A Collection of Cyclic Mean Stress Relaxation Data

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F.D.E. Spring 2019 Meeting
Cobo Hall, Detroit.
(*with additions.*
last update Nov 29 2021)

Stress-strain sequence from an un-notched axial loaded sample.

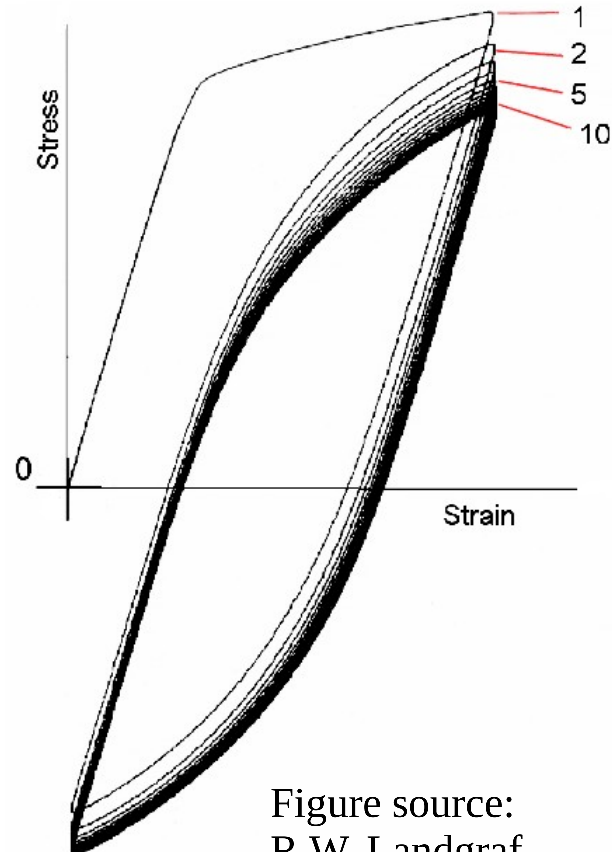
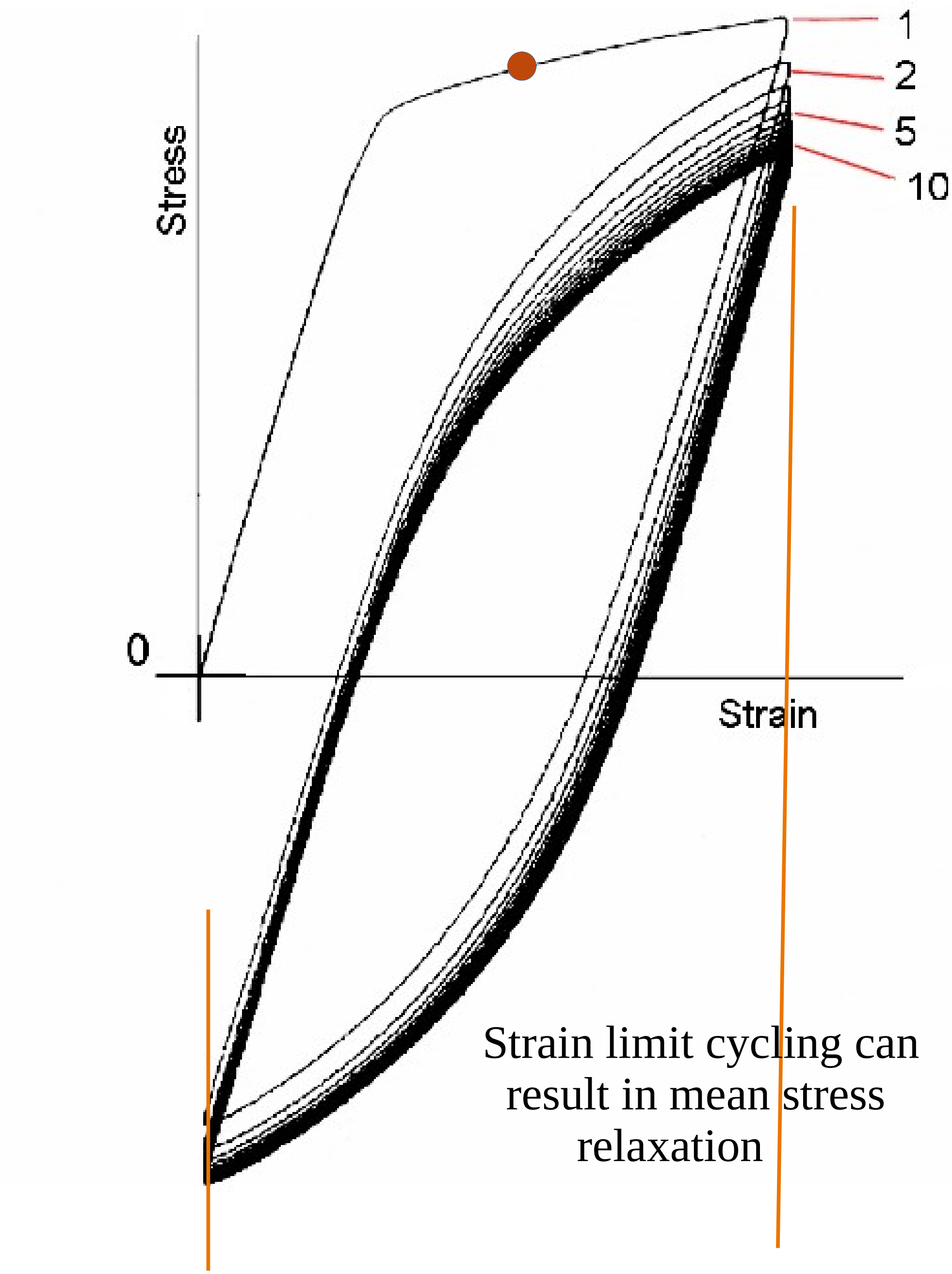


Figure source:
R.W. Landgraf

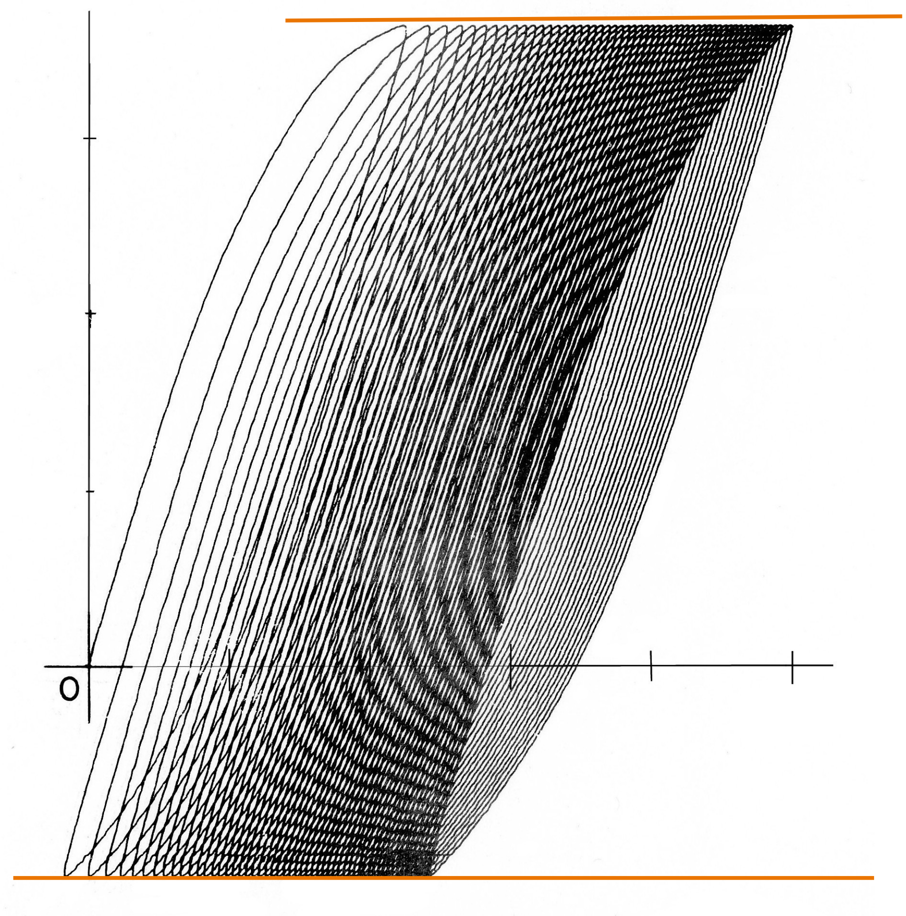
An animation of cyclic mean stress relaxation:
http://fde.uwaterloo.ca/Fde/Notches.new/Weld+Residuals/VideoA/animation.gif (9Mb)

Additional new web page on relaxation of mean stress in Aluminums (2022):
https://fde.uwaterloo.ca/Fde/Articles/relaxAlumPres-Nov2022-4web.pdf

Cyclic Mean Stress Relaxation



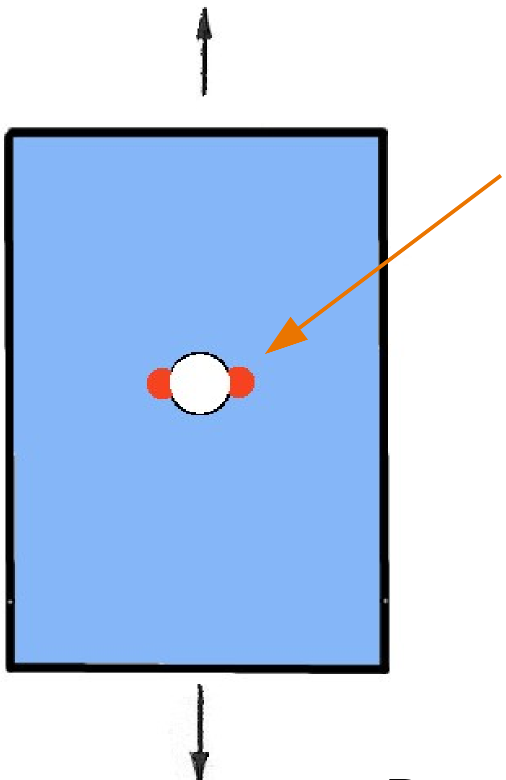
Strain limit cycling can result in mean stress relaxation



Stress limit cycling

When cycling with a mean stress the mean strain of loops will move. Termed Cyclic Creep or Ratcheting

Cyclic mean stress relaxation can “wash away” residual stresses created by processing such as peening or welding or by load history sequence. The state of mean stress is important in fatigue life prediction.



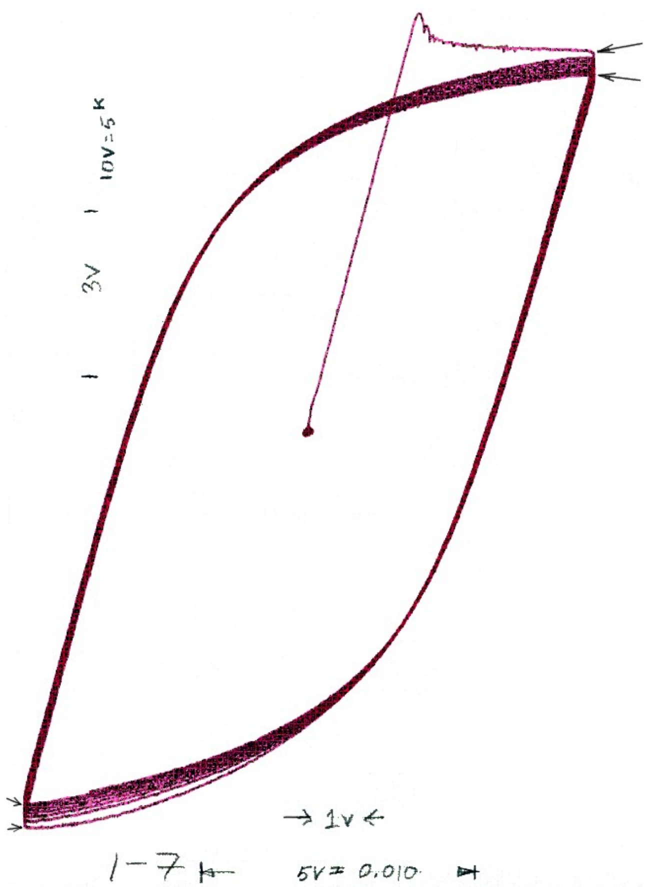
Tensile or compressive mean stresses can be created at notches by loading sequences.

Due to the large elastic field surrounding such hot-spots the local stress-strain cycles similar to a strain limit control axial specimen test.

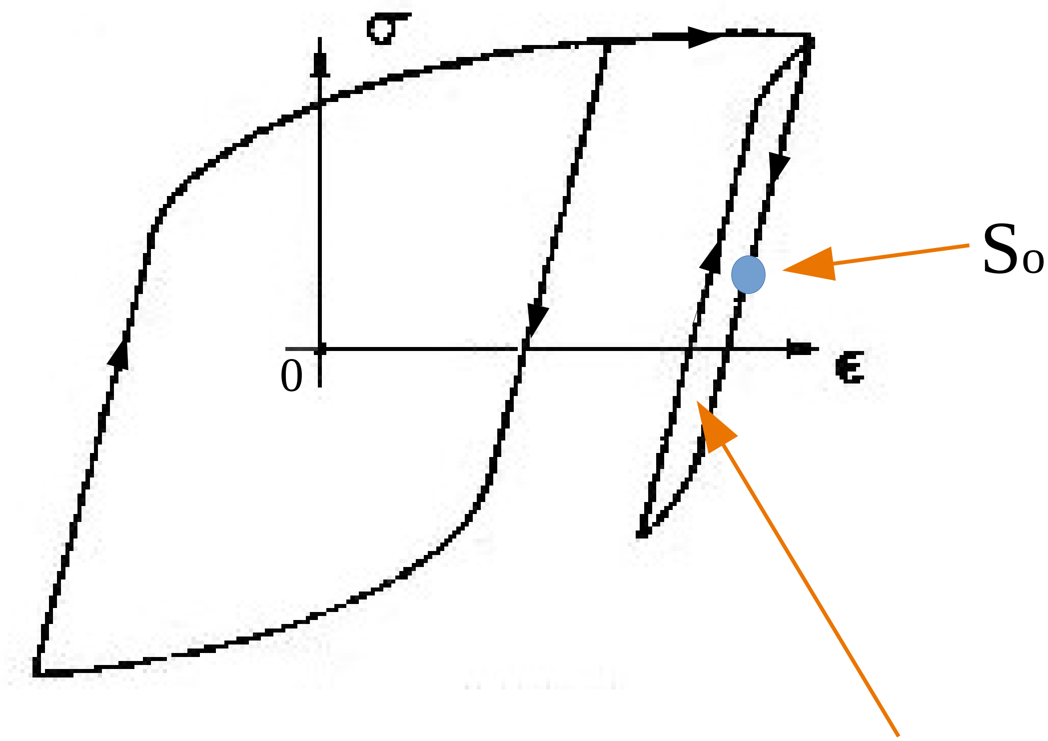
Tensile or compressive residual stresses are often present at the “toe” of welds.

