INFLUENCE OF SHOT PEENING ON THE CYCLIC DEFORMATION BEHAVIOUR OF THE STEEL 42 CrMo 4 IN A NORMALIZED STATE

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ABSTRACT

The cyclic stress-strain behaviour of a normalized 42 CrMo 4 (AISI 4140) was investigated under push-pull and cyclic bending loading ($R = -1$). For push-pull loading cylindrical specimens were used. The cyclic bending was realized with flat specimens. The push-pull tests were carried out under stress as well as total-strain control. Cyclic bending was performed under total-strain control.

The differences in the cyclic deformation curves ($\varepsilon_{a,p}$-N-curves) of unpeened and shot peened specimens are significant. For $N > 10$ cycles, the plastic strain amplitudes of shot peened specimens are smaller than those of unpeened ones. As a consequence, the number of cycles to crack initiation and failure for shot peened specimens increases in push-pull as well as cyclic bending tests. For the different kinds of loading, the cyclic stress-strain curves are presented and compared. In this context, the changes of the macro residual stresses as a function of the number of cycles are discussed. The influence of the type of loading (push-pull or cyclic bending) on the $\varepsilon_{a,p}$-N-curves and the cyclic stress-strain curves, respectively, are also modelled and discussed.

KEYWORDS

Push-pull test, cyclic bending test, stress-control, total strain-control, cyclic deformation curves, cyclic stress-strain-curves, macro residual stresses.

INTRODUCTION

Shot peening improves the fatigue behaviour of metallic materials by means of compressive residual stresses and work hardening of the surface layer. For this purpose, some work, especially regarding fatigue life increase at cyclic bending conditions, was done [see e. g. 1-3]. However, until now no information exists about the influence of shot peening induced compressive residual stresses and surface layer hardening on the cyclic deformation behaviour in the crack-free stage of fatigue. In the following, results obtained at normalized 42 CrMo 4 (AISI 4140) in the unpeened and the shot peened state under push-pull and cyclic bending loading, respectively, are presented.

EXPERIMENTAL DETAILS

The investigatons were carried out at the low-alloy steel 42 CrMo 4 (0.42 wt.-% C, 1 wt.-% Cr). Push-pull specimens with a gauge lengths of 4 mm were produced from round bars with a diameter of 20 mm, and cyclic bending specimens from plates of 20 mm thickness (Fig. 1). The specimens were normalized in vacuum (10^{-5} bar) at 930 °C for 2 hours. For both types of specimens, a yield strength of 380 N/mm^2 and a tensile strength of 690 N/mm^2 were determined.

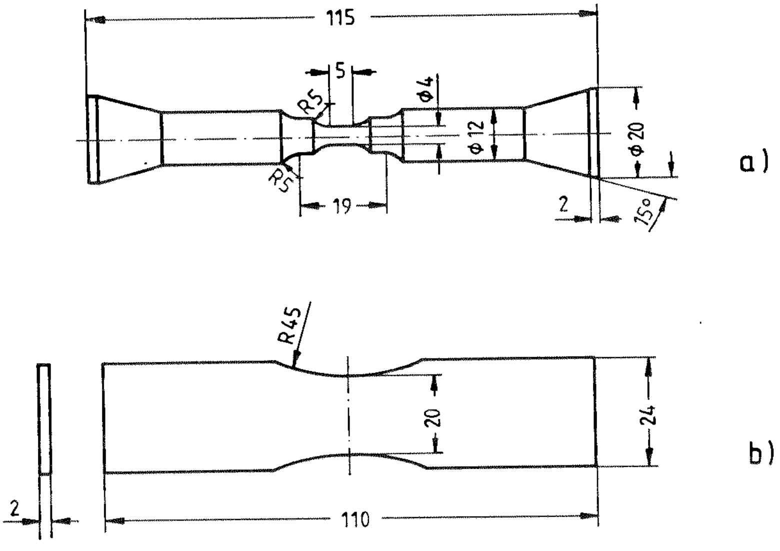

Fig. 1 Shapes and sizes of specimens used in push-pull tests (a) and cyclic bending tests (b)

The shot peening was carried out with an air blast machine (Baiker/Ch.). A cast steel shot S 170 (44-48 HRC) and a peening pressure of 1,6 bar was used. The coverage was 98 % and the resulting Almen intensity was 0.32 mmA.

