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SHOT PEENING AND STRESS PEENING OF AISI 4140 AT INCREASED TEMPERATURES

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ABSTRACT

With a new system shot peening and stress peening using an air blast machine at elevated temperatures is feasible. The effects of conventional shot peening, stress peening, warm peening and stress peening at elevated temperatures on the characteristics of near surface layers, on the stability of residual stresses and half widths and on the fatigue strength of a quenched and tempered AISI 4140 steel (German grade 42 CrMo 4) will be presented. The alternating bending strength is increased by stress peening as well as by warm peening compared to conventional shot peening.

KEYWORDS

stress peening, shot peening at elevated temperatures, fatigue strength, residual stresses

INTRODUCTION

Shot peening is an often used surface treatment process used to improve the fatigue strength and fatigue life of cyclically loaded components. This improvement is achieved by inducing compressive residual stresses and work-hardening effects in areas close to the surface. Beside the magnitude of the residual stresses, their stability during cyclic loading is of great importance. The possible increase in the fatigue resistance by using conventional shot peening treatments is limited. Therefore it is necessary to modify the shot peening process. One possible modification is to load the component in tensile direction while shot peening, which causes higher compressive residual stresses in the area close to the surface in tensile loading direction [1-3]. This process has been used in the spring industry for many years, already. Another possible way to improve the shot peening result is to carry out the process at elevated temperatures. Only few, not any systematic investigations have been made upon this topic [4].

For that, an air blast system was supplemented with a stress peening device and an air flow heater in order to perform the stress peening, warm peening and stress peening at elevated temperatures [5]. The investigations were performed with flat samples made from the steel AISI 4140 (German grade 42 CrMo 4) in a quenched and tempered condition. The characteristics of the regions close to the surface as well as their stability and the fatigue strength at alternating bending will be compared for differently shot peened variants.

MATERIAL AND SPECIMEN GEOMETRY

The investigations were carried out at the steel AISI 4140 (German grade 42CrMo4) with the chemical composition 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.

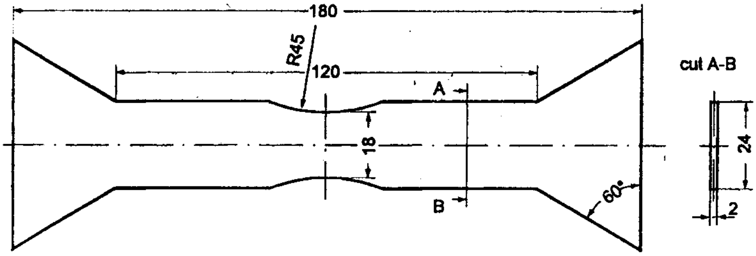

Fig. 1: **Sample geometry and dimension**

EXPERIMENTAL PROCEDURE

The shot peening treatments were performed using an air blast system, which is shown schematically in Fig. 2.

The stress peening device (SP) allows to set the sample under a defined load while shot peening. For shot peening at elevated temperatures a second air flow was heated up to a maximum of 500°C in an electrical flow heater (FH). This air flow was mixed with the cold air and the peening media in a nozzle system. This system allows a sample temperature while shot peening of $T_{peen} \leq 290$°C. The samples were peened from both sides simultaneously in order to avoid distortions. 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%.

After shot peening the residual stress state was determined in longitudinal direction of the specimen using the X-ray technique. The residual stresses were analyzed with CrKα-radiation at the {211}-interference lines of each specimen at 9 ψ-angles between -60° and +60° according to the $\sin^2\psi$-method [6]. For that a Young's modulus of $E = 210000$ N/mm^2 and a Poison's ratio of $\nu = 0{,}28$ were used. 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 [7].

The alternating bending tests were carried out on alternating bending machines at a frequency of 25 Hz. Therefore, the sample geometry was changed by sawing the ears of the samples in a way that 110 mm long specimens remained. Tests in order to determine the stability of the surface residual stresses upon alternating bending at a fixed initial stress amplitude were all performed using a single specimen by interrupting the test at predefined numbers of cycles, measuring the residual stresses and starting the test again.

