Surface Layer Characterization of Shot Peened Gear Specimens

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ABSTRACT

The production of gear components includes numerous manufacturing operations, which are carried out to ensure proper surface characteristics. Shot peening is one of the surface finishing processes used for transmission components like gears to improve their fatigue behavior. Shot peening increases the compressive residual stresses on the surface and the procedure also reduces the amount of retained austenite in the surface layer. In addition, shot peening has an influence on other mechanical properties such as surface roughness and surface hardness. An experimental design was conducted with varying shot peening process parameters, like coverage density and intensity, to alter the surface layer of 13 transmission gear samples. The correlation between shot peening parameters, Barkhausen noise (BN) features, and X-ray diffraction residual stress measurement was studied. Linear correlation was found between residual stress and shot peening parameters. The relationship between residual stress and BN root-mean-square (RMS) was not evident but was revealed by taking the ratio of BN measurements at different frequencies. Additionally, BN features such as peak position, coercivity, and integral area were found to have a linear trend with the intensity. Along with the aforementioned measurements, other material characterization measurements were also taken. The shot peening coverage density was observed to have a linear relationship with surface roughness values, while an intensity of over 0.6 mmA was noticed to affect the surface

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hardness. The results obtained can be used in the determination of suitable shot peening parameters to achieve a surface with desired residual stress and other surface properties.

Keywords: shot peening, residual stresses, Barkhausen noise, X-ray diffraction, material characterization

INTRODUCTION

The shot peening method is a cost-effective surface finishing method for power transmission components [1]. For these components, the fatigue phenomenon is always the key question and fatigue improvement issues have to be taken into consideration during production [1]. During the shot peening operation, the cold working phenomenon creates a strain-hardening effect on the surface, leading to an increase in the strength of the material surface [2]. The main benefits of the treatment are residual stress improvements [3,4] leading to better improved fatigue strength [5]. During the shot peening treatment, the plastic deformation is taken place in the surface layer: surface layer expands due to tensile stress created by the shots and leaves the surface layer in compressive residual elastic stress after the peening [6]. The affected zone where the compressive residual stresses are observed extends 0.13 - 0.5 mm below the surface [4] depending on the shot diameter used [7] and the other issues that have an effect on the intensity as i.e. media speed, size and hardness of shots. [2]. In addition, shot peening may be used for reducing the retained austenite in carburized products, due to the mechanical effect of the shot peening that transforms the austenite into martensite [7]. A high amount of retained austenite may degrade the performance of the part and thus shot peening treatment is also a solution to this problem [8]. Shot peening also affects the surface roughness of the component and this in turn influences the fatigue strength [4].

Gear manufacturing is a highly automated process and there is a clear need for the automated non-destructive quality control. The quality of the shot peening should also be easily verified by a non-destructive and fast method. The poor quality of shot peening means lower performance, fatigue strength and higher wear of the part. For automated quality inspection methods, magnetic Barkhausen noise (BN) is widely used in the gear manufacturing industry for grinding burn verification. Because the method is sensitive to both changes in the microstructure and residual stress, it could be utilized for shot peening surface quality control. The use of BN is based on the observation of irreversible domain wall motion in ferromagnetic material that produces changes in the magnetization [9]. Many factors affect the observed BN signal, such as dislocations and stress [10]. In their studies, Marconi *et al.* [11] noticed the effect of shot peening on transforming retained austenite into martensite and its effect on the BN root-mean-square (RMS) value.

The challenge for utilization of the BN method is how to link the surface Barkhausen noise measurements to correlate with the shot peening parameters and to verify how the changes in these parameters affect the BN features. For wider analysis, where BN is linked with other studies of the surface layer such as residual stress and retained austenite content measurements, changes can be verified. In this study, an experimental design was carried out to provide different and representative levels of coverage density and intensity values for the actual shot peening experiments. The samples were characterized after shot peening with many surface characterization methods. The main methods were residual stress measurements by X-ray diffraction and magnetic Barkhausen noise measurements. In addition, surface roughness, surface hardness, and scanning electron microscopy studies were carried out. In another study by the author, the same shot peened sample series was used and the effect of the residual stress depth distribution and Barkhausen noise were evaluated.

THEORETICAL BACKGROUND

Shot peening is a mechanical surface treatment used to create compressive residual stresses in the surface layer of the treated components. During the cold working action of shot peening, plastic deformation tends to create dislocation tangles and pile-ups at grain boundaries (lattice defects). These strain-hardening effects together with compressive residual stresses increase the strength of the material with an increasing amount of deformation [2]. The compressive residual stress created hinders crack nucleation and growth [12] and further increases the lifetime of the component.

The two universally accepted parameters for shot peening process repeatability control are coverage and intensity. Coverage can be defined by the amount of particles and shots covering the sample surface and is determined mainly by the exposure time or peening time [5,13,14]. The coverage of the shot peening process can be divided according to Kirk [14] into three categories, i.e., dent coverage, hardening coverage, and stress coverage. The latter two have a high impact on the fatigue strength of the shot peened component, while the first is a visible indication of the amount of shot peening. The stress coverage definition introduced by Kirk [14] includes the effects of the number of impacts, the impacted area, rate of impact formation, and peening time. The shot peening intensity [13] is composed of the velocity, hardness, size and weight of the used shots and in addition the angle of peening. This will influence the depth of the compressive residual stress layer [5]. As for surface residual stress generation, Tosha [15] concluded that surface residual stresses are generated rapidly when peening starts but then reach the saturation value when a coverage of 80 % is exceeded. After saturation, the surface residual stress formation is independent of the shot size or shot velocity, whereas the residual stress depth profiles were influenced at least by the shot diameter [15].

As mentioned above, shot peening has an influence on the hardness of the surface due to the cold working process [16]. The work-hardening effect requires that the applied stress exceed the yield value. During shot peening, the hardness increase varies depending on the strain-hardening capability of the treated material [16]. The hardening coverage is affected by the peening time, and the rate of the shot peening dent and zone created, according to Kirk [14]. As Shaw [16] describes, some materials can even double in surface hardness after shot peening compared to the original surface hardness. In addition, grain refinement with an increase in dislocation density may occur, and even surface nanocrystallization has been observed with an increase in intensive coverage according to Hassani-Gangaraj *et al*. [17]. Grain refinement can also prevent fatigue crack initiation and propagation [18]. In order to provide grain refinement, Fu *et al.* [18] carried out studies with triple shot peening with decreasing Almen intensities, varying the shot size and material. Also, double shot peening has been studied by Costa *et al.* [12] by applying a second shot-peening treatment. They observed that the residual stresses further away from the surface were relaxed, whereas those closer to the surface became more compressive.

As Kirk concluded [11], the dent, hardening, and stress coverage processes proceed together during the shot peening operation but have different rates as a function of peening time. The coverage of the shot peening action can be evaluated by visual methods, for example [5]. This procedure can be verified with reference photographs illustrating different coverage levels [5]. Other methods include the Straub method and the Valentine method, the latter using a layer removal technique [5]. Buchanan and John used the PEENSCAN application to verify the complete coverage and uniformity over the entire surface of the specimen [19].

The influencing factors for treatment intensity are shot size and weight, hardness of the peening media, velocity, and angle [5]. In addition, the nozzle type may also have an effect [20]. Almen strips have been used as an intensity indicator to verify the shot peening process [20]. However, the Almen process is not appropriate for online measurements and thus other alternatives have been introduced. Recently, the studies of Könitzer and Polanetzki [20] introduced a peening media velocity measurement for intensity verification. The study concluded that the intensity can be set directly by controlling the shot velocity [20]. Also earlier, Haubold *et al.* [22] found that the accuracy of velocity measurements is comparable to that of the Almen tests.

Some modeling work has been carried out by Gangaraj *et al.* [23] to detect the effect of the intensity of the shot peening process and recently also the coverage. Different modeling-based simulations [23–25] have been carried out to determine the residual stress profiles created by the shot peening operation. Finite-element analyses simulate the impacts of shots based on parameters such as material properties, shot diameter, and velocity. Gangaraj *et al.* [23] studied the effect of actual coverage development on the formation of residual stress depth profiles. Guagliano [25] concluded that the shot size and velocity of the shots affect the residual stress profile and the modeled residual stress depth profiles were verified by tests and a survey of the residual stress depth profiles by X-ray diffraction. As expected, based on the simulations and actual tests, the shot size was noticed to affect the distance below the surface where the higher compressive residual stress was observed by Guangliano [25].

Shot peening also influences the surface roughness of the peened component. After the shot peening process, surface roughness and the condition of the thin surface layer are very important for fatigue endurance. Surface roughness indicates macro-geometrical imperfections due to the shot peening of the surface. The major parameters affecting the obtained surface roughness values are pressure and peening duration. It was observed that the surface roughness intensified with an increase in the working pressure [27]. Zagar *et al.* [27] noticed higher roughness values with longer peening times. Tosha found that the surface roughness was in proportion to the shot size and velocity, and was inversely proportional to the square root of the work piece's hardness [15].

