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ASSESSMENT OF MICROSTRUCTURAL CHANGES IN S235 STEEL AFTER COLD ROLLING USING EDDY CURRENT TESTING

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This study investigates the eddy current testing (ECT) technique to assess microstructural changes in S235 low carbon steel after cold rolling. Specimens of varying thicknesses (12 mm, 8 mm, and 6 mm) were analyzed to evaluate the impact of deformation on such properties as dislocation density, grain texture, and hardness. Metallographic studies using light microscopy were performed, supplemented by dislocation density measurements via transmission electron microscopy (TEM). The ECT results demonstrated that microstructural changes, particularly cold-work hardening and grain elongation, significantly influenced the phase angle of impedance. Lower penetration depths were more sensitive to surface changes, highlighting the capacity of ECT for detecting near-surface deformation. This work establishes a robust, non-destructive methodology for characterizing manufacturing-induced microstructural changes in heat-resistant steels, with applications in quality control and material performance evaluation.

Keywords: cold rolling; eddy current; microstructure.

1. Introduction

Structural steels, such as S235, play a pivotal role in industries that demand materials capable of maintaining structural integrity under extreme operating conditions (Brnic, 2021). Applications in power generation, aerospace, petrochemical processing, and other high-temperature environments require materials that can withstand prolonged exposure to thermal and mechanical stresses without compromising their mechanical properties or dimensional stability. S235 has emerged as a preferred material for these demanding applications. However, processing techniques such as cold rolling, while essential for achieving desired mechanical and dimensional parameters, inevitably introduce microstructural changes that can influence the material's long-term performance.

Cold rolling is a widely used manufacturing process for refining grain structure, improving mechanical properties, and achieving dimensional precision (Ueji, 2002). However, it also induces localized plastic deformation, leading to microstructural variations, and as a consequence, to strain hardening, dislocation density increase, and possible changes in grain size and morphology. These changes directly affect key properties like strength, ductility, and resistance to corrosion and fatigue. Therefore, understanding and quantifying these microstructural changes are essential for ensuring the reliability and safety of components made of S235 steel.

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Traditional techniques for microstructural changes evaluation, including optical and electron microscopy, X-ray diffraction, Magnetic Barkhausen Noise and hardness testing, provide detailed information. However, they have notable limitations (Makowska, 2024). These methods often require destructive sampling, extensive preparation, and significant time investment, making them less practical for routine quality control or in-service inspections. In contrast, non-destructive testing (NDT) methods offer the potential for rapid, cost-effective, and non-invasive assessment of material properties. Among these, eddy current testing (ECT) has gained prominence due to its sensitivity to microstructural and compositional variations (Kukla, 2021).

Eddy current testing operates on the principle of electromagnetic induction, where alternating current in a probe coil induces eddy currents within the conductive material being tested. The interaction between the eddy currents and material's microstructure affects the impedance of the probe, which can be measured and analyzed. Changes in material properties such as electrical conductivity, magnetic permeability, and surface roughness, often associated with microstructural transformations, lead to measurable variations of ECT signals (Kukla, 2022). This makes ECT particularly well-suited for detecting deformation-induced changes, including those resulting from cold rolling processes.

This study explores the feasibility and effectiveness of using eddy current testing to assess microstructural changes in S235 steel subjected to cold rolling. By correlating ECT signals with metallurgical parameters such as dislocation density, grain structure, and phase composition, this research seeks to develop a reliable, non-destructive approach to evaluating the impact of manufacturing processes on material properties. The insights gained from this work have a potential to enhance the understanding of microstructural evolution in S235 steel and facilitate the broader adoption of NDT techniques for quality control and material characterization in industrial settings.

2. Materials and methods

S235 steel specimens with different degrees of deformation were used in this study. The initial specimen (S) was a 12 mm thick hot rolled sheet. It was then cold rolled into 8 mm and 6 mm thick sheets and designated as S1W and S2W, respectively. Metallographic examinations and stereological analysis were performed using a NIKON light microscope and were prepared with the standard metallographic techniques (mechanical polishing) and etched with 10 % Nital. Subsequent studies included the assessment of dislocation density based on transmission electron microscopy (TEM) observations of thin foil samples obtained by electrolytic thinning, on JEOL JEM 1200 EX. Microstructure images were used to estimate the density dislocation on samples S, S1W, and S2W. The intersection of dislocation and lines was counted based on 5 lines inserted into the images. Analyzed areas were observed with 50000× and 100000× magnification. Dislocation density was estimated from the equation:

$$\rho = N/LrT, \tag{2.1}$$

where N – the number of dislocations measured through line intersection; Lr – the total length of all lines; T – sample thickness (established $T = 200\,\text{nm}$).