Residual stresses appear as a mean stress in the stress-strain hysteresis loops at such fatigue “hot-spots”.

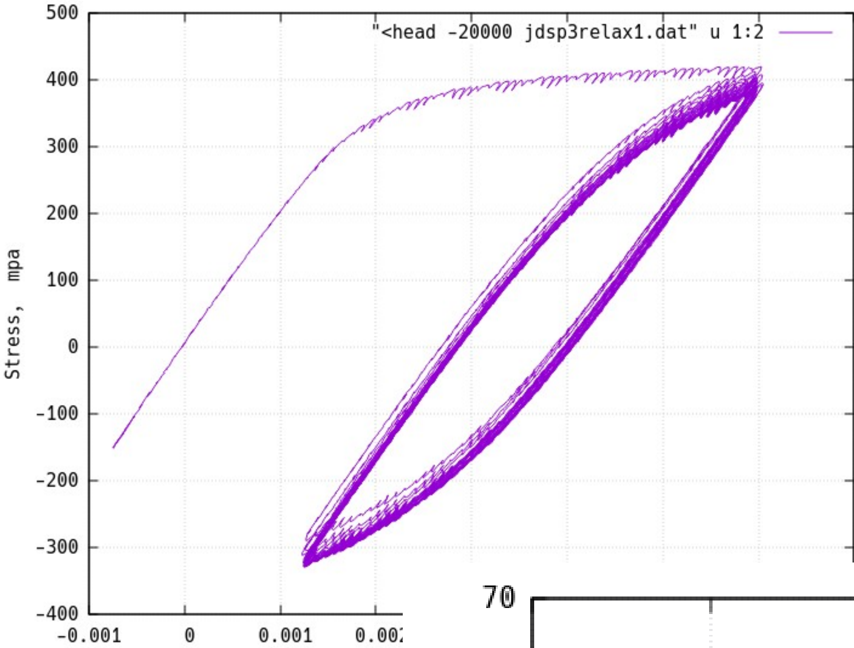
A steady state sequence without relaxation.



When extended to greater strains and run at smaller amplitudes a means stress So can be induced into the hysteresis loops

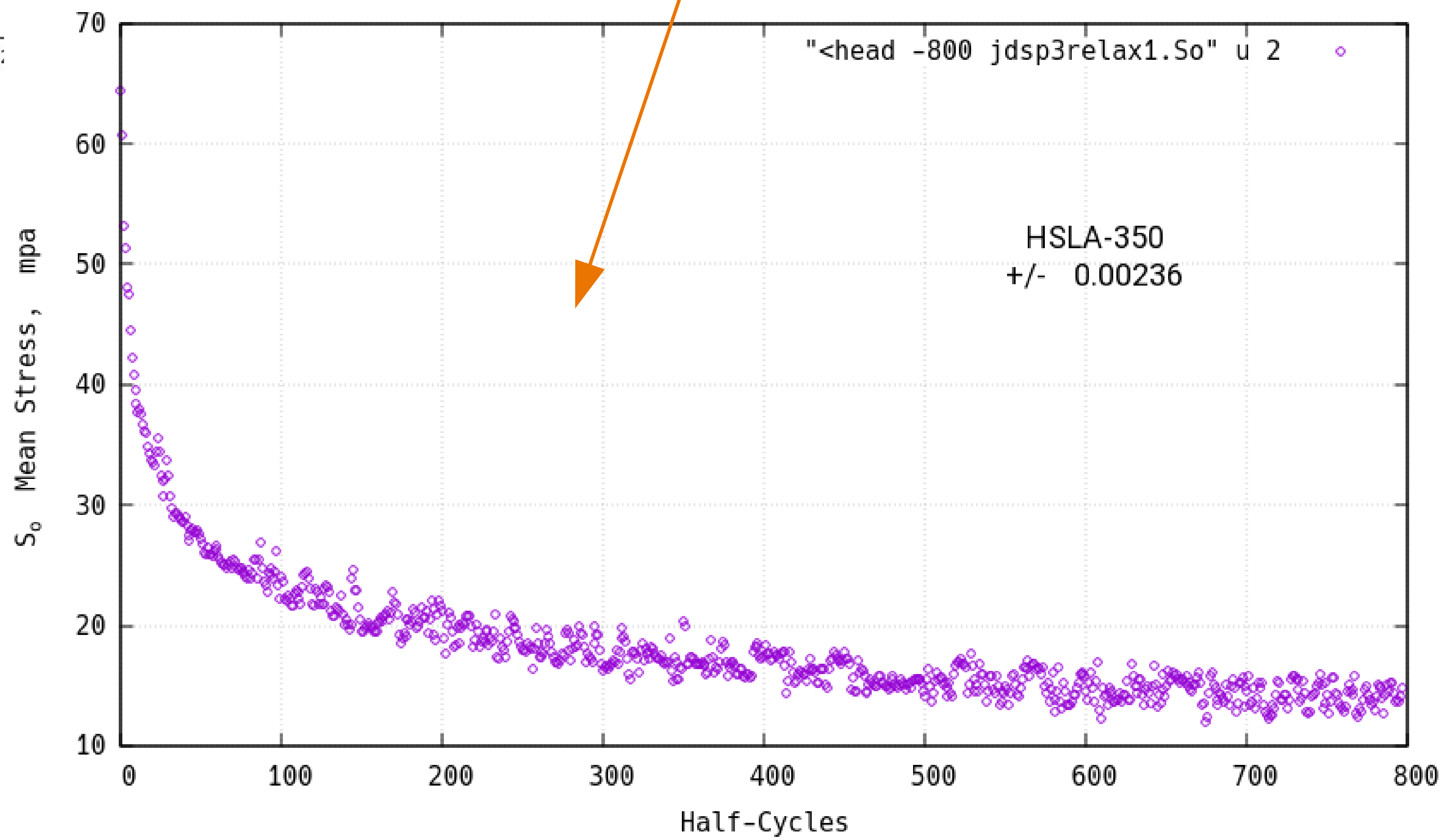


If the subsequent loops have sufficient plasticity (they are open) the mean stress will move towards zero as cycling continues.

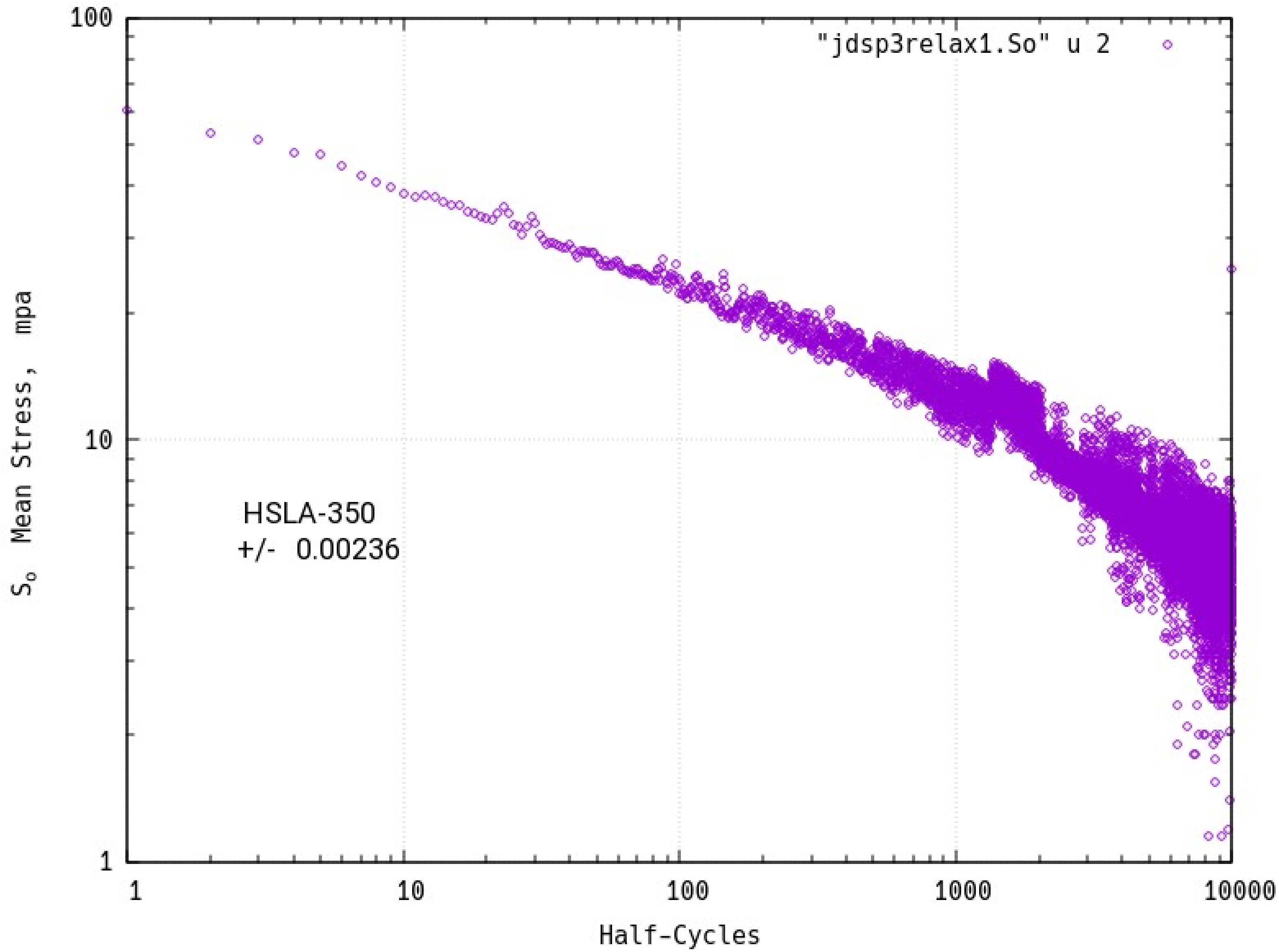


One can plot the progress of the So for each half-cycle (max to min or min to max).

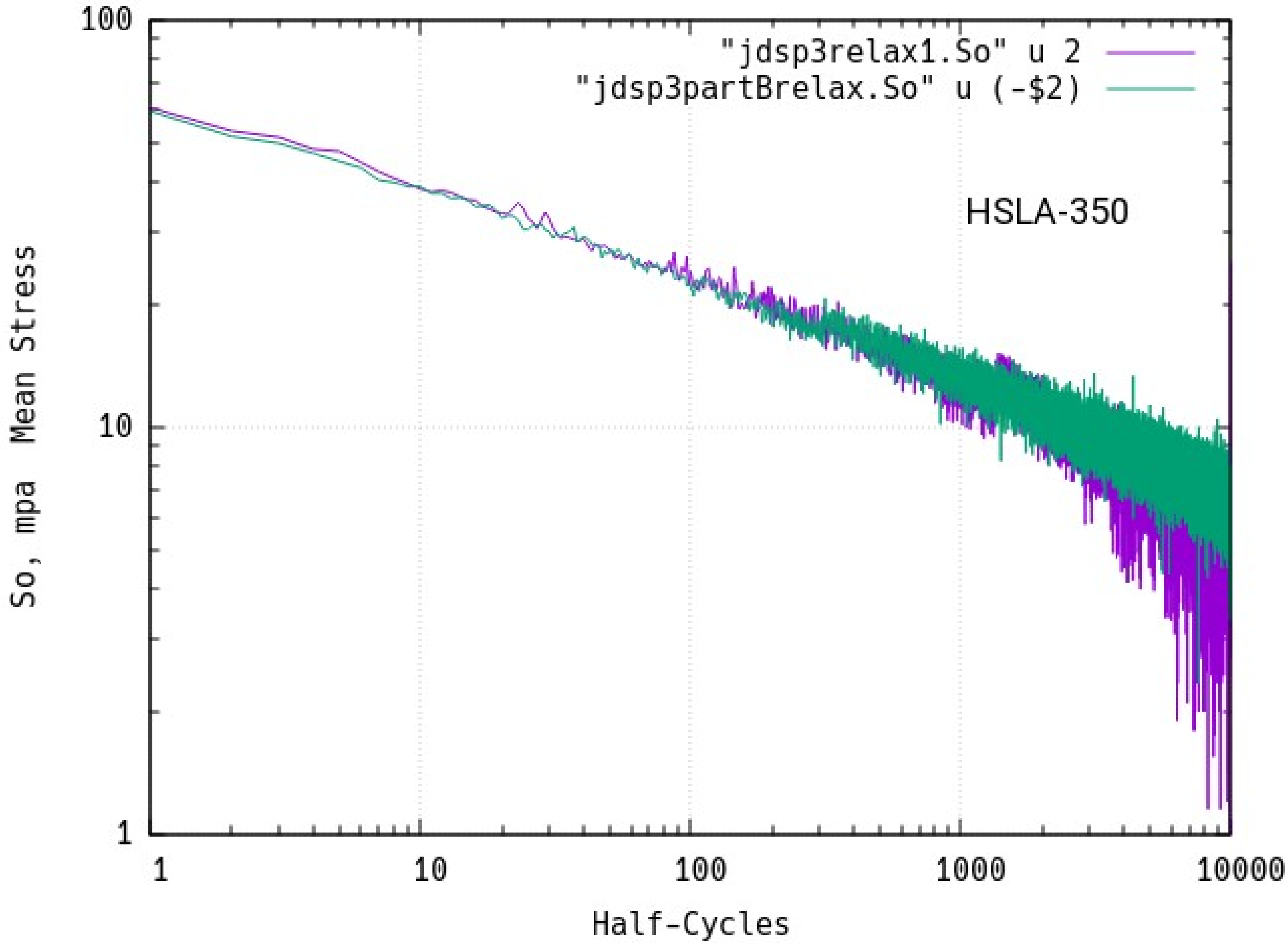
The result looks like a decay curve on a linear plot.



