

## Article

# The Role of Shot on Phase Transformation and Barkhausen Noise in AISI 304 After Shot Peening

Juraj Uriček <sup>1</sup>, Martin Pitoňák <sup>2</sup>, Miroslav Neslušan <sup>1,\*</sup>, Peter Minárik <sup>3,4</sup>, Tomáš Kmječ <sup>3</sup> and Zuzana Florková <sup>4</sup>

<sup>1</sup> Faculty of Mechanical Engineering, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia; juraj.uricek@fstroj.uniza.sk

<sup>2</sup> Faculty of Civil Engineering, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia; martin.pitonak@uniza.sk

<sup>3</sup> Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, 12116 Prague 2, Czech Republic; peter.minarik@mff.cuni.cz (P.M.); tomas.kmjec@matfyz.cuni.cz (T.K.)

<sup>4</sup> Research Centre, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia; zuzana.florkova@uniza.sk

\* Correspondence: miroslav.neslusan@fstroj.uniza.sk, Tel.: +421-908-811-973

## Abstract

This study investigates the role of shots on shot peening of austenitic steel AISI 304 as a function of shot peening cycles when the conventional steel shots are compared with the ceramic ones. The surface state is analysed in terms of dislocation density, stress state, and the phase transformation of the metastable paramagnetic austenite into the ferromagnetic strain-induced martensite. The sharp transition in magnetic state is monitored via Barkhausen noise emission. It was found that the height of the surface irregularities is unaffected by the number of shot peening cycles and by the different shots. On the other hand, an increasing number of shot peening cycles leads to greater surface damage, as evidenced by the strain-induced martensite fraction and dislocation density. The use of steel shots results in greater microstructural alterations at greater penetration depths due to their higher mass and lower shot velocity. In contrast, ceramic shots produce a higher amplitude of surface stress. Barkhausen noise emission from the steel shots is stronger, which is linked to the higher fraction of strain-induced martensite, especially in the deeper regions. The application of steel shots initiate formation of the ferromagnetic as well as non-ferromagnetic oxides on the surface, in contrast to the non-ferromagnetic oxides only for ceramic shots.

**Keywords:** shot peening; microstructure; strain-induced martensite; austenite; Barkhausen noise

Academic Editors: Xiaodong Li and Andrii Kostryzhev

Received: 4 September 2026

Revised: 30 September 2026

Accepted: 1 October 2026

Published: 4 October 2026

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## 1. Introduction

Shot peening (SP) is a well-known process for surface hardening in which the bombarded body absorbs the high kinetic energy of shots. The local stresses in the region of impact easily exceed the yield strength of metal bodies, and severe plastic deformation hardens the surface. This process is commonly used to obtain increased dislocation density and generate compressive stresses, thereby improving surface resistance to cyclic loading [1–3]. SP can be performed in various ways, with the degree of surface hardening customised by the optimised number of cycles, shot size, shot kinetic energy, etc. [4,5]. On the other hand, SP usually increases the height of surface irregularities [6] as the important aspects affecting fatigue behaviour of components. SP can be carried out in a variety of

manners including over peening, re-shot peening or severe shot peening in order to customise the final surface state with respect of the corresponding functionality of components in real use [6,7].

Austenitic steels are outstanding materials that combine high toughness with excellent corrosion resistance and low yield strength. For this reason, the hardened surface after SP can be combined with a soft core. On the other hand, these materials are susceptible to strain-induced martensite (SIM) transformation when the paramagnetic *fcc* austenite is transformed into *bcc* ferromagnetic SIM. The degree of this phase transformation depends on the matrix chemistry, austenite grain size, loading mode, process temperature, process conditions, and other factors [8–11]. SIM nuclei are usually found at the intersections of austenite dislocations when different dislocation slip systems are activated [12–14]. The fraction of austenite stabilisers, competing with ferrite ones, strongly affects the stacking fault energy and the predominant mechanism of plastic deformation [10,15,16]. Lower stacking fault energy favours the formation of SIM and medium-deformation twinning, whereas higher stacking fault energy favours dislocation slip [10].

The SP of austenitic steels has already been investigated from different points of view. Unal and Varol [6] reported the presence of a nano-grained structure in AISI 304 after severe SP, as well as deformation twinning of the matrix. Fargas et al. [17] analysed surface delamination in AISI 304 after SP, as well as the martensite fraction, under different regimes of this process. The authors reported increased surface roughness and the initiation of microcracks on the surface. Further studies investigated the role of sheet rolling direction on subsequent SP in terms of magnetic anisotropy, as well as the role of stainless steel strength in the height of surface irregularities [18,19]. These studies also employed electromagnetic Barkhausen noise (MBN) to monitor the phase transformation of austenite into SIM. The authors discussed the influence of the as-received microstructure on the depth microstructure gradient and on the magnetic interaction among neighbouring martensite islands. Kleber and Barroso [20] combined the SP of austenitic steel with tensile stress, correlating MBN with the depth of penetration of the SIM.

The MBN technique is based on measuring electromagnetic and/or acoustic pulses generated by domain walls (DWs) during their irreversible motion [21,22]. Therefore, this technique is used exclusively in the case of ferromagnetic bodies or those in which a paramagnetic matrix is replaced by a ferromagnetic one. The use of MBN for monitoring austenitic steels is a very sensitive tool for assessing the degree and specific nature of austenite phase transformation when ferromagnetic components are initiated by plastic deformation and/or thermal processing [23–25]. Formation of SIM in the parental austenite has already been reported when different loading modes were applied. Uniaxial tensile loading is used in pilot studies in this field [23,25] and can be contrasted with biaxial or multiaxial loading [18,19,24,26]. Initiation of the higher-dislocation slip system under more complex loading makes the formation of SIM easier due to a higher density of nucleation nuclei in the austenite. The study by Neslušan et al. [26] also discussed the role of SIM-preferential straining in rolling with integrated slip.

This study reports on the role of shots in SP, comparing conventional steel and ceramic shots in the phase stability of AISI 304. Authors use their experience collected in the previous studies [18,19] focused on the application of steel shots only when the SIM fraction depth profiles as well as the presence of the ferromagnetic oxides were discussed. This study is based on the concept in which the deeper SIM fraction penetration might be reduced, the near-surface hardening enhanced together with elimination of ferromagnetic oxides on the surface by the use of ceramic shots. The different shot masses and the corresponding differences in shot velocity affect the surface, resulting in meaningful differences in SIM fraction and MBN response. MBN is a function of stress state [27,28] and microstructure expressed in a variety of terms [29,30].

## 2. Materials and Methods

The experiments were carried out on AISI 304 (yield strength  $311 \pm 11$  MPa, ultimate strength  $705 \pm 15$  MPa, and elongation at break  $91 \pm 1.8\%$  obtained from 3 repetitive measurements along RD; see Figure 1a), received as a 3 mm thick sheet. The samples of length 60 mm (along the sheet rolling direction, RD) and 20 mm in width (along the sheet width, TD) were cut for SP. ND is the direction along the sample's thickness.

