

Article

Monitoring of Steel Road Barrier Flange by the Use of Barkhausen Noise as a Function of Its Yielding

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Abstract

This study investigates the sensitivity of Barkhausen noise emission against the stress state as well as microstructure alterations in the steel road barrier flange. The stress state is altered with respect to its residual state after the tensile test, as well as in the tensile and compression regions during the bending test. In order to provide deeper insight into the relationship between stress states, the Barkhausen noise and magnetostriction along two perpendicular directions is measured as well. The microstructure is expressed in terms of the dislocation density altered beyond the yield point. It was found that the increasing yielding during the tensile test reduces the bearing capacity of the flange as well as the notch toughness, and increases the dislocation density. The Barkhausen noise along the flange length exhibits a continuous descent with yielding due to the increased dislocation density, whereas this emission in the perpendicular direction increases due to the realignment of domain walls. The magnetostriction along the flange length is strong and positive, linked with the increasing Barkhausen noise along the flange length due to the tensile stresses, as contrasted against much the weaker magnetostriction along the perpendicular direction and the reversed evolution of the Barkhausen noise. However, the correlation between the MBN and magnetostriction is not straightforward; the systematic evolution of Barkhausen noise alterations as a function of plastic strain is fully missing.

Keywords: bending test; stress state; microstructure; Barkhausen noise; road flange



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1. Introduction

Road barriers are very important components in road traffic due to their critical role with respect to safety. These barriers can store a lot of impacted energy, and their bearing capacity is not a function of many variables. The bearing capacity as well as deformation behaviour of these barriers are routinely tested using the barrier tests, and their operation, required properties, etc. are usually defined in the national standards and/or technical standards [1–3]. Apart from the flange properties, the bearing capacity of the whole road barrier system depends on such variables as barrier grounding, vehicle mass, its speed, angle of impact, etc. [1,2]. The impacted flanges as well as connected components can be exposed to extreme loading with respect to the heavy mass, high speed, etc. [4,5]. The impacted flanges are usually curved when the impact load exceeds the flange yield point,

together with the removal of the protective Zn layer on their surface. Such flanges have to be replaced with a new one.

On the other hand, the loading of the impacted flange (or more flanges) can be redistributed to the neighbouring flanges (as well as connected components) since these flanges are fixed together via screws [6]. The stress redistribution therefore loads the flanges, which are usually straight after the impact, and this load can also yield the neighbouring flanges. It is well-known that this yield significantly affects the mechanical properties of the neighbouring flanges, considering that the increased yield causes a reduction in further bearing capacity. For this reason, the monitoring of the straight flanges neighbouring the flanges being impacted during the traffic accident is of vital importance with respect to the bearing capacity of the barrier system. Steel road barrier flanges are usually made of low-alloyed steels of variable strength [1]. The surface Zn protective layer provides excellent corrosion resistance in order to ensure the long-term reliable operation of flange barriers in operation without reducing the wall thickness and the corresponding loss of bearing capacity [7,8]. The low-alloyed steels are matrices having a *bcc* lattice containing the magnetic substructure and the corresponding magnetic long-range order resulting in ferromagnetic behaviour, as contrasted against the austenitic steels of the *fcc* lattice being paramagnetic [9]. The ferromagnetism of low-alloyed steels can be potentially used for the implementation of magnetic methods for their monitoring, such as Barkhausen noise (MBN).

Barkhausen noise emission is a well-known physical phenomenon in bodies having magnetic domains and the corresponding domain walls (DWs). The MBN effect can be activated by altering the magnetic field and/or stress state when magnetic domains and the corresponding DWs tend to align along the direction of the exerted magnetic field. However, DW motion is pinned by lattice imperfections and DW sudden motion in the form of irreversible jumps occurs when the magnetic field attains the pinning strength of the pinning sites [10,11]. Irreversible domains as well as DW motion produce electromagnetic as well as acoustic pulses which can be detected on the free surface by a suitable pick-up coil. Systems in the real industry for the monitoring of ferromagnetic steels are usually based on the detection of the electromagnetic components of Barkhausen noise pulses that originated from DWs [12–14]. Electromagnetic pulses originating from magnetic domains are usually about one order weaker, whereas the acoustic component is very often polluted by the surrounding acoustic noise. Furthermore, the acoustic signals very often exhibit quite wrong Barkhausen-noise-to-background-noise ratios.

MBN is sensitive to the stress state as well as microstructure. The positive magnetostriction results in the MBN growing along the tensile stress and decreasing in the compressive regions during external loading [14,15]. However, the role of residual stresses is usually limited due to the prevailing role of the microstructure. The MBN is very often linked with the dislocation density [12], presence and density of precipitates [16], non-ferromagnetic phase [17], grain boundaries [18], etc. The interpretation of MBN signals with respect to microstructure alterations can be complicated in some cases due to the superimposing contribution of the different microstructure features whose partial role is difficult to unravel. MBN signals can also be detected through the non-ferromagnetic layers on the surface of the limited thickness [19]. In such cases, it should be considered that MBN pulses are attenuated during their passing through the non-ferromagnetic layer, and the degree of attenuation mostly depends on the thickness of the layer as well as its physical properties [19].

With respect to road barriers, special attention is nowadays paid to the proposal of a new concept of these components being water or/and foam-filled [4], the usage of new materials of higher strength [20], and their specific design [21]. Moreover, the redistribution

of load during mechanical impact is analysed via modelling or/and barrier crash tests [5,6]. On the other hand, no attention is paid to the monitoring of barriers in use based on a fast non-destructive technique. Visual inspection can reveal damage only in those flanges that are curved, whereas the straight neighbouring flanges could have a reduced bearing capacity as well [5,6]. A suitable technique should provide fast information about flange stressing and/or yielding.

As mentioned earlier, steel road flanges are ferromagnetic bodies, and the MBN technique can be potentially employed for their monitoring, especially with respect to yielding. This study investigates the yielding, the loss of their bearing capacity, and, especially, the sensitivity against the stress state. The main focus of the study, as well as its novelty, can be considered in the investigation of magnetostriction as a function of yielding and the corresponding sensitivity of the MBN against the external load in the tensile as well as compressive regions by the use of a bending test. The study investigates the MBN evolution as well as magnetic anisotropy developed during plastic yielding and correlates these alterations with residual and external stress as well as microstructure alterations expressed mainly in the dislocation density. Such an approach should provide a methodology for the non-destructive monitoring of the employed steel road barrier flange with respect to its yielding as well as its sensitivity to stress in combination with the MBN measurement through the Zn protective layer of constant thickness. The study of magnetic anisotropy indicates the different MBN behaviour along the two perpendicular directions when DW realignment along the progressive yielding results in the non-monotonous evolution of the MBN. The results of this research should be employed for the monitoring of flanges not being directly impacted during traffic accidents, but those being loaded by redistributed stress. These flanges might be yielded and/or under the stress state, which reduces their bearing capacity. Furthermore, this study can be considered as the methodology for the non-destructive monitoring of steel flanges of variable shape and microstructure by the use of the MBN.

