

Effect of shot peening on the residual stress and mechanical behaviour of low-temperature and high-temperature annealed martensitic gear steel 18CrNiMo7-6

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Abstract. A martensitic gear steel (18CrNiMo7-6) was annealed at 180 °C for 2h and at ~ 750 °C for 1h to design two different starting microstructures for shot peening. One maintains the original as-transformed martensite while the other contains irregular-shaped sorbite together with ferrite. These two materials were shot peened using two different peening conditions. The softer sorbite + ferrite microstructure was shot peened using 0.6 mm conditioned cut steel shots at an average speed of 25 m/s in a conventional shot peening machine, while the harder tempered martensite steel was shot peened using 1.5 mm steel shots at a speed of 50 m/s in an in-house developed shot peening machine. The shot speeds in the conventional shot peening machine were measured using an in-house lidar set-up. The microstructure of each sample was characterized by optical and scanning electron microscopy, and the mechanical properties examined by microhardness and tensile testing. The residual stresses were measured using an Xstress 3000 G2R diffractometer equipped with a Cr K α x-ray source. The correspondence between the residual stress profile and the gradient structure produced by shot peening, and the relationship between the microstructure and strength, are analyzed and discussed.

1. Introduction

Shot peening is a process in which either spherical shots, made from cast/wrought/drawn high-carbon or stainless steel, or ceramic or glass beads/shots are shot against a target to mechanically treat the



surface and to introduce compressive residual stresses parallel to the surface by means of overlapping plastic deformation indents. This process, introducing compressive residual stresses in a surface layer, is well known to improve the fatigue or stress corrosion properties, by preventing or delaying cracking, and is widely used for components and parts such as bearings, shafts and gears, in the aerospace, chemical, petroleum, automotive and power industries. Shot peening has long been applied to the root fillet area of gear teeth to improve their bending strength [1], and from 1982, has also been used to increase the pitting fatigue life of the gear tooth contact surface [2]. In 1992, high-intensity shot peening was reported to improve surface fatigue life of hardened gears [3]. However, little information has been reported about the effect of shot peening process parameters on the microstructure, and residual stress, and on their relationship with mechanical properties. Such information is required to provide a baseline for the design of more complicated and advanced properties through adjusting the parameters, including such aspects as deformation level, (sub)grain size, residual stress, retained austenite, surface morphology and roughness, chemical gradient and hardness.

In the present research, for the understanding of the relationship between microstructure, residual stress, mechanical properties and shot peening, a martensitic gear steel 18CrNiMo7-6 has been annealed at low and high temperatures to design two beginning microstructures, and traditional and high-energy shot peening have been applied.

2. Experimental methods

A 1 mm thick plate made from the martensitic gear steel 18CrNiMo7-6 (composition 0.15-0.21C, 0.17-0.35Si, 0.5-0.9Mn, 1.5-1.8Cr, 1.4-1.7Ni, 0.25-0.35Mo wt.%; balanced Fe [4]) was annealed at 180 °C for 2h and at ~ 750 °C for 1 h to obtain two different starting microstructures for shot peening. The low-temperature annealing treatment maintains the original as-transformed martensite, while the high-temperature annealing treatments results in a microstructure consisting of lath-shaped sorbite with carbides distributed in ferrite matrix and equiaxed ferrite grains. These two materials were shot peened using two different peening conditions. The high-temperature annealed steel, with a sorbite plus ferrite microstructure (HT steel), was shot peened using 0.6 mm conditioned steel shots at an average speed of 25 m/s in a conventional shot peening machine, while the low-temperature annealed steel, with martensite structure (LT steel), was shot peened using 1.5 mm steel shots at a speed of 50 m/s in an in-house developed shot peening machine, using similar shot peening mechanisms at Nanjing University of Science and Technology, China. The shot speeds in the conventional shot peening machine were measured using an in-house lidar set-up through the glass window of the peening chamber [5].

The microstructures of two samples were characterized by optical microscopy (OM) and by scanning electron microscopy (SEM). The mechanical properties were examined by microhardness measurements, using a load of 100 g with 10 s hold at the maximum load, and by tensile testing using dog-bone plate specimens (gauge length of 60 mm, thickness of 1 mm, width of 6 mm; total length of 170 mm) at a strain rate of $4.7 \times 10^{-4} \text{ s}^{-1}$.

