RELAXATION OF RESIDUAL STRESSES DURING CYCLIC LOADING

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ABSTRACT

In annealed, normalized or stress free materials a build-up of residual stress may take place in the surface due to fatigue loading. The residual stress state may however vary during the fatigue process, changing between tensile and compressive values.

Shot peened components have mostly fatigue loads above the low-cycle fatigue region, and close to or below the endurance limit. Stress relaxation can occur, and several factors influences its behaviour. It looks as if the direction of the relaxation is determined by mean stress relaxation towards zero, but perhaps to an asymptotic non-zero value. The rate of the relaxation is then given by load amplitudes, stress gradients, environment, history dependant factors, softening/hardening materials parameters and so forth.

Variable fatigue loading may result in other rates of relaxation than that expected from constant amplitude loading. An appropriate predictive model has not yet been encountered.

Surface and bulk interaction has not been discussed in this presentation, although it may be of importance.

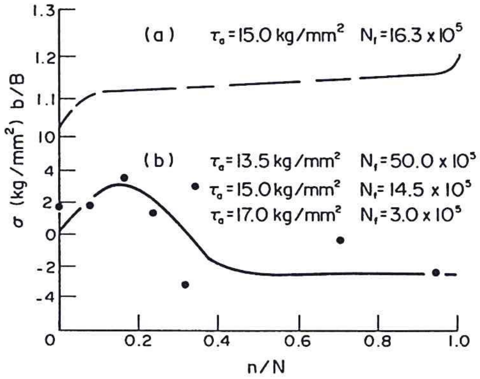
INTRODUCTION

The main purpose of shot peening is to induce a well defined and evenly distributed prestresses and work hardened layer. In design, processing and service-life one then relies on certain residual stress- and work hardening parameters of the component which is to be shot peened. It may be easy to obtain a desirable residual stress distribution, but once shot peened, what will happen to the component in its service-life? Evidently one has to take into account if one has a stable residual stress state or not. Will your beneficial residual compressive stress change during loading and if doing so, in what direction and at what rate? Is there any data available for design use? Will it be necessary to repeen the component?

The residual stress behaviour during fatigue load has drawn the attention to many researchers. A number of combinations of load and material has been investigated and some relaxation models has been put forward. Still, greater knowledge is required in order to understand the mechanisms of relaxation and to acquire materials data for design use and calculation models.

The objective of this presentation is to expose some of the work which has been carried out on the subject, and then to focus on a study from Linköping.

In the 1960s Taira and coworkers presented residual stress and X-ray line broadening behaviour of annealed metals at fatigue conditions in a number of articles. Their investigations showed how the X-ray line half-value breadth increased and how the residual stress depending on loading condition went towards tensile compressive values whereafter it decreased as the fatigue process progressed.



Plain carbon steel 0.13% C
200 MPa torsional yield strength
360 MPa torsional strength
140 MPa endurance limit

Fig. 1, Ref. [1] X-ray line broadening and residual stress as a function of number of fatigue cycles at torsional loading

As can be seen in Fig. 1, compressive residual stress developed in an annealed (normalized) steel at reversed torsional loading fatigue.

S. Kodama shot peened an annealed mild steel, of 250 MPa yield limit and 430 MPa tensile strength, and put it under a completely reversed plane bending fatigue load. He found the residual stress relaxation to vary linearly with the logarithm of the fatigue cycles, see Fig. 2, and the relaxation rate being proportional to the stress amplitude. It was also shown how the initial yielding from the first cycle varied linearly with the stress amplitude.

Kuo and Cohen examined AISI 1008 steel in a normalized and a cold rolled condition and put under fatigue load. They determined both residual stress by X-ray diffraction and X-ray line broadening.