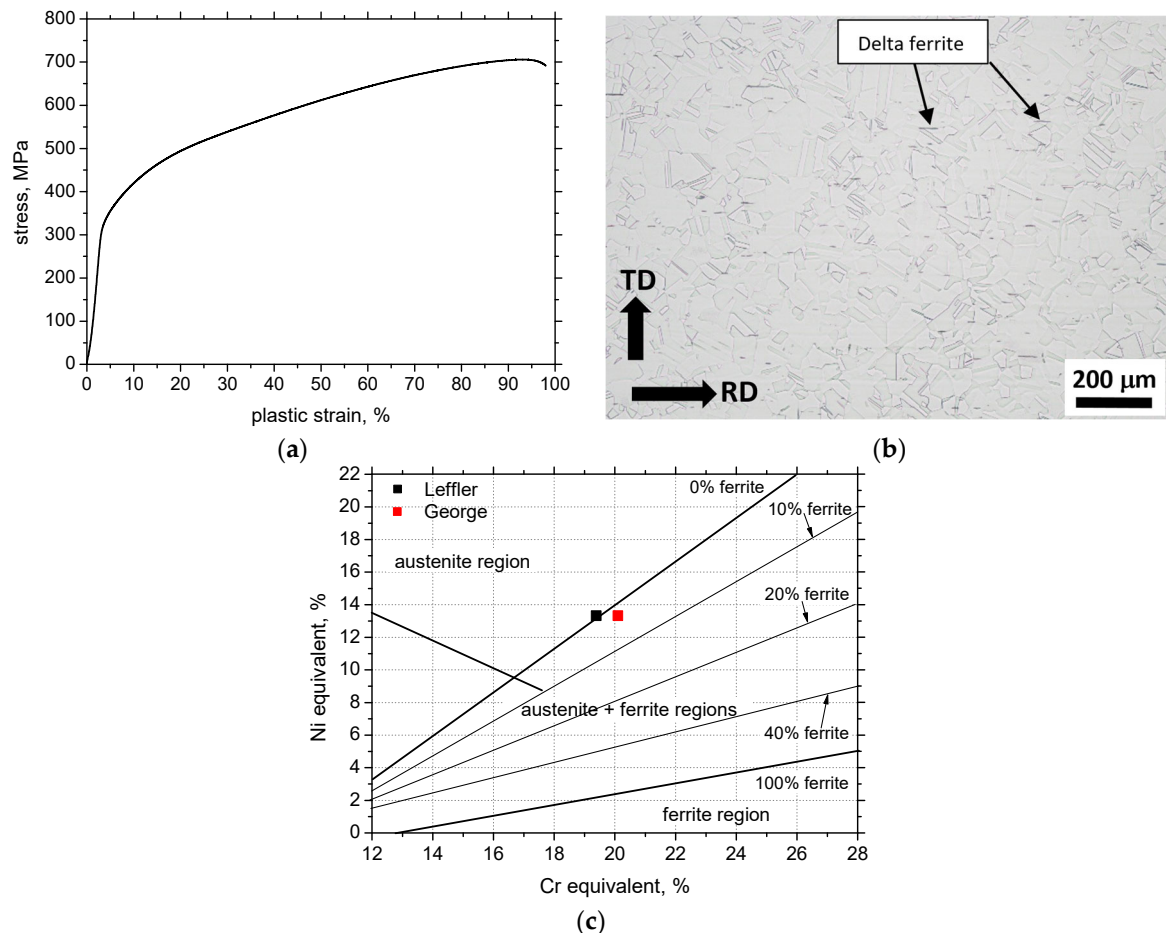


**Figure 1.** Stress–strain curve and metallography of the as-received AISI 304: (a) stress–strain curve, (b) metallography of AISI 304 (etched by Marble for 10 s); (c) Schaeffler–Delong diagram.

The chemical composition of the as-received steel (indicated in Table 1) meets the nominal composition of AISI 304 grade (all elements are within the allowed range with respect to valid standards). The microstructure (depicted in Figure 1b) is composed of equiaxed austenitic grains with a limited fraction of delta ferrite; see Figure 1b. Having chemical composition indicated in Table 1, a stacking fault energy ( $\Gamma$ ) of  $19.9 \text{ mJ.m}^{-2}$  can be calculated as follows [31]:

$$SFE = 39 + 1.59 Ni - 1.34 Mn + 0.06 Mn^2 - 1.75 Cr + 0.01 Cr^2 + 15.21 Mo - 5.59 Si - 60.69 \sqrt{C} + 1.2 N + 26.27 (C + 1.2 N) \times \sqrt{Cr + Mn + Mo} + 0.61 \sqrt{Ni(Cr + Mn)} \quad (1)$$

This low SFE is related to the higher susceptibility to SIM formation as the predominating mechanism of strain hardening at the expense of suppressed deformation twins and/or dislocation slip [10]. Furthermore, the calculated  $M_{d30/50} = 50.06 \text{ }^\circ\text{C}$  implies the lower austenite stability. This is the deformation temperature at which 50% of SIM is formed by a true tensile strain of 30%.  $M_{d30/50}$  can be calculated as follows [10]:

$$M_{d30/50} = 551 - 462(C + N) - 9.2Si - 8.1Mn - 13.7Cr - 28(Ni + Cu) - 18.5Mo - 68Nb - 1.42(G_s - 8) \quad (2)$$

**Table 1.** Chemical composition of AISI 304 measured using optical emission spectrometry.

| C     | Mn    | Si    | Cr    | N   | Ni    | Mo    | Co    | Cu    | Nb    | Fe   |
|-------|-------|-------|-------|-----|-------|-------|-------|-------|-------|------|
| 0.013 | 1.151 | 0.392 | 18.48 | 0.1 | 9.142 | 0.321 | 0.104 | 0.313 | 0.014 | bal. |

Using the chemical composition given in Table 1, Ni and Cr equivalents can be calculated [32,33] and the Schaeffler–Delong diagram can be plotted (see Figure 1c). This diagram confirms that the microstructure of the investigated AISI 304 is mainly composed of austenite.

SP was performed in the self-made device under the conditions listed in Table 2. SP was studied as a function of the number of cycles (2, 4, 6, and 8) and the shot type (conventional steel or ceramic), all with the same average diameter. For each number of cycles as well as shot type, 3 repetitive measurements were carried out. The energy stored in the samples during SP is expressed in Almen intensity as listed in Table 3 (measured by the use the A strips of thickness of  $1.295 \pm 0.025$  mm). Curvature of the strips after SP was measured by use of the digital dial indicators.

**Table 2.** SP details.

|                                           |                       |
|-------------------------------------------|-----------------------|
| Shot size                                 | 0.43 mm               |
| Shots type                                | steel and ceramic     |
| Gun                                       | Guyson                |
| Distance from the gun to the surface      | 70 mm                 |
| The angle between the gun and the surface | 98°                   |
| The linear speed of the sample motion     | 10 mm.s <sup>−1</sup> |
| Air pressure                              | 5 bars                |
| Coverage                                  | 100%                  |

**Table 3.** Almen intensity (in mm) as a function of SP cycle number and shot type.

| Number of Cycles | 2               | 4               | 6               | 8               |
|------------------|-----------------|-----------------|-----------------|-----------------|
| Steel shots      | $0.69 \pm 0.02$ | $0.75 \pm 0.02$ | $0.79 \pm 0.03$ | $0.82 \pm 0.02$ |
| Ceramic shots    | $0.41 \pm 0.02$ | $0.49 \pm 0.02$ | $0.52 \pm 0.02$ | $0.60 \pm 0.03$ |

The lower Almen intensities for the ceramic shots are due to:

1. The lower penetration depth of stress and microstructure alterations with respect to their lower mass as contrasted against the steel shots (as it is reported in Chapter 3);
2. The lower fraction of energy consumed by the shot-peened body with respect to the higher speed (stronger elastic response);
3. The ceramic shot tends to break into pieces during its collision with the shot-peened body due to its limited toughness.

The 98° angle between the gun and the surface avoids a shot backward motion towards the gun and has no significant influence on the final coverage.

The kinetic energy  $E_k$  of a shot can be calculated as follows:

$$E_k = \frac{1}{2}mv^2 \text{ (J)} \quad (3)$$

where  $m$  is a shot mass and  $v$  its velocity. When the mass is known, along with information about shot size and density (see Table 4), the shot velocity  $v$  is calculated using Equation (4):

$$v = \int \frac{pS}{m} dt = \frac{pS}{m} t \text{ (m.s}^{-1}\text{)} \quad (4)$$

where  $p$  is the air pressure,  $S$  is the cross-sectional area of the shot, and  $t$  is the time of a shot acceleration in the SP gun,

$$t = \sqrt{\frac{2md}{ps}} \text{ (s)} \quad (5)$$

where  $d$  is the acceleration distance in the SP gun. The quantities used for the calculations (indicated in Table 4) were converted into basic SI units.

**Table 4.** Quantities for the calculation of  $E_k$ .

|                                       |                                                                                       |
|---------------------------------------|---------------------------------------------------------------------------------------|
| shot density, kg.m <sup>-3</sup>      | 7850 for steel shots and 2661 for ceramic shots                                       |
| average shot diameter, mm             | 0.43                                                                                  |
| shot mass $m$ , g                     | $0.33 \times 10^{-3}$ for steel shots and $0.11 \times 10^{-3}$ for ceramic shots and |
| air pressure $p$ , bar                | 5                                                                                     |
| acceleration distance $d$ , mm        | 4.5                                                                                   |
| shot velocity $v$ , m.s <sup>-1</sup> | 128 for steel shots and 221 for ceramic shots                                         |
| kinetic energy $E_k$ , J              | 2.7 for steel as well as ceramic shots                                                |

Table 4 indicates that the  $E_k$  is the same for both shots. The higher mass of the steel shots,  $0.33 \times 10^{-3}$  g, is compensated by their lower velocity, 128 m.s<sup>-1</sup>, as contrasted against the lower mass of the ceramic shots,  $0.11 \times 10^{-3}$  g, and their higher velocity, 221 m.s<sup>-1</sup>.