2. Materials and Methods

The experiments were carried out on the flange depicted in Figure 1a with a wall thickness of 2 mm. In order to investigate the role of matrix yielding, especially expressed in terms of dislocation density as well as stress state expressed in the residual as well as external load, samples of the gauged shape (total length 175 mm and width 22 mm, with gauged length 50 mm and width 14 mm) were cut from the flange depicted in Figure 1b. The samples were cut off only in the flat regions since the curved regions represent the matrix being yielded during the flange forming. The strips of length 175 mm and width 25 mm were cut using the angle grinder (Bosch, Stuttgart, Germany), and the final shape as well as size were produced by milling cycles. The samples were cut along the length of the flange, and this direction represents the rolling direction (RD), whereas the perpendicular one is abbreviated TD (transversal direction). ND represents the direction along the flange wall thickness (see Figure 2b). The samples were yielded by the uniaxial tensile test in the device Instron 5985 (Instron, Norwood, MA, USA) at a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$. Chemical composition of the flange is indicated in Table 1, and its stress–strain curve is depicted in Figure 1b. Microstructure is composed of equiaxed ferritic grains—see Figure 2a. The Zn protective layer (depicted in Figure 2b) is composed of 2 clearly distinguishable regions. The first one (neighbouring directly with the underlying flange matrix) represents the Zn coating developed during the diffusion process, having the typical columnar appearance. The second one is only the solidified region of liquid Zn covering the underlying Zn coating—see Figure 2b. The flange matrix neighbouring the Zn coating is thermally softened and appears brighter as contrasted against the deeper,

less affected, darker bulk. The samples for metallographic observation were cut along RD, hot-moulded, and routinely prepared for metallographic observation (ground, polished, and etched by 2% Nital for 5 s). Metallographic observations were carried out in the microscope Neophot 32 (Carl Zeiss Microscopy GmbH, Jena, Germany) equipped with the software NissElements 5.42 (Nikon, Amstelveen, The Netherlands).

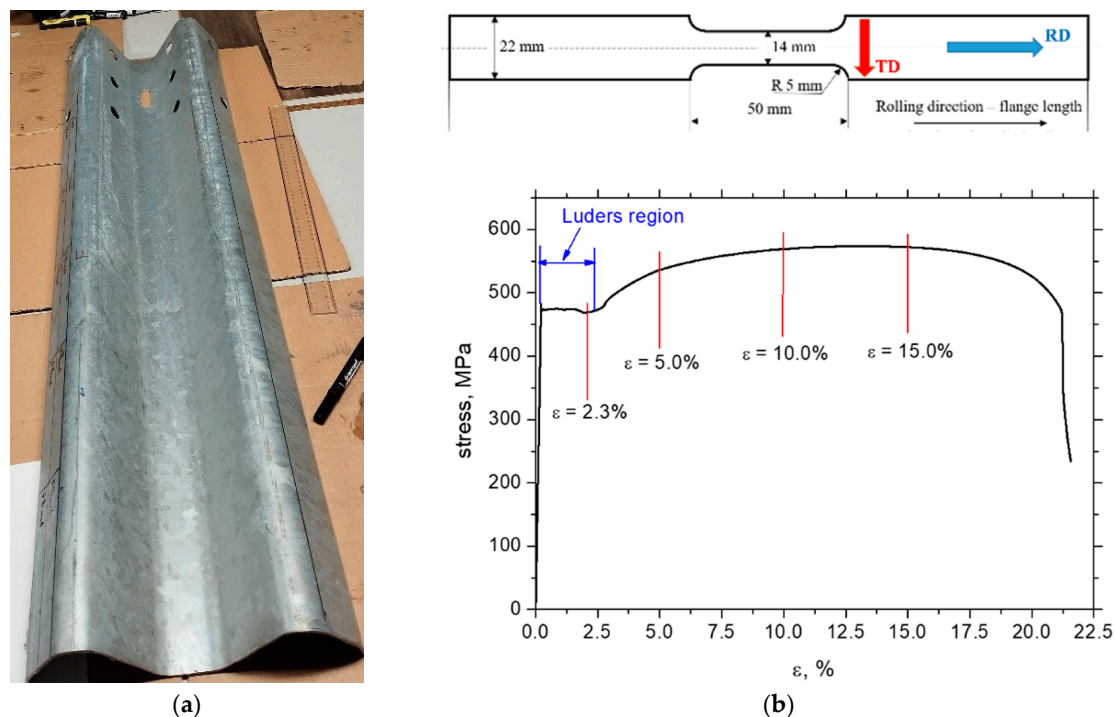


Figure 1. Investigated flange and stress–strain curve with indicated sample for tensile test: (a) investigated flange of width 305 mm, and (b) stress–strain curve and sample for tensile test.

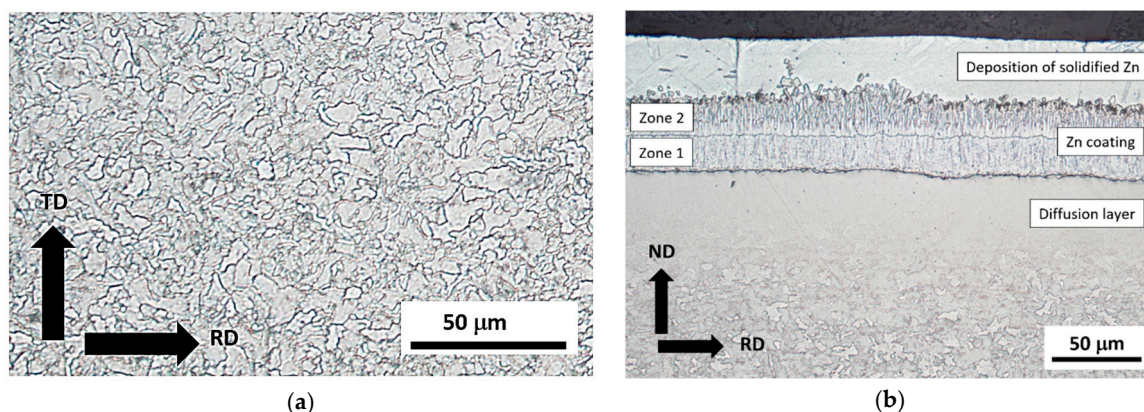


Figure 2. Microstructure of the investigated flange and the surface Zn protective layer: (a) bulk microstructure, and (b) Zn protective layer in the as-received state.

Table 1. Chemical composition of investigated steels in wt%.

Fe	C	Mn	Si	P	S	Al	Nb + Ti
bal.	0.08	1.1	0.02	0.008	0.02	0.04	0.1

Hardness HV_{10} was measured using the Falcon 450 device (Innovatest Europe BV, Maastricht, The Netherlands) (3 repetitive measurements). Charpy V-notch test (Zwick-

Roell, Ulm-Einsingen, Germany) (measurement of $KCV_{.2}$) was carried out on the samples of length 55 mm in accordance with the corresponding ISO standard EN ISO 148-1 [22].

Dislocation density as well as residual stresses were determined from the XRD patterns using Proto iXRD Combo diffractometer (diffractometer (Proto Manufacturing Ltd., LaSalle, ON, Canada) ($CrK\alpha$ radiation, Bragg angle 156.4°). XRD was measured on the surface without the Zn layer being electrolytically etched off. The residual stress was calculated from shifts of the 211 reflection (Winholtz and Cohen method, elastic constants $\frac{1}{2}S_2 = 5.75 \text{ TPa}^{-1}$, $S_1 = -1.25 \text{ TPa}^{-1}$). Dislocation density δ was calculated on the basis of the XRD peak width ($FWHM$ —full width at half maximum) as follows:

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

where D is crystallite size calculated via (2):

$$D = \frac{K \cdot \lambda}{\beta \cdot \cos \theta} (\text{nm}) \quad (2)$$

where K is the constant (0.89), λ is the X-ray wavelength ($2.291 \text{ \AA}$), $\beta = FWHM$, and θ is equal to the Bragg angle mentioned above.

