Mechanical surface treatment in the gear production

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Keywords: shot-peening, fatigue, gears

Introduction

The power density of industrial gear boxes increases continuously, so it is necessary to improve the performance of the gear wheels. Beside modified materials and adapted heat treatments mechanical surface treatments are a good possibility to increase the strength of gear wheels. For gears two failure methods must be differentiated [1, 2]: damage of the tooth flank and fracture of the tooth root. For the tooth flank different mechanical surface treatments e.g. shot peening or slide grinding can improve the strength. For the tooth root shot peening is the most common process to increase the performance. [2] explains the increase of tooth root strength to the compressive residual stresses. This benefit can be used in the calculation of tooth bending strength of gear wheels. Because of the great number of load cycles which a gear can see during his life cycle, the high cycle fatigue phoneme must not be neglected during the process optimization [3].

Objectives

The study focuses on the improvement of the tooth root strength of case hardened 18 CrNiMo 7-6 [4] gears by shot peening. Therefore an optimization of the shot peening parameters is necessary. The effectiveness of the shot peening parameters will be verified by fatigue tests with the shot peened gears. Additionally an arrangement of Almen strip is required to control the shot peening process for gears.

Methodology

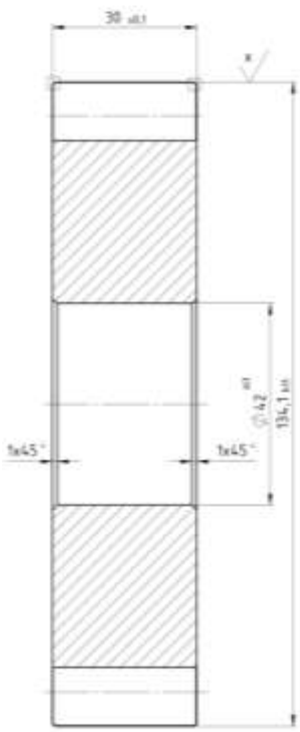
Case hardened test gears of 18 CrNiMo 7-6 were shot peened with different peening parameters. The technical drawing of the gears is illustrated in Figure 1 left. For the peening operation an air pressure peening device from Wheelabrator was used. For the first optimization step (initial condition and condition A, B, C and D) the peening pressure p and the coverage c were varied for the material charge I. The other parameters were kept constant. Based on these results a peening setup was deduced for the series production (compare Table 1).

Table 1: peening parameters and material charges

condition	initial	A	B	C	D	series
pressure p [bar]	0	3	4	4	5	/
coverage c [%]	0	100	100	200	100	/
other parameters	mass flow: 9 kg/min; number of nozzles: 3; nozzle diameter: 10 mm; nozzle distance: 150 mm; shots: StD-G3 (0,6) 700HV					/
material charge	I					II / III / IV/V

The resulting skin layer states were investigated. Beside the surface roughness, the hardness and residual stress depth distributions were measured at 30°-tangents. The residual stress measurements σ^{rs} were performed by X-ray diffractometry of the α-Fe peak {211} using Cr-Kα radiation based on the sin2 ψ-method. The depth distributions were measured by stepwise removal of the surface by electropolishing. The relaxation of the strains and hence effects on the residual stresses due to the removal were neglected.
Additionally the tooth root strengths were determined. Therefore fatigue tests were performed with an electromagnetic resonance machine. The gear wheels were gripped over four teeth. The test

equipment is illustrated in Figure 1 right. Because of the force-fit test gear gripping between two parallel pressure plates a minimum force was requested during the tests. So the tests were performed with stress ratio only nearby zero. A test was finished as soon as a tooth was broken or the ultimate number of cycles of 6 x 10^6 cycles was achieved. The results were evaluated with the staircase method according Hück [5]. The nominal stress value $\sigma_{F\,lim}$, which is very important for the design of gear wheels, was calculated according [1]. Thereby the results from the resonance machine were converted according [6] to the stress values which would result from a test in a gear box by using a factor 0.9. Additionally based on the 50%-failure probability the 1%-failure probability was calculated [7]. For the shot peened test gears the conversion factors $f_{1\%,\,shot\,peened}$ = 0.9 and for the initial condition $f_{1\%,\,not\,shot\,peened}$ = 0.86 were used.



