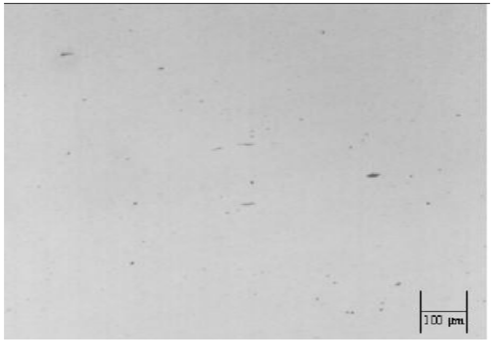
MATERIALS

- SAE 4140 steel
- Three S levels:
  - High (0.077% S)
  - Low (0.012% S)
  - Ultra Low (0.004% S)
- Each at two hardness levels:
  - 43 HRC
  - 52 HRC

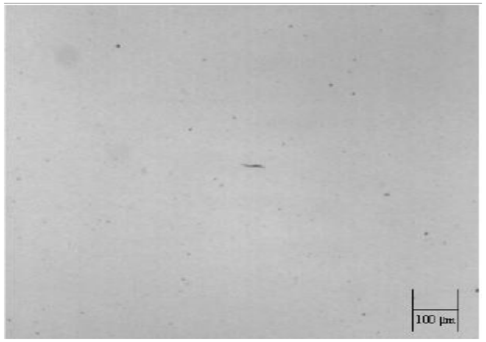
0.077 % S



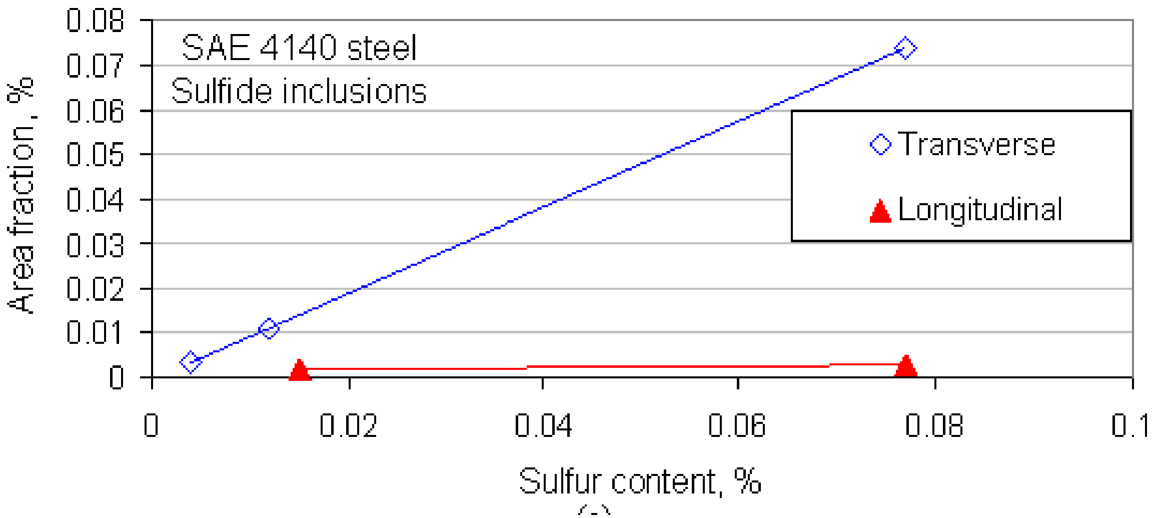
0.012 % S

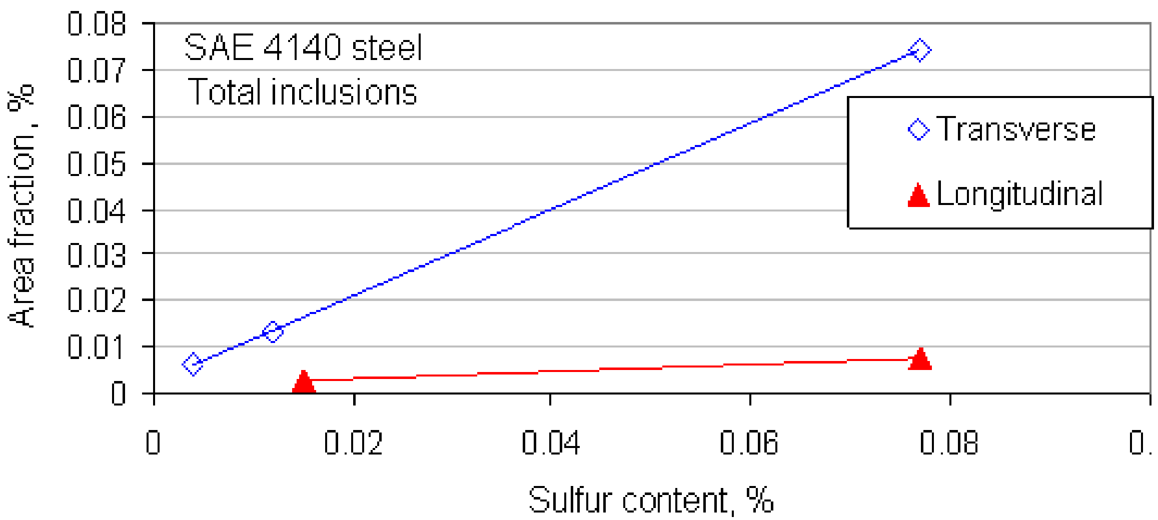


0.004 % S



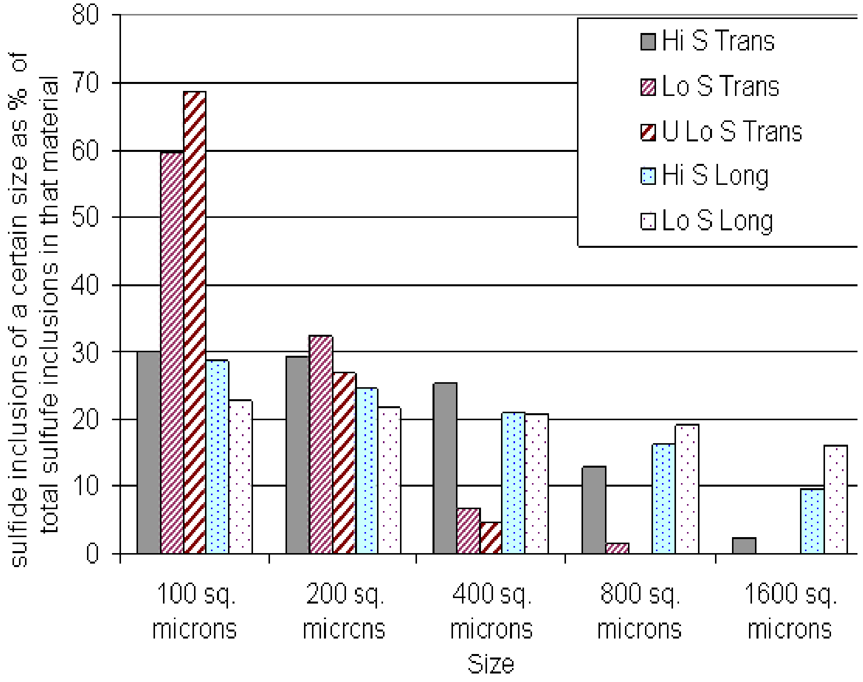
MATERIALS

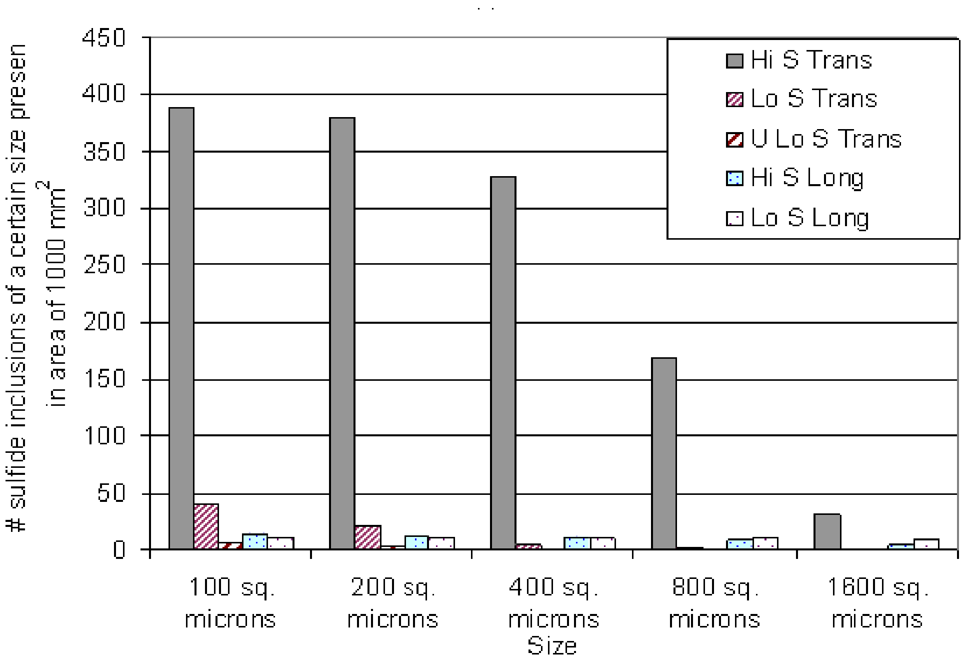




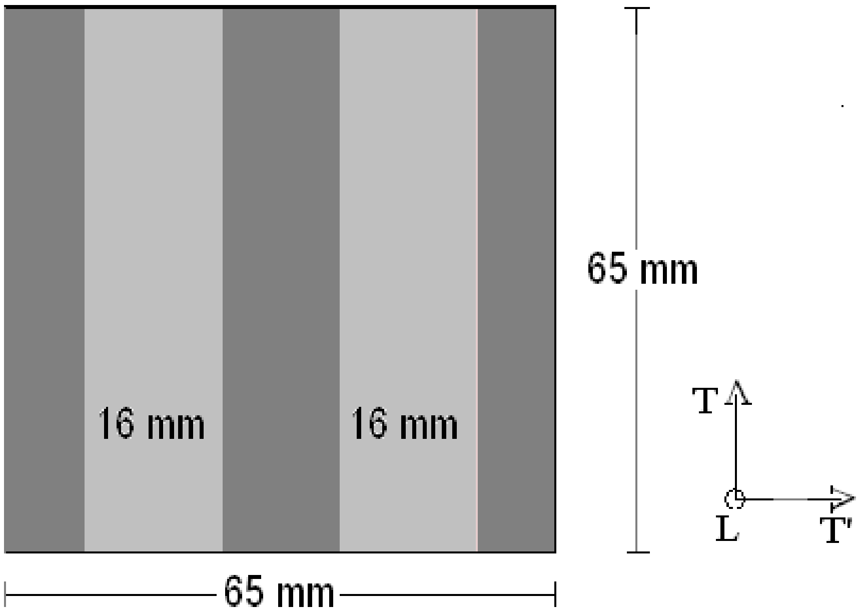
Inclusions were primarily sulfides

