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Selected Results of the Assessment of the Straightening Process of Steel Sheets Using the Barkhausen Noise Method

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The paper presents selected results of the assessment of straightening processes of steel sheets and plates in terms of monitoring changes in mechanical residual stresses. For the stress investigation, a method based on magnetic Barkhausen noise measurements was applied, and the custom measuring set-up was used. The study examined two different technological processes of leveling, based on tension for thin metal sheets and three-point overbending of thicker plates. The results are presented graphically in the form of directional diagrams of Barkhausen noise, as well as vectors representing orthogonal principal stresses in the cross-section plane. In general, an unfavorable stress state was observed on the opposite sides of the investigated sheets in the initial condition. The applied straightening operations resulted in a significant redistribution of residual stresses, in terms of both magnitude and sign.

topics: Barkhausen noise, residual stress, straightening process, steel sheet

1. Introduction

One of the key factors in modern steel sheets and plates processing is their flatness and reduced residual stress levels [1]. These quality parameters, related to the geometry and mechanical properties of workpiece products, significantly affect the efficiency of automated technological processes such as laser cutting, shaping with a press brake, rolls, or robotized welding [1, 2]. For example, the relaxation of internal stresses during the forming of long C-section members (i.e., members with a C-shaped cross-section) causes edge waviness or longitudinal curvature [3].

Residual stresses in steel sheets originate from several technological factors during production, including non-uniform roll bite geometry in the finishing stands, causing thickness variations across the strip width, as well as uneven heat-transfer conditions after cooling or coiling [4, 5]. If these stresses exceed the buckling strength limits of the material, they are released partially, and the strip will usually become wavy at the edges or bulge in the center after unwinding. Standard technological operations aimed at improving geometric parameters typically have an unfavorable effect on residual stresses, causing them to increase again. Therefore, ongoing research and development efforts focus on improving the straightening of flat products during production, considering flatness alongside residual stresses.

For ferromagnetic steels, the magnetic Barkhausen noise (MBN) method is a useful tool for evaluating leveling processes in terms of residual stress levels [6–8]. This relatively quick, safe, and simple non-destructive technique enables assessment of the effectiveness of various straightening methods, such as bending or stretching, by mapping changes in the near-surface stress state before and after treatment. It relies on physical phenomena associated with the magnetization process under an alternating magnetic field [9]. In contrast to other commonly used non-destructive techniques, such as X-ray diffraction or ultrasonic testing, which are based on measuring stress-induced changes in material properties (lattice spacing and sound velocity, respectively) [10, 11], the MBN method is an emission-based technique that measures characteristic voltage noise induced in the coil by microscopic magnetic flux fluctuations during magnetization. This effect is associated with discontinuous Bloch wall motion as magnetic domains align with the applied magnetic field and was first reported in 1919 by the German physicist H. Barkhausen [12]. In general, the microstructure (type, dislocation density) and chemical composition, as well as the magnetic field

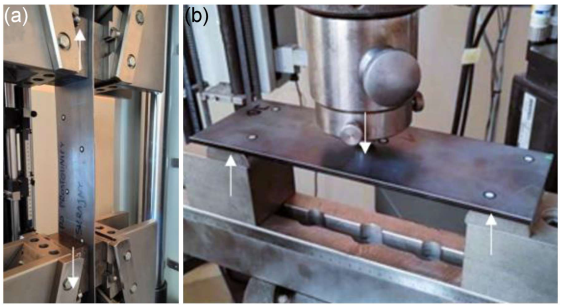

Fig. 1. Straightening process of (a) a thin sheet by tension and (b) a plate by the three-point bending.

strength H and the mechanical stress σ acting on the magnetic structure, are critical factors determining the Barkhausen phenomenon. Its intensity typically increases under tensile stress and decreases under compressive stress; this dependence forms the basis of the measurement method [13]. As a measurable parameter of MBN magnitude, the root mean square (RMS) value is commonly used and serves as an indicator of stress level. Although quantitative stress measurement requires determining calibration characteristics $\sigma = f(\mathrm{RMS_{MBN}})$ while maintaining the complementarity of the microstructure of the calibration samples and the tested component [14], as well as the magnetization conditions during calibration and on-site testing, for assessing the magnitude or transformation of stresses, it is often sufficient to interpret changes in the RMS value of MBN, presented in the form of directional diagrams [15]. Such a diagram illustrates the angular distribution of MBN measurements as a function of the magnetization direction, which can be interpreted and analyzed in terms of a stress ellipse — a geometric representation of the plane stress state.

