Microstructural analysis of shot and laser shock peened grey iron for increased fatigue strength

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Abstract

Mechanical surface treatments such as shot or laser shock peening are used in technical applications to improve lifetime properties of components. This is mainly caused by the formation of a compressive residual stress state and microstructural defect density fields in near surface regions that lead to a retardation of crack initiation and propagation. In particular for grey iron that is still in use for industrial applications, the stress state is decisive to avoid crack initiation. In this study cast iron with flaky graphite has been surface treated by conventional shot peening and laser shock peening to improve lifetime properties. A first comparison of microstructure modifications due to the different peening techniques is done. As first results, the residual stress state by means of X-ray stress analysis and the deformation state by means of electron backscatter diffraction (EBSD) and backscatter detector imaging are presented.

Keywords: Microstructural analysis, laser peening, shot peening, grey iron, residual stresses electron-backscatter-diffraction (EBSD).

Introduction

In modern automotive and aircraft industries mechanical surface treatments like shot peening, laser peening, roller burnishing, etc. are frequently used to enhance component lifetime or reduce weight under the same working conditions *[1,2]*. These treatments introduce plastic deformation into the material that lead to the formation of high defect densities and microstresses. With relaxation after the treatment a high amount of elastic strain or compressive macrostress remains. Both micro- and compressive macrostresses improve service life, macrostresses by delaying crack initiation while defect densities delay crack propagation. Each effect depends on the strength of the material and the external stress field over time.

Compared to other peening methods, laser peening shows an extraordinary compressive stress depth, yet low deformation *[3]*. Because of this low-strain hardening it is possible to increase the stress field to an even greater extent. Moreover, the process is fully controllable with every shot and allows the precise simulation of macrostress states. Currently, the costs of laser peening steadily decreases rendering it more and more interesting for broad industrial purposes, including automotive. In this sector, grey iron materials are frequently used in casting components, however in order to compete with other light-weight materials, e.g. Al, increased strength and lower weight are essential. Where surface treatments like shot peening are only used to remove e.g. casting sand, laser peening could introduce a definite compressive stress field at specific locations.

In the present work, the stress and strain state of conventional shot peened and laser peened grey iron microstructure are compared using typical X-ray diffraction (XRD), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) to investigate the changes in stress and strain.

Experimental Methods

The samples were taken from the core of a grey cast iron cylinder crankcase for maximum microstructure homogeneity. To relieve initial stresses the samples were heated up to 600°C for 2 h. The microstructure is shown in Figure 1. The graphite lamellae are incorporated in a pearlitic matrix (ferrite and cementite). The average grain size was about 50 µm.

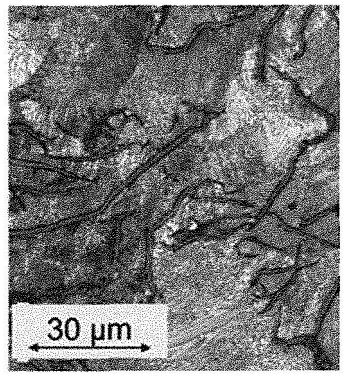

Figure 1: Optical micrograph of the examined grey iron material after etching with a 2 % Nital solution with ethanol. The graphite phase can be clearly seen as black lamellae in the pearlitic (ferrite and cementite) matrix phase.

The samples were shot peened and laser peened. The parameters of the two peening techniques used are listed in *Table 1* and *Table 2*, respectively. According to the technical possibilities and experimental considerations the shot peening intensity is much higher than laser peening intensity.

Table 1: Parameters of the shot peening treatment.

Blasting abrasive	Cut Wire Steel
Tool	blasting lance
Shot diameter	0,8 mm
Blasting angle	90°
Coverage	200 %
Almen Intensity	0,4 mm A2

Table 2: Parameters of the laser peening treatment.

