THE 7th INTERNATIONAL CONFERENCE ON SHOT PEENING
ICSP 7
INSTITUTE OF PRECISION MECHANICS WARSAW, POLAND

INFLUENCE OF THE SHOT PEENING TEMPERATURE ON THE RELAXATION BEHAVIOUR OF RESIDUAL STRESSES DURING CYCLIC BENDING

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ABSTRACT

Shot peening of steels at elevated temperatures (warm peening) can improve the fatigue behaviour of workpieces. For the steel AISI 4140 (German grade 42CrMo4) in a quenched and tempered condition, it is shown that this is not only caused by the higher compressive residual stresses induced but also due to an enlarged stability of these residual stresses during cyclic bending. This can be explained by strain aging effects during shot peening, which cause different and more stable dislocation structures.

KEYWORDS

shot peening at elevated temperatures, relaxation behaviour, stability of residual stresses

INTRODUCTION

By inducing compressive residual stresses in the surface region, the fatigue life and the fatigue limit of materials with medium and high hardness can be improved. The compressive residual stresses can be induced for example by shot peening. It was shown already that the fatigue life increases as well with increasing amount of the compressive residual stresses as with their stability [1;2]. Shot peening of steels at elevated temperatures (warm peening) is an effective way to increase the stability of the residual stresses. Whereas several investigations are known dealing with the mechanical stability of residual stresses induced by shot peening at room temperature [3-6] no systematic study is known concerning the stability of residual stresses induced by warm peening. Therefore, in this report results of alternating bending tests are presented for conventionally peened and warm peened samples made from the steel AISI 4140 (German grade 42 CrMo 4) in a quenched and tempered condition.

MATERIAL AND SPECIMEN GEOMETRY

The steeel AISI 4140 (German grade 42 CrMo 4) was used in the current experiments. The chemical composition was 0.40 C, 0.98 Cr, 0.17 Mo, 0.18 Si, 0.63 Mn, 0.01 P, 0.03 Al and the rest Fe (all in wt.-%). The samples were machined from flat material and ground to a thickness of 2.2 mm. Thereafter the samples were austenized for 20 min at 850°C, oil quenched down to 25°C, tempered at 450°C for 2 h and cooled down in a vacuum furnace. After the heat treatment the samples were ground to a thickness of 2.0 mm in order to eliminate distortions in the flatness of the material. After grinding small compressive residual stresses with $|\sigma^{rs}| < 100$ N/mm^2 were found in the near surface layer. The final geometry of the samples is shown in Fig. 1.

