Influence of Piezo Peening on the Fatigue Strength of quenched and tempered AISI 4140

F. Lienert, J. Hoffmeister, A. Erz, V. Schulze

Institute of Applied Materials (IAM – WK), Karlsruhe Institute of Technology, Germany

Abstract

Piezo Peening is a new alternative mechanical surface treatment process and can be assigned to machine hammer peening processes. Similar to ultrasonic impact treatment (UIT) processes a piezo actuator with an indenter is causing mechanical deformation of the surface area by multiple impacts in a previously defined pattern. However, in contrast to UIT, there is no horn or sonotrode to increase the amplitude. Only the piezo actuator induces the oscillation of the indenter. By different combinations of process parameters like frequency, amplitude, indenter hardness and diameter etc. a wide range of specific surface layer states with varying residual stress depth distributions and surface roughnesses can be created. By this process the whole range of surface layer characteristics from shot peening to deep rolling can be adjusted. An optimal surface layer state concerning axial cyclic loading of the utilized sample geometry with a measuring diameter of 7 mm was chosen and characterized concerning residual stresses, work hardening and surface roughness. An S-N curve for this parameter combination was determined and compared to the initial state. To show the benefit of this new process this is compared to shot peening and deep rolling as well. For this purpose a variation of Almen intensity and deep rolling pressure was performed in order to identify the best parameters for axial cyclic loading at 650 MPa. The S-N curve was determined afterwards for the sample with the highest number of cycles to failure, respectively. Furthermore the location of crack initiation was analyzed to show that a transition from crack initiation at the surface to crack initiation below the surface is possible.

Keywords Piezo peening, mechanical surface treatment, fatigue strength, AISI 4140.

Introduction

Mechanical surface treatments are widely used processes for strengthening the surface layer of components, especially cyclically loaded components. The mechanical surface treatment influences the surface layer concerning surface roughness, residual stresses and work hardening. In general a low surface roughness and high work hardening reduce crack initiation at the surface. Furthermore compressive residual stresses in the surface layer counteract crack propagation [1]. Nevertheless the surface layer properties have to be adjusted to the applied load. Comparing the increase in fatigue strength of a piezo peened state to a shot peened and a deep rolled state, the potential of the Piezo Peening [1] process needs to be evaluated.

Experimental Methods

The material used for experimental investigation was quenched and tempered (450°C/ 2 h) AISI 4140. The chemical composition of the steel is shown in Table 1. The hardness after heat treatment is about 450 HV0.1.

Table 1: Chemical composition of AISI 4140.

Chemical composition wt.-%						
C	Cr	Mo	Mn	Si	Ni	Fe
0.42	1.04	0.2	0.73	0.24	0.06	base

Round specimens with a diameter of 7 mm and a gauge length of 17 mm were used for cyclic tension-compression tests. The latter were carried out on a servohydraulic testing machine (type Schenck) with R = -1 and a testing frequency of 50 Hz. The limiting number of load cycles was set to 10^7. The experimental data were analyzed according to the arcsin√P method [3]. To determine the state with the highest fatigue strength for each mechanical surface treatment, a parameter variation was carried out. Specimens were shot peened with a compressed air shot peening system type Baiker. Regarding shot peening the Almen intensity was varied. The specimen were deep rolled with a hydrostatic device of ECOROLL AG, with a ball diameter of 6.35 mm. Regarding deep rolling the hydrostatic pressure was varied. For Piezo Peening a self-developed tool [1] was used. Different parameter combinations based on [1] and [4] were chosen. For all states, the number of cycles to failure at a load level of 650 MPa was compared and the best state was chosen for a full S-N-curve. Besides this, the surface layer of the chosen states was characterized. Residual stresses in axial direction were measured using X–ray diffraction technique according to the $\sin^2\Psi$-method [2]. The measurement was done with Cr-Kα-radiation at the {211}-α-ferrite diffraction line at $2\theta_0 = 156.394°$ and 13 different ψ–angles from ±60° with equidistant $\sin^2\psi$ steps. The primary beam was formed by a pinhole collimator with a nominal diameter of 0.5 mm and on the secondary side a symmetrization slit was used in front of the detector. Fitting of the interferences lines was done by using a Pearson VII function and for stress calculations $E^{\{211\}} = 219911$ MPa and $\nu^{\{211\}} = 0.28$ were applied. Furthermore the average value for full width at half maximum (FWHM) was calculated from $\psi = \pm 20.7°$ and $\psi = 0°$ interference peaks. An incremental electrolytic layer removal was used to obtain the residual stress depth distribution. Stress redistributions due to layer removal are not taken into account. Surface topography and roughness were measured using a confocal white light microscope.