The residual stresses were determined with X-rays according to the $\sin^2\psi$-method [4]. After the electrolytical removal of surface layers, all values of residual stresses were corrected [2]. The half width values of the X-ray inteference lines were determined from $\psi = -9^o, 0^o$ and 9^o.

The push-pull experiments were carried out with a servohydraulic testing machine (Schenck) under stress control and total-strain control, respectively, and with a frequency of 5 Hz. The strains were determined with a capacitive extensometer. Mechanically driven cyclic bending machines (Schenck) with a frequency of 25 Hz were used for the bending fatigue tests. The bending moment was determined with a strain gauge equiped measuring bar, the total surface strain was measured using a strain gauge which was applicated in the centre of the specimen, and the bending of the specimen was determined by means of an inductive distance measuring system.

EXPERIMENTAL RESULTS

The depth distributions of the residual stresses and half width values occurring after shot peening are presented in Fig. 2a for flat specimens and in Fig. 2b for round specimens. In spite of identical shot peening parameters, the compressive surface residual stresses measured at the flat specimens (σ_S^{RS} = -450 N/mm^2) are larger than those of the round specimens (σ_S^{RS} = -400 N/mm^2). For both types of specimens, the penetration depth of the compressive residual stresses was about 0,3 mm. The distributions of the half width values are nearly identical for both types of specimens. The half width values reach a maximum at the surface and decrease with increasing distance from surface.

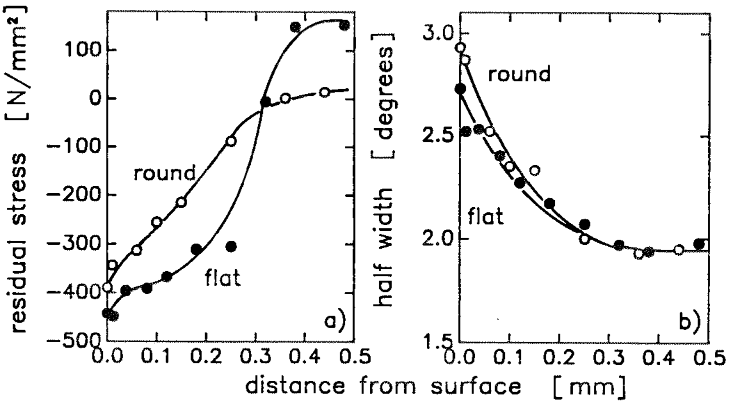

Fig. 2 Residual stress (a) and half width of X-ray interference lines (b) as a function of distance from surface for round and flat specimens after shot peening

The cyclic deformation curves resulting from stress-controlled push-pull experiments with unpeened specimens show the development which is typical of normalized steels (Fig. 3a), starting with a quasielastic incubation interval followed by cyclic softening and subsequent cyclic hardening until macroscopic crack initiation. Shot peened specimens (Fig. 3b), however, show plastic deformations right from the beginning of cyclic loading. But with regard to the entire fatigue life, the plastic deformation of shot peened specimens is smaller than that of unpeened ones.