EXPERIMENTAL METHODS

The studied samples were small gear samples manufactured from gear steel 17NiCrMo6-4. The gears were carburizing case-hardened, tempered, and honed. The case depth was 0.8 mm and the surface hardness was 720 HV1. To investigate the effect of shot peening parameters on the Barkhausen noise and residual stresses, an experiment was conducted using statistical design of experiment. A 2^3 full factorial design consisting of 21 experiments with five central points was planned and conducted. The center point tests were used to estimate the pure error. The maximum and minimum intensity values for the design were obtained from the shot peening equipment used. The total number of different parameter shot peening groups was 13, as shown in Table 1. The parameters included six different intensity levels (obtained by variating the air pressure) and five coverage density levels (obtained by variating the peening time). The peening intensities (mm A) were measured as per SAE J443 [21] with Almen strips Type A. Intensity and coverage as defined in SAE J2277 [28] are not truly independent parameters as higher intensity which realized in this study by increasing the speed of the media through higher pressure, will yield bigger impacts, which influences coverage. Therefore, the concept of coverage is replaced in this study by a coverage density expressed in kg/cm^2 defined as:

$$coverage\ density = \frac{\mathrm{CT} * \mathrm{n} * \mathrm{F}}{\mathrm{S}} \qquad (1)$$

where *CT* was the total peening time [s], *n* was the total number of nozzles (4), *F* was the shot media flow per nozzle [6.5 kg/s], and *S* was the area to be peened [220.7 cm^2]. This way the parameters varied in Table 1 are truly independent, a prerequisite for the statistical design of experiment. The shot peening media was steel cut wire 0.7 mm G3 with a hardness of 640 HV1, meaning that the gear samples were harder than the shots used.

TABLE 1. Shot peening coverage density, peening time and intensity values of samples. The results of the bolded samples are discussed in more detail.

Shot peening sample code	Coverage density (kg/cm^2)	Peening time [s]	Intensity (mm A)
A	**0.05**	25.5	**0.4**
B	0.05	25.5	0.53
C	0.05	25.5	0.65
D	0.065	33.1	0.44
E	**0.065**	33.1	**0.61**
F	0.1	50.9	0.4
G	0.1	50.9	0.53
H	0.1	50.9	0.65
I	0.135	68.8	0.44
J	0.135	68.8	0.61
K	0.15	76.4	0.4
L	0.15	76.4	0.53
M	**0.15**	76.4	**0.65**

A total of 13 different samples from the different shot peening groups were investigated with an optical profilometer, scanning electron microscope, and surface hardness measurements. The original honed sample and three other samples: A, E, and M, are discussed in more detail in this article taken as to represent low, middle and high coverage density and intensity values. The results of microhardness, residual stresses and residual austenite depth profiles for samples A, E, M and honed are also given besides the optical profilometer and microscopy results. The gear sample surfaces were studied with a Zeiss Ultraplus UHR FEG-SEM (Carl Zeiss NTS GmbH) scanning electron microscope. The Zeiss Ultraplus was also utilized for cross-sectional micrographs. Cross-sectional samples were ground using SiC papers and polished with 3 and 1 µm diamond suspensions and etched with Nital 4% solution. The optical focus variation non-contact profilometer InfiniteFocus G5 (Alicona) was used for studying the surface roughness values of the gear flank surface from the middle of the flank area. Line analysis was made to the perpendicular direction compared to the honing direction. The surface roughness parameter Ra, the average height of the profile, was used for evaluation of the surface condition. Surface hardness measurements were carried out with a Duramin-A300 (Struers) Vickers hardness testing device with HV1. The hardness depth profiles were carried out with a digital hardness tester Matsuzawa MMT-X7 with HV0.1.

The Barkhausen noise measurements were made with a Rollscan 300 Barkhausen noise analyzer, manufactured by Stresstech Oy (Finland). A commercial gear sensor to fit the gear surface was used in the measurements of the tooth axis direction. The Barkhausen noise measurements were recorded with MicroScan software. Different measurement parameters were utilized: a magnetizing voltage of 5 Vpp (voltage peak to peak) was used with magnetizing frequencies of 80 and 200 Hz. In addition, BN measurements were carried out after shot peening by varying both the voltage and frequency as follows: 1.5, 2, 3, 5, and 6 Vpp and 20, 40, 125, 250, and 500 Hz. In the analyses, the results were an average of 20 Barkhausen noise bursts filtered to 70-200 kHz. In addition, an averaging operation was carried out on the measurements of the whole series of samples by taking off the effect of either coverage density or intensity: the measurement data was normalized as a function of intensity to eliminate the effect of coverage and vice versa. Detailed introduction to Barkhausen noise can be found in [10].

In order to conduct X-ray measurements on the tooth flank, one tooth was cut from every gear for residual stress and austenite profiling. The surface residual stresses (RS) and full width at half maximum (FWHM) of the diffraction peak values were examined from the samples using an X-ray diffractometer (XRD) XStress 3000, manufactured by Stresstech Oy (Finland). Residual stress measurements were performed using CrKα radiation and the modified χ (Chi) method. Residual stresses were derived from measurements on the {211}-Fe reflection using the standard $\sin^2\psi$ method. In order to determine the residual stress and retained austenite depth profiles, some material was removed to expose the deeper layers to X-rays. Layer removal was carried out using an electrochemical cell with electrolytic polishing equipment Movipol-3 (Struers) with commercial perchloric acid solution Struers A2. The removed layer was verified with a dial indicator. In the studies of Alkaisee and Peng [29], the electrochemical polishing method was found to give a fine quality of polished surface with good reproducibility. The material removal with electrochemical polishing may influence on the local relaxation of stresses but it is considered suitable in this purpose because it does not cause additional residual stresses as Alkaisee and Peng [29] stated.

The retained austenite content was measured using the four-peak method with the XStress 3000 device. The method uses totally four diffracted peaks; two peaks from ferrite $2\Theta = 106^\circ$ from {200} plane and $2\Theta = 156^\circ$ from {211} plane and two austenite peaks $2\Theta = 79^\circ$ from {200} plane and $2\Theta = 128^\circ$ from {220} plane. The retained austenite measurement was carried out with the comparison of intensities. The integrated intensities, meaning area of peak above the background, are proportional to the volume fraction of the phases [30]. The retained austenite depth profiles were done with the same layer removal depths as the residual stress profiles from the same samples.

Data analysis

The Barkhausen noise parameters for analysis were obtained from MicroScan software. In total, 10 different BN parameters were used: RMS, peak, peak position, FWHM, coercivity, remanence, permeability, integral area, spectrum area, and pulse count. From the X-ray diffraction measurements, the parameters were residual stress, full-width-half-maximum (FWHM) of the peak, and retained austenite content. The analysis was carried out for all different samples introduced in Table 1. The averaging of the Barkhausen noise results were carried out either by taking of the effect of the coverage density of intensity to make the interpretation of the results more simple.

RESULTS AND DISCUSSION

Scanning electron microscopy and surface roughness results

The SEM images taken from the surfaces of the detached teeth in Fig.1 show the effect of shot peening. These various SEM pictures taken from differently treated samples in Fig. 1 show the effect of shots forming the surface structure in a way that the deep valleys of the original honed structure are diminished and the surface directionality is reduced. The gear samples had surface directionality in the longitudinal direction of the tooth due to the honing operation carried out prior to shot peening (Fig.1a).

