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The 15th International Conference on
Barkhausen noise and Micromagnetic testing

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15th International Conference on Barkhausen noise and Micromagnetic testing (ICBM15)
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Electron phase microscopy for imaging magnetic materials

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Abstract

This talk presents the electron microscope as a flexible and powerful scientific instrument to probe magnetism at the nanoscale. As the functionality and emerging properties of nanostructured magnetic materials and devices are fundamentally linked to the arrangement elementary magnetic moments, by imaging with near-atomic resolution the spin topography of the active parts of materials we gain a privileged view on how structure-functionality links develop. This is made possible by electron imaging techniques that are "phase sensitive", meaning that the signal we record carries information on electric and magnetic fields that are otherwise inaccessible.

The talk will focus on phase sensitive techniques, in particular Lorentz-TEM, Transport of Intensity and electron holography. With these, we add an extra layer of information to our data: the magnetic fields generated by localized spin textures, for example those of magnetic nanoparticles, skyrmions, vortices, domain walls, etc. Case studies are presented with emphasis on applications in real-world materials.

Printed eddy current/Giant Magnetoresistor Hybrid testing sensors: toward thickness monitoring applications

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The necessity for periodic infrastructure inspection is widely acknowledged and implemented. This monitoring primarily relies on non-destructive testing methods. Unfortunately, control sensors are expensive, complex, and time-consuming to manufacture. Their designs typically accommodate as many scenarios as possible, aiming for versatility. Unfortunately, this versatility often compromises optimization for specific applications.

Monitoring specific parts over time for safety purposes gave rise to the principle of Structural Health Monitoring (SHM) [1,2]. SHM aims to autonomously deploy sensors throughout the structure's lifetime to track its evolution. A potential solution to this challenge involves using flexible patch-form sensors, enabling rapid and cost-effective prototyping and manufacturing. These patches can be utilized in traditional applications, such as manual scanning by operators; they also offer the flexibility to function as a permanent monitoring tool. Eddy current testing is a non-destructive technique well adapted for such applications. Innovative techniques can print planar coils fabricated into patch forms that can be used for a wide range of applications at a very low cost.

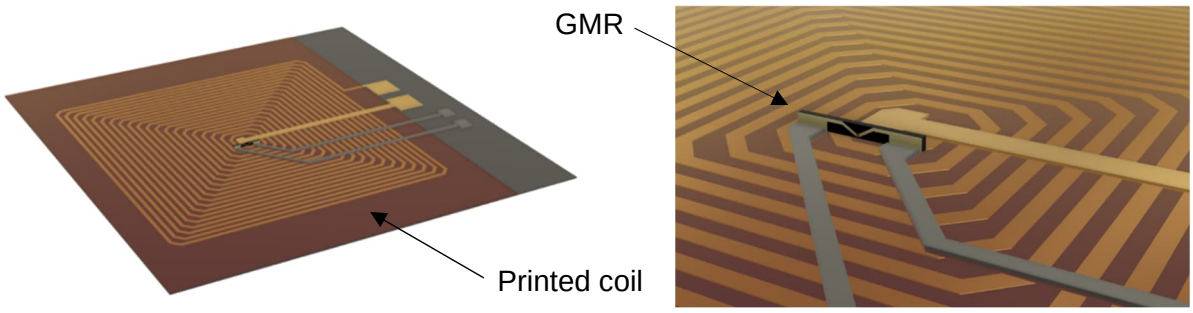

Figure 1. Printed eddy current sensor including giant magnetoresistor.

This study focuses on the possibility of combining printed Eddy current and miniaturized GMR sensors for thickness measurements of steel blocks and, in the background, additional applications in the framework of corrosion monitoring as illustrated in Figure 1.

Two types of sensors were produced and used:

- Single planar coil eddy current sensors.

- Transmitter/receiver eddy current sensors: including a planar coil for the emissions and a miniaturized Giant Magneto-Resistor (GMR) for the reception.

Three manufacturing techniques were tested for the development of the printed coils: dispenser printing, screen printing, and flex PCB [3]. The dispenser and the screen printing techniques required dielectric and conductive inks. With these techniques, the manufacturer can print the sensor directly on the part to be controlled. A layer of dielectric insulation has to be added in a preliminary stage when the part to be monitored is electrically conductive. Then comes the flat spiral coil layer (conductive ink), followed by a dielectric layer to protect the sensor from the external environment. A last conductive ink layer is required to connect the center of the spiral coil and enable electrical measurements. The GMR sensors were built using a thin-layer deposition method and manufactured by CEA Paris-Saclay. The tested specimens were SS400 steel shims of varying thicknesses.

The single coil measurements were carried out using an HP 4194A Impedance/Gain-Phase Analyzer. We monitored the sensor impedance for frequencies ranging from 100 Hz to 3000 Hz. The results plotted in the impedance plane showed a shift in the curve as a function of the tested specimen thickness, confirming that the thickness variation was correctly detected and proving the feasibility of the proposed technique.

For the transmitter/receiver sensors, the excitation coil was supplied with a low-frequency alternating current, and a Dewesoft acquisition card was used to monitor the GMR resistance fluctuations. Again, the linear correlation between resistance and the varying thickness confirmed the method's feasibility.