Experimental Results

The shot peening experiments showed that the state with Almen intensity of 0.21 mmA had the highest number of cycles to failure. The shot peening parameters are listed inTable 2; the coverage was 100 %.

Table 2: Shot peening parameter for S-N curve determination

Pressure	1 bar
Mass flow rate	1.5 kg/min
Blasting material	S170 46 HRC
Nozzle diameter	4 mm
Distance nozzle-specimen	80 mm

The deep rolling pressure with the highest number of cycles to failure was 200 bar. The deep rolling parameters and the chosen Piezo Peening parameters are listed in Table 3. For all three mechanical surface treated states and the initial state, surface roughness Rz, residual stress and FWHM depth distributions were determined. The surface roughness is reduced by half with Piezo Peening and deep rolling. In contrast to that, shot peening leads to an increase of the roughness, see for Table 4.

The corresponding residual stress depth distributions are displayed in Figure 1a. In the initial state after milling there are tensile residual stresses of 200 MPa at the surface. The mechanical surface treatments induce compressive residual stresses. The surface residual stresses after Piezo Peening and deep rolling are about -800 MPa. The residual stresses induced by shot peening are about 100 MPa lower. In the further course there is a decrease up to 150 µm. After deep rolling the maximum residual stresses are in a depth of 60 µm with -900 MPa, the penetration depth is about 350 µm. The residual stress depth distribution of the Piezo peened state decreases steadily from the surface and reaches a penetration depth of about 100 µm.

Table 3: Deep rolling and Piezo Peening parameters for S-N curve determination.

Parameter	**Deep rolling**	**Piezo Peening**
Pressure	200 bar	-
Amplitude	-	18 µm
Frequency	-	500 Hz
Feed rate	29.3 mm/s (=80 rpm)	36.7 mm/s (=100 rpm)
Line pitch	0.315 mm	0.24 mm
Head diameter	6.35	5 mm
Head material	Ceramic	AISI 52100
Load factor	-	0.5

Table 4: Roughness Rz after mechanical surface treatment.

Treatment	Initial state	Piezo Peening	Shot peening	Deep rolling
Roughness [µm]	4.09 ± 0.162	2.01 ± 0.18	6.83 ± 0.859	2.47 ± 0.165

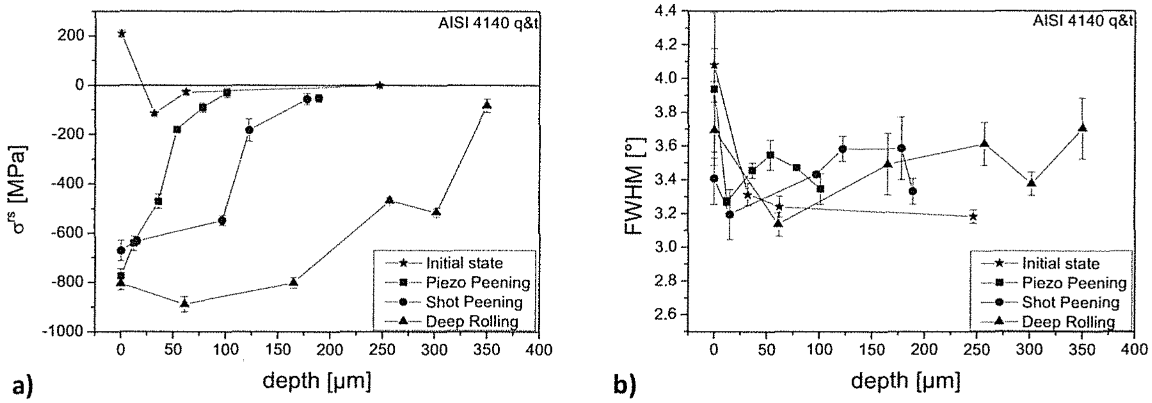

Figure 1: a) residual stress depth distributions before and after different mechanical surface treatments; b) FWHM depth distributions before and after different mechanical surface treatments.