MBN emission was measured using RollScan 350 and software MicroScan 5.4.1 (magnetising frequency 125 Hz of the sine profile and the magnetising field $\pm 9.8 \text{ kA} \cdot \text{m}^{-1}$, sampling frequency 6.7 MHz, serial MBN sensor S1-18-12-01). MBN is the effective value of detected pulses obtained in the frequency range from $20 \div 1000 \text{ kHz}$. MBN signals were also used for the analysis of MBN envelopes and quantification of magnetic hardness expressed in terms of PP (magnetic field in which the MBN envelope attains the maximum).

MBN was measured as a function of tensile as well as compressive stresses by the use of a bending test. The employed amplitude of stresses was set in the region of elastic stresses. The samples for MBN as well as $HV10$ measurements, determination of residual stress, dislocation density, and microstructure observations were yielded on the plastic strains indicated in Figure 1b. The yielded samples were also used for the bending test in order to investigate the sensitivity of MBN against the stress state as a function of sample yielding. MBN during bending was measured along RD as well as TD directions. MBN during the bending test was measured via the Zn protective layer, whereas XRD and magnetostriction measurements were carried out directly on the steel matrix when the Zn layer was etched off.

The bending test was carried out in the self-made device in which the sample was clamped between two plates—see Figure 3a. The stress state was monitored using the strain gauge HBM 6/120 LY11 (Brüel & Kjaer, Darmstadt, Germany) mounted on the opposite side of the sample (Zn layer etched off—the strain gauge fixed directly on the Fe matrix). Amplitude of the stress was developed by the use of the loading screw, and direction of the stress (tensile or compressive) was altered by altering the load screw position in the device—see Figure 3b. Information about the stress state was detected in the software DasyLab2016. The elastic region of $\pm 400 \text{ MPa}$ was set on the basis of the stress–strain curve depicted in Figure 1b. The conversion of signal in mV into MPa was obtained via multiplying by the constant $\text{const} = 4E/k$, in which E is the elastic modulus of the steel and k is the strain-gauge factor (1.97 in this particular case).

Magnetostriction λ was measured along RD (λ_{RD}) as well as TD (λ_{TD}) on small specimens of size $25 \times 20 \times 2 \text{ mm}$ when the direction of the magnetic field followed RD. The Zn layer was etched off, and the gauge as referred above was fixed on the surface. The sample was fixed on the auxiliary non-ferromagnetic plate between two coils of the device Phylatex Physic Gerate (PPG, Frankenberg, Germany), generating the uniaxial magnetic

field controlled by the voltage source XG100-15 (Sorensen, Oakley, Bedfordshire, UK). Data about the magnetising current was measured using the Tektronix A622 AC/DC current probe (Tektronix, Beaverton, OR, USA) and converted into the magnetic field strength (stored together with the information about magnetostriction in DasyLab 2016, sampling frequency 1000 Hz).

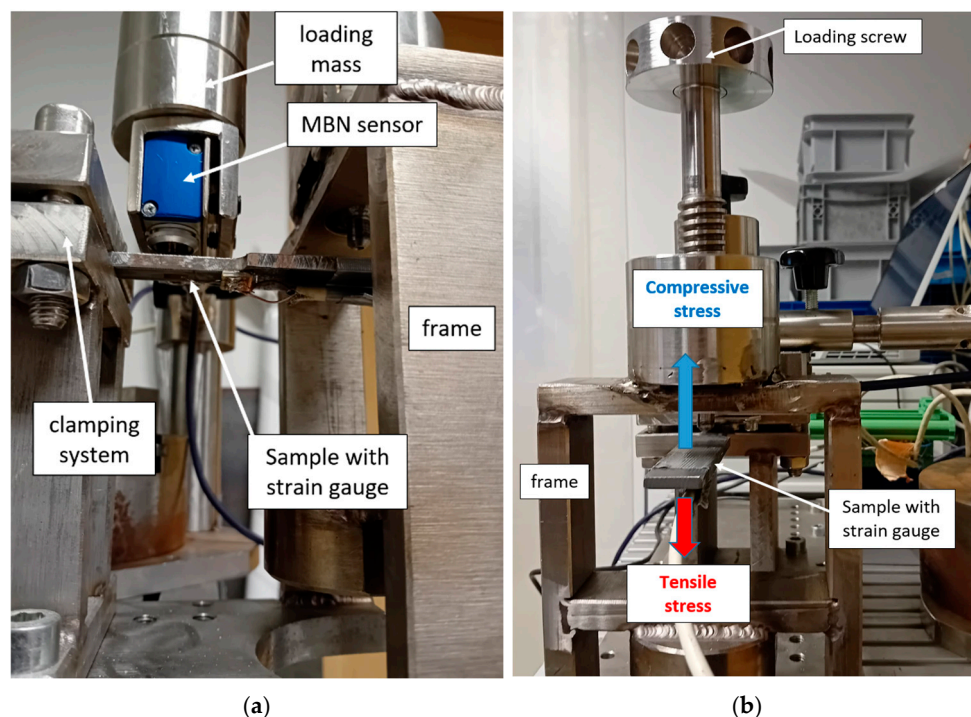


Figure 3. Sample fixed in the self-made device during the bending test: (a) side view, and (b) front view.

Six samples (as those depicted in Figure 1b) were yielded for each plastic strain. Three samples were used for the measurement of MBN, HV_{10} , and δ , as well as λ , and three yielded samples were broken during the KVC_2 measurement. The error bars represent the standard deviations associated with the repetitive measurements. Taking into account the real flange load, the experimental plan is based on the flange microstructure as well as stress alterations as a function of plastic yielding ϵ in the region of homogenous strains (as those depicted in Figure 1b). The first yielding is placed in the Luders' region and represents the phase of limited dislocation multiplication, followed by the regularly separated homogenous plastic strains and the corresponding strain hardening due to dislocation multiplication. The further constant process parameters are listed in Table 2. Figure 4 depicts the methodology framework with investigation steps for easier navigation through the paper.

Table 2. Constant process parameters.

Thickness of Zn protective layer	about 80 μm
Strain rate	$1 \times 10^{-3} \text{ s}^{-1}$
Temperature	22 $^{\circ}\text{C}$
Direction of sample cut off	RD

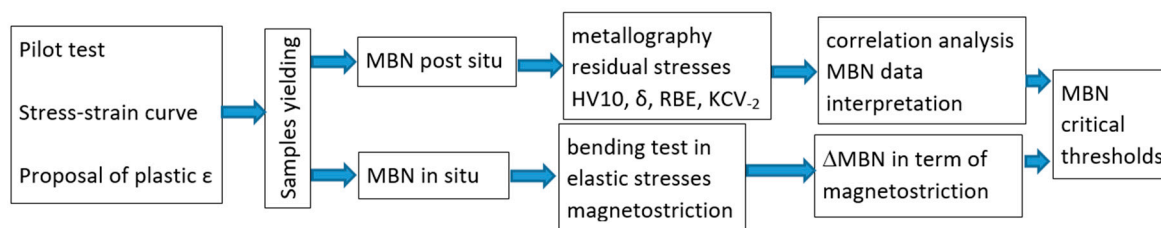


Figure 4. Short methodology framework figure with investigation steps for easier navigation through the paper.

