Investigation on the Mechanisms Improving Fatigue Strength in Surface Layers after Micropeening

R. Weingärtner, J. Hoffmeister and V. Schulze

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

Abstract

Micropeening differs from shot peening by smaller blasting shots. From this, low penetration depths and high velocities result. Micropeening offers many prospects for mechanical surface treatment and optimization of surface properties. Besides high surface quality, high compressive residual stresses and strong work hardening near the surface, also grain refinement up to nanocrystalline sizes can be achieved. These properties affect the mechanical properties, particularly the fatigue limit of processed surfaces, in a complex manner. Despite the very low penetration depth in comparison to conventional shot peening, an unexpectedly high increase of fatigue limit is found. Therefore the correlations describing conventional shot peening cannot be transfered to micropeening in unrestrained manner. Especially the effect of grain sizes is of interest for estimating the reinforcing mechanisms achieved by surface treatment, for example by the concept of local fatigue strength.

For an optimum improvement of fatigue properties of steel the achievable surface properties are explored. In particular, changes of the microstructure are of great interest. For this purpose, the depth distribution of compressive residual stresses, cold work and grain sizes have been studied, taking account of the peening conditions. The methods are mainly based on X-ray measurements and Focussed-Ion-Beam microscopy. In addition, the surface topography has been observed by scanning electron microscopy and the roughness has been measured by confocal microscopy. Finally in bending fatigue tests the fatigue strength has been determined in relation to the adjusted surface properties. The observed effects are described and discussed with the aim to elaborate the relations between the surface characteristics and the fatigue limit. Thus, it is shown, that micropeening is an effective tool for improving fatigue properties.

Keywords peening, micropeening, grain refinement, compressive residual stresses, fatigue limit.

Introduction

Shot peening offers a wide range of achievable surface and surface layer characteristics and therefore touches manifold fields of application. Micropeening or fine particle peening which is characterized by using small particles with diameters lower than 100 µm broaden the feasibilities not only to wider classes of parts and their geometries but also to improved surface layer qualities. For instance, the restrictions to the minimum wall thickness and the accessibility are reduced due to lower peening intensities and accordingly smaller jet nozzle geometries. Furthermore, small impact geometries and simultaneously high impact velocities result in a comparatively low surface roughness, high compressive residual stresses and strain hardening [1, 2]. In addition, grain refinement up to the nanocrystalline range can be observed, which exhibit a higher hardness than those areas, which have been subject to smaller strain or have not been strained [3]. Hence, micropeening is capable to increase the fatigue limit of different materials [4, 5]. Therefore, the correlation between the peening conditions and surface layer characteristics and their effects on the fatigue performance are of mayor interest to enhance the suitability of micropeening as an effective process of mechanical surface treatment.

Experimental Methods

The experiments were conducted using samples of the quenched and tempered steel AISI 4140. The chemical composition and mechanical characteristics are shown in Tables 1 and 2, respectively. AISI 4140 was austenized at 850 °C, quenched in oil and tempered at 450 °C for

2 hours. Bending fatigue samples of a thickness of 1 mm were fabricated by eroding to ensure minimal process forces.

Table 1. Chemical composition of AISI 4140 [weight-%].

	C	Cr	Mo	Si	Mn	Ni	Al	Cu
AISI 4140	0,43	1,01	0,22	0,25	0,80	0,10	0,05	0,06

The topography was determined by the measurement of roughness using a confocal white light microscope type "Nanofocus" and on the other hand by pictures recorded by scanning electron microscopy (SEM).

