Comparison of Water Jet Peening and Laser Shock Peening with Shot Peening for the improvement of fatigue properties of casehardened steel gears

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Abstract

In this study, the methods of Water Jet Peening (WJP) and Laser Shock Peening (LSP) were compared to Shot Peening (SP) and investigated in terms of induced residual stresses (RS), microstructure, surface topography and fatigue properties for a casehardened steel. Different modifications of the surface topography were observed for the different peening methods: after SP, a strong plastic deformation of the surface occurred while the LSP had only a minimal influence on surface topography. After WJP with very high pressure (4500 bar), microscopic damages can occur at the surface. SP leads to the highest compressive RS (up to -1650 MPa) with a maximal affected depth of about 170 µm. After WJP, maximum RS of about -1000 MPa with very low depth (50 µm) are present, while the LSP leads to very large affected depths (< 1 mm) and RS of about -1300 MPa. In terms of fatigue properties, the SP process shows the highest improvement compared to the heat treated state (+47 %) while the LSP and the WJP leads to an improvement of +15% and +23 % respectively but with larger scatter.

Keywords Laser Shock Peening, Water Jet Peening, Shot Peening, Fatigue, Residual Stress

Introduction

The positive effect of mechanical surface strengthening treatments on the fatigue properties of notched components is well known and widely used in industrial applications [1, 2]. Responsible mechanisms are inhomogeneous elastic-plastic deformations and possible phase transformations leading to cold working and creation of high compressive Residual Stresses (RS) in surface layers [1]. The most widely used technique is the Shot Peening (SP). The state of knowledge about this method is well documented within the frame of the International Conferences on Shot Peening (ICSP) since 1981 [1]. As well, alternative methods like Laser Shock Peening (LSP), Water Jet Peening (WJP), Cavitation Peening (CP), Ultrasonic Peening (UP), Deep Rolling (DP) or other techniques are reported in the literature [1- 8]. However, besides the positive effects of mechanical surface treatments on hardness and residual stresses, negative effects on the surface topography might occur. This can lead to a lower potential for fatigue endurance increase [3]. Moreover, sticking shots that might take place for SP techniques could lead to early failure in the case of gears and therefore require careful control and cleaning of the workpieces.

The methods of WJP and CP, both using a high pressure water jet either in air or within water are developed since 3 decades [1, 5, 6]. These methods do not require several types of shots for different materials and the related expensive equipment for separation of the shot material. Moreover, shotless peening methods using high pressure water jet present the advantage that sticking shots (as it can happen in SP) are fully avoided and that minor influence on the surface topography can be achieved [5, 6]. Several works on the methods of WJP and CP can be found, but few well-documented results can be found on the fatigue increase of carburizing steel [5, 6]. Moreover, compared to works performed in the 90's using pressures of up to 1000 bar [6], new developed pumps allowing the use of pressure of up to 6000 bar might lead to further increase of RS and fatigue properties.

Due to its shotless character, the technique of Laser Shock Peening (LSP) can also represent an interesting alternative to SP for components of automotive power train. The principle is based on very short, high-energy laser pulses inducing a plasma in an ablative layer (or at the surface of the material itself) leading to the propagation of a nearly planar shockwave within the treated material [3, 7, 8]. Due to this, very high peening depths can be reached (up to several mm). Up to now, this method has been mostly used at ductile materials like aluminium, titanium or austenitic steels but only few results are known for high-strength steels [3, 7, 8]. In the present study, systematic investigations on the effect of WJP and LSP on residual stresses, surface topography and resulting fatigue properties were performed with casehardened, notched model-samples (as simplified model for gear teeth) made of 18CrNiMo7-6 and compared to SP, performed with two different sets of parameters.