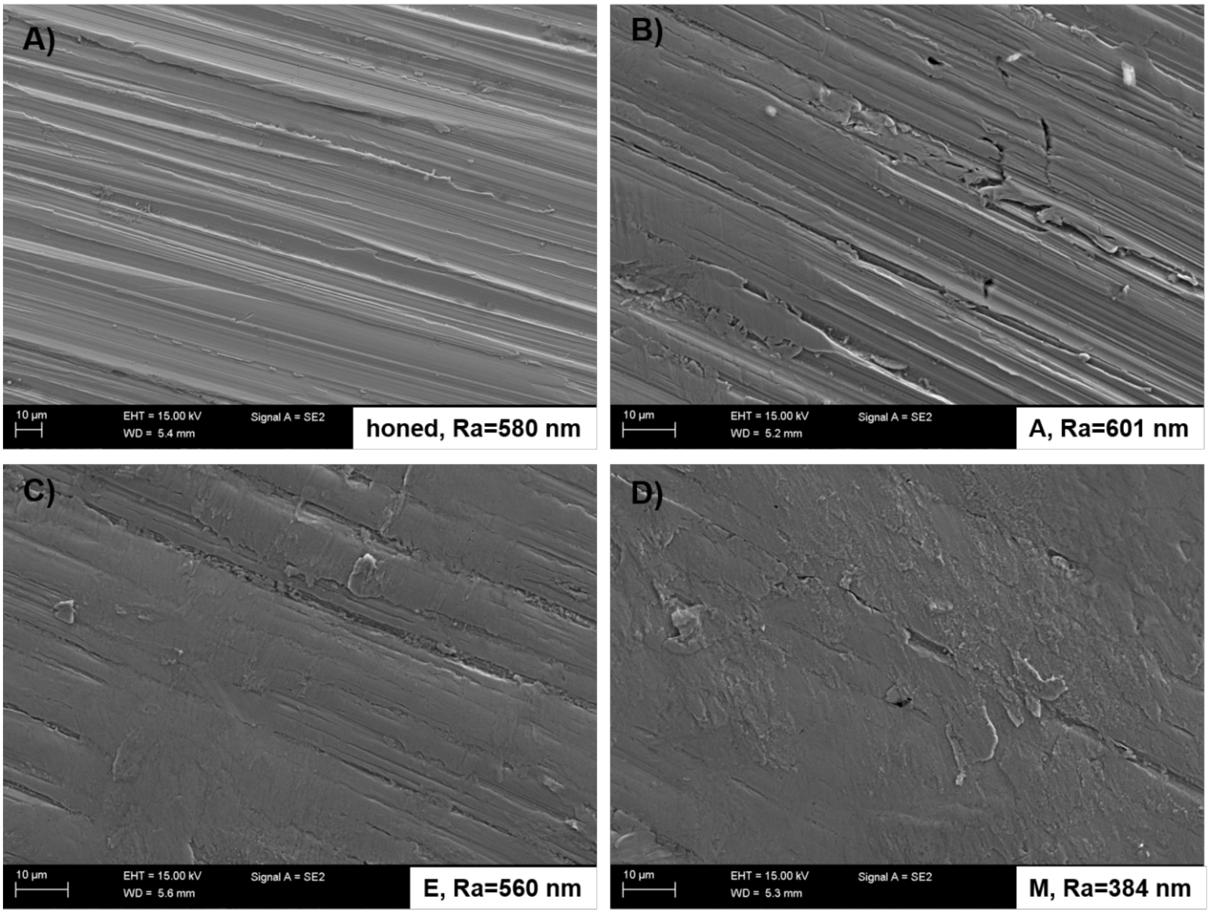


Figure 1. SEM images from differently treated surfaces with different shot peening parameters: a) original honed surface, b) sample A with shot peening intensity of 0.4 mm A and shot peening coverage density of 0.05 kg/cm^2, c) sample E with shot peening intensity of 0.61 mm

A and shot peening coverage density of 0.065 kg/cm^2, and d) sample M with shot peening intensity of 0.65 mm A and shot peening coverage density of 0.15 kg/cm^2.

The gear material was harder than the shots (gear/material hardness ratio of 1.125) but the plastically formed surface and impacts of the shots can clearly be seen from the SEM images (Fig. 1b-d). Shot peening group M, with the greatest coverage density and intensity values, produced the lowest surface roughness value to the perpendicular direction compared to the honing direction and also the surface directionality was the most diminished (Fig. 1d). In addition, some wear ridge formation is highly visible in Fig. 1d. Some surface cavities are visible in sample A as shown in Fig. 1b) and thus the surface roughness was observed to have increased when compared to the original honed structure. Samples E and M (Fig.1 c-d) show a large amount of plastic deformation due to the shot peening bombardment. The cross-sectional SEM images are shown in Fig. 2a-d from the same samples as Fig.1. Scanning electron microscopy cross-section studies reveal the very narrow plastic deformation layer: bumps, shown in red arrow, are formed due to the higher impact of the shots. Surface layer cuts shown in white arrows are also visible in Fig. 2d. The microstructure is verified to be lath martensite in all the studied samples from the cross-sectional SEM images (Fig. 2). However, there are no clear changes observable at the edge of the samples, meaning that the plastic deformation had taken only place in a very narrow layer below the surface. This narrow deformed layer is due to the gear being harder than the shots. Wohlfahrt [31] concluded that only a little direct plastic deformation occurs in this situation when the shots are softer than the gear.

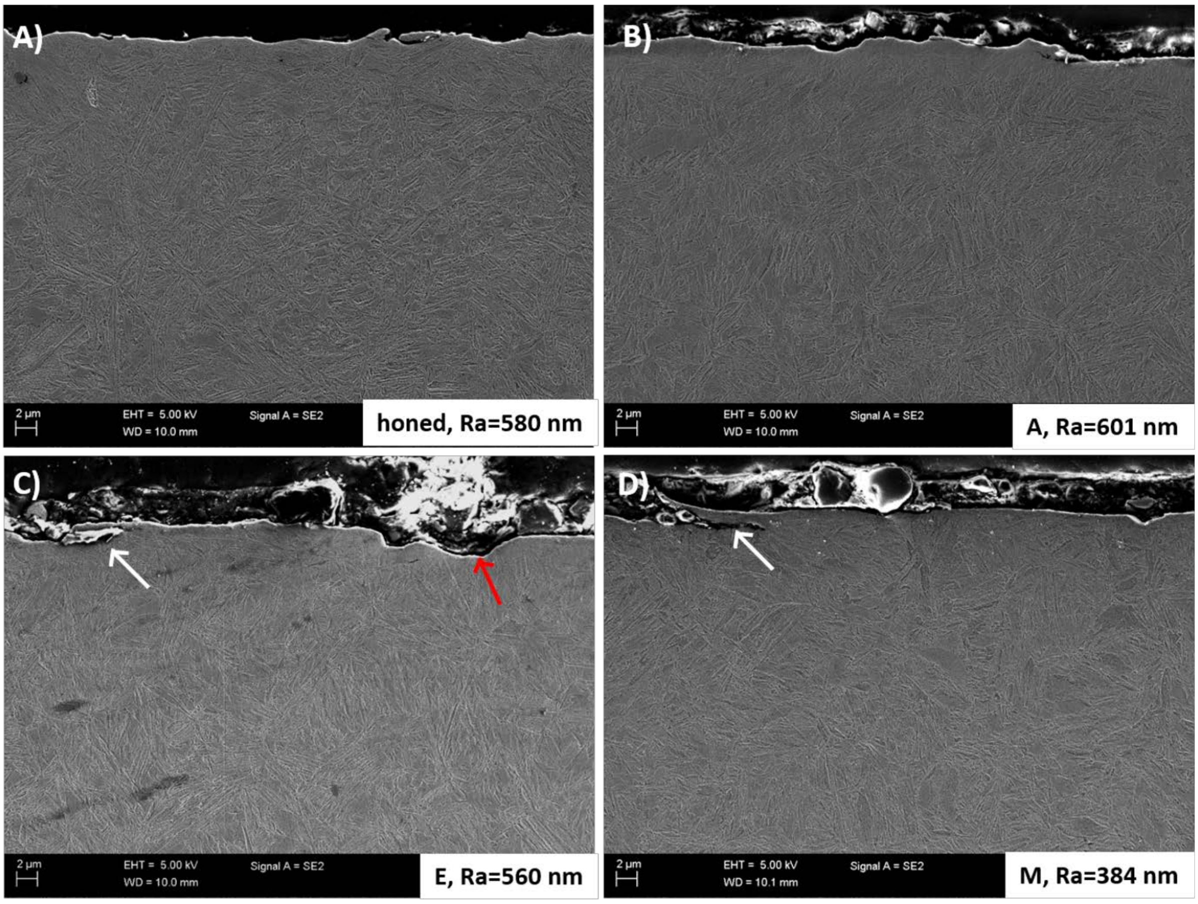


Figure 2. Cross-sectional SEM images from differently treated surfaces with different shot peening parameters: a) original honed surface, b) sample A with shot peening intensity of 0.4 mm A and shot peening coverage density of 0.05 kg/cm^2, c) sample E with shot peening intensity of 0.61 mm A and shot peening coverage density of 0.065 kg/cm^2, and d) sample M with shot peening intensity of 0.65 mm A and shot peening coverage density of 0.15 kg/cm^2. Red arrow shows bump and white arrows shows the surface cuts.

Based on the optical profilometer images, the dent coverage explained by Kirk [14], meaning a visible indication of the amount of shot peening can be evaluated. The bombardment effect of the shots on the surface can be seen from the optical profilometer images in Fig. 3 as a difference in surface color; the impacts of the shots are seen as darker areas as the surface roughness decreases when the coverage density and intensity values are increased. For the original honed sample, the same directionality than in SEM micrograph Fig.1 a, is observed also in the optical profilometer 3D picture in Fig. 3 a. In addition, to earlier studied surfaces with SEM, two samples, G and K were added to show the evolution of the surface due to peening. As seen in Figs. 1 and 3, the surface directionality vanishes when the roughness values decrease with increasing shot peening action. However, it was noticed that there were still some grinding marks visible in sample M (Fig. 3 f) with the highest intensity and coverage density values.

A line analysis was taken from the optical profilometer data where the surface roughness, Ra, meaning the average height of the profile, was calculated to the perpendicular direction of the honing stripes. The honed surface had a surface roughness value Ra of 580 nm while the largest intensity and coverage density treated sample, M, had a surface roughness Ra value of 384 nm. This means that the original honed surface was rougher and that the shot peening action smoothened the surfaces and the average height of the profile (Ra) was decreased in all other cases except sample A, where the surface roughness was increased in comparison to the original honed structure due to the surface cavities (Fig. 1b).

