Changes in surface layer after Piezo Peening of quenched and tempered AISI 4140

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Abstract

Piezo-Peening is a new alternative mechanical surface treatment process which may be addressed as a machine hammer peening treatment. Thereby a piezo actuator with an indenter is causing mechanical deformation of the surface area by multiple impacts in a previously defined pattern. Using this approach, advantages of shot peening and deep rolling can be combined. In order to get a process understanding and an idea of influence of the process parameters, different parameters like hardness and size of the indenter are changed. After the mechanical surface treatments the residual stress and full width at half maximum (FWHM) depth distributions were measured using X-ray diffraction technique. The surface topography was investigated with confocal white light microscopy. By changing these parameters systematically a wide range of compressive residual stress depth distributions can be generated. This goes from medium surface residual stresses of about -600 MPa and low penetration depths like induced by shot peening to large surface residual stresses of -1200 MPa and penetration depths comparable to deep rolling. Furthermore, surface roughness can be reduced. The dependency of surface residual stresses, penetration depths, FWHMs and surface roughnesses on the process parameters is analysed in order to determine their effects on the resulting surface layer. In addition, the variety of adjustable surface layer states can be shown. They reach from states comparable to shot peening to states comparable to deep rolling and even beyond that. By means of the knowledge of the parameter influence, the possibility of finding the best set of parameters to increase the fatigue strength for a certain load case is given.

Keywords Piezo Peening, mechanical surface treatment, residual stresses, AISI 4140.

Introduction

In general, the surface layers of components are the most stressed parts under cyclic load, tribological stress and corrosion hence, there are different ways to strengthen it. An established way is to use a mechanical surface treatment. Next to the conventional mechanical surface treatments shot peening and deep rolling lots of alternative processes which can be collectively referred as machine hammer peening have been developed. One special case of path dependent machine hammer peening processes is Piezo Peening. By means of a spherical hammer head attached to an oscillating piezo actuator, the surfaces layer is elastic-plastically deformed in a deterministic way.

Process Description

As already described in [1], the Piezo Peening system consists of an oscillating piezo actuator which impacts on the specimen surface in a certain pattern, see for Figure 1. The main process parameters are the amplitude, the hammering frequency, the feed rate, the line pitch l_p and the load fraction. The load fraction describes the ratio of time of contact between hammer head and specimen and no contact. It is controlled by movement of the soft bearing.

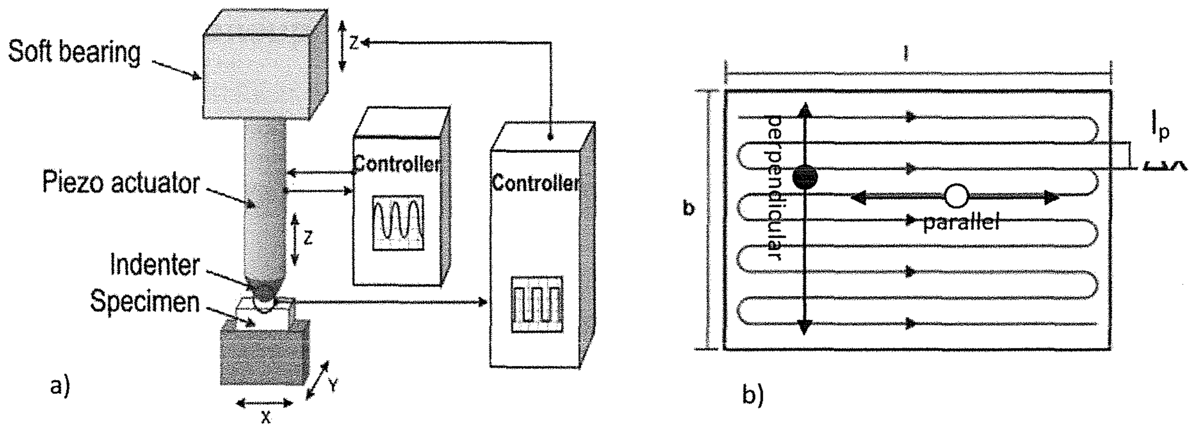


Figure 1: a) Schematic illustration of a Piezo Peening plant. b) Meandering processing pattern.