Laser power (avg.)	16 W (Nd::YAG, 1064 nm wavelength, 10 ns pulse duration)
Spot diameter	2 mm (round shape)
Power density per pulse	5,2 GW/cm²
Number of shots	3
Overlapping	50 %
Confining medium	Water (~2 mm thickness)
Absorber medium	Zinc foil (100 µm thickness)

To investigate the stress state of the individual peened samples, residual stress measurements were done using a Philipps XPert MRD diffractometer and Cr radiation for the {211} reflection of the ferritic phase. Electrolytic polishing in combination with interferometric depth measurements were used for layer removal. The zone of compressive stresses was delimited by stress values in the same order of magnitude as the initial stress state, including the error. To characterize the deformation state, SEM techniques were used in a FEI Helios NanoLab 600. In a highly plastically deformed microstructure a high density of dislocations leads to a high amount of small orientation changes. A dedicated low voltage backscatter detector (vCD) images individual microstructures and is highly sensitive to orientation and atomic contrast. In a single phase with homogenous atomic concentration, the main contrast mechanism is attributed to orientation changes. EBSD analysis was used to quantify these changes, with a Hikari camera in an EDAX system, at a 200 nm stepize. Kernel average misorientation (KAM), which averages misorientations between a pixel and its neighbours (in this study: only the second neighbours are considdered) permits a lower estimation to the density of geometrically necessary dislocations (GND – dislocations that provide grain rotations; in contrast to statistically stored dislocations (SSD)).

Experimental Results

Stress state:

The results of the residual stress measurements are displayed in Figure 2 for the shot peened state and in Figure 3 for the laser peened state. The measurement accuracy of the initial stress state was better than 28 MPa.

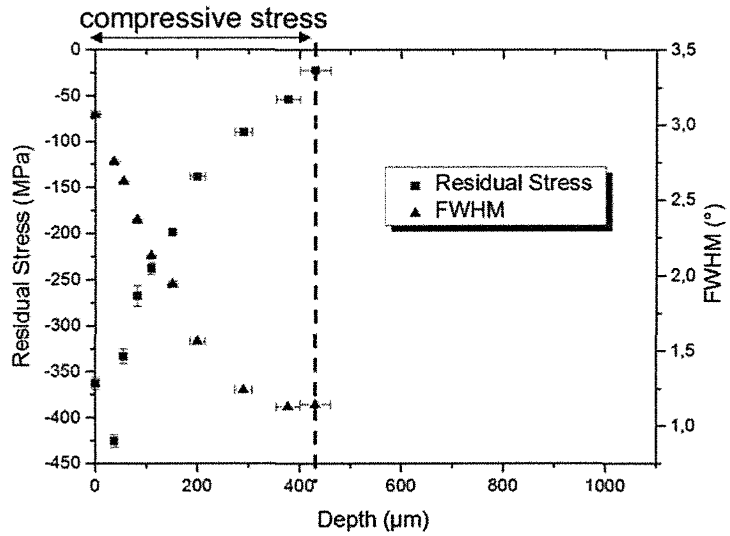

Figure 2: Residual stresses (macrostress) and FWHM (microstress) of the shot peened state. As indicated, a zone of ~400 µm depth shows compressive stresses and an increased FWHM.

It is shown that the depth of laser peening compressive stresses is roughly double that of shot peening, yet with a lower maximum. The XRD peak full width at half maximum (FWHM) is significantly lower and shows a slight increase near the surface at 50 µm, whereas the shot peened state shows an increase that is in good agreement with the macrostress development at 400 µm.

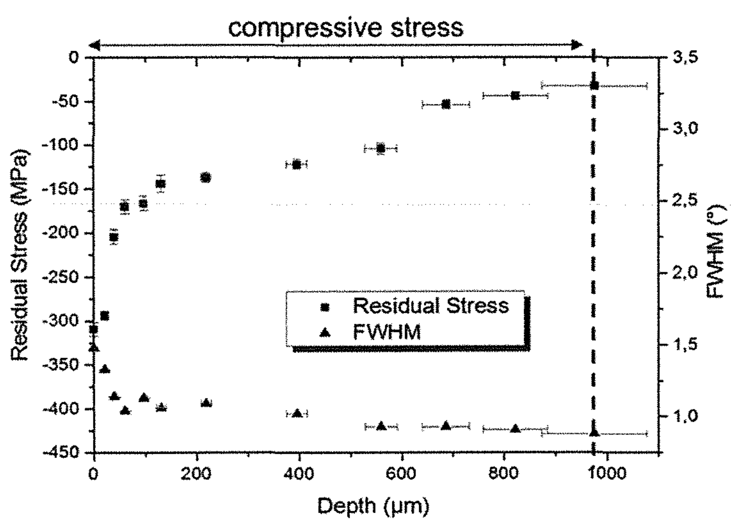

Figure 3: Residual stresses (macrostress) and FWHM (microstress) of the laser peened state. As indicated, a zone of ~1000 µm depth shows compressive stresses, roughly double that of shot peening. FWHM increases only slightly near the surface.