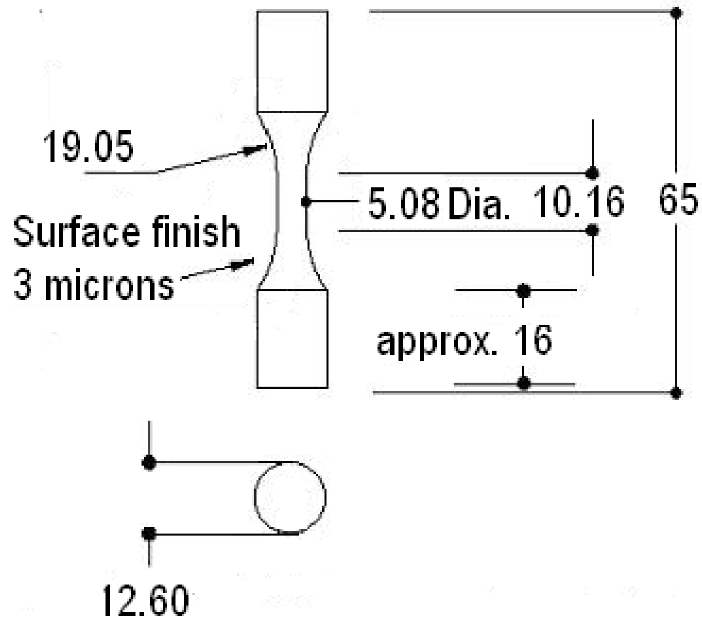
MATERIALS

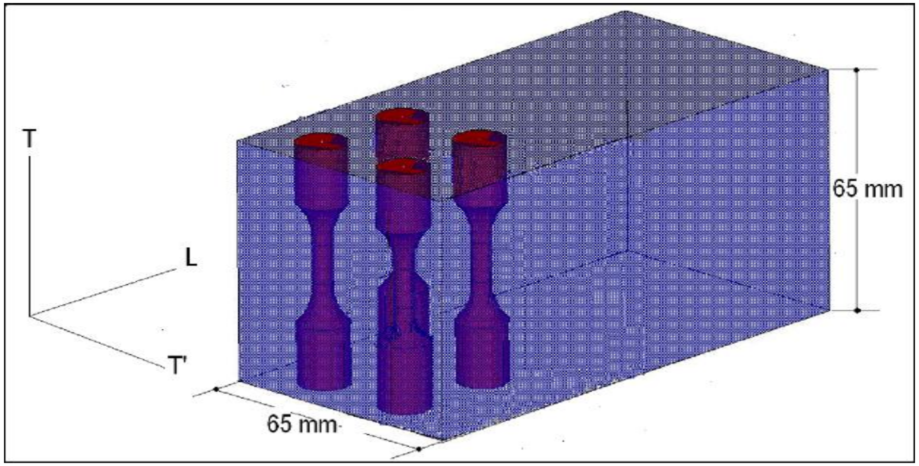

sulfide inclusions of a certain size as % of total sulfufe inclusions in that material
80
70
60
50
40
30
20
10
0
Hi S Trans
Lo S Trans
U Lo S Trans
Hi S Long
Lo S Long
100 sq. microns
200 sq. micrcns
400 sq. microns
800 sq. microns
1600 sq. microns
Size


sulfide inclusions of a certain size presen in area of 1000 mm2
450
400
350
300
250
200
150
100
50
0
Hi S Trans
Lo S Trans
U Lo S Trans
Hi S Long
Lo S Long