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
0.425	1.011	0.222	0.803	0.252	0.101	base

The sample geometry is a flat bar with a thickness of 4 mm. The peening area is of a size of 10 * 10 mm^2. Residual stresses in the middle of the peening area were measured using X–ray diffraction technique according to $\sin^2\Psi$-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 1 mm and on the secondary side a symmetrisation 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 FWHM was calculated from ψ = ±20.7° and ψ = 0° interference peaks. To obtain the residual stress depth distribution an incremental electrolytic layer removal. 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

After the heat treatment the specimens were ground to the final thickness of 4 mm. The surface is affected by grinding grooves which mark the grinding direction and the resulting roughness Rz is about 2.7 µm. After grinding the surface is nearly stress free, only parallel to the grinding grooves a surface value of about -300 MPa was measured. The initial FWHM in the unaffected material is about 2.9°. For the ground surface a FWHM of about 3.3° was determined (compare also [1]). The influence of the head diameter was investigated with three different head diameter sizes: 2.5 mm, 5 mm and 10 mm. The material of the hammer head was AISI 52100 (100Cr6). The used process parameters are listed in Table 2 In the beginning, the diameter of the indentation was measured in single line experiments to provide the same coverage perpendicular to the feed direction. For all head diameters an overlap of 50 % in perpendicular direction was chosen. The feed direction of peening was parallel to the grinding grooves. The resulting surface roughnesses are shown inTable 3. For the 2.5 mm hammer head roughness is nearly quadrupled. The 5 mm and the 10 mm hammer head lead to a slight decrease of the surface roughness. The residual stress depths distributions perpendicular and parallel to the feed direction can be seen in Figure 2a.

Table 2: Process parameters for the variation of head diameters.

Frequency	500 Hz		
Amplitude	18 µm		
Feed rate	50 mm/s		
Load fraction	0.5		
Head diameter	2.5 mm	5 mm	10 mm
Line pitch l_p	0.25 mm	0.4 mm	0.35 mm

Table 3: Roughness Rz after Piezo Peening using different head diameters.

Head diameter [mm]	0	2.5	5	10
Roughness [µm]	2.7 ± 0.231	10.5 ± 0.444	2.18 ± 0.268	2.0 ± 0.345

For all three head diameters the maximum residual stresses in perpendicular direction are slightly beneath the surface. The absolute values of maximum compressive residual stresses differ: The highest residual stresses are induced by the 2.5 mm hammer head, -1150 MPa, the 10 mm hammer head induces about -850 MPa and the 5 mm hammer head -700 MPa. The same applies for the penetration depths: the highest penetration depth (1 mm) is caused by the 2.5 mm head diameter, 500 µm is the depth for the 10 mm hammer head and 250 µm for the 5 mm head diameter.

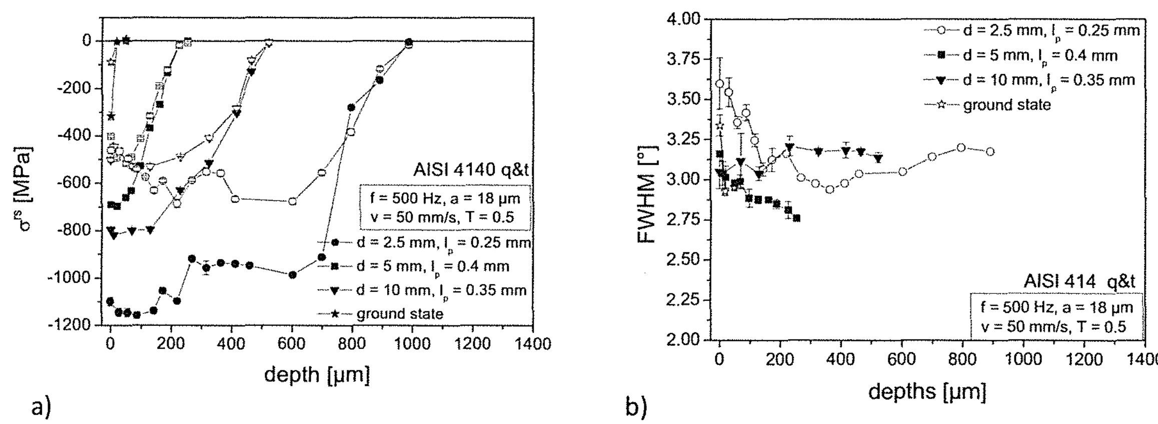


Figure 2: a) Residual stress depth distribution perpendicular (full symbols) and parallel (open symbols) to the feed direction after Piezo Peening using three different hammer head diameters. b) FWHM distribution after Piezo Peening using different hammer head diameters.