Strain/deformation state:

Scanning electron backscatter micrographs and EBSD scans were done on untreated and treated areas to evaluate the strain state of the peened materials.

The backscatter images in Figure 4 show the high grey-scale contrast within the lamellae of the shot peened state. The contrast changes in the initial state and in the laser peened state are relatively low and only subgrain boundaries are attributed to orientation changes.

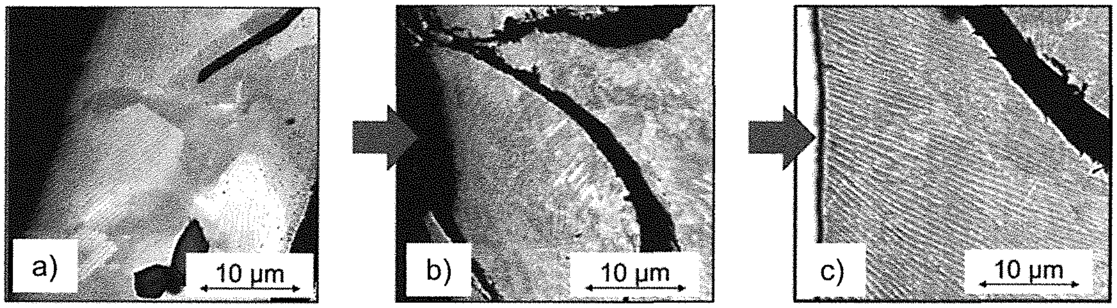

Figure 4: Scanning electron backscatter micrographs show no contrast changes within the pearlitic lamellae in the reference state *(a)*, high frequency of contrast change in the shot peened state *(b)* and low contrast change in the case of laser peened state *(c)*. The peened surface is indicated in *(b)* and *(c)* by the dark arrow.

EBSD and KAM calculations were used to quantify this deformation state with high local resolution. Figure 5 shows the KAM map (a higher grey value is attributed to a higher misorientation) and the averaged value over a small depth range. The misorientation, and therefore the density of GNDs, remains low; only the first 20 μm present a slight increase. This will be discussed later.

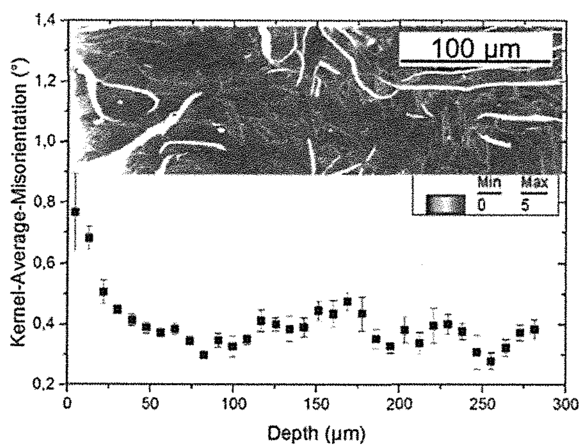

Figure 5: KAM map and averaged (over 8,66 μm) KAM values .

The peened states in Figure 6 *(a)* and *(b)* reveal a higher deformation degree. In the case of shot peening, the highest degree is observed near the surface. Compared to the inital state the misoriention is increased approximately at the same depth as the XRD results show. The plateau in *(a)* will also be discussed later. Laser peening lies in between.

