X-ray microstructure and residual stress analysis of shot peened surface layers during fatigue loading

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Introduction

Fatigue is basically a surface related phenomenon as the fatigue cracks usually initiate at the surface and grow from there into the material. Surface hardening is therefore often used to improve fatigue properties and an important example of this is shot peening. Shot peening work hardens the surface layer and induces compressive residual stresses. Roughly speaking, the residual stress acts as an applied mean stress and a compressive residual stress will therefore retard fatigue crack initiation and growth (1). The work hardening results in an increased dislocation density which hinders dislocation movements due to the fatigue load and supresses localized plastic deformation which is a starting feature for crack initiation.

Residual stresses have a greater influence on hard metals than on soft. For steels it is well known that residual stress relaxation will occur due to cyclic loads for low strength grades and the resistance against relaxation will increase with increasing strength (1). There is also a medium strength interval where neither the amount of relaxation nor its mechanisms are well defined. Cold work gives a larger increase in fatigue strength at low strength level, ie a softer material work hardens more than a harder one. The effect of work hardening may also be reduced due to so-called cyclic softening under cyclic loads.

The two effects, residual stress relaxation and cyclic softening are interdependent. By using X-ray diffraction technique residual stress can be measured in the surface layer (2) (3) and stress relaxation can be followed. By doing so called profile analysis of X-ray intensity peaks the degree of cold work and cyclic softening can be studied (3) (4). Thus X-ray diffraction offers a mean to study the interdependant processes of residual stress relaxation and cyclic softening. Here such a study is presented for a shot peened quenched and tempered steel subjected to constant amplitude loading with R=-1 and R=0 and R=-1 with single overload peaks. The object of the study has been to i) map the residual stress behaviour, ii) evaluate its determining parameters, iii) evaluate the inelastic strain history by determining dislocation structure changes and iv) to correlate these with residual stress behaviour. The present paper is based on a thesis (5). Other parts of the complete work has been published elsewhere (6) (7) (8) (9) (10).

Experimental details

The specimen material was a low alloyed 0.4%C steel, SS 2244-05, equivalent to AISI 4140, quenched and tempered to 945 MPa tensile and 815 MPa yield strength. The test specimens were cylindrical with 14 mm diameter at the nominal cross-section, 2.5 mm notch radius and notch factor K_t = 1.75. The specimens were ground in the peripheral direction to a surface roughness of R = 1 μm and shot peened to 0.30-0.35 Å (mm/100) Almen intensity and 100% coverage with cast steel S 330 shots.

Fatigue testing with constant amplitude and uniaxial loading in electro servohydraulique MTS-machines was executed at stress ratios R ($\sigma min/\sigma max$) equal to 0 and -1, at three load levels in the fatigue life range 10^4-10^7 cycles. Also, R=-1 plus peak load at 10^6 cycles, R=-1 on smooth specimens and variable loading on notched specimens have been performed. The cyclic yield stress was 580 MPa and the monotonic 830 MPa measured from the first loading 1/4 cycle as derived from incremental step testing.

X-ray diffraction line broadening analysis was performed using single peak analysis of the same diffraction peaks used for the residual stress measurements with ψ=0. The single peak method used was an integral breadth method (11), where the diffracted intensity distribution was assumed to be represented by a Voigt function, which is a convolution of a Cauchy and a Gaussian functions. By determining the Cauchy and Gaussian integral breadth components the X-ray microstructural parameters domain size D and microstrain, $\bar{e}$, was then evaluated (5).

The domain size, D, (also referred to as particle size) is the coherently diffracting crystal regions of which the diffracted volume is built up. The domain boundaries consist of dislocation formations such as low angle boarders or cell formations in deformed materials (4) (12). The micro-strain, $\langle\epsilon_L^2\rangle^{1/2}$ is the variation of lattice strain averaged over a crystal distance, so it is a disorder quantity. Both the domain size and micro-strain are depending on the dislocation density. If ρ_o is the dislocation density estimated from domain size and ρ_ϵ is that estimated from micro-strain, then the dislocation density ρ may be given by their geometric mean value (12)

$$\rho = \rho_D^{1/2} \cdot \rho_\epsilon^{1/2} \qquad \rho_D = \frac{K_D}{D^2} \qquad \rho_\epsilon = K_\epsilon \cdot \langle\epsilon_L^2\rangle$$

where K_D and K_ϵ are constants depending on the dislocation configuration.

Results and discussion

Shot peening introduced a 0.3 mm surface layer with compressive residual stresses having a minimum value of -500 MPa, (fig 1). The residual stress distribution is similar for both axial and tangential specimen direction.