Parallel to the feed direction the maximum compressive residual stresses are located below the surface. At the surface, all three residual stress depth distributions have similar values. Like in perpendicular direction, the residual stresses induced by the 2.5 mm hammer head are the highest, about -700 MPa. The maximum is between 200 µm and 600 µm. For the 5 mm hammer head, the maximum of -500 MPa occurs at depths of 70 µm. The residual stresses of the 10 mm hammer head are maximal at 80 µm with -550 MPa.

Figure 2b shows the FWHM values related to the above mentioned residual stress measurements. Generally, there are rather high fluctuations of the FWHM values [1]. At the surface, the FWHM of the 5 mm and 10 mm head diameters are a little below the ground state. The values of the 5 mm

depth distribution decrease continuously to 2.75°, the 10 mm depth distribution shows a slight increase from 3.04° to 3.2° at 230 µm and stays constant with further depth. The 2.5 mm head diameter leads to an increase of the FWHM at the surface from 3.3° of the ground state to 3.6°. The distribution decreases to 2.95 ° at about 400 µm, followed by a slight increase to 3.2°.
The analysis of the influence of the hardness of the hammer head was done with three different hammer heads with 5 mm diameter. One hammer head of AISI 52100 with a hardness of about 63 HRC (≈ 765 HV) was used. The second hammer head was of AISI 52100 as well, but additionally tempered at 450 °C for two hours (53 HRC ≈ 555 HV) and will be referred to as AISI 52100 temp. The hardest hammer head was of tungsten carbide (WC) with a hardness of 91 HRA (≈ 1500 HV). As already mentioned before, in a first step single line experiments to determine the indentation diameters have been done. The resulting line pitches are shown in Table 4. All other process parameters are according to Table 2.

Table 4: Line pitch for different hammer head materials.

Head material	AISI 52100	AISI 52100 temp.	WC
Line pitch l_p	0.4 mm	0.2 mm	0.25 mm

The measured surface roughnesses are shown in Table 5. All hammer head hardnesses lead to a decrease of the surface roughness. The highest observed decline from 2.7 µm to 1.5 µm was achieved by the softest hammer head. With increasing hardness of the hammer head the surface roughness increases.

Table 5: Roughness Rz after Piezo Peening using different hammer head materials.

Head material	none	AISI 52100	AISI 52100 temp.	WC
Hardness	-	765 HV	555 HV	1500 HV
Youngs modulus	-	210 GPa	210 GPa	830 GPa
Roughness [µm]	2.7 ± 0.231	2.18 ± 0.268	1.47 ± 0.526	2.16 ± 0.236

The generated residual stress depth distributions are displayed in Figure 2a. It is revealed, that the highest hammer head hardness leads to the highest compressive residual stresses. In perpendicular direction the WC hammer head yields in maximum residual stresses of -1100 MPa at the surface. The zero crossing is at about 550 µm. Concerning the AISI 52100 hammer head the depth distribution was already described before: Maximum residual stresses of -700 MPa beneath the surface and zero crossing at about 250 µm. Surface residual stresses of the AISI 52100 temp. are about -350 MPa, the increase to -500 MPa at 50 µm, followed by a decrease and a zero crossing of about 250 µm. For all hammer head materials maximum residual stresses are below the surfaces in parallel direction. For the AISI 52100 hammer heads the maximum is at 50 µm (-380 MPa for AISI 52100 temp. and -500 MPa for AISI 52100), the maximum of -700 MPa for WC is between 100 µm and 300 µm. At the surface residual stresses increase from -250 MPa to -400 MPa up to -580 MPa with increasing hardness. The FWHM depth distributions are depicted in Figure 3b.FWHM distribution for AISI 52100 was already described for Figure 2. The other distributions start at the surface with the same value as for the ground state. For the AISI 52100 temp. hammer head a sudden drop to 3.1° at 20 µm is measured, afterwards there are only small changes. The distribution of the WC hammer head decreases a little bit slower and reaches 3.1° at 100 µm followed by an oscillation around this value.