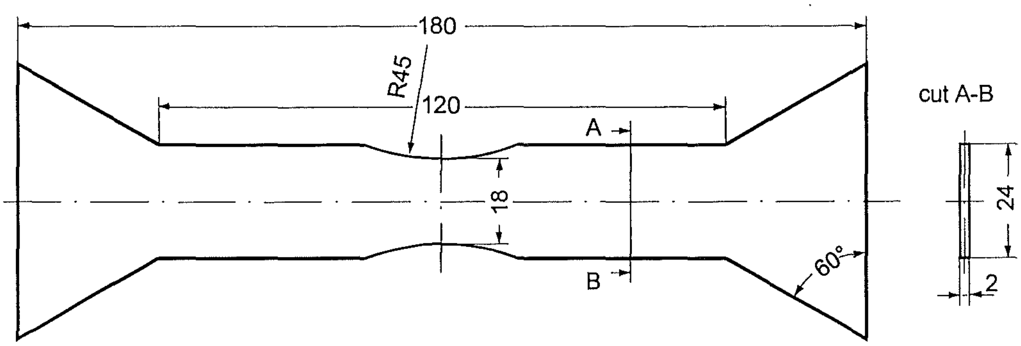

Fig. 1: **Sample geometry**

EXPERIMENTAL PROCEDURE

The shot peening treatments were performed using an air blast system with supplemented flow heater [7], allowing peening temperatures 20°C $\le T_{peen} \le$ 290°C. By simultaneously peening both surfaces shot peening induced distortions were avoided. Cast iron shot S 170 56 HRC was used at a peening pressure of 1.2 bar and a media flow rate of 1.0 kg/min. The resulting coverage was about 98%.
The bending fatigue experiments were performed on alternating bending machines at 25 Hz. Therefore, the sample geometry was changed by sawing the ears of the samples in a way that 110 mm long specimens remained. In order to get knowledge about the relaxation behaviour, the residual stresses and the half width of the interference lines as a measure of work-hardening and dislocation density, respectively, at the surface were determined after predefined cycle numbers, using the X-ray technique. The residual stresses were determined using CrKα-radiation and the {211}-interference lines of each specimen at 9 ψ-angles between -60° and +60° according to the $\sin^2\psi$-method [8], with a Young's modulus of E = 210000 N/mm^2 and a Poison's ratio of ν = 0,28. The depth distribution of the residual stresses was determined by electrolytic removal of thin surface layers and subsequent X-ray measurements. These residual stress values were corrected according to the method of [9].

EXPERIMENTAL RESULTS

The depth distributions of the residual stresses and half widths of samples shot peened at different temperatures are shown in Fig. 2. It can be seen that an increase of peening temperature has little influence for the residual stresses (Fig 2, left). The surface value σ_s^{rs} is increasing slightly with T_{peen}. For a peening temperature of 250°C this value shows its maximium (σ_s^{rs} = -700 N/mm^2). At the samples peened at 200°C and 290°C σ_s^{rs} = -605 N/mm^2 and -660 N/mm^2 is measured at the surface, which is higher than the value of the conventional (T_{peen} = 20°C) peended sample (σ_s^{rs} = -600 N/mm^2).

The depth x_0 where the residual stresses change their sign, is also slightly increasing with the peening temperature. For the sample peened at 20°C x_0 = 0,155 mm is determined, for the one warm peened at 290°C x_0 is 0,170 mm.

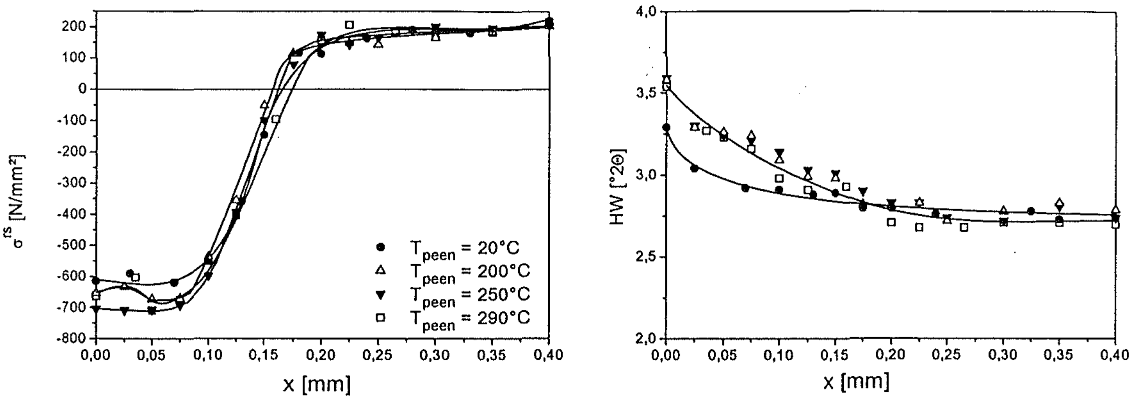

Fig. 2: **Distribution of residual stresses (left) and half widths (right) of samples shot peened at different temperatures**

The distributions of the half widths for the samples peened at different temperatures show clear differences. For all samples examined the values in the core region are smaller than in the near surface region. The maximum value can be found at the surface in all cases. For the conventional peened variant the surface value is 3,3 °2Θ, compared to 3,6 °2Θ for the three variants peened at elevated temperatures.
The fatigue strengths of the variants peened at 20°C, 200°C and 290°C were investigated in alternating bending tests. The resulting S-N-curves for a failure probability of 50% are shown in Fig. 3.