Residual stress measurements were conducted via X-ray diffractometry of the α-Fe peak {211} using Cr-Kα radiation, which results in an information depth of $z^{\{211\}} = 5.5$ µm. Seven tilt angles ± 60.0 °, ± 52.5 °, ± 45 °, ± 37.8 °, ± 30.0 °, ± 20.7 ° and 0 ° were applied in the range of $2\Theta = 144.1 - 165.7$ °. The peaks were fitted by a Pearson-VII function and were evaluated by the $\sin^2 \psi$-method. For the calculation of residual stresses the values $2\theta_0 = 156.394$ °, E = 219.911 GPa and ν = 0.28 were applied. The full width at half maximum (FWHM) was evaluated using the peaks at $\psi = \pm 20.7$ ° and 0 °. The depth distribution was measured by stepwise removal of the surface by electropolishing. The relaxation of the strains and hence effects on the residual stresses by the removal were neglected [6].

Micropeening was conducted using an "AccuFlo" micro-abrasive blaster from COMCO Inc., accelerating the peening particles in an airstream. Glass beads with a size of 20 – 30 µm served as peening particles, which were only used once. The peening pressure was varied from 1.5 to 7 bar. The favorable surface to volume ratio of the small particles resulted in particle velocities up to 200 m/s. The particle velocity as a function of the peening pressure measured by COMCO Inc. is shown in Fig. 1. In all cases, a nozzle diameter of 0.7 mm was used and the nozzle was moved in lanes of distances of 1 mm along the surface. The distance between the nozzle and the surface amounted to 10 mm and was adjusted perpendicular to the surface. Besides the variation of the peening pressure, also different feed rates of the nozzle were applied.

For tests of the bending fatigue two different states were selected. The peening pressures were chosen to 1.5 bar which results in an impact velocity of 105 m/s and 7 bar which results in a velocity of 193 m/s with a feed rate of the nozzle of 2 mm/s and accordingly 4 mm/s.

To investigate the fatigue performance, bending fatigue tests were conducted. The samples were tested until failure or the tests were interrupted after 10^7 cycles. The evaluation of the fatigue limit was conducted by the arc sin $\sqrt{P}$ transformation for a fracture probability of 50 %.

Cross sections of the peened surfaces were cut using Focussed Ion Beam (FIB) technique to investigate the grain size distribution. Additionally, the fracture surfaces were investigated by SEM to determine the crack initiation site.

Table 2. Mechanical properties of AISI 4140.

Hardness	430 HV 0.3
Ultimate tensile strength, UTS	1375 MPa
Yield strength, YS	1200 MPa

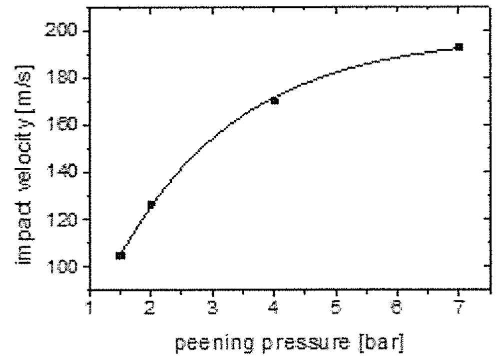
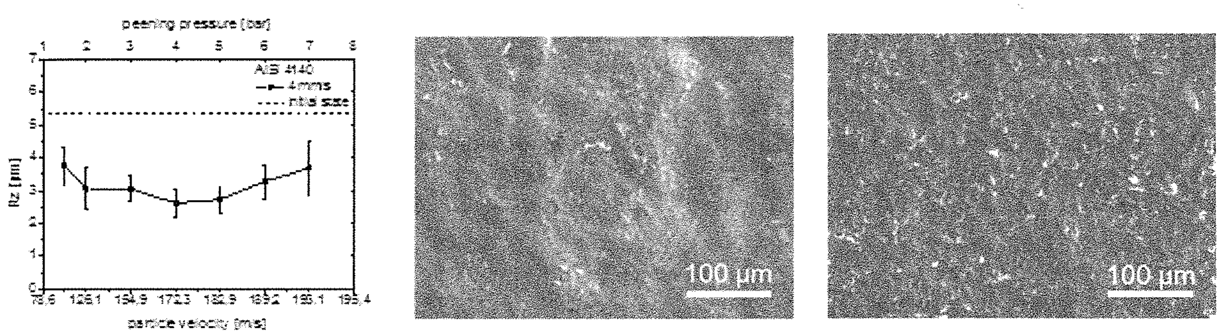


Fig. 1: Particle velocities as a function of peening pressure for the given peening parameters measured by COMCO Inc.