3D surface topography was visualised using a confocal microscope (©EISS Axio Observer ©1, LSM 700, ©eiss Oberkochen, Germany) with a 405 nm laser and the ©-stack function. The scanned raw data were also filtered using the aforementioned software 3.0 SR version, and specific surface features associated with the height of surface irregularities were subsequently exported.

MBN was measured using the RollScan 350 device (Stresstech Oy, Jyväskylä, Finland), operated with the MicroScan software 5.4.1 (magnetising frequency 125 Hz sine profile and magnetic field strength  $\pm 9.87 \text{ kA} \cdot \text{m}^{-1}$ , sensor S1-18-12-01, sampling frequency 6.4 MHz). The measured MBN signal was filtered using a bandpass filter (30 ÷ 1000 kHz), and the background noise, with an effective value of 29.56 mV, was subtracted from the MBN signal, following the methodology reported earlier [34]. MBN was measured along RD and TD. MBN refers to the effective value of the signal. The software also provides information about the MBN envelope, as well as extracted features such as  $PP$  (position of MBN envelope maxima in the magnetic field, usually linked to magnetic strength).

The microstructure of the sub-surface deformed layer was analysed by electron backscatter diffraction (EBSD). The samples were cut, embedded in conductive resin, and mechanically polished down to a 50 nm alumina suspension. Subsequently, the measurement was performed using an EDAX EBSD camera integrated into a ©EISS Auriga compact scanning electron microscope (SEM) (©eiss Oberkochen, Germany). The analysis was performed in OIM TSL 9.0 software, and points with a confidence index  $CI < 0.1$  were excluded from the analysis.

The <sup>57</sup>Fe Mössbauer spectra of the samples were collected at room temperature in the reflection and the CEMS (Conversion Electron Mössbauer Spectroscopy) arrangements using a self-made constant-acceleration spectrometer equipped with a <sup>57</sup>Co/Rh source. The CEMS reading depth is about 200 nm.

Residual stresses after SP were determined from XRD diffraction patterns using the XRD technique (Proto iXRD Combo diffractometer, the average effective penetration depth ~5 µm, scanning angle  $\pm 39^\circ$ , Bragg angle  $78.2^\circ$ ) (Proto Manufacturing Ltd., Ontario, Canada). The residual stress and dislocation density in SIM were measured using Cr  $K\alpha$  radiation, with shifts in the 211 reflection used to calculate them. The Winholtz and Cohen method and X-ray elastic constants  $\frac{1}{2}S_2 = 5.75 \text{ TPa}^{-1}$  and  $S_1 = -1.25 \text{ TPa}^{-1}$  were applied [35]. The residual stress and dislocation density in austenite were measured using Mn  $K\alpha$  radiation, with shifts in the 311 reflection used to calculate them. The Winholtz and Cohen

method and X-ray elastic constants  $\frac{1}{2}S_2 = 7.80 \text{ TPa}^{-1}$  and  $S_1 = -1.20 \text{ TPa}^{-1}$  were applied. The stress and dislocation density depth profiles were obtained by sequentially removing the layers via electrochemical removal. The subsequent layer removals followed the sequence 5, 5, 10, 20, 30, 30, 45 and 45  $\mu\text{m}$ , resulting in the total removed depth 190  $\mu\text{m}$ .

Dislocation density in the austenite as well as in SIM was calculated as follows [35]:

$$\delta = \frac{1}{D^2} \text{ (m}^{-2}\text{)} \quad (6)$$

where  $D$  is the crystallite size obtained from Equation (4)

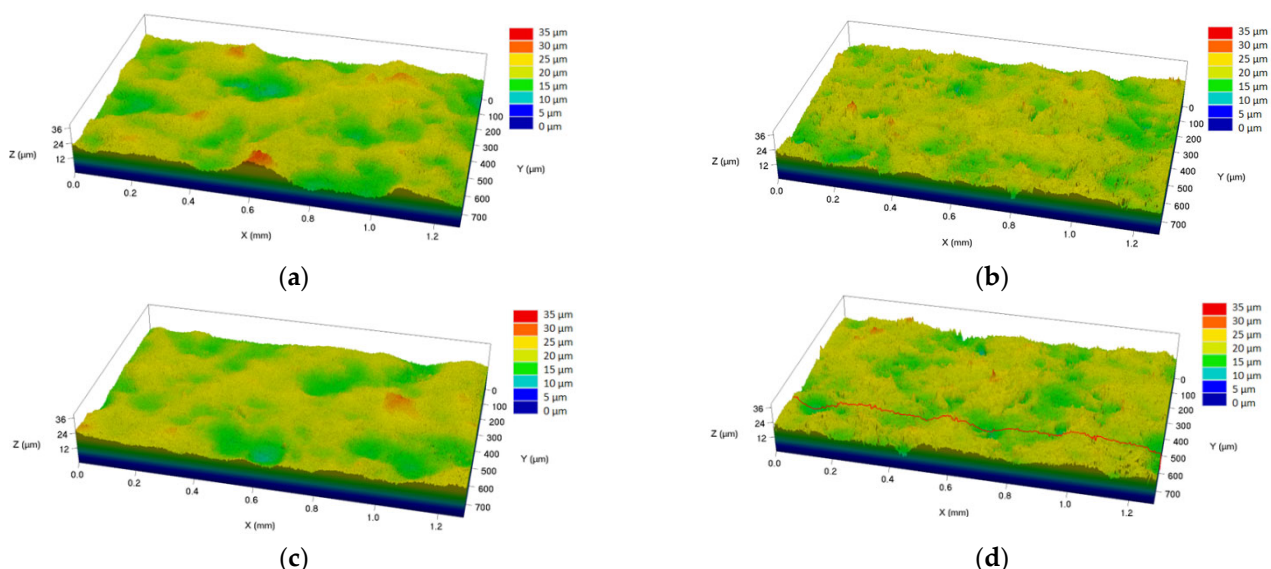
$$D = \frac{K\lambda}{\beta \cos \theta} \text{ (nm)} \quad (7)$$

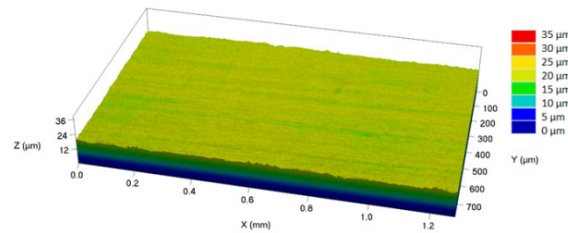
where  $K$  is the constant (0.89),  $\lambda$  is the X-ray wavelength (2.291 Å for ferrite and 2.103 Å for austenite),  $\beta$  represents the width of the XRD pattern at half of its maximum, and  $\theta$  is the Bragg angle equal to  $78.2^\circ$ .

### 3. Results of Experiments and Their Discussion

#### 3.1. Height of Surface Irregularities

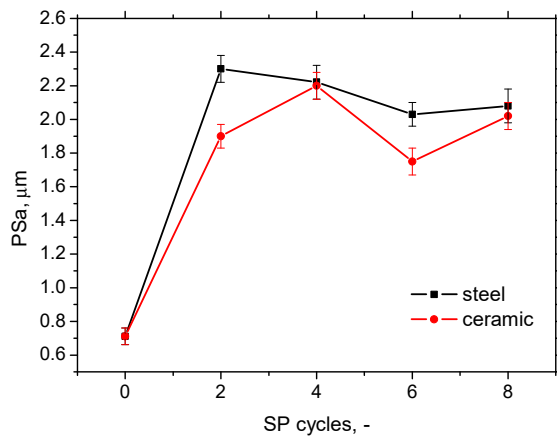
The local stresses during the shot impact easily exceed the yield strength of the shot-peened surface, especially when AISI 304 is employed. Plastic deformation extrudes the matrix from the impact points and generates the typical grater-like surface, in contrast to that after cold rolling; see Figure 2. The height of irregularities on the surface, expressed in terms of the primary profile parameter  $PSa$ , increases steeply in the early phases of the SP process (for two SP cycles) and then exhibits a subtle drop for higher numbers of SP cycles; see Figure 3a. Also, Figure 3b and  $PSz$  show that the surface is gently smoothed as repeated impacts lower the highest peaks on the surface. The steel and ceramic shots produce surfaces with similar  $PSa$ ; see Figure 3a. However, the maximum distance between the deepest valley and the highest peak, expressed in terms of  $PSz$ , is greater for the ceramic shots; see Figure 3b. Parameter  $PSz$  also exhibits smoothing behaviour at the higher SP cycles. Despite the same  $PSa$  values for the ceramic and steel shots, Figure 2 depicts that the surface after SP using steel shots is composed of larger craters with a smoother profile than that produced by ceramic shots. The lower ceramic shot mass makes extrusion of the shot-peened matrix less intensive at the expense of the higher crater density, as contrasted against the surface produced by the steel shots.