The surface residual stress behaviour of fatigued specimens is shown in figures 2-4. After loading at stress ratio R=-1, zero mean stress, it can be seen, fig 2 and 3, that both axial and tangential surface residual stresses relax due to the fatigue load.

The first cycle causes an immediate decrease of compressive stress and thereafter relaxation continues throughout the specimen life. The amount of relaxation depends on the load range and there is more relaxation in the axial than in the tangential direction. Fig 1 also shows the residual stress profile after fatigue at R=-1 loading for 10^6 cycles.

Fig 4 shows the surface residual stress behaviour when fatigue loading at stress ratio R=0. Here, the axial residual stress does not relax at all until shortly before failure, but, on the contrary, may increase somewhat. The tangential stress, though, relaxes in the same manner as with the R=-1 load (not shown here).

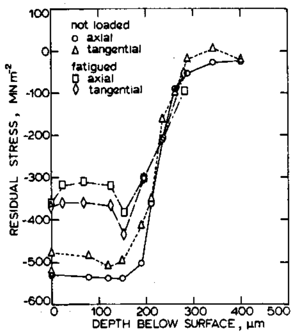

Fig 1 Residual stress profiles for axial and tangential directions at bottom of notch of specimens shot peened under 30-35 A (mm/100) Almen intensity conditions: data are shown for shot peened and shot peened plus fatigued (R=-1, nominal stress amplitude = 283 MPa, 10^6 cycles) states.

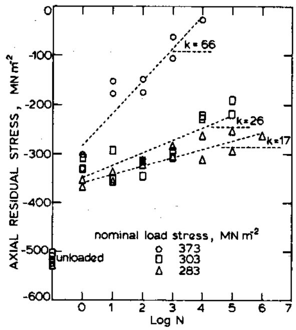

Fig 2 Axial residual surface stress as function of number of load cycles N and nominal stress amplitude at R=-1 load: specimens shot peened to 30-35 A (mm/100); k = relaxation rate.

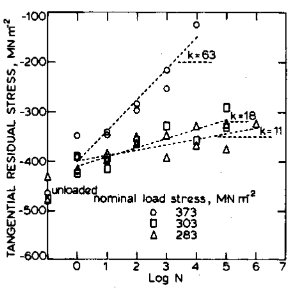

Fig 3 Tangential residual surface stress as function of number of load cycles N and nominal stress amplitude at R=-1 load: specimens shot peened to 30-35 A (mm/100); k = relaxation rate.

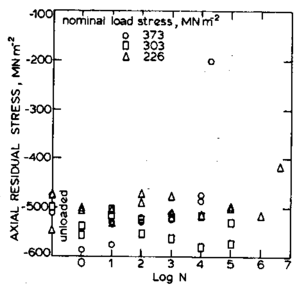

Fig 4 Axial residual surface stress as function of number of load cycles N and nominal stress amplitude at R=0 load: specimens shot peened to 30-35 A (mm/100); k = relaxation rate.

The notch surface stress can be represented in a biaxial stress diagram with residual and applied stress superposed. As yielding will take place we may use v. Mises yield criteria. The material cyclically softens and a cyclic yield criteria, based on v. Mises equations is included.

The nominal push-pull loading, R=-1, with the residual stress behaviour shown in fig 2 and 3, is illustrated in fig 5 and 6. In this case the mean stress is equivalent to the residual stress, where the inclination of the load stress vector arises from the biaxiality in the notch. The local stress amplitudes indicated in the figures are calculated from the product of the notch factor and nominal stress amplitude, not considering plasticity or softening.

It is seen in the fig 2 and 3 how already in the first cycle yield will take place, reducing the initial compressive residual stress. The amount of reduction depends on the size of the load stress amplitude, while the direction of residual stress change depends on where on the yield surface the yield stress is exceeded. Since the plastic flow will be directed normal to the yield surface, the resultant residual stress change, when unloading, will have the same but opposite direction. Consistent to this, the change will be positive in both the axial and tangential directions in the R=-1 case.

After the initial yielding residual stress relaxation will take place with continued cycling. The direction of the relaxation seems to be governed by mean stress relaxation towards zero. Similar results were found by (13).

The nominal pull-pull loading, R=0, with the residual stress behaviour shown in fig 4 is illustrated in fig 7. The mean stress is no longer equivalent to the residual stress but to the sum of the residual stress and the local stress amplitudes. According to the previous reasoning, the residual stress change after the first cycle is negative in the axial and positive in the tangential direction. Also consistent with the R=-1 case, there is a mean stress relaxation towards zero with continued cycling.