Gearing dimensions

module m_n	5 mm
number of teeth z	24
helix angle β	0°
pressure angle α	20°
root diameter d_f	110,1 mm
case hardening CHD	0.8+0,4 mm
hardness of surface	720±40 HV

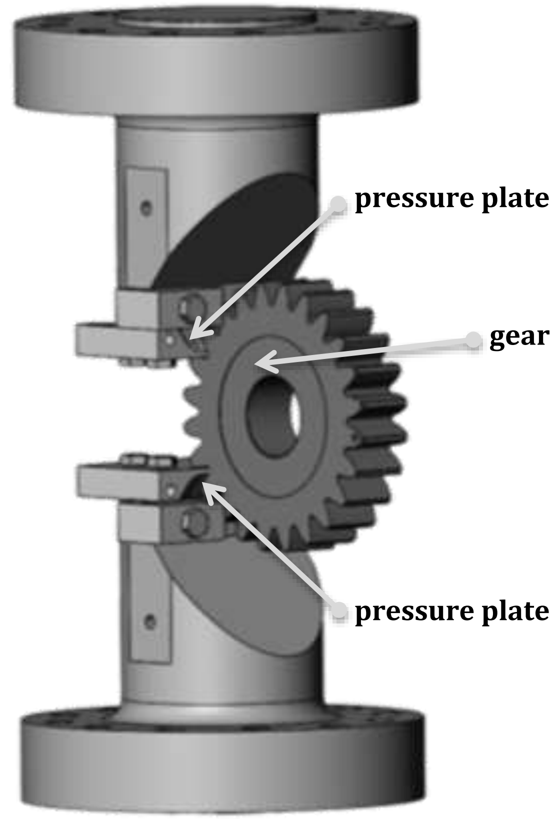


Figure 1: technical drawing of the test gear (left) and the test gear gripped in the test equipment (schematically, right)

The resulting optimum peening setup was executed with different material and heat treatment charges. Based on these results an arrangement of almen strip holders was deduced to control the shot peening process under production conditions. With this almen strip arrangement the process stability could be ensured.

Results and analysis

In Figure 2 the polished sections of the tooth root are shown in the etched and not etched condition. In Figure 2 a) an overview of the tooth root in the etched condition is illustrated. The material shows a typical microstructure banding. In Figure 2 b) a greater image enlargement of the tooth root can be seen. Thereby troostite in the near surface areas can be detected. Figure 2 c) shows the not etched polished section. The surface oxidation can be determined until a depth of 16 μm. The surface oxidation and the corresponding effusion of alloying elements correlate with the troostite near the surface.

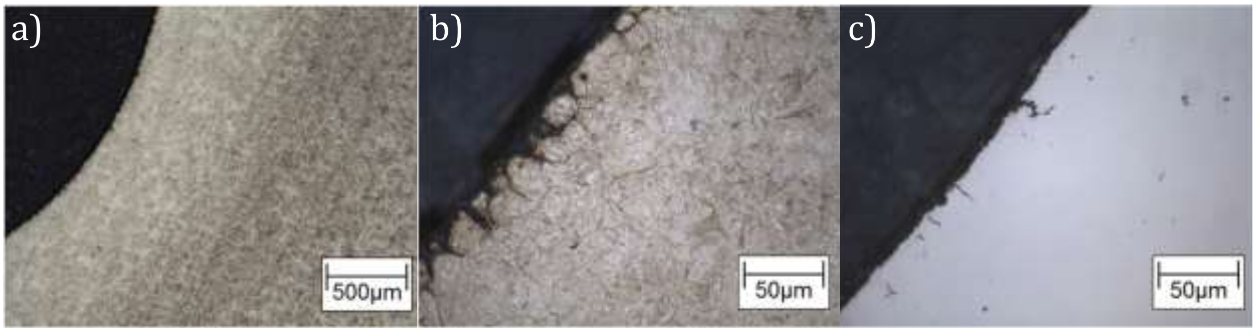


Figure 2: microstructure before shot peening (initial condition): a) overview of the tooth root in etched condition and b) near surface zone in etched and c) not etched condition