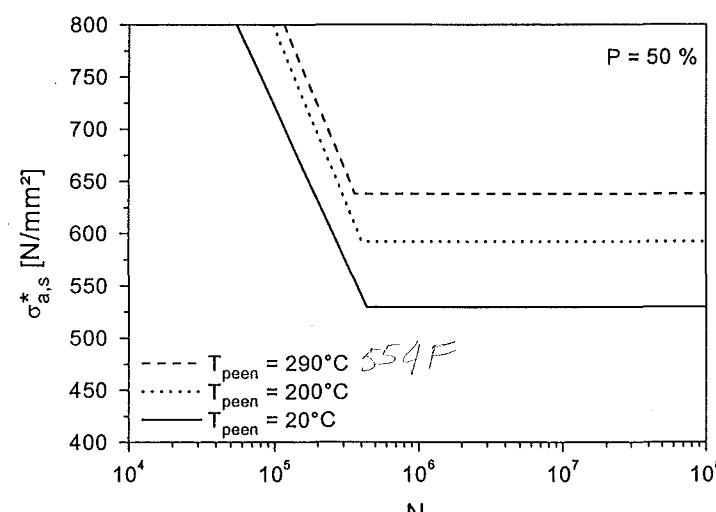

Fig. 3: **S-N-curves for samples peened at different temperatures for a failure probability P = 50%**

Each curve was determined using 25-30 samples at different ficticious surface stress amplitudes $\sigma^*_{a,s}$. The fatigue strength $R_{bW,50}$ is increasing with the peening temperature. The variant peened at 20°C has the smallest fatigue strength ($R_{bW,50}$ = 530 N/mm^2). Peening at 290°C (200°C) increases $R_{bW,50}$ to 640 N/mm^2 (590N/mm^2). The fatigue life at higher loadings also increases with the peening temperatures.
For the samples peened at 20°C and 290°C the stability of the residual stresses was investigated in detail. The distribution of the residual stresses and the half widths in the region close to the surface was determined at different numbers of cycles at a ficticious surface stress amplitude $\sigma^*_{a,s}$ = 1000 N/mm^2. The curves for the conventionally peened samples show that the compressive residual stresses and the half widths in the region close to the surface are strongly reduced with increasing number of cycles (see Fig. 4). During the first cycle the residual stress amount of the surface decreases from about 600 N/mm^2 to 350 N/mm^2. After N = 1000 this amount is 150 N/mm^2. The depth where the residual stresses change their sign is not significantly affected. The half widths at the surface are reduced from 3,3°2Θ to 2,8°2Θ after N = 1000.

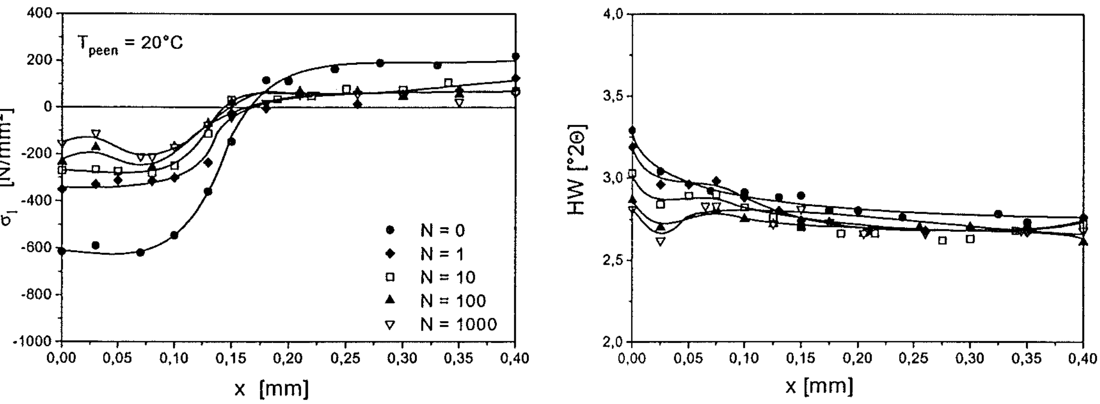

Fig. 4: **Distribution of residual stresses and half widths for samples shot peened at 20°C after different numbers of cycles at $\sigma^*_{a,s}$ = 1000 N/mm^2**

The curves for the warm peened samples (T_{peen} = 290°C) can be seen in Fig. 5.