A similar approach was employed in this work to assess the stress state in sheet metal samples before and after straightening, relying both on the calibration characteristics to determine stress values quantitatively and on a general evaluation of changes in the RMS value of the Barkhausen noise.

The relatively small measurement depth of the applied method (typically a few hundred micrometers) is a positive feature for the investigated sheets, as it enables the detection and analysis of differences in stress states between the opposite surfaces.

2. Experiments

The conducted research and development works on the straightening processes involved simulating in scale real industrial operational conditions using testing machines *Zwick Z200* and *Zwick Z100* equipped with dedicated instrumentation. In the first case, the presented results concern the straightening of thin sheets by tension (Fig. 1a) close to the yield point, corresponding to fine tension leveling of a several-meter-long sheet metal strip after preliminary roller leveling and before cutting into commercial sheets [16]. The second case focuses on thicker plates deformed by three-point bending, using a stamp leveler (Fig. 1b) as an equivalent to hydraulic-press leveling of massive laser-cut components made from thick plates, which is required prior to welding due to their twisting.

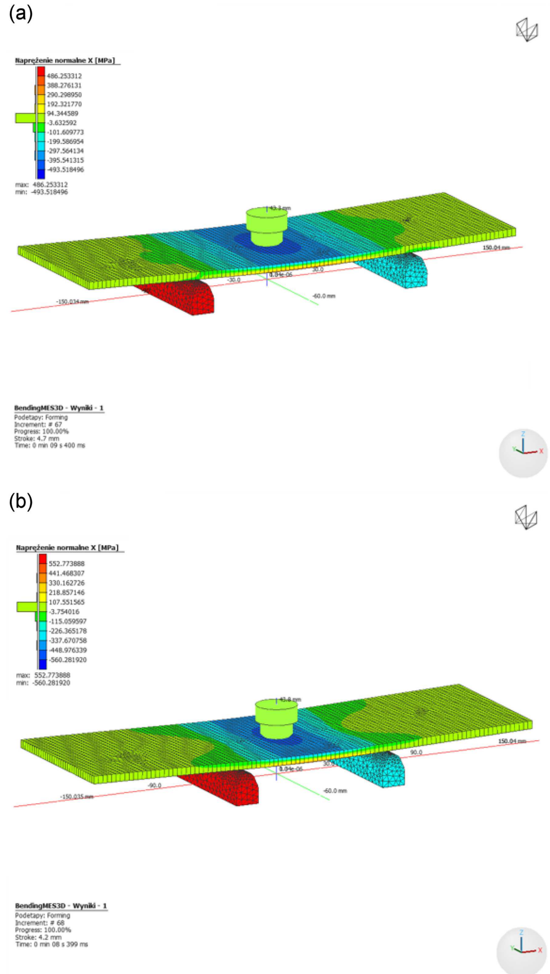

Fig. 2. Example of FEA simulations of the straightening process. Results of normal stress calculations with support spacing: (a) 150 mm and (b) 100 mm.

The straightening investigations were carried out on specimens taken from high-strength low-alloy steel with a thickness of 2 mm and dimensions of 500 mm × 100 mm, and low-carbon structural steel with a thickness of 5 mm and dimensions of 300 mm × 100 mm. In both cases, sets of three samples were cut from the center and the edges of the metal sheet to account for differences in their free-shape deflection profile (even up to several millimeters for thin sheets) and residual stress state. The samples were subjected to 3D surface mapping using a *Shining 3D EinScan HX* handheld

Fig. 3. Laboratory MBN testing equipment for the steel sheet investigations.

scanner to transfer their geometry into computer-aided design (CAD) software in digital form. The resulting geometric models, along with the mechanical material properties obtained from tensile tests, were then used in computer simulations of sheet metal straightening, based on finite element analysis (FEA). Numerical calculations based on the material flow stress function under applied deformation enabled the determination of required initial technological settings for the experiments, including target displacement of a tool or support spacing (Fig. 2) and process parameters such as forces or stresses.