Experimental Results

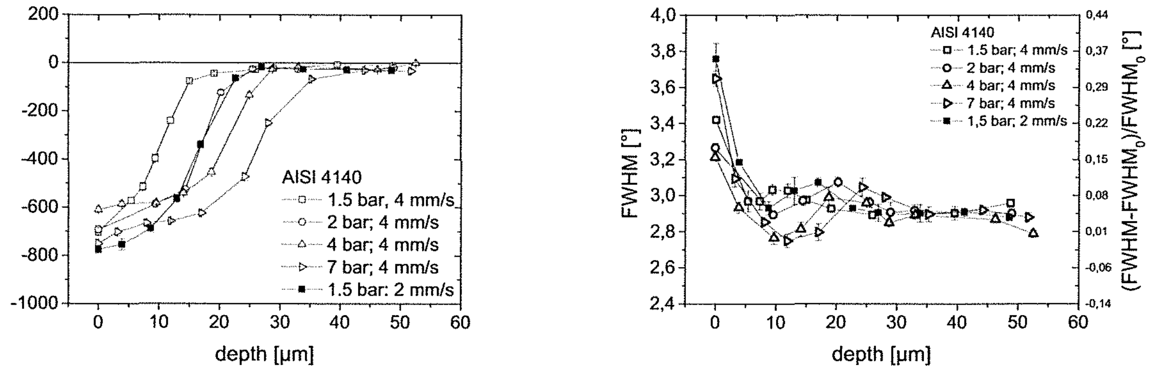
The surfaces show considerable changes in topography after peening compared to the initial state. In the whole investigated range of the peening pressure the initial roughness of Rz = 5.3 µm is reduced considerably (Fig. 2 a) in case of a feed rate of 4 mm/s. Whilst a low peening pressure of 1.5 bar reduces the roughness to Rz = 3.75 µm, with increasing pressure the roughness decreases until the minimal value of about Rz = 2.6 µm is found at 4 bar. However, a further increase of the pressure results in higher Rz values of up to 3.7 µm for 7 bar, which still represents a significant enhancement compared to the topography before peening. As shown in Figs. 2 b) and c), the topography is characterized by rounded marks of low depth, which can be attributed to the impinging glass beads.



a) b) c)

Fig. 2: Topography after micropeening: a) roughness Rz as a function of the peening pressure and accordingly of the particle velocity for a feed rate of the nozzle of 4 mm/s and SEM pictures of the micropeened surface: b) 1,5 bar; 2 mm/s; c) 7 bar, 4 mm/s.

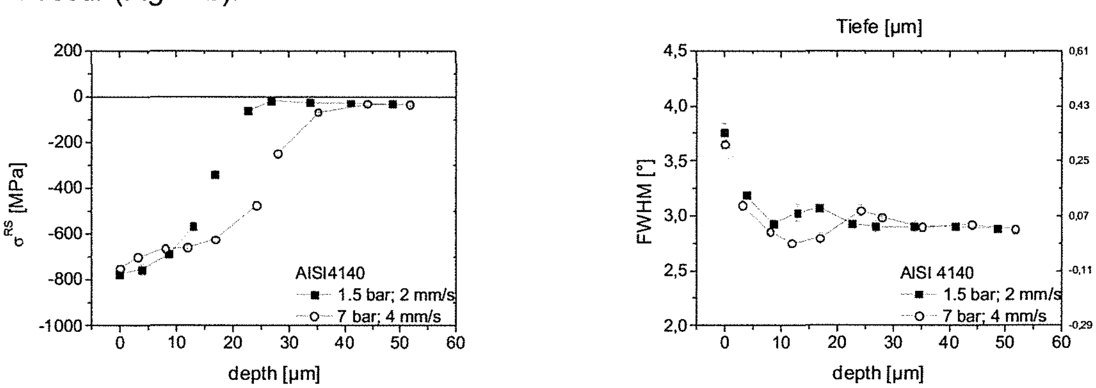
As expected, the process generates compressive residual stresses close to the surface. After peening with a feed rate of the nozzle of 4 mm/s the maxima of the residual stresses are found at the surface. For the peening pressures under test, the surfaces show values from - 600 to - 750 MPa, as can be seen in Fig. 3 a. Notably, the penetration depth increases with the peening pressure from about 16 µm for 1.5 bar to 32 µm in the case of 7 bar. The measurements also show an increase of FWHM at the surface up to about 35 % compared to the FWHM beyond the penetration depth of the strain. The highest peening pressure, correlating to the highest particle velocity, results in the highest increase of FWHM, whilst the lower pressures show no distinct correlation. The penetration depth is constricted close to the surface and also does not show a clear correlation.