MORE STABLE DISLOCATION ARRANGEMENT

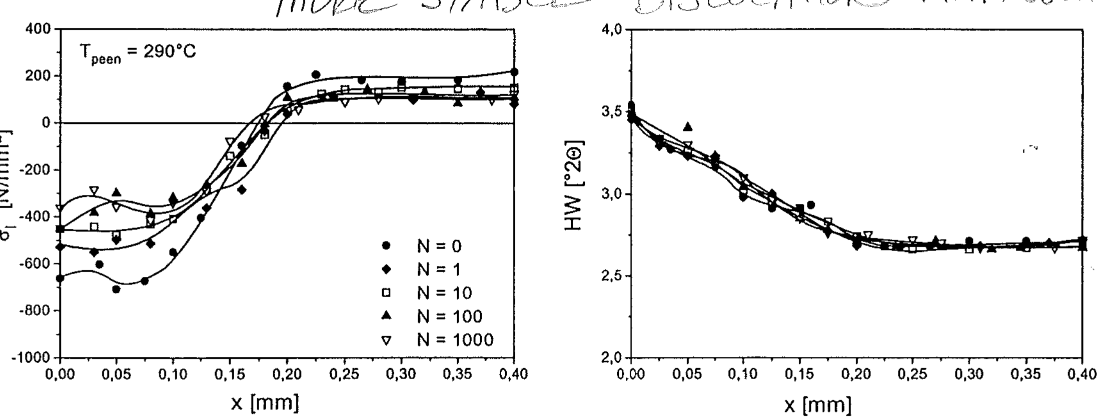

Fig. 5: **Distribution of residual stresses and half widths for samples shot peened at 290°C after different numbers of cycles at $\sigma^*_{a,s}$ = 1000 N/mm^2**

During the first cycle the initial amount of the residual stresses at the surface | σ_s^{rs} | = 660 N/mm² is only reduced by about 140 N/mm². After N = 1000 | σ_s^{rs} | = 380 N/mm² is measured. The half widths distribution has not significantly changed during all 1000 cycles.

In order to get complete information about the stability of the surface residual stresses in longitudinal direction, samples were loaded at different ficticious surface stress amplitudes with 300 N/mm² $\leq \sigma_{a,s}^* \leq$ 1000 N/mm² for different numbers of cycles up to failure or 10^7 cycles. The results of these investigations can be seen in Fig. 6 for conventional peened samples (left) and samples warm peened at 290°C (right). The given residual stresses are mean values at the measures of the upper and lower side of the sample.