In Figure 3 left the hardness depth distributions are illustrated for all measured conditions. All distributions show a typical characteristic of case hardened specimens. The maximum hardness is near the surface followed by a gradient to the core hardness. The core hardness is located in the range of 440 HV1. The case hardness depths CHD vary between 0.98 and 1.2 mm and are all in the tolerance [compare Figure 1]. The distributions for the material charge I (initial condition and condition A, B, C and D) are similar and the differences between the distributions are in the measurement tolerance, but the initial condition (not peened) shows no increase of the hardness to the surface. The first hardness values near the surface seem to be influenced by shot peening. The material must be work hardened. The series condition represents another material as well as another heat treatment charge and therefore cannot be compared with the distributions of the material charge I.

In figure 3 right the residual stress depth distributions for the initial and the shot peened conditions are shown. For the initial condition the residual stresses at the near surface area are in a tensile range. In a depth of 10 μm already compressive residual stresses can be measured. These residual stresses are already in the range of the maximum compressive residual stresses of about -350 MPa and stay nearly constant in the measured depth range.

All shot peened conditions show compressive surface residual stresses of about -325 MPa. The differences between the five different shot peened conditions are all in the measurement tolerance. The maximum compressive residual stresses beneath the surface range from -1000 to -1230 MPa and increase with higher peening pressure and higher coverage. The penetration seems to depend only on the peening pressure.

By shot peening the initial tensile surface residual stress can be changed into compressive residual stress. But there are no relevant differences between the different residual stress values. It seems that higher residual stresses cannot be introduced in the material. The material seems to be at its limit of hardness increase. Probably the material is influenced by surface oxidation and the resulting microstructure.

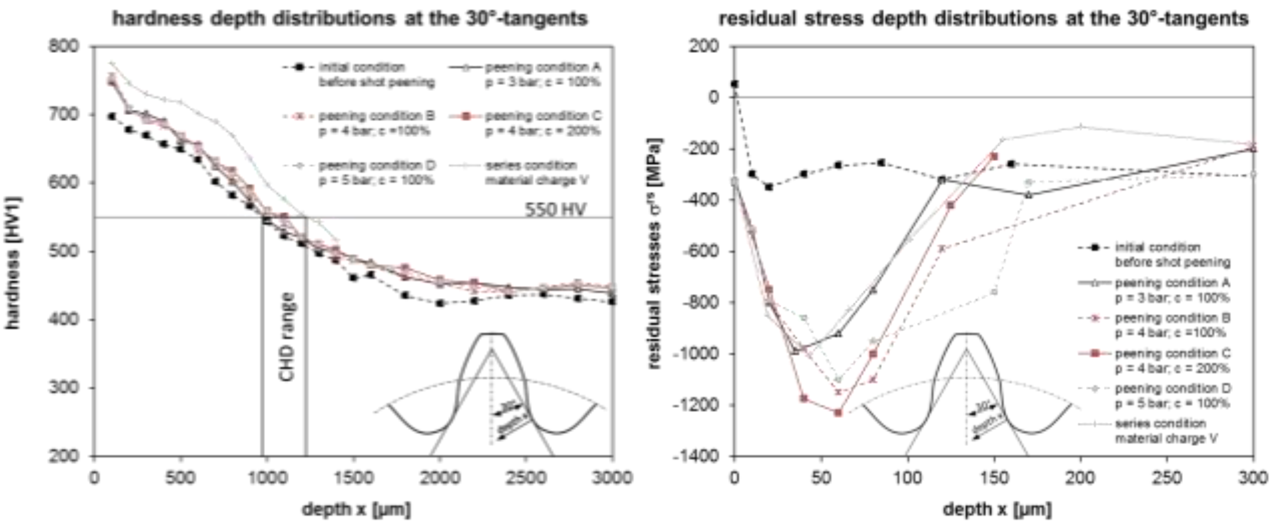


Figure 3: hardness (left) and residual stress (right) depth distributions at the 30-tangents for different peening conditions

In order to get reproducible surface conditions after shot peening the shot peening setup must be controlled. Therefore three Almen strip holders were arranged on a reference circle. So it is possible to measure the Almen intensity under an angle of ± 30° which correspond to the left and the right 30° tangents and tangential which correspond to the tooth root (compare Figure 4 left). With this setup of Almen strip holders and required Almen values, with the corresponding coverage on the shot peened gears and with the determined shot peening media the quality of the shot peening process can be ensured. In Figure 4 right the measured Almen intensity for the three different Almen strip holder are illustrated over a small time period. The values show a very low variation.

