“Estimating Changes in Residual Stress due to Fatigue Cycling”

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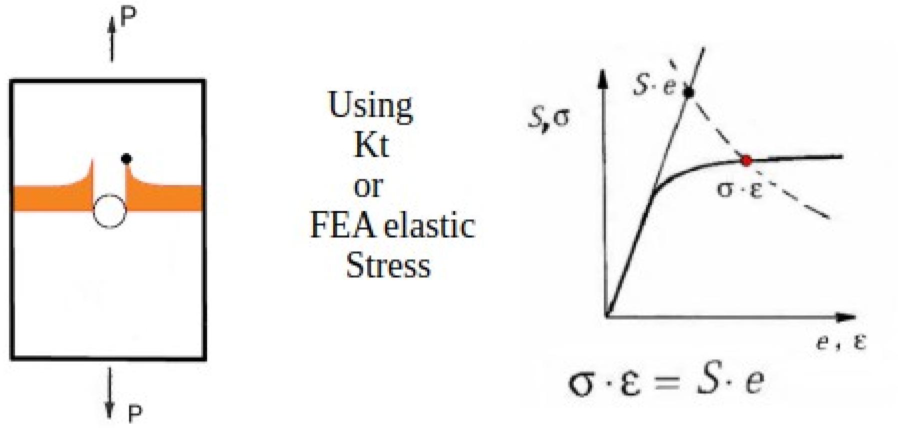
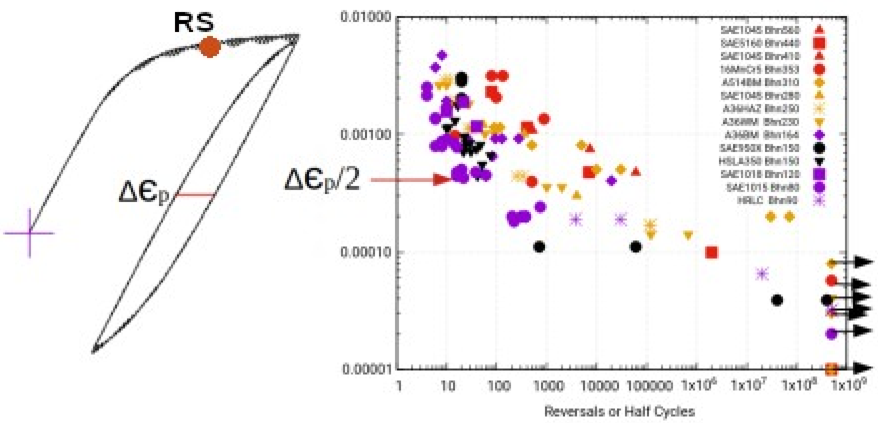
Abstract:





Will an initial Residual Stress be changed due to cyclic mean stress relaxation during fatigue ?

Introduction

Research on changes in residual stress of specimens or components due to cyclic load applications has been documented for a number of decades (e.g.: Refs.[1-4]). The present chapter focuses on how data from cyclic mean stress relaxation fatigue tests can be used to help estimate if the Residual Stress (RS) pattern expected in a fatigue specimen or component will change due to application of cyclic loading in susequent test or service situations.

The basic premise adopted for making such evalutations is that the material behavior at a fatigue “hot-spot” that has an induced RS prior to cycling, will be similar in the mechanism and rate of change, to the cyclic stress-strain behavior of an axial loaded, un-notched specimen subjected to strain limit controlled cycling, which, due to its prior loading history, has a non-zero mean stress in its stress-strain hysteresis loops.
In this article we will first describe the cyclic mean stress relaxation process, then describe how the cyclic stress and strain behaves when confronted with an initial RS, and finally how the data from axial un-notched tests can be used to estimate how or if the initial RS will change during fatigue.

Example of cyclic mean stress relaxation while fatigue cycling between fixed strain limits:

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

Cyclic Mean Stress Relaxation

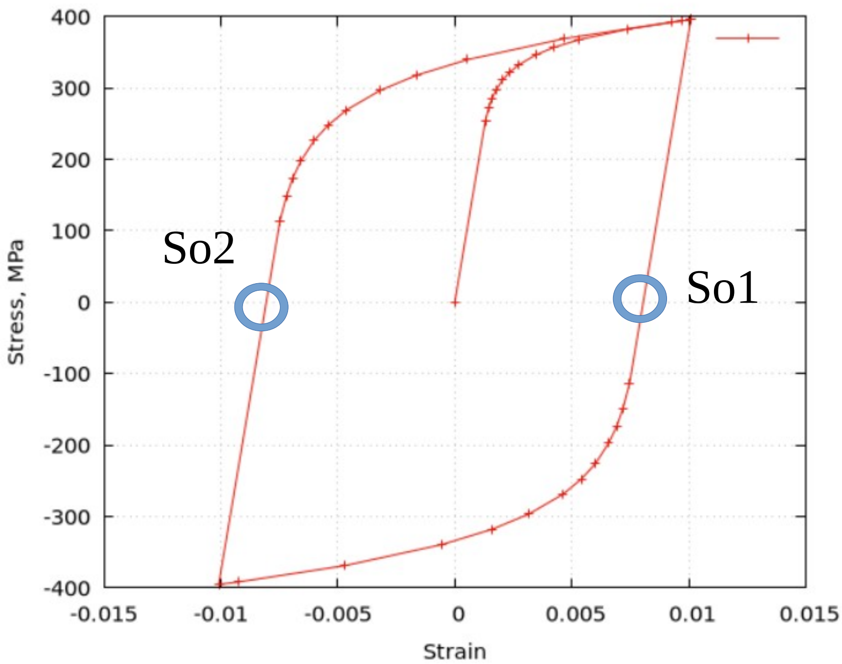
(for a short video of a relaxation test view Ref.[5])

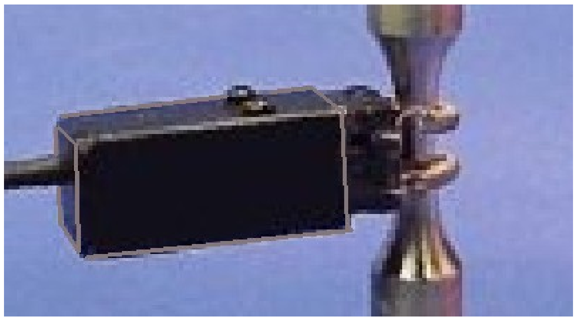
```
#xcalc2 Loop    Smax    Smin          N  Sigmax  Sigmin Delta Epsmax Epsmin DeltaEps  %Eps %SWaT %Sts %Mor
#xcalc2    1   900.0  -900.0         1.0    395.   -395.   791. 0.01009 -.01009 0.02019 100.0 100.0 100.0 10
```