3. Results of Experiments and Their Discussion

3.1. Metallographic Observations, HV10, KCV₂ and XRD Measurements

As mentioned above, the Zn protective layer is composed of two distinguishable regions. The first one is lying directly on the flange surface and represents the typical Zn coating region produced during the diffusion process in the Zn bath. This region has the typical columnar appearance [7,8] of a thickness of $44.7 \pm 4.3 \mu\text{m}$. Figure 2b, as well as Figure 5, clearly demonstrate that this region also exhibits two separable zones whose origin is not known. The thickness of the Zn solidified layer is $34.4 \pm 2.7 \mu\text{m}$, and this duplex system prolongs the matrix protection against corrosion by 1.2 to 2.5 times [7].

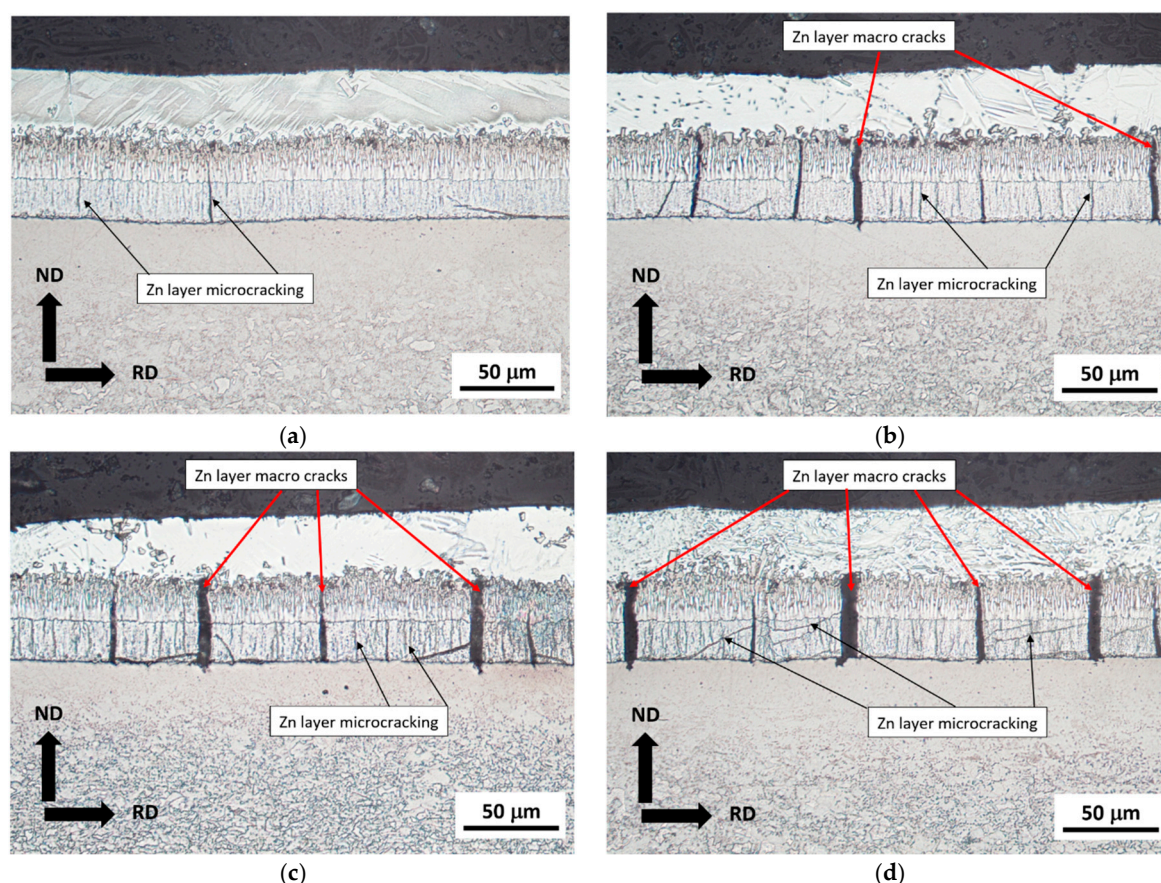


Figure 5. Cracking of the protective Zn layer as a function of yielding: (a) $\epsilon = 2.3\%$, (b) $\epsilon = 5.0\%$, (c) $\epsilon = 10.0\%$, and (d) $\epsilon = 15.0\%$.

Figure 5 clearly demonstrates that the first layer is more or less firmly connected with the steel matrix because, during the flange yielding, its microcracking is transformed into macrocracks. This figure also depicts the contrast against the flange steel plasticity and brittle behaviour of the Zn layer. While the steel matrix exhibits no visible cracks

during the whole investigated yielding, Zn layer microcracking is initiated early beyond the yielding. The density of the microcracks increases along the progressive yielding, and some microcracks are transformed into the macrocracks of increasing size—see Figure 5. The increasing density of microcracks along the steel matrix yielding corresponds with the increasing density of macrocracks since the microcracks represent a preliminary phase for the macrocracks. Furthermore, the microcracks that are formed early along TD become tilted closer to the RD at higher plastic strains (see especially Figure 5d). The density of microcracks in zone 1 is higher, which indicates that the stress in zone 1 is not fully transmitted into zone 2. Moreover, zone 2 exhibits nearly no longitudinal and/or tilted microcracks. The full lack of stress transmission into the second layer indicates no cracking of the solidified Zn layer—see Figure 5.

While the response of the Zn layer on the flange yielding is its brittle cracking, the steel's matrix exhibits the accumulation of dislocation density δ and the corresponding growth in hardness $HV10$ —see Figure 6a. Dislocation multiplication is a typical mechanism of low-alloyed steels' response to stress above the yielding limit [23,24]. The very good correlation between $HV10$ and δ confirms (see Figure 6b) that the increasing $FWHM$ of the XRD peaks is mainly a function of δ in this type of steel as reported earlier [25]. On the other hand, matrix yielding is quite limited, and the ratio between the ultimate σ_u and yield strength σ_y is low (σ_u/σ_y is only 1.2). Due to the higher strength of the employed steel as well as its corresponding fine-grained structure, the dislocation path, as well as the corresponding degree of dislocation accumulation, is limited. For this reason, the increase in $HV10$ as well as δ in the only medium corresponds to the limited dislocation hardening beyond the yielding—see Figure 1b.

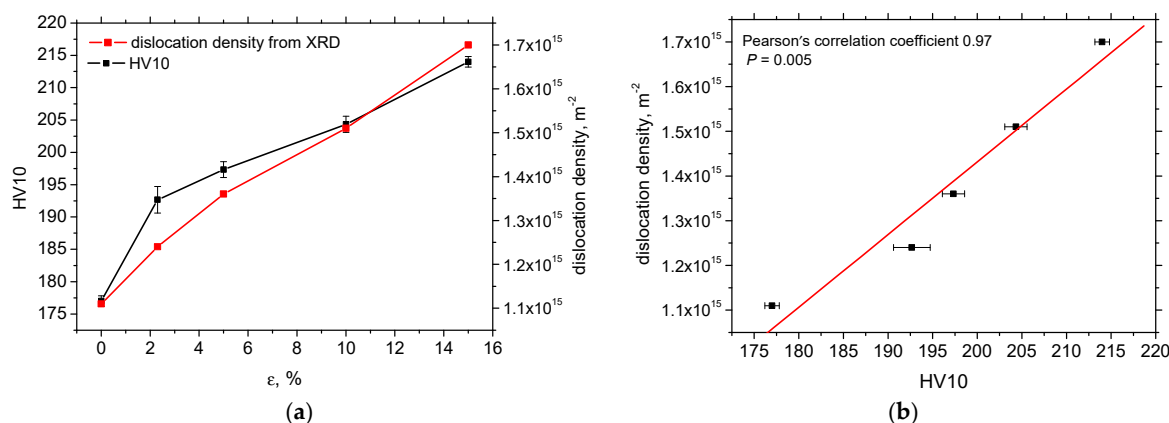


Figure 6. Evolution of hardness $HV10$ and δ , as well as their correlation: (a) $HV10$ and δ as a function of yielding, and (b) correlation between $HV10$ and δ . Note: The uncertainties with respect to δ oscillate in the range of 2.85×10^{11} up to 1.14×10^{12} .