Total-strain controlled experiments carried out with unpeened and shot peened specimens lead to the cyclic deformation curves shown in Fig. 4a and b for different total strain amplitudes. It becomes obvious that for identical total strain amplitudes (with the

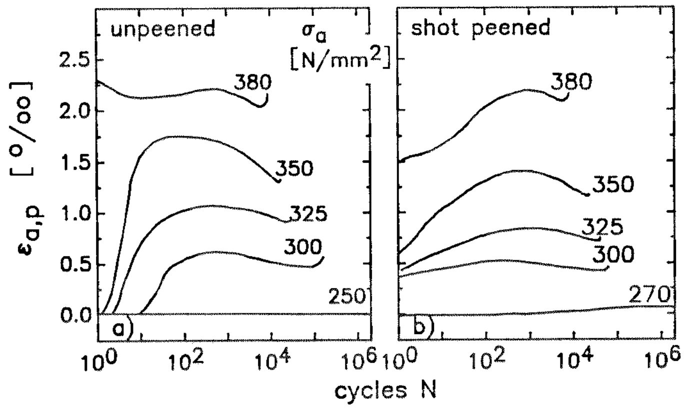

Fig. 3 $\varepsilon_{a,p}$-N-curves of stress-controlled push-pull tests for unpeened (A) and shot peened (b) specimens

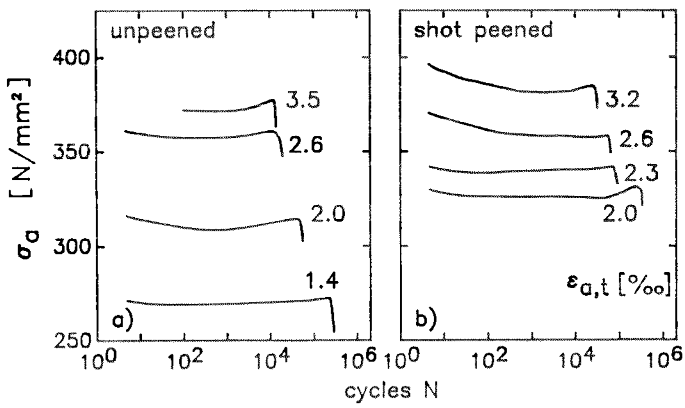

Fig. 4 σ_a-N-curves of total-strain-controlled push-pull tests for unpeened (A) and shot peened (b) specimens

exception of $\varepsilon_{a,t} = 2.6$ ‰), the shot peened specimens reveal higher stress amplitudes *than the unpeened ones. Both the cyclic deformation curves of unpeened and those of* shot peened specimens show a weak cyclic hardening effect for $N \gtrsim N_B/2$.

In Figs. 5a and b, the fictitious surface stress amplitudes $\sigma^*_{a,s}$ are plotted for different total strain amplitudes as a function of the number of cycles for unpeened specimens under cyclic bending. In the material state under examination, all total strain amplitudes investigated produce already at the beginning of the cyclic bending loading plastic deformations which in turn cause a decrease of the stress amplitudes combined with cyclic softening processes. At similar total strain amplitudes, the $\sigma^*_{a,s}$-values are larger for shot peened than for unpeened specimens. Moreover, the cyclic softening processes are more pronounced for the shot peened specimens.

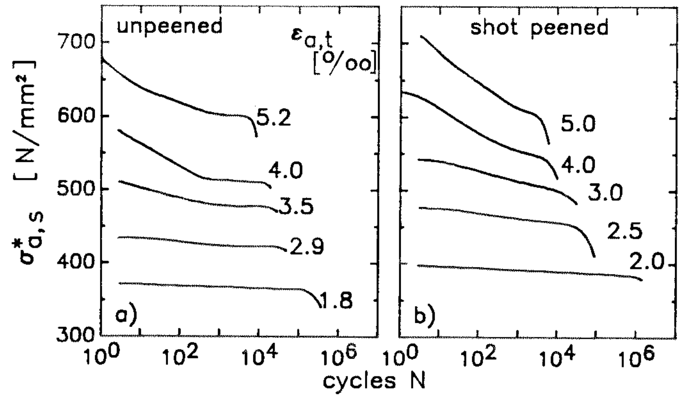

Fig. 5 $\sigma^*_{a,s}$-N-curves of total-strain-controlled cyclic bending for unpeened (a) and shot peened (b) specimens