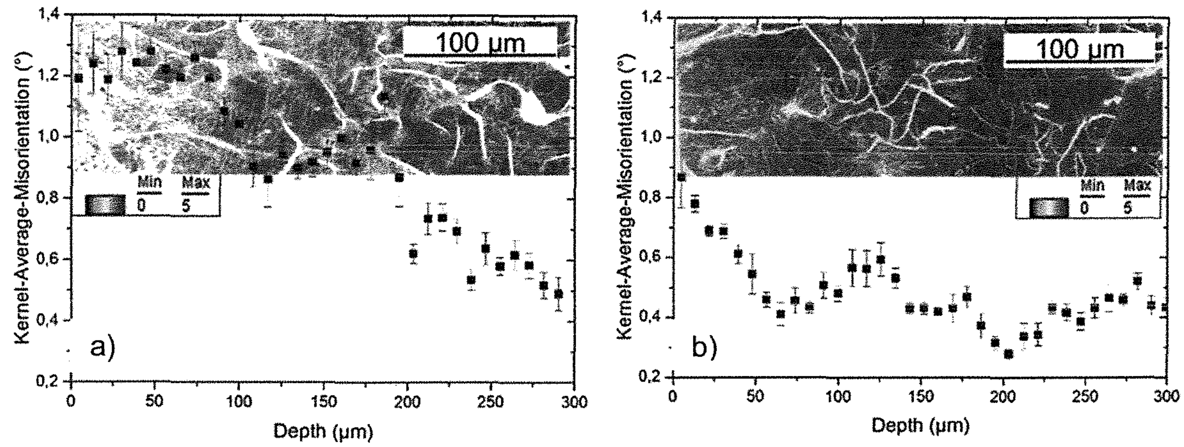

Figure 6: KAM maps and averaged KAM values in the case of shot peening *(a)* and laser peening *(b)* show a high degree of plastic deformation for the shot peened and a low degree for the laser peened samples. The average is calculated over a depth range of 8,66 µm.

Discussion and Conclusions

Stress state

The resulting curves agree in both cases with results from Lundberg et al. and Clauer et al. for grey iron materials *[3,4]*. Both show a steep decrease in the first tens of micrometers. A maximum below the surface is only observed in shot peened samples. This is attributed to the amount of thermal interaction during shot peening and the Hertzian pressure of the shots.
No layer removal corrections have been applied because the analytical correction methods are only valid for model cases of infinite plates. In this study cylindrical holes have been removed. Only FEM simulations could give a most valid correction. This method has not been applied because the influence of the stress error is assumed to be low and the same removal method has been applied for all samples. Even with this error, the compressive stress depth would arguably be higher.
For depth measurements, white light interferometry was used. This has showed a better accuracy, especially for higher roughnesses at higher depths, and is more representative of the entire removed surface. At higher depths, electropolishing of grey iron shows R_a values up to 50 µm, probably due to the graphite phase.

Strain/Deformation state

There are two types of dislocations, GNDs and SSDs *[5,6]*. XRD directly resolves SSDs and GNDs. EBSD, however, only measures GNDs. Additionally, FWHM values are influenced by instrumental broadening, grain size (if grains are in the nm range) and defect density. Kumagai et al. showed how the defect density (SSDs and GNDs) in austenitic steel continuously increases towards the surface *[7,8]*. With higher laser intensity or higher peening time the misorientation should only slightly increase but still be lower than in the case of shot peening.
The increased misorientation for the initial sample state near the surface is attributed to the metallographic preparation, producing a heavily deformed layer.
The visible plateau in Figure 6 is possibly due to plastic deformation that cannot be accommodated by the very high peening intensity in this study. Moreover, the high defect density and the metallographic preparation at the edge of the sample could lead to a remarkable decrease in EBSD pattern quality and therefore low statistics. It should be noted that EBSD cannot integrate over large sample volumes in comparison to XRD. Nevertheless EBSD shows high resolution strain imaging that also provides information about local strain fields, e.g. the higher degree of deformation around the graphite phase.
Hardness measurements are still difficult to perform because of the direct influence of local stress. The error seems to be quite high and no tendency could be observed.
Finally, shot peening and laser peening lead to a different stress and strain state of the resulting grey cast iron microstructure. Laser peening leads to a much higher depth of compressive

stresses. The microstructural cause for that is not yet proved and will be investigated within future work.

Acknowledgements
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