On a log-log plot the change in mean often has the form of a straight line.

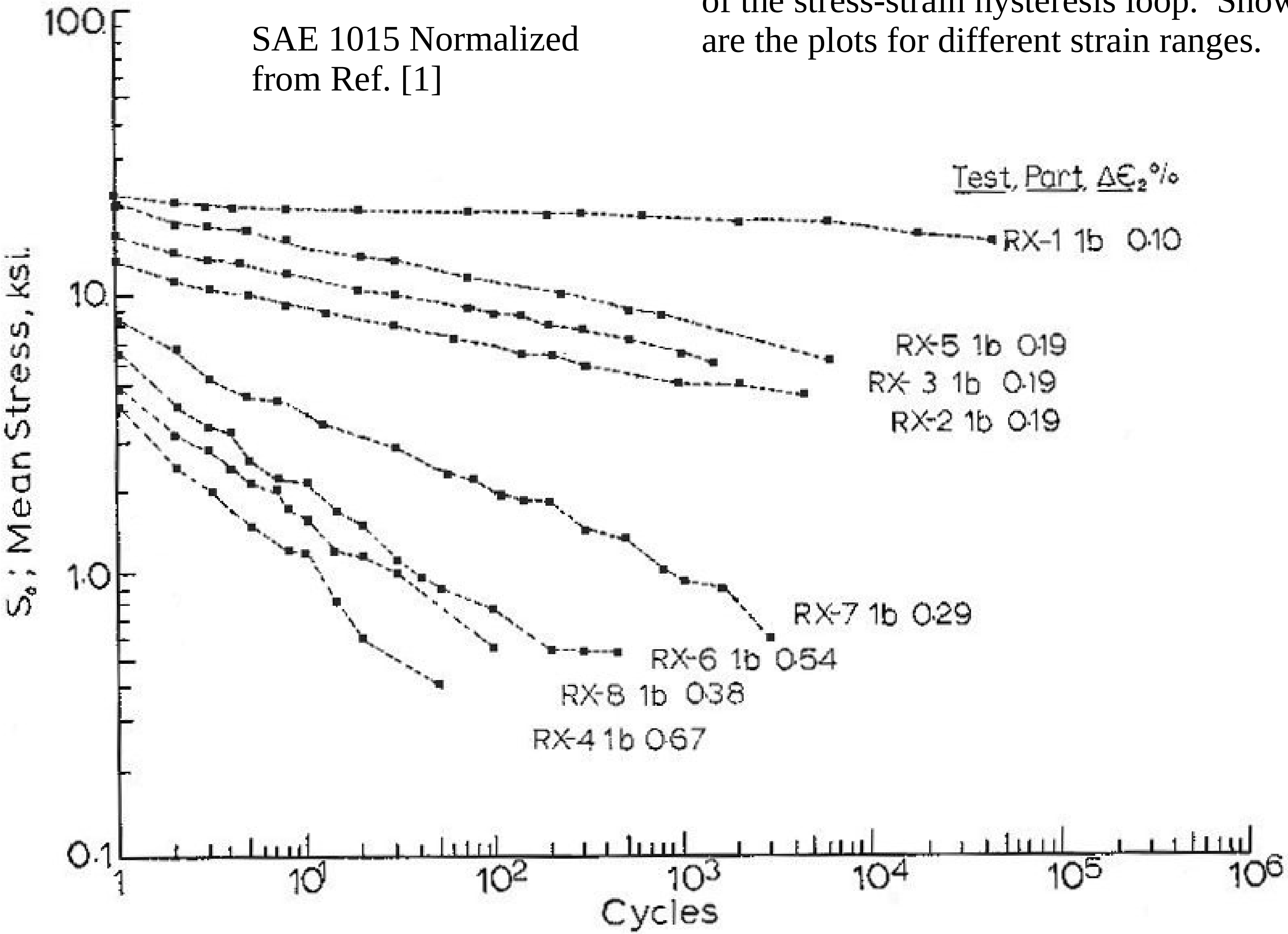


Both tensile and compressive mean stresses relax in the same manner. Here green is a compressive test plotting -So and purple is a tensile So relaxation plot.



The rate of relaxation is dependent upon the size of the stress-strain hysteresis loop. Shown here are the plots for different strain ranges.

SAE 1015 Normalized
from Ref. [1]



Mean Stress vs. Cycles at Secondary Strain Range $\Delta\epsilon_2$ for Part 1b of all Tests. (First application of Cycles at $\Delta\epsilon_2$)

The relaxation rate appears to not be dependent upon the initial So value.

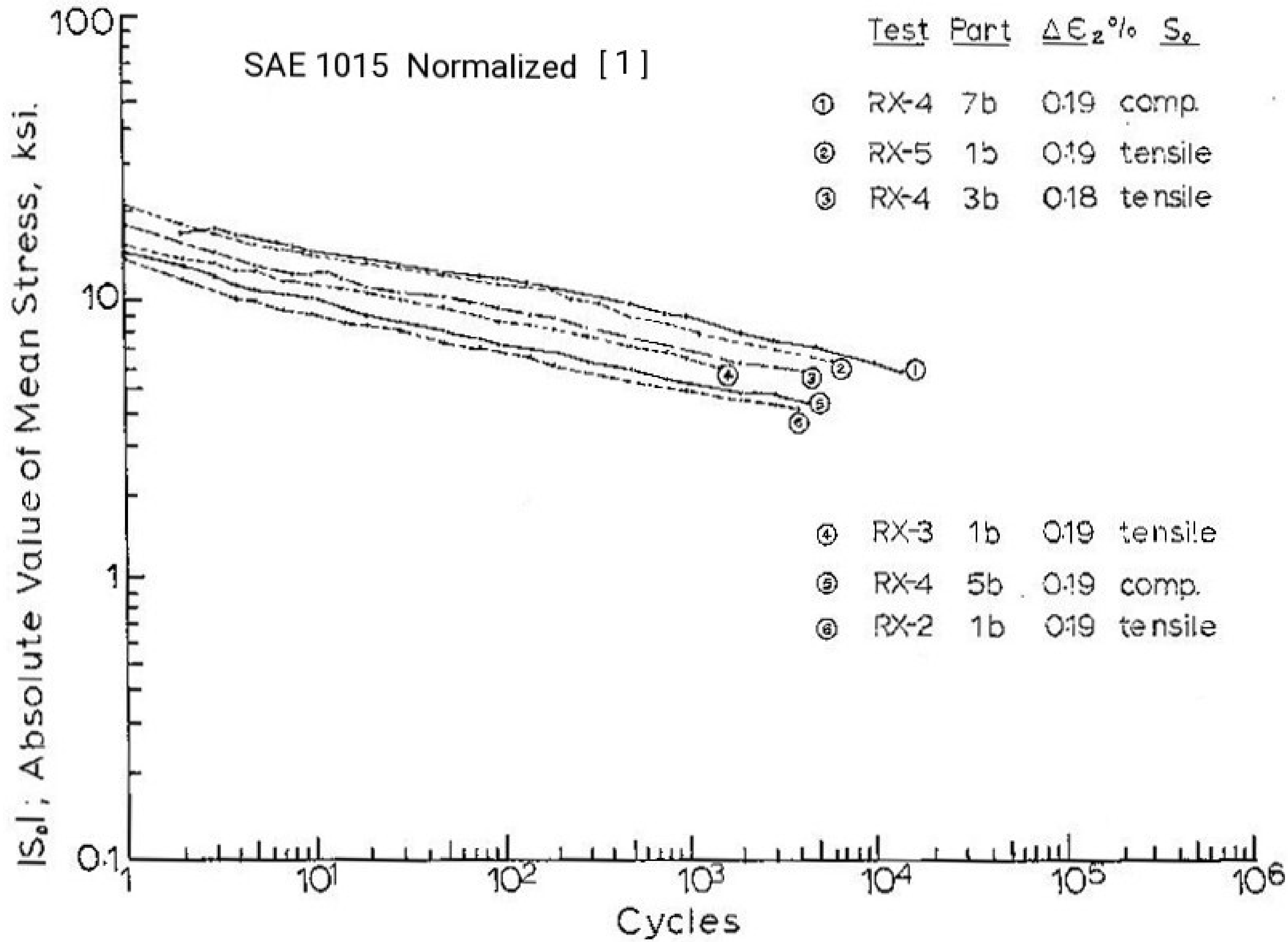
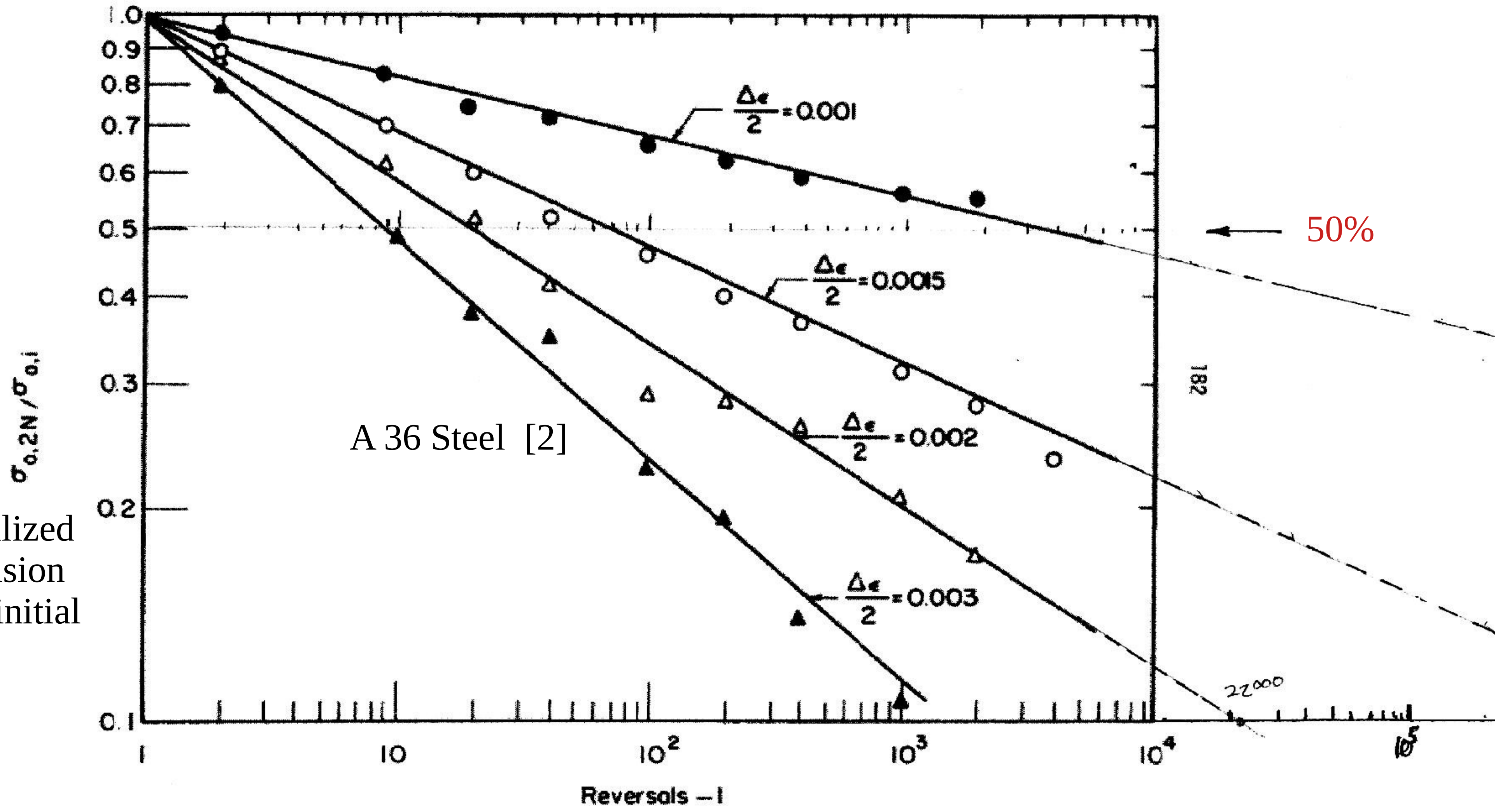


Fig.4 Absolute Value of Mean Stress vs. Cycles at Secondary Strain Range $\Delta\epsilon_2 \doteq 0.2$ %

Relaxation plot for A36 steel   Ref. [2]



Normalized by division of the initial So

Relaxation plot for Weld metal   Ref. [3]