Beyond their eddy current primary functionality, considering that GMR sensors are very sensitive, combining them with still printed and flexible multi-layer excitation coils, magnetization levels are predicted to be high enough to trigger magnetization mechanisms like the domain wall bulging or the irreversible domain wall motions. In this context, these innovative sensors will be tested in the near future for magnetic Barkhausen noise characterization.

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A Multiscale model for the magnetic Barkhausen noise energy cycles

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Magnetic Barkhausen Noise (MBN) is often studied through the use of time independent indicators, such as the MBN energy [1]. MBN energy is obtained by integrating the square of the MBN voltage signal with respect to time. Such an operation plotted against the excitation magnetic field *H*, results in a typical hysteresis loop resembling the usual induction-field loops *B*(*H*). Inspired from a multiscale model for the description of magneto-elastic behaviour [2], a model for MBN energy cycles is described in this presentation [3]. It combines a statistical representation of the magnetic domain configuration with a dry-friction model for the description of hysteresis. Two illustration examples are given in Fig. 1 for an Iron-Cobalt alloy (left) and for a Grain Oriented Silicon steel (right) for an excitation along the rolling direction. The proposed approach can be used to predict the effect of stress on the MBN energy cycles. A detailed presentation of the modelling approach will be given at the conference and predictions of the effect of stress on the MBN energy cycles will be discussed.

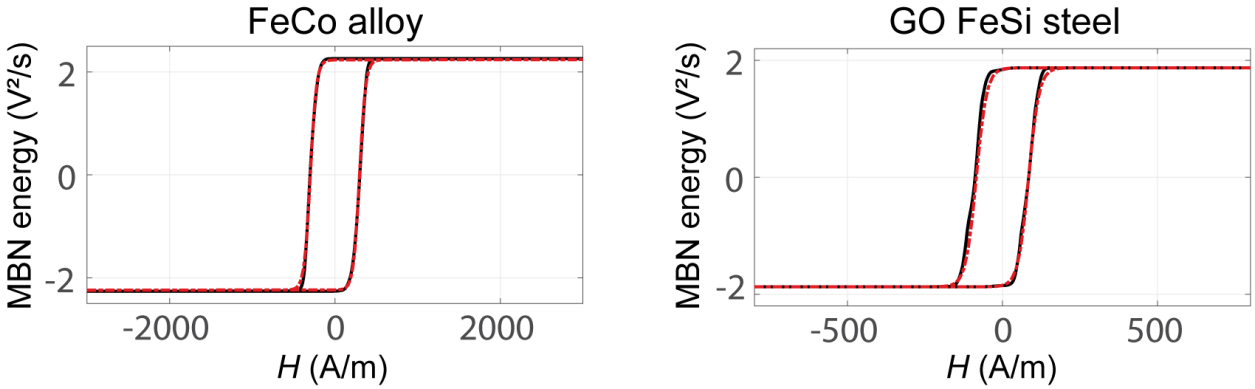

Figure 2. Magnetic Barkhausen Noise energy cycles for an Iron-Cobalt alloy (left) and for a Grain Oriented Silicon steel (right). Comparison between experimental measurements (plain line) and modelling (dashed line).

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Magnetic Barkhausen noise measurement under rotational magnetization process for mechanical stress identification

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Steel is omnipresent in our daily lives, from major infrastructure to buildings, cars, and kitchenware. Steelmaking is emission-intensive, and the nearly 2 billion tons of steel produced yearly generate around 8% of global $C0_2$ emissions. Still, steel is vital to modern economies, and global demand is expected to grow to meet rising social and economic welfare needs. Manufacturers can follow many innovative ways to make steel more sustainable, including fully reusing byproduct gases from furnaces, fully embracing renewable energy, improving overall quality and lifespan, etc. The average expected steel product lifespan is thirty-five years, ranging from fifty-two years in construction to eleven years in metal products. Degradation (corrosion, fatigue, accidental damage) is the most common failure mode of steel parts [1]. Both restorable design-in and durable design-out strategies could be applied to prevent failure. For example, an airplane reactor's lifespan could be increased by installing more durable bearings made from alloys that have increased fatigue resistance.

Mechanical Internal Stresses (MIS) (stresses that occur within the material itself, also called residual stresses in some cases), desired or not, are a determinant factor in steel performance. MIS has a significant effect on fatigue crack propagation. MIS can result from various mechanisms, including plastic deformations, temperature gradients, or structural changes (phase transformation). Manufacturing processes such as machining, welding, and surface treatments generate MIS. MIS must be monitored throughout the production line to evaluate a steel part's performance precisely. All MIS measurement methods focus on type-I MIS*. They are indirect and require monitoring of a physical quantity combined with a calculation stage. The most common mechanical techniques are the hole-drilling process, the contour method, and the crack compliance method. Together with the chemical processes, they form the so-called destructive methods. They are reliable but expensive and wasteful, as viable materials must be irrevocably damaged. Non-destructive testing (NDT) methods for evaluating MIS have also been reported. They retain a significant advantage as analysts can avoid damaging functional parts and find more flaws in the process while scanning larger areas. They include X-Ray Diffraction (XRD), ultrasonic, or acoustic emission. These techniques can be applied successfully independently of a tested specimen nature. Even if these methods give recognized capabilities to detect cracks, they show relatively poor quantitative sensibility to MIS [2].

