RELAXATION OF SHOT PEENING INDUCED RESIDUAL STRESSES IN QUENCHED AND TEMPERED STEEL AISI 4140 DUE TO UNIAXIAL CYCLIC DEFORMATION

V. Schulze, K.-H. Lang, O. Vöhringer, E. Macherauch
Institut für Werkstoffkunde I, Universität Karlsruhe,
Kaiserstr. 12, D 76128 Karlsruhe, FRG

ABSTRACT

As a consequence of stress and total strain controlled cyclic deformations the fatigue lives of quenched and tempered specimens of the steel AISI 4140 (German grade 42 CrMo 4) are significantly higher for shot peened specimens than for unpeened ones at high numbers of cycles to failure. Shot peening also influences the cyclic deformation behaviour. The changes of shot peening induced superficial residual stresses during stress and total strain controlled experiments are investigated with respect to the cyclic deformation. At half of the number of cycles to crack initiation, a correlation independent of the experimental procedure exists between the remaining superficial residual stresses and the apparent plastic strain amplitudes.

KEYWORDS

cyclic deformation behaviour, relaxation of residual stresses, quenched and tempered steel AISI 4140

INTRODUCTION

Shot peening is a far spread process in technical practice with the aim of increasing the fatigue limit of metallic materials [1-5]. According to inhomogeneous plastic deformation processes it causes changes of the topography, the superficial residual stress state and the superficial workhardening state [6 - 11]. While the increased roughness itself influences the fatigue limit negatively, the residual stress and work hardening state close to the surface significantly increase the fatigue limit, if they are sufficiently stable. Up to now numerous experimental studies exist dealing with the fatigue behaviour of shot peened material states, which in most cases are only fatigue life oriented and do not deal with shot peening induced changes of the cyclic deformation behaviour in the fatigue period before crack initiation as done by [12,13]. Only a few reports include the stability of the residual stresses in their investigations [14-16]. Consequently, the cyclic deformation behaviour and the stability of residual stresses shall be explored in this study at the quenched and tempered steel AISI 4140 (German grade 42 CrMo 4).

MATERIAL AND SPECIMEN GEOMETRY

Bars with 25 mm diameter of the steel AISI 4140 (German grade 42 CrMo 4) with the chemical composition 0.43 C, 1.10 Cr, 0.23 Mo, 0.28 Si, 0.77 Mn, 0.16 Ni, 0.011 P,

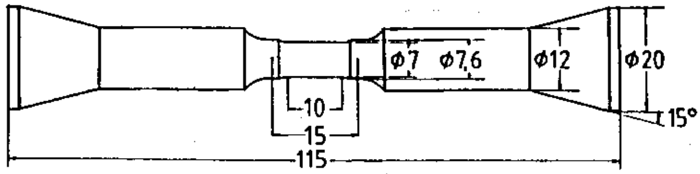

Fig. 1: Specimen geometry.

0.030 S and rest Fe (all in wt.-%) were used for the investigations. The experiments were accomplished with specimens in the quenched and tempered state of delivery, which was produced by a 20 min austenitizing at 850 °C, a quenching in oil down to 30 °C and a tempering treatment at 650 °C for 2 h. The investigations were performed with specimens of the dimensions shown in Fig. 1. The specimens were manufactured by turning and grinding. The shot peening was performed in an air blast machine (Fa. Baiker) with cast steel shot of the size S170 (medium diameter 0.43 mm) and the hardness 44-48 HRC. A pressure of 1.6 bar and a flow rate of 1.5 kg/min were adjusted at the machine.