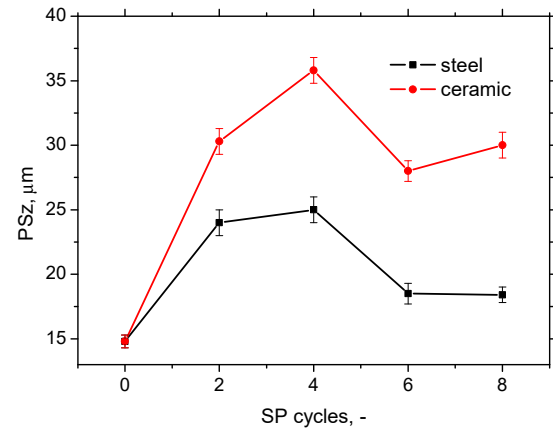


(e)

**Figure 2.** 3D images of surfaces after SP: (a) steel shots—2 SP cycles; (b) ceramic shots—2 SP cycles; (c) steel shots—8 SP cycles; (d) ceramic shots—8 SP cycles; (e) after rolling.



(a)

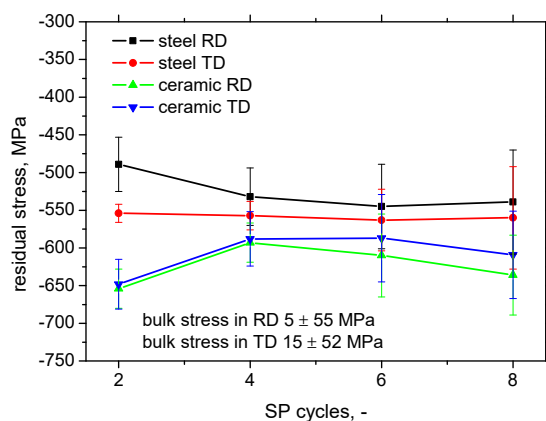


(b)

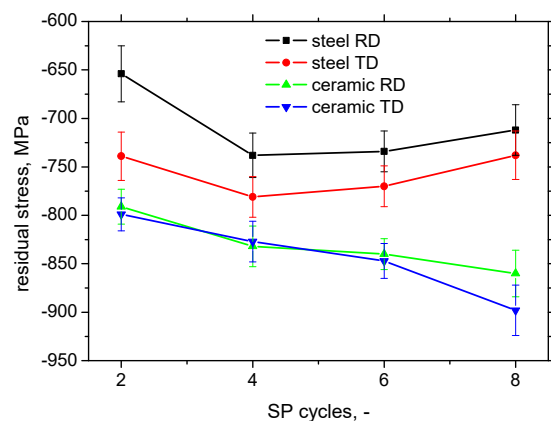
**Figure 3.**  $PSa$  and  $PSz$  as a function of SP cycles and types of shot: (a)  $PSa$ ; (b)  $PSz$ .

### 3.2. XRD Measurements

The higher  $PSz$  values for the ceramic shots correlate with higher compressive stresses in austenite and SIM; see Figure 4. Furthermore, the lower magnitude of residual stress in SIM along RD for the steel shots can be found compared with TD. The same magnitudes of stresses along RD and TD, especially for the lower SP cycles, can be found for the ceramic shots. Residual stresses in the austenite are unaffected at the higher SP cycles (within standard deviations); see Figure 4a. On the other hand, the continuous drop in residual stresses in SIM for the ceramic shot contrasts with the saturation phase in the medium SP cycles, followed by a decreasing magnitude for the eight SP cycles, as depicted in Figure 4b.



(a)



(b)

**Figure 4.** Surface residual stresses as a function of SP cycles and types of shot: (a) in austenite; (b) in SIM.

Such behaviour indicates that the energy consumed by the surface during bombardment attains the critical threshold. The 3% release in the magnitude of residual stress along RD (5% release for TD) can be observed beyond this threshold (comparing the magnitude of residual stress after six and eight SP cycles), and this behaviour more or less overlaps with the region of surface smoothing depicted in Figure 3. This release is also overlapping with the lower dislocation density in austenite for the steel shots compared with the ceramic ones; see Figure 5a. This figure also shows that the dislocation density in austenite increases with SP cycles, whereas fully unaffected behaviour is observed in SIM. On the other hand, the SIM fraction for the steel shots exhibits steep growth up to four SP cycles, followed by a subtle drop later, in contrast to the monotonous growth of the SIM fraction for the ceramic shots; see Figure 5b. Comparing Figures 4b and 5b, one might find that the continuous increase in residual stresses for the ceramic shots can be linked to the monotonic growth of the SIM fraction. On the other hand, the stress release depicted in Figure 4a overlaps with the subtle fall in the SIM fraction illustrated in Figure 5b.

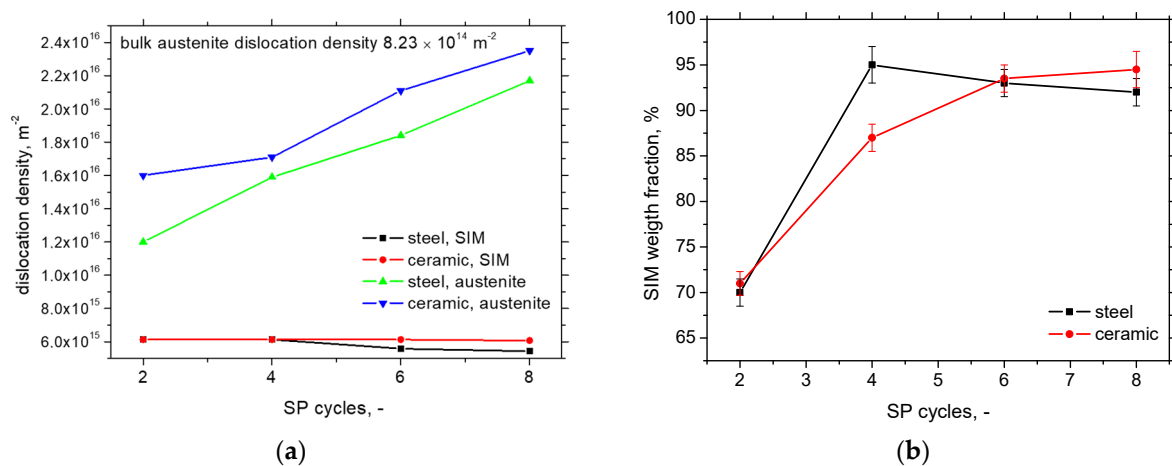


**Figure 5.** Surface dislocation density and SIM fraction as a function of SP cycles and types of shot: (a) dislocation density in austenite; (b) SIM fraction.

The big difference can be found with respect to the depth profiles of residual stress (Figure 6) and SIM fraction. Residual stress in the SIM is more or less similar with depth below the surface, at about  $-725 \pm 50$  MPa for the steel shots and about  $-790 \pm 45$  MPa for the ceramic shots. On the other hand, the slightly higher amplitude of the compressive residual stresses in the ceramic shots is offset by the lower penetration depth. The dislocation density  $\delta$  for the steel shots is lower on the surface, at the expense of higher  $\delta$  in the deeper regions; see Figure 7a. The SIM fraction in the near-surface region is slightly higher for the ceramic shots; see Figure 7b. However, the phase transformation penetrates much deeper in the steel shots, and the SIM fraction in the deeper regions is also higher than that produced by the ceramic shots. The  $\delta$  in SIM is unaffected with respect to shot type, as well as penetration depth, with density depicted in Figure 5a.