The progressive yielding of the flange steel matrix consumes the energy which can be stored in the further plastic work due to the limited dislocation-free path as well as their density. The residual bearing energy (RBE) is an important factor of the whole flange when the flange is impacted during road traffic [1]. RBE can be calculated as follows:

$$RBE = \int_0^{\epsilon_y} \sigma d\epsilon + \int_{\epsilon_i}^{\epsilon_b} \sigma d\epsilon \quad (\text{kJ}) \quad (3)$$

where ϵ_y is the strain at yield strength, ϵ_i is the plastic strain in which RBE is calculated, and ϵ_b is the plastic strain in which the sample breakage occurs. Figure 7a illustrates that the RBE progressively dropped down together with the notch toughness expressed in terms of KCV_{-2} . However, the significant reduction in RBE is contrasted against the less valuable

decrease in KCV_{-2} due to the limited dislocation hardening and the corresponding low σ_u/σ_y as mentioned earlier. Despite this different sensitivity, the correlation between RBE and KCV_{-2} is good, as depicted in Figure 7b. One might argue that the different sensitivity between RBE and KCV_{-2} is due to the quasi-static load during the tensile test and the corresponding RBE , whereas the KCV_{-2} is the dynamic measure. However, $HV10$ and δ , as quantities extracted from the tensile test, exhibit a low degree of alteration.

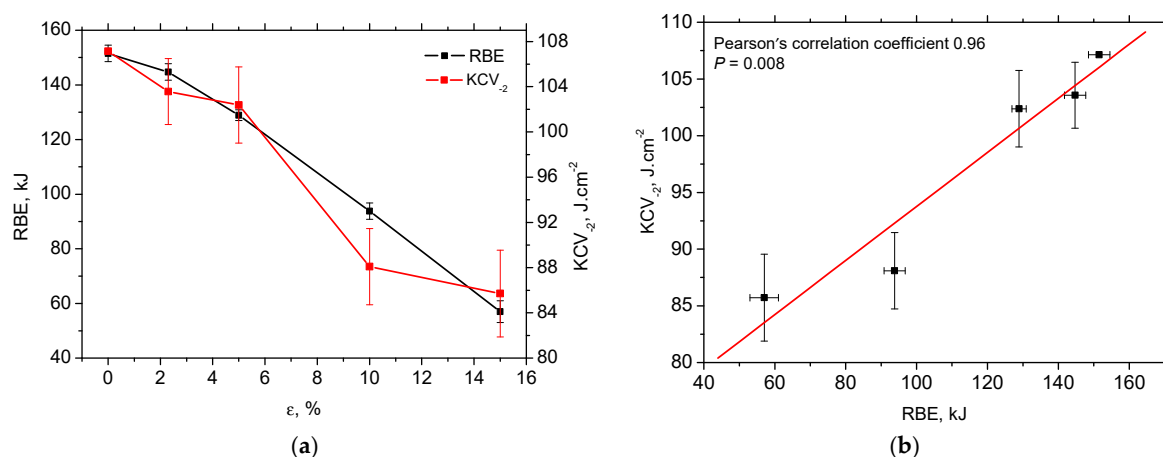


Figure 7. Evolution of RBE and KCV_{-2} as a function of yielding and their correlation: (a) RBE and KCV_{-2} as a function of yielding, and (b) correlation between RBE and KCV_{-2} .

The residual stresses along RD and TD are compressive. The residual stresses along RD do not exhibit a significant change. The gentle growth with ϵ is mostly within the standard deviation. The residual stress in TD beyond the yielding exhibits a steep increase in the magnitude, followed by the phase of nearly unaffected stresses at the higher ϵ —see Figure 8.

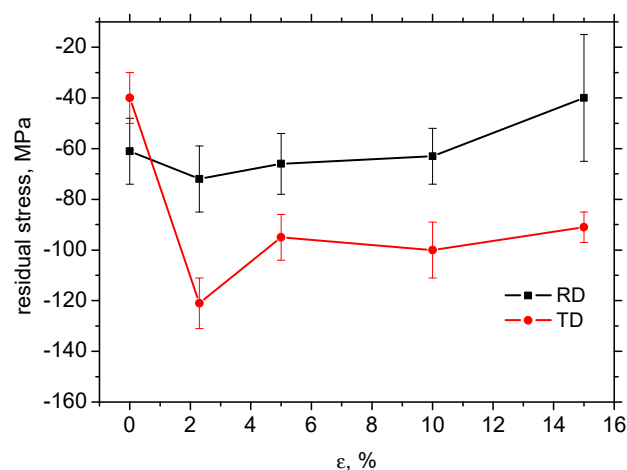


Figure 8. Evolution of residual stresses along RD and TD as a function of yielding.

3.2. MBN as a Function of Residual Stresses, Dislocation Density, and DW Alignment

The MBN is measured through the Zn protective layer on the flange surface. As was reported earlier [19,26], a non-ferromagnetic layer on the ferromagnetic body makes the MBN weaker depending on the thickness of the non-ferromagnetic region, especially the weakening of the magnetising field as well as the attenuation of MBN pulses during their propagation through the non-ferromagnetic surface [27,28]. Figure 5 depicts that the gap between the sensor and the ferromagnetic matrix of the flange is more or less constant with respect to the progressive yielding (the total gap is about 80 μm) and the alterations

in the MBN, as those depicted in Figures 9–11, should be linked with the microstructure alterations with respect to its yielding.

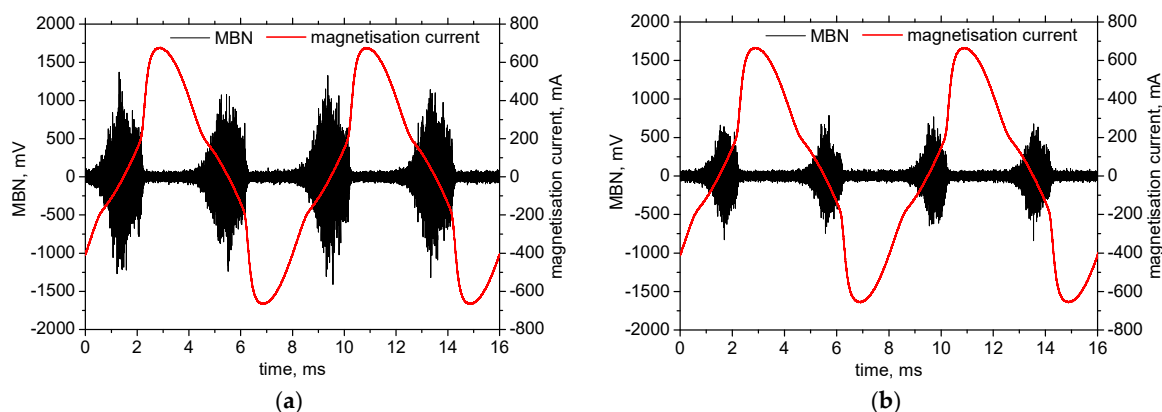


Figure 9. MBN filtered signals in RD: (a) 0%, and (b) 15%.