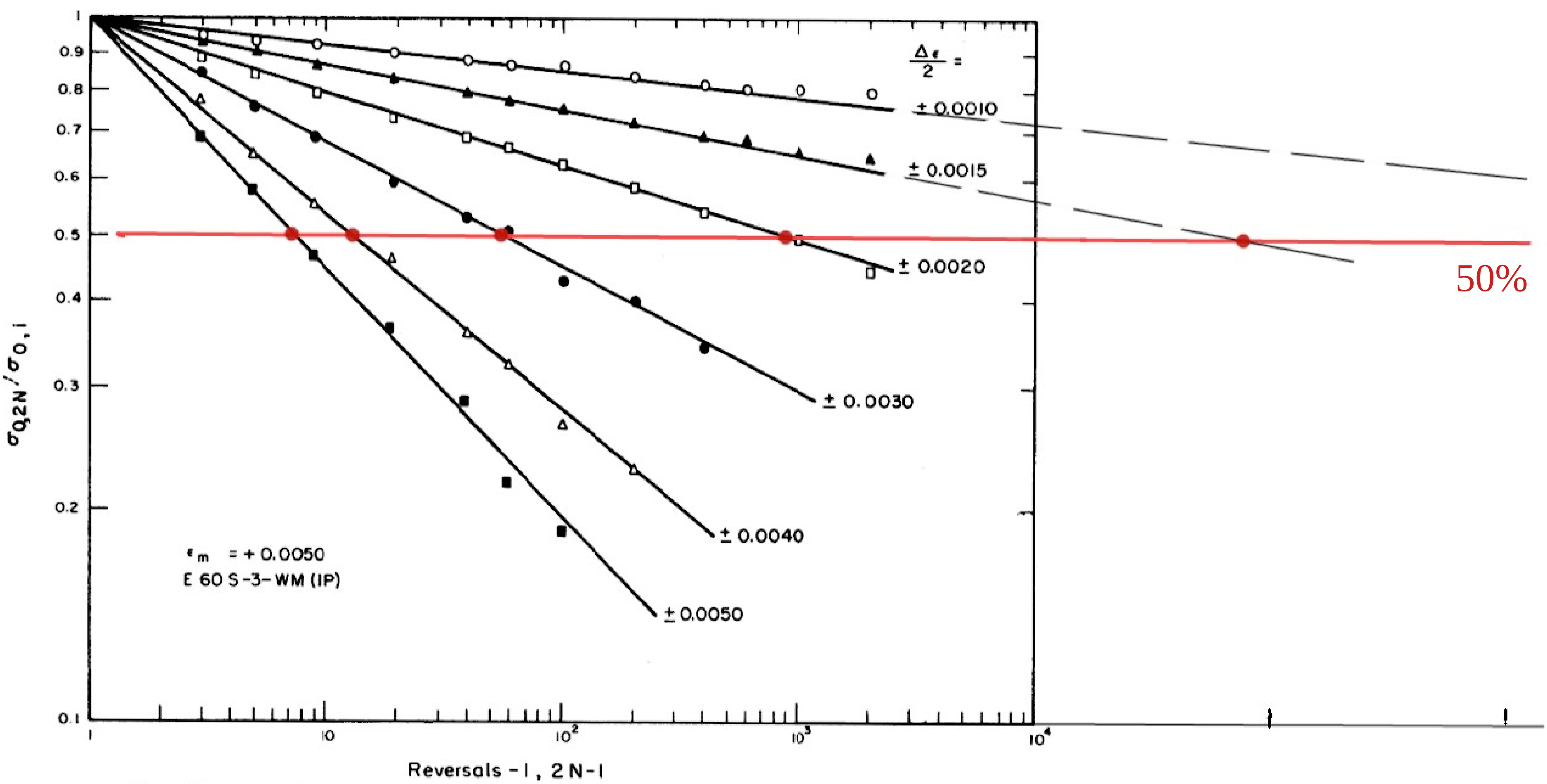


Fig. 71 Cyclic Relaxation Data of the Mean Stress (Dimensionless Value) for E60S-3-WM(1P) at Constant Mean Strain of +0.005

Ref. [3]

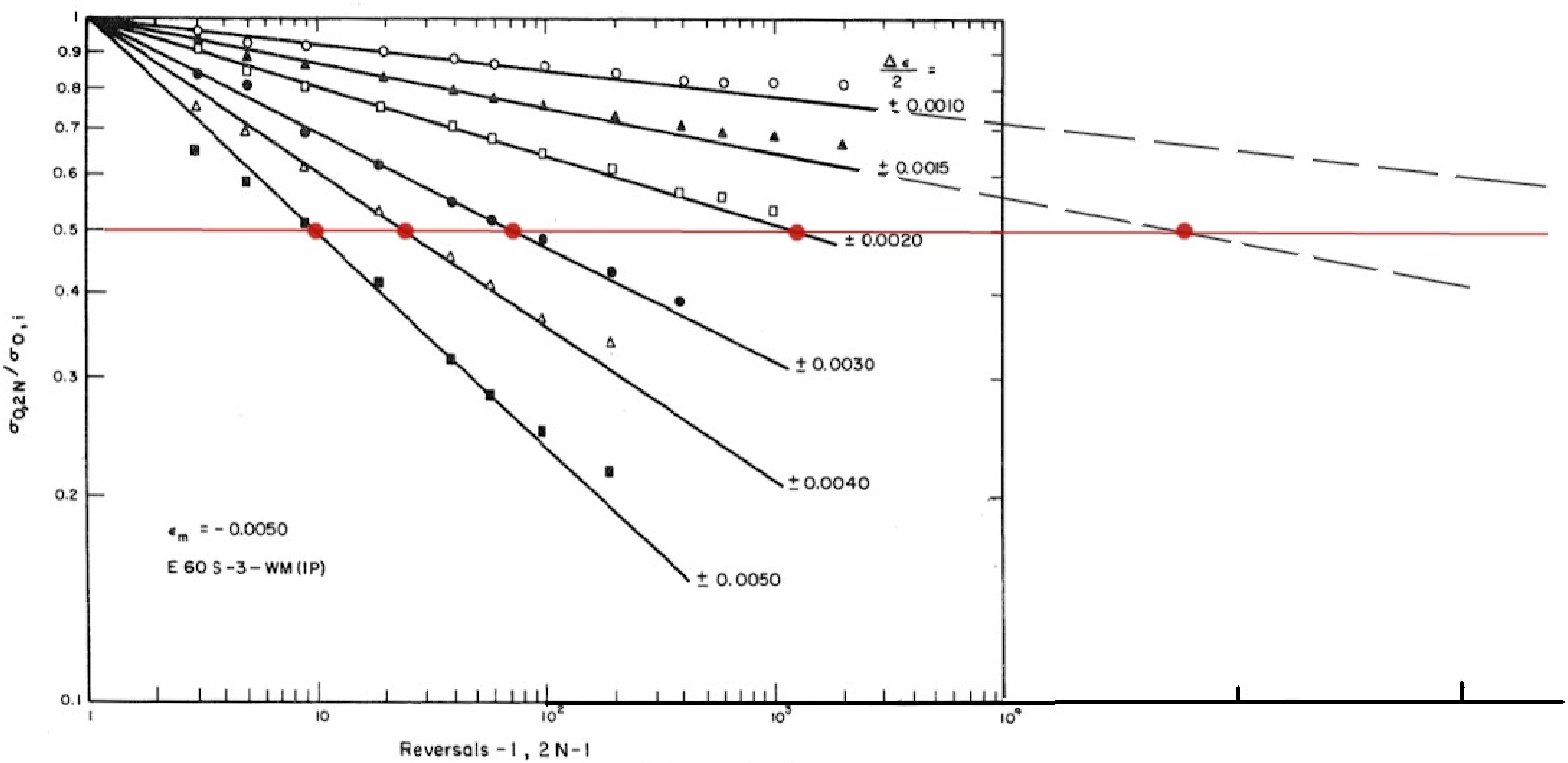
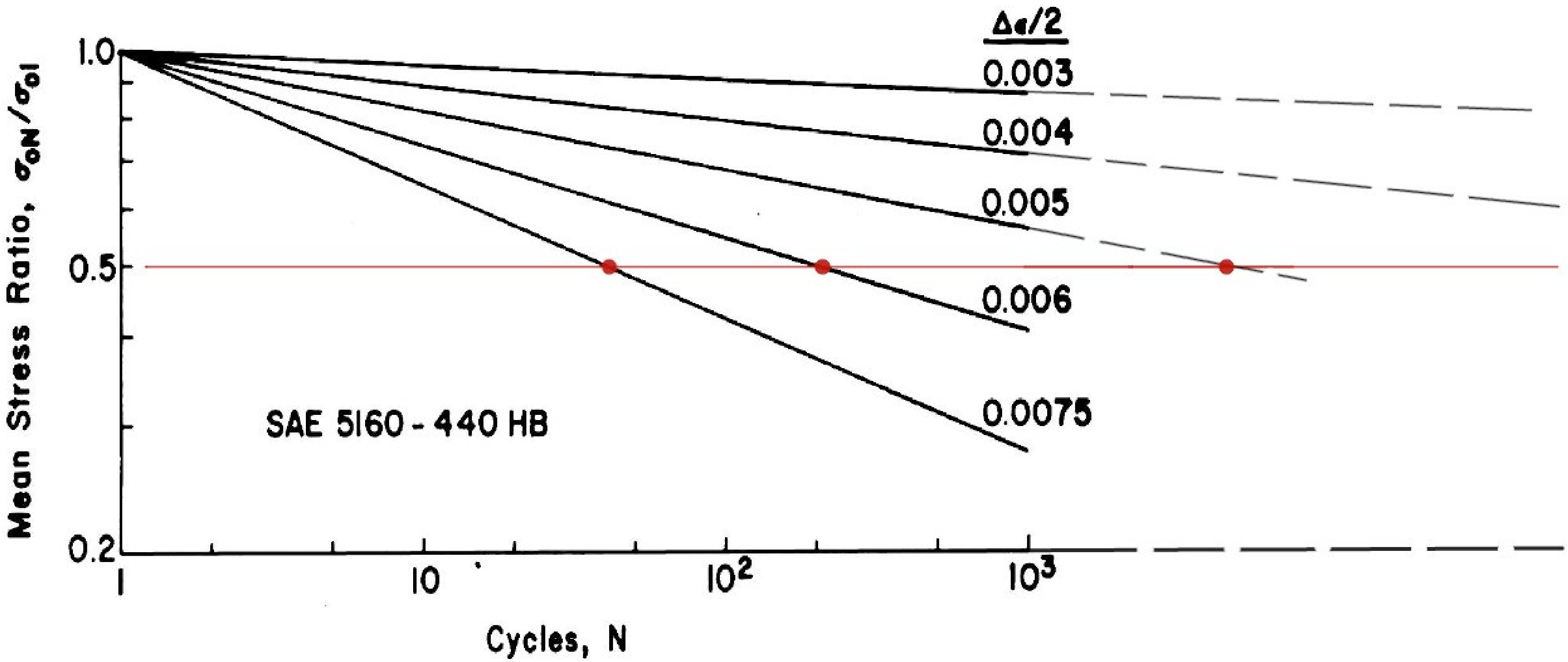


Fig. 72 Cyclic Relaxation Data of the Mean Stress (Dimensionless Value) for E60S-3-WM(1P) at Constant Mean Strain of -0.005

Harder steels behave in a similar fashion:

Ref. [5]



Similar behaviour in various steels of various hardness:

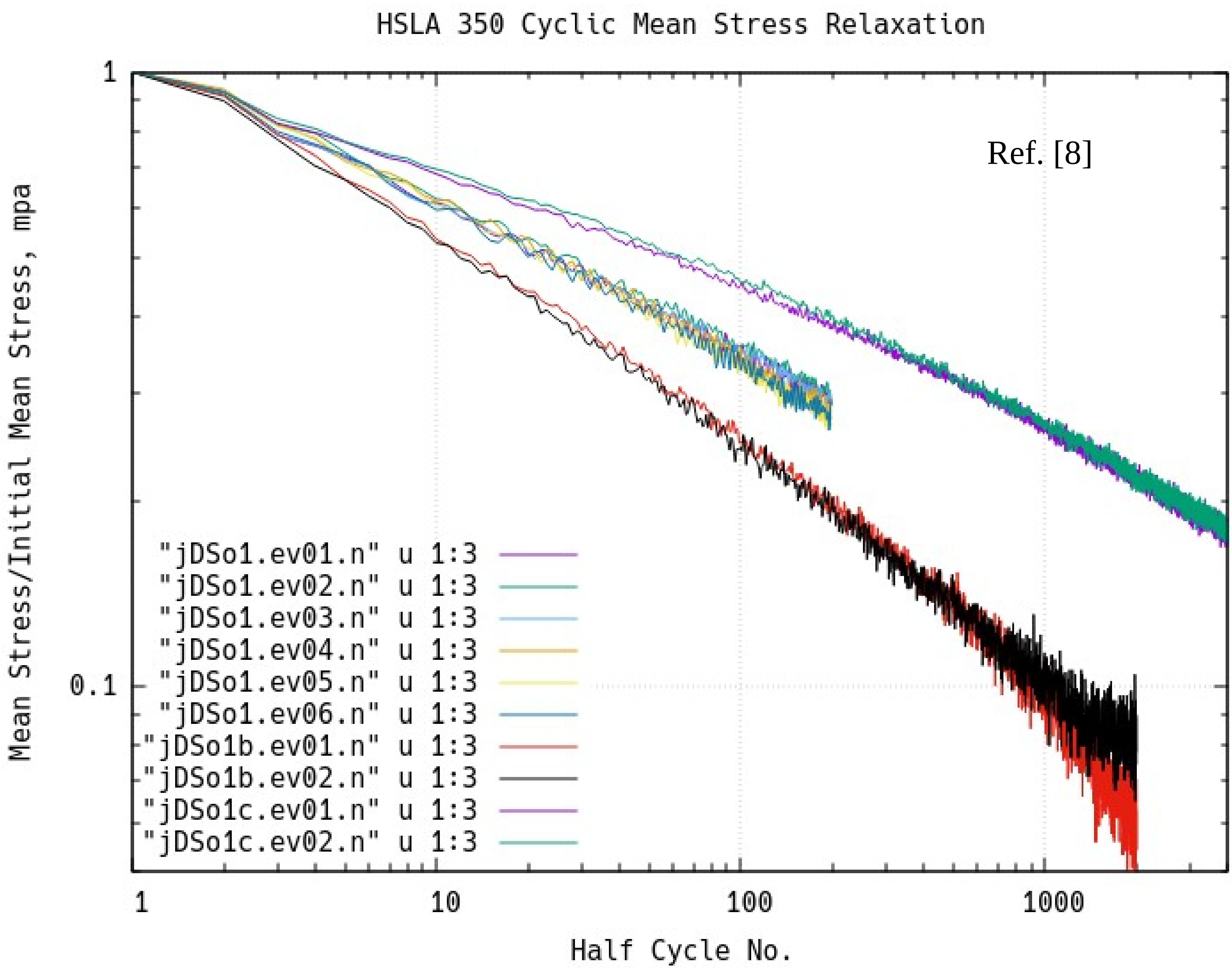
Ref. [6]