The residual stresses were measured using an Xstress 3000 G2R diffractometer equipped with a Cr $K\alpha$ x-ray source. A standard $\sin^2(\psi)$ technique with five tilts from $-45^\circ/+45^\circ$ was used for determining the stress values. The lattice deformation for the $\{211\}$ α -Fe peak (diffraction angle 156.4°) was measured. X-rays were irradiated through a circular collimator of diameter 1.5 mm. The diffraction peaks were fitted with the StressTech XTronic software, using a cross-correlation method with a linear background. The stress conversion was carried out assuming an elastic modulus of $E = 211 \text{ GPa}$ and Poisson's ratio $\nu = 0.3$. A 2.0 mm collimator was also used for one set of angles, and it was verified that collimator size did not influence the result. For measurement of subsurface stresses, an area of 3.5 mm was etched stepwise using a 3M NaCl solution as electrolyte. After every step, a stylus profilometer was used to measure the etch pit depth and geometry.

3. Results

Figure 1 shows example backscatter electron micrographs of the high-temperature and low-temperature annealed martensitic gear steel 18CrNiMo7-6. The LT steel (figure 1b) shows a similar structure to that of the original, with a characteristic martensitic microstructure. The microstructure of HT steel (figure 1a) is heterogeneous, containing both clean ferrite equiaxed grains and a micron-scale lath ferritic structure with (sub)micron-sized carbides (sorbite).

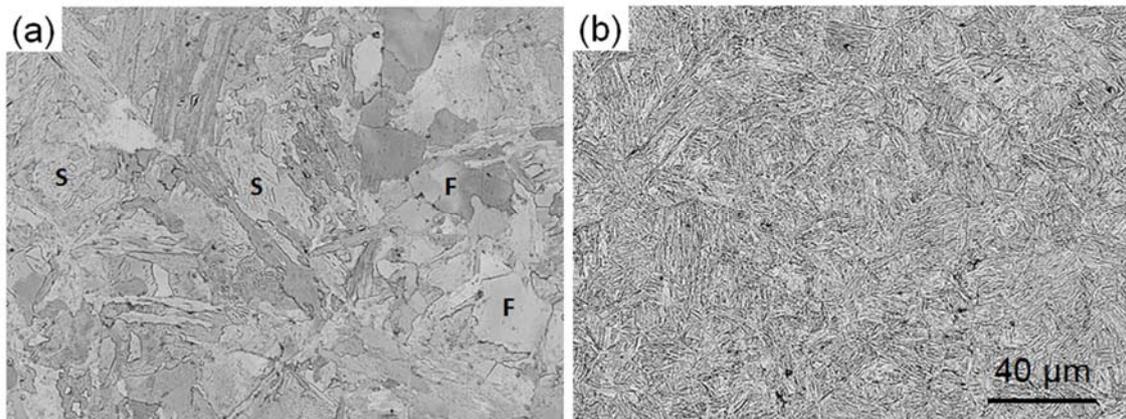


Figure 1. Backscatter electron micrographs showing the high-temperature (a) and low-temperature (b) annealed martensitic gear steel 18CrNiMo7-6. The letters “F” and “S” represent ferrite and sorbite, respectively.

Figure 2 shows the microstructure, in cross section, from the surface regions of the peened specimens. The shot peening introduces a gradient microstructure where the structure gets finer as the surface is approached. In the HT steel a lamellar spacing of ~ 59 nm is seen at the top surface. In the LT steel the gradient structure is not so obvious, due to the fine original martensite structure. A rotation of the martensite lamellar structure to be parallel to the surface is nevertheless seen, with the lamellar structural size reaching a value of 60 nm close to the top surface.