Magnetic NDT techniques are available in the specific case of ferromagnetic materials. Most conventional carbon steels are ferromagnetic and magnetic control compatible [3]. These methods offer fast response, low cost, small size, and easy maintenance, but only two commercial devices have crossed the line between academy and industry: The MBN-based controller Rollscan® from Stresstech (Finland) and the micromagnetic, multi-parametric, microstructure and stress analysis 3MA® developed by IZFP Fraunhofer institute (Germany). From its atomic origin to its human-scale observation, ferromagnetic steel magnetization is ruled by distinct mechanisms [4]. Each mechanism is characterized by its time constant and sensitivity to magnetic excitation. Most of these mechanisms overlap during a unidirectional magnetization cycle. It is challenging to list them exhaustively. Still, the main mechanisms can be filed into three categories, as follows:

The magnetization mechanisms associated with the structure and kinetic of the magnetic domains:

- Magnetic domain walls bulging (the magnetic domain walls bend reversibly under low magnetic excitation).
- Magnetic domain wall irreversible motions (under medium magnetic excitation).
- Magnetic domains nucleation and annihilation (under high magnetic excitation).

The magnetization mechanisms associated with the atomic magnetic moments:

- Magnetization Rotation (under high and very high magnetic excitation).

The magnetization mechanisms related to the macroscopic behavior:

- Macroscopic eddy currents (under dynamic magnetic excitation).

Even if never specified this way, experimental tests achieved by magnetic NDT commercial equipment are indirect observations of some of the magnetization mechanisms described above with no access to quantitative magnetic properties. The MIP test run by the 3MA® is associated with the domain wall bulging. Similarly, Magnetic Barkhausen Noise (MBN) measurements from the Rollscan® are indirect observations of the domain wall's irreversible motions. These examples belong to the same range of mechanisms related to the magnetic domains and their variations.

MIS is an essential factor of the domain structure distribution but, unfortunately, not the only one: dislocation density, precipitates, and micro-strains are just as influential, making it difficult to distinguish the only stress effect. The typical way to apply MBN non-destructive testing involves imposing a unidirectional magnetic field on the tested specimen [5]. This method is relatively successful, but the influential factors mentioned above appear especially significant in these working conditions.

In this work, we decided to test an alternative approach based on rotational magnetization. Magnetic domain walls disappear when the level of rotational magnetization increases, forcing us

to remain in the low magnetization range. A specific experimental setup was used to impose rotational magnetization and mechanical stress [6] simultaneously.

Testing the magnetic Barkhausen noise under rotational magnetization offers a promising avenue for characterizing residual stress non-destructively. We can explore the nuanced interactions between magnetic domains and stress fields within the material structure differently. Ultimately, this work presents an opportunity to advance non-destructive testing techniques and better comprehend the intricate relationship between residual stress and material properties.

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Ferromagnetic steel surface treatment assessment from magnetic non-destructive testing

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The advancement of surface treatments for ferromagnetic steel parts, encompassing both desired processes like nitriding and carburization [1] and undesired conditions like corrosion [2], presents a critical challenge in ensuring the integrity and performance of engineered components. Ferromagnetic behaviour is highly complex and sensitive; it encompasses multiple mechanisms and processes that happen over different geometrical scales, and even small effects like very early-stage corrosion can strongly impact it.

This work explores the application of magnetic signature analysis as a non-destructive method for evaluating a spectrum of surface treatments, including the not-so-typical silicon diffusion [3] and the dealloying treatments [4].

Recognizing that the sensitivity of magnetization mechanisms varies with the nature and depth of the treatment, the focus is on identifying and characterizing the most sensitive magnetization mechanism. This approach enhances reproducibility and diminishes dependence on experimental conditions, thereby enabling precise and reliable surface treatment [5].

Magnetic methods prove advantageous for non-destructive evaluation, offering a means to scrutinize surface treatments without compromising the structural integrity of the tested ferromagnetic steel parts.

To implement this approach, it is imperative to define experimental situations wherein the targeted magnetization mechanisms are isolated and stimulated. Techniques, including the magnetic hysteresis loop analysis, the magnetic Barkhausen noise measurement, the magnetic incremental permeability measurements, etc., can stimulate the material in different ways and provide magnetic indicators strongly bonded to a given mechanism.

Importantly, each magnetization mechanism possesses unique characteristics, such as time constants and the amount of required magnetic field, some being frequency-dependent (e.g., microscopic and macroscopic eddy currents) and others not (e.g., reversible and irreversible domain wall motions or magnetization rotation). Leveraging these properties allows for defining experimental situations tailored to isolate specific mechanisms.

This nuanced approach contributes to a more precise and targeted evaluation of the surface treatments, fostering a deeper understanding of the intricate magnetic responses induced by them.

In conclusion, this abstract highlights the innovative use of magnetic signature analysis to assess surface treatments on ferromagnetic steel parts comprehensively. By identifying the most sensitive magnetization mechanism and tailoring experimental situations to isolate these mechanisms, the study establishes a reliable and controlled framework for characterizing diverse surface treatments. This approach enhances the reproducibility of assessments and deepens our understanding of the magnetic responses associated with conventional and unconventional surface treatments in ferromagnetic steel components.

In the upcoming presentation, we will investigate specific experimental scenarios that isolate and stimulate magnetization mechanisms sensitive to different surface treatments. We will go through a large range of surface treatments and establish the best magnetization mechanism and the best scenario to assess them. Then, based on these specific examples, we will try to explain and understand the origin and the reason for these good correlations.