In this report it was found that

(1) in the normalized condition:

- compressive residual stress develops in the same manner in LCF & HCF

- microstructural properties as determined from line broadening parameters, microstrain and particle size, behaves differently at LCF & HCF

(2) in the cold rolled condition: (see Fig. 3, HCF condition)

- compressive residual stress develops from initially zero residual surface stress, in both LCF & HCF

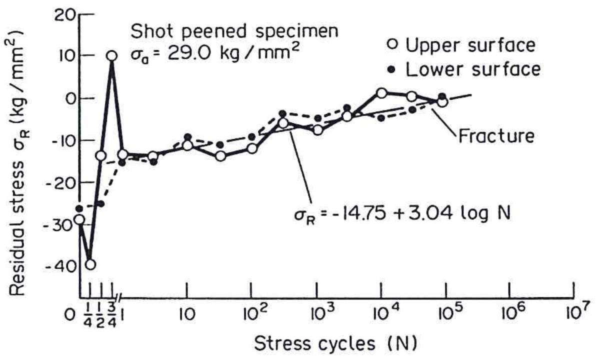


Fig. 2, Ref. [2] Residual stress relaxation in reversed bending fatigue

- microstrain and domain size behaves similar in LCF & HCF but with different magnitudes (microstrain decreases, domain size increases).

(LCF and HCF means Low- respectively High Cycle Fatigue).

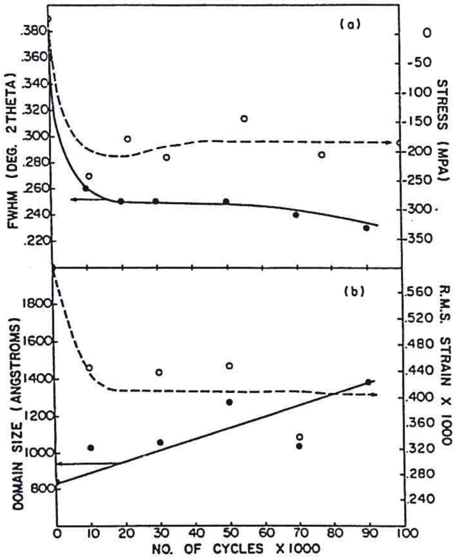


Fig. 3, Ref. [3] Residual stress and X-ray line broadening parameters (domain size and microstrain) of a cold rolled steel. A fatigue loading (constant strain amplitude of 0.15%, R = -1)

McClinton and Cohen tested SAE 1040 steel in tension-tension load conditions, and both normalized and shot peened specimens.

- the normalized developed compressive residual stress.

the shot peened induced compressive stressed relaxed towards zero, except when cycling close to the yield limit, σ_y = 408 MPa, see Fig. 4.

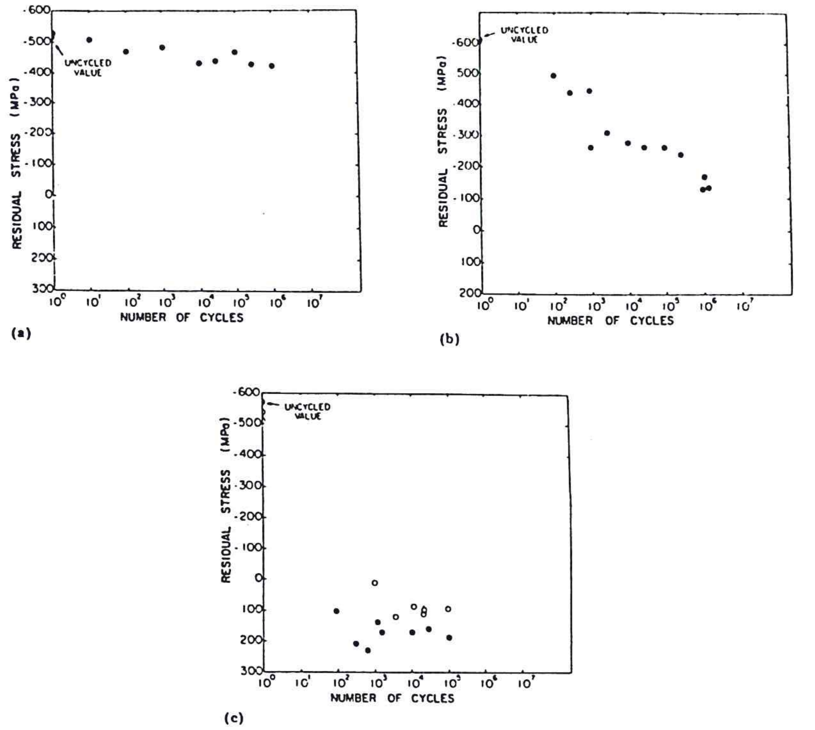


Fig. 4, Ref [4] Residual stress relaxation in shot peened steel in bending fatigue

Esquivel and Evans investigated and AISI 4130 steel, tensile strength (1034-1172) MPa in bending vatigue, tension-tension R = 0.06. Some relaxation occurred at the surface, approx. from -590 to -400 MPa, which equals 30% relaxation, at 5 x 10^5 cycles.