SAE 1045

1. BHN= 560
2. BHN= 410
3. BHN= 280

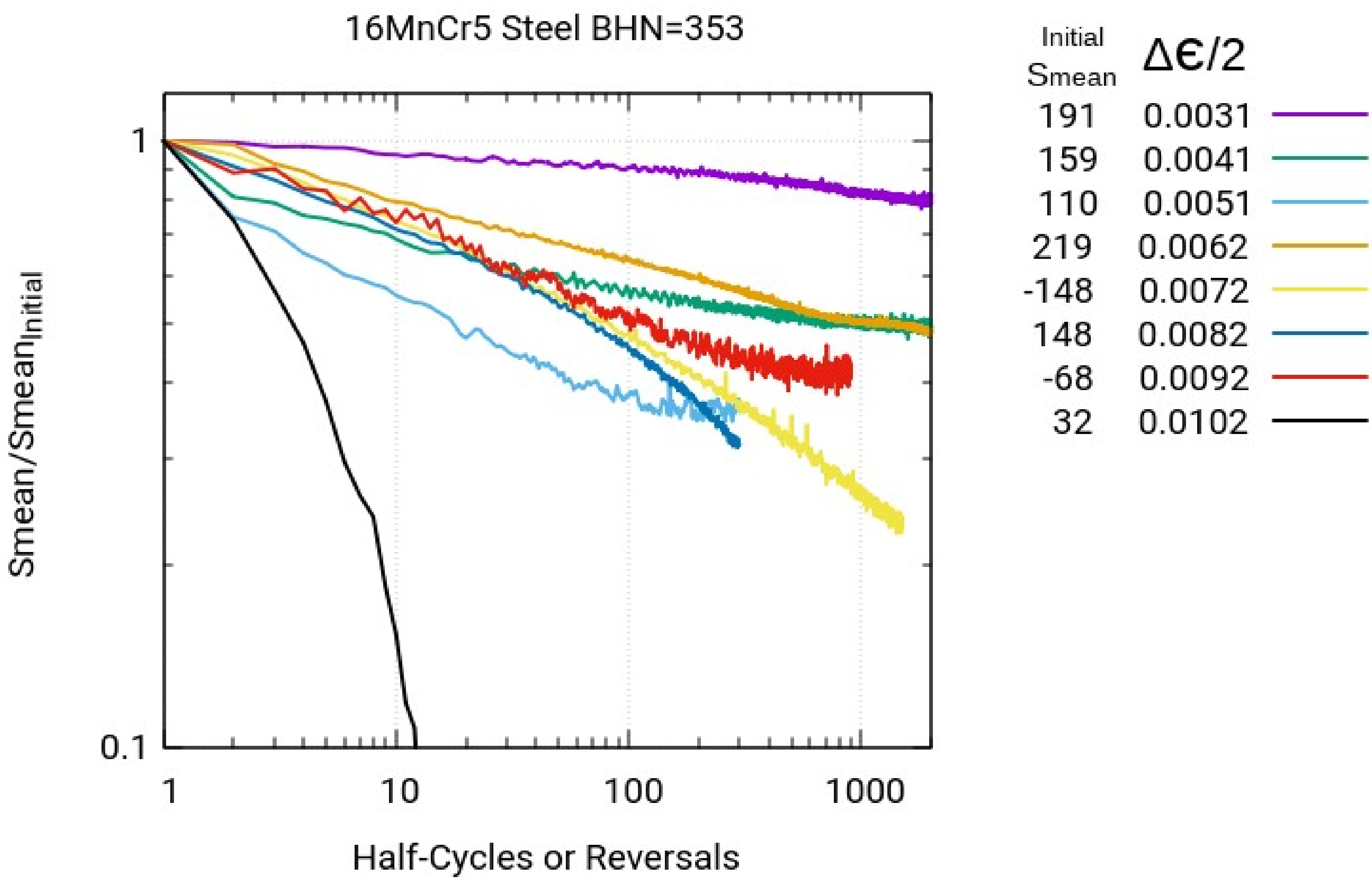
Ref. [7]

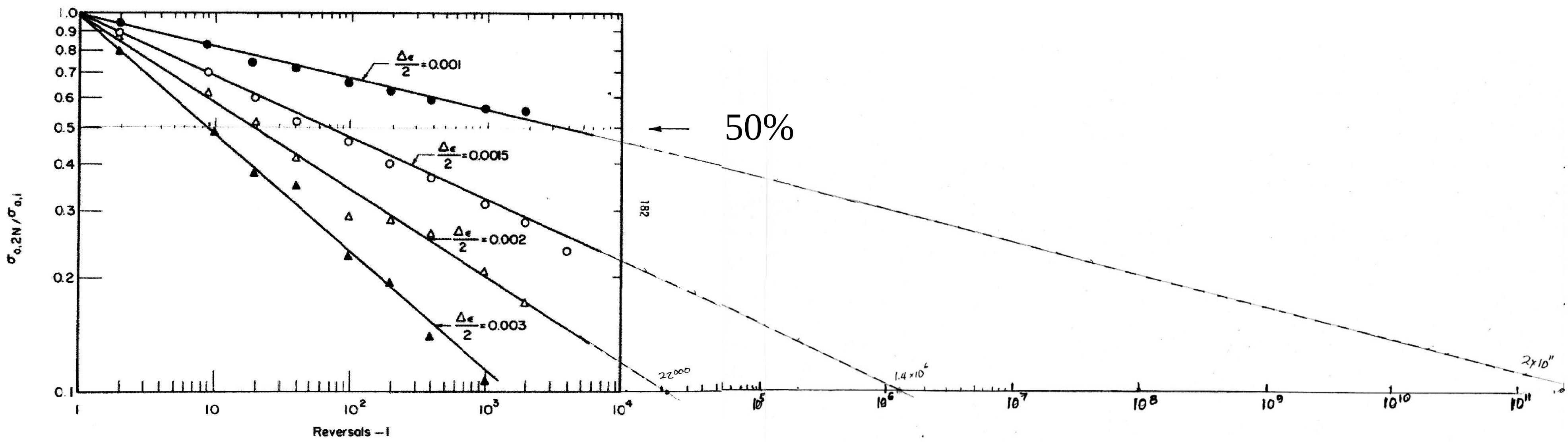
1. HRLC
   (Hot Rolled
   Low Carbon)
2. SAE950X
   (HSLA 350X)
3. SAE980X
   (HSLA 560X)



HSLA 350 Cyclic Mean Stress Relaxation
Ref. [8]
Mean Stress/Initial Mean Stress, mpa
Half Cycle No.
1
0.1
1
10
100
1000
"jDSo1.ev01.n" u 1:3
"jDSo1.ev02.n" u 1:3
"jDSo1.ev03.n" u 1:3
"jDSo1.ev04.n" u 1:3
"jDSo1.ev05.n" u 1:3
"jDSo1.ev06.n" u 1:3
"jDSo1b.ev01.n" u 1:3
"jDSo1b.ev02.n" u 1:3
"jDSo1c.ev01.n" u 1:3
"jDSo1c.ev02.n" u 1:3

Data from Wanhua Liang study. Ref.[9]



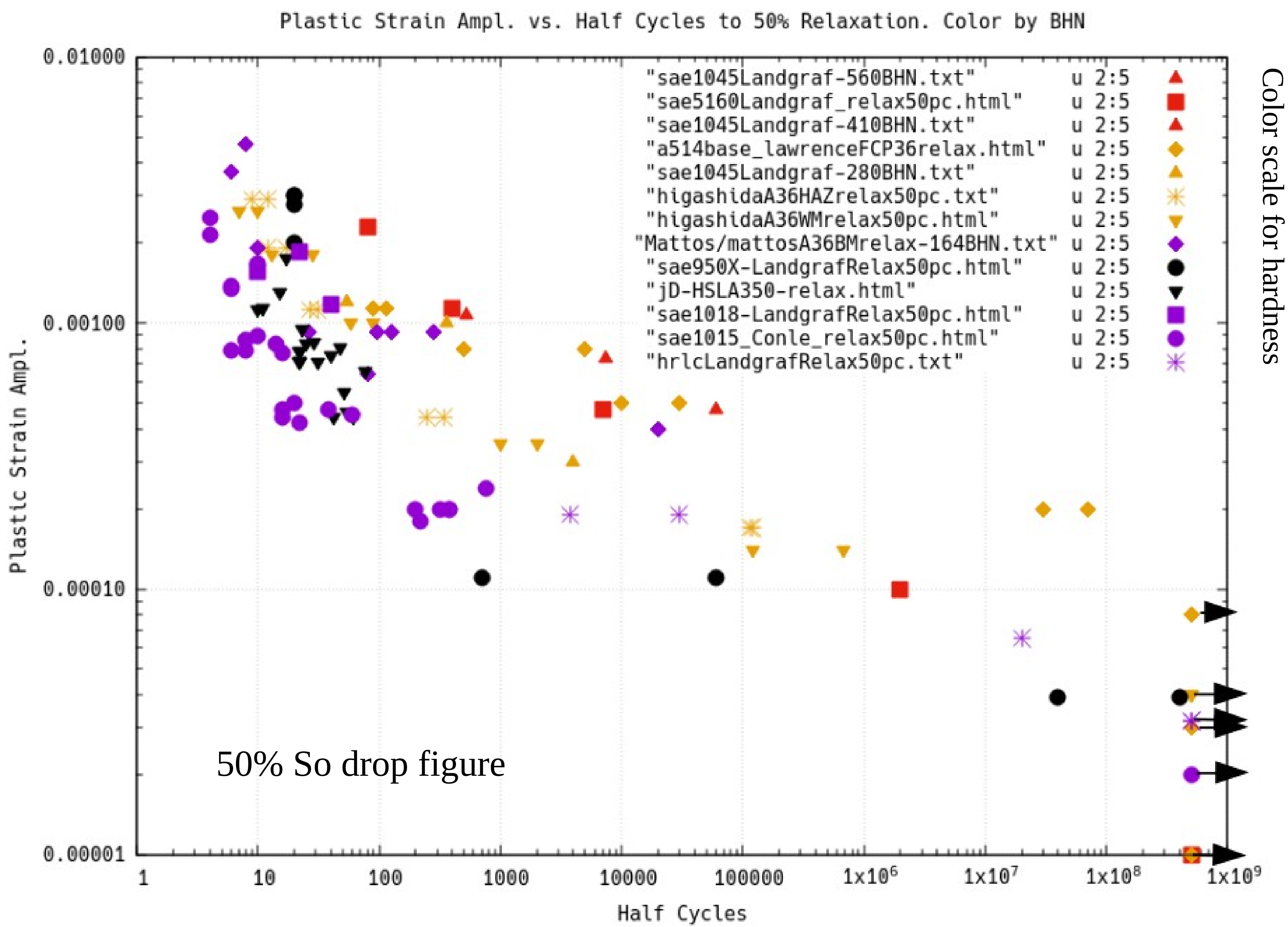


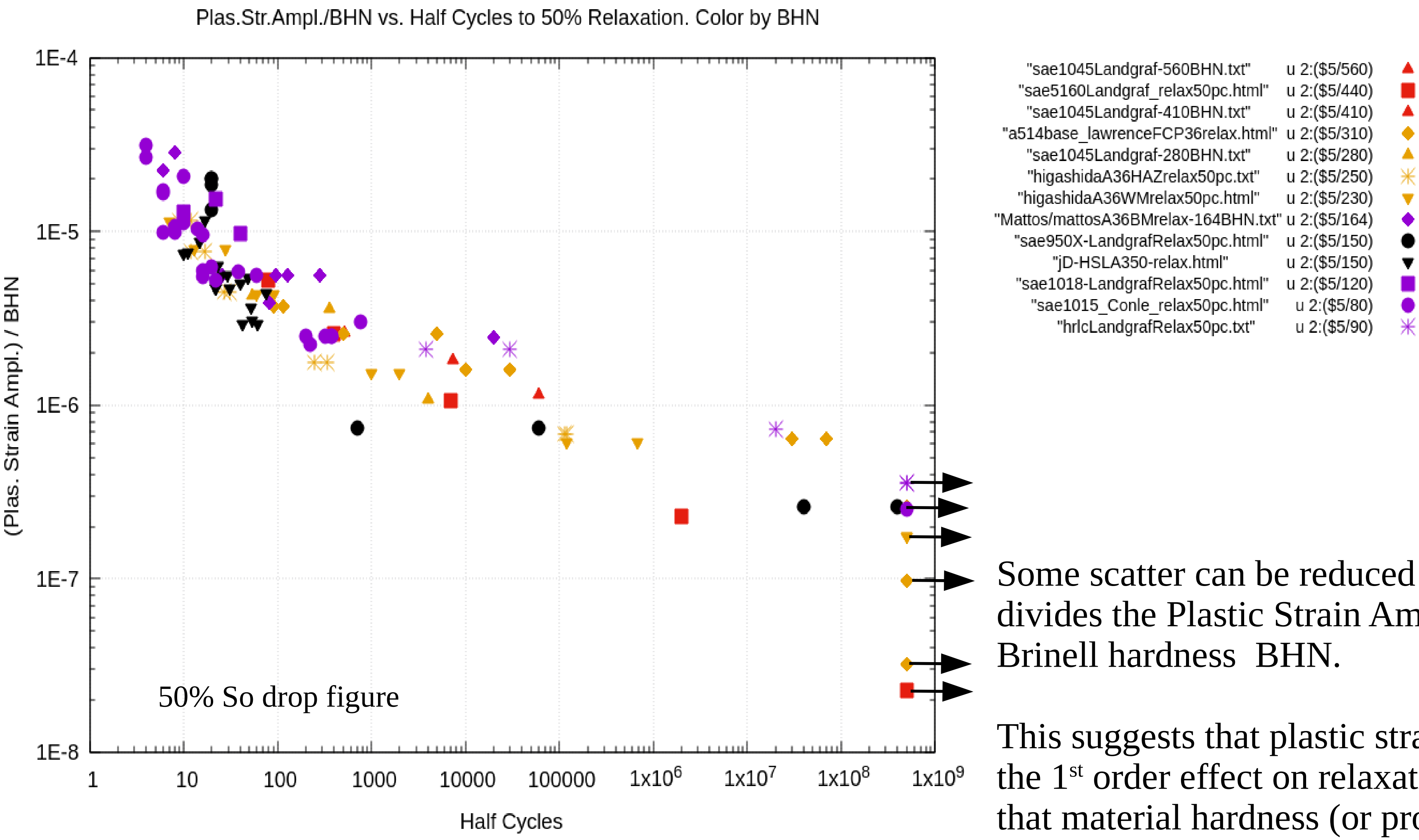
In order to summarize the relaxation rates of the previous plots, when the means stress decreased to 50% of its original value, the reversals up to that point were computed.