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Impact on residual stresses and Barkhausen noise signal after hard turning and grinding of case carburised spur gears

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Gear manufacturing of slender spur gears may suffer from machining distortion due to inherent stresses originating from the case hardening. Therefore, the subsequent machining step becomes a critical operation in order to finalising the parts within geometrical and surface integrity requirements. This may require optimising the part integrity by using a suitable machining operation both in regard to residual stresses and deformation. Securing such process is also of great importance, why Barkhausen noise as a well-established method for grinding, may be used for other machining applications as well.

In this work the surface integrity from grinding and hard turning has been compared when face machining AISI 9310 (14NiCrMo13-4), gears. This has been correlated to the Barkhausen noise measurements in order to establish a quality control of the machined surface quality. Additionally, a set of provoked ground surfaces was developed and evaluated to study the sensitivity of the Barkhausen noise method for the application.

The result show great impact from the machining operation with a clear difference between grinding and hard turning in regard to residual stresses and deformation. Consequently, the two machining operations show similar BN response. The provoked ground samples, on the other hands showed a great increase of tensile stresses and also consequently the BN. By changing the magnetizing and analyzing frequencies for the Barkhausen noise measurements, it was investigated how the settings could optimize the separation of different manufacturing conditions.

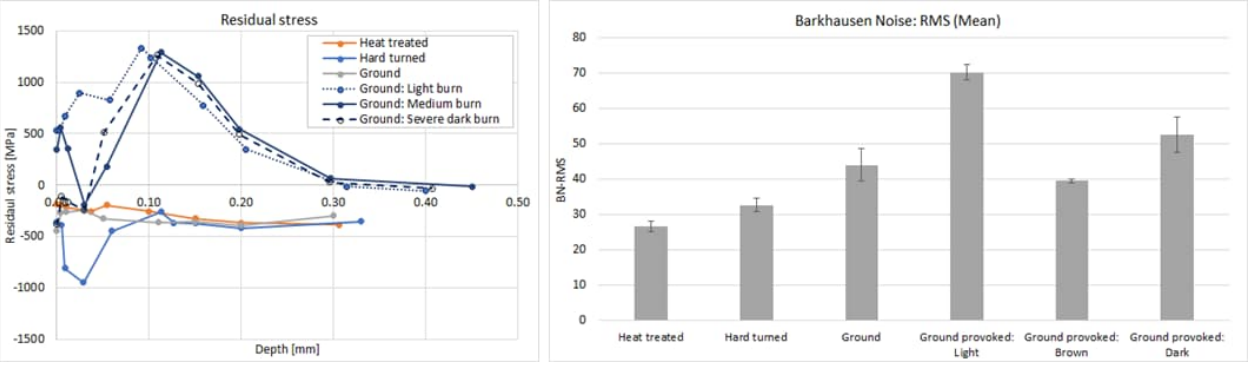

Figure 1. Left) Residual stress profiles of machined gears and Right) BN measurements of the machined gears.

Effects of Mechanical Excitation on in-process Barkhausen Noise Measurements during Grinding

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Magnetic Barkhausen noise (BN) analysis is an established method for the non-destructive detection of thermo-mechanical surface changes from grinding, which can reach from changes of the residual stress state over different pronounced tempering zones to rehardening [1]. In addition to post-process testing already used in industry, current research also focuses on the in-process application during grinding. The analysis during the grinding process is the base for a process control to achieve tailored surface condition [2]. Besides these advantages, in-process measurements bear some challenges due to the superposition of magnetic excitation and effects from grinding on BN. Grinding wheel contact leads to an additional BN signal especially in the area of saturation but up to now it is not completely understood how this effect superimposes the influence of the generated surface state [3]. In some cases, even a mechanical excitation of BN without excitation by an external magnetic field was observed [4].

Aim of this study is a deeper understanding of the effect of grinding induced BN signals. For this, raw signals, envelopes (Fig. 1) and derived characteristic values of the BN were observed during different cylindrical grinding processes. To distinguish between influences from the generated surface state and the grinding process itself, measurements were also performed on already ground surfaces while grinding next to it, thus without direct influence of the process itself. Additional investigations were performed outside the grinding machine with mechanical excitation by e.g. a piezo actuator to confirm the mechanical excitation effect.