The specimens were shot peened, and Fig. 5 shows the relaxation at different depths in the specimens when cycled around the endurance limit of 500 MPa. They tried to find a correlation between residual stress gradient and residual stress relaxation.

The depth d = 0.013 inches is the zero stress cross-over point, which is in the vicinity of steep residual stress gradients.

H. Wohlfahrt examined the residual stress behaviour of three different steels, Ck 35, Ck 45 and 16MnCr5, under reversed bending fatigue conditions. He found that both initially tensile and initially compressive residual stress relaxed towards zero stress during fatigue. The 16MnCr5 steel was also shot peened to obtain a compressive residual stress state, see Fig. 6.

M. R. James proposed a model for relaxation, which is based on an effective shear stress acting on primary slip planes oriented at an angle to the surface. He

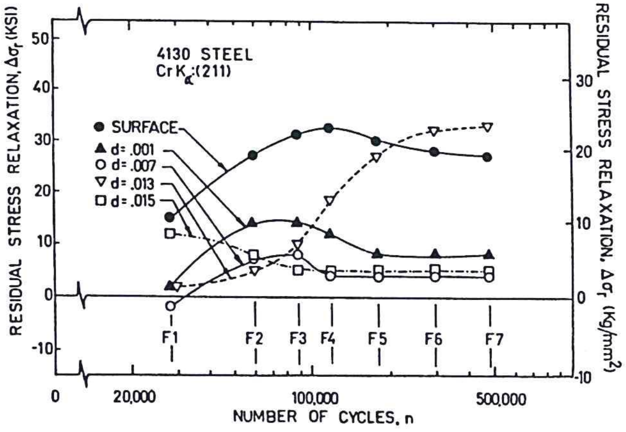


Fig. 5, Ref. [5] Residual stress relaxation at different depths of a shot peened steel, in bending fatigue close to the fatigue limit

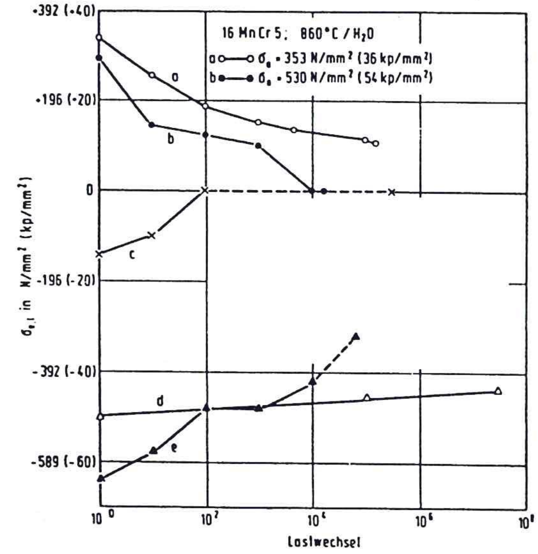


Fig. 6, Ref [6] Residual stress relaxation of both initially tensile and compressive residual stress in steel in reversed bending fatigue

derived an equation for a measured residual stress at N cycles

$$\sigma_R(N) = \sigma_R(0) \int_{0}^{\tau_0} H(\tau_{eff})\, d\tau_{eff} +$$

$$+ \int_{\tau}^{\tau} \max H(\tau_{eff}) \exp\left[-\beta/\theta\cdot(\tau_{eff} - \tau_0)(1 - e^{-\theta N})\right] d\tau_{eff}$$

τ_{eff} = effective shear stress

τ_{max} = maximum applied shear stress

τ_o = minimum shear stress that produces slip

$\tau_R(0)$ = initial surface stress

β = material parameter, sensitive to the gradient in residual stress

θ = cyclic hardening parameter

$H(\tau_{eff})$ = probability of occurrence of τ_{eff}

Tests were conducted on an Al-alloy with R = -1 fatigue loading and some different surface conditions. Relaxation occurred from initial compressive values towards lower compressive value. Their result supported the idea that relaxation is sensitive to residual stress gradients. This could explain the oscillations during fatigue as observed of measured surface residual stress, see Fig. 7.