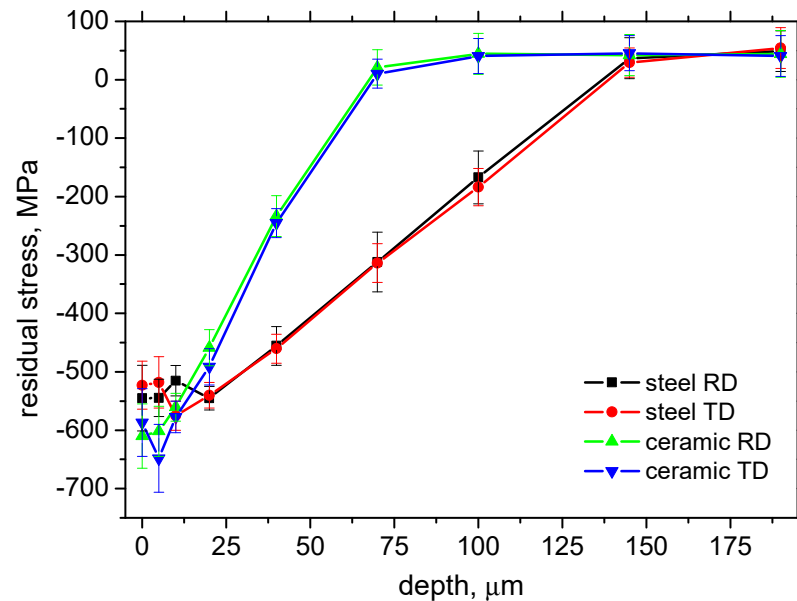


Figure 6. Depth profile of residual stresses after 6 SP.

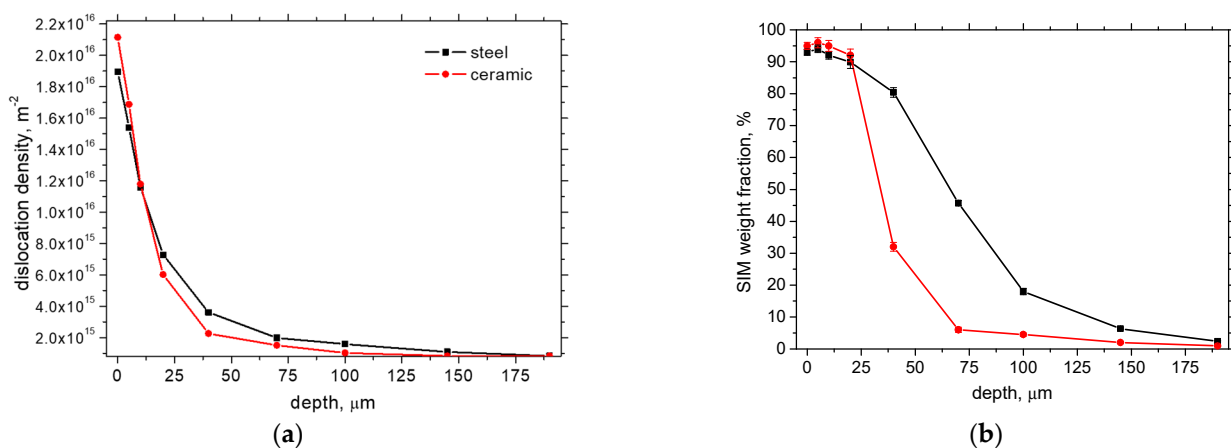


Figure 7. Depth profile of dislocation density in austenite as well as SIM fraction after 6 SP cycles: (a) dislocation density in austenite; (b) SIM fraction.

### 3.3. EBSD Observations and Mössbauer Spectroscopy

EBSD images depicted in Figure 8 confirm that the penetration depth of microstructural alterations in the steel shots is greater than that in the ceramic ones. IPF maps in the near-surface region exhibit extreme matrix fragmentation due to severe plastic deformation, which vanishes towards greater depth. Austenite neighbouring the SIM regions is of high dislocation density as contrasted against the less affected austenite at greater depth; see KAM maps in Figure 8. The lath martensite is the response of AISI 304 on severe plastic deformation due to its low *SFE*. This phase transformation occurs in the grains that have suitable crystallographic orientations against the direction of the applied load, whereas the neighbouring regions represent less affected grains that have mainly austenitic *fcc* lattices with certain degrees of yielding. The valuable degree of the phase transformation after eight SP cycles also confirms the Mössbauer spectra illustrated in Figure 9. However, the surface after application of the steel shots also contains the ferromagnetic oxides as contrasted against the ceramic shot when only the non-ferromagnetic oxides of limited intensity can be obtained after eight SP cycles, see also the relative intensities in Table 5. The non-ferromagnetic  $\text{Cr}_2\text{O}_3$  oxide is spontaneously

produced on the surface of austenitic stainless steels as a result of the passivation process providing the exceptional corrosion resistance of these materials.

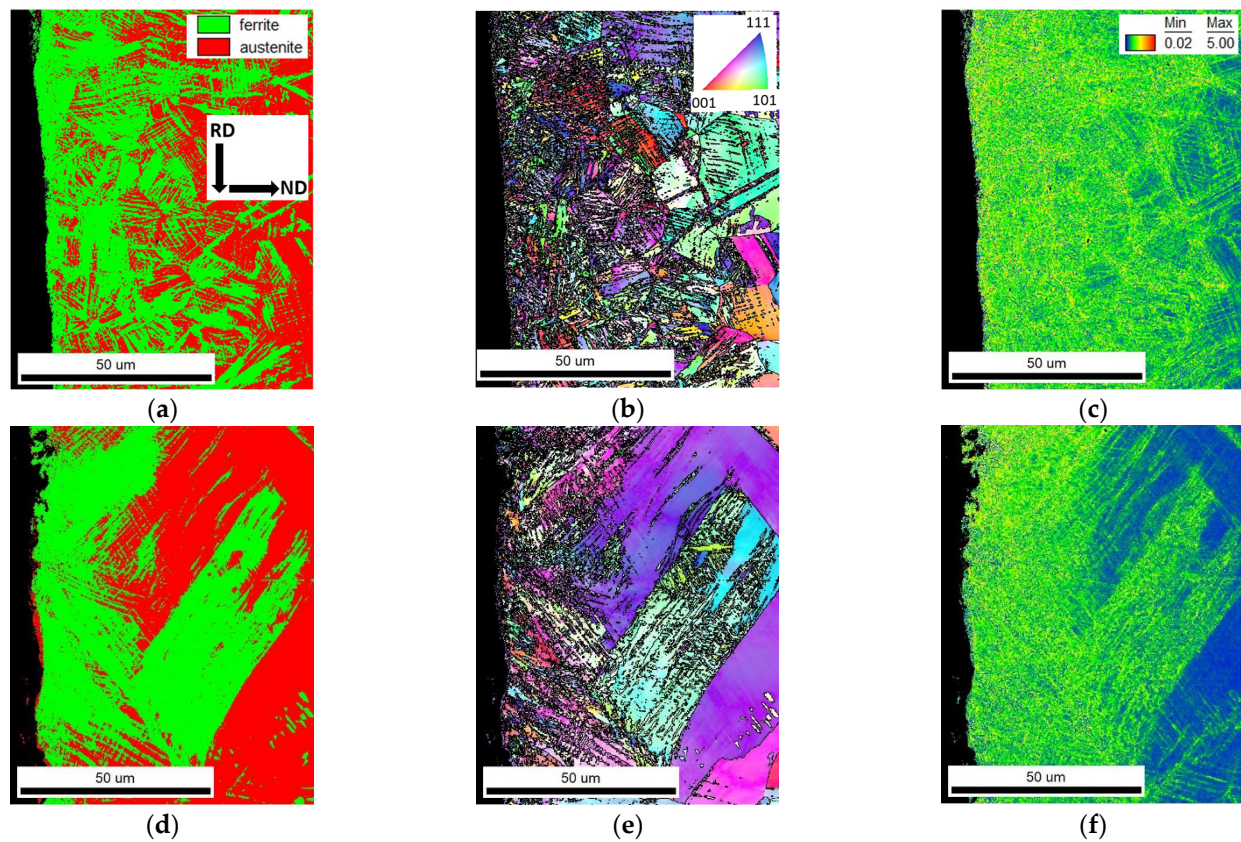


**Figure 8.** EBSD images of surfaces after 6 SP cycles: (a) phase map for steel shots; (b) IPF map for steel shots; (c) KAM map for steel shots; (d) phase map for ceramic shots; (e) IPF map for ceramic shots; (f) KAM map for ceramic shots.