Residual stress measurements, taken both before and after straightening, were carried out using specialized equipment designed for MBN testing, developed at the Faculty of Production Engineering and Materials Technology of the Czestochowa University of Technology [17]. The setup shown in Fig. 3 includes an apparatus with a magnetization block, a Barkhausen noise amplification and conditioning unit, a measuring head, and a data acquisition and processing system based on *LabVIEW* software.

The magnetizing current I_m supplying the excitation winding (400 turns) of the measuring head had a triangular waveform (to obtain a constant rate $\mathrm{d}H/\mathrm{d}t$) with a frequency f_m of 12 Hz. The current intensity was adjusted for each steel grade and thickness to achieve the maximum dynamics of MBN changes with stress, in accordance with the procedure presented in [18]. For the investigated low-carbon steel, the magnetization current during the experiment was ≈ 0.56 A. The corresponding magnetic field strength, calculated from Ampère's law based on the number of coil turns and the average length of the magnetic circuit, was ≈ 2 kA/m. Minimization of field fluctuations was achieved through the design of the measuring head, which ensured uniform and repeatable yoke pressure.

The Barkhausen noise induced in the pick-up located between magnetization yoke poles consists of a series of very low-amplitude voltage pulses (typically a few μV) generated by the jerky motion of domain walls between pinning sites. Therefore, this signal must be significantly amplified, and the dominant components of the magnetizing current must be filtered out. During the investigations, the total gain of the two-stage amplifier was set to 105 dB, and the high-pass filter had a -3 dB cutoff frequency of 1 kHz. Due to high amplification, the effective upper frequency of the MBN signal does not exceed a few tens of kHz. Such a conditioned MBN signal was then processed using an integrated wide-band true RMS converter.

This quantity, along with the unprocessed Barkhausen noise and the magnetization current waveform measured via a shunt resistor, was acquired using a National Instruments *USB-6218* DAQ card (250 kS/s sample rate) for visualization and data storage in a LabVIEW application. Two of these signals can be simultaneously displayed on the digital oscilloscope for reference.

In the tested specimens, MBN measurements were carried out at three points on the top and bottom surfaces, with a spacing of 100 mm. At the center points, directional measurements were performed with an angular resolution step of 30°, using a reference baseline aligned with the rolling direction. In the other points, measurements were taken only for magnetization directions α_m of 0° and 90°, corresponding to the principal stress directions.

Calibrations to determine absolute stress values were performed following procedures similar to those described in detail in [14, 18], using samples collected concurrently with the specimens for the main investigations.

3. Results

Figure 4 presents typical oscillograms of MBN captured at the output of the experimental setup. They were obtained for the investigated low-carbon steel plate and are characteristic of the unstressed state ($\sigma \approx 0$ MPa; Fig. 4a), tensile stress ($\sigma = +60$ MPa; Fig. 4b), and compressive stress ($\sigma = -110$ MPa; Fig. 4c). The results illustrate the general principle of the Barkhausen method, namely that tensile stresses in a given direction cause an increase in MBN intensity, whereas compressive stresses lead to a decrease relative to the reference MBN value at $\sigma = 0$ MPa. An example of the angular distribution of MBN intensity, $\mathrm{RMS_{MSB}} = f(\alpha_m)$, before the straightening process, characteristic of 5-mm-thick samples, is shown in Fig. 5. The reference MBN level corresponding to the stress-free state is marked with a black line. Shape analysis of the directional diagrams indicates that compressive stresses prevail along the rolling direction on the upper surface, while tensile stresses are present on the lower surface. In the perpendicular direction, however, the situation is