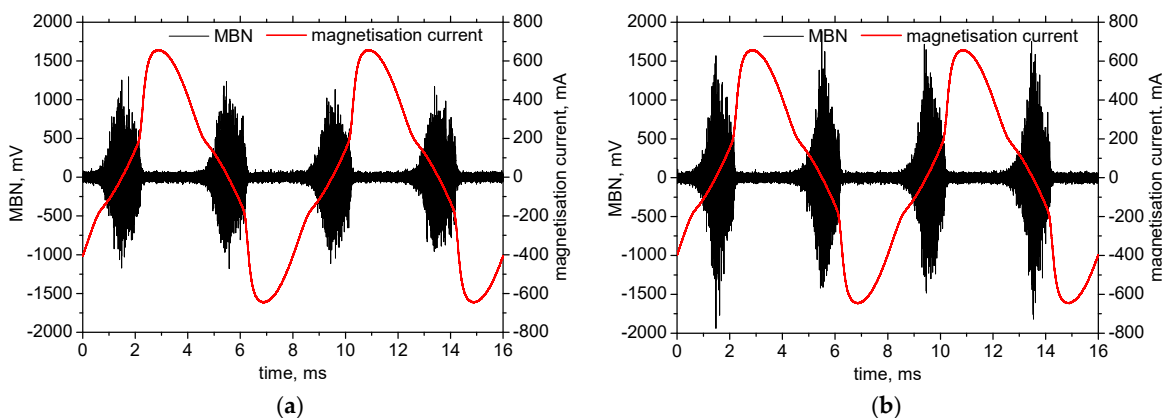


Figure 10. MBN filtered signals in TD: (a) 0%, and (b) 15%.

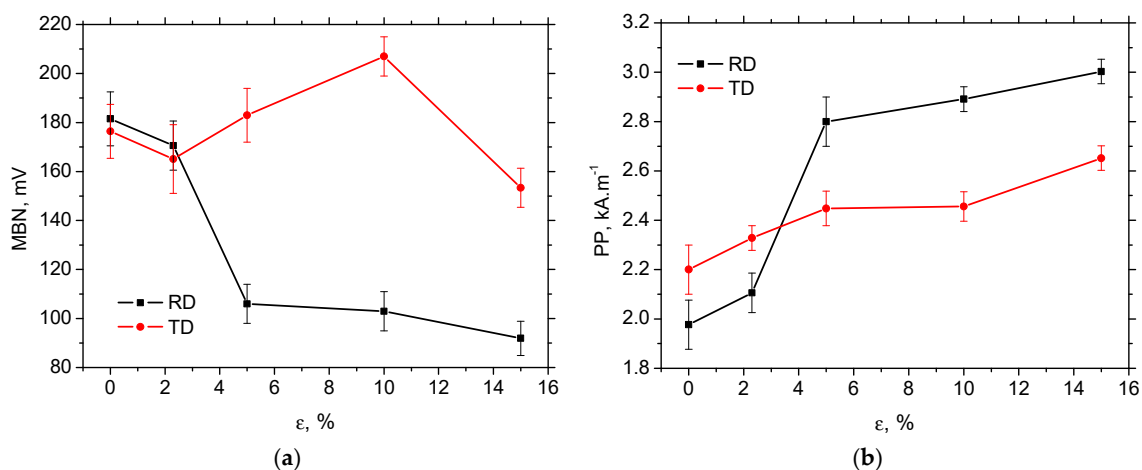


Figure 11. MBN and PP as a function of yielding; (a) MBN, and (b) PP .

The increasing dislocation density takes a major role in hindering DWs in motion as well as their free path of motion [12,29]. For this reason, the MBN in RD drops down (see Figures 9 and 11) continuously, and the moderate decrease in Luder's region ($\epsilon = 2.3\%$) can be contrasted against the much steeper decrease for the $\epsilon = 5.0\%$ (followed by the moderate decrease for the highest ϵ). This effect is compensated for by the DW realignment into TD as reported earlier [30] when the MBN in TD exhibits valuable growth for $\epsilon = 5.0$ and

10.0%, followed by a visible decrease for $\varepsilon = 15.0\%$ afterwards—see Figures 10 and 11 (this drop down is a result of the high dislocation density pinning the realigned DWs). This paragraph, therefore, indicates that the MBN is mainly a function of the dislocation density and the superimposing DW realignment. While the dislocation density does not depend on the direction of measurement, DW realignment takes a strong role in the developed magnetic anisotropy when the evolution of the MBN along RD and TD is different—see especially Figure 11a.

The increasing dislocation density also proves the growing *PP*—see Figures 11b and 12. *PP* progressively grows with the yielding since the stronger field is necessary to initiate irreversible DW jumps as a result of the growing opposition to the matrix containing the increasing dislocation density. For this reason, the MBN is shifted towards the stronger magnetic field—see Figure 12. The less steep growth of *PP* in TD is due to the compensational effect of DW realignment into TD, which plays the main role in the lower magnetic hardness—see Figure 11b. The role of residual stresses is only minor when the nearly unaffected stresses, depicted in Figure 8, are confronted with the MBN evolution in Figure 11a. The summing correlation analysis based on the MBN and *PP* on one side and residual stress, *RBE*, *HV10*, *KCV₂*, and δ on the other side can be found in Table 3. It is worth noting that the microstructure quantities (*HV10*, δ , *RBE*, and *KCV₂*) listed in Table 3 are related to each other. For this reason, the correlation coefficients for *HV10* are similar to those for dislocation density δ since *HV10* and δ are closely related in the ferritic steels (see Figure 6b). Furthermore, Figure 7b clearly proves a close correlation between *RBE* and *KCV₂*, resulting in the similar Pearson's correlation coefficients listed in Table 3.

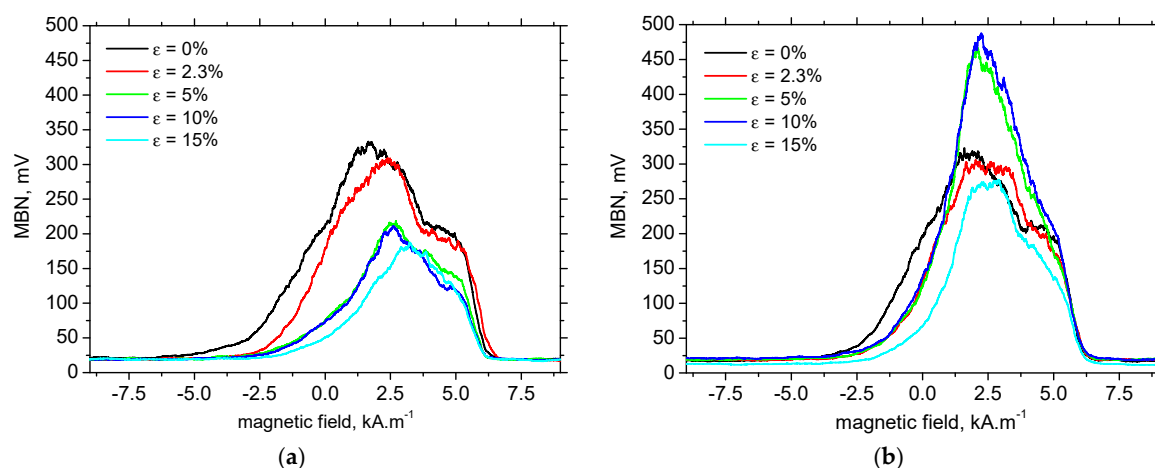


Figure 12. MBN envelopes as a function of yielding: (a) along RD, and (b) along TD.