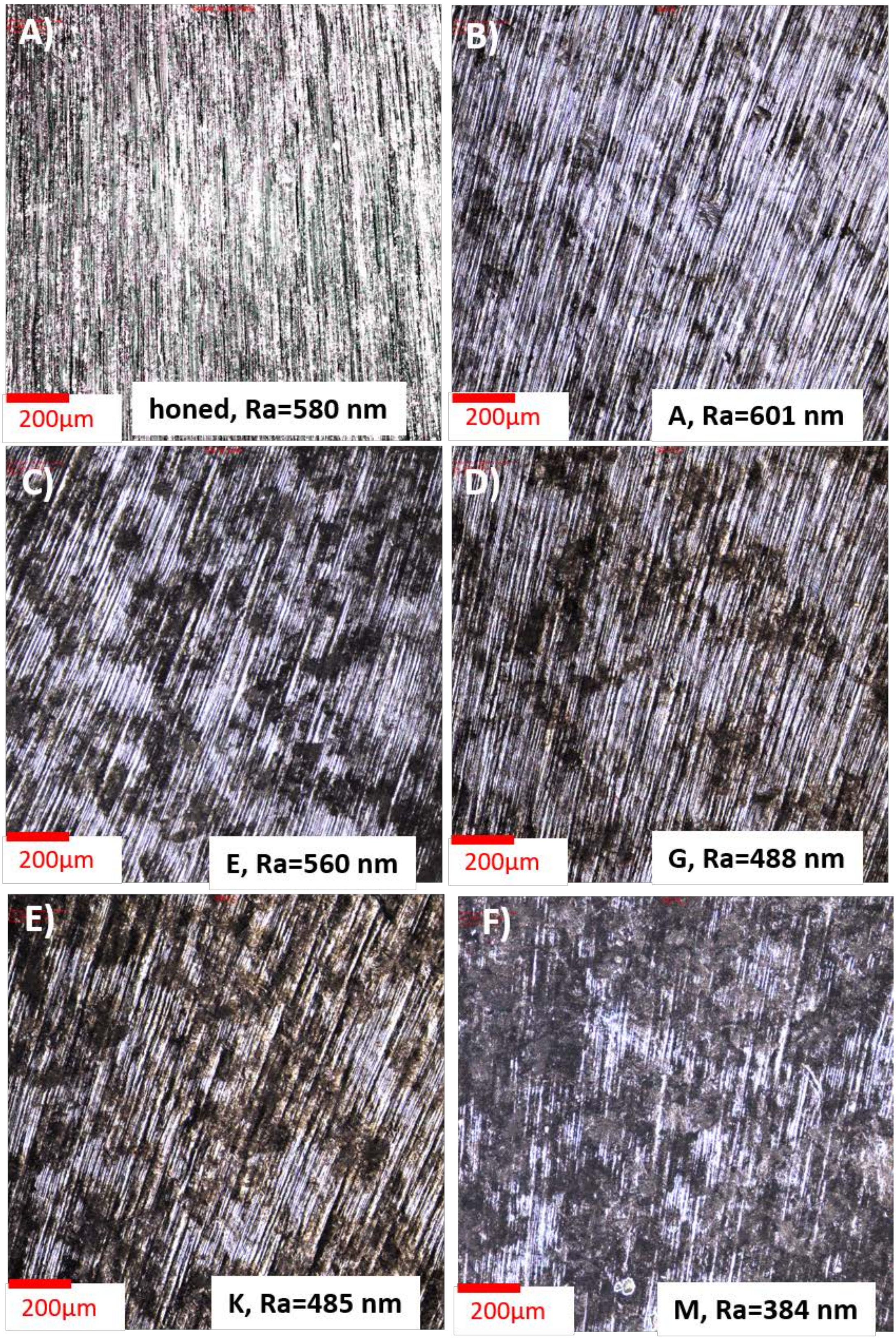


Figure 3. Optical profilometer images from differently treated surfaces with different shot peening parameters: a) from honed sample with Ra 580 nm, b) from sample A with Ra 601nm,

c) from sample E with Ra 560 nm, d) from sample G with Ra 488 nm, e) from sample K with Ra 485 nm, and f) from sample M with Ra 384 nm.

The coverage density of the shot peening had only a minor effect on the surface roughness values (Ra). The higher coverage density values produced lower surface roughness values as presented in Fig. 4 for all studied samples although there was some deviation. The standard deviation average value for all measurements was 7.5 nm. However, in our study, the intensity of shot peening provided only a very small effect on the surface roughness values: the surface roughness decreased with increasing intensity but the trend was more evident for the coverage density.

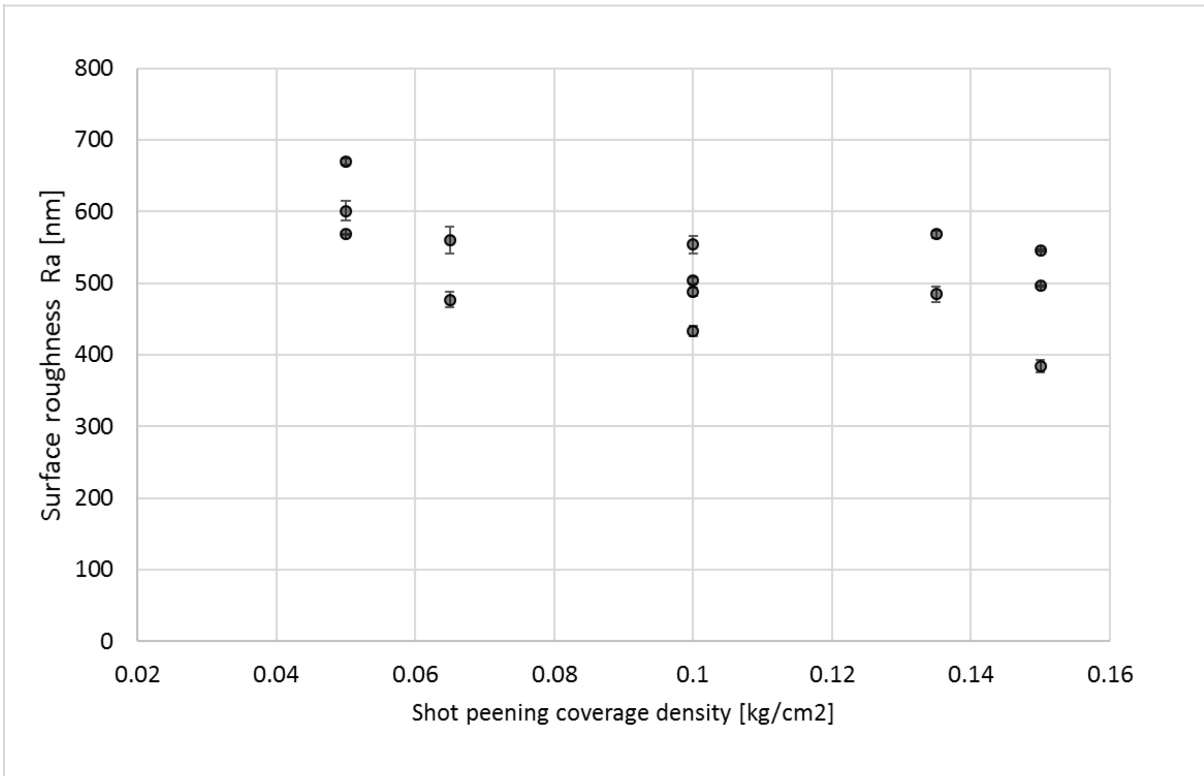


Figure 4. Shot peening coverage density as a function of surface roughness Ra. Markings A, E and M indicate specified shot peening gear samples.

Surface roughness effect has been investigated as a function of coverage or shot peening treatment duration by several researchers. In contrast with our studies, Tosha [15] found that surface roughness was in proportion to intensity via shot size and shot velocity. For ground surfaces, surface roughness should increase with increasing velocity (intensity of peening), as determined by Pandey and Deshmukh [32] and Zagar *et al.* [27]. Zagar *et al.* [27] also concluded that air pressure has an influence on surface roughness; increasing pressure led to increasing surface roughness values with other parameters staying constant. In addition, in the studies of Pakrasi *et al*., it was noted that the surface roughness values decreased as the shot peening time (coverage density) increased [33], and these results are similar to ours. In our study, the shot peening operation after honing tended to smooth the peaks formed during honing. Unfortunately, their studies did not provide any information on the surface finish before the shot peening procedure [27] nor the details of the media/shot hardness ratio [25]. The material parameters (such as hardness) of the shots have an impact on the surface roughness values obtained with different peening parameters. Pandey and Deshmukh [32] concluded the higher hardness shots would provide smaller roughness than lower hardness shots with the same velocity.

Hardness measurement results

Surface hardness was 720 HV1 (standard deviation of 20 HV1) before shot peening, which means that all the samples were work-hardened as the surface hardness increased in all the studied shot peened samples (Fig.5). Surface hardness increased to intensity of 0.6 mmA after which it slightly decreased, as shown in Fig.5. The original gear and shot media hardness ratio was 1.125, meaning that the gear surface was harder than the shots and the intensity was high enough to reduce the surface hardness values, perhaps due to some work softening. The increase in surface hardness is due to the transformation of the retained austenite into martensite due to plastic deformation as well as work hardening. The original retained austenite volume fraction percent in the honed surface was measured to be 9.4 % with standard deviation of 1.2 %. After shot peening retained austenite contents are systematically lower than before peening (Fig. 8).

Pakrasi *et al.* [33] concluded that an increase in the surface hardness for shot peening samples increased continuously with the shot peening duration (coverage). This was caused partly by the transformation of residual austenite into martensite and the work hardening of the original structure. Fu *et al.* [18] observed that the influence depth of shot peening on the hardness and microstructure increased with the increasing of peening intensity. The increasing hardness of the shot peened surface acts as a protective shield for deeper layers and dampens the kinetic energy of the shots, so that the biggest influence is on the residual stresses in the deeper layers rather than on the hardness. Herzog *et al.* [34] verified that the hardness of the component mainly has an effect on the depth of the maximum compressive residual stresses and that both the hardness of the shots and the component have an influence on the near-surface residual stresses.