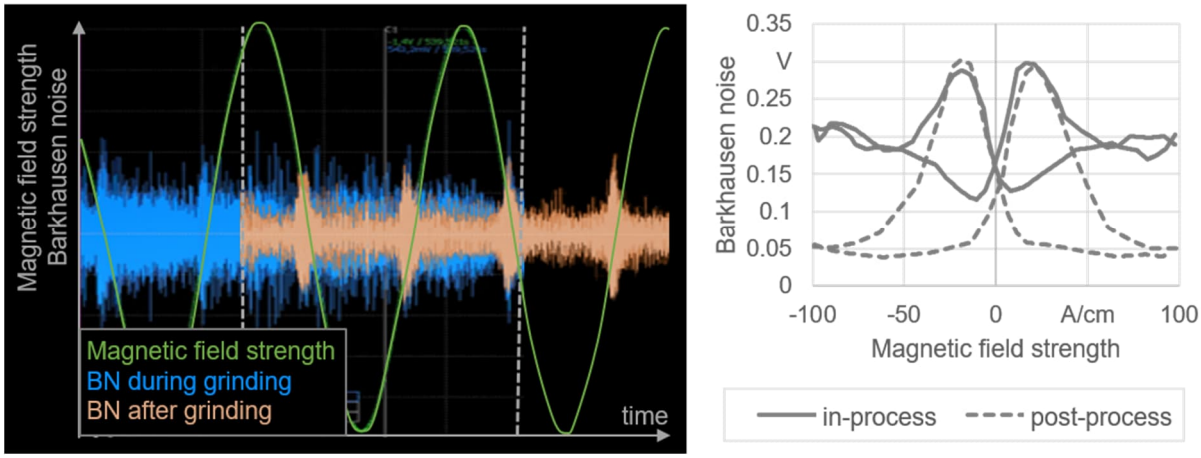

Figure 3. Raw signal and envelopes of the BN with and without mechanical excitation by the grinding process.

The results point out the overlap of influences from surface state and mechanical excitation on BN signal. Especially in the case of heavier grinding damages, mechanical excited BN follows the same dependencies of hardness and residual stresses as the magnetic BN. Investigations outside the grinding machine confirmed the mechanical cause of the grinding induced Barkhausen noise and rule out electromagnetic fields as root cause for the additional signal.

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Barkhausen noise with micromagnetic simulations

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Barkhausen noise (BN) is generally understood to originate from the jerky movement of magnetic domain walls (DWs) as induced by the pinning effect of crystal defects and impurities in the material. However, the underlying details of the DW behavior and its differences between different materials are largely unknown from the physics point of view. Here, we break the theory-oriented research of BN in pieces and simulate the dynamics of *single domain walls* in thin steel films by micromagnetic simulations. The results are then directly compared with Lorentz-mode transmission electron microscope (TEM) results so as to perfectly match the system dimensions between the experiments and simulations. That is, we simulate the domain wall dynamics via the semi-classical Landau-Lifschitz-Gilbert equation, where the full vectorial nature of magnetization is regarded, and where energy contributions comprise the magnetostatic, exchange, and anisotropic effects as well as the applied field.

First, we aim to explain the TEM observations considering the DW behavior in carbide (cementite, Fe_3C) particles, embedded in the ferritic steel matrix [1]. We can successfully reproduce the vanishing of the domain walls inside the carbide with increasing external field (see Fig. 1), but the reappearance of the domain walls, observed with TEM while decreasing the applied field back to zero, seems more challenging to be simulated. We will briefly account for possible reasons for this deficiency of the simulations. Secondly, we implement the stress fields of dislocations in the micromagnetic simulations and simulate the effect of dislocations on the mobility of the domain walls. The model is used to study how the driven domain walls respond to dislocations in the ferrite matrix [2].

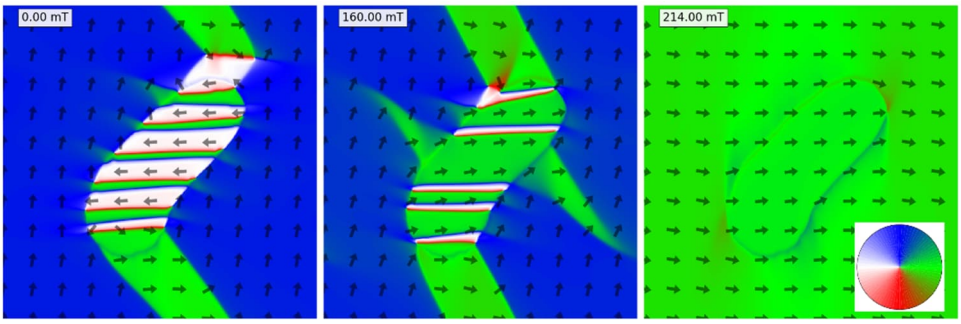

Figure 4. Micromagnetic simulation of domain walls disappearing from the cementite carbide particle embedded in ferritic steel matrix. The value of the vertical field is shown on the top left corner of each panel. Figure from Ref. [1].

The presented results offer the deepest-to-date understanding of the microscopical behavior of magnetic domain walls in low-carbon steel thin films and pave the way towards more complete, physics-based understanding of the origin of BN in different materials and microstructures.

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Usage of Barkhausen noise analysis for detection of surface integrity properties in different grinding steps

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Heavily loaded components are subjected to targeted heat treatment and ground to the specified contour in the final process step to produce high-quality surfaces with high dimensional accuracy [1]. In addition to geometric parameters, the thermo-mechanical load induced during grinding has a significant influence on the final properties of the subsurface layer. Surface integrity characteristics, such as hardness, microstructure, and residual stresses, have a significant impact on the fatigue life of ground components [2,3,4]. Incorrect process design can lead to rejections due to the generation of thermal effects, such as tensile residual stresses or tempering zones [5,6]. During grinding, the material stock is removed in several process steps, with material removal rate and consequently thermo-mechanical load decreasing from step to step. In conventional process design, thermal damage to the subsurface layer is always intended to be avoided during rough grinding. However, process design does not take into account the fact that negative effects on the surface caused by rough grinding can still be removed by subsequent process steps (finishing and fine finishing). If the desired part contour still lies within the remaining grinding stock, good parts can be produced through damage-free material removal, resulting in a shorter process time. To inspect the surface integrity of the finished parts, usually time consuming residual stress and hardness measurements are carried out on individual components. However, as long as these measurements are conducted at the surface, no information can be obtained about the depth of material modification. Metallographic cross section analyses or the application of nital etching are also suitable for the subsequent identification of tempering zones (grinding burn) but have disadvantages due to subjectivity of results or necessary destruction of the components [7].