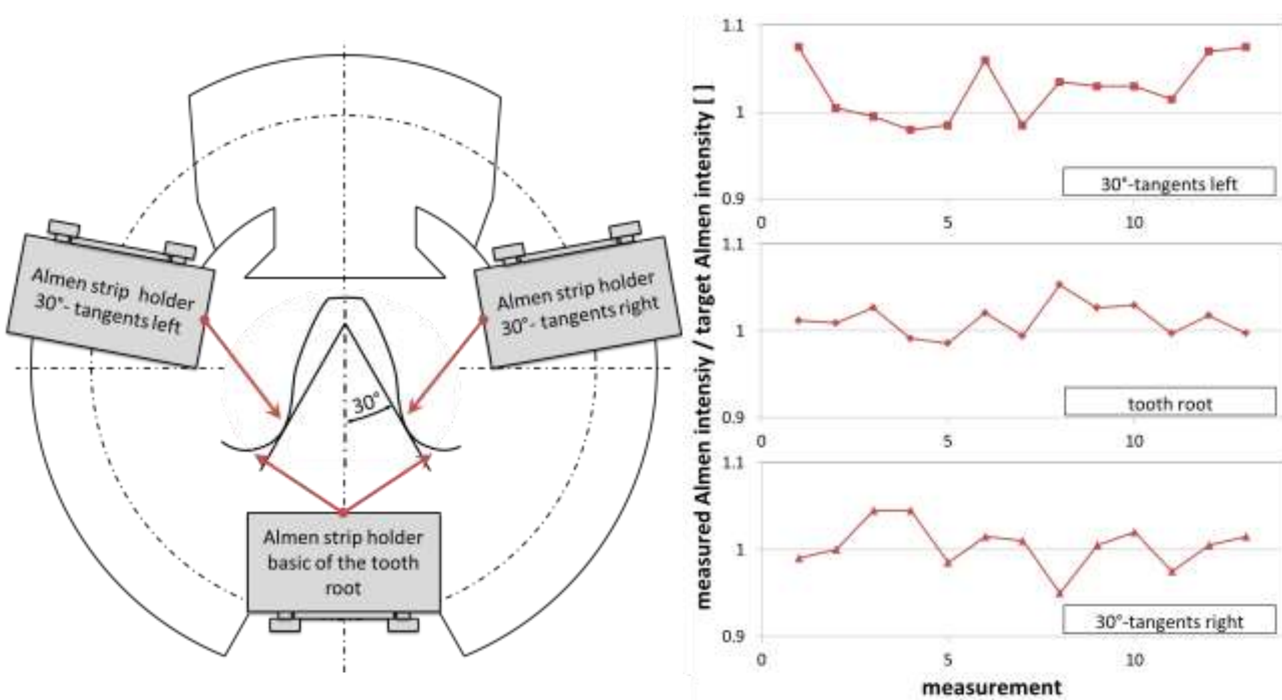


Figure 4: schematical arrangement of Almen strip holders (left) and the corresponding Almen values over a small time period (right)

The results of the fatigue test after the evaluation are illustrated in Figure 5. With optimum shot peening parameters the performance of the tooth root strength of case hardened gears can be improved significantly. In the optimization step increases of 50% of the nominal stress values $\sigma_{F\,lim}$ compared to the non-peened condition are realized. The differences between the five different shot peened conditions are not significant. There is the tendency to get higher stress values with higher peening pressures and higher coverage.

Based on these results a peening setup was fixed. Therefore following parameters were adapted to gears: mass flow, peening pressure, coverage, nozzles number and orientation. Aim of this adjustment was it to get a peening setup which produces the equivalent nominal stress values $\sigma_{F\,lim}$ as in the optimization step and to get a setup which can be used for gear wheels as well as pinon shafts. Additionally the high cycle fatigue phoneme was taken into account. Because compressive residual stresses always result in tensile residual stresses somewhere else in the component a peening setup was chosen, which does not introduce the highest compressive residual stresses and also high penetrations should be avoided. So the tensile residual stresses in the inner material can be minimized. With this new peening setup, the first gears in series were shot peened. The result can be seen in **F**igure **5**, first series setup. Comparable nominal stress number value $\sigma_{F\,lim}$ as during the optimizations step can be achieved.