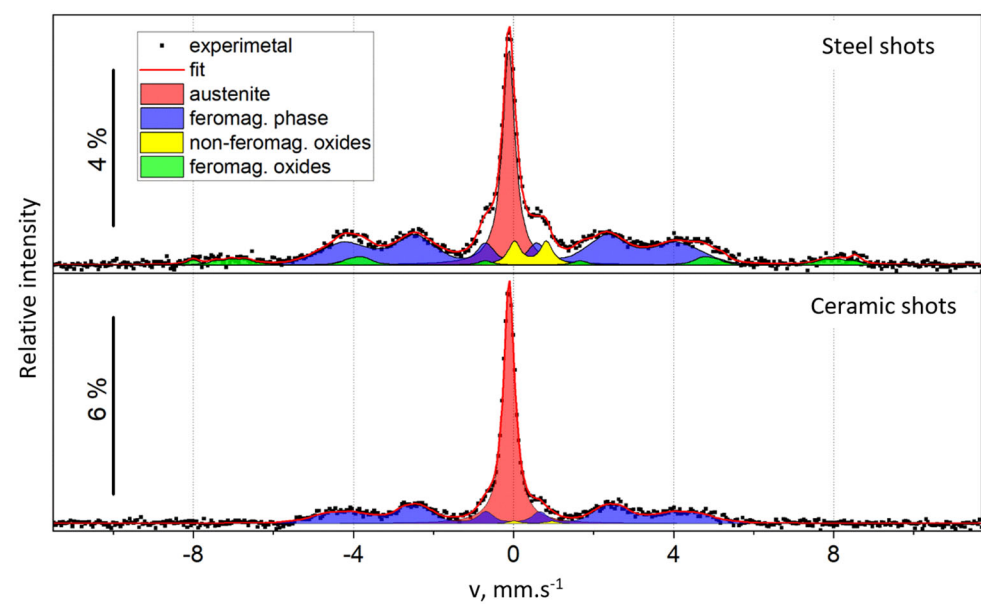


**Figure 9.** Mössbauer CEMS spectra of surfaces after 8 SP cycles.

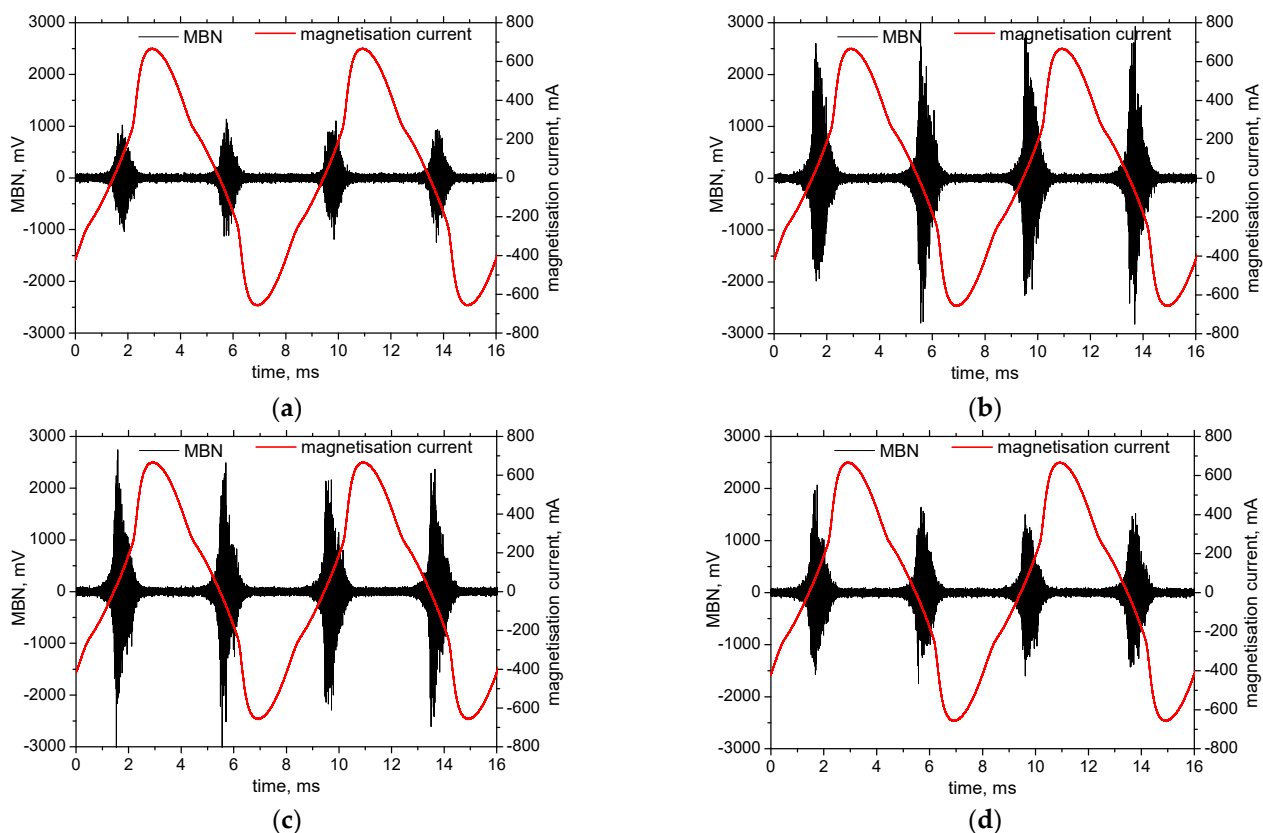
**Table 5.** Phase fractions based on the relative CEMS intensities for the different shots after 8 SP cycles.

|               | Austenite | SIM  | Non-Ferromagnetic<br>Oxides | Ferromagnetic<br>Oxides Haematite | Ferromagnetic<br>Oxides Magnetite |
|---------------|-----------|------|-----------------------------|-----------------------------------|-----------------------------------|
| Ceramic shots | 54.2      | 44.6 | 1.2                         | -                                 | -                                 |
| Steel shots   | 32.4      | 47.7 | 6.9                         | 3.3                               | 9.7                               |

One might find that the SIM fraction extracted from EBSD, XRD and Mössbauer techniques differs. Such a finding is closely connected with the different scanning area as well as the different sensing depth of these techniques. Mössbauer CEMS spectra suffers from the very low sensing depth. On the other hand, this technique is capable of detecting very fine surface alterations associated with the oxides presence, as mentioned above. The fraction of SIM obtained by the EBSD technique is usually smaller due to the higher sensitivity of the XRD technique; it has the ability to detect the *bcc* lattice in very fine spots, along with a larger irradiated area as compared with the limited region observed in EBSD images.

### 3.4. MBN Measurements

MBN originates from the SIM only, and its valuable growth is exclusively linked to the growing fraction of SIM, along with the SP cycles; see Figures 10 and 11a. These figures also demonstrate that the differences in MBN with respect to RD and TD are mostly minor, and the higher MBN for the steel shots can be linked to the higher SIM fraction, especially in the deeper region [36].

**Figure 10.** MBN filtered signals: (a) 2 SP cycles, RD—steel shots; (b) 8 SP cycles, RD—steel shots; (c) 8 SP cycles, TD—steel shots; (d) 8 SP cycles, RD—ceramic shots.

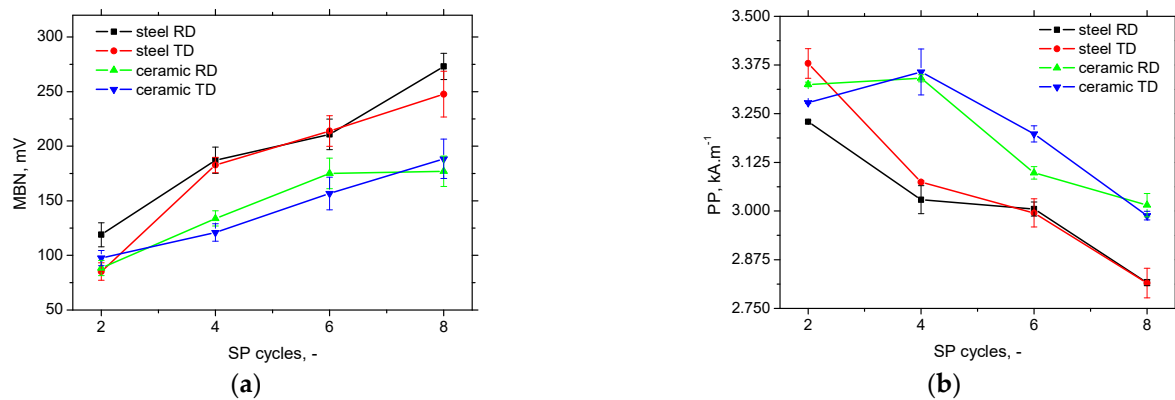


**Figure 11.** MBN and *PP* as a function of SP cycles and types of shot; (a) MBN; (b) *PP*.

Figures 11b and 12 also indicate that magnetic hardness decreases with SP despite the increasing SIM fraction. This behaviour is linked to the magnetic exchange among the neighbouring SIM islands [18,19]. DWs occur in the form of avalanches [37,38], and magnetic communication with the neighbouring ferromagnetic region is important. When the SIM fraction is growing with SP cycles, the SIM island net is denser, and the distances among the neighbouring islands are shorter. For this reason, magnetic exchange is mediated more effectively when bridging gaps among the SIM islands is easier. Such behaviour also explains the higher *PP* and the corresponding magnetic hardness of the ceramic shots compared with the steel shots. The increasing SIM fraction makes the free path of DW motion longer and increases the number of DWs in motion, which in turn generates stronger MBN pulses detected on the free surface; see Figure 13a. The lower density of SIM islands for the ceramic shots, therefore, results in the absence of the stronger MBN above 1.4 V, as depicted in Figure 13b (and the corresponding lower MBN).