A non-destructive method of assessing surface integrity is the measurement of micromagnetic properties, such as Barkhausen noise. The measurement of Barkhausen noise provides a quantitative, rapid, and non-destructive characterization of the workpiece surface integrity of ground components [8].

The focus of this study is the identification of thermal damage during single-stage surface grinding of differently case-hardened workpieces made of steel grade AISI 1.7131 (16MnCr5) using Barkhausen noise measurements. Barkhausen noise measurements with a 3MA-II (Fraunhofer IZFP) and Rollscan 350 (Stresstech GmbH) devices are carried out on the initial states after heat treatment as well as on ground workpieces to compare the measurement devices and evaluate

the influence of different heat treatment states. To induce varying thermal loads leading to grinding burn, depth of cut is increased stepwise, and cutting forces are simultaneously recorded. Surface integrity modifications are evaluated by metallographic cross sections, suitable for the detection of tempering zones. Additionally, residual stress, full width at half maximum (FWHM), and hardness depth profiles are measured to obtain additional information about the introduced depth modification. The assessment of the thermal load introduced by the process into the workpiece is done by calculating the contact area-specific grinding power [9,10].

Subsequently, multi-stage grinding experiments are considered. The thermal damage introduced during rough grinding, with known depth modification, is intended to be removed in the subsequent finishing steps. Finally, it is demonstrated to what extent Barkhausen noise is capable of detecting various thermo-mechanical damages during different grinding steps.

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Profound hardness assessment from low-frequency incremental permeability

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Maintaining the integrity of high-performance mechanical components, especially those made from high-quality steel, is of fundamental importance in various industries. Deep carburizing treatments enhance the mechanical properties of these components, improving hardness and wear resistance [1, 2]. However, incomplete surface treatments (carburization, etc.) can compromise this integrity [3, 4] and lead to structural instabilities. Precise evaluation methods of the surface treatments are needed. Historically, such assessments have relied on destructive testing methods, implying additional costs and material loss [5,6].

The Low-Frequency Magnetic Incremental Permeability technique (LF-MIP) offers a nondestructive alternative, providing insights into the structural changes induced by carburization without damaging the component [9, 10]. LF-MIP involves magnetizing the specimen at low frequencies (fDC < 1 Hz) and applying Eddy Current Testing (ECT) within the low-frequency range (<2 kHz) to assess the trajectory of the carburization treatment [11]. This technique exploits the interaction between the magnetic properties and the carburization characteristics, offering a comprehensive evaluation beyond surface layers [12].

A full benefit of LF-MIP can be obtained by developing a simulation method to fill the gap between the electromagnetic measurements, the magnetic properties, and the complex evolution of the carburization treatments. In this aim, in [11], we described a semi-analytical method combining the Dodd & Deeds analytical expression for a flat sensor coil above a two-layer conductor with the Jiles-Atherton theory to consider the ferromagnetic hysteresis. Even if, by exploiting this model, we reveal magnetic indicators highly correlated with the carburization depth and led to optimal conditions for NDT observations, this two-layer consideration cannot provide any information about the hardness profile nor the exact penetration depth of the LF-MIP.

Still, this information is crucial for the industrials. Therefore, we opted for an alternative simulation method based on a 3D Finite Element Model in this new study. The 3D-FEM model simulates a flat sensor coil over a multilayer conductor. Each layer is characterized by its specific magnetic properties (electrical conductivity σi, magnetic incremental permeability μi).

By accurately considering the magnetic and electromagnetic aspects of LF-MIP, the model can reconstruct the experimental data with accuracy and finesse. Unlike the semi-analytical method, simulation predictions are not limited to defining magnetic indicators correlated with carburization depth [4][10] but provide fine 3D magnetic field distributions and precise LF-MIP scanned depths.

Together with experimental tests on virgin and fully carburized specimens, they allow us to predict the hardness trajectory of newly tested specimens precisely and non-destructively.

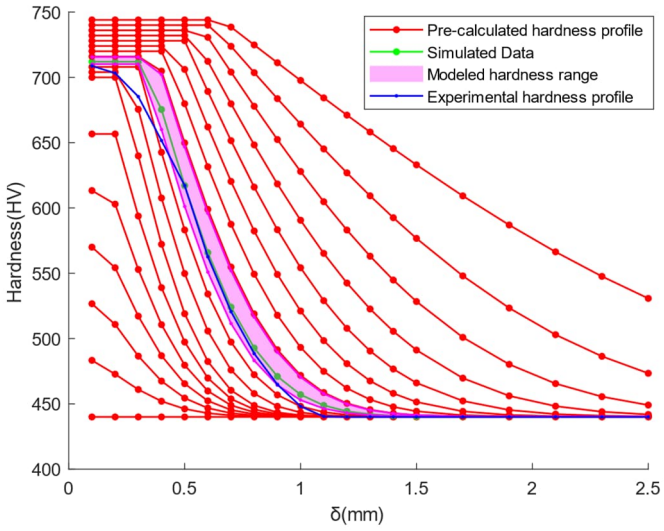

Figure 1. Comparison between the experimental characterization (hardness destructive measurement in blue) and the simulation predictions (purple area) in the case of a 16NiCrMo13 specimen of undisclosed cementation treatment.