Experimental Methods

Material, sample geometry and manufacturing: The typical 18CrNiMo7-6 carburizing gear steel for high-performance components was used. The chemical composition of the continuous cast material which was delivered in ferrite-pearlite condition is given in Table 1. The microscopic cleanness of the steel was evaluated meeting the quality class MQ [9]. According to the large amount of investigations, the use of gears would have been very time consuming. Therefore, model-samples were used. In order to be able to transfer the results to industrial gears, a model-sample geometry consisting of a main body, a fillet and a notch with a defined radius of 1.5 mm was used. The samples were machined and ground in the notch before heat treatment.

Table 1: Chemical Composition of 18CrNiMo7-6 determined by OES (Mass.-%)

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N
Content	0.167	0.205	0.531	0.012	0.027	1.640	0.311	1.490	0.018	0.175	0.012

Heat Treatment (HT): The samples were low pressure carburized in a two-chamber furnace (Ipsen, Germany) and quenched. The samples were lying in one layer of about 35 samples for each batch. The HT was performed as follows: carburizing with 600 l/h acetylene at a pressure of 4 mbar at 940°C, cooling to 840°C within 20 min in vacuum, holding for 20 min at 840 °C in vacuum, quenching with 10 bar nitrogen to room temperature, tempering for 120 min at 180 °C. The carburizing consisted in following boost and diffusion steps: 1/20..1/20..1/30..1/30..1/40..1/70 with the small numbers representing the boost steps in min and the large numbers representing the diffusion steps in min. A surface C content of 0.7 Mass.-% and a Case Hardening Depth (CHD) of 0.75 to 0.8 mm were specified.

Shot peening: For the Shock Peening (SP) treatments, performed by the company OSK Kiefer in Germany, two different conditions were selected: the 1st is called "standard" and the 2nd "duo-process". For both conditions, the treatments were performed by using an air-blast equipment. For the standard condition, a steel wire shot StD-G3 with a diameter of 0.6 mm with a coverage of 1.00 to 1.25 × 98 % was used, leading to an Almen intensity of 0.27 mmA. For the duo-process, a two step peening was performed with first a similar treatment as for the standard condition, but with a higher intensity leading to an Almen-value of 0.42 mmA. In the second peening step, glass beads with a diameter of 0.25 to 0.42 mm and a coverage of 1.75 to 2.00 × 98 % were used (Almen intensity of 0.12 mmA).

Laser Shock Peening: The LSP treatments were performed by the Metal Improvement Company in Earby, England, using a Nd:glass laser. For the treatment, following parameters were varied in order to investigate their influence: ablative layer (without layer, paint, paint + tape, tape×2), coverage (100, 200, 300%), energy (4, 6, 8 GW/cm²) and incident angle (60 and 90°). All treatments were performed by using treatment durations of 18 ns and spot sizes of 3.5 × 3.5 mm (slightly varying for 60° incidence). The zone treated is shown in Fig 1, together with the schematic representation of the spot positions used for the treatment with 100, 200 and 300 % coverage. In order to obtain a homogeneous distribution of residual stresses, shifts of the layers in x and y direction were required. For the treatment of samples for fatigue tests, following parameters were used after selection by preliminary tests: energy: 6 GW/cm², ablative layer: Tape × 2, incidence: 90°, coverage: 300%.

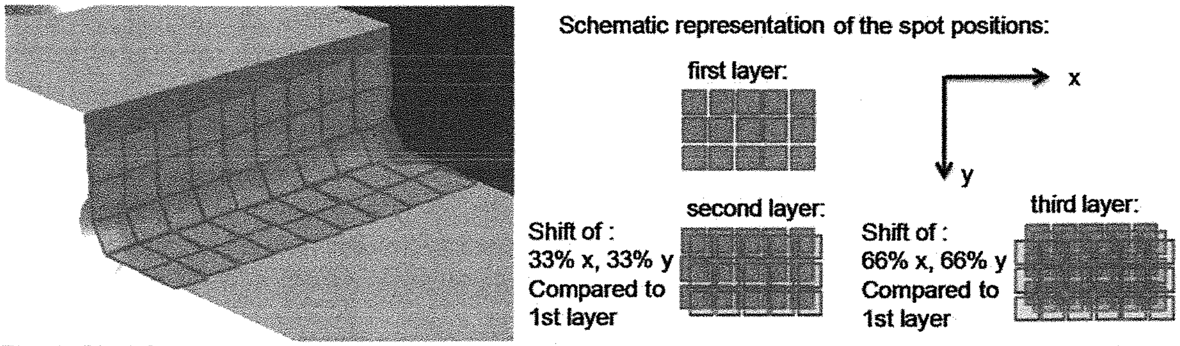

Fig. 1: Sketch showing the treated zone and schematic representation of the spot positions and associated shifts between the treated layers.