Life Predictions (history repetitions):

```
#xcalc3  StrainLife_Reps SWaT_Life_Reps StressLife_Reps   Morrow_Reps   Goodman_Reps (Reps= Repetions)
#xcalc3       1062.9          1062.9          1062.9          1062.9          1062.9
```

Local Stress and Strain Response:





When a specimen without any RS is cycled in a fully reversed condition, as displayed in the stress-train path in Fig.1, it is to be expected that the mean stress So =(Smax + Smin)/2 will be close to zero stress. In Fig.1 each side of the hysteresis loop has a mid-point stress of So=(400+(-400))/2 = 0 mpa. The stress-strain path shown inf Fig.1 was generated from a on-line computer cyclic deformation model using a merge of three data sets for HSLA-350 strain life fatigue (see Ref.[6]). In the model the initial loading to a strain of 0.01 uses the cyclic stress-strain curve (ASTM-E606) and the two “arms” or “half cycles” of the hysteresis loop traversing from strains +0.01 to -0.01 and back to +0.01 have a shape that is a double of the initial cyclic stress-strain curve.

#MagFactor= 1.0 # Enter your Strain Reversal Points:

0.005 | 0.008 | 0.002 | 0.008

Click here

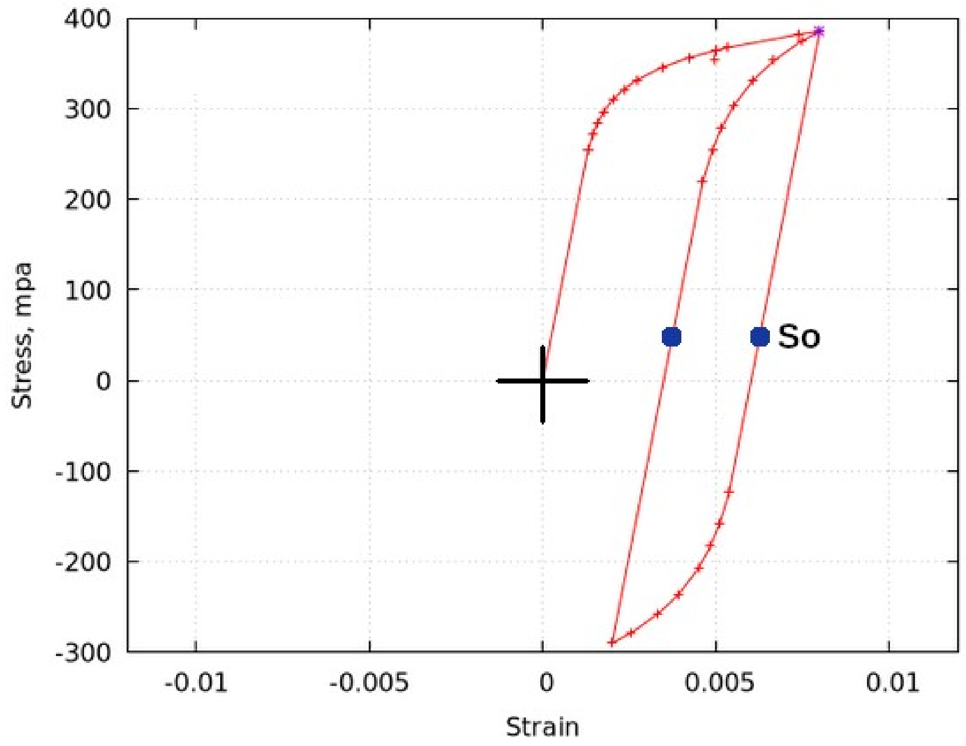


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Fig. 2 Simulated stress-strain path during straining from 0.0 to 0.008 to 0.002 to 0.008 HSLA-350 (without any relaxation) Modelled using Ref.[7]

Figure 2 shows a simulation of the stress-strain path of an un-notched axial specimen subjected to cyclic limits of 0.008 and 0.002 strain. The simulation uses the stable cyclic stress-strain curve for the shape of the initial loading from zero, with subsequent half-cycles having the shape of the doubled cyclic stress-strain curve.

Because of the non-zero mean stress of the hysteresis loop the path from 0.002 to 0.008 (left side of loop) would not actually return to the top as shown. A test with real material using similar strain limits is shown in Fig.3: The tips of the hysteresis loop change during fatigue cycling until the hysteresis loop's mean stress (So) is near zero stress, as shown in the figure.