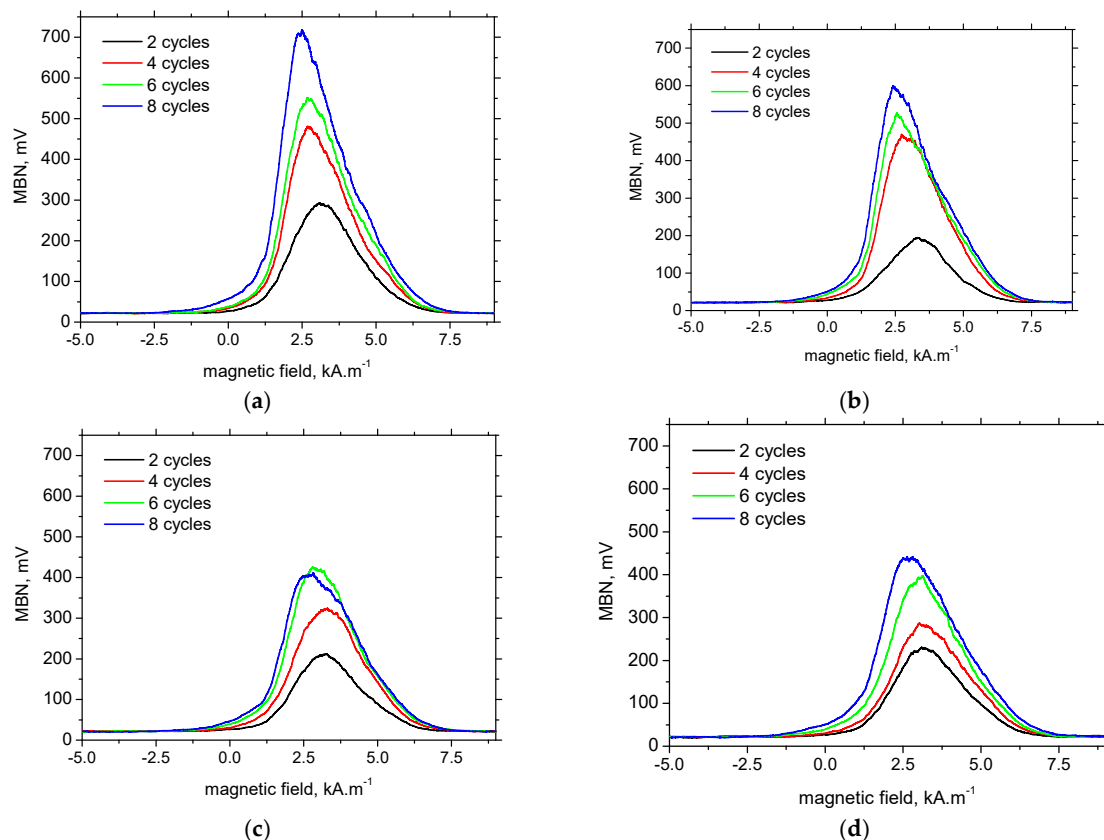


**Figure 12.** MBN envelopes as a function of SP cycles: (a) steel shots—RD; (b) steel shots—TD; (c) ceramic shots—RD; (d) ceramic shots—TD.

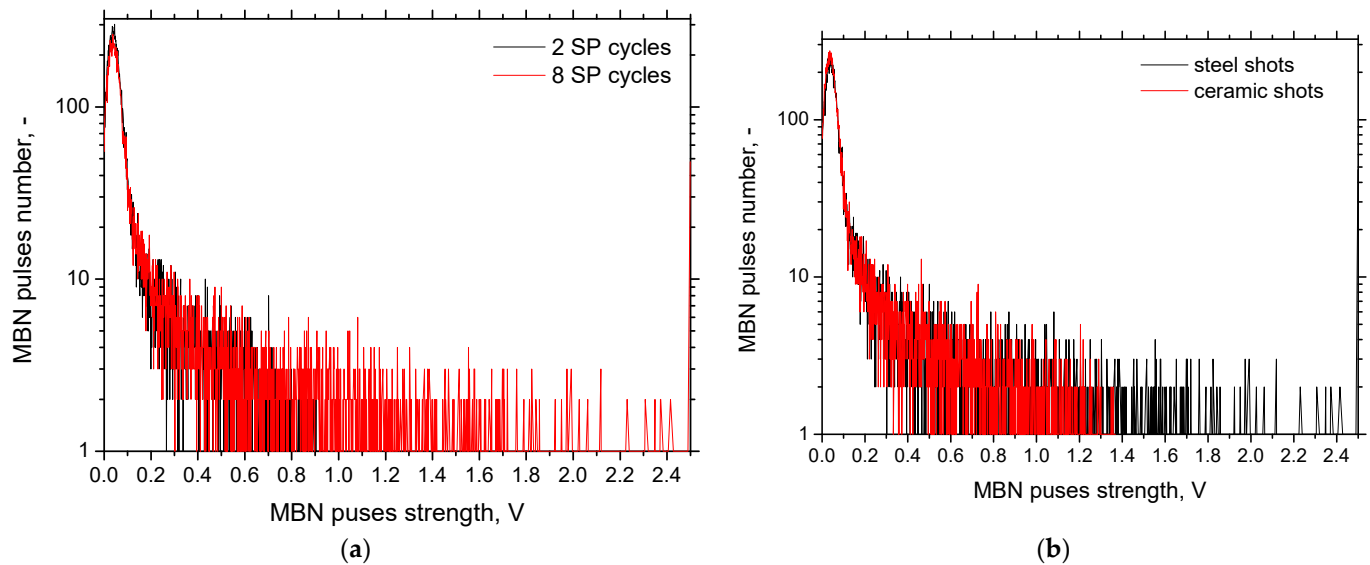


**Figure 13.** Distribution of MBN pulse strength: (a) steel shots in RD; (b) 8 SP cycles in RD.

The aforementioned findings indicate different energy consumption processes during bombardment with steel shots and ceramic shots. The calculated kinetic energy  $E_k = 2.7$  J is composed of that consumed by the bombarded surface  $\Delta E_k$  for the alteration of stress state as well as microstructure and  $E_{k-reb}$  after a shot rebounding.

$$\Delta E_k = E_k - E_{k-reb} \text{ (J)} \quad (8)$$

The higher ceramic shot speed increases the strain rate of plastic deformation, which in turn contributes to a stronger elastic response at the expense of attenuated plasticity of the shot-peened body [39], especially in the deeper regions. The higher mass and the lower speed of the steel shots contribute to the higher  $\Delta E_k$ . For this reason, the alterations in stress state and microstructure penetrate deeper in the case of steel shots; see also Figure 14.