The last stage involved the analysis of the eddy current signal on various surfaces of S235 steel specimens with various degrees of deformation. The impact of cold-work hardening on the value of the impedance phase angle was analyzed.

3. Results

The microstructure of rolled sheets exhibited a strong texture, which is visible in the cross-sectional view (Fig. 1). Its presence could be also confirmed based on the results of stereological

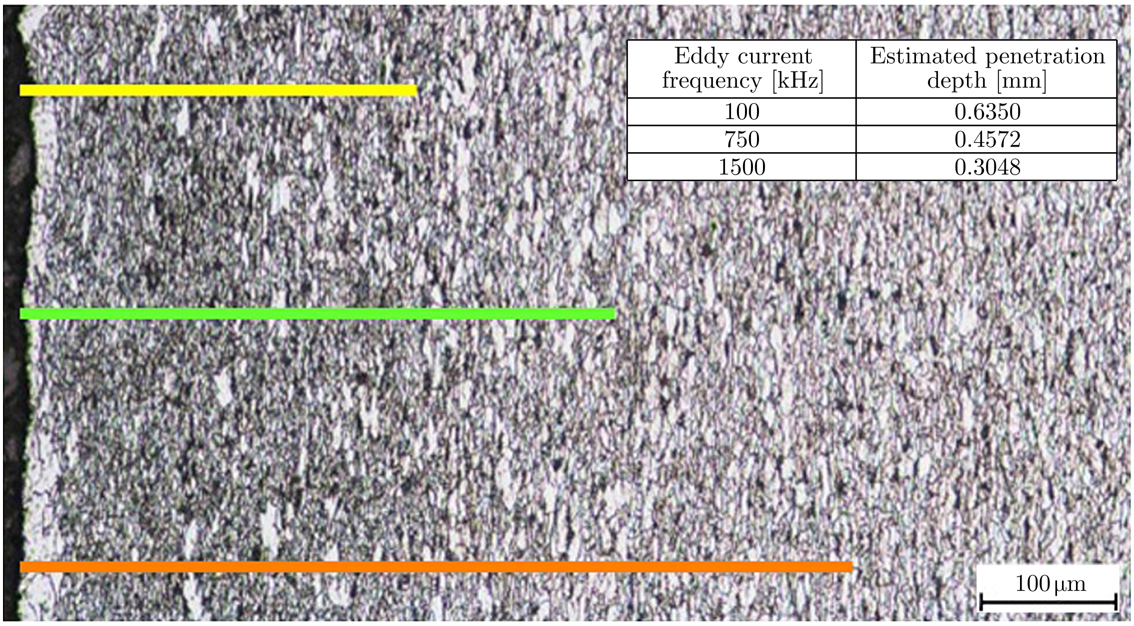

Fig. 1. Microstructure of the cross-section of the rolled sample S2W with estimated penetration depths of eddy currents for different induction frequencies.

tests, including a quantitative assessment of grain elongation. Figure 1 shows the estimated penetration depths of eddy currents for three values of the excitation frequency that were selected for testing. The impedance phase angle was measured on the surfaces of rolled specimens with different deformations and cross-sections in transverse and longitudinal directions to the rolling. It was observed that the most notable differences were found for the lowest penetration depth (Fig. 2). Such behavior was related to the highest deformation degree of the surface due to cold-work hardening. The deeper the measurement frequency was, the lower the recorded differences were. It was directly connected with the microstructural changes that occurred below the surface (Fig. 1).

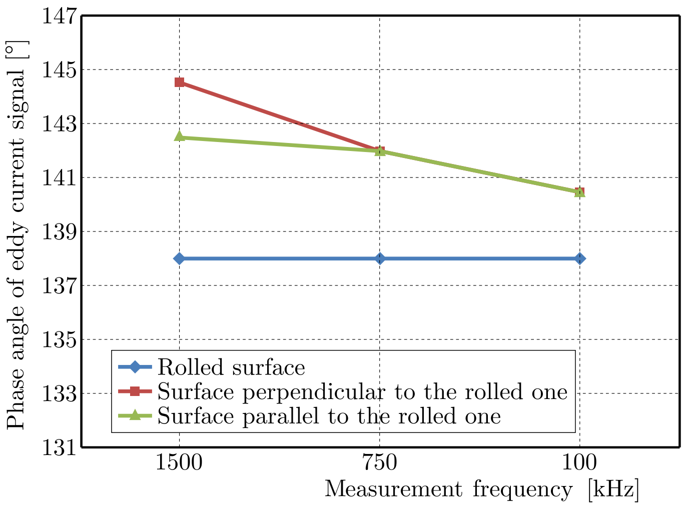

Fig. 2. Changes in the phase angle as a function of frequency for three surfaces of the sheet with a thickness of 6 mm.