100 sq. microns
200 sq. microns
400 sq. microns
800 sq. microns
1600 sq. microns
Size

SPECIMENS


16 mm
16 mm
65 mm
65 mm
T
L
T'


19.05
Surface finish
3 microns
5.08 Dia.
10.16
65
approx. 16
12.60

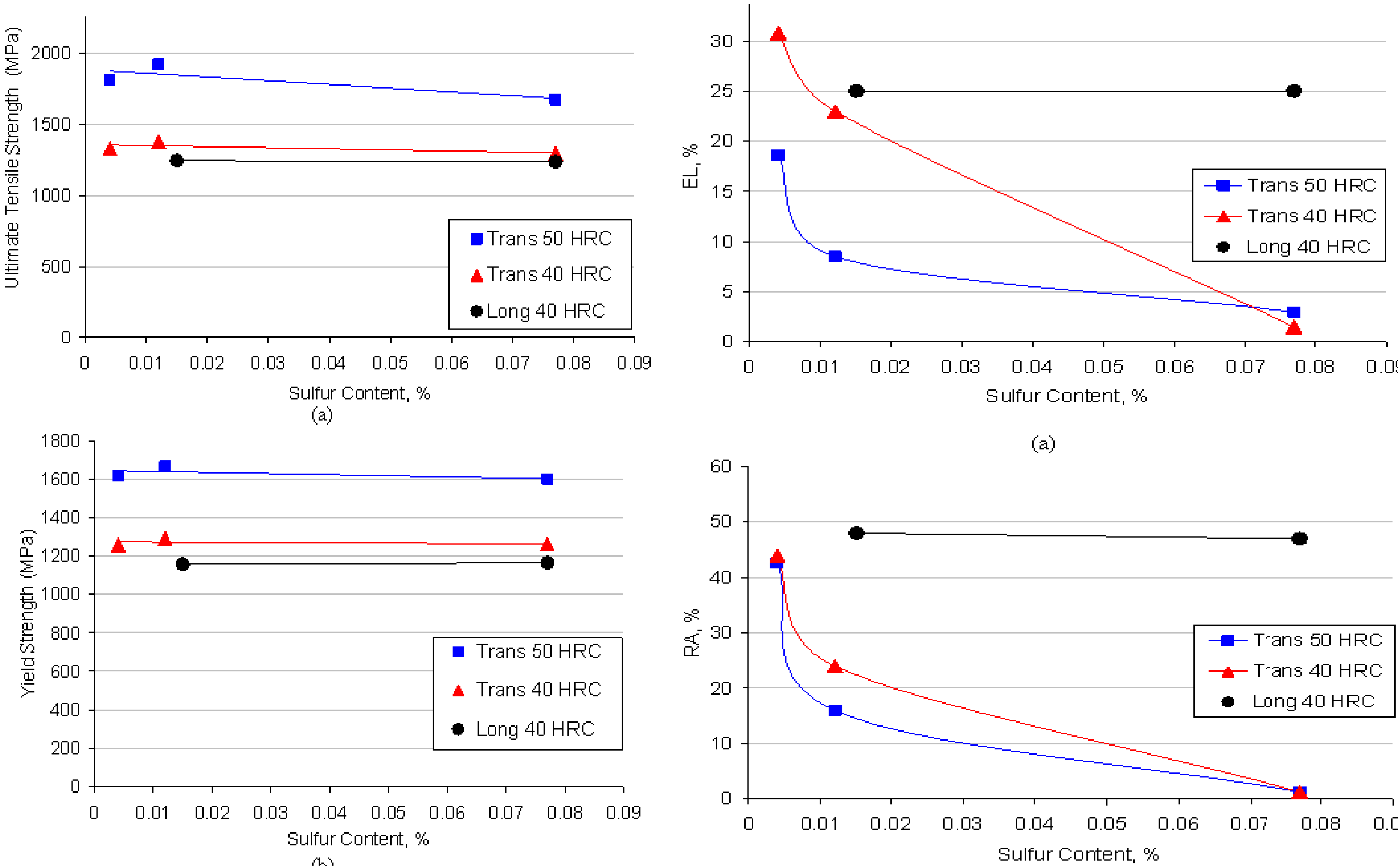

T
L
T'
65 mm
65 mm

EXPERIMENTS

- Testing Program Included:
  - Tensile tests
  - Strain-controlled fatigue tests
  - CVN impact tests
- Procedures and practices as outlined by ASTM
- Specimens cut-out from the transverse direction
- Some longitudinal test results also available