Fig. 6 shows the cyclic stress-strain curves at $N = N_B/2$ as a result of the above described cyclic deformation curves. The cyclic stress-strain curves resulting from push-pull tests occur in the same scattering range. It can be seen that under push-pull loading, there is no significant difference between unpeened and shot peened and

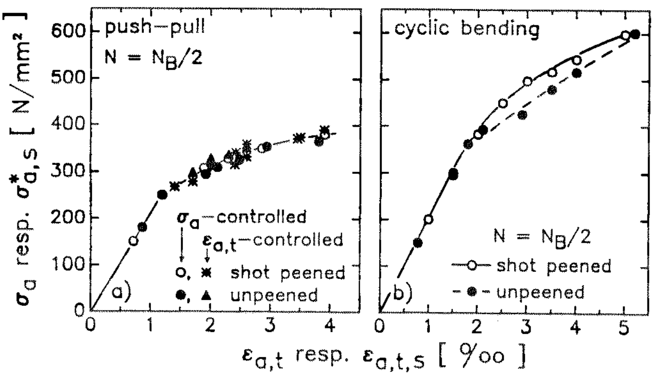

Fig. 6 Cyclic stress-strain-curves at $N_B/2$ of stress- and total-strain-controlled push-pull tests (a) and total strain controlled cyclic bending (b) for unpeened and shot peened specimens

between stress- and total-strain controlled material states. The cyclic stress-strain curves of the total surface strain controlled cyclic bending specimens shown in Fig. 6b illustrate that the shot peened samples have higher stress values.

In order to estimate the cyclic deformation behaviour, it is important to evaluate the development of peening-induced residual stresses. For this purpose, the surface residual stress curves for push-pull and cyclic bending tests are plotted in Figs. 7a and b. From Fig. 7a it can be seen that during the first compression half cycle (●) the residual stresses significantly decrease. If, however, the same test is carried out under tension, only small residual stress changes occur during the first tension half cycle (o). In the following compression half cycle, the residual stresses are also markedly reduced. Upon continuing cyclic loading, the residual stress formation in both material states does not reveal any differences. The compressive residual stresses continually decrease until fracture.

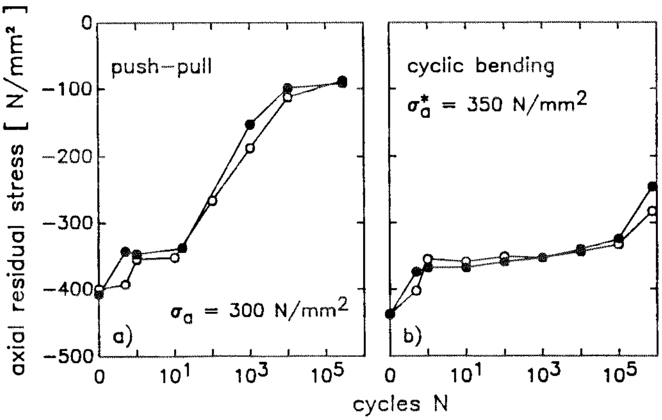

Fig. 7 Surface residual stresses as a function of number of cycles for push-pull loading (a) and cyclic bending loading (b)
(● first half cycle under compressive loading)
(o first half cycle under tensile loading)

During bending fatigue loading (Fig. 7b) with $\varepsilon_{a,t,s} = 1.7$ ‰ ($\sigma^*_{a,s} = 350$ N/mm²) the side of the specimen which is under compressive loading (●) reveals a significant decrease in residual stresses. On the tensile-loaded side of the specimen, however, only slight changes of the residual stress state can be detected. During further cyclic bending loading, only small changes of compressive residual stresses occur. Altogether, the residual stress relaxation is much more pronounced during push-pull loading than during cyclic bending loading.