EXPERIMENTAL PROCEDURE

For the tension-compression cyclic deformations servohydraulic testing machines (Fa. Schenck) with maximum testing forces of 60 and 100 kN were used. Strains were measured using a capacitive measuring device. With the PC-controlled machine it was possible to generate triangular load-time-correlations with a frequency of 5 Hz, which were controlled in stress or total strain. The number of cycles to crack initiation N_I was determined from the development of the modulus of unloading in the tensile half cycle and can be correlated with a crack depth of 500 µm [17].
The X-ray measurements of residual stresses and half width breadths were performed after shot peening and after certain numbers of cycles, the last half cycle always being the compressive one. The {211}-planes of the bcc. phase were measured with CrKα-radiation on a ψ-diffractometer (Karlsruhe-type). The residual stress values were determined according to the $\sin^2\psi$ - method [18] using 11 ψ - angles between -45° and +45°. Therefore a Young's modulus of E = 210000 N/mm^2 and a Poison's ratio of ν = 0.28 were used, not considering the elastic anisotropy. For the inquiry of the depth distribution of the residual stresses thin surface layers were removed electrolytically and the residual stresses were measured at the new surfaces. The measurements were corrected with regard to the superficial removal according to [19].

EXPERIMENTAL RESULTS

Characterization of the Surface Layers

Fig. 2 illustrates the depth distributions of the residual stress components and the half width breadths measured in the grinded and in the additionally shot peened condition. Fig. 2a) shows that in the unpeened condition axial superficial residual stresses σ_{ax}^{rs} = -440 N/mm^2 exist which already vanished at a distance to surface of x = 0.05 mm. After shot peening these residual stresses amount to about -500 N/mm^2. They remain constant up to x ≈ 0.15 mm and then decrease continuously to zero at x ≈ 0.3 mm. Fig.

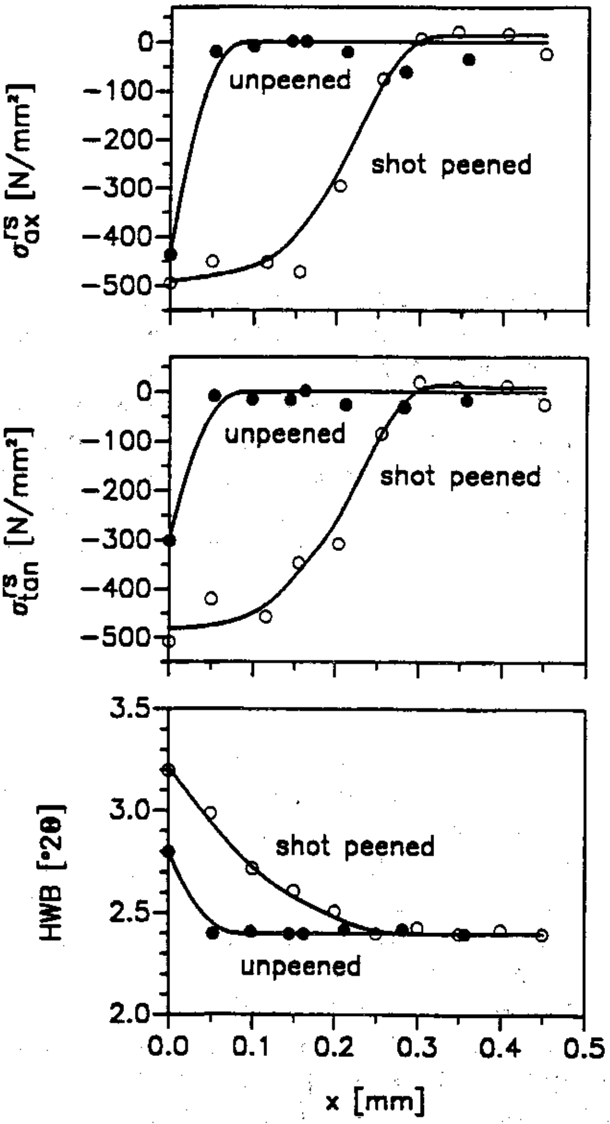

Fig. 2: Depth distribution of the axial and tangential residual stresses as well as of the half width breadths.