a) b)

Fig. 3: Depth distribution of residual stresses (a) and FWHM (b) of AISI 4140 after micropeening with different peening pressures and a variation of the nozzle feed rate.

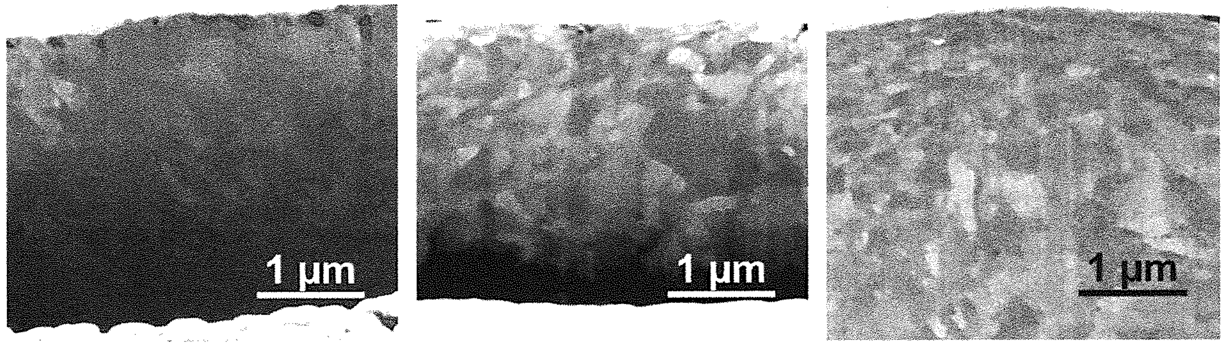
The further results focus on two states, the first one micropeened with a pressure of 7 bar and a feed rate of 4 mm/s and the second one micropeened with a pressure of 1.5 bar and a feed rate of 2 mm/s. The selected states were chosen because they differ in the penetration depth of compressive residual stresses (Fig. 4 a), whilst the surface values coincide. Again, the higher peening pressure results in a higher penetration depth of the compressive residual stresses. However, appreciable differences in surface values or the distribution of the FWHM don't occur (Fig. 4 b).



a) b)

Fig. 4: Depth distribution of residual stresses (a) and FWHM (b) of AISI 4140 after micropeening with a peening pressure of 1.5 bar and a feed rate of 2 mm/s compared to the state peened with 7 bar (4 mm/s).

The FIB cross sections in Fig. 5 show significant differences in the grain size distribution of the peened surface layer compared to the initial state. While the initial state shows an equal grain distribution over the whole cross section (Fig. 5 a), after micropeening the grains are smaller than before. In particular, very close to the surface a considerable grain refinement is found. The lower peening intensities reduce the grain size in the investigated area up to a depth of about 3 µm sufficiently (Fig. 5 b), even though with increasing distance to the surface, the grain size is less modified. However, by higher impact velocities, the grain size is reduced even further (Fig. 5 c). Moreover, minor variations of the size distribution occur with increasing depth. The minimum grain sizes are found perpendicular to the surface and are less than 100 nm.