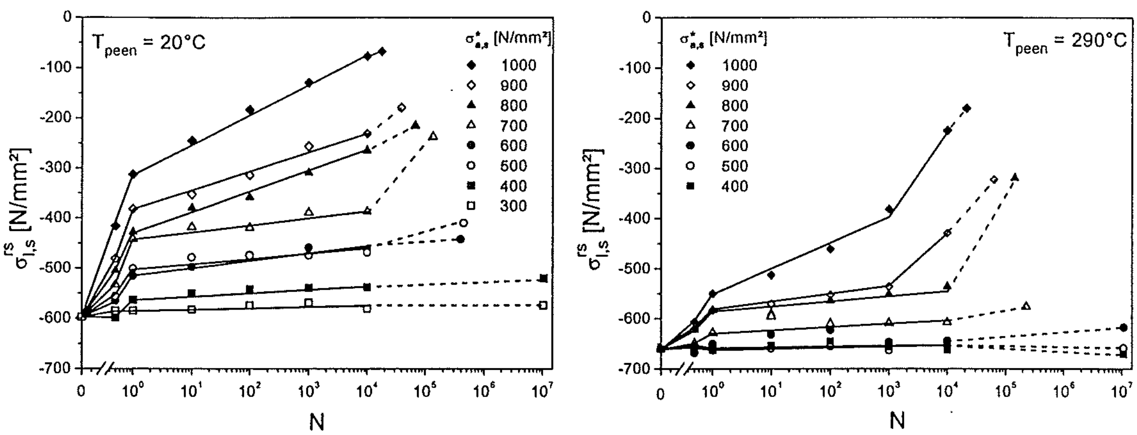

Fig. 6: **Surface residual stress values in longitudinal direction $\sigma_{l,s}^{rs}$ vs. number of cycles at different ficticious surface stress amplitudes $\sigma_{a,s}^*$ for samples peened at T_{peen} = 20°C (left) and T_{peen} = 290°C (right)**

For both peening variants the residual stresses at the surface relax more rapidly with increasing load amplitude as well during the first cycle as during further cycling. A linear correlation between residual stresses and the logarithm of the number of cycle N can be recognized over wide intervals of N ≥ 1.

In the conventionally peened samples, however, the residual stresses relax much more than in the warm peened samples. Pronounced differences can be seen especially for N ≤ 1 where the residual stresses in the warm peened samples show a much higher stability than the conventionally peened ones. For N ≥ 1 the residual stresses in the variant peened at room temperature relax also much more than in the variant peened at T_{peen} = 290°C.

The resulting half widths at surface HW_s are shown in Fig. 7 related to their initial values $HW_{s,0}$. As in Fig. 6 the conventionally peened variant is shown on the left, the warm peened variant on the right side of Fig. 7. The half widths of the conventionally peened samples relax for $\sigma_{a,s}^* \geq$ 700 N/mm². With increasing loading amplitude an increasing relaxation is observed.

The samples peened at elevated temperatures show big differences in the relaxation behaviour of the half widths at surface. The measured values after cycling are often a little bit higher than the initial values. Only for $\sigma_{a,s}^* \geq$ 900 N/mm² and N ≥ 10^4 a significant decrease can be seen.

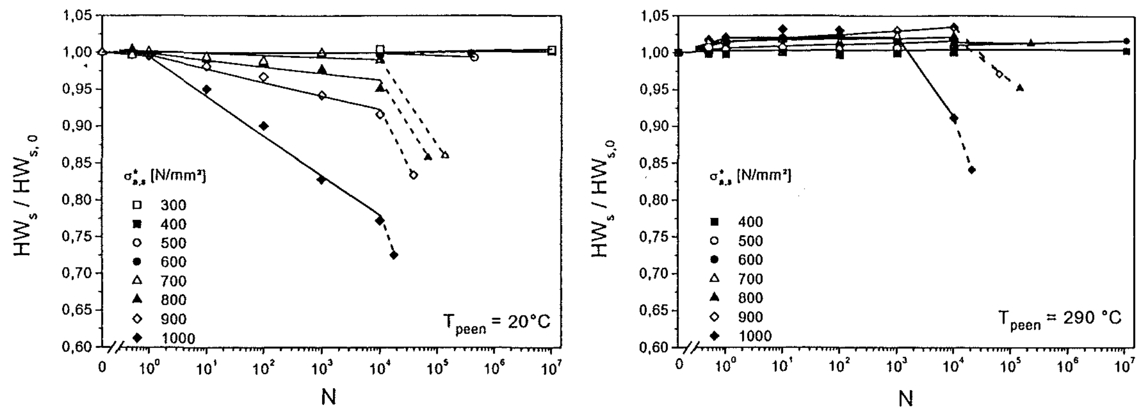

Fig. 7: **Ratio $HW_S/HW_{s,0}$ vs. number of cycles at different ficticious surface stress amplitudes $\sigma^*_{a,s}$ for samples peened at $T_{peen} = 20°C$ (left) and $T_{peen} = 290°C$ (right)**

DISCUSSION

The relaxation of the residual stresses can be subdivided into a quasistatic ($N \leq 1$) and a cyclic ($N \geq 1$) phase.