2b) displays qualitatively the same behaviour for the tangential residual stresses σ^{rs}_{tan}. The micro residual stress state close to the surface is described by the half width breadths of the {211}-interference lines shown in Fig. 2c). In the unpeened specimens, they are increased by grinding from HWB = 2.4°2θ to HWB = 2.8°2θ close to the surface. Thus a microstructural surface hardening exists, but this is already vanished at x = 0.05 mm. In contrast, shot peened specimens show HWB = 3.2 ° at the surface. With growing distance to surface the half width breadths decrease to the value of the core material, which is reached at x ≈ 0.25 mm.

Stress Controlled Experiments

Fig. 3 shows the stress Wöhler-curves of unpeened and shot peened specimens. Three regions can be found ($N_f < 10^4$, $10^4 < N_f < 10^6$ and $N_f > 10^6$), within which different linear

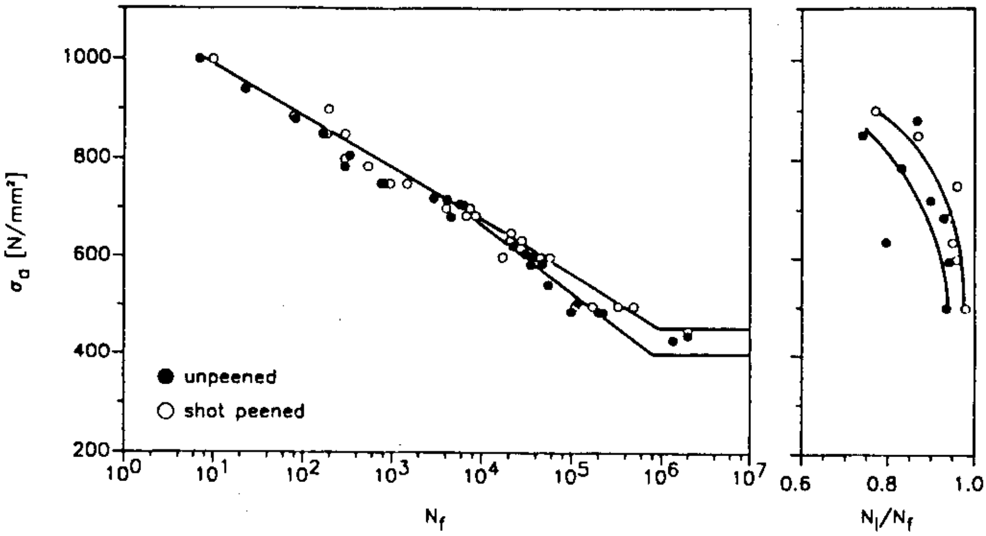

Fig. 3: Influence of shot peening on the stress Wöhler-curves and the N_I/N_f-values.

relationships between the stress amplitude σ_a and the logarithm of the number of cycles to failure N_f exist. While in the low cycle fatigue region no influence of shot peening could be found, in the high cycle fatigue region and in the area of the fatigue limit the shot peened specimens show higher bearable stress amplitudes at equal numbers of cycles to failure. By extrapolation of the high cycle fatigue curve to $N_E = 10^6$, the fatigue limit was determined as $R_E = 400$ N/mm² in the unpeened condition and as $R_E = 430$ N/mm² in the shot peened condition. The σ_a, N_I/N_f-correlations in the right part of Fig. 3 show values, which become smaller with increasing stress amplitude and are not influenced significantly by the shot peening treatment. The influence of the stress amplitude on the cyclic deformation curves registered at unpeened specimens can be taken from Fig. 4. Up to a number of cycles to incubation, which decreases with