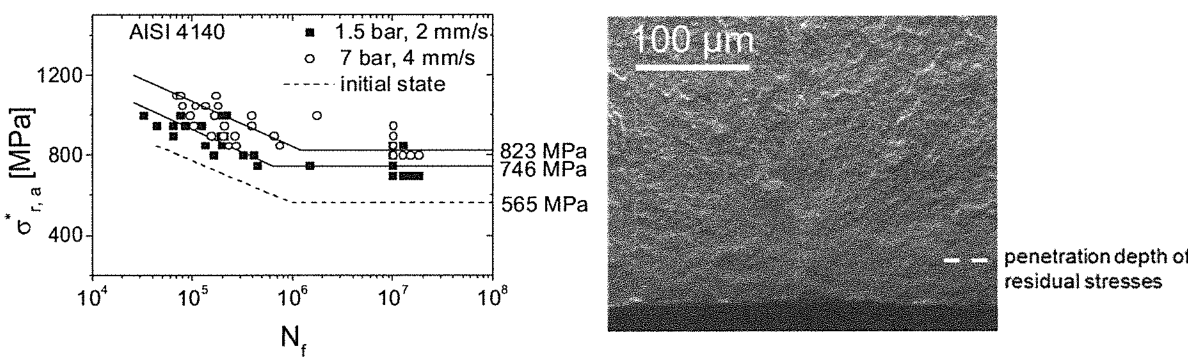


a) b) c)

Fig. 5. FIB cross sections before (a) and after Peening of AISI 4140 with a peening pressure of b) 1.5 bar (feed rate 2 mm/s) and c) 7 bar (feed rate 4 mm/s).

Significant differences are also found in the bending fatigue performance. The micropeened states show higher numbers of fracture in the low cycle range as well as higher values of the fatigue limit (Fig. 6 a). Whilst the fatigue limit of the initial state is 565 MPa, it increases after peening up to 746 MPa in the case of 1.5 bar peening pressure and to 823 MPa in the case of 7 bar.

In the case of the 7 bar peened samples it was proved that at least in some cases crack initiation does not take place at the surface, but is shifted below the surface. Fig. 6 b shows, that the crack initiation occurred at a defect below the surface beyond the penetration depth of the compressive residual stresses.



a) b)

Fig. 6: a) SN-curve of AISI 4140 before and after micropeening with a peening pressure of 1.5 bar (feed rate 2 mm/s) and 7 bar (feed rate 4 mm/s). b) Fracture surface of AISI 4140 after micropeening with 7 bar (feed rate 4 mm/s) and crack initiation site below the surface.

Discussion and Conclusions

The investigation of the residual stress distributions shows that micropeening enables the generation of compressive residual stresses of high surface values in AISI 4140. Particle velocities of about 100 m/s are effective to achieve maximal residual stresses of about - 700 MPa. For the penetration depth the velocity is crucial. Contrary to conventional shot peening, in every case the maximal residual stresses are found at the surface for the investigated material and material state. The depth distribution is characterized by a high gradient, thus resulting in much lower penetration depths. The distribution of the FWHM of the diffraction peaks is also characterized by a relatively high increase at the surface and a low penetration depth. The increase at the surface indicates strain hardening by an increase of the dislocation density. Also the reduced grain size potentially contributes to the increase of FWHM.

The achieved surface layer properties increase the fatigue limit considerably. Especially, high impact velocities are beneficial due to higher penetration depths and grain refinements. Hence, the critical limit of crack initiation at the surface is not only increased, but also the crack initiation can be avoided in the case of suitable peening parameters. Instead, cracks occur below the surface beyond the penetration depth of impinging particles and the resulting deformation. Hence, micro peening enables a high increase of fatigue limit and offers a suitable way of surface treatment and complementation of shot peening for many applications which require a high quality of surface layer.

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