DISCUSSION

During stress-controlled push-pull loading with $\sigma_a \geq 300$ N/mm², shot-peened specimens reveal already during the first loading cycle plastic deformations and cyclic softening effects. This is a consequence of the superpostition of compressive residual stresses and loading stresses, which immediately during the first half cycle leads to the exceedence of the compressive yield strength [6]. This is also proved by the residual stress developments plotted in Fig. 7. As a consequence of peening-induced increased dislocation density due to peening and of the occurring deformations, fatigue Lueders bands are immeditely teared off, which leads to cyclic softening of the specimens. The appearance of smaller plastic deformation amplitudes for N > 10 cycles may be caused by the shot peening induced surface workhardening.

For a better estimation of the cyclic deformation behaviour of shot-peened specimens, not only unpeened and shot-peened but also prestrained tensile specimens were investigated. A tensile prestraining of $\varepsilon_p = 5\ \%$ nearly corresponds to the plastic deformation induced during peening directly at the surface. The cyclic deformation curves of these specimens are characterized by very small plastic strain amplitudes [7]. Fig. 8 illustrates the cyclic stress-strain curves determined at a reference number of cycles of N = 200 for prestrained, unpeened and shot-peened specimens. The reference number of N = 200 was chosen firstly in order to eliminate the influence of cyclic softening on the cyclic stress-strain curve, which occurs in normalized material conditions at the beginning of cyclic loading [8], and secondly in order to maintain as far as possible the material state produced by the pre-treatment. In shot-peened specimens, whose material properties differ across the cross section, only the total strains remain constant over the cross section during push-pull loading. If one tries to describe the cyclic deformation behaviour of shot peened specimens, taking into account the behaviour of unpeened specimens representative of the interior of the specimen and that of predeformed specimens representative of the surface area, the following mixture rule must be valid at $\varepsilon_{a,t}$ = const. upon neglecting the still existing residual stresses:

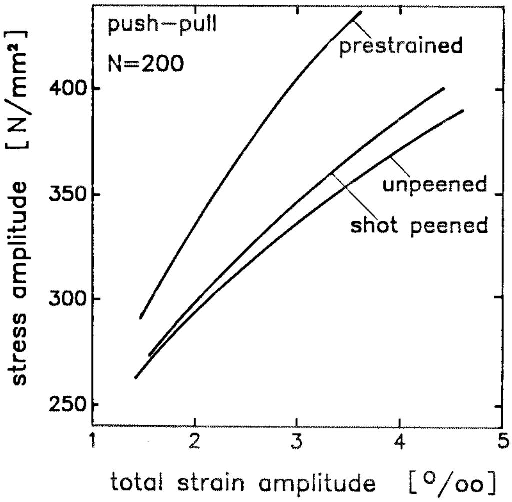

Fig. 8 Cyclic stress-strain curves at N = 200 cycles of stress-controlled push-pull loading for unpeened, shot peened and prestrained specimens

$$\bar{\sigma} = \sigma_S \cdot \frac{A_S}{A_t} + \sigma_C \cdot \frac{A_S}{A_t} . \qquad (1)$$

$\bar{\sigma}$ is the mean value of the stress amplitude generated in the shot peened specimen, σ_S is the stress amplitude of the predeformed and σ_C that of the unpeened specimen. A_S/A_t and A_C/A_t are the cross section ratios of the peening influenced and thus predeformed surface and the unaffected core. After being shot peened, the investigated round specimens show an A_s/A_t-value of about 0.23. If the arising stress amplitudes are plotted for the different material states versus the prestrained cross section ratio $\Delta A_p/A_t$, linear relationships are to be expected. $\Delta A_p/A_t$ is zero for not predeformed specimens, 0.23 for shot peened specimens and 1 for tensile predeformed specimens. For different $\varepsilon_{a,t,s}$-values, the appertaining stress amplitudes are taken from Fig. 8 and drawn in Fig. 9. It becomes obvious that the cyclic materials resistance of normalized, shot peened specimens at N = 200 cycles can be described by the aid of the mixture rule, using a simple composite model.