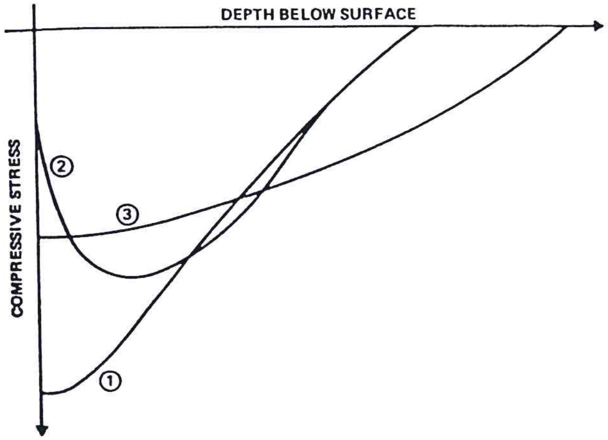


Fig. 7, Ref. 7 An explanation to oscillations of surface residual stress in fatigue

Landgraf executed mean stress relaxation in strain controlled fatigue for a number of different heat treats on SAE 1045 steel. He demonstrates how the mean stress relaxation varies as an exponential decay function towards zero mean stress.

It is worth noting that in these experiments we have macroscopic plasticity and low cycle fatigue conditions. One can clearly see that the harder the steel is, the less will the stress relaxation be, Fig. 8.

Chang and Lawrence have also performed some mean stress relaxation tests on strain-aged A36 steel. One can power function relation of the mean stress relaxation to the strain amplitude, Fig. 9. This was then used to predict the fatigue strength of welded steel structures.

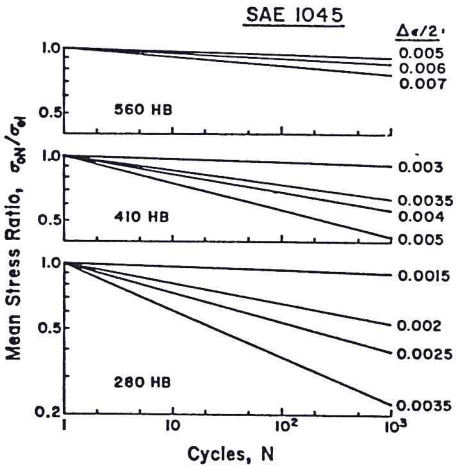


Fig. 8, Ref [8] Mean stress relaxation in strain controlled fatigue

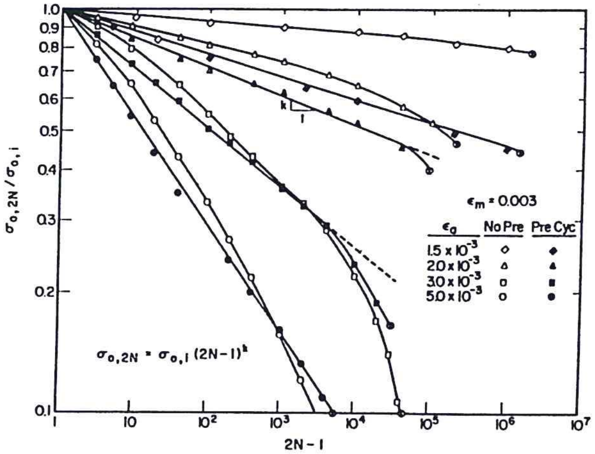


Fig. 9, Ref [9] Mean stress relaxation in strain controlled fatigue

Rotvel recognized the fact that service-life for a component often is under variable loading conditions. In order to obtain a residual stress state he preloaded a carbon steel, approx. SAE 1064, of 440 MPa yield strength and 870 MPa tensile strength, 240 HV. Thus, he could achieve a compressive residual stress down to -300 MPa. By measuring the residual stress at intervals when the piece was put under random load, Fig. 10, he ended up with an empirical relation for the relaxation behaviour.

$$\frac{\sigma_R + K_T \cdot s_m}{\sigma_{RO} + K_T \cdot s_m} = - \ln \left(\frac{n}{n+K}\right) / \ln (1+K); \quad K = K(\sigma_{rms}, \varepsilon_{rms}, K_T, F_{ty}, C)$$