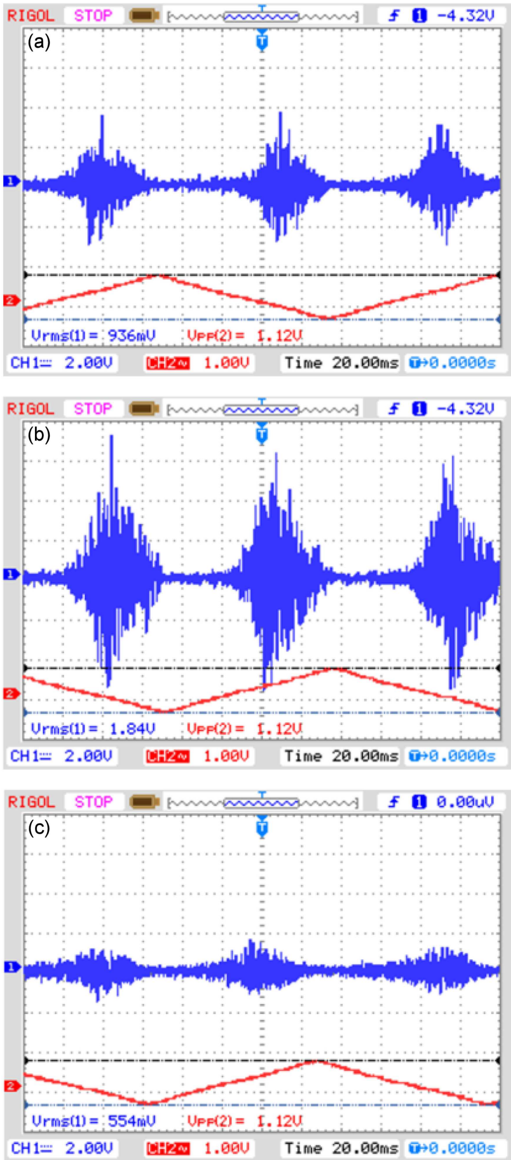

Fig. 4. Oscillograms of the Barkhausen noise at different stress levels (blue waveforms) and magnetization currents (red waveforms) in low-carbon structural steel.

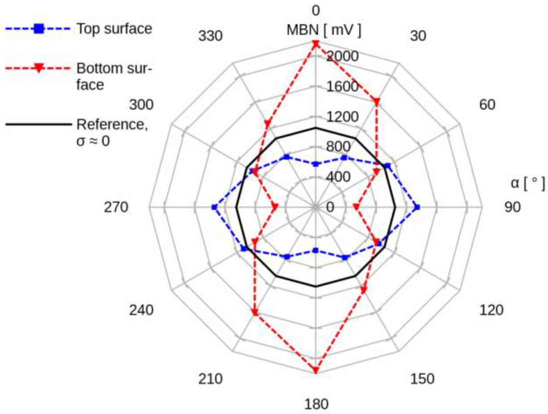

Fig. 5. Directional diagram of the MBN intensity (RMS value) before straightening.

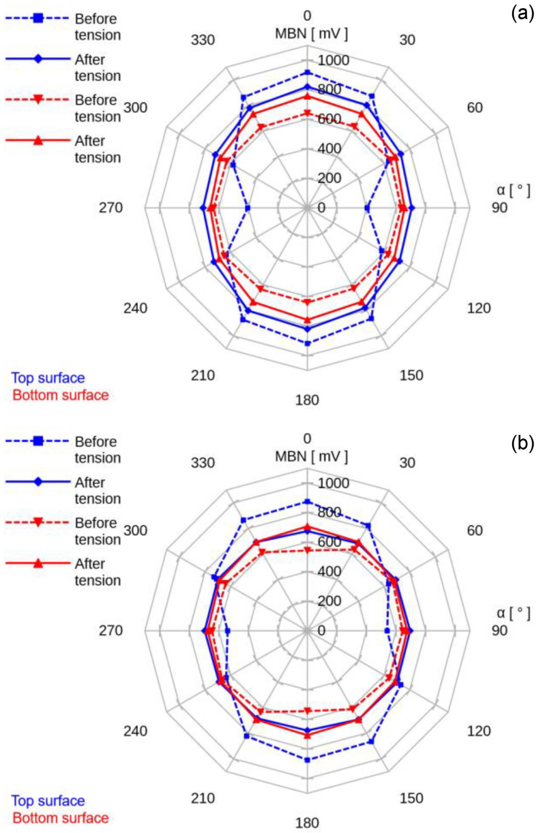

Fig. 6. Example of directional diagrams of the MBN intensity (RMS value) in the thin steel sheet samples taken from the edge (a) and center (b) of the band, before and after tension leveling.

essentially reversed — slight tensile stresses are observed on the upper surface, whereas compressive stresses dominate on the lower surface.