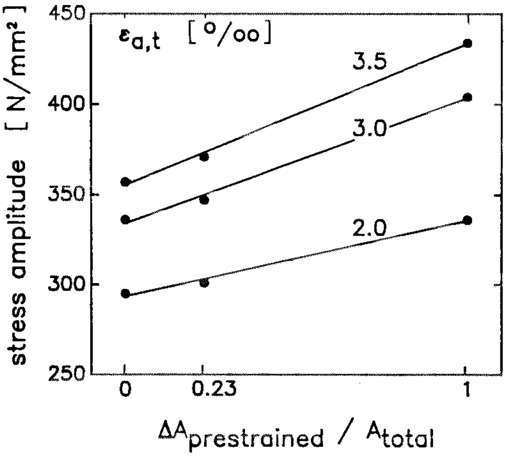

Fig. 9 Stress amplitudes as a function of prestrained cross section ratio for different total strain amplitudes

At $N > 10^3$ cycles, an approximation of the cyclic deformation curves of shot peened an unpeened specimens can be stated. However, the cyclic stress-strain curves of shot peened and unpeened specimens do not show any differences at $N_B/2$ (Fig. 6a). This finding is quite obviously a consequence of the rearrangement of the dislocation structure induced by shot peening into a dislocation structure which is characteristic for fatigue loading [6].

The fact that the stress amplitudes are higher in total strain-controlled experiments for shot peened specimens than for unpeened ones, is a result of a reduced plastic deformation effect and/or greater friction resistance due to larger internal stress fields of the existing dislocation structures. The cyclic stress-strain-controlled curves calculated in total-strain experiments for specimens of both material conditions are also plotted in Fig. 6a and show that also in this case there is no influence of the shot peening treatment at $N = N_B/2$. The cyclic stress-strain curves of both material conditions as well as the cyclic stress-strain curves from total-strain and total stress controlled experiments are in agreement. As a result it can be stated that the cyclic deformation behaviour of normalized specimens in both the unpeened and the shot peened condition is nearly identical under stress and total strain control.

If one analyses the cyclic stress-strain curves resulting from the cyclic bending test at $N_B/2$ (Fig. 6b), the fictitious surface stress amplitudes for shot peened specimens are markedly larger than those for unpeened ones at surface total strain amplitudes $\varepsilon_{a,t,s}$ between 2 ‰ and 4 ‰. These higher stress amplitudes are caused by the same microstructural processes as in the case of push-pull-loading. As a consequence of the stress gradient, the rearrangement of the dislocation structures proceeds much more slower during bending loading so that at $N_B/2$ a significant effect of the shot peening treatment on the cyclic deformation behaviour still exists for mean loadings. This conclusion is supported by the development of the residual stresses the relaxation of which proceeds slower under cyclic bending than under push-pull loading.

At small total strain values, the modelling of quasistatically calculated tensile stress-strain curves into bending stress-strain curves leads to a good agreement between theoretical considerations and experimental results [9]. Therefore, it seems to be reasonable to apply theses considerations also to cyclic stress-strain curves. For this purpose the stress-strain curves resulting from push-pull tests were approximated from the beginning of the cyclic yield strength, using a polygonal progression with 15 straight lines. Assuming a linear progression of the total strain amplitudes as a function of bending height, the distribution of the true stress amplitude can be estimated. Furthermore, taking into account the balancing of bending moments, it was possible to determine from the distribution of the true stress amplitude the fictitious stress amplitudes and the fictitious surface stress amplitudes. In the case of unpeened specimens, the calculated and the measured cyclic stress-strain curves are in good agreement at all reference numbers of cycles investigated [7].