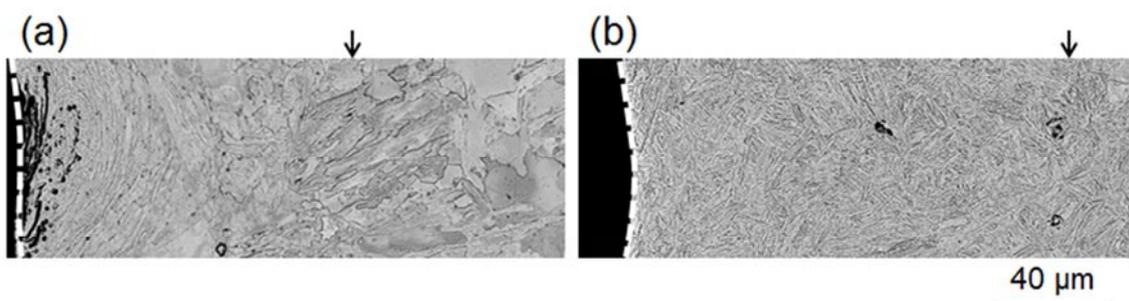


Figure 2. Backscatter electron micrographs showing the gradient structures produced in high-temperature (a) and low-temperature (b) annealed martensitic gear steel 18CrNiMo7-6 by traditional shot peening and high-energy shot peening, respectively. The dashed lines represent the surface positions and the surface direction is vertical. The vertical arrows mark the positions at 120 μm (a) and of 160 μm (b) from the shot-peened surfaces.

Figure 3 shows the microhardness measured from the cross section of the peened specimens. The HT steel has a matrix hardness around 230 kgf/mm², while the LT steel has a higher value ~ 480 kgf/mm². In the HT steel the shot peening introduces a 56% increase of hardness up to

360 kgf/mm² at a distance $\sim 10 \mu\text{m}$ from the peened surface, with a hardened gradient structure to a depth of $\sim 120 \mu\text{m}$. For the LT steel the high-energy shot peening increases the hardness up to 570 kgf/mm² at a distance of 10 μm from the peened surface.

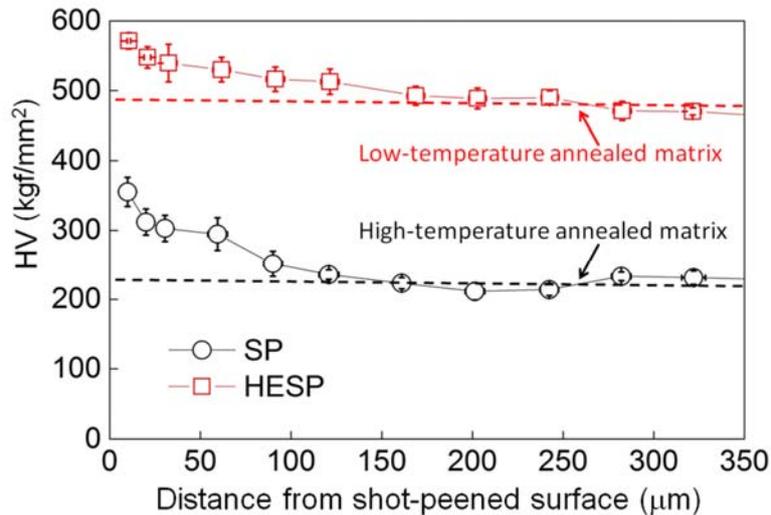


Figure 3. Microhardness as a function of distance from the shot-peened surface of the high-temperature and low-temperature annealed martensitic gear steel. The error bars represent the standard deviation of the hardness data. The dashed lines represent the matrix hardness of both steels. Letters “SP” and “HESP” represent traditional shot peening and high-energy shot peening. Note that the hardness close to the top surface is measured at a distance $\sim 10 \mu\text{m}$ from the actual surfaces taken into account the hardness indent size $\sim 6 \mu\text{m}$.