Water Jet Peening: The WJP treatments were performed with an equipment dedicated to water cutting but without abrasive media (type Mach4c, Flow, Germany). A round nozzle with a diameter of 1 mm was used for all treatments. In the first stage of the study, parameter investigations were performed with flat samples with followings variations: sample-nozzle distance between 20 and 80 mm, pressure between 680 and 4900 bar, feed rate between 30 and 3500 mm/min and varying overlapping. Optimal parameters were determined and used for the treatment of the model samples: distance 80mm, pressure 4500 bar, feed rate 900 mm/min. The treatments were performed along the complete notch length from -3.2 to +4.0 mm from the notch ground in 19 equidistant steps (Fig. 2).

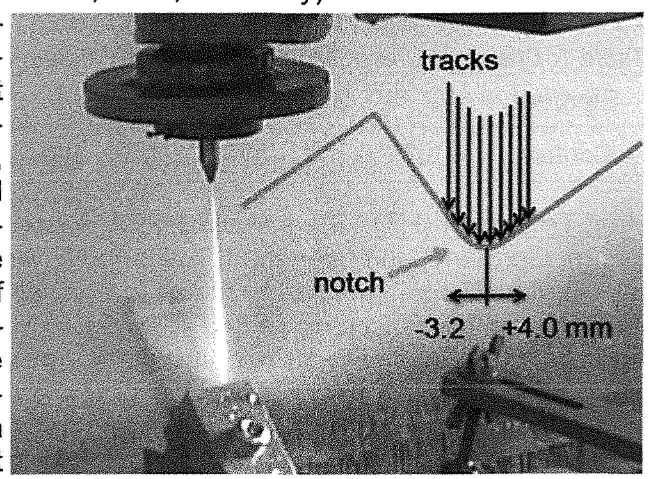

Fig. 2: Picture of WJP of a model sample and sketch showing the positions of the treated tracks

XRD measurements of residual stresses and retained austenite: X-ray diffraction measurements of residual stresses and retained austenite have been executed with a Bragg-Brentano diffractometer (type MZ VI E, GE Inspection Technologies) equipped with Vanadium filtered Cr-Kα-radiation. The primary beam was focused to a diameter of 0.3 mm by a focusing-lens and using an oscillating translation in notch direction in order to improve the grain statistic. A position sensitive detector recorded the diffracted beam of {211} lattice planes of martensite and {220} of retained austenite. Measurements were performed respectively with 15 tilt-angles from -45° to +45° parallely (σ_{11}) and from -45° to +41° perpendicularly to the notch (σ_{22}) as shown in Fig 3. Diffraction line positions were determined by mean values of the centre of gravity method for thresholds between 30 and 80 % of the maximum peak intensity after linear background subtraction. From the slope of the regression line through the 15 line positions, residual stresses were calculated according to the standard $\sin^2\psi$-method with following X-ray elastic constants: Martensite-{211} Young's Modulus: 220 GPa, Poisson's ratio: 0.28; Austenite {220} Young's Modulus: 207 GPa, Poisson's ratio: 0.28 [10]. For the evaluation of the amount of retained austenite, phase analyses were performed in the notch ground with the same equipment by measuring the diffraction lines {110}, {200} and {211} of martensite and {111}, {200} and {220} of retained austenite. The evaluation of the diffraction patterns was performed with the software TOPAS 4.2 (Bruker-AXS) using the Rietveld-Method. In order to establish the depth profiles for RA and RS, X-ray measurements were conducted at different pre-selected depths after electro-polishing. The electro-polishing was carried out using an electrolyte solution containing 80% H_3PO_4 and 20% H_2SO_4. Correction of layer removal was performed according to Moore and Evans [11].