Table 3. Pearson's correlation coefficients. Note: RS means residual stress.

	<i>HV10</i>	δ	<i>RBE</i>	<i>KCV₂</i>	RS in RD	RS in TD
MBN in RD	−0.89	−0.90	0.85	0.81	−0.52	0.35
MBN in TD	−0.10	−0.10	0.14	−0.06	−0.46	0.01
<i>PP</i> in RD	0.90	0.91	−0.85	−0.83	0.54	−0.35
<i>PP</i> in TD	0.97	0.97	−0.93	−0.86	0.69	−0.44

3.3. MBN as a Function of Elastic Stresses During Bending in Terms of Magnetostriction

The evolution of the MBN during bending, when the external stress is altered in the range of elastic stresses ± 400 MPa, is depicted in Figures 13 and 14. Due to the positive magnetostriction along RD λ_{RD} (see Figure 15) in the lower magnetic fields (as related to the DW jumps), the MBN along RD is dropping down in the region of increasing compressive

stresses, as contrasted against the increasing MBN in the tensile region. However, the MBN exhibits a continuous decrease in the region of compressive stresses, whereas the growing phase in the tensile region is followed by the saturation of MBN and its decrease at the higher magnitude of the stresses—see Figure 14a. The local maximum occurs at the higher tensile stresses for the higher strains.

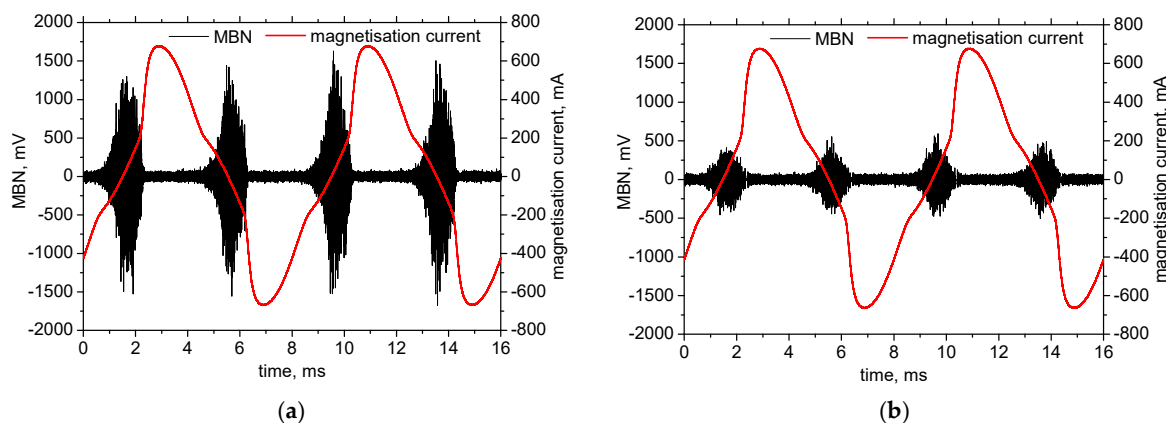


Figure 13. MBN filtered signals along RD for $\varepsilon = 2.3\%$: (a) +400 MPa, and (b) −400 MPa.

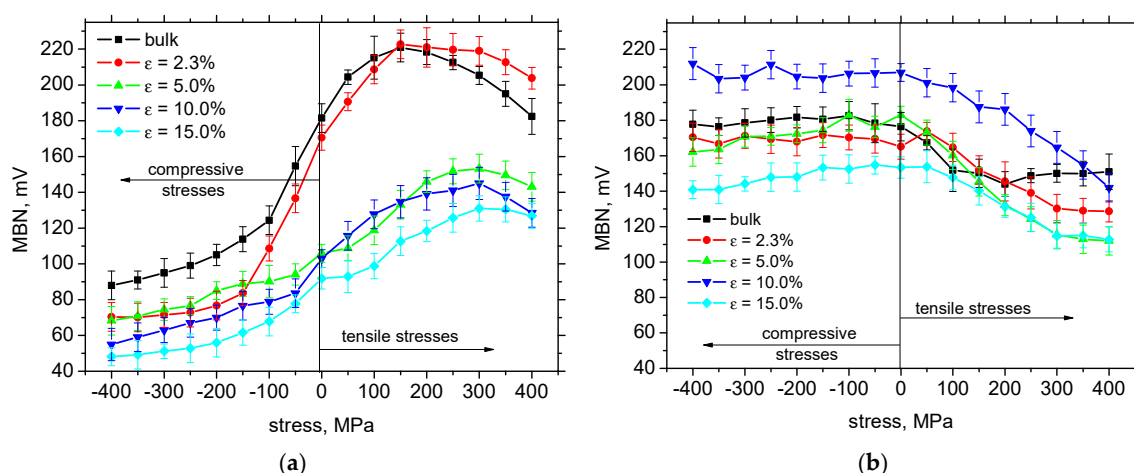


Figure 14. MBN as a function of external stress: (a) along RD, and (b) along TD.

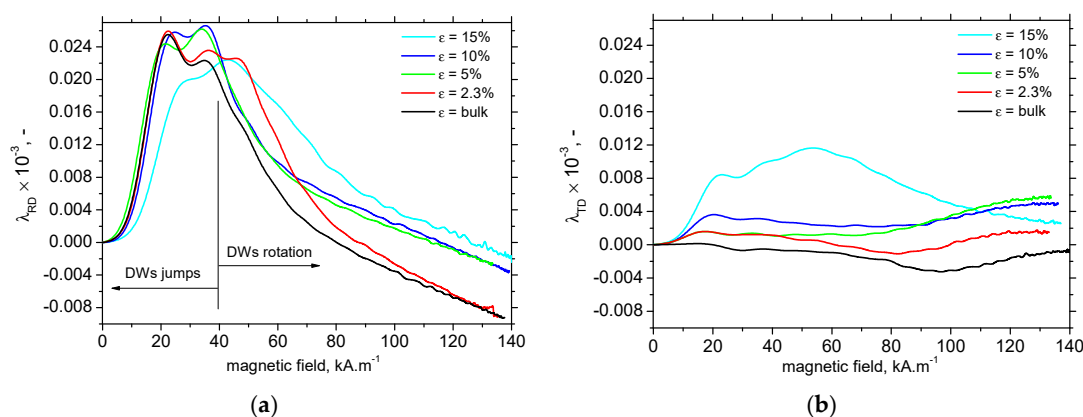


Figure 15. Evolution of λ_{RD} and λ_{TD} as a function of yielding: (a) RD, and (b) TD.

The evolution is reversed when the MBN is measured along TD. Apart from the moderate decrease for $\varepsilon = 15\%$, the MBN is nearly unaffected for the lower strains within the compressive stresses, whereas the MBN drops down in the tensile region. This drop

saturates for the lower ε , but the continuous decrease can be obtained when the declared DW realignment and MBN growth occur—see Figures 11a and 14b.

The evolution of the MBN along with elastic stresses is driven by magnetostriction as well as magneto-crystalline anisotropy and their competition. The energy of magnetocrystalline anisotropy E_a can be expressed by the use of the following equation [11]:

$$E_a = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) \quad (4)$$

where α_1 , α_2 , and α_3 are the direction cosines of the magnetisation vector and K_1 and K_2 are the magnetocrystalline anisotropy constants.