Some other load histories different from the pure R=-1 and R=0 were used. The effect of peak load was explored with two specimens subjected to +100% and two others to -100% peak load, fig 8. Previously to the peak load the specimens were run 10^6 cycles at R=-1 and 283 MPa nominal stress amplitude, and subsequently being cycled at the same conditions. It is clearly seen how the yield behaviour due to the initial and peak load agrees with the discussion on the R=-1 and R=0 cases. It is also seen how the reduction of the residual stresses due to the -100% peak load makes the relaxation to cease, while the increased residual stress level due to the +100% peak load causes a new relaxation history.

Smooth specimens were used to evaluate the constraining effect of the notch on the relaxation behaviour. The comparison of the notched and smooth conditions is not altogether justifiable, since the notch surface will experience a strain controlled and the smooth surface a stress controlled testing situation. However, from fig 9 it is observed that the general smooth specimen behaviour is equivalent to the notched. It is also noted that, even though the nominal loading is uniaxial, a biaxial stress approach must be used to evaluate the relaxation.

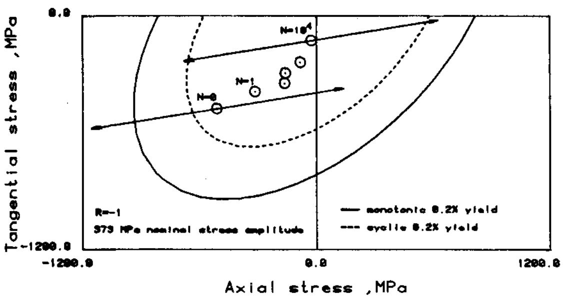

Fig 5 Mean surface stress relaxation in shot peened specimens with residual and applied stresses superposed at R=-1 load with 373 MPa nominal stress amplitude, with stress ranges drawn in the figure.

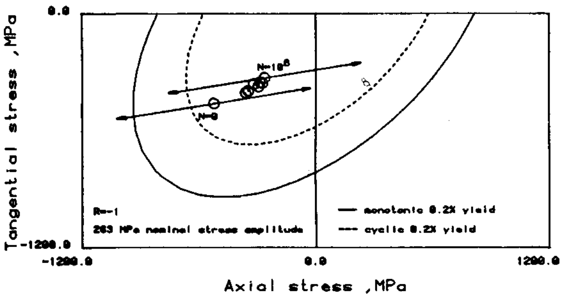

Fig 6 Mean surface stress relaxation in shot peened specimens with residual and applied stresses superposed at R=-1 load with 283 MPa nominal amplitude, with stress ranges drawn in the figure.

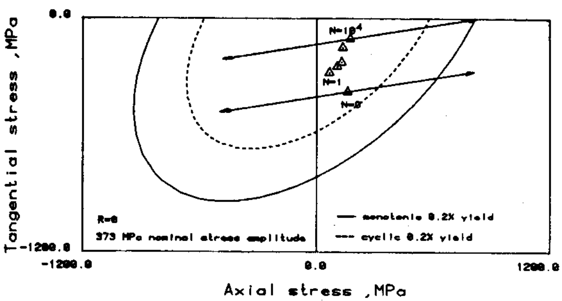

Fig 7 Mean surface stress relaxation in shot peened specimens with residual and applied stresses superposed at R=0 load with 373 MPa nominal stress amplitude, with stress ranges drawn in the figure.

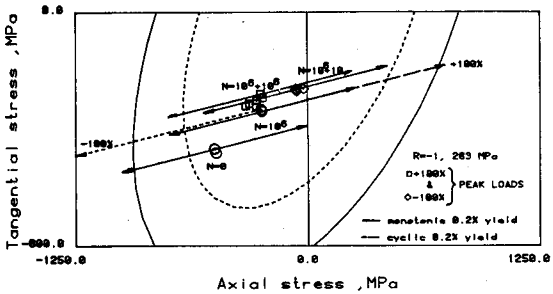

Fig 8 Mean surface stress in shot peened specimens subjected to +100% or -100% peak load at 10^6 cycles and fatigued at R=-1 load with 283 MPa nominal stress amplitude, with stress ranges and load vectors drawn in the figure.