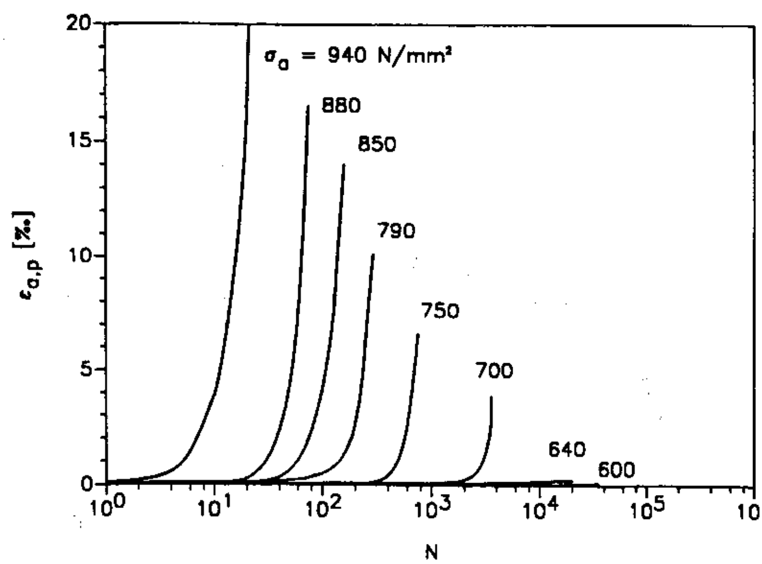

Fig. 4: Cyclic deformation curves of unpeened specimens at different stress amplitudes.

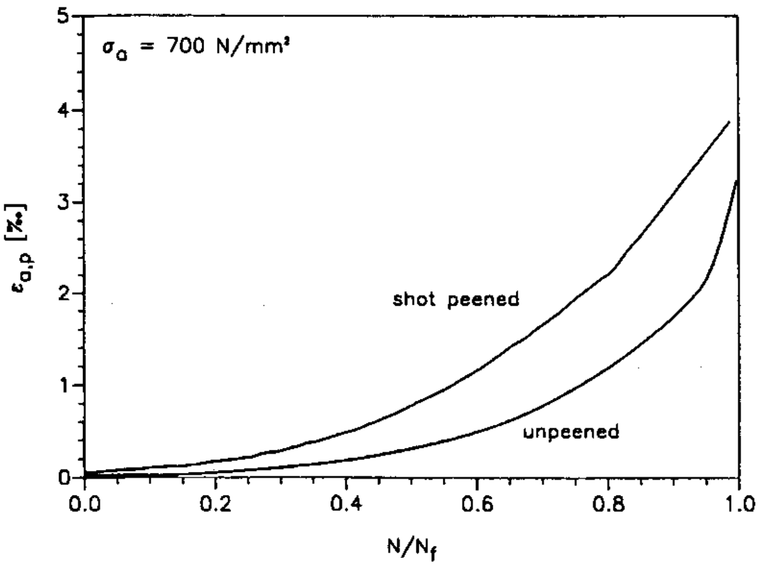

Fig. 5: Influence of shot peening on $\varepsilon_{a,p}$ vs. N/N_f at σ_a = 700 N/mm^2.

increasing stress amplitude, macroscopically elastic behaviour occurs. Then a continuous cyclic worksoftening being more distinctive with increasing stress amplitude is measured. Exemplarily, the influence of shot peening on the cyclic deformation is presented in Fig. 5 using the $\varepsilon_{a,p}$, N/N_f-correlations observed at σ_a = 700 N/mm^2. In comparison to the unpeened specimen the shot peened one always shows higher plastic strain amplitudes and therefore a quicker and more distinctive cyclic worksoftening.

Fig. 6 shows the axial residual stress values vs. the number of cycles registered at specimens loaded with the stress amplitudes σ_a = 400, 500, 600 and 700 N/mm^2. At all