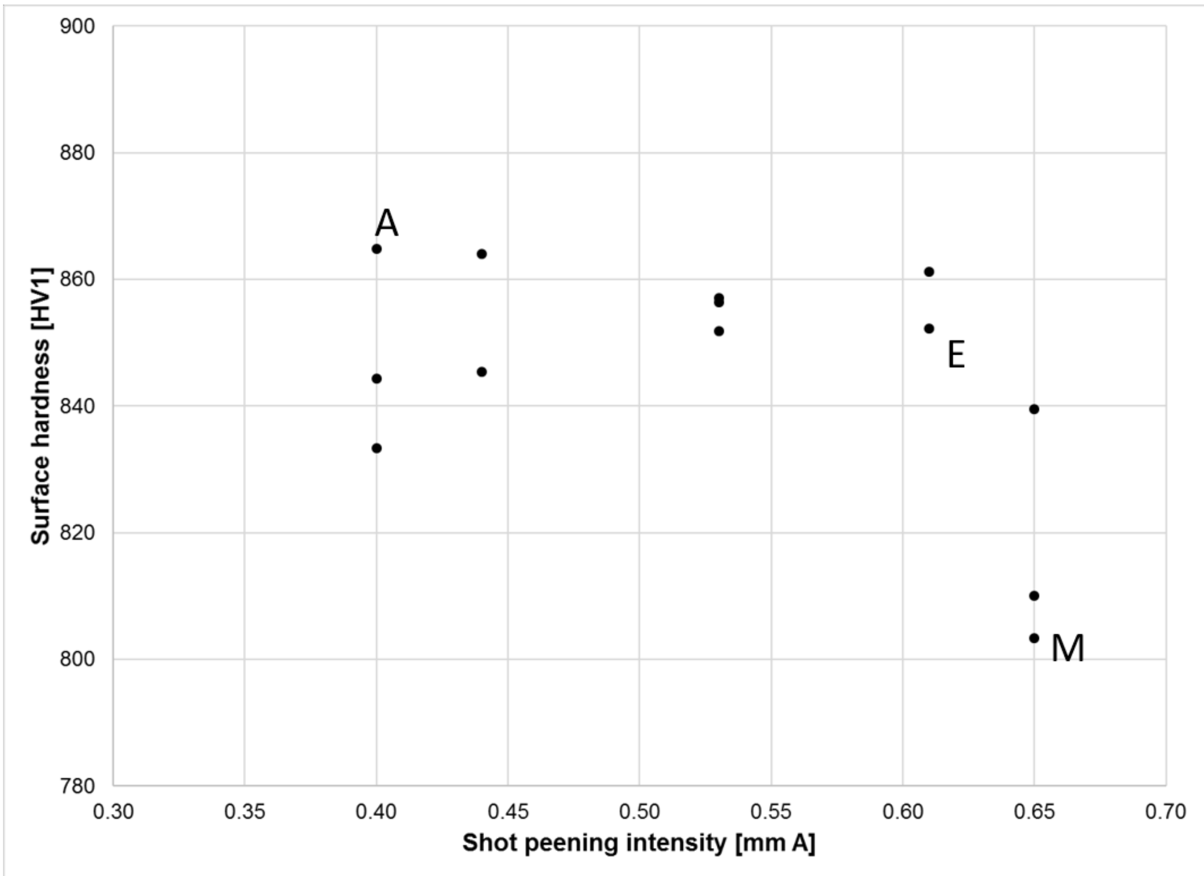


Figure 5. Shot peening intensity as a function of surface hardness. Markings A, E and M indicate specified shot peening gear samples.

The surface work hardening can also be evaluated from the broadening of the X-ray diffraction peak by calculating the full-width-half-maximum (FWHM) of the peak. The corresponding variations in the surface FWHM values for tilt angles of 0˚ and 45˚ and surface hardness are presented in Table 2. The original honed sample had the lowest surface hardness. The surface XRD FWHM for the 0˚ tilt angle with penetration depth of about 5 µm with CrKα radiation [35] had a linear relationship with the surface hardness. A tilt angle of 45˚ provides more information about the surface due to the lower penetration depth, about 3.5 µm, compared to 0˚ tilt, higher FWHM values of 45˚ tilt are observed in all samples because the deformation is bigger closer to the surface.

TABLE 2. Surface XRD FWHM (0˚and 45˚ tilts) and surface hardness results (tooth axis direction).

Sample	XRD FWHM (0˚tilt) average	XRD FWHM (45˚ tilt) average	Surface hardness [HV1]
honed	6.01	6.13	720
A	6.24	6.46	833
E	6.33	6.35	852
M	6.02	6.25	810

The depth profiles from the cross-sectional samples are shown in Fig. 6. Compared to the original honed sample, the shot peening effect can be seen in all three samples shown in Fig. 6: A (coverage density 0.05kg/cm^2, intensity 0.4 mm A), E (coverage density 0.065kg/cm^2, intensity 0.61 mm A), and M (coverage density 0.15kg/cm^2, intensity 0.65 mm A). For the subsurface hardness evolution, the milder shot peening for sample A produced somewhat smaller hardness values for all studied depths. For samples E and M, the hardness values were quite similar at all studied depths even though their surface hardness values varied as shown in Table 2. This increase of hardness for E and M compared to honed is consistent with the increased affected depth with the increased intensity value. The shot peening treatment led to an increase in hardness of up to 500 μm in all of the 13 samples studied.

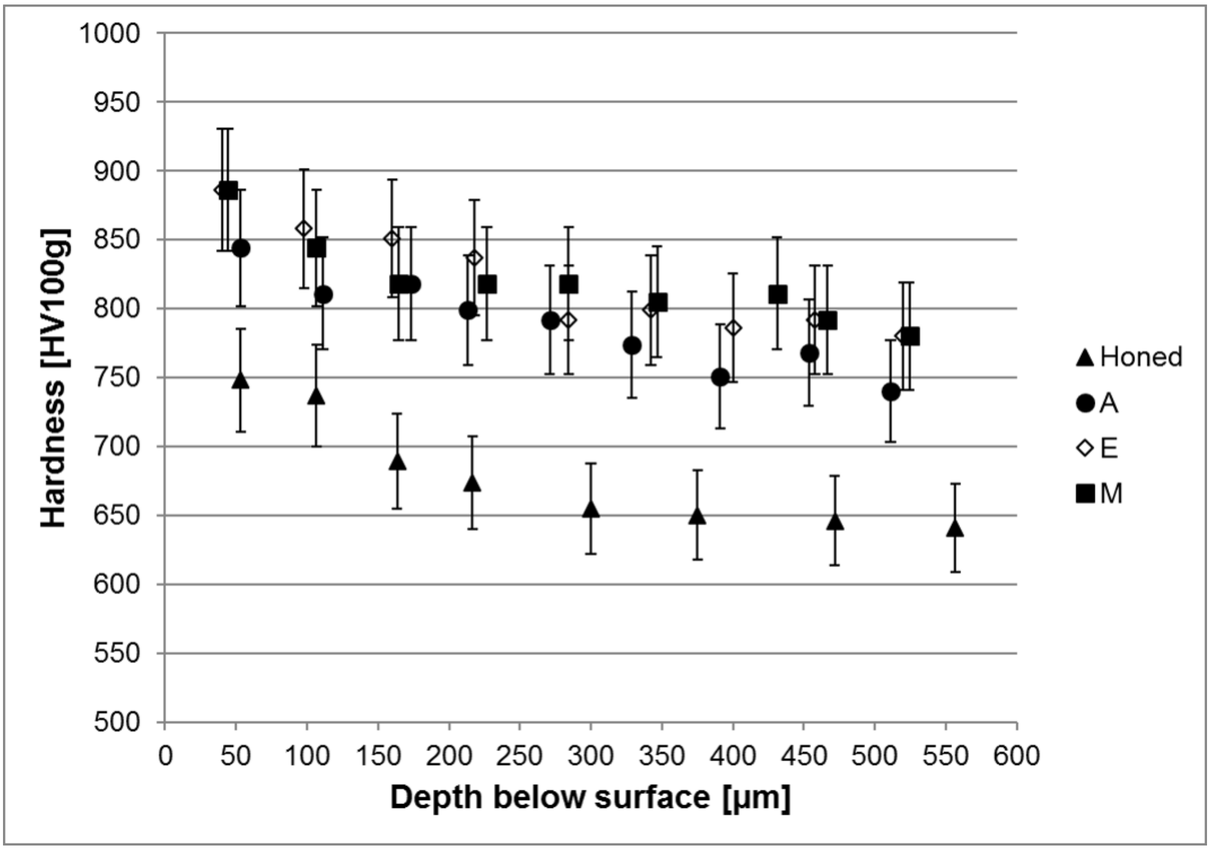


Figure 6. Hardness depth profiles for samples A, E, M, and honed.