Some of the graphs had relaxation lines that did not go to 50% until many half-cycles beyond the plot, so extrapolation was necessary.

In order to normalize between steels of different hardness a plot was made of the plastic strain of stable hysteresis loops versus the 50% relaxation half-cycles.

The result has a lot of scatter partially due to different methods of recording data by different authors, the extrapolation for rate, and the estimation of plastic strain ampl., but the trends can be used to draw conclusions about expected relaxation for fatigue life computation.





Some scatter can be reduced if one divides the Plastic Strain Ampl. by Brinell hardness BHN.

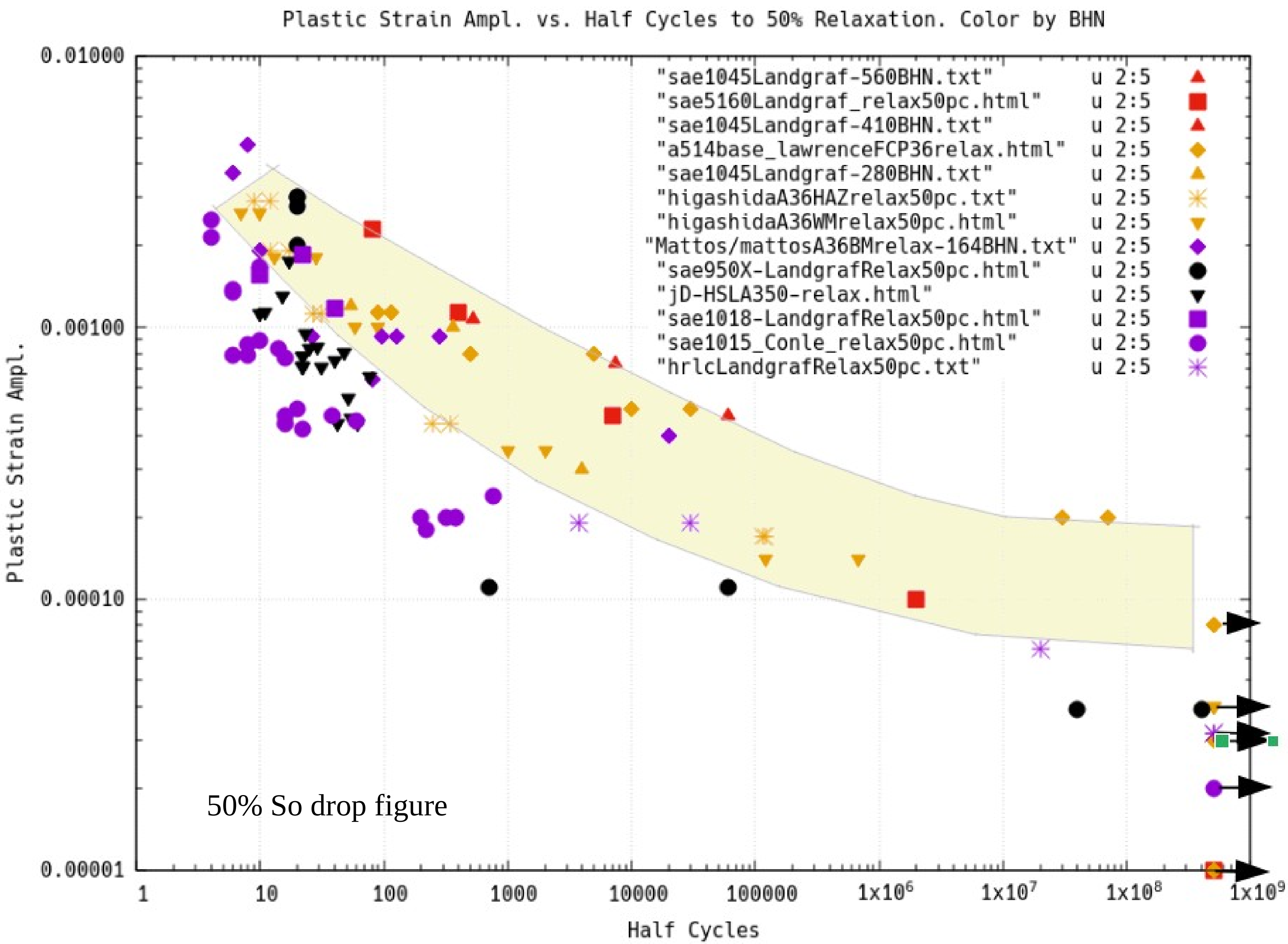
This suggests that plastic strain is the 1st order effect on relaxation and that material hardness (or probably microstructure) is a 2nd order effect.

The plot is usable but the Y axis is not as convenient as simple plastic strain

Slide added July 28 2020

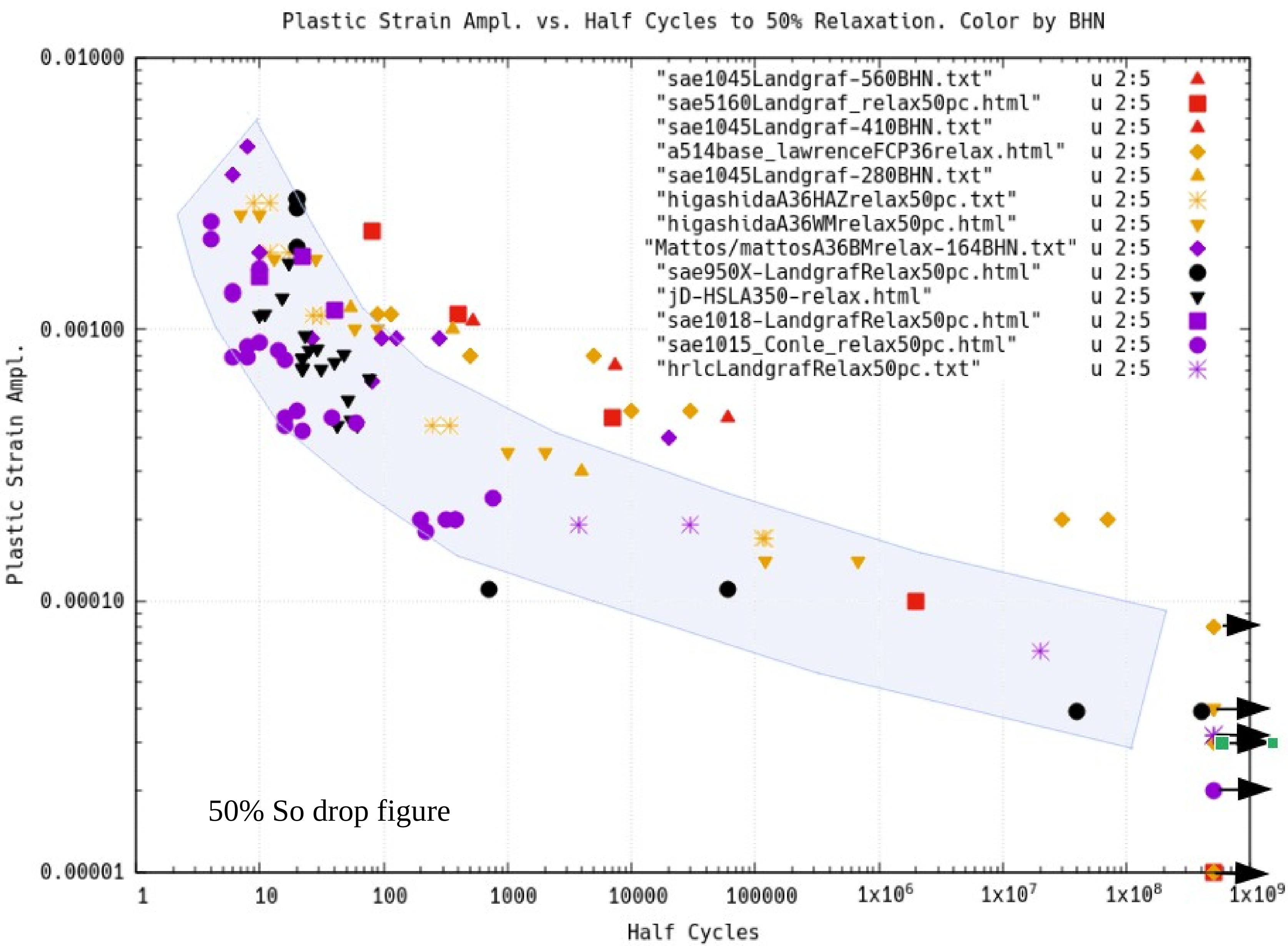
It is easier for estimation purposes to just define two zones

Suggested zone for hard steels



Slide added July 28 2020

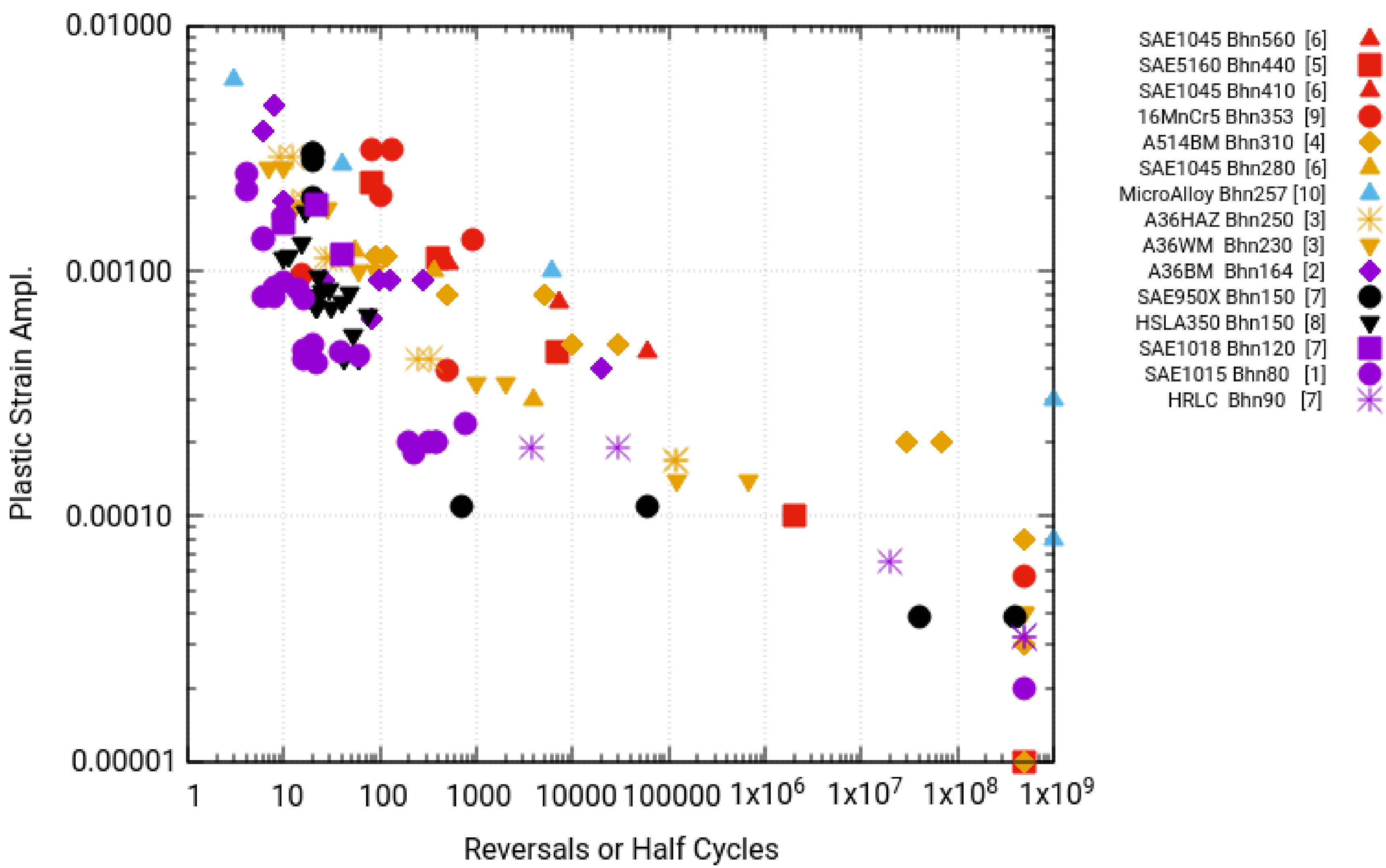
Suggested zone for soft steels



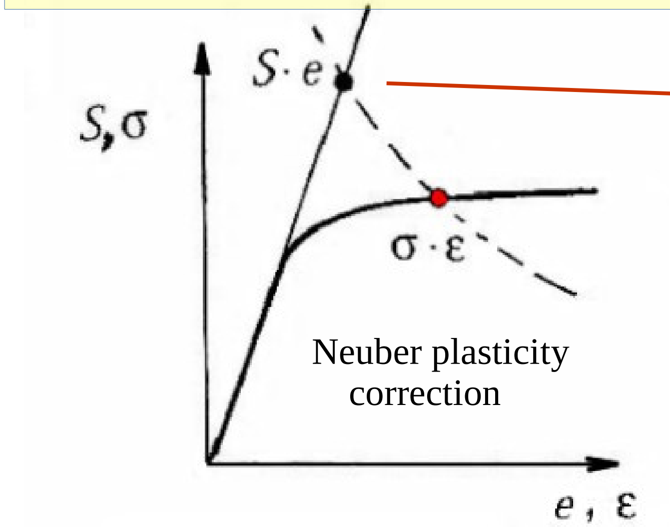
Slide added July 28 2020

Added
Nov 29
2021

It appears that Shot-Peened induced residual stresses may also relax due to fatigue cycling in a similar manner. Below is a data set from Dalaei et al [10] of surface residual stresses measured by XRD during fatigue cycling shown as blue triangle points.