The FWHM values are shown in Figure 1b. In the initial state, a slightly increased surface value of 4.1° can be observed, which decreases with depth to 3.2°. For the shot peened state, the value at the surface is about 3.4 ° and oscillates around 3.3° with at deeper layers. The surface value for the deep rolling distribution is about 3.6° and oscillates around 3.4 ° with further depth. Piezo Peening leads to a surface value of 3.9° and the depth distribution decreases to 3.4 ° and oscillates in the following course as well.

For each surface layer state, tension-compression tests were carried out and the numbers of load cycles were analyzed according to the arcsin√P method. The experimental results and the resulting S-N-curves are displayed in Figure 2a)-d). In the initial state (Figure 2a)) the 50% probability of fracture is at 557 MPa, 5% and 95% probability of fracture is 462 MPa and 652 MPa, respectively. Shot peening leads to an increase of fatigue strength in the low cycle fatigue range (Figure 2b)). The 5%, 50% and 95% probabilities of fracture in the high cycle fatigue range are 511 MPa, 546 MPa and 580 MPa, respectively. This means, the 50% probability of fracture decreased by about 10 MPa, but the variance declined. For all specimens with a number of cycles to failure below 10^6 the crack initiation occurs at the surface and for a number of cycles to failure above 10^6 it is located below the surface. The results of the tension-compression tests of the deep rolled state are depicted in Figure 2c). Similar to the shot peened state, an increase of fatigue strength in the low cycle fatigue range can be observed. In the high cycle fatigue range there is a decrease of the 50% probability of fracture of about 40 MPa to 519 MPa. But there is less variation again (5%: 494 MPa; 95%: 543 MPa). In addition, the location of crack initiation was always below the surface. The results of the Piezo peened tension-compression tests are displayed in Figure 2d). In the low cycle fatigue range the level of the S-N-curve is increased, but the variance is higher than in the initial state. Further on, in the high cycle fatigue range an increase in fatigue strength can be observed as well from 557 MPa to 560 MPa for the 50% probability of fracture. 5% and 95% probability of fracture are 535 MPa and 585 MPa, respectively. As already found at the shot peened specimen, for a number of cycles to failure below 10^6 crack initiation sites are at the surfaces, otherwise crack initiation is below the surface.