$_R$ = residual stress

$_{RO}$ = initial residual stress

K_T = notch factor

s_m = mean nominal stress

n = number of maximum

$_{rms}$ = local root mean square averaged stress

$_{rms}$ = local root mean square averaged strain

F_{ty} = 0.2% yield stress

C = clipping ratio

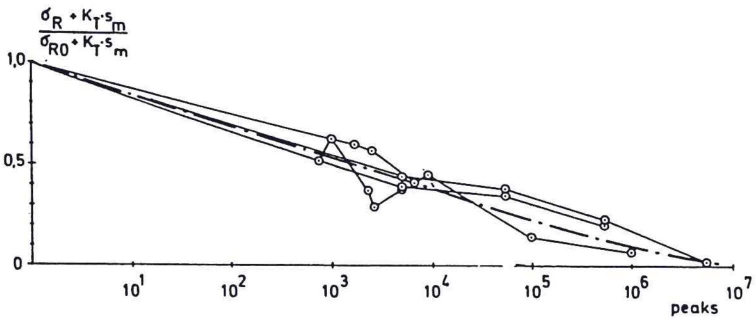


Fig. 10, Ref. [10] Residual stress relaxation in variable loading

At the Division of Engineering Materials, Dept. of Mechanical Engineering, Linköping Institute of Technology we have studied the residual stress relaxation behaviour of a 0.4% carbon low-alloyed steel, SS 2244-05. The steel was quenched and tempered to 940 MPa tensile strength and 815 MPa yield strength, 300 HB, from where cylindrical specimen with a notch, 2.5 mm notch radius and K_t = 1.75, were manufactured. The specimens were ground to surface roughness R_a = 1 μm and then shot peened in the notch to Almen-intensity 30-35 A (mm/100) with 100% coverage using steel shot of S330 standard.

A reference test for constructing Wöhler-curves was performed with both only ground and ground plus shot peened specimens. The fatigue testing was done in UHF-machines with R = -1 loading. One can estimate from the Wöhler-curves an increase in fatigue strength of 6% by shot peening the ground specimens, Fig. 11.

The relaxation studies were done by imposing a fatigue load on the specimen and removing the specimen at intervals from the fatigue testing machine to the X-ray diffractometer. The fatigue machine was a MTS servo controlled electrohydraulic machine, and all loadings were performed in load control mode.

The X-rays were directed in the specimen notch by a 0.5 mm pinhole collimator, mounted on a JEOL diffractometer equipped with a position sensitive detector. All X-ray residual stress measurements were done with diffraction on the (211) plane in the ferrite/martensite phase, the $\sin^2\psi$-method was used in the calculations with an X-ray elastic constant $(1+\nu)/E$ of 5.73×10^{-6} MPa^{-1}.

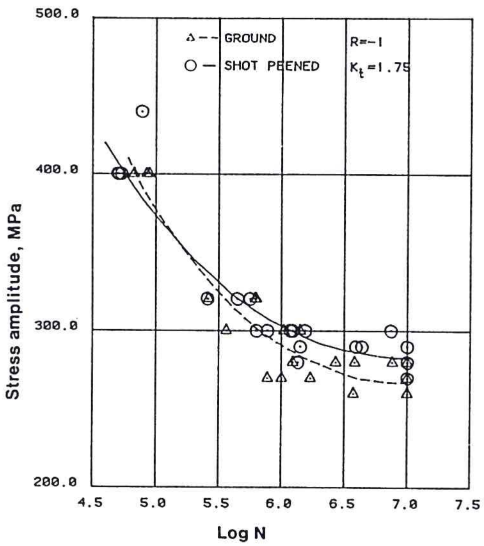


Fig. 11 Wöhler-curves of ground and shot peened notched specimen in axial loading

As can be seen in Fig. 12, the shot peening produces an approximately 0.25 mm thick layer of compressive stress of the same magnitude in both axial and tangential direction. We can assume that the residual stress state is isotropic in the surface plane of the notch.