Method of Application :
Find the Plastic Strain amplitude of the Hot-Spot Local Stress-Strain Hysteresis Loop



$$\sigma \cdot \varepsilon = S \cdot e$$

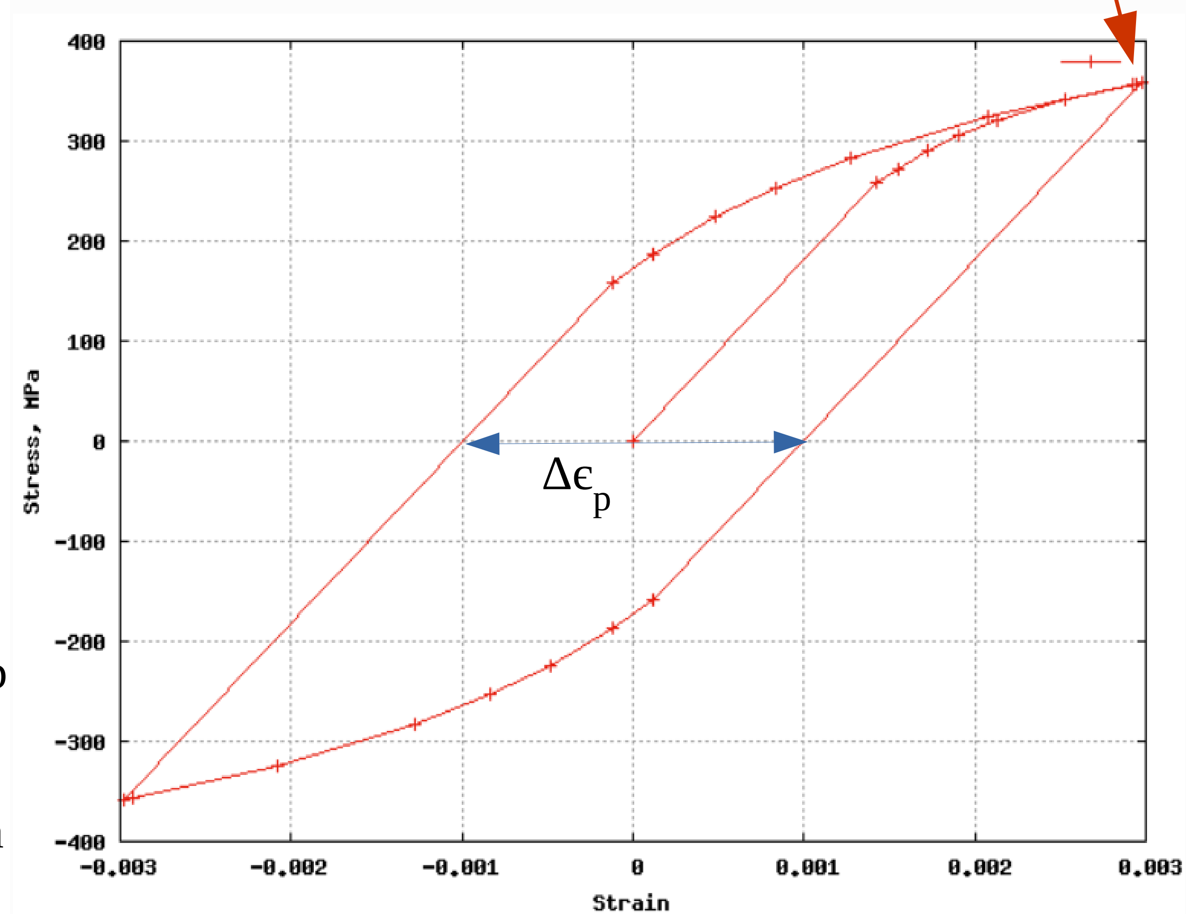
Nominal and Local Stress-Strain:

#xcalc2	Loop	Smax	Smin	N	Sigmax	Sigmin	Delta	Epsmax	Epsmin	DeltaEps
#xcalc2	1	450.0	-450.0	1.0	358.	-358.	717.	0.00298	-.00298	0.00596

Life Predictions (history repetitions):

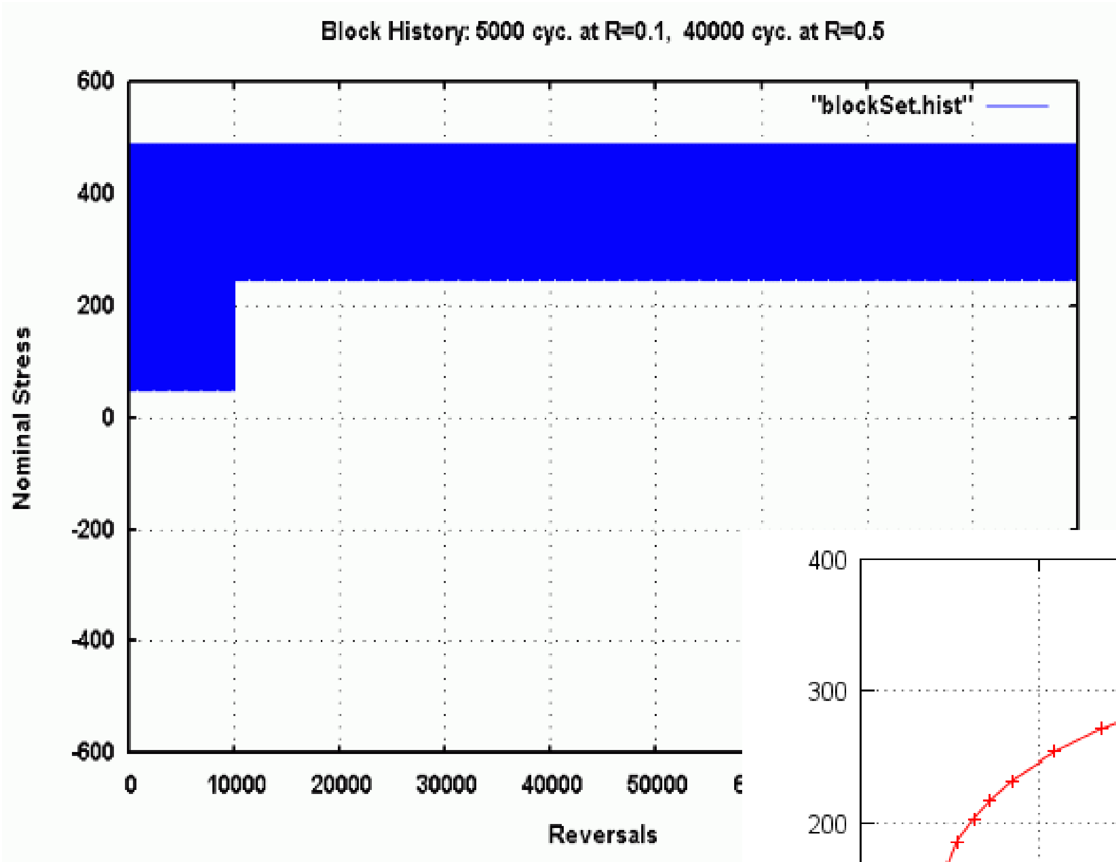
#xcalc3	StrainLife_Reps	SWaT_Life_Reps	StressLife_Reps	Morrow_Reps	Goodman_Reps
#xcalc3	47982.2	47982.1	47982.2	47982.2	47982.2

Local Stress and Strain Response:



Estimate the $\Delta\epsilon_p/2$ of the local stress-strain loops and check 50% drop figure for relaxation

Note that in this case of a loop with So= 0 that all the life predictions are very similar and, since So=0, no relaxation estimate is necessary.



For the F.D.E. block history for example, the initial loading causes a large So in both local loops of the subsequent cycles. One would expect that the larger of these loops would relax its So, but the smaller loop, with little plasticity, would not significantly relax, but would be dragged towards zero by relaxation of the larger loop.

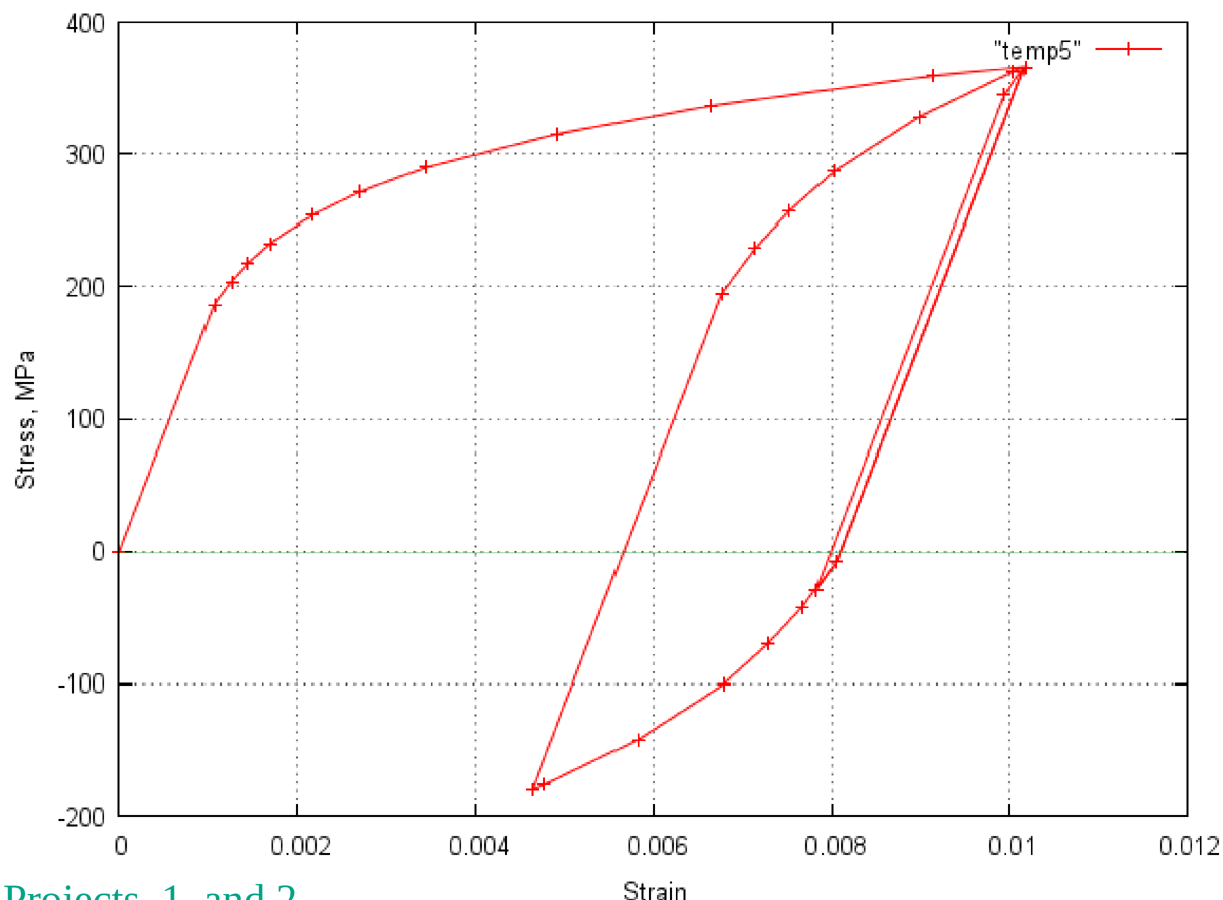
Thus in this case one should **not** correct for mean stress in the fatigue life estimation; at least for the larger loop's damage.