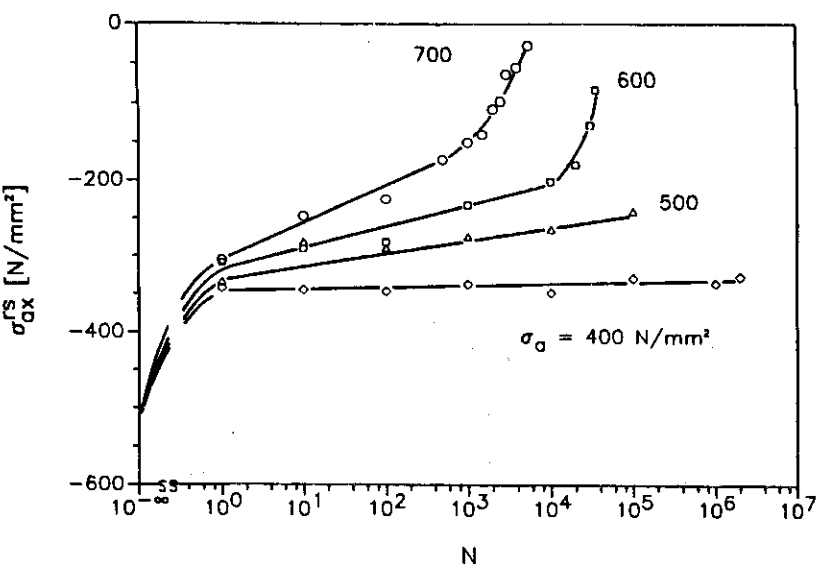

Fig. 6: Influence of stress amplitude on axial residual stresses at the surface vs. number of cycles for shot peened specimens.

stress amplitudes the strongest decrease of the residual stress amounts occurs in the first cycle of loading. Subsequently, with increasing number of cycles the residual stresses are reduced the stronger, the higher σ_a is. This does not hold for σ_a = 400 N/mm^2, which is below the fatigue limit. Thereby the axial residual stress relaxation is linearly dependent on lg N in intervals of number of cycles which become smaller with increasing σ_a. At σ_a = 600 and 700 N/mm^2 close to the number of cycles to failure the rates of relaxation are once more clearly enlarged.

Total Strain Controlled Experiments

Like in stress controlled tests, the strain Wöhler-curve of the shot peened condition shows higher fatigue lives in the high cycle fatigue region than the unpeened condition. The strain fatigue limit is raised by shot peening from $R_{\varepsilon,E}$ = 1.9‰ to $R_{\varepsilon,E}$ = 2.15‰. The cyclic deformation curves of unpeened specimens at total strain controlled experiments exclusively show cyclic worksoftening like in stress controlled experiments. This process starts in total strain controlled tests with $N_f > 10^3$ at the beginning of the experiment. Fig. 7 shows a comparison between cyclic deformation curves at $\varepsilon_{a,t}$ = 4.5 ‰ of unpeened and shot peened specimens. A quick work softening appears at the beginning of the test and leads to quickly decreasing stress amplitudes because of the selfunloading effect of the experimental procedure. This causes a continuous extenuation of cyclic worksoftening [17]. Like in the stress controlled experiments, the smaller plastic strain amplitudes in the fatigue region before crack initiation are measured at the unpeened specimen.

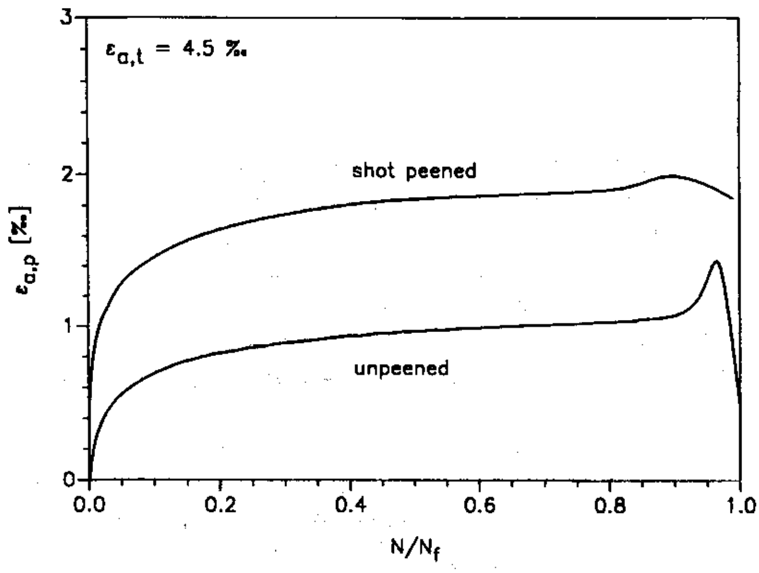

Fig. 7: Influence of shot peening on $\varepsilon_{a,p}$ vs. N/N_f at $\varepsilon_{a,t}$ = 4.5‰.