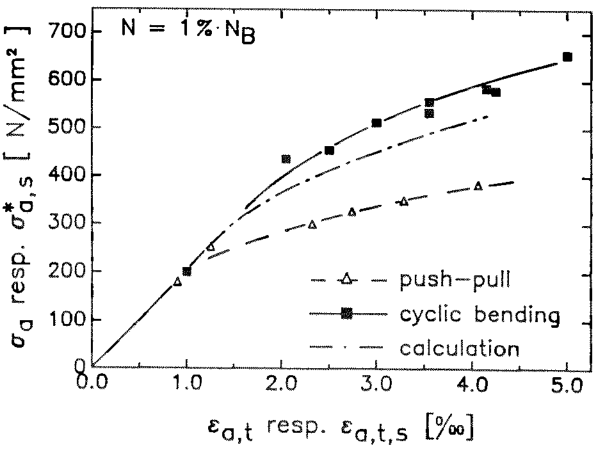

Fig. 10 Experimental and calculated cyclic stress-strain-curves of stress-controlled push-pull loading and strain-controlled cyclic bending for shot peened specimens

In the case of shot-peened specimens, however, smaller fictitious surface stress amplitudes are calculated at reference numbers of cylces of $N < N_B/2$ than experimentally observed. This finding is illustrated in Fig. 10 for 1 % of fatigue life ($N = N_B/100$).

In Fig. 11, the differences between measurement and calculation are illustrated for various surface total strain amplitudes plotted as a function of fatigue life. It can be seen that the differences significantly decrease with increasing number of cycles until 50 % N_B are reached.

Finally, it can be stated that due to inhomogeneous loading shot peening causes a stronger increase of the stress amplitudes during bending fatigue loading than during push-pull loading.

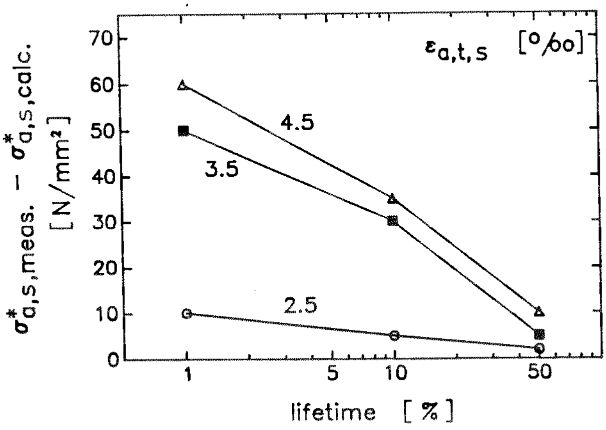

Fig. 11 Differences between measurement and calculation of cyclic stress-strain-curves as a function of fatigue lifetime

CONCLUSIONS

Shot peened specimens of the normalized 42 CrMo 4 show plastic deformations already during the first cycle independent of the experimental conditions. These plastic deformations result from the superposition of loading and compressive residual stresses. At N > 10 cycles, shot peened specimens reveal smaller plastic strain amplitudes than unpeened ones. This phenomenon results from the higher dislocations density in the surface layer. The deformation behaviour of shot peened specimens after push-pull loading can be described qualitatively using a composite model which allows to combine the behaviour of both unpeened and homogeneously predeformed specimens. With increasing number of cycles, the difference in the behaviour of shot peened and unpeened specimens, which is observed during push-pull loading as a result of rearrangement of dislocations, increases. Shot peening has a more pronounced influence on the cyclic deformation behaviour during bending fatigue loading than during push-pull loading. This effect is mainly caused by the inhomogeneous stress distribution with its maximum stress at the surface. If, cyclic stress-strain curves for cyclic bending, are calculated from those obtained from push-pull tests, the shot peened specimens show smaller stress values than experimentally determined. This is also a consequence of the different stress distributions during push-pull and cyclic bending loading, which cause a different effect on the shot peened surface layers.

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