In conclusion, we propose a 3D Finite Element Model (3D-FEM) was developed to simulate LF-MIP measurements and predict hardness profiles. Experimental validation involved testing a series of flat specimens made of 16NiCrMo13 martensitic stainless steel with varying carburization treatments. The resulting LF-MIP butterfly loops were compared with pre-calculated curves to estimate hardness profiles, as depicted in Fig.1. The resulting LF-MIP hardness profile estimation chart enabled the prediction of hardness profiles for unknown specimens based on LF-MIP measurements. This study demonstrates the feasibility and effectiveness of LF-MIP as a nondestructive method for evaluating carburization depth in steel components. Integrating COMSOL Multiphysics for modeling hardness profiles enhances the accuracy and reliability of the proposed NDE technique. Future research will focus on refining the modeling techniques to provide even more precise assessments of hardness profiles, thereby expanding the potential applications of LF-MIP in the industry.

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Academic studies of Barkhausen noise at Tampere University

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The Materials Characterization research group at Tampere University started the Barkhausen noise (BN) related studies in 1997. During the years, different aspects of the magnetic measuring method has been studied by the group in several projects in collaboration with other academic institutes and companies like BN system manufacturer Stresstech Oy or other ones utilizing the BN. The main role of the research group has been in the BN measurements and structural characterization of the studied materials. The academic collaborators have provided their expertise in the field of data analysis, modelling, simulations, and special characterization techniques. Industrial collaborators have provided the expertise on BN measuring system and provided the actual practical research questions arising from the daily use on the BN.

The first phase of the BN research in the group headed by Prof. Lepistö concentrated on the utilization of BN in residual stress measurements and fatigue damage estimations. Fundamental effects of e.g. prestrain and biaxial stress on the stress vs. Barkhausen noise relation were studied [1]. At that time, the scientific work provided background knowledge for industrial applications. The 3rd ICBM (International Conference on Barkhausen Noise and Micromagnetic Testing) conference was held at Tampere on 2–3 July 2001.

The second phase of BN research continued after few years of break in 2007. Group still headed by Prof. Lepistö got acquainted with the novel data processing method called neural networks which was studied at University of Oulu and soon a research project (INTELBARK, Implementing intelligent systems on multiparameter Barkhausen noise measurements) covering both BN measurements and data processing with this novel technology was started. The research work of the utilisation of Barkhausen noise (BN) for characterization of hardened component surfaces with neural networks in the INTELBARK project funded by Academy of Finland (2007–2009) was continued in a Finnish funding agency for technology and innovation (TEKES) -funded research project NOVEBARK (Novel Barkhausen Noise System for Induction Hardened Components and Material Defect Identification) during 2010–2013. INTELBARK focused on the gear grinding burns and the first novel data processing with neural networks of the multiparameter BN data captured with Microscan software (Stresstech Oy). Close collaboration with data processing and modelling was carried out with Control Engineering Laboratory (University of Oulu, UO) during years 2007–2019 in various projects. One of the NOVEBARK project's highlights was development of the laser processing system for creating artificial thermal damages mimicking grinding burns altogether with detailed material characterization work of the calibration samples. The calibration sample preparation for BN method [2] with different methods has been improved and developed

since 2009 in various projects involving companies utilizing the BN method. The second highlight of the NOVEBARK project was the development of Magnetic voltage sweep (MVS) measurement concept for case depth studies, which also other researchers [3] have utilized and further developed.

The 3rd phase of BN research started along the change of group leader from Prof. Lepistö to Prof. Vippola. Continuing work was acquired in Academy of Finland funded project FUNBARK (Fundamentals of Barkhausen noise and magnetic field modelling – Multidisciplinary approach to implement sweep measurements for industrial quality control) which was performed during 2015–2019. The highlights of this project were sophisticated magnetic field modelling related to the BN sensors, grinding quality control actions with data driven models and detailed characterization work related to Jominy end quench samples studied with BN. After this, the focus of the BN-related projects moved towards the basic fundamental understanding of the magnetic domain walls and domain wall interactions in different structures during Research council of Finland funded project BarFume (Magnetic Barkhausen Noise: From Fundamental Physics to Non-Destructive Testing, 2021–2025). The new JEOL JEM-F200 transmission electron microscope (TEM) at Tampere Microscopy Center provided the use of Lorentz microscopy which allows the observation of the magnetic domain structures. The BN studies now, with link to the origins of the signal connected to micromagnetic simulations, offer a new perspective for microstructural characterization and understanding the complex interactions of material, stress, and BN measurement results [4].

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Using Barkhausen noise for verification of grinding process for transmission components of heavy construction vehicles

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The grinding process of hardened automotive heavy transmission components needs to be optimized, both regarding process speed, to receive the highest possible productivity output, and regarding quality, to receive the highest possible product quality and component fatigue life.

A very good optimization tool is to use Barkhausen noise as a non-destructive testing method for the ground components directly after the grinding process. Barkhausen noise will detect changes in microstructure and residual stresses in the surface of the ground components and can be used to control and fine-tune the grinding process. This to avoid thermomechanical damages of the ground component surface, so called grinding burns

This presentation will discuss the use of Barkhausen noise for optimizing the grinding process for hardened transmission components for heavy construction vehicles.