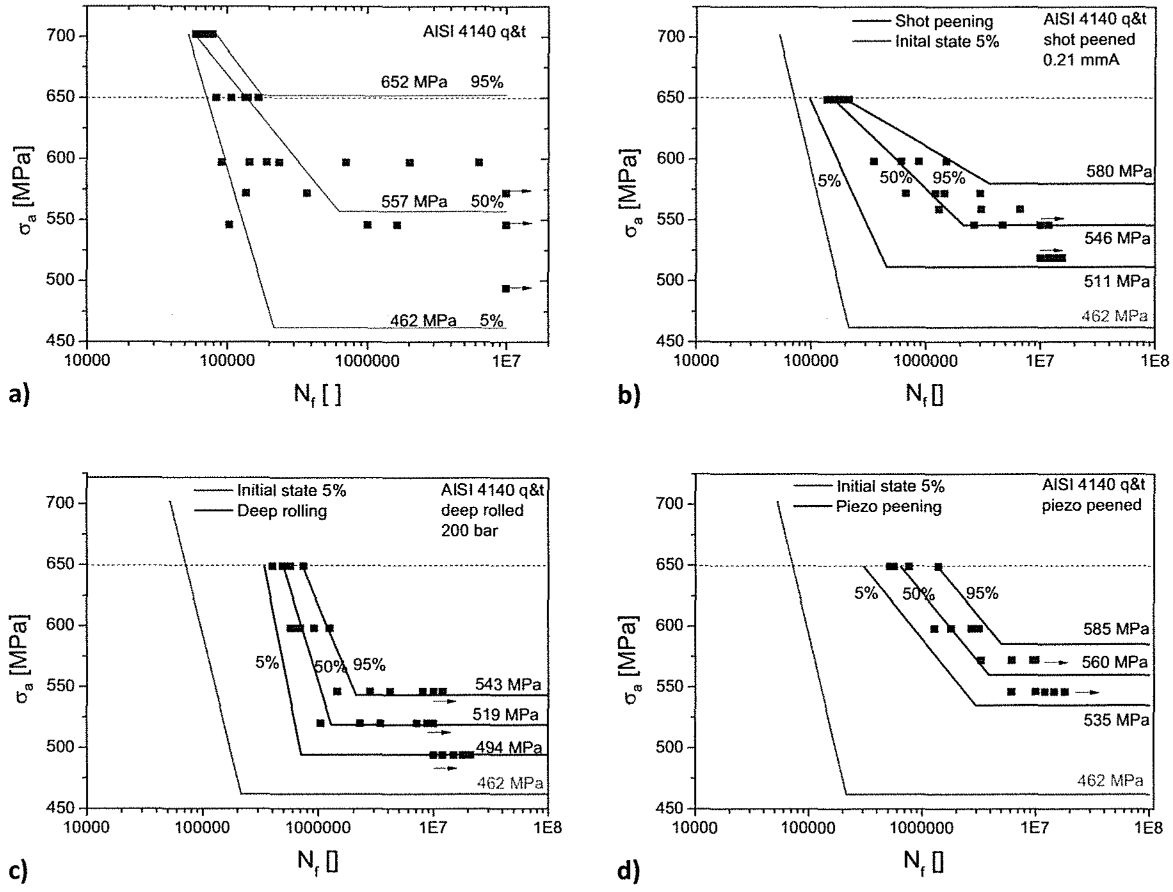

Figure 2: S-N curves of the different mechanical surface treated states for AISI 4140 q&t. The dotted line represents the load amplitude used for parameter selection. a) Initial state; b) Shot peened state with an Almen intensity of 0.21 mmA; c) Deep rolled state with a pressure of 200 bar; d) Piezo peened state.

Discussion and Conclusions

The influence of three different mechanical surface treatments on the fatigue strength of axial cyclic loaded specimen was analyzed. To compare the different surface layer states, the 5% probability of fracture lines are chosen, because they are important for component design. They are directly compared in Figure 3.

For all three mechanical surface treatments an increase of fatigue strength in the low cycle fatigue range was measured. In these high stress ranges a significant relaxation of residual stresses is possible [6]. The surface roughness and work hardening are more important concerning the number of cycles to failure. For the shot peened state an increase in surface roughness was measured which facilitates crack initiation. The slightly increased FWHM at the surface and the associated work hardening encounters this effect, so that there is a small overall increase in fatigue strength. With smaller loads and less residual stress relaxation the difference to the initial state increases. This means, that the influence of the compressive residual stresses on the crack propagation behavior affects the result with decreasing load. Deep rolling reduces the surface roughness, so that even at high stress levels the crack initiation at the surface can be prevented. Cracks only initiate at inclusions inside the specimen. Piezo Peening reduces the surface roughness as well. The Piezo peened state has a little lower surface roughness than the deep rolled state and the FWHM value at the surface is higher. Therefore even higher numbers of cycles to failure are possible at high stresses. On the other hand the process management of the Piezo Peening is more difficult than that of hydrostatic deep rolling. Deviations in run-out can lead to a non-equal processing due to the small amplitude.

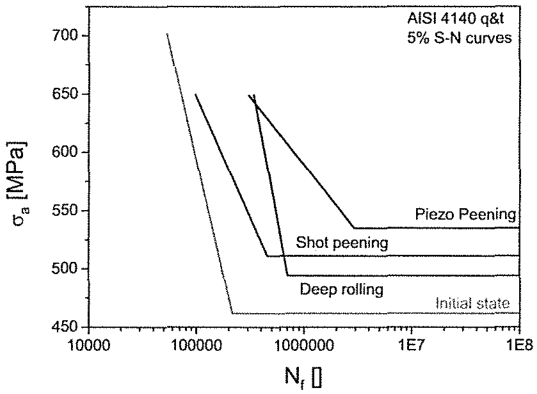

Figure 3: Comparison of 5% S-N curves of the initial state and the three mechanical surface treated states.