Figure 4 presents the compressive residual stress profiles perpendicular to the peened surfaces. The traditional shot peening used for the HT steel introduces a maximum magnitude of compressive residual stress of around 400 MPa, at a distance of 10 μm from the surface. The high-energy shot peening used for the LT steel introduces a compressive stress of maximum magnitude $\sim 560 \text{ MPa}$, at a distance of 160 μm from the surface. The residual stress distribution in two samples shows different trends. In the HT steel, the compressive residual stress increases slightly with distance from the surface, and then decreases reaching a small plateau of $\sim 320 \text{ MPa}$ at a depth of 120 μm from the surface. At further depths the residual stress continues to decrease. In the LT steel, the residual stress increases with increasing depth up to a maximum magnitude at a distance $\sim 160 \mu\text{m}$ from the surface, after which the residual stress decreases sharply, reaching a value of near zero at a depth of around 400 μm . The depth with residual stress of $\sim 320 \text{ MPa}$ is about 280 μm .

Table 1 shows the tensile properties of four types of specimens. The traditional shot peening, applied to the HT steel, results in an increase of the $\sigma_{0.2\%}$ flow stress by $\sim 14\%$, but to a decrease in the UTS by 7%. The high-energy shot peening, used for the LT steel, results in increases to the $\sigma_{0.2\%}$ flow stress and to the UTS of $\sim 11\%$ and $\sim 4\%$, respectively.

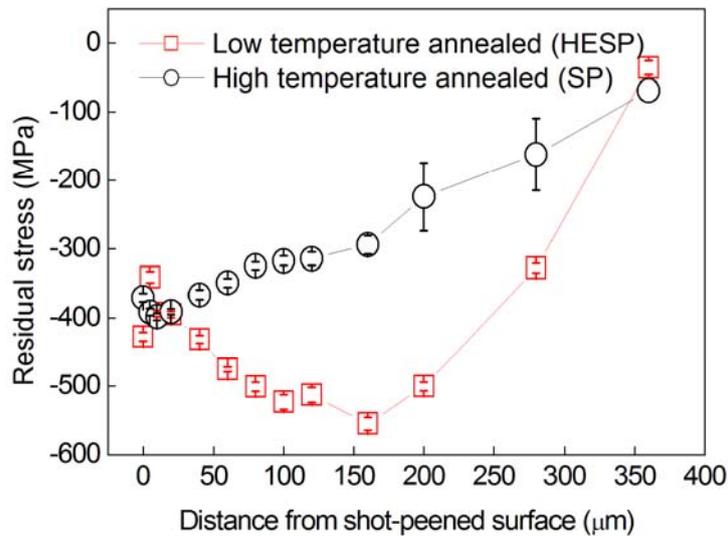


Figure 4. Residual stress as a function of the distance from shot-peened surface for the of high-temperature and low-temperature annealed martensitic gear steel 18CrNiMo7-6.

Table 1. Tensile properties of as heat-treated and shot-peened specimens

| Specimen | $\sigma_{0.2\%}$ (MPa) | UTS (MPa) | UTS/ $\sigma_{0.2\%}$ | Total elongation (%) |
|-----------------|------------------------|-----------|-----------------------|----------------------|
| HT steel | 344.4 | 582.6 | 1.69 | 17.1 |
| LT steel | 1124 | 1410.5 | 1.25 | 5.7 |
| HT steel _ SP | 392 | 542 | 1.38 | 11.6 |
| LT steel _ HESP | 1250 | 1470 | 1.18 | 6.2 |

4. Discussion

The annealing treatments used in this study result in a sorbite + ferrite microstructure in the HT steel and a tempered martensite in the LT steel, resulting in $\sigma_{0.2\%}$ flow stress almost three times higher for the LT steel. For the HT steel, traditional shot peening results in an increase of the $\sigma_{0.2\%}$ flow stress, but leads to a decrease in the ultimate tensile strength (UTS) and in the total elongation. For the LT steel, high-energy shot peening results in an increase in the $\sigma_{0.2\%}$ flow stress and in the UTS, with a slight reduction in the total elongation. Both traditional and high-energy shot peening work-harden the microstructure and introduce gradient structures and compressive residual stresses in the HT and LT steels. The thickness of gradient structures is in good accordance with the maximum compressive residual stress magnitude (plateau): $\sim 120 \mu\text{m}$ in the HT steel and $\sim 160 \mu\text{m}$ in the LT steel.