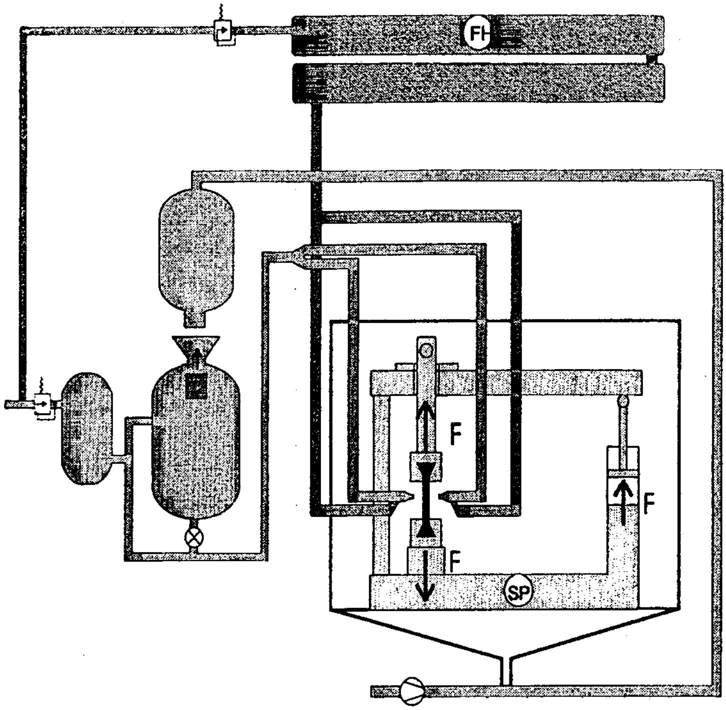

Fig. 2: **Air blast system with supplemented stress peening device (SP) and air flow heater (FH)**

EXPERIMENTAL RESULTS

The different shot peening methods, conventional shot peening (T_{peen} = 20°C, σ_{pre} = 0), stress peening at room temperature (T_{peen} = 20°C, σ_{pre} = 500 N/mm^2), warm peening (T_{peen} = 290°C, σ_{pre} = 0 N/mm^2) and stress peening at elevated temperature (T_{peen} = 290°C, σ_{pre} = 500 N/mm^2), cause clear differences in the surface roughness, the residual stress state and the micro deformation state of the samples, which is characterized by the half widths of the X-ray interference lines.
The surface roughness R_Z for the differently shot peened samples are listed in Tab. 1. It can be seen that applying a load while shot peening has no significant effect on the roughness of the peened sample. Shot peening at elevated temperature, however, increases the R_Z values markedly.

	T_{peen} = 20°C	T_{peen} = 290°C
σ_{pre} = 0	8,1 µm	11,3 µm
σ_{pre} = 500 N/mm^2	8,5 µm	10,4 µm

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Tab. 1: **Surface roughness R_Z for differently shot peened samples**

The residual stress distribution of the different variants are shown in Fig. 3, the distribution of the half widths in this samples is given in Fig. 4. The conventionally peened sample shows the smallest compressive residual stresses and the depth x_0 where the residual stresses change their sign is also minimal (x_0 = 0,165 mm). These values are only slightly higher for the warmly peened sample. Marked differences to the conventionally peened sample can be recognized for the stress peened variant. Here at the surface a residual stress of σ_s^{rs} = -790 N/mm^2 is measured, compared to -610 N/mm^2 for the sample that is peened without load. Moreover, the depth where the residual stresses change their sign is also higher. The highest values for the induced compressive residual stresses and x_0, however, is found at the specimen, which is stress peened at elevated temperatures (σ_s^{rs} = -950 N/mm^2 and x_0 = 0,21 mm).

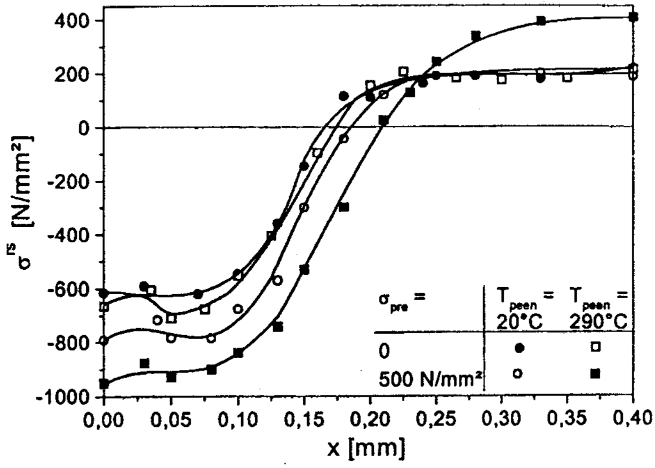

Fig. 3: Depth distribution of the residual stresses of differently shot peened samples