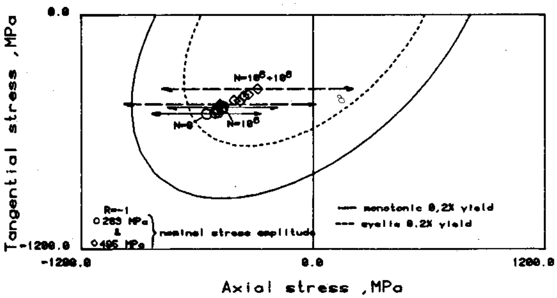

Fig 9 Mean surface stress relaxation in smooth shot peened specimens with residual and applied stresses superposed at R=-1 load with 283 MPa nominal stress amplitude up to 10^6 cycles and subsequently with 495 MPa, with stress ranges drawn in the figure.

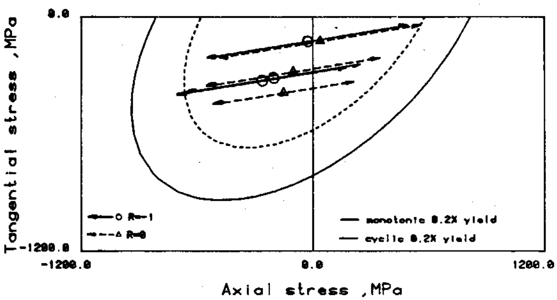

Fig 10 Final mean surface stress and stress ranges with residual and applied stresses superposed with cyclic softening considered and the load conditions: R=-1, 373, 303 and 283 MPa; R=0, 373, 303 and 226 MPa.

A linear relation can be assumed to hold between the local notch strain, ϵ, and the nominal (elastic) strain, $\epsilon = K_t \cdot e$, where K_t is the notch factor. The local stress range in the notch can then be estimated from the nominal load stress range using the cyclic stress strain curve.

The stress ranges in the R=-1 and R=0 from fig 5-7 is reevaluated to final stress ranges with softening considered, fig 10. It is then seen that the superposition of residual and applied stress, the local strain approach and the cyclic yield criteria can be used to predict the amount of relaxation in these experiments. We then assume that the combination of residual and applied stress will tend to fall within the limits of the cyclic yield criteria. A similar experience is reported in (14).

The relaxation rate is also an important variable. This is expressed in fig 11 and 12 as an effective mean stress relaxation, including both residual and applied stresses, and normalized with the effective mean stress after the first cycle initial yielding. Thus it appears as if the relaxation rate is higher in the R=-1 than in the R=0 case even at the same stress and strain amplitudes.

Up to here we have seen that the residual stress relaxation direction is determined by total mean stress relaxation towards zero, while the degree of relaxation is determined by a softening criteria. As the softening in itself is a microstructural process it then implies a coupling between the degree of residual stress relaxation and the extent of microstructural rearrangement in the softening process. Thus, the relaxation rate may be determined by the microstructural behaviour, since it is described by the ease of which the microstructural rearrangement will take place.

The shot peening process has deformed the specimen surface layer, giving it a structure more fine and densely packed with dislocations than that of the core. The core structure is a quenched and tempered martensitic structure. Fig 13 shows the in-depth distribution of the diffraction intensity half-breadth. The microstrain and dislocation density curves have the same shape while the domain size increases with depth. An estimate of the degree of cold work caused by the shot peening process can be evaluated from the ratio of the dislocation density, ρ, at the surface to that of the bulk, $\rho_{surf}/\rho_{bulk} = 15$.

Notice that there is no plateau in the half breadth (and in the dislocation density) near the surface as it is in the residual stress curve, fig 1. The degree of cold work seems to decrease steadily into the bulk.

The softening may be due to a dislocation density change, since the flow stress is proportional to the square root of the dislocation density. In fig 14 and 15 is the dislocation density parameter depicted for the R=-1 and R=0 load cases. They show the dislocation density decrease in the shot peened layer due to the fatigue loading. After the initial yielding in the first load cycle, it is seen that the dislocation density change is the same for the same load amplitudes at the two load modes R=-1 and R=0. Hence, it is concluded that the amount of softening is the same for both the R=-1 and R=0 load cases, that is the same cyclic flow criteria should be applied. The same rate of softening should be valid in both load cases at the same load (strain) amplitude. This means that for a given strain amplitude the softening will be completed within a given number of load cycles, and the rate of stress relaxation will therefore be determined by

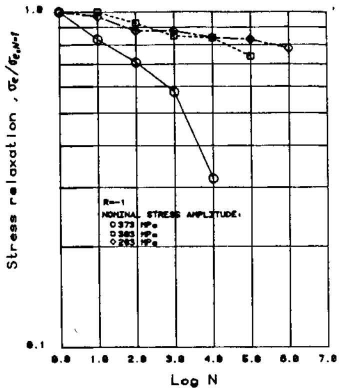

Fig 11 Effective mean stress relaxation after the first load cycle with residual and applied stresses superposed at R=-1 load.