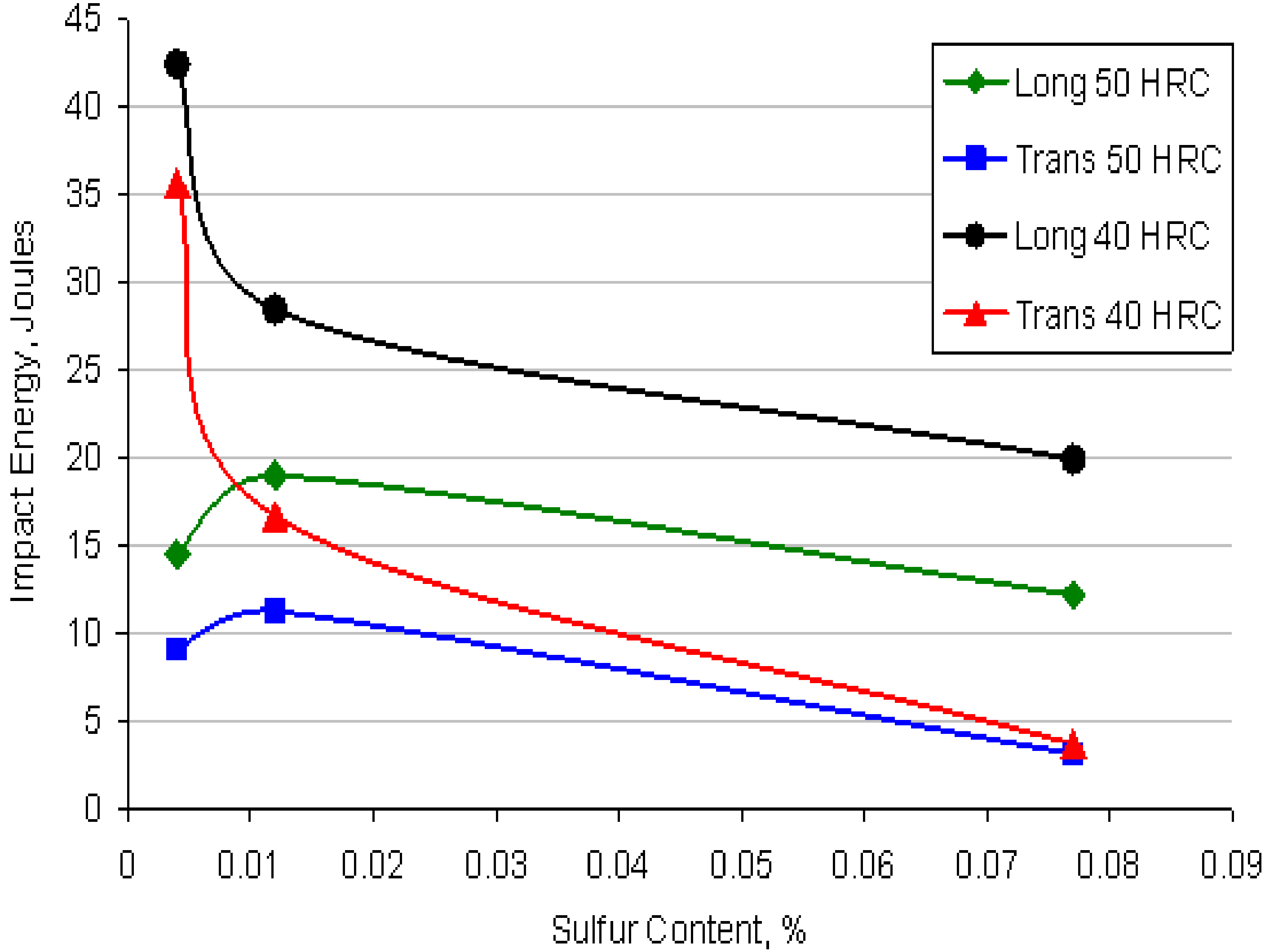
Closed-loop servo-hydraulic axial load frame