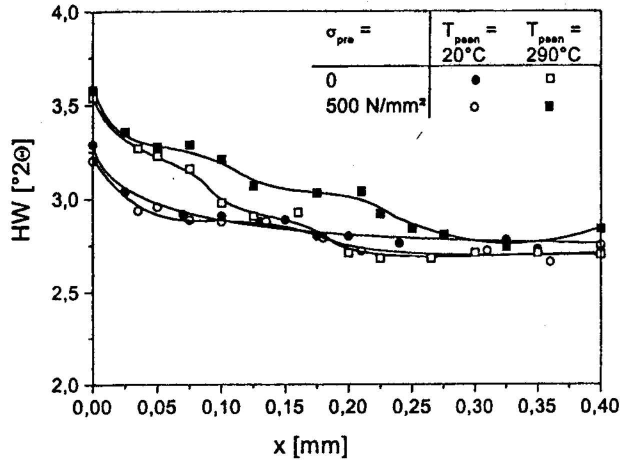

Fig. 4: Depth distribution of the half widths of differently shot peened samples

The depth distribution of half widths of the conventionally peened sample shows no significant differences to the one of the stress peened samples (T_{peen} = 20°C, σ_{pre} = 500 N/mm^2). In both cases the values close to the surface are higher than in the core region (2,7 °2Θ). At the surface the largest half width ($HW_s \approx 3,2$ °2Θ) is measured. For the variants peened at elevated temperatures the half widths close to the surface region is much higher ($HW_s \approx 3,55$ °2Θ). The thickness of the layer that shows higher values than the core does, is much larger for the sample that was stress peened at T_{peen} = 290°C, compared to all other variants. The residual stress relaxation at the surface for differently shot peened samples after alternating bending at $\sigma^*_{a,s}$ = 1000 N/mm^2 is shown in Fig. 5. The given residual stress values are average values of the measured residual stresses of the upper und lower sample side after a specific cycle number.

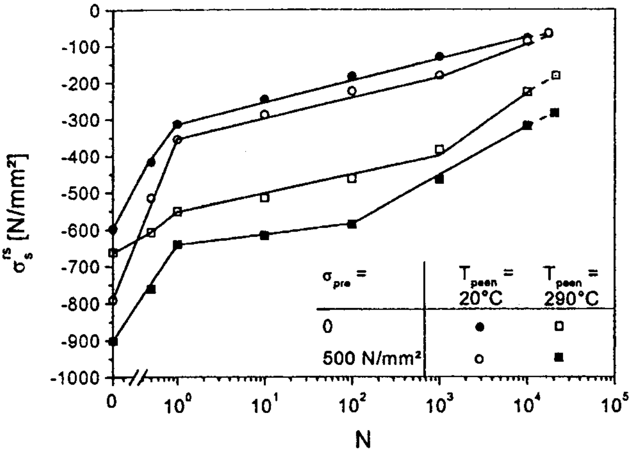

Fig. 5: **Residual stress vs. number of cycles for differently shot peened samples upon alternating bending at $\sigma_{a,s}^{*} = 1000$ N/mm²**

During the first cycle a distinct relaxation of the residual stresses occurs. Especially the stress peened sample shows a strong reduction so that after the first cycle the residual stress is similar to that in the conventionally peened sample. During cyclic loading, it can be seen that the residual stress relaxation of the two samples that were peened at room temperature is quite similar, nevertheless the benchmarks of the residual stresses are much higher for the stress peened sample than for the conventionally peened one.

The samples that were shot peened at T_{peen} = 290°C show a much higher stability of the residual stresses. Especially after the first cycle much higher residual stresses than the samples peened at room temperature remain. Also for $1 < N < N_f$ the warm peened specimen have markedly higher compressive residual stresses and show a slightly smaller decrease with increasing N compared to the ones peened at T_{peen} = 20°C.

The relaxation behaviour of the half widths at the surface for the differently peened variants is shown in Fig. 6. Here the measured surface values HW_s are related to the surface values $HW_{s,0}$ of the samples directly after shot peening.

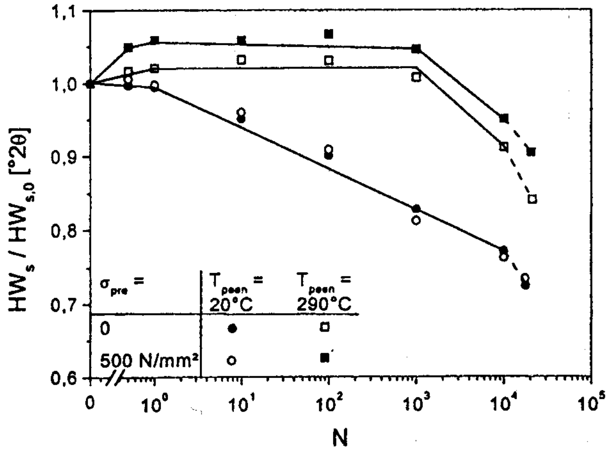

Fig. 6: **Half width vs. number of cycles for differently shot peened samples upon alternating bending at $\sigma_{a,s}^{*} = 1000$ N/mm²**