Fig. 8 shows the changes of the axial residual stresses of shot peened specimens at total strain controlled loadings at four loading horizons as a function of the number of cycles. As seen at stress controlled experiments, the highest relaxation of residual stresses occurs in the first cycle of loading and is the stronger, the higher $\varepsilon_{a,t}$ is. At the total strain amplitude $\varepsilon_{a,t}$ = 1.75 ‰, which is below the fatigue limit, no further residual stress relaxation is observed until $N \approx 10^4$. At higher $\varepsilon_{a,t}$-values the residual stresses

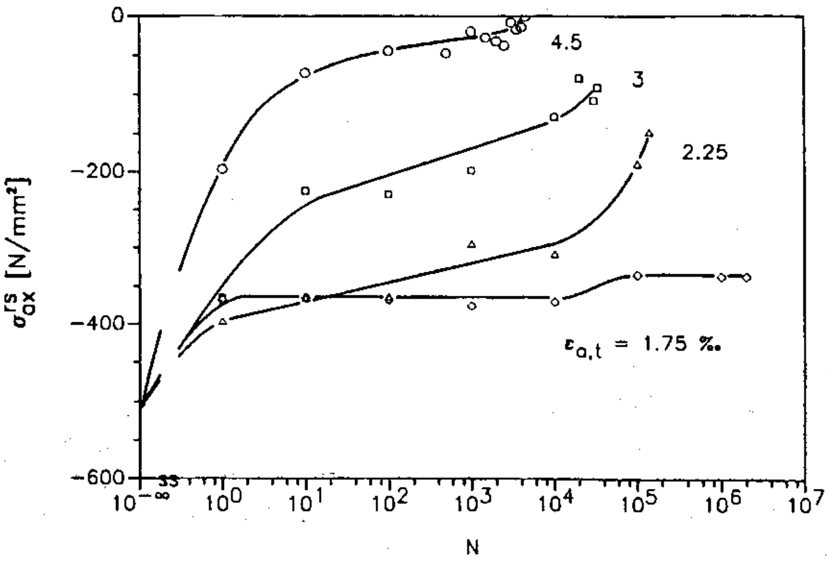

Fig. 8: Influence of total strain amplitude on axial residual stresses at the surface vs. number of cycles for shot peened specimens.

continue to decrease directly after the first cycle of loading, whereby the rates of relaxation increase with growing $\epsilon_{a,t}$. At $\epsilon_{a,t}$ = 4.5 ‰ the axial residual stress amounts are lower than 100 N/mm² already after ten cycles of loading.

DISCUSSION

The shot peened specimens always show higher cyclic worksoftening than the unpeened ones. This is caused by the part of the cross section, which is forced to show plastic strains in the first compressive half cycle because of the superposition of loading and residual stresses. Consequently the density of mobile dislocations increases causing further worksoftening in the following cycles. This is confirmed by experiments with σ_a = 700 N/mm² at differently shot peened specimens of the same heat treatment condition, where higher plastic strain amplitudes were found at $N_f/2$ with increasing shot size and shot pressure [17].
The changes of the superficial axial residual stress state at stress and total strain controlled experiments presented in Figs. 6 and 8 show that at all loadings the highest changes of residual stresses are caused after exceeding the tensile and/or compressive yield strength in the first loading cycle. Then amplitudes smaller than or equal to the fatigue limit cause no further relaxation of residual stresses. In intervals of loading cycles, in which macroscopically elastic behaviour is observed, an approximately linear residual stress relaxation with increasing lg N was found. At the beginning of cyclic worksoftening, relaxation of residual stresses occurs which progresses more than linearly with lg N. The cyclic residual stress relaxation cannot be described using the linear σ^{RS}, lgN-relationship presented in [20]. Considerable deviations appear, which are due to the cyclic deformation behaviour. The residual stress values remaining at $N_f/2$ can be taken from Figs. 6 and 8 and the $\epsilon_{a,p}$-values at this loading cycle from the $\epsilon_{a,p}$,lgN-correlations.

