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Dual-Sensor Electromagnetic Non-Destructive Testing for Material State Assessment of different Quenched and Tempered Steels in the Context of Circular Production

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1 Abstract

Electromagnetic non-destructive testing enables the assessment of material states in remanufactured ferromagnetic components in the Circular Factory. This study investigates the combined use of Magnetic Barkhausen Noise (MBN) and Eddy Current Testing (ECT) for the characterization of quenched and tempered CrMo steels with different carbon contents. All materials were fully martensitically hardened under identical austenitization conditions and tempered at different temperatures to generate distinct tempering states. Microhardness and surface residual stress measurements were used as reference methods to capture the coupled evolution of microstructure and stress during tempering. MBN and ECT measurements were performed under constant magnetization conditions to ensure comparability. The dual-sensor approach is evaluated for the classification of variations in the tempering states in Q&T steels relevant to remanufacturing. The results show distinct magnetic responses across tempering stages and carbon levels, indicating the suitability of combined MBN and ECT for robust inline monitoring of material states in circular manufacturing.

Keywords: Magnetic Barkhausen Noise, Eddy Current Testing, Quenched and Tempered Steels, Material State Assessment, Micromagnetic NDT

2 Introduction

Reliable non-destructive assessment of material states is essential for the reuse of components in circular manufacturing and remanufacturing systems. High-load components, such as shafts and gears, are typically manufactured from quenched and tempered low-alloy steels [1], where tempering induces coupled changes in microstructure, hardness, and residual stresses. These material state characteristics directly influence component performance and are defined as quality-relevant properties that must be verified prior to reintegration into the production cycle. Conventional characterization methods, such as destructive material analysis or microhardness testing, are not suitable for inline inspection due to their destructive and localized nature. In contrast, electromagnetic non-destructive testing methods provide fastand production-integrable alternatives. Magnetic Barkhausen noise (MBN) is sensitive to microstructural evolution and residual stress, while eddy current testing (ECT) responds to changes in effective magnetic permeability. However, systematic studies on the combined use of MBN and ECT for material state assessment of quenched and tempered steels with varying carbon content in a remanufacturing context remain limited. This study therefore investigates a dual-sensor electromagnetic NDT approach for the classification of tempering states in CrMo steels relevant to inline quality control in circular manufacturing.

2.1 Experimental Approach:

Four quenched and tempered CrMo steels with different carbon contents (25CrMo4,

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34CrMo4, 42CrMo4, 50CrMo4) were fully martensitically hardened under identical austenitization conditions and subsequently tempered at 30 °C (as-quenched), 250 °C, 375 °C, 500 °C, and 625 °C. Magnetic Barkhausen Noise (MBN) measurements were performed under constant magnetization parameters (sinusoidal excitation, 260 Hz, 12V) to ensure comparability. Eddy current testing (ECT) was applied to capture variations in effective permeability and electrical conductivity. Emission spectral analysis, Vickers microhardness, X-ray diffraction residual stress measurements served as reference measurement methods for the characterization of tempering-induced material state changes.

2.2 Results & Discussion:

Clear correlations were observed between MBN RMS values, hardness, carbon content, and residual stresses. For low-carbon steels, residual stresses after tempering were close to neutral, allowing the effects of hardness and carbon content on the MBN response to be distinguished more clearly. In contrast, higher carbon steels exhibited significant tensile residual stresses near the surface, which strongly influenced the Barkhausen signal and partially masked the hardness-related trends. This indicates a coupled influence of microstructure and residual stress on the magnetic response, highlighting the necessity of a multi-parameter interpretation for reliable material state assessment.

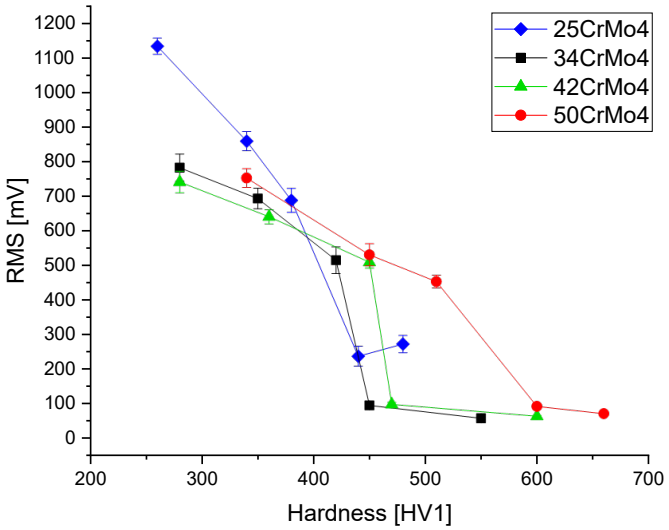

Fig. 1. A Development of MBN RMS value as a function of Vickers hardness [2] for the steels 25CrMo4, 34CrMo4 42CrMo4 and 50CrMo4 across different tempering levels.

ECT measurements showed noticeable changes in the sample impedance with tempering state, which are related to the higher effective magnetic permeability of fresh martensite compared to tempered martensite. This indicates a potentially high sensitivity of ECT to hardness-related material state changes. This effect can be considered complementary to the Barkhausen signal, which showed a higher sensitivity to residual stresses. The complementarity of the dual-sensor approach therefore enables a more reliable assessment of the material state during inspection in circular manufacturing.

References

[1] M. Areitioaurtena, U. Segurajauregi, M. Fisk, M. J. Cabello, and E. Ukar, 'Numerical and experimental investigation of residual stresses during the induction hardening of 42CrMo4 steel', *Eur. J. Mech. - ASolids*, vol. 96, p. 104766, Nov. 2022, doi: 10.1016/j.euromechsol.2022.104766.

[2] J. Orlich, A. Rose, P. Wiest. Atlas zur Wärmebehandlung der Stähle Band 3. Verlag Stahleisen, 1973.