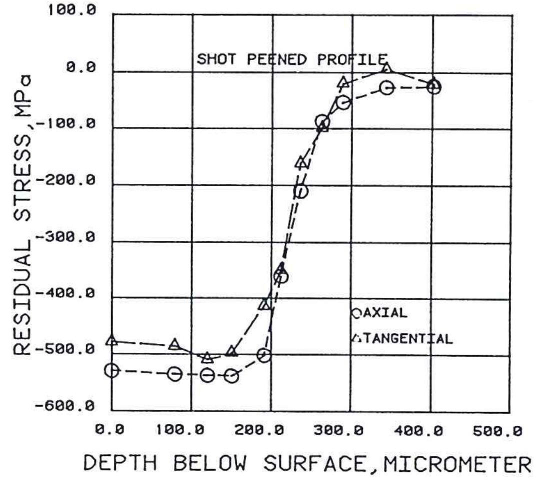


Fig. 12 Residual stress profile of a shot peened specimen

Specimens were loaded in R = -1 condition, Figs. 13 and 14. Here we observe an initial decrease in compressive residual stress after the first cycle, whereafter it decreases continuously with subsequent cycling. The same behaviour shows up for both axial and tangential directions, although different in magnitude.

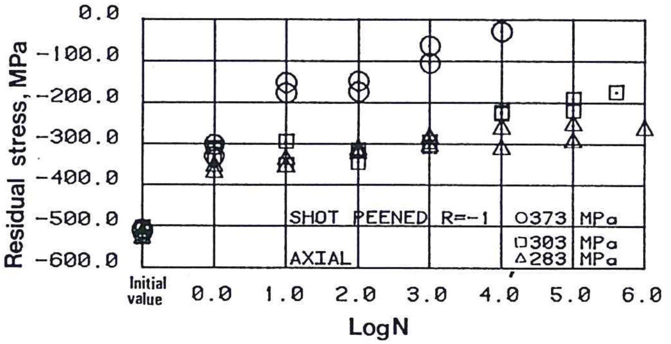


Fig. 13 Residual stress relaxation in axial direction, R = -1 loading and different load amplitudes

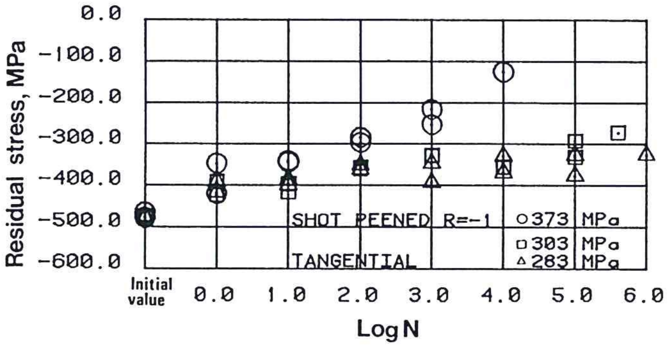


Fig. 14 Residual stress relaxation in tangential direction, R = -1 loading and different load amplitudes

Specimens loaded in R = 0 conditions, Figs. 15 and 16. In this case we have an increase of the compressive stress in the axial direction, while the residual stress in the tangential direction varies as in the R = -1 case.

The residual stress depth profile from a fatigued specimen and R = -1 load is depicted in Fig. 17.

One may try a higher Almen-intensity to see if the relaxation rate will differ from that previously. Ten specimens were shot peened to Almen intensity 50-55 A(mm/100). The resulting residual stress depth profile is shown in Fig. 18 and in Fig. 19 we have the corresponding profile for a fatigued specimen, R = -1 load.

A simple approach to explain the behaviour from the two load conditions R = -1 and R = 0, is to plot a biaxial stress diagram with von Mises yield criterion filled in, as is done in Fig. 20. The residual stress and the loading stress may now be superimposed on each other. The initial yielding in the notch from the first load cycle is determined by where the stress goes beyond the yield surface. The plastic strain will then be directed normal to the yield surface. With continued cycling mean stress relaxation will occur.

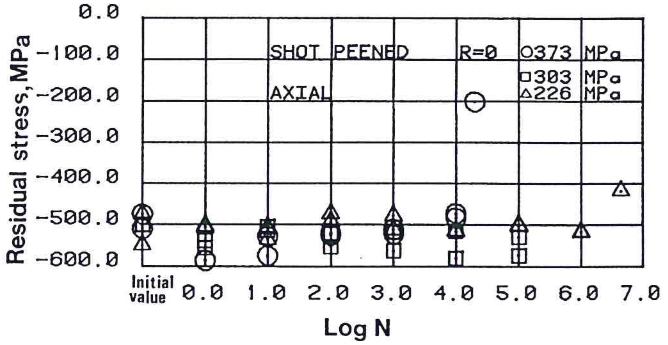


Fig. 15 Residual stress relaxation in axial direction, R = 0 loading and different load amplitudes