During the first phase the residual stresses are not changed as long as the applied load at the surface σ^*_s is smaller than a critical load $\sigma^*_{s,crit.}$. The critical load can be found when the residual stress values after the first cycle are plotted over the applied load σ^*_s. In Fig. 8 this was done for the conventionally peened (left) and the warm peened (right) variant for data points which are characterized by N = 1.

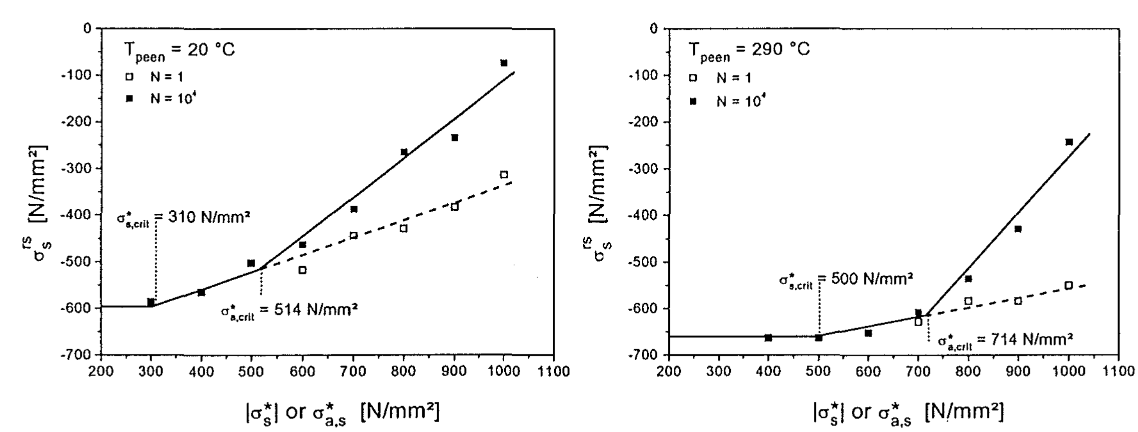

Fig. 8: **Surface residual stresses after N = 1 or 10^4 for conventionally peened (left) and warm peened (right) samples**

It can be seen, that the critical load where quasistatic residual stress relaxation begins, is much smaller for the conventionally peened variant ($\sigma^*_{s,crit.}$ = 310 N/mm^2) than for the variant peened at 290°C ($\sigma^*_{s,crit.}$ = 500 N/mm^2).

By use of the critical load and the initial residual stress value at the surface, the compressive yield strength of the peened surface region $R_{e(c),s}$ can be estimated. Since shot peening generates a biaxial residual stress state with nearly identical components in longitudinal and transverse direction, $R_{e(c),s}$ can be calculated using the v. Mises hypothesis [10]:

$$\left|R_{e(c),s}\right| = \sqrt{\left(\sigma_s^{rs} + \sigma^*_{s,crit}\right)^2 + \left(\sigma_s^{rs}\right)^2 - \left(\sigma_s^{rs} + \sigma^*_{s,crit}\right)\sigma_s^{rs}} \qquad (1)$$

When this is carried out for the two variants investigated, clear differences of $R_{e(c),s}$ can be recognized (see Tab. 1). For both variants, however, the resulting compressive yield strength of the surface is smaller than the one of the core region, which was found to be 1300 N/mm^2 in compression tests [11]. This is due to the Bauschinger-effect, which is quite distinct in quenched and tempered steels. However, the work-softening is much smaller for the warm peened samples than for the samples peened at room temperature. This is due to strain aging effects occuring while and after warm peening. This results in a different and more stable dislocation structure caused by pinning of dislocations and formation of finest carbides.