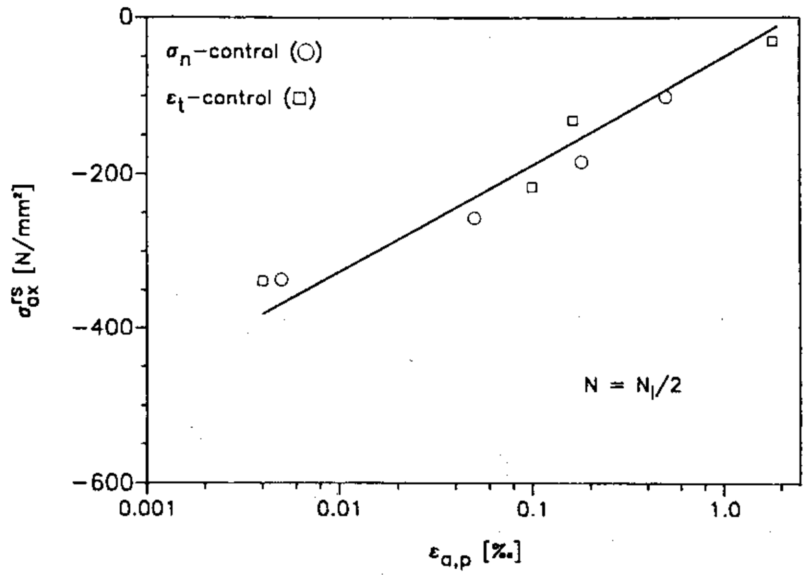

Fig. 9: Axial superficial residual stresses at the surface vs. plastic strain amplitudes at $N_i/2$ for shot peened specimens in stress and total strain controlled tests.

In Fig. 9 they are both plotted for the stress as well as for the total strain controlled experiments as a function of the logarithm of the plastic strain amplitudes. Evidently the correlation

$$\sigma_{ax}^{rs} = \sigma_{ax,o}^{rs} + \sigma^{rs'} \lg \frac{\epsilon_{a,p}}{\epsilon_o^{rs}} \tag{1}$$

counts independently of the experimental procedure. In this formula, $\sigma_{ax,o}^{rs}$ = -500 N/mm² is the starting value of the axial residual stresses before cyclic loading, $\sigma^{rs'}$ = 137 N/mm² the change of the axial residual stresses per decade of plastic strain amplitude and ϵ_o^{rs} = $5.5 \cdot 10^{-4}$ ‰ a characteristic strain value. Therefore the extent of the cyclic relaxation of residual stresses is decisively determined by the cyclic plastic deformations.

SUMMARY

Stress and total strain controlled cyclic deformations were performed at industrially quenched and tempered and shot peened specimens of the steel AISI 4140 (German grade 42 CrMo 4) in a computer controlled servohydraulic machine. At numbers of cycles to failure higher than 10^4, shot peened specimens show significantly longer fatigue lives than unpeened specimens. In the fatigue period before crack initiation cyclic worksoftening is exclusively observed, which is more distinctive under total strain than under stress control. The amounts of the shot peening induced superficial residual stresses decrease at stress as well as at total strain control with increasing number of cycles the more, the higher the loading amplitude is. Relaxation of the residual stresses, which occurs already in the macroscopically elastic fatigue period, increases at the beginning of cyclic worksoftening. At half of the number of cycles to crack initiation a

correlation between the remaining superficial residual stresses and the appearing plastic strain amplitudes exists, which is independent of the experimental procedure.

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