To evaluate the residual stresses, X-ray diffraction measurements were performed on all samples. All the shot peening treatments shown in Table 1 introduced significant levels of pseudo-macro compressive residual stresses in the near-surface regions of the specimens. The residual stress depth profiles of the chosen samples (honed, A, E, and M) are shown in Fig. 7 in the tooth axis direction. Samples M and E with higher coverage density and intensity values had lower compressive residual stresses near the surface although the maximum compressive residual stress was located deeper below the surface than sample A, which had lower coverage density and intensity values. Marconi *et al.* [11] received similar results with their shot peening tests: the higher intensities in shot peening produced lower compressive residual stresses near the surface than the lower intensities. The gear/shot hardness ratio also influences to the obtainable residual stress depth profile. Wohlfahrt [31] concluded when high hardness material is being shot peened by softer shots, only a little direct plastic deformation occurs in the surface layer and the magnitude of surface residual stresses is rather low. The real depth distribution of the residual stresses is an effect of total plastic deformation on the surface layer which is affected by the ratio of material/shot hardness, shot diameter, and kinetic energy. The effect of the Hertzian pressure of the shots dominates in this situation when the shots are softer than the gear: the magnitude of the maximum residual stresses can be very large because less energy is consumed for the plastic deformation of the surface due to the narrow contact zone and more energy is available for plastic deformation in deeper layers [31]. The magnitude and depth of the maximum compressive residual stresses may be affected by kinetic energy [31]. This same effect can also be seen in the retained austenite depth profiles in Fig. 8.

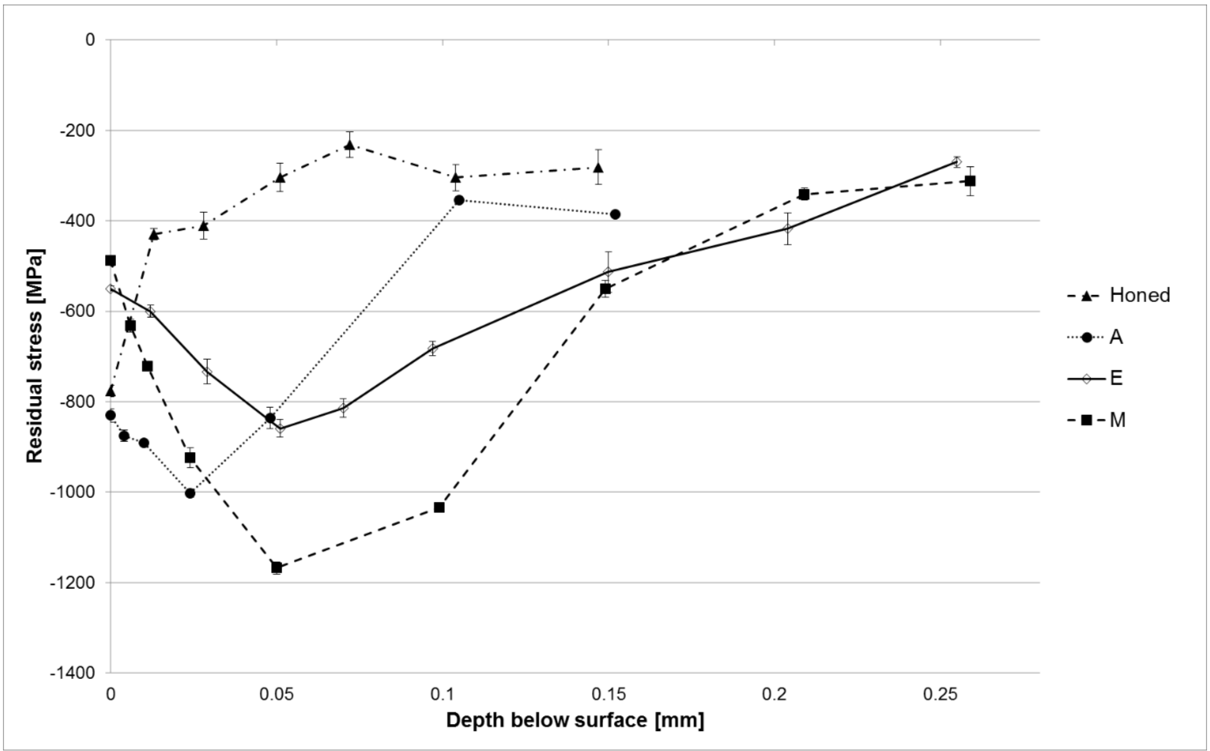


Figure 7. Residual stress depth profiles for samples A, E, M, and honed, measured in the tooth axis direction.

Normally the peening intensity of shot peening affects the maximum compressive residual stresses, as in the work by Fu *et al*. [18]. Higher intensity during shot peening produced higher maximum compressive residual stresses.[18]

Retained austenite depth profile studies

The transformation of retained austenite into martensite due to the mechanical peening action can increase not only the hardness of the surface but also the compressive residual stress on the surface, because the specific volume of martensite is larger than that of austenite. Sample M, with a coverage density of 0.15kg/cm^2 and intensity of 0.65 mm A, had the biggest decrease in retained austenite values through the studied depths; the maximum decrease was located at a depth of 0.01 mm from the surface (Fig. 8). The retained austenite depth profiles for samples A and E were quite similar except little lower retained austenite content of sample A on the surface.

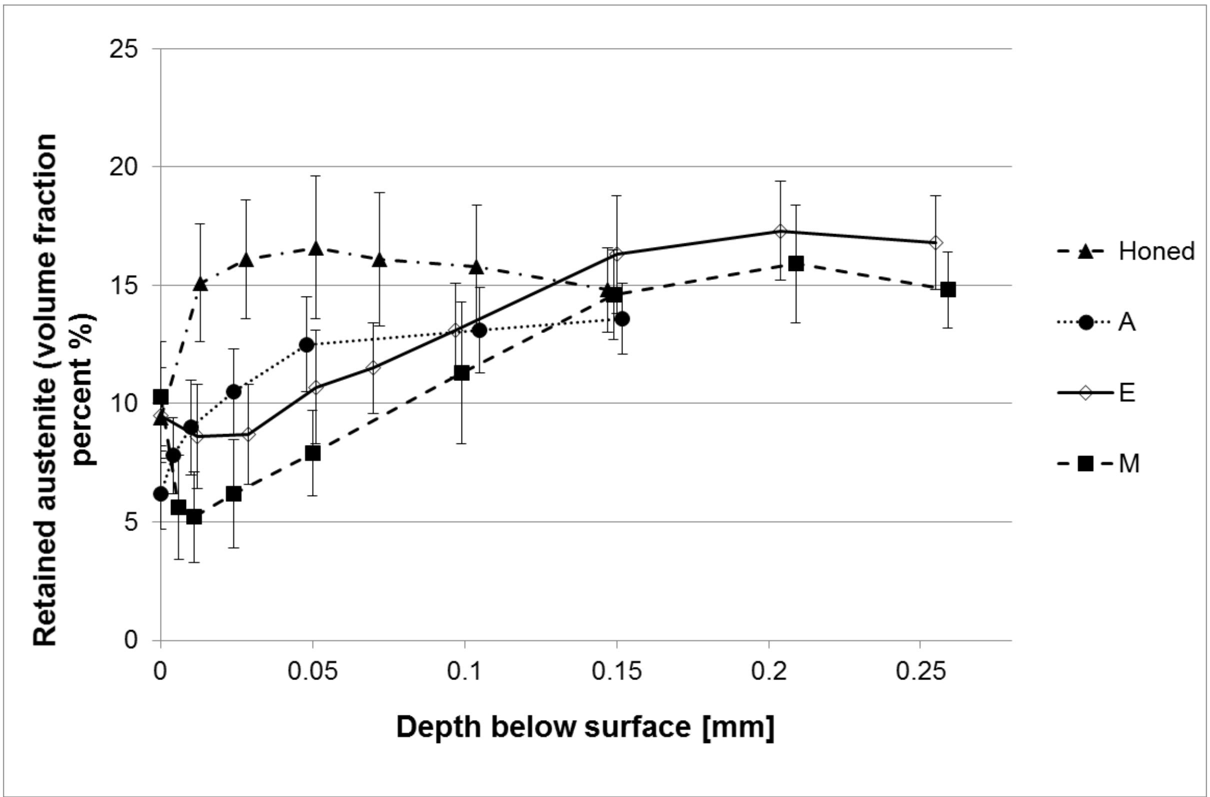


Figure 8. Retained austenite depth profiles for samples A (shot peening coverage density 0.05kg/cm^2, shot peening intensity 0.4 mm A), E (shot peening coverage density 0.065kg/cm^2, shot peening intensity 0.61 mm A), and M (shot peening coverage density 0.15kg/cm^2, shot peening intensity 0.65 mm A).