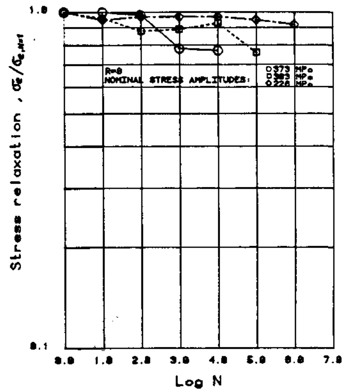

Fig 12 Effective mean stress relaxation after the first load cycle with residual and applied stresses superposed at R=0 load.

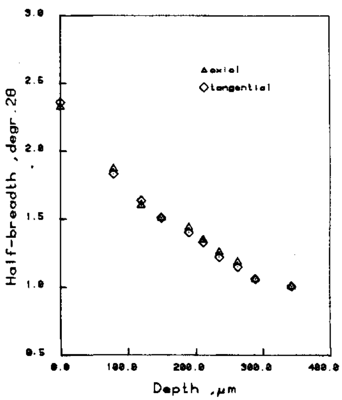

Fig 13 The half breadth, FWHM, of the X-ray diffraction intensity distribution versus depth below the notch surface for a shot peened specimen.

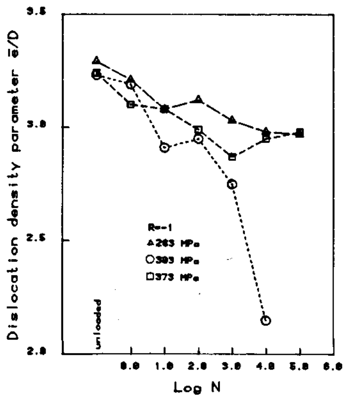

Fig 14 The dislocation density parameter e/D versus number of load cycles at different nominal stress amplitudes with R=-1 load, measured in the notch surface of shot peened specimen.

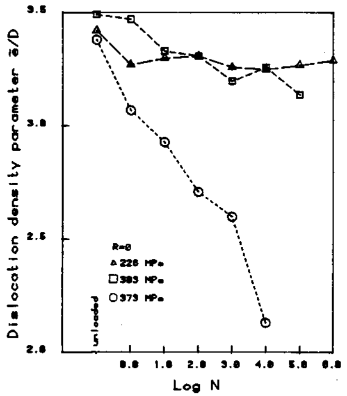

Fig 15 The dislocation density parameter $\bar{e}/D$ versus number of load cycles at different nominal stress amplitudes with R=0 load, measured in the notch surface of shot peened specimen.

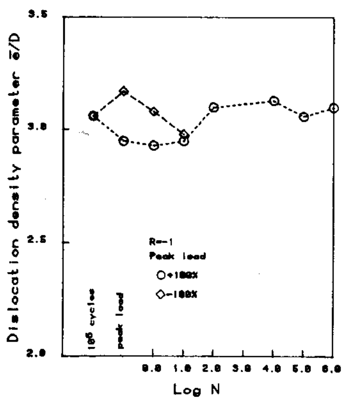

Fig 16 The dislocation density parameter $\bar{e}/D$ of specimens subjected to +100% or -100% peak load at 10^6 cycles, fatigued at R=-1 load and 283 MPa nominal stress amplitude. Cycles subsequent to peak load indicated on x-axis. Shot peened specimens.

the magnitude of the effective stress relaxation as given by the cyclic flow stress criteria.

The dislocation density from the peak load data is presented in fig 16. The peak load were introduced after 10^6 cycles at 283 MPa nominal stress amplitude in R=-1 loading. A larger degree of plastic deformation in the -100% peak load case results in an increase in dislocation density, while there is a decrease in the +100% case. Continued cycling made both cases regain their dislocation density at the level prior to the peak load.

Concluding remarks

The relaxation process has been treated as a surface phenomena not including surface to bulk interaction. In large, with due regards to the presented results, in this case it seems to be a fair approach. Obviously, if possible, it would be interesting to further explore such an interaction. Also, other types of material and load conditions would be desirable to look into.

Some main points can be made however, for this experimental setup.

1) Mean stress relaxation direction is towards zero.

2) For a relaxation end value take the residual plus applied stress to be within yield limit using cyclic properties.

3) Relaxation rate is depending on total mean stress relaxation.

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