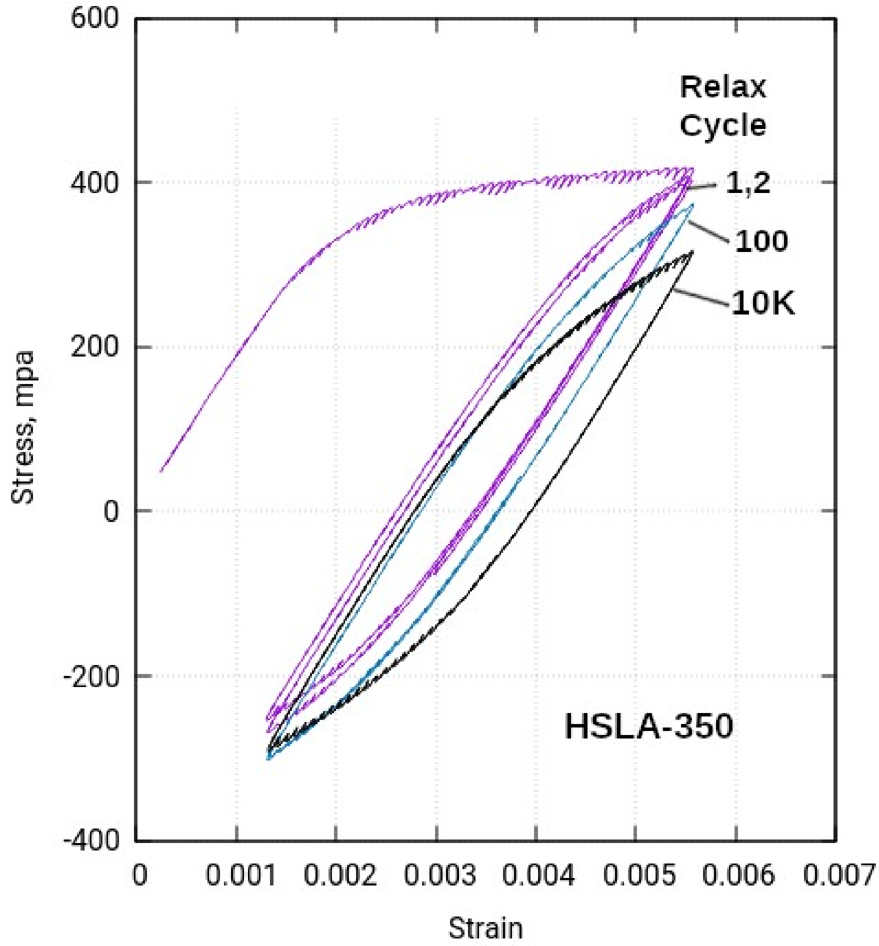

Fig.3 Cyclic stress-strain relaxation during repeated fatigue cycling of an un-notched axial specimen

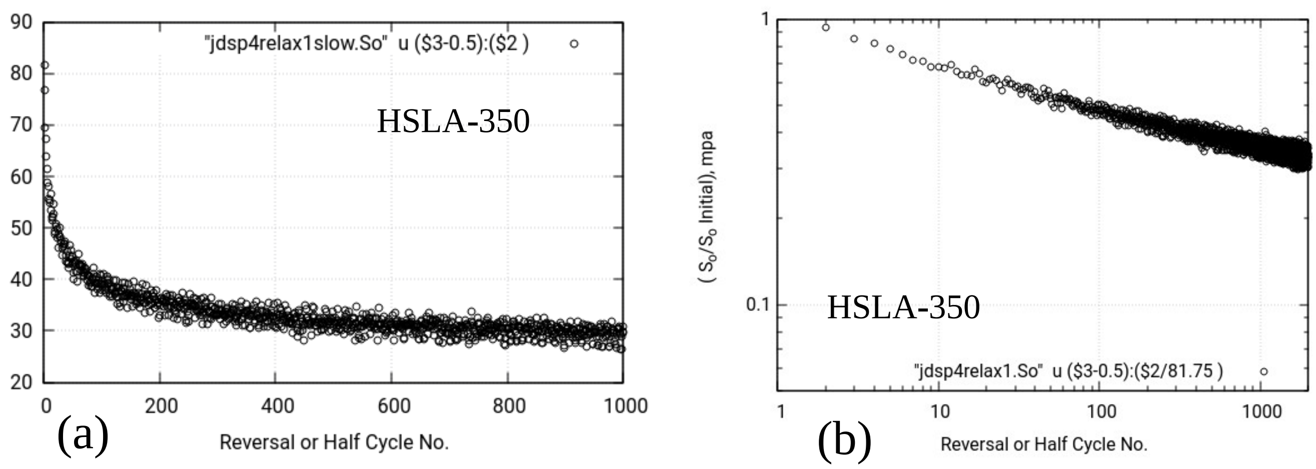

Fig.4 Cyclic So1 and So2 relaxation during repeated fatigue cycling of an un-notched axial specimen. Same test as shown in Fig.3

One can plot the change in the So of each half cycle as shown in a linear plot of Fig. 4(a). If one uses log-log co-ordinates, as shown for the same data in Fig.4(b), the mean stress points appear to approach a straight line.

Fig. 5 shows multiple test results for this type of cyclic relaxation in a normalied SAE1015 steel (data from Ref.3). As indicated by the total strain range for each line, the rate of relaxation increases with increased strain range.

The plots can be normalized arithmetically by dividing the cyclic So values by the first half cycle's mean stress So_Init and the data of Fig 5 is re-plotted in Fig.6. Also shown in this normalized plot is a line that represents a 50% drop in the So. The rate of drop for a wide variety of steels (data collection described in Refs.[8,9]) is primarily dependent upon the width of the stress-strain hysteresis loop i.e.: the plastic strain. Figures 7(a) and (b) show the data collected from various studies with a plot of plastic strain amplitude, $\Delta\varepsilon_p/2$ versus the number of half-cycles (or reversals) it takes to reduce the hysteresis loop's mean stress to 50% of the first half-cycle's mean stress.

There is considerable scatter in these plots primarily due to the assumptions needed to account for missing information of the various reseach studies. Values such as elastic modulus, cyclic hardening/softening, cyclic stress-strain curves were not always reported in the studies; also for tests with low relaxation rates the straight log-log lines of the test data had to be extrapolated to intersect with the 50% drop line. Many of the reported test data sets were terminated around 1000 cycles hence extrapolations probably caused additional scatter.

The two figures 7(a,b) are the primary indicators of the rate, if any, of cyclic relaxation of mean stress, and by analogy of the relaxation of any initial residual stress state.

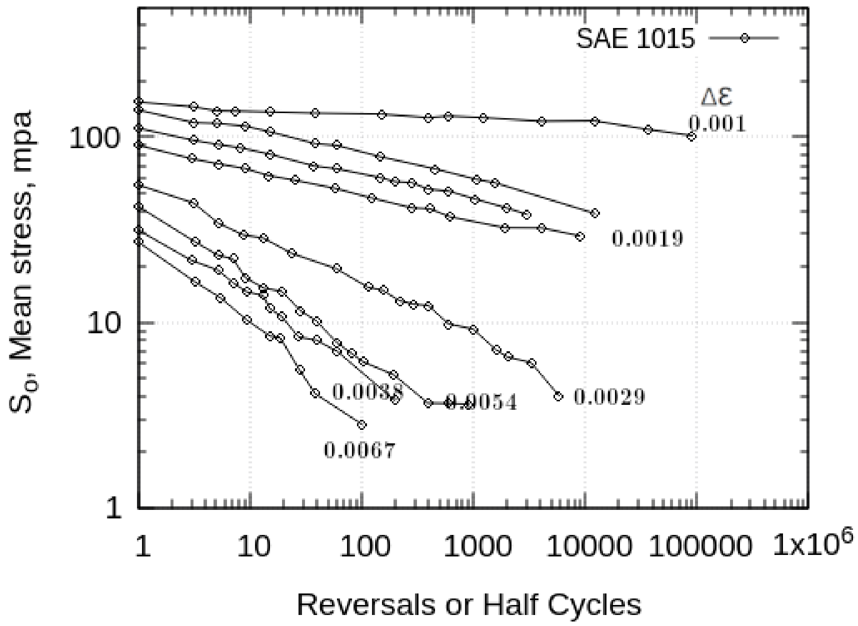

Fig. 5 Cyclic mean stress relaxation test data from strain control tests with un-notched axial SAE 1015 steel. Ref. [xx]