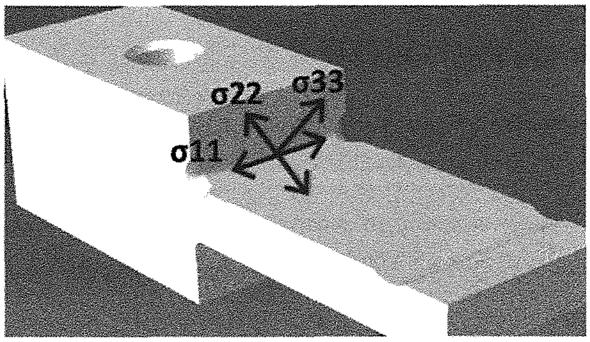

Fig. 3: Sketch of a model-sample with the position of the measurements (notch ground) and direction of the stress components

<u>Fatigue tests:</u> The fatigue properties were evaluated by performing cyclic bending tests of the model samples. The samples were fixed by the central hole and an uniaxial force was applied at the end of the fillet, inducing a bending stress in the notch ground. Due to the notch, a similar loading condition was obtained as in gears. A high-frequency pulsator (Amsler, Germany) with a maximum force of 10 kN was used. The tests were performed with a stress amplitude ratio (R) of 0.1 with a frequency of about 50 Hz. All tests were run at predefined loading amplitudes until 10^7 loading cycles were reached (samples without rupture) or until a frequency drop of 1 Hz was reached, indicating the creation of cracks. The determination of Wöhler curves was done by testing 5 load levels with at least 4 samples each and calculated by using a 2-parametric Weibull function [9]. Due to the notch, a form factor α of 1.53 was determined by FEM simulation (Abaqus, Dassault systems).

Experimental Results

The residual stress distributions measured in longitudinal (σ_{11}) and transversal (σ_{22}) direction in the notch ground at SP "Standard", SP "Duo-Process" and WJP samples together with the as heat treated reference sample are presented in Fig. 4. After heat treatment, compressive RS of about -200 MPa (longitudinal) and -300 MPa (transversal) are present. For WJP and SP treatments, the induced RS are deeper in compression in transversal direction than in longitudinal direction. Maximum RS of -900 (σ_{11}) to -1000 MPa (σ_{22}) are reached at the surface after WJP, while for the SP treatments, the maximum RS is always located around 50 µm depth. Maximum values of -1000 (standard) and -1120 MPa (duo-process) are achieved in longitudinal direction while in transversal direction values of -1500 (standard) and -1650 MPa (duo-process) are reached. The affected depth after WJP is very low (about 50 µm) compared to the SP treatment (about 170 µm).

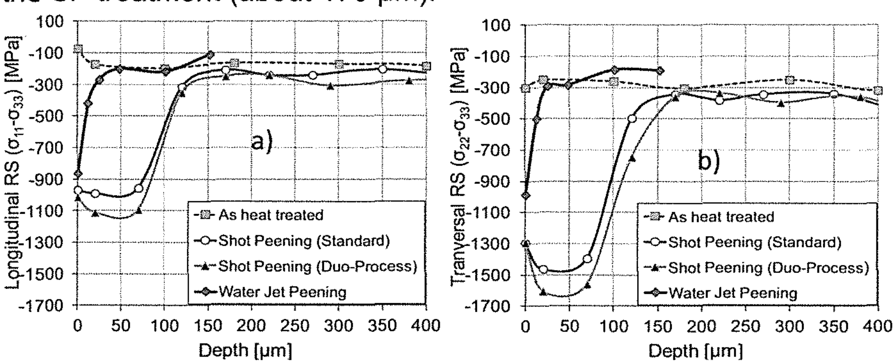

Fig. 4: Residual stress depth profiles measured in longitudinal (a) and transversal direction (b) in the notch ground of SP standard, SP duo-process, WJP and as heat treated samples