TENSILE TEST RESULTS

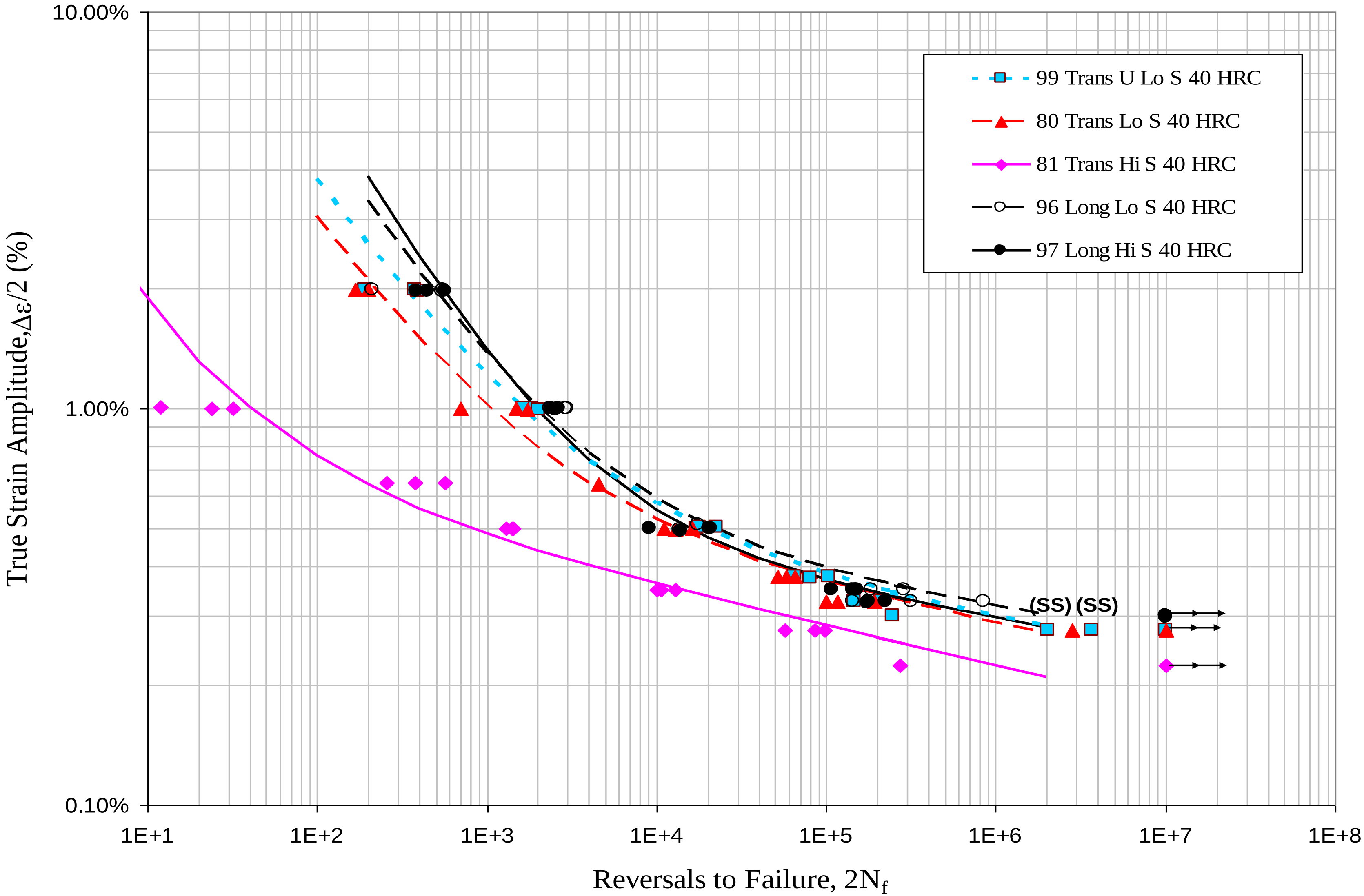


CVN IMPACT TEST RESULTS

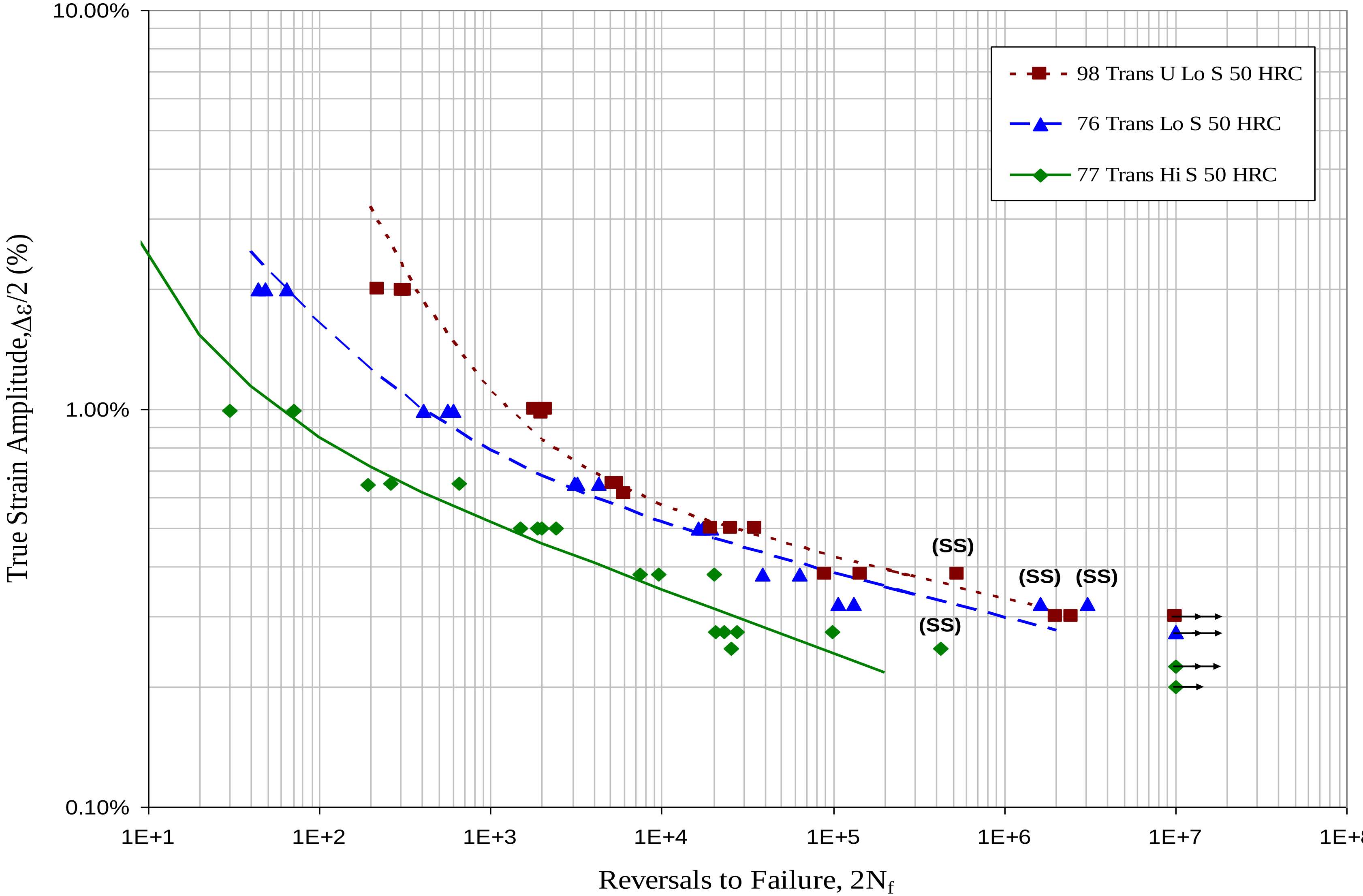
Test results at RT



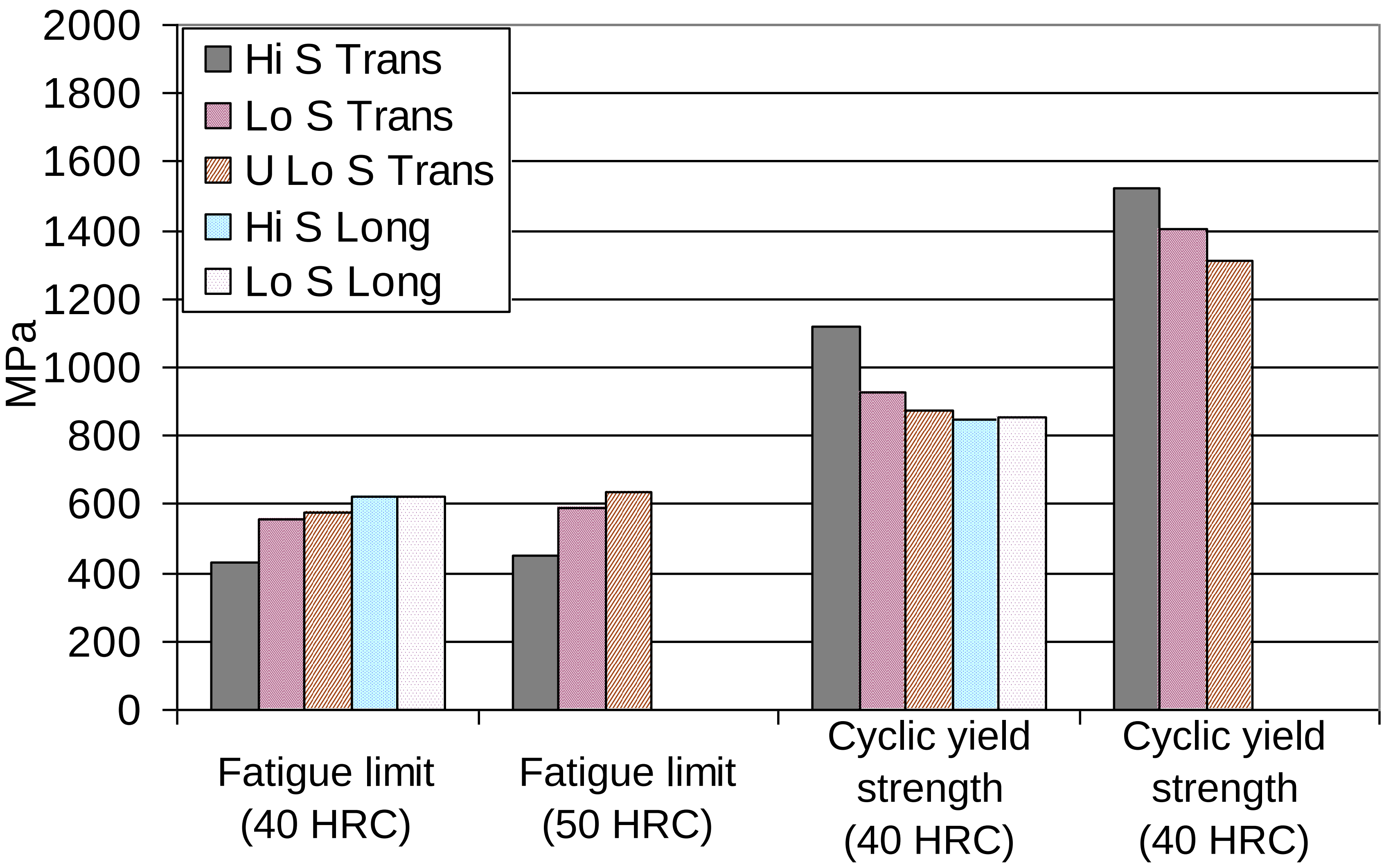
FATIGUE TEST RESULTS AT 40 HRC



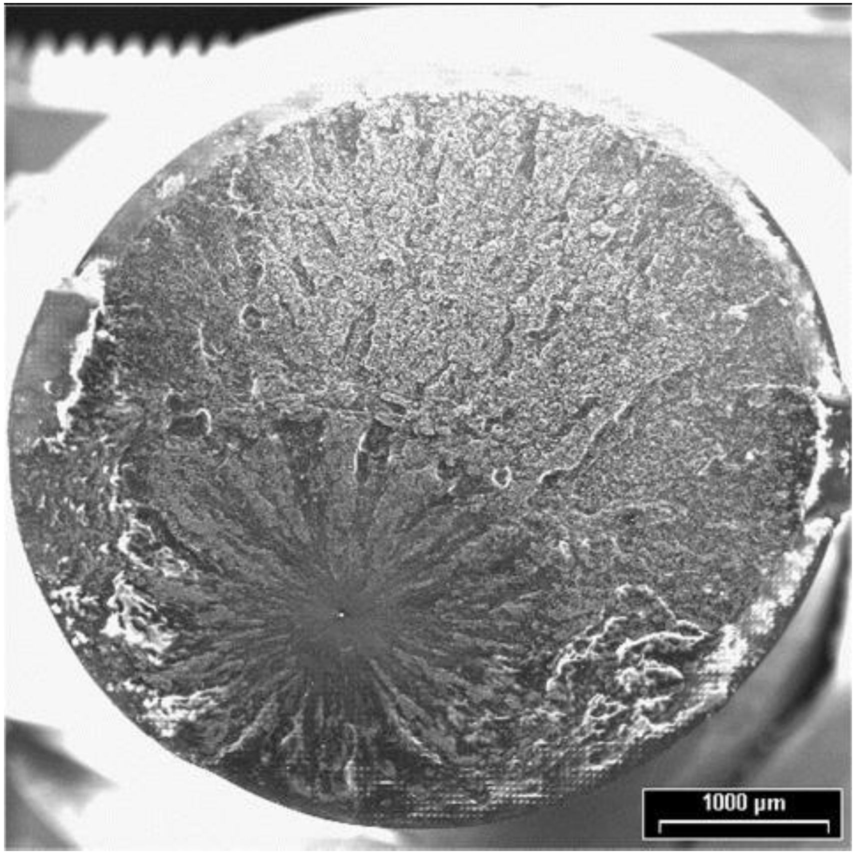
FATIGUE TEST RESULTS AT 50 HRC



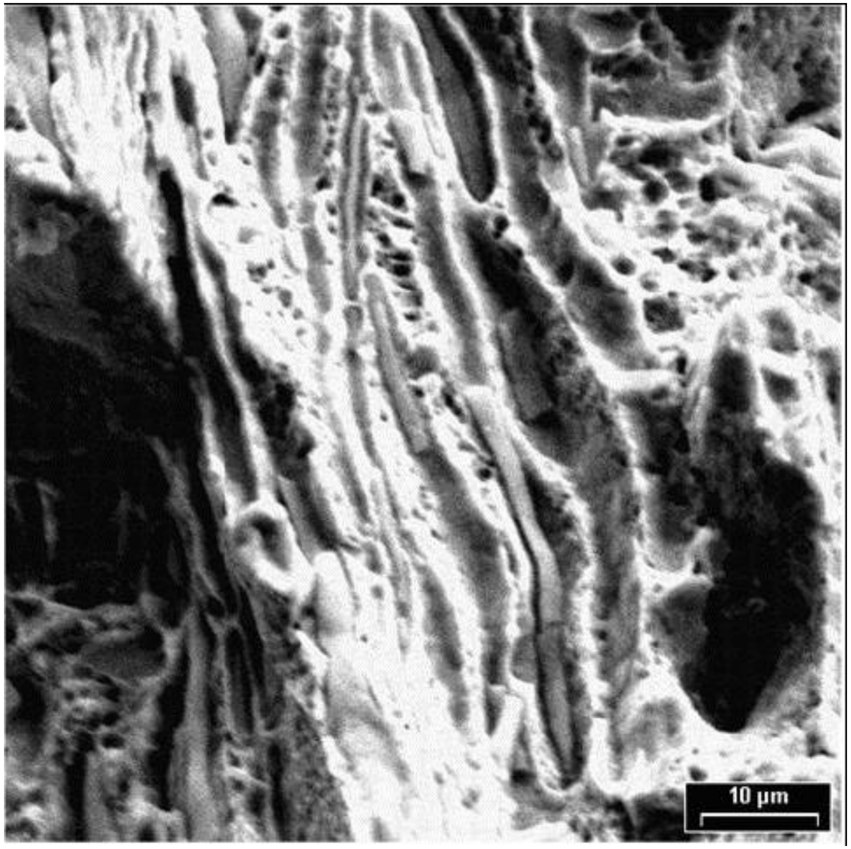
FATIGUE LIMIT & CYCLIC YIELD STRENGTH



FATIGUE FRACTURE SURFACES

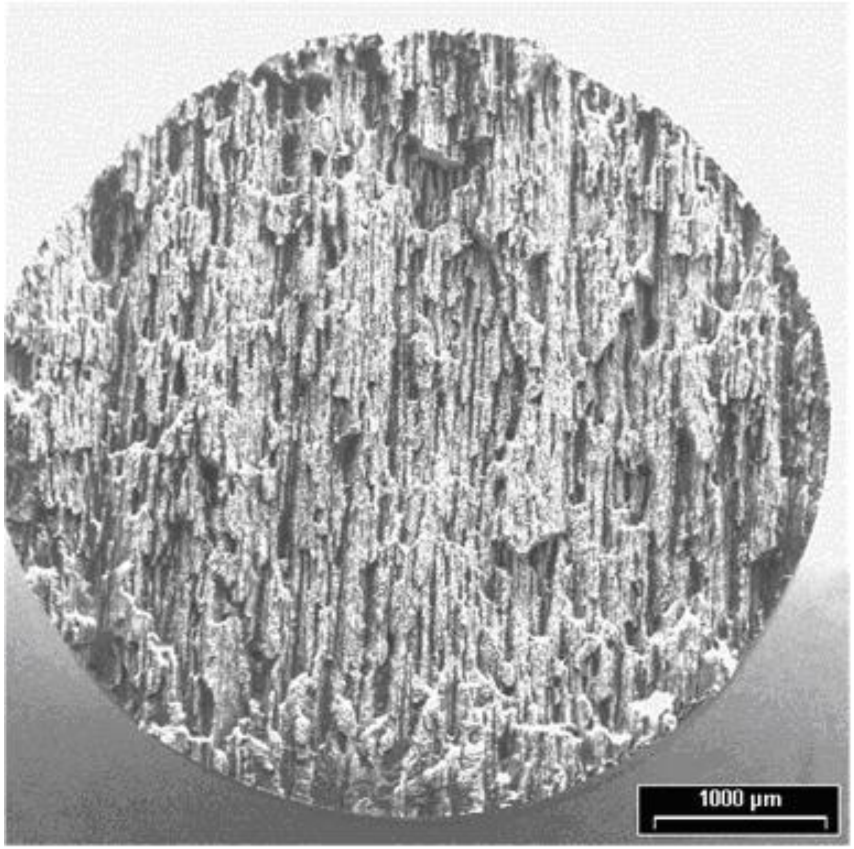


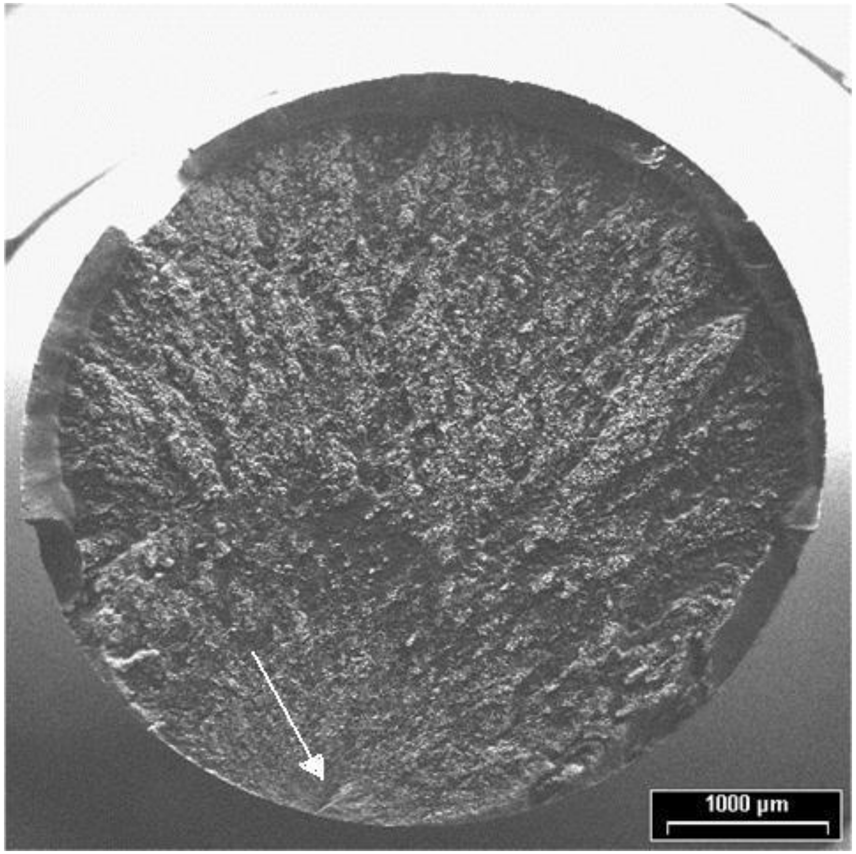
Fish-eye on fracture surface for low S material at 52 HRC at long life.



Elongated inclusions at and around the fracture origin for high S material at 52 HRC at short life.

FATIGUE FRACTURE SURFACES





Flat and rough fracture surface for high S material at 43 HRC at long life, resulting from initiation & growth of several cracks.

Fracture surface for surface initiated failure of low S material at 52 HRC at long life showing initiation site & shear lips.

FATIGUE CURVE ESTIMATION

Roessle-Fatemi Strain-Life Equation:

- For **longitudinal** loading condition
- Based on hardness
- Reference:

Roessle, M. L. and Fatemi, A., "Strain-controlled fatigue properties of steels and some simple approximations," *International Journal of Fatigue*, Vol. 22, 2000, pp. 495-511.

$$\frac{\Delta\epsilon}{2} = \frac{4.25(HB) + 225}{E}(2N_f)^{-0.09} + \frac{0.32(HB)^2 - 487(HB) + 191000}{E}(2N_f)^{-0.56}$$

ESTIMATION CURVE MODIFICATION

Roessle-Fatemi Strain-Life Equation Modification:

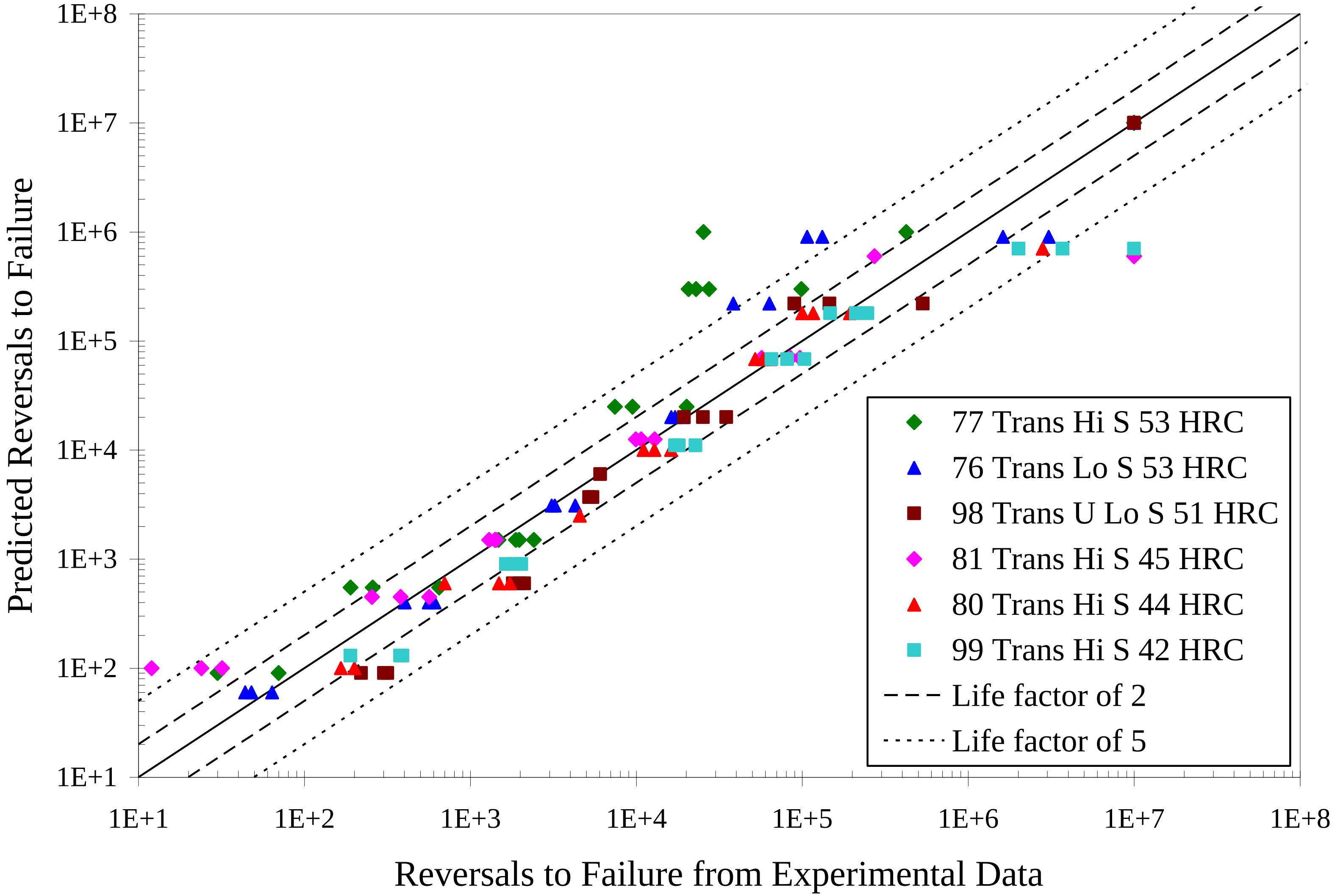
- For **transverse** loading condition
- Based on hardness and sulfur (S) content
- Reference:

N. Cyril and A. Fatemi, "Experimental Evaluation and Modeling of Sulfur Content and Anisotropy of Sulfide Inclusions on Fatigue Behavior of Steels ", *International Journal of Fatigue* (to appear).

$$\frac{\Delta\varepsilon}{2} = \frac{4.25(HB)+225}{E}(2N_f)^{[-0.3(S)-0.09]}$$

$$+\frac{0.32(HB)^2 - 487(HB)+191000}{E}[1-7.25(S)](2N_f)^{[-1.22(S)-0.65]}$$

PREDICTED VS EXPERIMENTAL LIFE



CONCLUSIONS

- The inclusions were predominantly sulfides and for the transverse samples the percent of sulfide area fractions were very close to the percent sulfur weight.
- The maximum inclusion size was about the same for the low sulfur and the ultra low sulfur materials, although the ultra low sulfur material had a sparser distribution of sulfides.
- Ductility and toughness reduced considerably by the increase in sulfur content for the transverse samples. However, the differences in either the yield strength or the ultimate tensile strength for the different sulfur level materials at a given hardness level were not significant.

CONCLUSIONS

- Strain-life curve at 50 HRC for the ultra low S material showed considerable improvement over the low S material at very short life, as a consequence of better ductility, while in the long life regime the two curves were close to each other.
- At 50 HRC, there was about a factor of 30 difference in fatigue life in LCF regime and about two orders of magnitude difference in HCF regime between the high and the ultra low S materials.
- At 40 HRC, there was about a factor of 40 difference in life in LCF and about one order of magnitude difference in HCF between the high sulfur and the ultra low sulfur materials.
- At 40 HRC, the strain-life curves for the ultra low and low sulfur materials in the transverse direction were close to each other and to the curves for the longitudinally loaded samples.

CONCLUSIONS

- The increase in hardness from 40 HRC to 50 HRC did not result in improved HCF behavior of the high sulfur material in the transverse direction, due to a more pronounced effect of inclusions at higher hardness and at long life.

- The three sulfur level materials at 50 HRC exhibited sub-surface as well as surface failure modes at long lives, resulting in considerable scatter of fatigue life.

- The fracture surfaces of the high sulfur transverse material were very rough, caused by several cracks originating from inclusions, propagating and merging.

- A modified model to predict strain-life curves for transverse loading based on Roessle-Fatemi equation showed good predictions for most of the data.

REFERENCE PUBLICATIONS

- N. Cyril, A. Fatemi and B. Cryderman, "Effects of Sulfur Level and Anisotropy of Sulfide Inclusions on Tensile, Impact, and Fatigue Properties of SAE 4140 Steel", ***SAE Technical Paper, SAE World Congress***, Detroit, Michigan, April 2008.

- N. Cyril and A. Fatemi, "Experimental Evaluation and Modeling of Sulfur Content and Anisotropy of Sulfide Inclusions on Fatigue Behavior of Steels ", ***International Journal of Fatigue*** (to appear).

ACKNOWLEDGEMENT

- **Financial Support: *AISI* (David Anderson)**
- **Bar Fatigue Committee: Chaired by Tom Oakwood**
- **Heat Treatment: *Chrysler* (Peter Bauerle)**
- **Residual Stresses: *Cummins Engine* (Steve Ferdon)**