In an analogous manner, the results of measurements performed for thin sheets made of high-strength low-alloy steel are presented, together with those obtained after the tensile straightening process (see Fig. 6a and b). Prior to stretching, due to differences in the rolling process, material properties, and deformation mechanics during uncoiling and preliminary straightening, these samples exhibited a stress state opposite to that observed in thicker sheets (~ 5 mm). Tensile stresses prevailed on the upper surface, whereas compressive stresses were present on the lower surface.

Although the applied tensile straightening process successfully achieved the desired flatness, a clear relaxation of the tensile residual stresses is also evident. This is reflected in the Barkhausen noise intensity, which decreases along the rolling direction on the upper surface of the sheet and increases in the transverse direction. On the lower surface, the

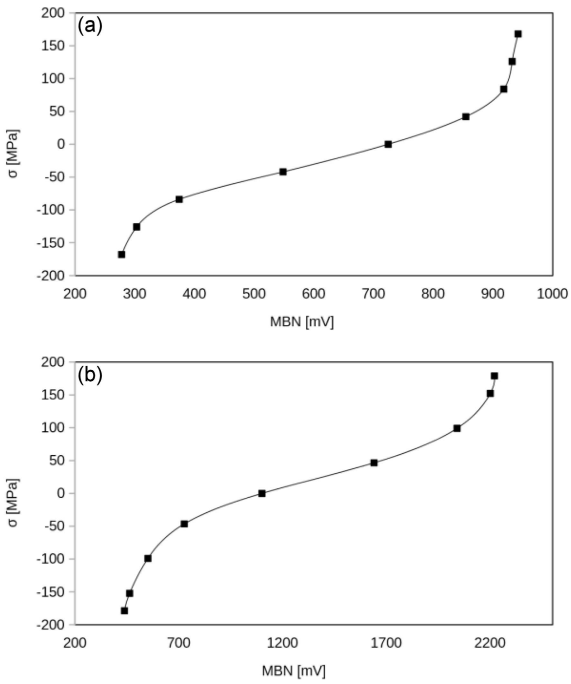

Fig. 7. Calibration function model that relates stress to the measured MBN (RMS value) for (a) high-strength low-alloy steel, (b) low-carbon structural steel.

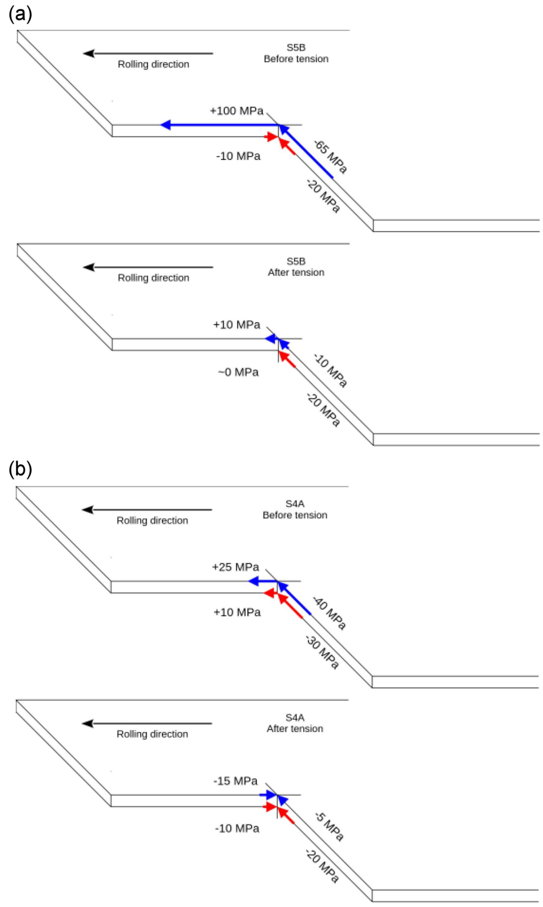

Fig. 8. Example of cross-sectional views of residual stress transformation in the sheets straightened by tension.