Magnetoelastic energy E_σ is strongly dependent on magnetostriction λ [11]:

$$E_\sigma = (-3\lambda\cos^2\varphi)/2 \quad (5)$$

where λ is the magnetostriction and φ is the misalignment between the magnetic field direction and stress direction of magnitude σ .

Figure 15a depicts that the positive magnetostriction in RD at the lower magnetic fields is reversed at the higher ones. Such behaviour is explained by the difference between the DW motion when the ascending phase is linked with the DW irreversible motion, followed by the descending phase linked with the DW rotation in Fe and its alloys [11]. Figure 15b also depicts that λ_{RD} is nearly unaffected along with variable ε . However, when the magnetostriction is measured along TD, the initial very weak negative magnetostriction is reversed into the positive λ_{TD} growing along ε due to the DW realignment into TD (and its growing degree with ε)—see Figure 15b.

The correlation between the MBN (and its alteration with stress) and magnetostriction is not straightforward in this particular case. Figure 16a demonstrates that the systematic evolution of ΔMBN as a function of ε is fully missing. One might only distinguish that the high λ_{RD} can be linked with the high ΔMBN in RD and the much lower λ_{TD} can be linked with the lower ΔMBN in TD. ΔMBN as a function of elastic stress is therefore driven by many aspects, and magnetostriction (in this particular case) is only a superimposing factor together with the alteration in dislocation density and/or DW alignment—see Figure 16b. Note that ΔMBN is arbitrarily set to be positive when the MBN is growing in the direction from the compressive towards the negative stresses. However, their clear contribution is difficult to unwarp, especially due to the close correlation between magnetocrystalline anisotropy and magnetostriction [11]. The complex visualisation of the influence of the input experimental parameters on the observed responses can be found in Figure 17.

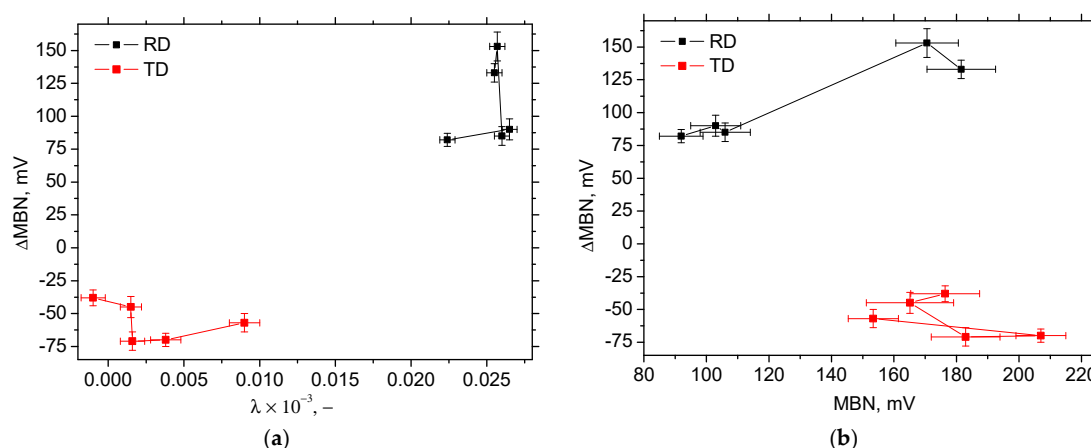


Figure 16. λ_{RD} and λ_{TD} versus ΔMBN and MBN versus ΔMBN : (a) λ_{RD} and λ_{TD} versus ΔMBN , and (b) MBN versus ΔMBN .

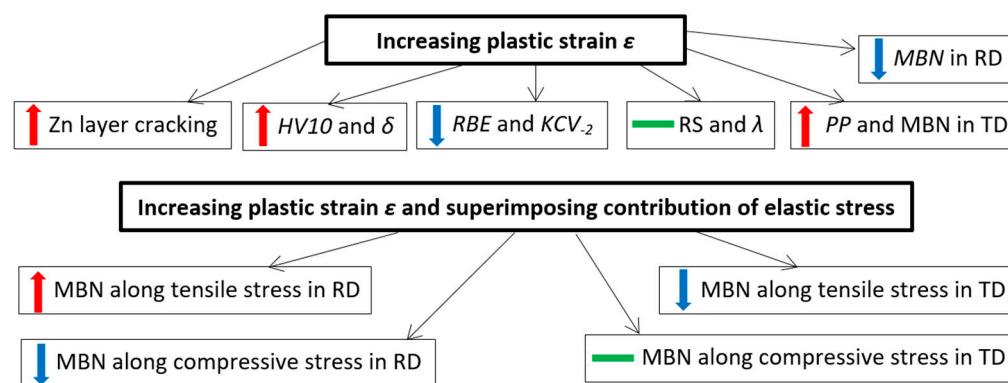


Figure 17. Visualisation of input experimental parameters influences on observed responses, (red arrow—ascending evolution, blue arrow—descending evolution, green line —nearly unaffected).

4. Conclusions

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

- The flange yielding initiates the Zn protective layer microcracking, which transforms into the macrocracks along the progressive yielding;
- The flange yielding increases the matrix dislocation density and reduces RBE as well as KCV_{-2} ;
- MBN along RD exhibits a continuous decrease due to the growing dislocation density, as compared with the increasing MBN in TD due to the DW realignment;
- MBN is descending along RD when the amplitude of compressive stresses grows, but this growth in the region of tensile stresses is saturated, in contrast to the reversed evolution along TD;
- λ_{RD} is positive and nearly unaffected by ϵ , whereas the bulk λ_{TD} is negative and reversed into positive with ϵ ;
- Strong magnetostriction is linked with a positive ΔMBN and vice versa.

The monitoring of the investigated flange by the use of the MBN technique needs the proposal of suitable Barkhausen noise parameters and their critical thresholds. Table 3 clearly demonstrates that the MBN is mainly a function of the microstructure features (highlighted in yellow) such as $HV10$, δ , RBE , and KCV_{-2} , especially along RD. PP in TD also exhibits good Pearson's confidence, but its growth is less valuable as compared with RD—see Figure 11b. It is therefore reasonable to carry out the measurement of the MBN along RD. When the flange is yielded in the Luder's region, the MBN drop along RD is only limited together with RBE (the regions overlap with respect to standard deviations), as well as the Zn protective layer cracking—see Figures 5a, 7a and 11a. For this reason, it is proposed that we monitor the investigated flange using the MBN (its effective value). The monitoring of the flanges' yielding and stressing by the use of the MBN is based on the data obtained in chapters 3.2 and 3.3. Flange yielding can be easily recognised by the increasing PP along RD, whereas its loading by tensile stress can be measured via the increasing MBN—see Figures 11b and 14a. All flanges (as with those depicted in Figure 1a of the Zn layer thickness about 80 μm) emitting PP below $2.2 \pm 0.1 \text{ kA.m}^{-1}$ and MBN above $160 \pm 11 \text{ mV}$ in RD should be approved for further use (these thresholds are valid when RollScan 350 and sensor S1-18-12-01 are employed under the magnetising conditions listed above). These thresholds correspond to the MBN and PP within Luder's region (see Figure 1b), in which dislocation multiplication does not take place, and the corresponding matrix alterations are very limited. As soon as the steel road barrier microstructure, shape, and Zn layer thickness are altered and/or magnetising conditions (including sensors and measuring device) differ from those listed in this study, the critical thresholds would differ

from those mentioned above, and a new calibration procedure (similar to that presented in this study) should be carried out.

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