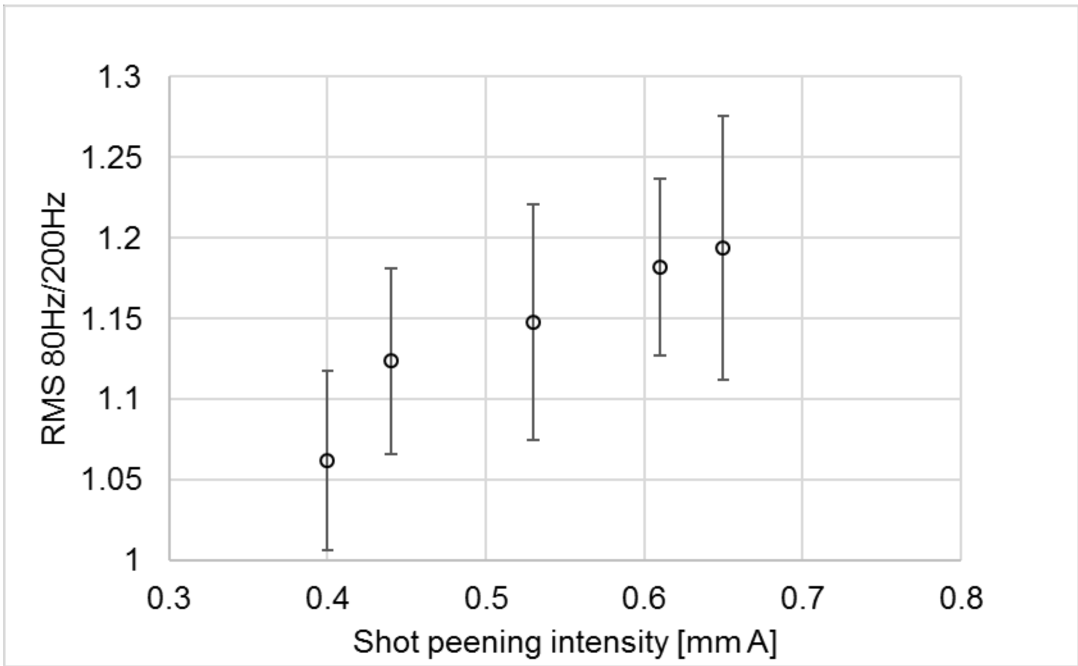
The studies of Pakrasi and Betzold [33] showed that the XRD results on retained austenite revealed decreased austenite content when the shot peening duration (coverage) was increased. The measurement was carried out from the surface of the samples. Fu *et al.* [18] studied the retained austenite content after the triple shot peening procedure. They noticed that, at the same depth, higher intensities led to smaller retained austenite content. This means that when the peening was carried out three times, the higher intensities accelerated the transformation of austenite into martensite. Our results are similar to the results of Fu *et al.* [18], except for the surface measurement of the retained austenite.

When using higher intensity values, the surface of the peened samples had lower hardness linked to lower compressive residual stresses (Figs. 6 and 7). The maximum compressive residual stress depth and amount correlate with decreasing retained austenite content. In addition, the decrease in retained austenite was largest deeper below the surface. The original structure was already hard so it would not display as great amounts of plastic deformation as a softer structure would [36]. The intense cyclic shot peening loading with the highest intensities might relax some stresses [36] and thus produce lower surface hardness and decrease in surface compressive stresses. The high retained austenite content of sample M on the surface with the highest shot peening intensity reveals that the retained austenite did not transform into martensite at the surface, and thus might provide lower surface hardness. Higher intensity values tend to produce more changes of residual stresses and retained austenite content deeper below the surface (Figs. 7 and 8).

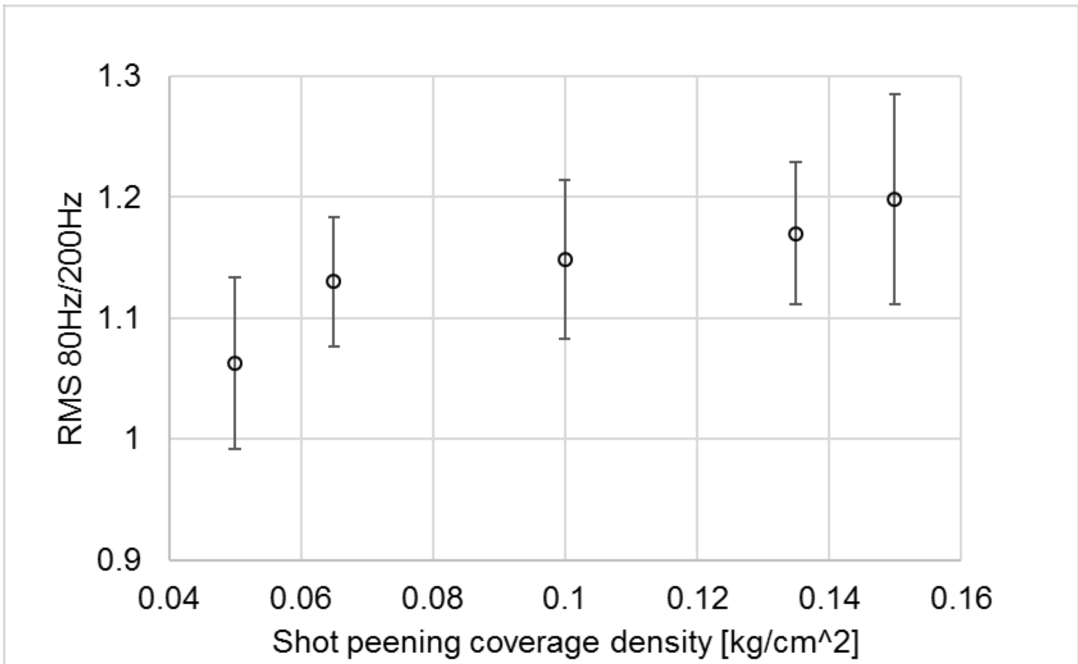
Results of Barkhausen noise measurements and surface residual stress vs. shot peening parameters

The Barkhausen noise method is efficient in finding variations in residual stresses because stress has an effect on the magnetic properties of the materials; however, it should be noted that the signal is affected simultaneously by the microstructure. In some cases, the RMS value of the BN cannot be linked directly to the surface residual stresses [38]. In addition, the BN method does not give directly absolute stress values. It requires comparison measurements with another method; in this study, residual stress were measured by X-ray diffraction. The Barkhausen noise measurements were carried out only at the surface of the samples. The root mean square (RMS) values were calculated from the original measurement signals taken at two different frequencies, 80 Hz and 200 Hz. The BN measurement depth is influenced by the measurement frequency: the lower frequency, the deeper is information depth [37]. To calculate the relative effect of frequency with the skin depth formula [37], the 80 Hz frequency would gave 1.6 times deeper penetration than 200 Hz frequency. The direct results of BN measurements taken at one frequency did not provide good correlations with the residual stresses. Therefore different combinations as ratio of two frequency data was used. In addition, an averaging operation was carried out on the measurements of the whole series of samples by taking off the effect of either coverage density or intensity: the measurement data was normalized as a function of intensity to eliminate the effect of coverage and vice versa. The ratio of measurement data of two frequencies, the gradient of the RMS, gives good correlation between BN RMS and the residual stress in this case. It was noticed by the current authors [38] that the ratio of the maximum slope taken from a magnetizing voltage sweep and the slope position correlated with the measured surface residual stresses in one case when there was no direct correlation between the RMS and the residual stresses.

As indicated by the analysis, the Barkhausen noise RMS ratio with two different frequencies and the surface residual stresses are both influenced by the intensity of the shot peening operation when the effect of coverage density is omitted. Averaging has been carried out for different intensity levels of shot peening, meaning that the effect of coverage density is omitted in Fig. 9 a) for the RMS ratio taken at 80 HZ/200Hz.



a)



b)

Figure 9. (a) Shot peening intensity and (b) coverage density as a function of the ratio of Barkhausen noise RMS recorded at two different measurement frequencies, 80 Hz and 200 Hz.

In addition, the coverage density was also found to have a linear relation (Fig. 9 b) with the RMS ratio of two frequencies, 80 Hz and 200 Hz, when the intensity was averaged. To study the effect of BN features other than the signal, the measurement data was normalized as a function of intensity to eliminate the effect of coverage and vice versa. From these analyses, the most promising features of the BN signal directly were peak position, coercivity, and integral area, which were found to have high correlation coefficients with the intensity, as illustrated in Table 3, for all the studied measurement frequency and voltage combinations. The peak position [37] and coercivity [39] are generally linked to the hardness of the material and thus give high correlations with the different BN measurement frequencies utilized. The measurement frequency change can provide a BN signal from different near-surface structures. In addition, the coverage density was noticed to have only high correlations with the direct results of peak position, coercivity and FWHM, as also illustrated in Table 4.

TABLE 3. Correlation coefficients between shot peening intensity and Barkhausen noise features: peak position, coercivity, and integral area.

Measurement frequency [Hz]	Measurement voltage [vpp]	Peak position	Coercivity	FWHM	Integral area
20	1.5	0.88	0.88	0.99	0.62
40	2	0.94	0.94	0.99	0.79
125	3	0.99	0.98	0.97	0.85
250	5	0.99	0.98	0.96	0.91
500	6	0.99	0.99	0.97	0.89

TABLE 4. Correlation coefficients between shot peening coverage density and Barkhausen noise features: peak position, coercivity, FWHM and integral area.

Measurement frequency [Hz]	Measurement voltage [vpp]	Peak position	Coercivity	FWHM	Integral area
20	1.5	0.84	0.92	0.97	0.22
40	2	0.71	0.77	0.77	0.40
125	3	0.92	0.94	0.95	0.10
250	5	0.90	0.96	0.98	0.48
500	6	0.90	0.95	0.95	0.52

The surface residual stresses in two different perpendicular directions (0 and 90 degrees, tooth axis and perpendicular) prior to shot peening were -570 MPa and -780 MPa, respectively. The shot peening had an effect on the surface residual stresses: balancing and making the values the same in both measurement directions. As shown in Fig. 10 a), the averaged intensity value had an increasing linear trend with the surface residual stress values measured in the two directions up to an intensity value of 0.65 mmA. Averaging the different intensity levels of the shot peening means that the effect of coverage density was omitted. In addition, it was observed that the surface residual stresses were also affected by the averaged coverage density up to 0.135 kg/cm^2, as shown in Fig. 10 b). Averaging means that for different coverage density levels of shot peening, the effect of intensity was omitted. In this case, the linear trend was observed up to a coverage density value of 0.135 kg/cm^2 and after that, the trend sign changed. However, the BN division of two measurement frequencies was also found to be linear with coverage density values higher than 0.135 kg/cm^2, as indicated in Fig.8 b).