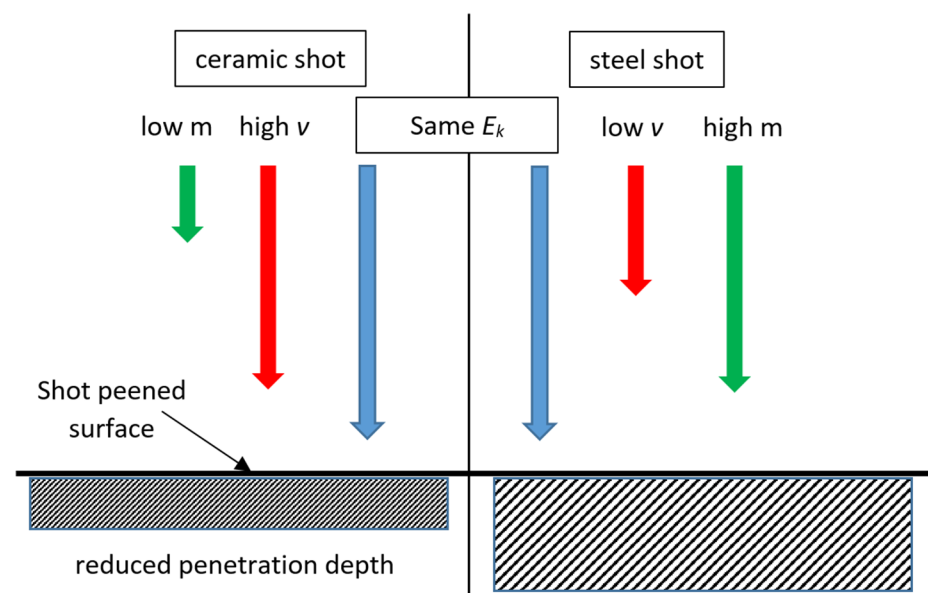


**Figure 14.** Brief illustration of the effect of shot mass and velocity on the energy consumed during impact.

Figure 15 indicates a good correlation between MBN and Almen intensity, as well as the energy consumed by the matrix ( $E_k$ ). On the one hand, Almen intensity reflects the role of austenite yielding and SIM formation, whereas MBN is exclusively linked to the SIM

fraction. On the other hand, these processes are closely related when the austenite yielding is the preliminary phase of SIM nucleation [10–13]. Figure 15 also depicts the systematic shift between MBN and Almen when comparing the steel and ceramic shots. This shift should be related to the aforementioned differences in shot mass and velocity and the corresponding differences in the depth profiles depicted above.

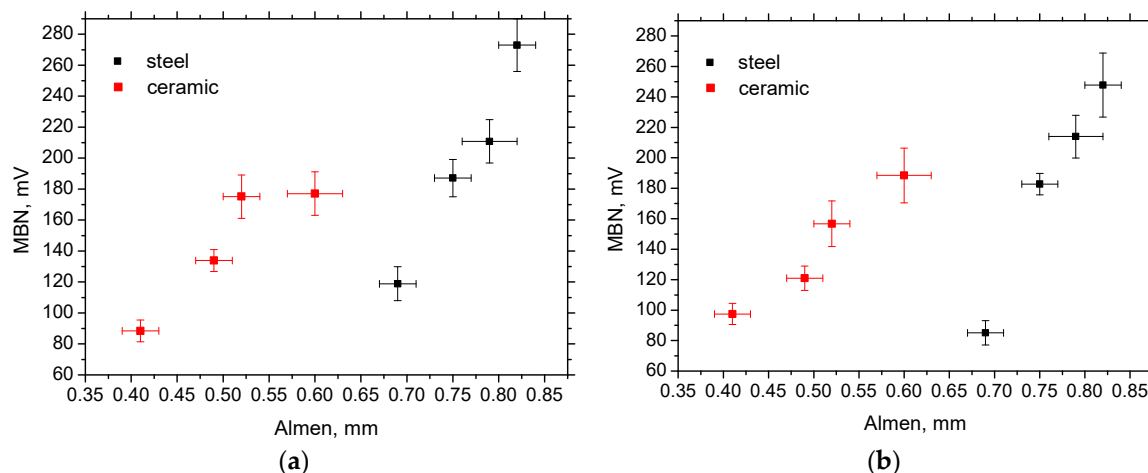


**Figure 15.** Almen versus MBN: (a) RD; (b) TD.

Figure 16 as well as the Pearson's correlation coefficients in Table 6 indicate that the correlation between MBN and SIM for the steel shot is weaker than that for the ceramic shots. The main explanation is linked with the different sensing depth of the XRD and MBN techniques (75  $\mu\text{m}$  for MBN and only 5  $\mu\text{m}$  for XRD). SIM fraction on the near surface in the case of the steel shots saturates early and becomes more developed in the deeper layers beyond the XRD sensing depth. On the other hand, the ceramic shots affect mainly the near-surface and sub-surface region and deeper layers are less affected, resulting in higher correlation coefficients (see also Figure 8a,d). The negative correlation coefficients between the PP and SIM fractions confirm that the reduced gaps among the neighbouring SIM islands makes the magnetic exchange interaction more effective. On the one hand, the correlation coefficients between MBN and the residual stress are high. On the other hand, their negative sign makes them irrelevant since the increasing magnitude of compressive stresses is linked with the stronger MBN emission. This finding makes the correlation coefficient as well as the relationship between MBN and stresses irrelevant due to the positive magnetostriction of Fe and its alloys. Correlation between PP and stress state is mostly weak since this parameter is usually affected mainly by the microstructure and/or external stresses.

**Table 6.** Pearson's correlation coefficients.

|                         | Steel Shots |       | Ceramic Shots |       |
|-------------------------|-------------|-------|---------------|-------|
|                         | RD          | TD    | RD            | TD    |
| MBN versus SIM fraction | 0.76        | 0.88  | 0.98          | 0.88  |
| PP versus SIM fraction  | −0.77       | −0.83 | −0.76         | −0.55 |
| MBN versus stress       | −0.62       | −0.20 | −0.94         | −0.98 |
| PP versus stress        | 0.62        | 0.10  | 0.78          | 0.76  |

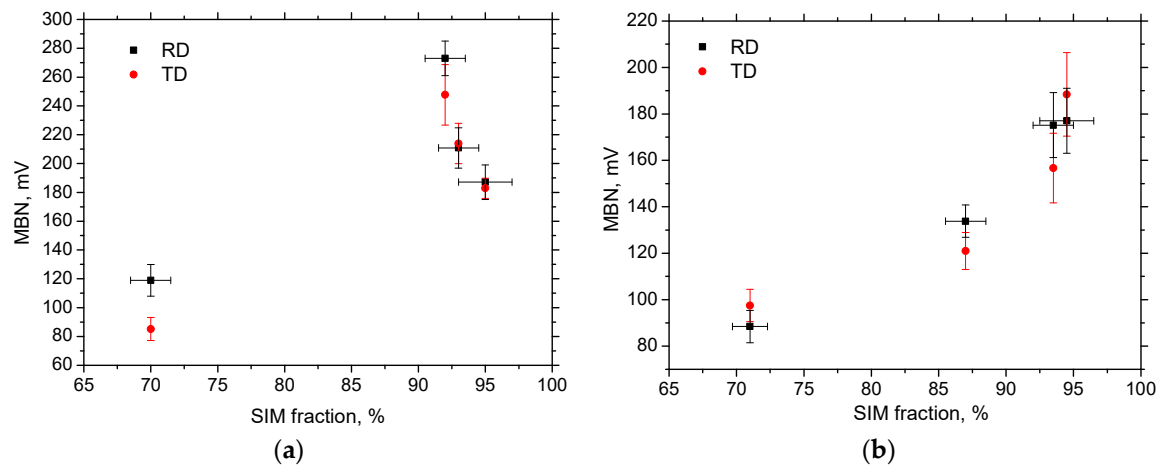


**Figure 16.** SIM fraction versus MBN: (a) steel shots; (b) ceramic shots.

## 4. Conclusions

The main findings of this study can be summarised as follows:

- The use of ceramic shots introduces higher compressive stresses and a higher near-surface dislocation density compared with steel shots.
- The penetration depth at which valuable alterations in stress and microstructure can be observed is much greater for steel shots.
- The kinetic energy of the steel and the ceramic shot is the same, but the ceramic shot's lower mass compensates for its higher velocity.
- MBN increases with SP cycles, and it is stronger for the steel shots due to the greater depth at which the significant SIM fraction is found.
- Ferromagnetic oxides initiated by steel shots cannot be detected after SP with ceramic shots.

**Author Contributions:** Conceptualisation, J.U. and M.N.; methodology, M.N. and M.P.; software, T.K.; validation, P.M.; formal analysis, J.U.; investigation, J.U., M.P., P.M., T.K., M.N. and M.F.; resources, M.N. and J.U.; data curation, M.P. and J.U.; writing—original draft preparation, M.P., M.N. and J.U.; writing—review and editing, J.U. and M.N.; visualisation, M.F.; supervision, M.P.; project administration, M.P.; funding acquisition, M.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors gratefully acknowledge the financial support provided by VEGA project no. 1/0008/25 and KEGA project no. 005ŽU-4/2025.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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