Similar graphs of RS depth profiles are given for several LSP samples treated with different parameters in comparison with the as heat treated reference in Fig. 5. Here, a fundamental difference compared to the SP and WJP samples can be observed. The RS values in longitudinal direction are deeper in compression than in transversal direction while it was the opposite for the previous treatments. This can be explained by the fact that the shockwave induced by LSP at the notch ground propagates in a divergent manner in transversal direction in the depth leading to a rapid loss of energy while in longitudinal direction, no such loss of energy occurs. This explains also why the affected depth in longitudinal direction is larger than in transversal direction. In general it can be noticed that the depth where a significant increase of compressive RS is present, is much larger than for SP and WJP treatments (up to 1 mm or more). According to the treatment parameters, very different RS distributions were measured: for LSP without and with paint as ablative layer, tensile RS are present at the surface. This can be explained by the presence of a rehardened zone occurring due to the plasma creation at the surface and associated large temperature increase of the samples' surface (even up to remelting). In deeper layers, compressive RS are present but with low values and low affected depth. Compressive RS from -900 to -1300 MPa (longitudinal) and from -900 to -1100 MPa (transversal) were reached at the surface for the different treatment parameters. The treatment using tape (with 2 layers) as ablative layer leads to the highest RS and affected depths.

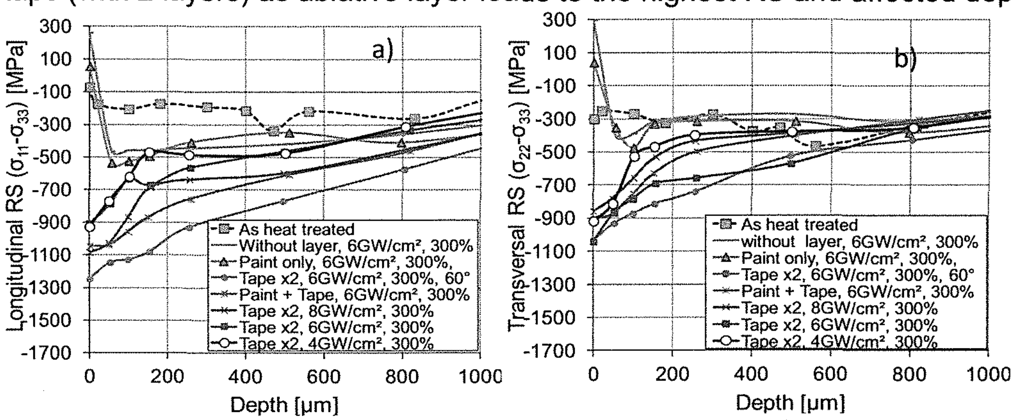

Fig. 5: Residual stress depth profiles measured in longitudinal (a) and transversal direction (b) in the notch ground of as heat treated and of different LSP samples

Surface topography recorded with a roughness measurement module in a Scanning Electron Microscope of different conditions is shown in Fig 6. Before heat treatment, slight grinding scratches are present. After HT, grains boundaries were hot etched, as known for low pressure HT and represent deep micro-notches when superimposed to grinding scratches. These will lead to stress concentration during loading and to crack initiation. Due to strong plastic deformation of the surface after SP standard, the etched grain boundaries are smoothed and after SP duo-process, these cannot be recognized anymore. Even if the SP treatment leads to changes of macroscopic roughness, the diminution of microroughness through plastic deformation is expected to have a positive effect on the fatigue properties. After LSP, the surface topography remains almost. unchanged, as after WJP, but in this case, surface erosion also occurred locally at former grain boundaries. This is expected to reduce to potential of fatigue limit increase reached by high compressive RS.