It is well known that the effectiveness of shot peening depends both on the intensity and coverage. The intensity dictates the amount of energy transferred from the shot stream into the target parts or components, and is closely related to the shot size, shape, flow, shot material, hardness, velocity and impingement angle. To illustrate the difference between traditional shot peening and high-energy shot peening, we can estimate the energy of a single shot, assuming that in both cases the shots are of similar material and hardness (high carbon steel shot, HRC ~ 60) and that the only differences are the size and velocity of the shot. Such a calculation reveals that the energy of a single shot for high energy shot peening is 62.5 times higher than that for traditional shot peening, on the assumption that the energy (E) of single shot is proportional to the product of the mass (m) and the square of the velocity (v^2):

$$E \sim mv^2 = \frac{4}{3}\pi r^3 \rho \times v^2 \quad (1)$$

where ρ is the density of the shot and r is the radius of the spherical shot. This large difference may be the reason why the high-energy shot peening can still introduce a thicker deformation layer in the hard steel, in comparison with the traditional shot peening on soft steel.

The soft HT steel exhibits a strong work hardening before shot peening (69%, from the data in table 1), but after the peening process, the work hardening capability is reduced in the surface layer and the strain hardening ratio (UTS/ $\sigma_{0.2\%}$ flow stress) decreases considerably. During plastic deformation in the tensile test, the residual stress magnitudes decreases [6] as the plastic flow increases but the deformed surface microstructure remains. The reduced strain hardening capability in the surface leads to earlier localization of the fracture, resulting in a lower UTS and lower total elongation. In the hard LT steel exposed to high energy shot peening, the degree of plastic deformation in the surface is much lower, but because of the higher energy and larger indents, plastic deformation extends to larger depth [7]. The maximum shear strain occurring beneath the surface has its correspondence in the maximum in compressive residual stress observed at 160 μm (around 15 μm in the SP). The tensile straining of the high-energy shot peened hard LT steel also reduces the residual stress field on plastic flow, but here the surface layer retains sufficient work hardening capability. Localization of plastic strains leading to necking is delayed, giving higher UTS and less reduced total elongation. The HESP treatment thus improves the performance in monotonic uniaxial straining.

For the further quantitative understanding of the shot peening process on mechanical properties, such as the tensile properties examined in the present experiments, the surface integrity, including surface morphology, roughness and texture needs should be taken into account in addition to the gradient structure and the residual stress profile. More detailed information on the microstructure and (sub)surface texture is being acquired by using electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM), described in our recent studies [8-12] on microscale to nanoscale metallic structures with strength ranging from several hundred MPa up to ~ 5 GPa. These additional studies will constitute a forthcoming paper and will further the understanding of the shot peening process and its effect on the microstructure, texture, surface morphology, roughness, residual stress and mechanical properties including fatigue.

5. Conclusion

A martensitic gear steel 18CrNiMo7-6 was annealed at 180 °C for 2h and at ~ 750 °C for 1h to allow the design of two different starting microstructures for a study of shot peening. One microstructure consists of tempered martensite (LT steel), while the other consists of a mixture of sorbite and equiaxed ferrite (HT steel). Traditional shot peening and high-energy shot peening have been applied to the HT steel and the LT steel, respectively. The conclusions are as follows.

- Both traditional and high-energy shot peening introduce a gradient microstructure in the HT and LT steels.
- The depth of the developed gradient structures and maximum compressive residual stress (plateau) introduced by shot peening are in good accordance: ~ 120 μm in the soft steel and ~ 160 μm in the hard steel.
- The traditional shot peening applied to the softer HT steel results in an increase of the $\sigma_{0.2\%}$ flow stress and a decrease the UTS. In contrast the high-energy shot peening used for the harder LT steel results in increases both in the $\sigma_{0.2\%}$ flow stress and in the UTS.

Acknowledgements

The authors thank Mr. Huilong Lu (Nanjing High Speed Gear Manufacturing Co. Ltd., PR China) for the supply of the raw gear steel 18CrNiMo7-6 used in this investigation. R Yang and G Wu appreciate the financial support from the Natural Science Foundation of China (Grants No. 51471039, 51327805) and from the State Key Research and Development Program (2016YFB0700401, 2016YFB0700403).

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