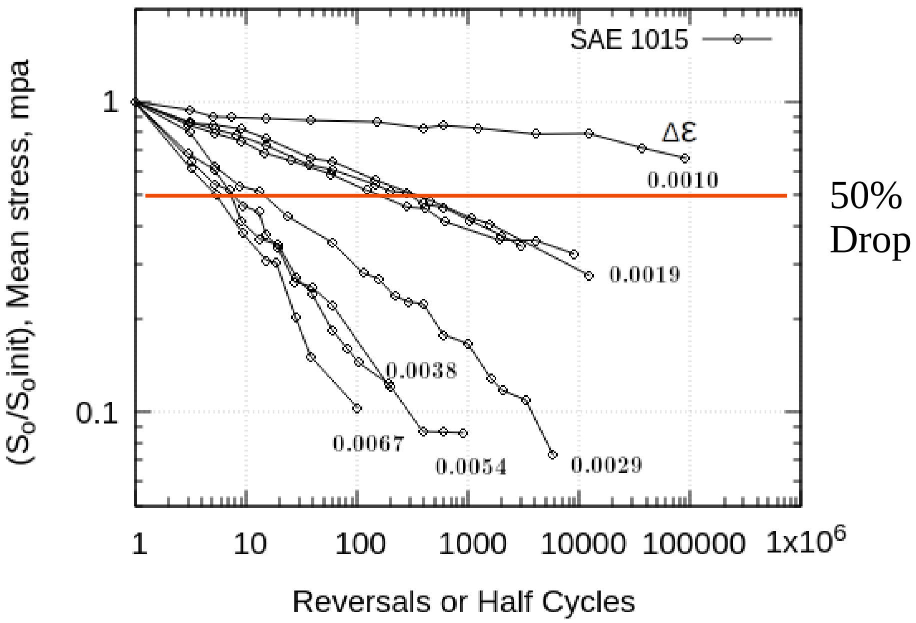

Fig.6 Data from Fig.5 normalized by division of So by the initial So.

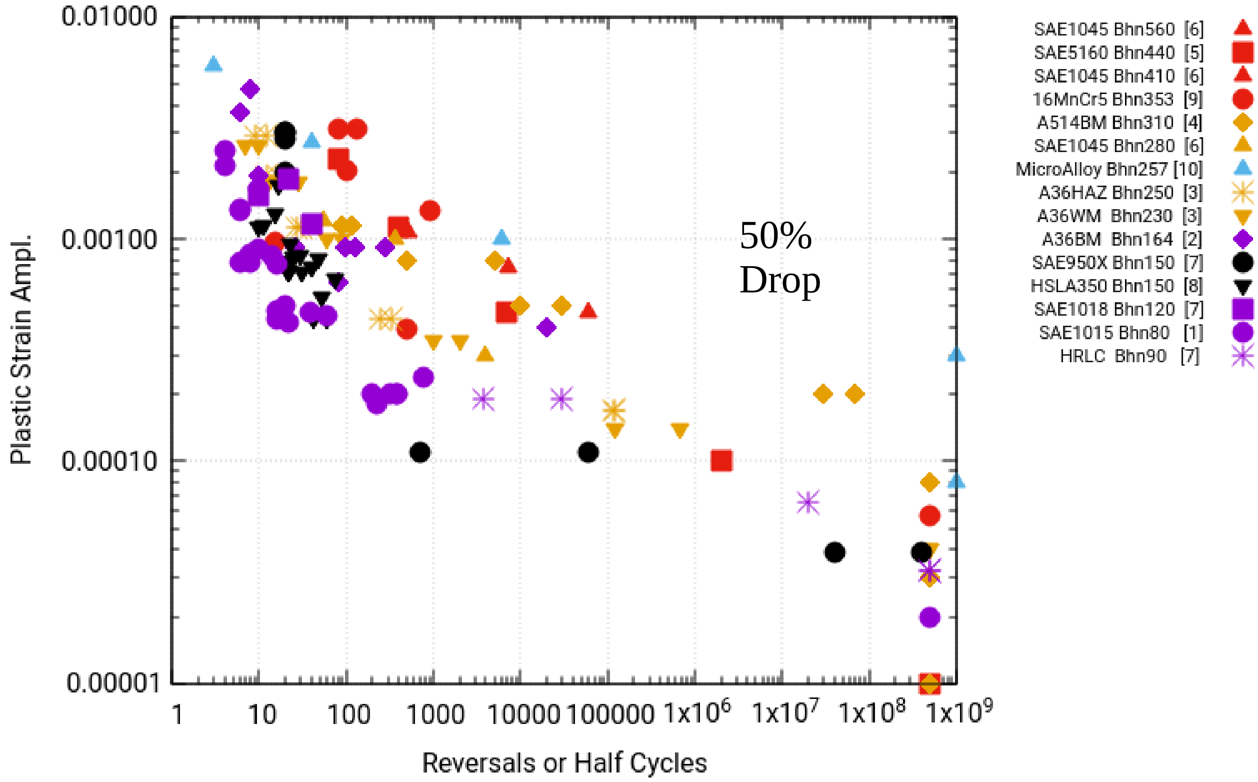

Fig.7(a) Number of fatigue reversals required to drop the mean stress to 50% of its initial value for various stress-strain hysteresis loop plastic strain amplitudes from a steels of different hardness.