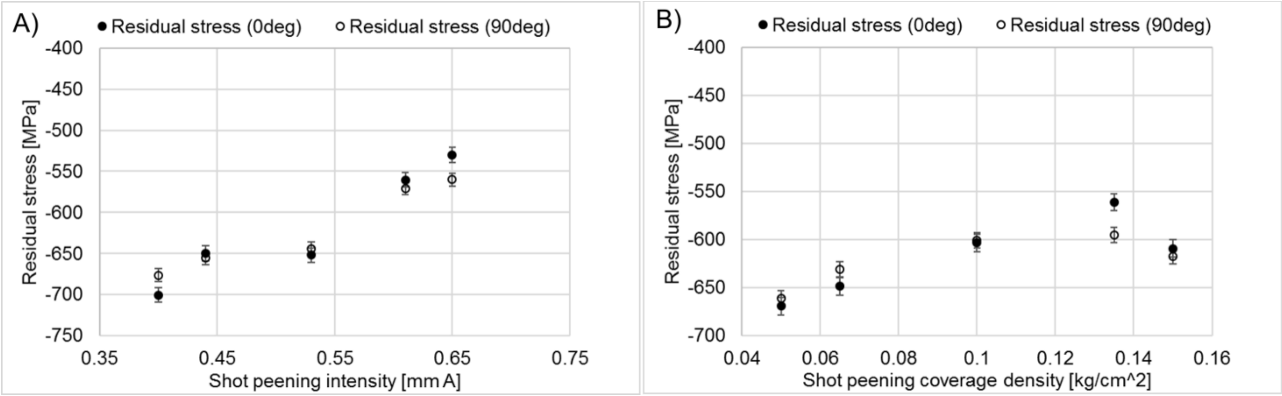


Figure 10. a) Shot peening intensity and b) coverage density as a function of surface residual stresses in two perpendicular directions.

The relationship between the surface residual stresses and BN root-mean-square (RMS) was not evident but was revealed by taking the ratio of BN measurements at different frequencies. The surface residual stresses in both measured directions showed a linear correlation to the BN ratio taken at two different measurement frequencies, as shown in Fig. 11. Thus, based on the ratio of BN, the surface residual stresses could be evaluated. The effect of higher amounts of retained austenite, which is not ferromagnetic, could be seen from the lower compressive residual stresses as a poor correlation.

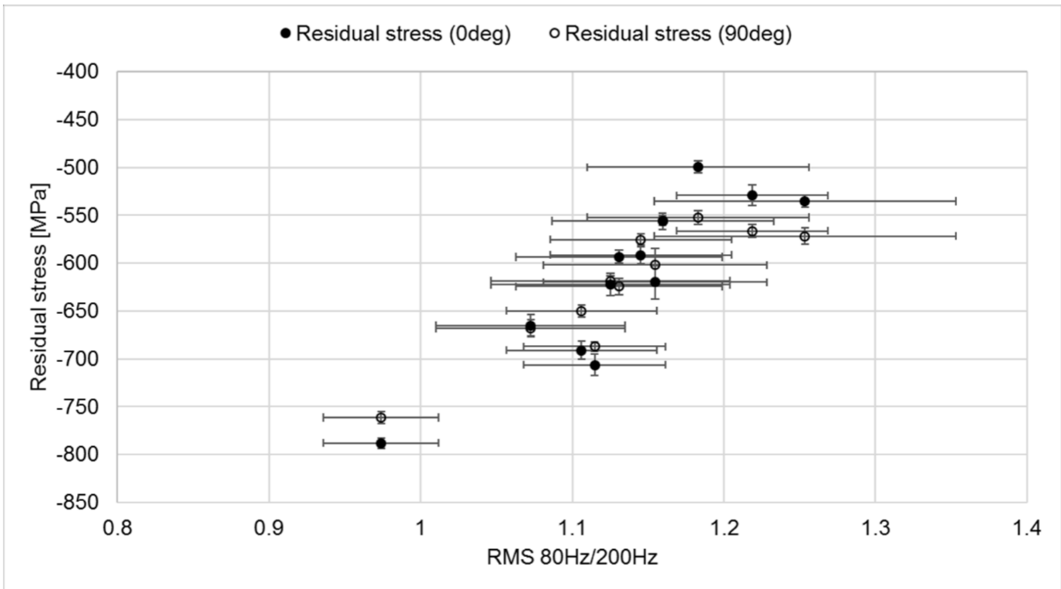


Figure 11. The ratio of Barkhausen noise RMS recorded at two different measurement frequencies, 80 Hz and 200 Hz, as a function of surface residual stresses in two directions.

Many studies [13], [18], [40] have determined the effect of the peening action on residual stress depth distribution. However, the depth distribution studies of residual stresses are difficult to incorporate into the quality control of actual production lines. The depth distributions are not further analysed here.

CONCLUSIONS

In this study, a shot peened gear sample series was studied with residual stress measurements based on Barkhausen noise and X-ray diffraction. During shot peening, several changes occur in the surface layer and surface structure of the component.

The original honed surface was observed to have many deep valleys, and by evaluating the surface characteristics with an SEM and an optical profilometer, it was noticed that the surface directionality disappeared and the roughness values decreased with increasing shot peening action. The most influential factor for a decrease in surface roughness was noticed to be the coverage density, although there were some deviations. The surface hardness was observed to increase to a certain level despite the intensity used but higher intensities, above 0.6 mm A, produced a drastic decrease in the surface hardness that could be due to higher retained austenite content at the surface. However, the shot peening action produced only a noticeable deformed layer of 1-2 µm on the surface observed with SEM.

The most influential changes were obtained in residual stresses and in the retained austenite content. Samples with higher coverage density and intensity values had lower compressive residual stresses near the surface although the maximum compressive residual stress was located deeper below the surface compared to the sample that had lower coverage density and intensity values. In addition, when using higher intensity values, the surface of the peened samples had lower hardness and higher retained austenite content linked to lower compressive residual stresses at the surface. The fact that the shots used were softer than the gear had an effect on the studied structure: less energy was consumed for plastic deformation on the surface and more energy was available for deeper layers.

The relationship between the surface residual stress and BN root-mean-square (RMS) was not evident but was revealed by taking the ratio of BN measurements at different frequencies. The direct surface measurement results of BN RMS taken at one frequency did not provide meaningful correlations with the surface residual stresses. However, linear correlations were found between the residual stress and the shot peening parameters. Also, other BN features such as peak position, coercivity, and integral area were found to have a linear trend with the intensity. The results obtained could be used in the determination of suitable shot peening parameters in order to achieve a surface with the desired residual stress and other properties.

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List of Figure Captions

FIG.1 SEM images from differently treated surfaces with different shot peening parameters: a) original honed surface, b) sample A with shot peening intensity of 0.4 mm A and shot peening coverage density of 0.05 kg/cm^2, c) sample E with shot peening intensity of 0.61 mm A and shot peening coverage density of 0.065 kg/cm^2, and d) sample M with shot peening intensity of 0.65 mm A and shot peening coverage density of 0.15 kg/cm^2.

FIG 2 Cross-sectional SEM images from differently treated surfaces with different shot peening parameters: a) original honed surface, b) sample A with shot peening intensity of 0.4 mm A and shot peening coverage density of 0.05 kg/cm^2, c) sample E with shot peening intensity of 0.61 mm A and shot peening coverage density of 0.065 kg/cm^2, and d) sample M with shot peening intensity of 0.65 mm A and shot peening coverage density of 0.15 kg/cm^2. Red arrow shows bump and white arrows shows the surface cuts.

FIG 3 Optical profilometer images from differently treated surfaces with different shot peening parameters: a) from honed sample with Ra 580 nm, b) from sample A with Ra 601nm, c) from sample E with Ra 560 nm, d) from sample G with Ra 488 nm, e) from sample K with Ra 485 nm, and f) from sample M with Ra 384 nm.

FIG 4 Shot peening coverage density as a function of surface roughness Ra. Markings A, E and M indicate specified shot peening gear samples.

FIG 5 Shot peening intensity as a function of surface hardness. Markings A, E and M indicate specified shot peening gear samples.

FIG 6 Hardness depth profiles for samples A, E, M, and honed.

FIG 7 Residual stress depth profiles for samples A, E, M, and honed, measured in the tooth axis direction.

FIG 8 Retained austenite depth profiles for samples A (shot peening coverage density 0.05kg/cm^2, shot peening intensity 0.4 mm A), E (shot peening coverage density 0.065kg/cm^2, shot peening intensity 0.61 mm A), and M (shot peening coverage density 0.15kg/cm^2, shot peening intensity 0.65 mm A).

FIG 9 (a) Shot peening intensity and (b) coverage density as a function of the ratio of Barkhausen noise RMS recorded at two different measurement frequencies, 80 Hz and 200 Hz.

FIG 10 a) Shot peening intensity and b) coverage density as a function of surface residual stresses in two perpendicular directions.

FIG 11 The ratio of Barkhausen noise RMS recorded at two different measurement frequencies, 80 Hz and 200 Hz, as a function of surface residual stresses in two directions.