Test total life: 6.9 blks average

Sim.:

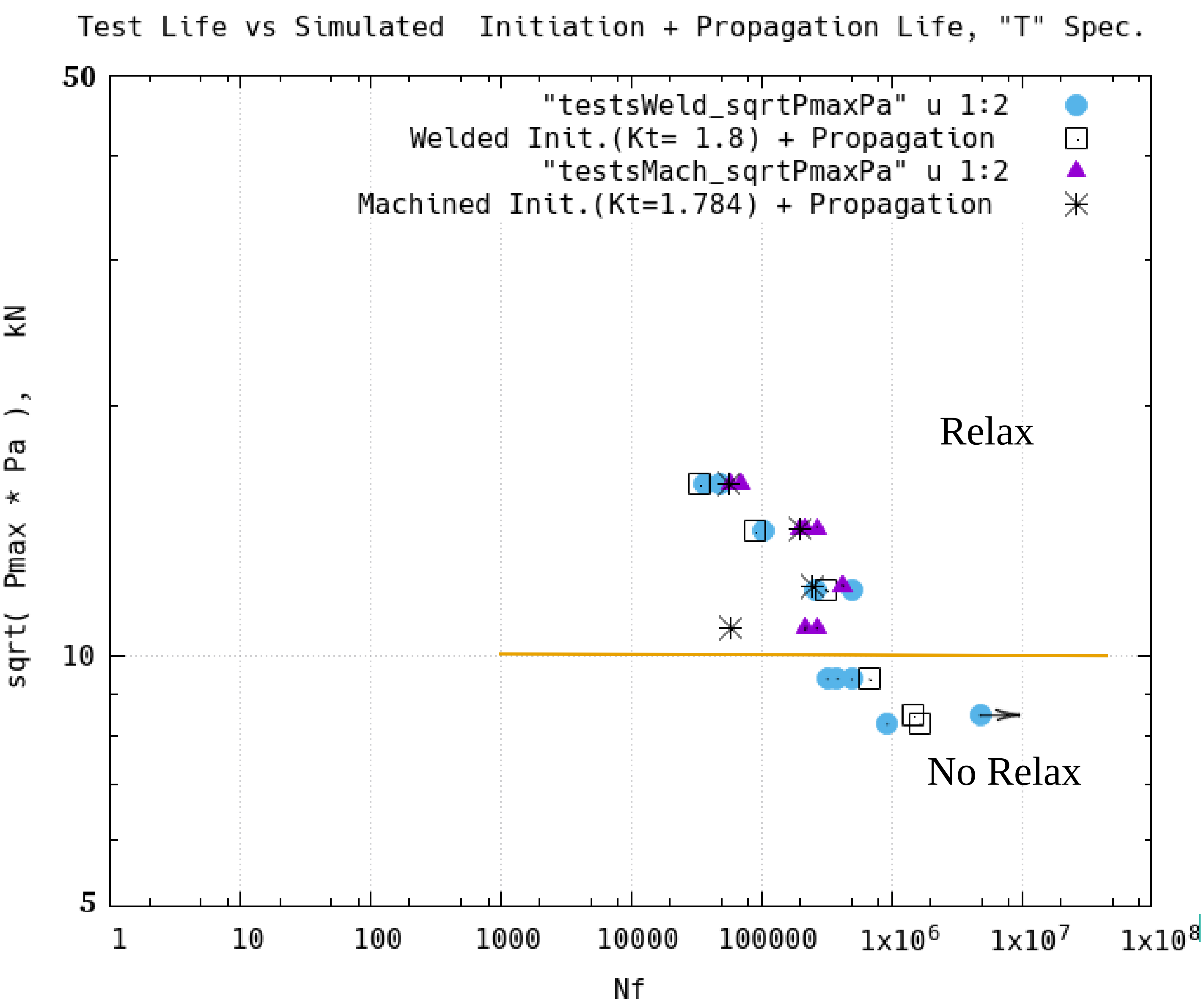
Initiation 7.4 blks
(non-periodic o/s with relaxation)

Propagation <1 blk



For more information see: F.D.E. Total Life Projects 1 and 2
http://fde.uwaterloo.ca/Fde/CaseStudies/casestudies.html

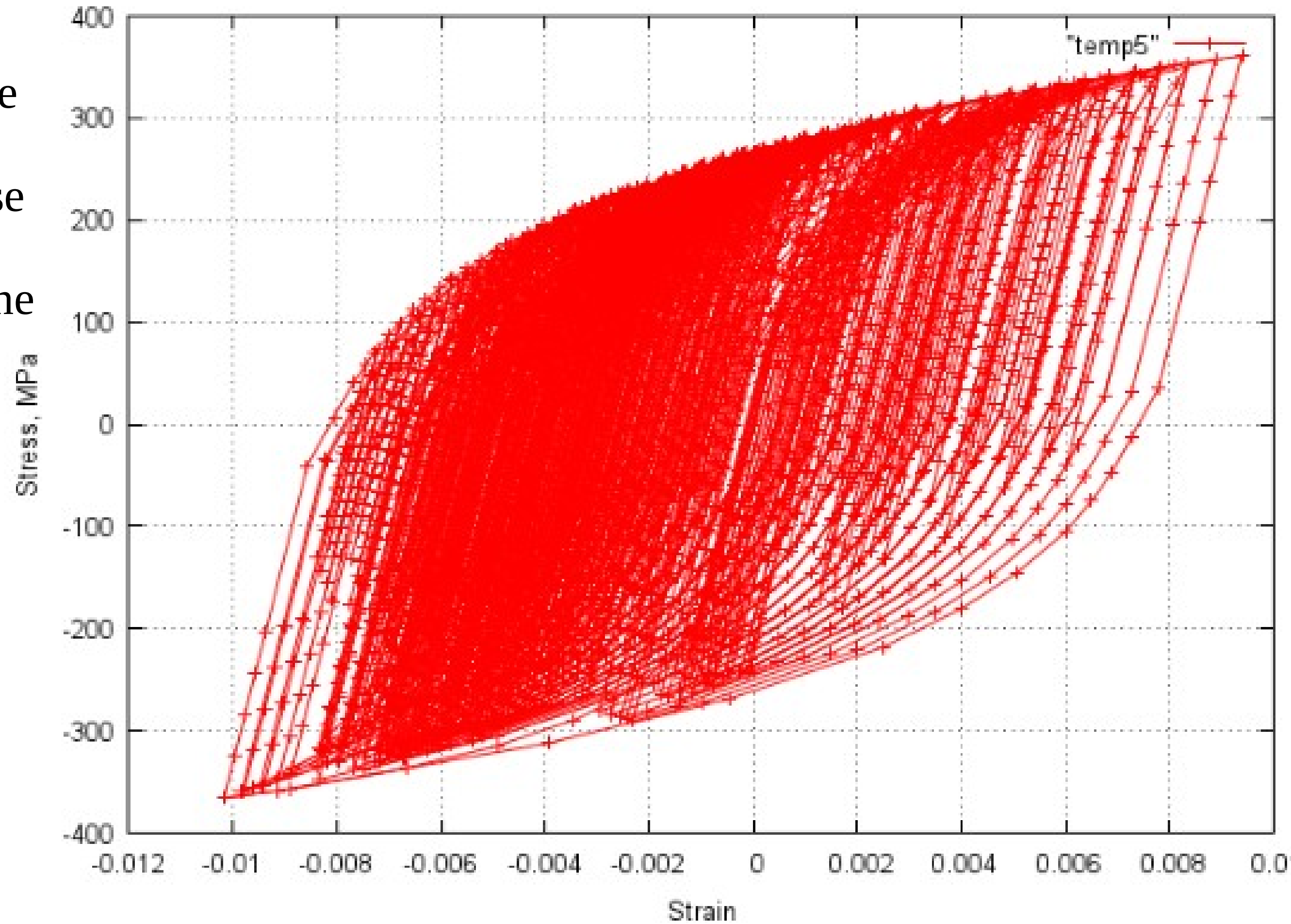
For the F.D.E. Total Life Projects 1 and 2 http://fde.uwaterloo.ca/Fde/CaseStudies/casestudies.html
one can back calculate from the local stresses and strain values to nominal stress levels which will, or will not relax mean stress and, accordingly, require adjustments in the life calculation.
The approximated dividing line is shown in the figure below:



The same process can be applied to variable amplitude histories. A large overall stress-strain loop will enclose many smaller loops. The overall loop will dominate the relaxation process if it has sufficient plasticity.

In this case the overall loop is very large and already with So=0 so no relaxation corrections are needed.

See: F.D.E. Total Life Project 2



Test total life: 28.5 Blocks, average

Simulation:

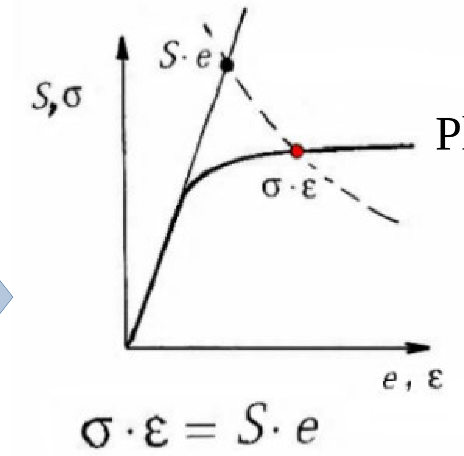
Initiation: 22.3 Blks (with periodic o/s)
Propagation= < 1 Blk.
Total: 22.5 Blks.

Summary of Suggested Process:

Kt

Smax

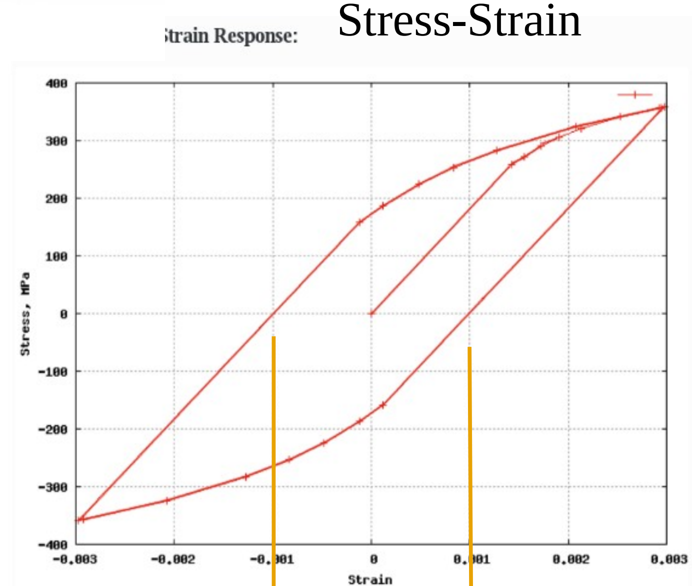
Smin



$$\sigma \cdot \varepsilon = S \cdot e$$

Apply Neuber Plasticity Correction

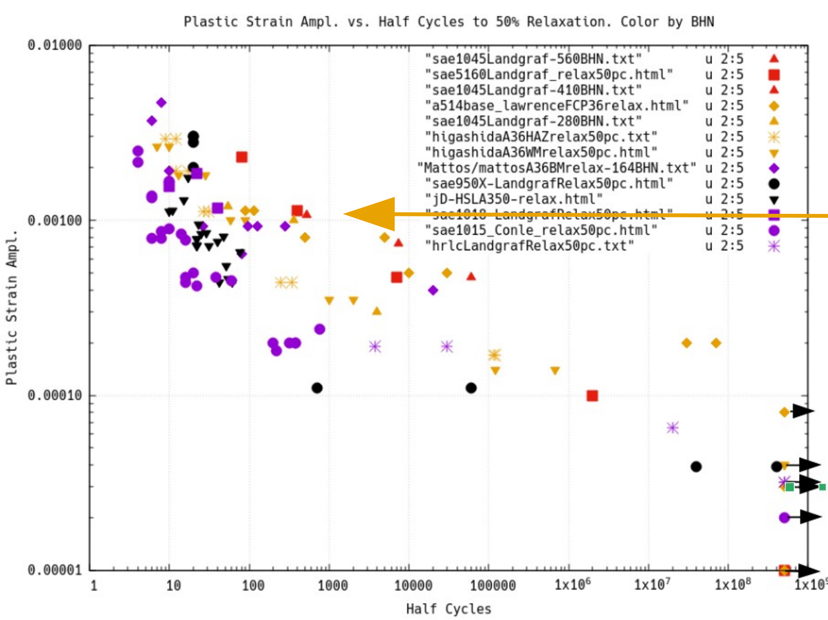
Get Local Stress-Strain



$\Delta\epsilon_p$

$\Delta\epsilon_p /2$

Estimate Plastic Strain Amplitude



Determine if relaxation is expected.

Compute life accordingly.

References:

[1] A. Conle, “Data on Cyclic Mean Stress Relaxation in Mild Steel,” 3A Civil Engr. work term report, U.Waterloo, April, 1970. http://fde.uwaterloo.ca/Fde/Articles/Relax/conleSo.html

[2] R.J. Mattos, F.V. Lawrence, "Estimation of the Fatigue Crack Initiation Life in Welds Using Low Cycle Fatigue Concepts," Fracture Control Rep.19 Univ. of Illinois, Oct. 1975.

[3] Y. Higashida, F.V. Lawrence, “Strain Controlled Fatigue Behavior of Weld Metal and Heat-Affected Base Metal in A36 and A514 Steel Welds,” Fracture Control Report 22, Univ. of Illinois, Aug. 1976

[4] Y. Higashida, J.D. Burk, F.V. Lawrence jr, “Strain -Controlled Fatigue Behavior of ASTM A36 and A514 Grade F Steels and 5083-O Aluminum Weld Materials,” Welding Res. Supplement, Nov. 1978, pp. 334-s,344-s

[5] R.W. Landgraf, R.C. Francis, "Material and Processing Effects on Fatigue Performance of Leaf Springs," SAE Tech. Report 790407, 1979.

[6] R.W. Landgraf, R.A. Chernenkoff, "Residual Stress Effects on Fatigue of Surface Processed Steels," ASTM STP 1004 1988, pp.1-12.

[7] R.W. Landgraf, Prof., Virginia Tech., Personal Communication.

[8] F.A.Conle, “Cyclic mean stress relaxation test results on HSLA-350 steel Material supplied by John Deere, Unpublished work, April 2018.

[9] Wanhua Liang, Personal communication March 2021. Mean stress relaxation in 16MnCr5 steel BHN=353, Part of Ph.D. studies to be published in 2022 U.Waterloo, Dept. Civil & Env. Engr.

[10] K. Dalaei, B. Karlsson, L.-E. Svensson, "Stability of shot peening induced residual stresses and their influence on fatigue lifetime", Materials Sci. and Engr. A v528 2011 pp.1008–1015