	$\sigma^*_{s,crit.}$ [N/mm^2]	σ_s^{ES} [N/mm^2]	$R_{e(c),s}$ [N/mm^2]	$R_{e(c),s}/R_{e(c)}$
T_{peen} = 20°C	-310	-600	801	0,60
T_{peen} = 290°C	-500	-660	1008	0,78

Tab. 1: Estimation of quasistatic surface yield strength in compression at quasistatic loading

The residual stress relaxation during cyclic loading is characterized by a linear reduction of residual stresses reduction with the logarithm of the number of cycles for $1 \leq N \leq 10^4$. Therefore, the residual stress values at the surface after 10^4 cycles can be taken as a measure of the degree of cyclic relaxation. These values are shown in Fig. 6 for the conventionally and warm peened variant vs. the magnitude of the applied load amplitude at the surface $\sigma^*_{a,s}$. The linear fit of these points is intersecting the line fitted through the residual stresses measured at N = 1. At this point the critical load amplitude $\sigma^*_{a,crit.}$ occurs, which is a measure for the onset of cyclic residual stress relaxation. By using the residual stresses at the surface after N = 1 and the assumption, that the residual stress state at the surface is still almost axisymmetric, the cyclic yield strength at the surface $R^{cycl.}_{e,s}$ can be calculated based on Eq.1 (see Tab. 2).

	$\sigma^*_{a,crit.}$ [N/mm^2]	σ_s^{rs}(N = 1) [N/mm^2]	$R^{cycl.}_{e,s}$ [N/mm^2]	$R^{cycl.}_{e,s} / R^{cycl.}_{e}$
T_{peen} = 20°C	514	-520	895	0,82
T_{peen} = 290°C	714	-620	1156	1,07

Tab. 2: Estimation of the cyclic surface yield strength for differently shot peened variants for cyclic loading

It can be seen that $R^{cycl.}_{e,s}$ for the conventionally peened samples is much smaller than the one for the warm peened samples. Moreover the ratio of the calculated cyclic yield strength at the surface and the one for the core region $R^{cycl.}_{e}$ found in push-pull tests [12] indicates, that the cyclic work-softening typical for quenched and tempered material states does not appear in the warm peened variant ($R^{cycl.}_{e,s} / R^{cycl.}_{e}$ = 1,07). The increase of $R^{cycl.}_{e,s}$ at the warm peened samples is assumed to be the result of a very strong pinning of

dislocations by clouds of carbon atoms and finest carbides which are results of dynamic and static strain aging effects during and after warm peening treatment. This pinning is so strong that even at highest load amplitudes $\sigma^*_{a,s}$ the pinned dislocations can not move. Therefore, dislocations that were newly generated during cyclic loading cause the residual stress relaxation. The increase of the half widths for the warm peened variant during alternating bending tests (see Fig. 6) is a hint for this assumption.
The increase of the fatigue strength with increasing peening temperature for $T_{peen} \leq 290°C$ (see Fig.3) is also due to the strain aging. At about 300°C the maximum effect of dynamic strain aging is expected. Therefore, the fatigue life of the variant peened at 290°C is highest, although the compressive residual stresses measured at the sample peened at 250°C are higher than those for the variant peened at 290°C.

SUMMARY

Shot peening of quenched and tempered steel AISI 4140 at elevated temperatures increases the stability of the compressive residual stresses and the half widths compared to conventional shot peening at room temperature. The stability of the residual stresses is improved as well at quasistatic loading as at cyclic loading. As a qualitative measure of the residual stress stability, the compressive yield strength and the cyclic yield strength of the influenced surface region were determined for conventionally peened and warm peened samples. For the samples peened at elevated temperature (T_{peen} = 290°C) these measures are significantly higher. This is caused by strain aging effects occurring while and after shot peening, resulting in different dislocation structures due to pinning of dislocations by carbon clouds and finest carbides.

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