The results of impedance measurements performed on surfaces with various degrees of deformation were compared with dislocation density measurement, as shown in Table 1. Example images of the dislocation structures and measurement lines are shown in Fig. 3. The numbers of estimated dislocation for the analyzed samples are shown in Table 1.

Table 1. Mean value for dislocation density in specimen S, S1W, and S2W.

Specimen	Dislocation density
S (initial state, 12 mm thick)	$5.50 \times 10^{12}\,\mathrm{m}^{-2}$
S1W (cold rolled, 8 mm thick)	$9.14 \times 10^{12}\,\mathrm{m}^{-2}$
S2W (cold rolled, 6 mm thick)	$1.10 \times 10^{13}\,\mathrm{m}^{-2}$

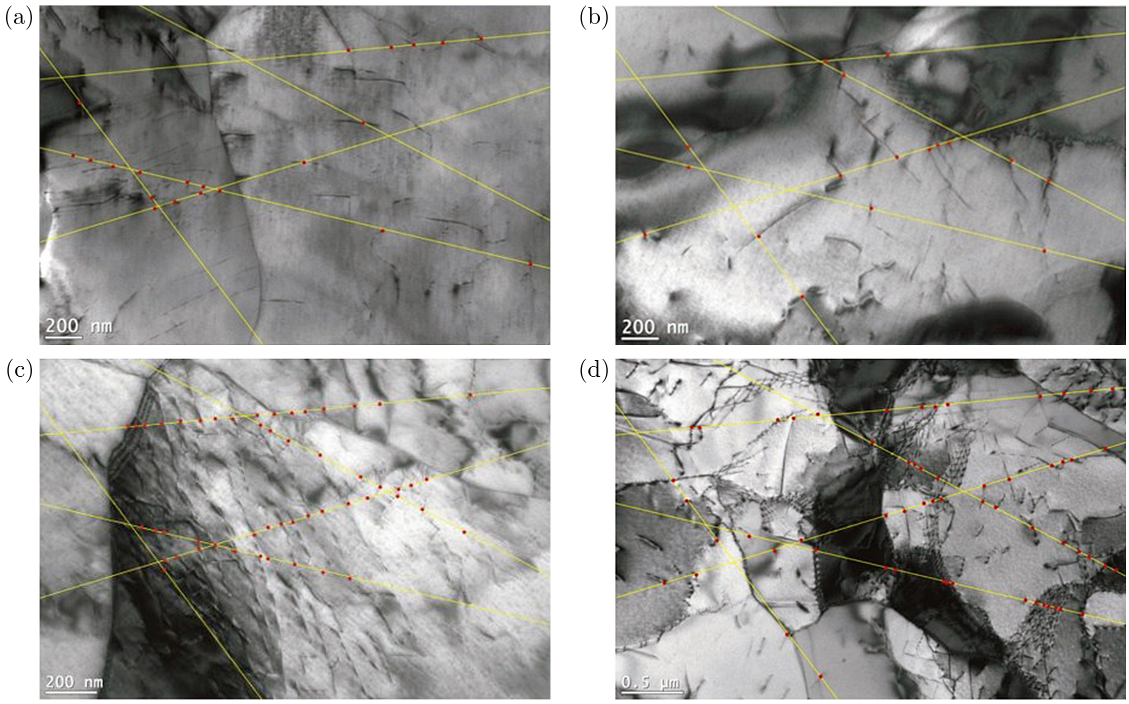

Fig. 3. Dislocation structure of S235 (sample S) with visible dislocation and measurement lines, the number of intersections is 21 for image (a) and 17 for image (b); dislocation structure of S235 after cold rolling (sample S2W) with visible dislocation and measurement lines, the number of intersections is 48 for image (c) and 51 for image (d).

Such comparison clearly indicates an increase in dislocation density for specimens after cold rolling in comparison to the initial state. The higher the dislocation density was, the more material hardening was introduced.