MBN intensity rises, and the angular distributions on both surfaces become nearly circular, reflecting a more uniform stress state.

To obtain quantitative information about the residual stress state in the tested sheets, the measured RMS_{MBN} values [in mV] were converted to stress values [in megapascals, MPa] using calibration function models (see Fig. 7).

Calculations were performed in two directions, i.e., along the rolling direction and transverse to it, which generally correspond to the principal stress directions [19]. Selected results obtained before and after treatment were presented either as pairs of surface stress vectors in a cross-sectional view (Fig. 8) for high-strength steel, or as two orthogonal projections parallel and transverse to the rolling direction (Fig. 9) for low-carbon constructional steel.

The redistribution analysis revealed that the averaged initial residual stresses, locally exceeding +100 MPa (tensile) in the rolling direction and reaching approximately −50 MPa (compressive) in the transverse direction, were reduced to low levels within the range of measurement uncertainty as a result of straightening by tension.

When assessing the stress transformations in sheets straightened by bending, the initial longitudinal and transverse residual stresses were found to range from 100 to 150 MPa, which can be considered significant. Moreover, the principal stress directions on the opposite sheet surfaces exhibited an unfavorable orthogonal orientation.

Depending on the straightening parameters (punch offset and support arrangement), two distinct cases were observed. In the first case (Fig. 9a), the longitudinal stresses essentially changed only in sign, while the transverse stresses transformed from an initial tensile value of +36 MPa to high compressive stresses of −136 MPa. In the second case (Fig. 8b), the residual stresses were favorably reduced.

4. Conclusions

This paper presents selected results regarding the measurement of residual stresses during the straightening process of steel sheets. The application of a non-destructive method based on Barkhausen noise measurements enabled rapid, large-area evaluation of stress state transformations.

The results provide valuable insight into the type, magnitude, and distribution of residual stresses in flat steel products in their initial condition, as well as into the effect of straightening operations on their

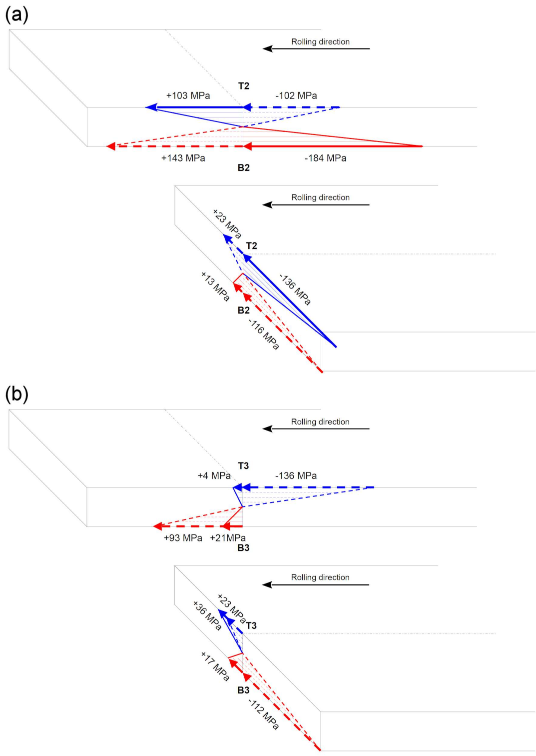

Fig. 9. Example of cross-sectional views of residual stress transformation in plates straightened by overbending. Dashed arrows represent stresses before straightening operations.

redistribution. These changes may significantly influence the functional properties of the products manufactured from sheets.

The conducted investigations confirm that the Barkhausen method is a reliable and time-efficient tool for assessing residual stresses, offering strong potential for industrial applications.

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