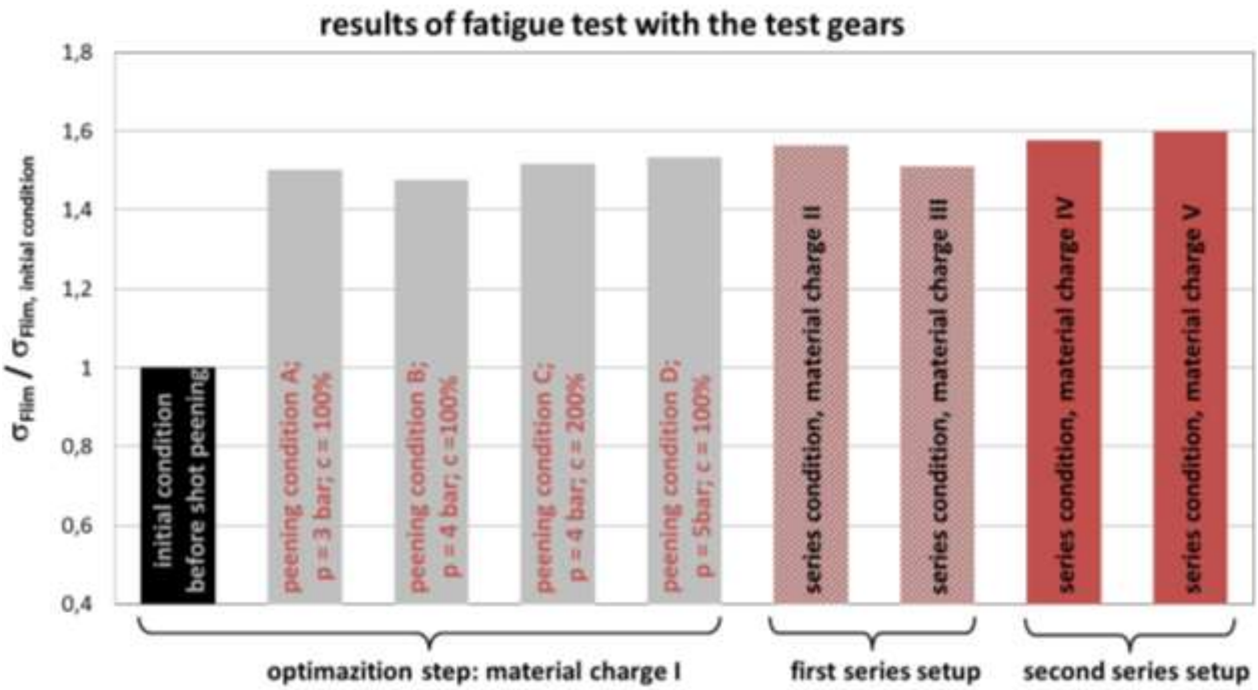


Figure 5: nominal stress numbers value $\sigma_{F\,lim}$ normalized to nominal stress numbers value of the initial condition $\sigma_{F\,lim,\,initial\,condition}$

To get further improvements of these good results another setup with a different nozzle orientation was chosen. Additionally the material specification was marginal modified and the heat treatment was adjusted. The result of this new setup can also be seen in figure 4, second series setup. It is possible to achieve an increase of 60% of the nominal stress values $\sigma_{F\,lim}$ compared to the non-peened condition.

Conclusions

With optimized shot peening parameters the nominal stress numbers value $\sigma_{F\,lim}$ of test gears can be significantly increased of about 60% compared to the non-peened condition. To ensure the optimum performance not only the shot peening process must be optimized and controlled but also the material and the heat treatment have to be considered. Only if these three requirements material, heat treatment and shot peening are balanced the quality of the generated skin layer state can be ensured and the maximum nominal stress numbers value $\sigma_{F\,lim}$ can be achieved.

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