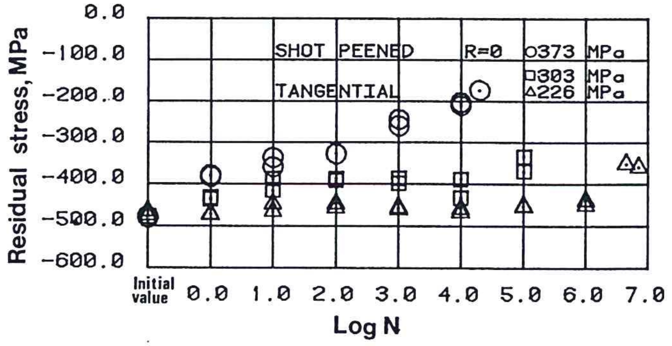


Fig. 16 Residual stress relaxation in tangential direction, R = 0 loading and different load amplitudes

Now then, there is not only constant amplitude loading, so we would like to use our knowledge from it on variable loading conditions. First we can try to do some linear curve fitting with R = -1 loading, taking into account the initial yield and the cyclic relaxation, see Fig. 21. We may then obtain a logarithmic function of the form

$$\sigma_R = a \log N + b, \text{ here: } \quad a = k \cdot \sigma_a + 1$$

If we now have a load distribution for random fatigue load, we may try to estimate the residual stress relaxation by taking the sum of the relaxation at each load amplitude as derived from the constant amplitude test i.e.

$$\sigma_R = \sum_N (\sigma_R)_i \ ; \quad (\sigma_R)_i = f\,(\sigma_a)$$

A load distribution was constructed, Fig. 22, and variable loading was performed with a zero mean load and one of + 250 MPa mean load. X-ray residual stress measurement were done between load blocks, and the residual relaxation can be seen in Fig. 23.

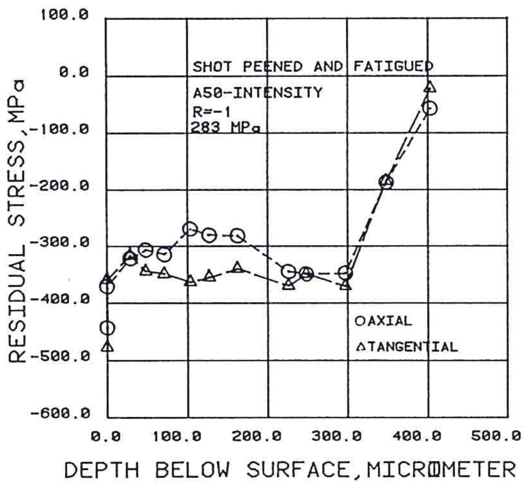


Fig. 17 Residual stress profile of a shot peened and fatigued specimen at R = -1 loading

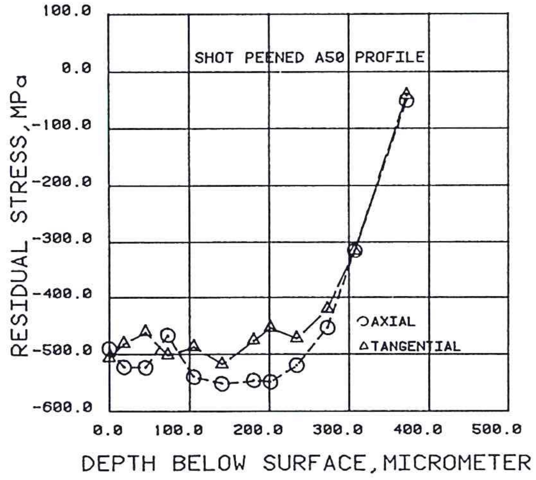


Fig. 18 Residual stress profile of a specimen shot peened to a higher Almen intensity