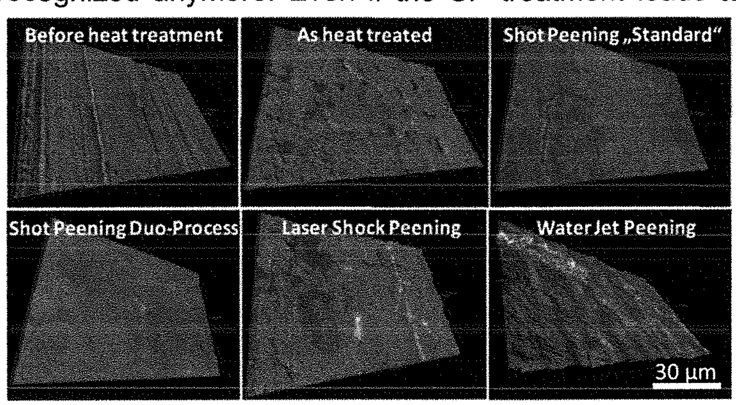

Fig. 6: Surface topography of model-samples recorded with a scanning electron microscope in different condition

The Wöhler curves obtained for the different treatment conditions are present in Fig.7. The SP duo-process leads to the highest increase (+47% compared to the as heat treated state), followed by the SP standard treatment with + 41%. After LSP and WJP, an increase of the fatigue limit of +15% and +23% respectively was reached. However, for these both treatments, high scattering of the number of cycles was obtained for the lower loading range. For the LSP treatments, it has to be remarked that all cracks started at the edge of the notch while for all other treatment, the cracks always started in the center of the notch. After RS measurements, it could be observed that after LSP, lower compressive RS were present towards the edges.

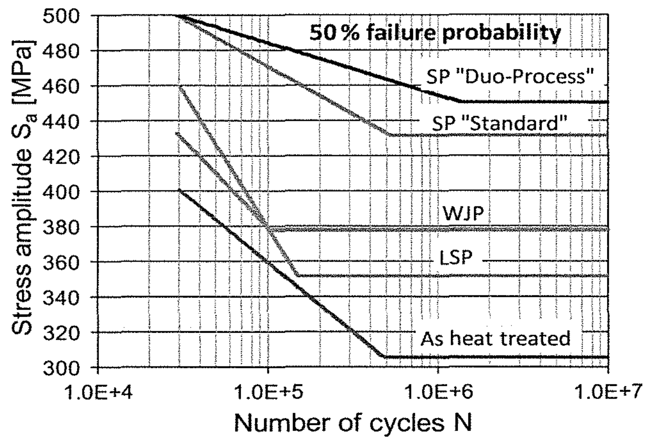

Fig. 7: Woehler-curves obtained for the different treatments

Discussion and Conclusions

The methods of Water Jet Peening (WJP) and Laser Shock Peening (LSP) were compared to Shot Peening (SP) in terms of induced residual stresses, surface topography and fatigue properties. The study was performed at model samples comparable to gear teeth. The samples were low pressure carburized. Due to heat treatment, grain boundaries were hot etched at the surface (stress concentrating micro-notches). After SP, a strong plastic deformation of the surface occurred while the LSP had only a minimal influence on the surface topography. After WJP with very high pressure (4500 bar), local microscopic damages were introduced at former grain boundaries. The reduction of micro-notches due to strong plastic deformation of the surface in SP is expected to have a positive effect.

Large differences in RS were observed. SP leads to the highest compressive RS (up to -1650 MPa) with an affected depth of about 170 µm. After WJP, maximum RS of about -1000 MPa with very low depth (50 µm) are present while the LSP leads to very large affected depths (< 1 mm) and maximum values of about -1300 MPa in longitudinal direction. In terms of fatigue properties, the SP duo-process leads to the highest improvement compared to the heat treated state (+47 %), while the LSP and the WJ P lead to improvements of + 15% and +23 % respectively but with larger scatter. Despite that WJP has a much lower affected depth than LSP, higher fatigue limit was reached. When the surface damages can be reduced, further increase is expected for WJP. On the other hand, it has been shown that the treatment strategy and parameters for LSP are decisive and that an application at high-strength steel components appears possible, in particular for large dimension components, where high affected depths are required due to stress gradients.

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