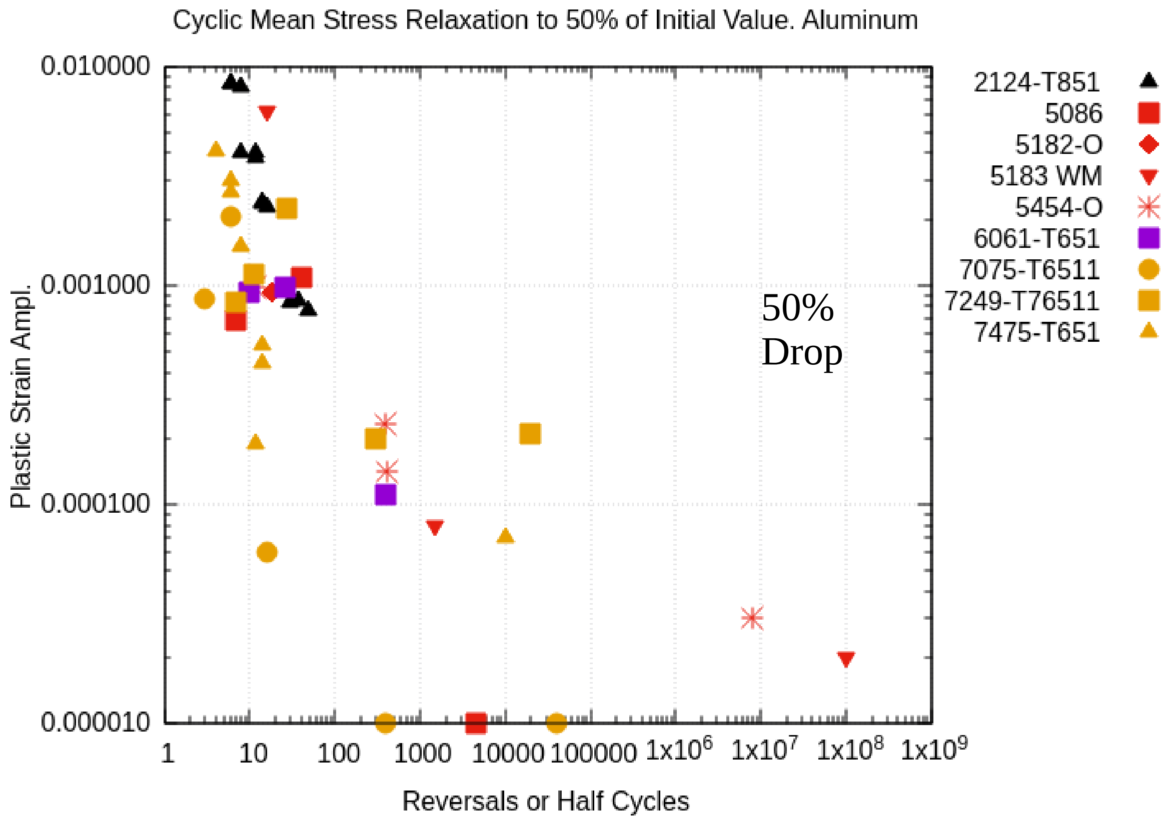

Fig.7(b) Number of fatigue reversals required to drop the mean stress to 50% of its initial value for various stress-strain hysteresis loop plastic strain amplitudes from a variety of aluminum tests.

Residual Stress Relaxation During Fatigue Cycling

It is assumed in this study that an initial RS induced by processing will change due to fatigue cycling in the same way that the above cyclic mean stress relaxation occurs. References [10] and [11] have shown this to be correct in their study of the changes in RS, as measured by xray diffraction (XRD) methods, for residual stresses induced by multi-pass welding of an A36 component which is then subjected to fatigue loading.

The following figures are used to show what probably happens to the fatigue hot-spot stress-strain paths when one starts cycling from an initial RS state of stress.

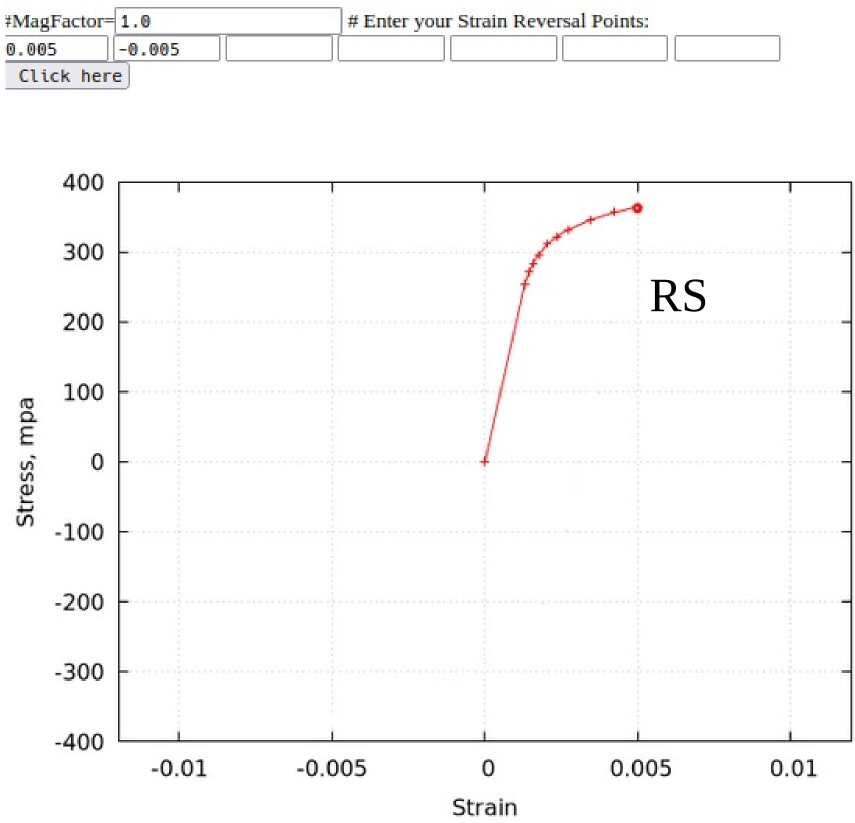

Fig. 8 An assumed Resitudal Stress state in an HSLA-350 un-notched axial specimen.

Figure 8 shows a red dot at the end of an assumed stress-strain path that represents an initial RS induced by some deformation or metallurgical process. The path in the figure is for an HSLA-350 steel’s cyclic stress-strain curve (Ref.[7]).
At this RS point of ~370mpa and 0.005 strain one can now add cyclic fatigue loading and observe the stress-strain results.