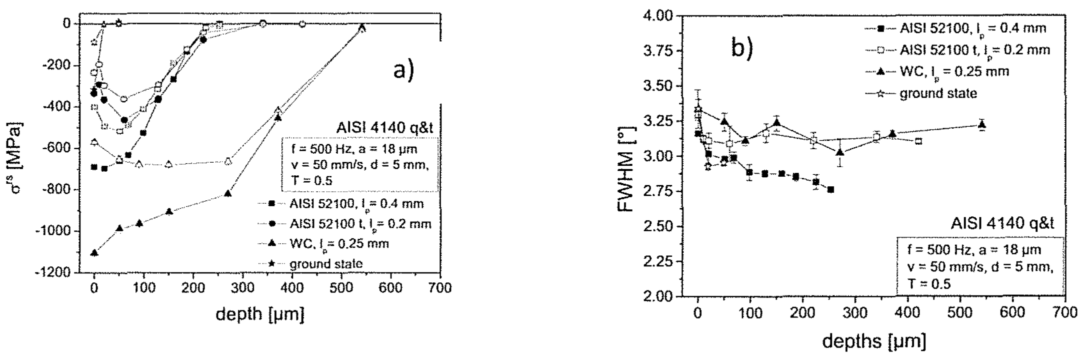
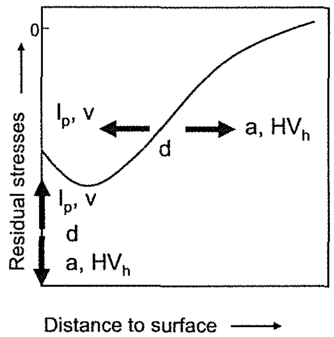


Figure 3: a) Residual stress depth distribution perpendicular (full symbols) and parallel (open symbols) to the feed direction after Piezo Peening using different hammer head materials. b) FWHM distribution after Piezo Peening using different hammer head materials.

Discussion and Conclusions

The process parameters hammer head diameter and hammer head hardness influence the surface layer concerning surface roughness, residual stresses and FWHM depth distributions. The bigger the head diameter and the softer the hammer head diameter, the more the surface roughness is reduced. With small hammer heads the surface roughness can be even dramatically increased. In general there is a leveling of the surface caused by the impacts. Comparable to hardness indentations, at the edges of the indentations a material accumulation called piling-up or a sinking-in of the surrounding material is possible. Which one occurs is depending on the strain hardening exponent [3]. In the case of AIS4140 q&t piling-up was observed. Due to the Piezo Peening process the kinetic energy per indentation is the same for the same amplitude, frequency and load fraction. The smaller the diameter of a sphere and therefore the higher the load per area, the more plastic deformation and piling-up around the sphere is possible. Furthermore, the higher the Young's modulus of the hammer head, the higher the Hertzian pressure is.Therefore also more plastic deformation is possible. FWHM values show generally little changes compared to the ground state, which is mainly due to the heat treatment state which has been shown by [4]. Only the 2.5 mm head diameter leads to an increase, which can be correlated with a strain hardening of the surface layer. Regarding the hammer head diameter, no clear effect on residual stresses was found. Hertzian pressure is influenced by the diameter of the sphere. Larger diameters lead to lower Hertzian pressure but higher depths of maximum Hertzian pressure in case of constant force. So there are two competing effects. The residual stress distribution of UIT process for a pin diameter of 3 mm induces higher residual stresses and higher penetration depths than a pin diameter of 6 mm was shown by [5]. For larger diameters the plastic deformation zone can be shifted to greater depths, so that there are higher penetration depths possible. The influence of head diameter cannot be directly compared to shot peening. In shot peening particle size determines the particle mass and therefore impact energy. Due to the Piezo Peening process, impact velocity is only influenced by the amplitude and frequency not by the head diameter. Concerning the different hammer head hardnesses the experimental results show that with increasing hardness the surface residual stresses and the penetration depths are increased and the maximum is shifted towards the surface. This corresponds to the observations of [6] of the influence of particle hardness on residual stresses in shot peening. If the hardness of the particle is similar to the workpiece hardness, Hertzian pressure is the dominating and maximum residual stresses are below the surface. With increasing hardness the effect of plastic surface stretching gains in importance and the maximum residual stresses occur at the surface.

In [1] a scheme of the influence of the process parameters according to [7] for shot peening was shown. This can be extended on hammer head hardness and hammer head diameter and is depicted in Figure 4. All parameters show clear tendencies and can be compared to shot peening, only the hammer head diameter differs. In contrast to shot peening no defined effect has been observed due to the constant impact velocity of the Piezo Peening process.



- a: amplitude
- l_p: path distance
- v: feed rate
- HV_h: hammer head hardness
- d: hammer head diameter

Figure 4: Extended schematic illustration of the effect of different parameters on the residual stress state after Piezo Peening based on [1].

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