The half widths of the samples peened at room temperature decrease strongly with increasing number of cycles. Within the first cycle a slight decrease can already be recognized. For the two variants peened at T_{peen} = 290°C, a completely different relaxation behaviour of the half width is observed. After N = 1 cycle the measured values are slightly higher than the values directly after shot peening. Up to 1000 cycles the half width state seems to be stable. Thereafter a decrease of the half width values can be seen.
The fatigue strength of the four different variants was investigated in alternating bending tests. The resulting S-N curves for a failure probability of 50% are shown in Fig. 7. Each curve was determined using 25-30 samples at different ficticious surface stress amplitudes $\sigma^*_{a,s}$.

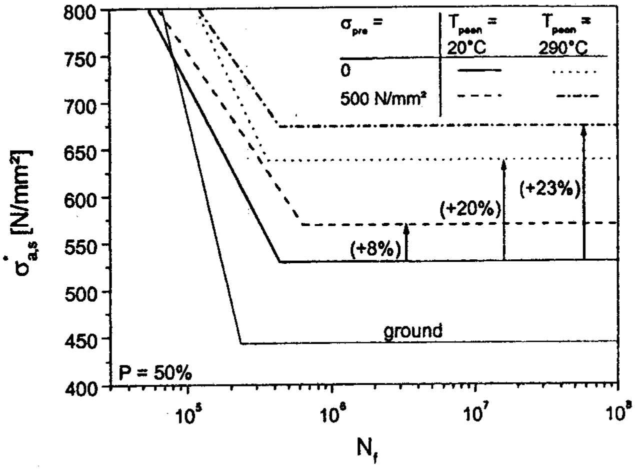

Fig. 7: S-N curves for grinded and differently shot peened samples (P = 50%)

Shot peening at room temperature increases the fatigue strength for about 85 N/mm² from 440 N/mm² to 530 N/mm² compared to the ground condition. Stress peening (σ_{pre} = 500 N/mm²) at T_{peen} = 20°C results in a further increase of the fatigue strength (R_{fat} = 570 N/mm²). However, the effect of warm peening on the fatigue strength is even higher. Compared to the conventionally peened condition, the peening at T_{peen} = 290°C increases the fatigue strength for about 20% to R_{fat} = 640 N/mm². An even higher value for this property (R_{fat} = 670 N/mm²; +23%) was determined for the samples stress peened at elevated temperatures.

DISCUSSION

The increasing fatigue strength caused by stress peening can be explained by the higher longitudinal compressive residual stresses close to the surface. They form a higher obstacle for crack propagation than the smaller compressive residual stresses induced by conventional shot peening. The work hardening state, however, is not influenced by the load applied during the shot peening treatment. Therefore, no significant differences in the depth distribution of the half widths of samples peened at room temperature with and without a load can be found. The cyclic relaxation behaviour of the residual stresses and the half widths of the conventionally peened and the stress peened variant is similar.
Compared to the conventionally peened condition, the significantly higher fatigue strength of the warm peened variant cannot only be explained with the slightly higher compressive residual stresses. Moreover the higher stability of the residual stresses seems to have a marked influence. This increase of the residual stress stability is due to dynamic and static strain aging appearing while and after the shot peening at elevated temperatures. A higher dislocation density and a different dislocation structure due to pinning of dislocations and formation of finest carbides close to the surface is the result of the strain aging. The limited dislocation mobility in the warm peened condition causes the increase of the fatigue strength. Another hint

for the assumptions made are the higher half widths in the affected surface layer and their high stability during cyclic loading.

The further increase of the fatigue strength at the variant stress peened at elevated temperatures is an effect of both, the higher compressive residual stresses and their higher stability caused by strain aging.

SUMMARY

Shot peening during loading (stress peening) and at elevated temperatures increase the fatigue strength of the samples made of quenched and tempered AISI 4140 compared to conventional shot peening. For the stress peened variant this is caused by higher compressive residual stresses. The warm peened samples also have slightly higher compressive residual stresses than the conventionally peened ones. But more important, the stability of the residual stresses and half widths is improved by peening at elevated temperatures. This is due to strain aging processes while and after warm peening. For the samples stress peened at elevated temperatures the highest fatigue strength is achieved. This is caused by the higher residual stresses induced as well as their high stability.

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