The results clearly show an increase in the dislocation number for samples after cold rolling in comparison to the initial state. However, a higher number of observed dislocations was expected. This fact can be explained by the low dimension of the analyzed area (TEM sample) which can make the analyzed volume of the material insufficient for proper estimation of dislocation density. Another explanation is the possible annihilation of dislocation being a result of residual stress relaxation during TEM sample preparation.

The variation of the eddy current parameter as a function of dislocation density measured for samples after various degrees of deformation, with different penetration depths, is shown in Fig. 4. It is easy to notice that the same deformation degree represented by the specific dislocation density value can be more precisely detected for higher measurement frequency applied.

The experimental results highlight the intricate relationship between the microstructural changes due to cold-rolling and corresponding ECT signals. As shown in the cross-sectional microstructures, the deformation process caused a pronounced grain elongation and texture development. This was quantitatively confirmed through stereological and TEM analyses. The differences in crystallographic texture between the initial state and cold-rolled states underscore the significant alterations in the material's internal structure.

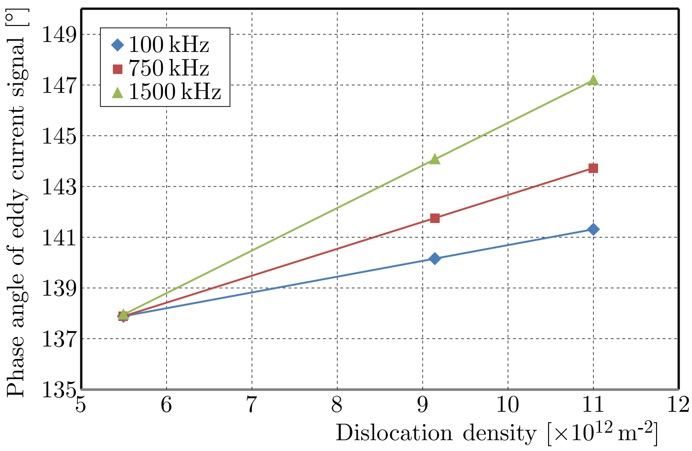

Fig. 4. Influence of dislocation density on the phase angle for different ET penetration depths.

The phase angle of impedance, measured at various ECT penetration depths, revealed distinct trends tied to the degree of deformation. At the lowest penetration depth, the most substantial differences in the phase angle were observed, correlating with the pronounced surface deformation induced by cold rolling. This behavior reflects the higher sensitivity of shallow measurements to surface changes, where cold-work hardening and increased dislocation density are predominant. In contrast, deeper penetration depths exhibited attenuated differences, as the subsurface regions experienced comparatively less deformation. The correlation between dislocation density and the phase angle further elucidates the role of cold rolling in modification of the steel's microstructure. Dislocation density, which increased from $5.50 \times 10^{12}\,\mathrm{m}^{-2}$ in the initial state to $1.10 \times 10^{13}\,\mathrm{m}^{-2}$ in the 6-mm thick rolled specimen, aligned with progressive material hardening. This increase was directly mirrored in the ECT data, where higher dislocation densities corresponded to more pronounced changes in the impedance phase angle. Notably, these effects were most discernible at higher excitation frequencies, which enhanced the detection precision for specific deformation degrees.

The results also underscore the efficacy of ECT in distinguishing microstructural gradients within the material. By leveraging varying penetration depths, ECT demonstrated its capability to detect surface versus subsurface changes. This feature is particularly valuable for assessing surface treatments or identification of the localized deformation zones that may impact material performance.

4. Conclusions

This study successfully demonstrated the utility of ECT in evaluating microstructural changes in S235 heat-resistant steel subjected to cold rolling. Key conclusions include:

- ECT effectively detected changes in grain elongation, crystallographic texture, and dislocation density induced by cold rolling. These microstructural alterations significantly influenced the impedance phase angle, particularly at lower penetration depths;
- the highest sensitivity to deformation-induced changes was observed at shallow penetration depths, making ECT a powerful tool for surface-level assessments where cold-work hardening is predominant;
- a strong correlation between increased dislocation density and changes in the ECT phase angle was established, providing a quantitative link between microstructural changes and ECT signal variations;
- the results highlight the potential of ECT as a non-destructive technique for the characterization of manufacturing-induced microstructural changes in heat-resistant steels. The

method is applicable to quality control processes and can aid in predicting material performance in service.

Future work should focus on extending the methodology to other materials and deformation processes, as well as exploring the integration of ECT with other non-destructive techniques for comprehensive microstructural evaluations.

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