These deviations are corrected by the control unit, but can't be completely prevented. This leads to a higher variance of number of cycles to failure than for the deep rolling process. Fatigue strength (5% probability of fracture) is increased in the high cycle fatigue range for mechanical surface treated states as well. All relevant cracks are initiated below the surface, in depths of several hundreds of µm. Therefore it can be concluded that the surface roughness does not matter for this result. Also no work hardening affects crack initiation in this depth. The cyclic residual stress relaxation is lower in this stress range, which means residual stresses have to be taken into account. Due to the compressive residual stresses in the surface layer, tensile residual stresses are induced inside the specimen, see for Figure 4.

In case of axial loading there is a constant load along the whole specimen cross section. If the external load and these tensile residual stresses are superimposed the local fatigue strength can be exceeded and the specimen can fail at lower stresses than the initial state with no residual stresses inside. The value of these tensile residual stresses depends on the amount and the penetration depth of the induced compressive stresses. This explains why the results of the deep rolling process with the highest compressive residual stresses cause the lowest fatigue strength.

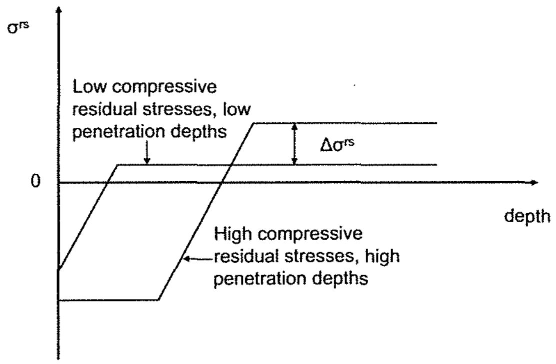

Figure 4: Schematic illustration of tensile residual stresses inside the specimen depending on compressive residual stresses in the surface layer.

The Piezo peened state shows the least compressive residual stresses in the surface layer and therefore the highest fatigue strength. Nevertheless, the enormous variance of the fatigue behavior of the initial state was reduced by mechanical surface treatment. Due to the same elastic plastic deformation in the surface layer, the surface layer state of the different specimen is more comparable than before. The presented results show, that the surface layer state has to be adapted to the applied load to achieve the best possible result. In case of axial loading a reduced surface roughness, work hardening in the surface layer and medium compressive residual stresses with small penetration depths lead to the highest fatigue strength. The results show as well that axial loading is not the best load case to show the improvement by mechanical surface treatment, although it occurs in real life. Mechanical surface treatment is much more effective if a component is subjected to bending. Flat samples which were used for alternate bending experiments led to edge fractures in case of deep rolling and Piezo Peening. Due to this rotating bending loadings should be preferred to components treated in this manner.

Acknowledgement

The authors gratefully acknowledge the financial support of the German Research Foundation (DFG).

References

[1] L. Wagner, *Mechanical surface treatments on titanium alloys: fundamental mechanisms*, in Proc. Symp. Surface Performance of Titanium, Cincinnati, J. Gregory, H. Rack, and E. D., Eds. (1997), pp. 199–215.
[2] F. Lienert, J. Hoffmeister, and V. Schulze, *Residual stress depth distribution after Piezo Peening of quenched and tempered AISI 4140*, Material Science Forum, Vol. 768-769 (2014), pp. 526–533.
[3] D. Dengel, *Die arcsin P-Transformation - ein einfaches Verfahren zur grafischen und rechnerischen Auswertung geplanter Wöhlerversuche*, Journal of Materials Technology, Vol. 6, no. 8 (1975), pp. 253–288.
[4] F. Lienert, J. Hoffmeister, and V. Schulze, *Changes in surface layer after Piezo Peening of quenched and tempered AISI 4140*, submitted.
[5] E. Macherauch and P. Müller, *Das sin^2psi-Verfahren der röntgenographischen Spannungsmessung*, Zeitschrift für angewandte Physik, Vol. 13 (1961), pp. 305–312.
[6] O. Vöhringer, *Abbau von Eigenspannungen.* DGM-Informationsgesellschaft, Eigenspannungen (1983), pp. 49–83.