#MagFactor= 1.0 # Enter your Strain Reversal Points:

0.005 0.0065 0.0035 0.0065

Click here

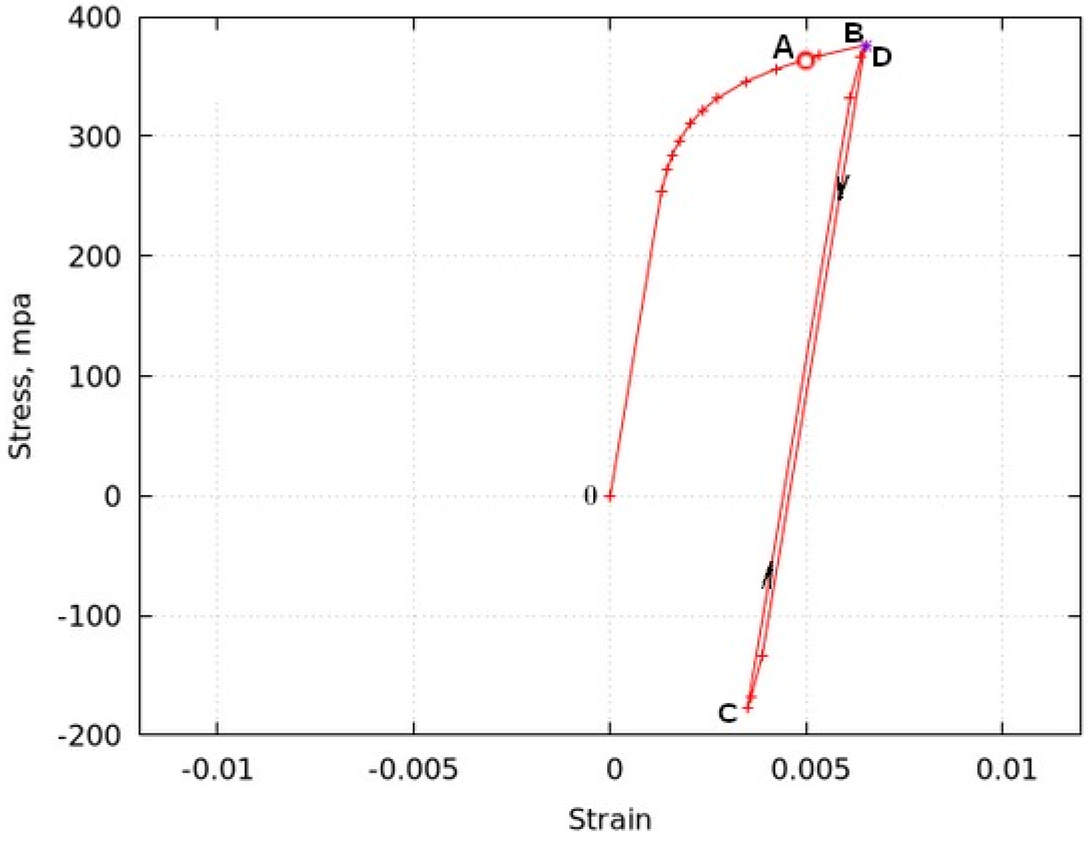

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Fig.9 Cyclic straining added to the RS state of Fig.8. Specifically a cycle between strain limits of 0.0065 and 0.0035.

In Fig.9 the stress-strain locus will move from RS at “A” to point “B” then unload to point “C” and reload to point “D”. The width of the stress-strain hysteresis loop is very small indicating mostly elastic deformation i.e.: the plastic strain amplitude of the loop is near zero. Reffering to Fig.7 one enters the plot on the “Y” axis and observes that the cycles required to obtain a 50% drop of So is close to 10**9, thus one would not expect the fatigue loading of Fig.9 to cause any cyclic mean stress relaxation. This does not mean that the RS state has not changed. The RS state at the end of cycling depends upon where in the A-B-C-D stress-strain path the fatigue loading is terminated. If the loading ends at point “D” one would be back to nearly the same stress as the initial RS state.