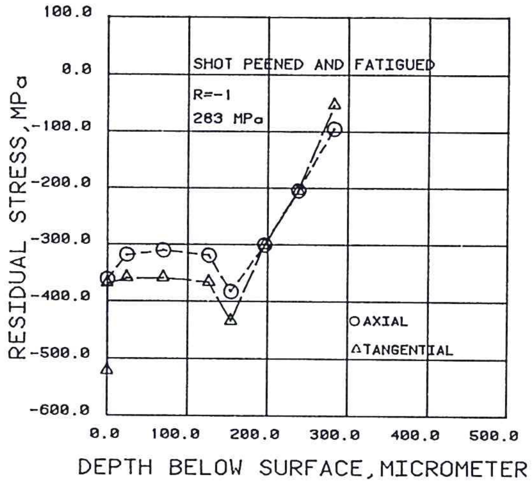


Fig. 19 Residual stress profile of a specimen shot peened to a higher Almen intensity and fatigued at R = -1 loading

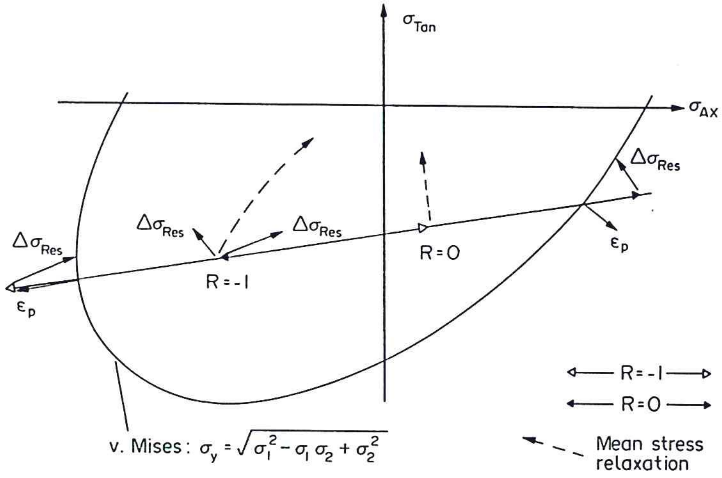


Fig. 20 Biaxial stress diagram composed of residual and loading stresses

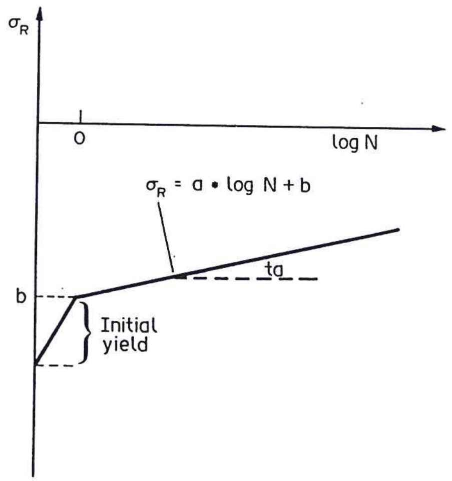


Fig. 21 Figure showing initial yield and logarithmic linear cyclic relaxation

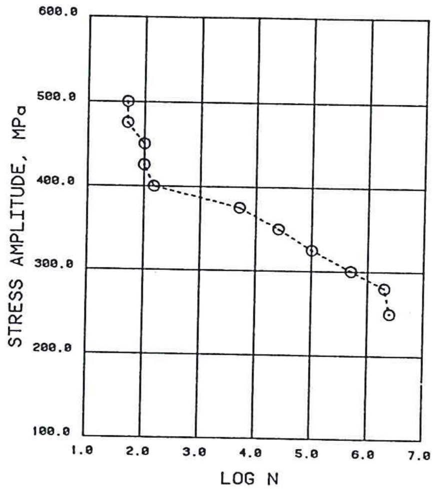


Fig. 22 Load distribution of variable loading test

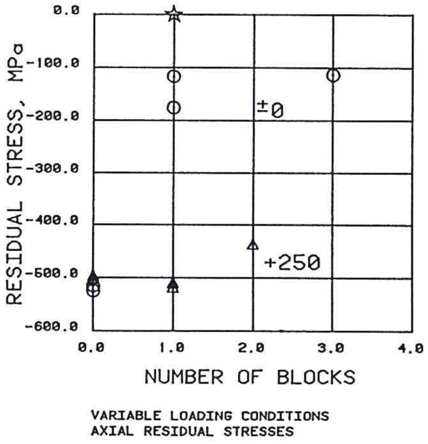


Fig. 23 Measured and estimated residual stress from variable loading test

* = estimate

We now use our simple model from above and sum up all the expected stress relaxation from each load amplitude. This estimate is marked in Fig. 23, and we can see that it was not a good estimation. A more complex model may be necessary.

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