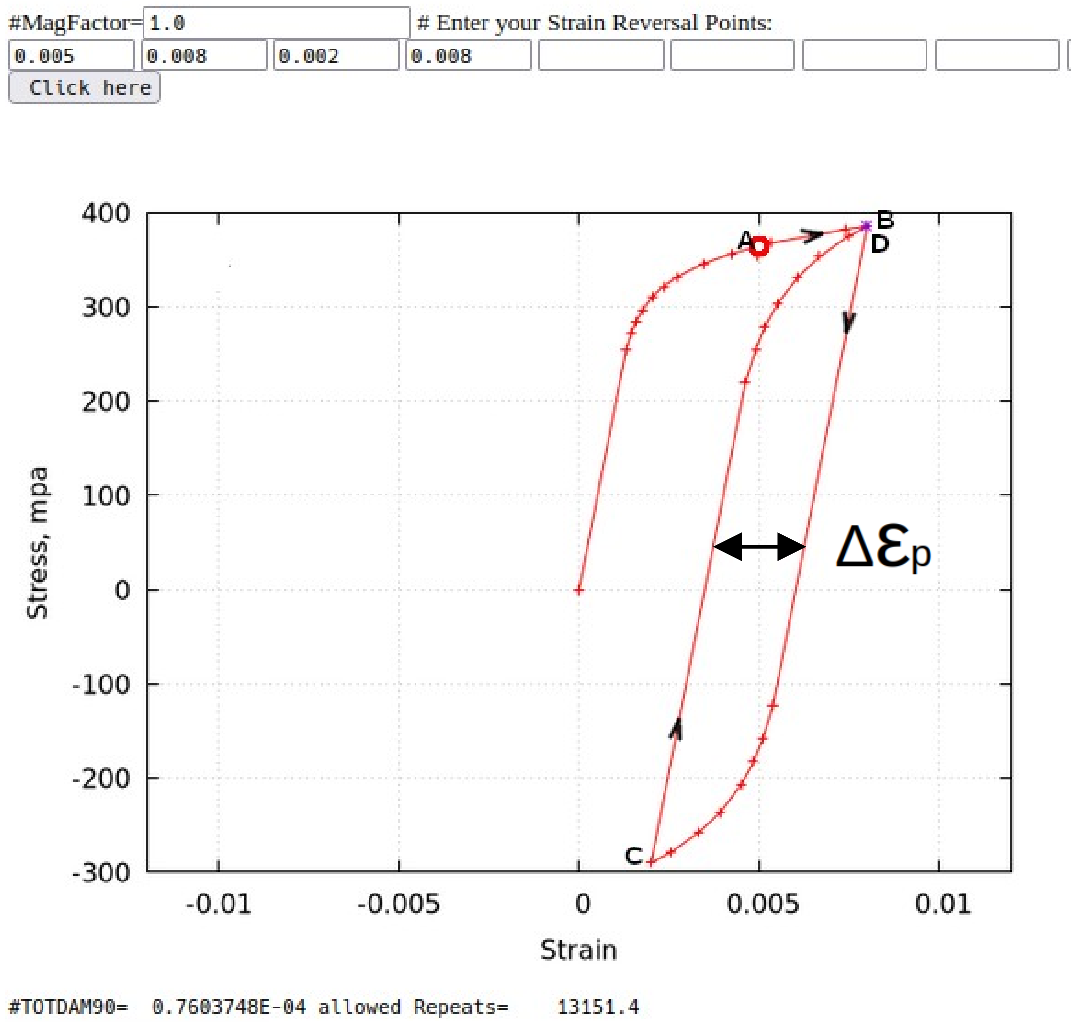


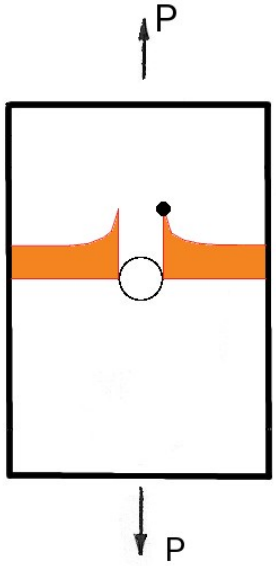
Fig.10 Cyclic straining added to the RS state of Fig.8. Specifically a cycle between strain limits of 0.008 and 0.002.

If one increases the strain limits of the “A-B-C-D” sequence to limits of 0.008 and 0.002 strain(Fig.10), the consequent stress-strain hysteresis loop will exhibit a much larger plastic strain range $\Delta\varepsilon_p$ (in this case 0.0025). Dividing by two to obtain amplitude one can again enter Fig.7(a) plot’s Y axis and determine that the cyclic mean stress of this stress-strain hysteresis loop would relax to 50% of its starting mean stress after from 10 to 1000 reversals (5 to 500 cycles) are applied. This indicates that the mean stress, and thereby its initial RS would change considerably due to the fatigue cycles.

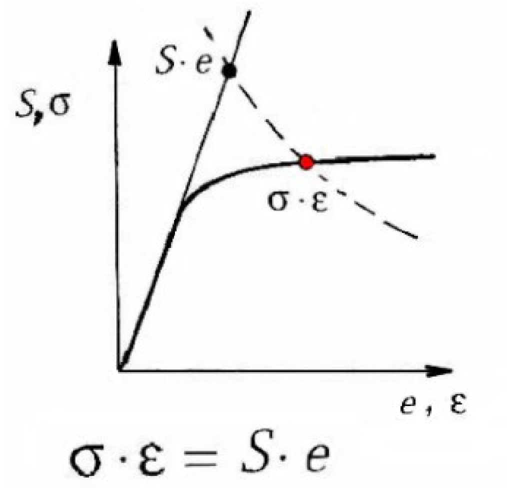
Without cyclic relaxation the projected life of this test would be about 13K cycles. If there were no initial RS and one applied the same strain range cycles the projected life would be about 19K cycles. Due to the expected relaxation the projected life for a specimen with the initial RS followed by relaxation to 50% So would be somewhere between these two values, and if needed some sort of fractional calculation could be used.

Residual Stress Changes at Stress Raisers

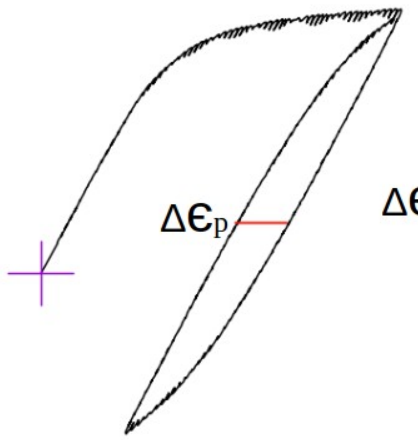
The above process for estimating RS change can be extended to fatigue of notches and other stress-raisers by adding plasticity correction to nominal loading of notches in order to compute the expected stress-strain paths at the fatigue "hot-spot".

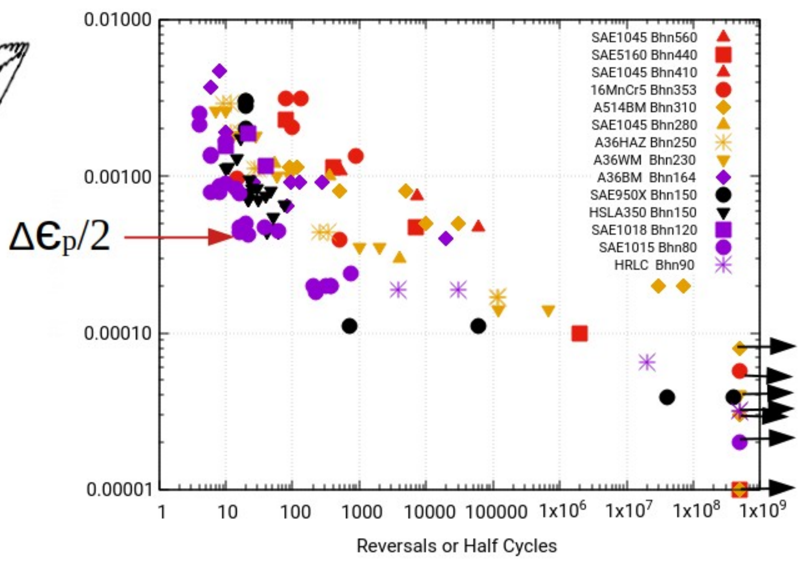


Using
Kt
or
FEA elastic
Stress



1. Transform the loading sequence and elastic local stress analysis using a Neuber[xx] type plasticity correction to determine the hot-spot stress-strain path. e.g.: using calculator at Ref.[12]





2. Estimate the width of the local stress-strain hysteresis loop, and, using the plastic strain amplitude, estimate the number of reversals or cycles to reduce the mean stress by 50%

3. Decide if RS relaxation will occur in your service fatigue history and compute expected fatigue life either with or without the mean stress.

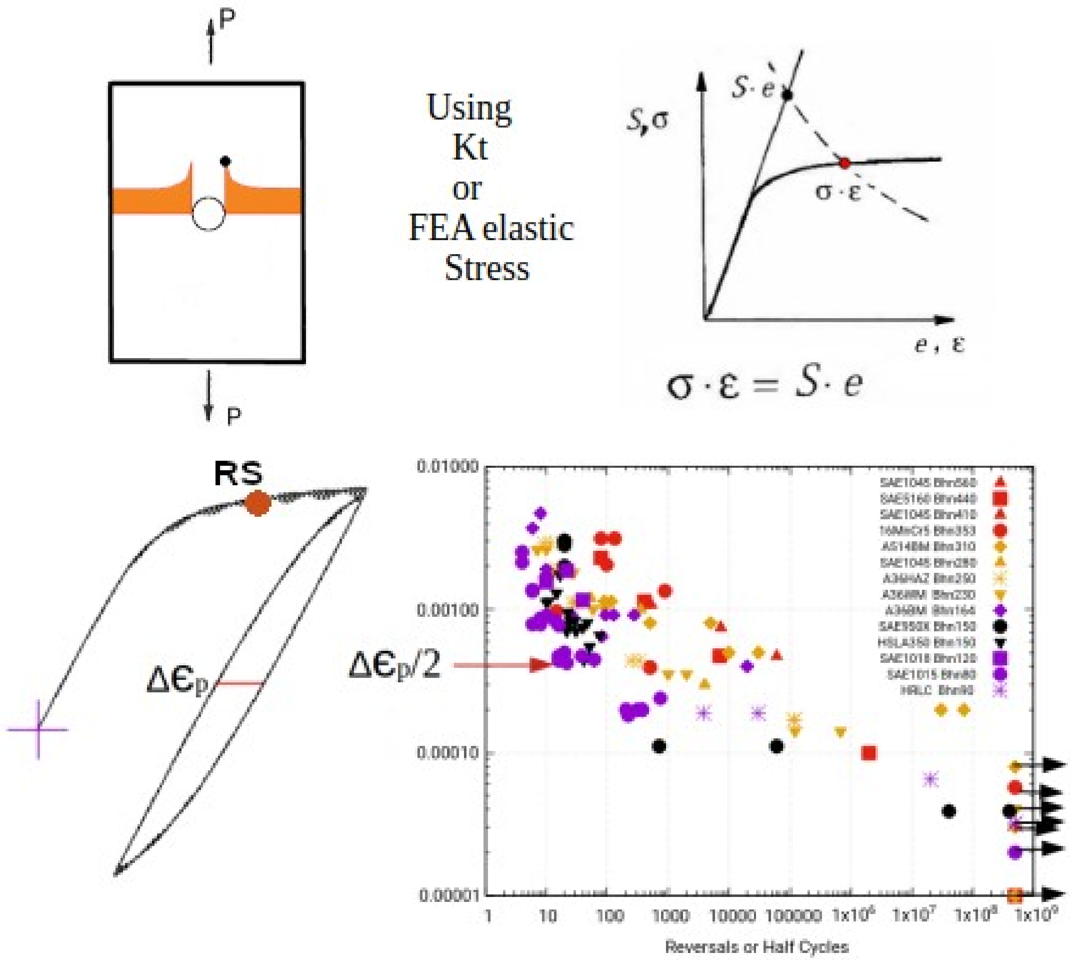
Summary

References [10] and [11] have indicated that measurements of cyclic mean stress relaxation in steels can be used to estimate the changes in the initial residual stress state of welded components.

The present article, based on this observation, describes a method that can be used generally to determine if a particular fatigue loading condition will relax initial residual stresses.

The process consists of:

1. Determine the size of the hot-spot stress-strain hysteresis loop; specifically the plastic strain of such a loop.
2. Using the compiled data of Refs.[8] for steels or Ref.[9] for aluminums, use the plastic strain amplitude of the loop to determine the number of reversals (or cycles) needed to reduce the cyclic mean stress to 50% of the initial mean stress.
3. Adjust the fatigue damage calculations(predictions) according to this expected change. Damage calculations with and without mean stress are described here:
https://fde.uwaterloo.ca/FatigueClass/Chap8Damage/chap8damagePt-2.pdf



References

[1] Wallace, W.P. and Frankel, J.P., “Relief of Residual Stress by a Single Fatigue Cycle,” Welding Journal 38 (Nov.1949): 565s.

[2] Morrow, J. and Sinclair, G.M., “Cyclic Dependent Stress Relaxation,” Symp. on Basic Mechanisms of Fatigue, ASTM STP 237 (1958): 83-101.

[3] 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

[4] Holzapfel, H., Schulze, V., Vöhringer, O., and Macherauch, E., “Residual Stress Relaxation in an AISI 4140 Steel Due to Quasistatic and Cyclic Loading at Higher Temperatures,” Materials Science and Engineering A248 (1998): 9-18.

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

[6] From F.D.E. database: HSLA-350(SAE950X) https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/saeHSLA.html Specifically: https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/Merged950X/merged3_SAE950X.html

[7] FDE database: Stress-Strain Model, Merged 3 files of HSLA-350 https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/Merged950X/merged3_SAE950X_sim.html

[8] A. Conle, “A Collection of Cyclic Mean Stress Relaxation Data,” F.D.E. 2019 Spring Meeting, Cobo Hall, Detroit. https://fde.uwaterloo.ca/Fde/Articles/fde2019RelaxPres4Web.pdf

[9] F.A. Conle and R.W. Landgraf, " A Collection of Aluminum Cyclic Mean Stress Relaxation Data", Prepared for Fatigue Design and Evaluation Committee, Aug. 20 2022 https://fde.uwaterloo.ca/Fde/Articles/relaxAlumPres-Nov2022-4web.pdf

[10] Pineault, J., Gales, C., and Conle, A., “Evolution and Redistribution of Residual Stress in Welded Plates During Fatigue Loading,” SAE Technical Paper 2022-01-0257, 2022, doi:10.4271/2022-01-0257.

[11] C.Gales et al, "Relaxation of Residual Stress in Welded Plates During Long Life Fatigue Loading", To be submitted to Int.J.Fat. Initially presented by C.Gales at Int.Conf.Fatigue-15, Atlanta, USA, June 12 2023

[12] FDE database HSLA-350 Stress-Strain and Fatigue Life Calculator
https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/Merged950X/merged3_SAE950X_fc.html