Examples will show how the component quality will be influenced by different grinding process parameters like; cooling flow problems, grinding disc dressing cycle, and also mechanical instability by wear of the grinding machine. Figure 1 is showing polar graphs of Barkhausen noise measurements of a ground gear shaft from heavy construction vehicles.

Application examples of grinding of shafts and grinding of gears for heavy construction vehicles.

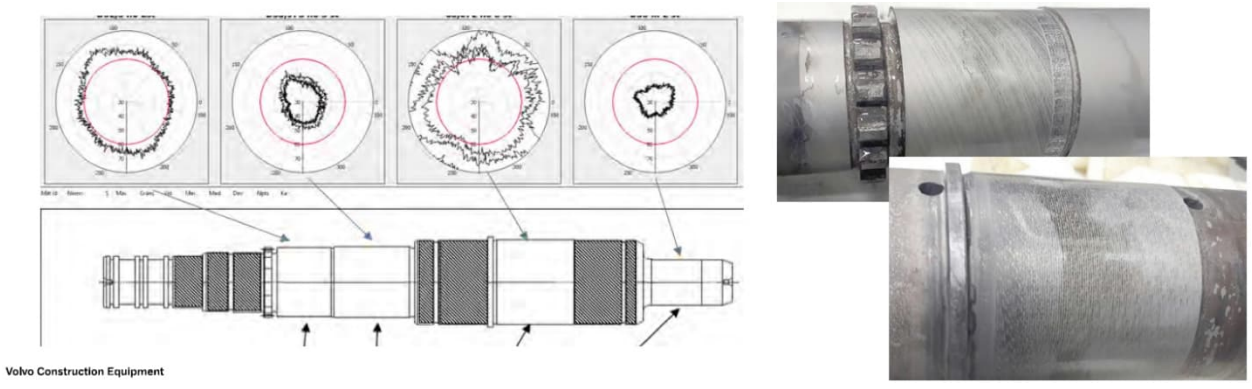

Figure 1. Gear shaft with ground areas measured with Barkhausen noise. Results shown with polar graphs.

It will also be shown how statistics over time can help in both monitoring the grinding process and possibly be used as a tool in predictive maintenance of the grinding machine equipment.

More complex evaluation of surface integrity using residual stress depth profile testing

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In many segments of industry, preciously machined hardened steels are used. In addition to hardness and geometrical parameters like shape, dimensions and surface roughness, some other parameters are also important which indirectly describes fatigue properties. These are summarized below by the term “Surface integrity”. This term is very wide, complex and sometimes too arbitrary. For these purposes, parameters mined from Barkhausen Noise Analysis (BNA) and from Residual Stress (RS) measurements such as residual stress profiles can be created. The measured RS profiles can be used for calculation of Sum of Effective Residual Stresses (SERS). This paper introduces new parameter called Effective Residual Stresses Integral (ERSI) which describes plot of residual stress below the surface. This approach of smoother ERSI allows to describe surface integrity as the surface damage physically reasonable scale. In experimental part based on carburized steel samples some comparison of parameters based on BNA, RS tests, SERS and ERSI is presented.

Keywords: ground steel, surface integrity, fatigue, Barkhausen Noise Analysis (BNA), Residual Stress (RS), Sum of Effective Residual Stresses (SERS), Effective Residual Stresses Integral (ERSI)

Characterisation of laser hardened layer in crankshafts by using magnetic Barkhausen noise

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Crankshafts are critical components of the vehicle powertrain. An important process to assure their reliability is the surface hardening treatment, which usually is done either by induction or laser hardening processes. The heat treatment causes the material microstructure to transform into austenite, then is followed by quenching to transform into martensite and subsequent tempering to complete the process and release residual stress [1]. The crankshaft components, especially mains and pins should meet minimum criteria of hardness to present the best performance and guarantee failure resistance [2].

A set of mains and pins of a crankshaft were laser treated with different surface hardening depths ranging from 500 µm to 2 mm, with a surface hardness of 60 HRC. The depth was measured by microhardness measurements (HV) made in the transversal section up to 3 mm in the perpendicular distance from the surface. The effective hardening depth was measured as the hardness depth reached HRC 45. Another set of journals were treated changing the tempering time to obtain states with different surface hardness keeping the same hardening depth.

A customised yoke was designed and manufactured to transversally magnetize the crankshaft journals to make magnetic Barkhausen noise (MBN) measurements from the surface of the journals and test its sensitivity to characterise their hardening depth and hardness. A range of magnetising frequencies were tested, and a double peak envelope was obtained. The larger the frequency the larger the amplitude of the second peak. An evolution of the second peak was observed both in position and amplitude with the variations on the depth and hardness of the hardened layer. The amplitude of the second peak increases gradually as the hardening depth increases, and enlarges and moves to lower magnetic field values as the hardness of the surface decreases.

An additional MBN and magnetic field sensor were used to indirectly measure the distance from the hardened zone to the collar/undercut, which is the distance of the non-hardened area at both sides of the journals. In this case, a single-peak envelope is obtained, as the MBN sensor is located near the unhardened area and its amplitude is proportional to the distance from the hardened zone to the collar.

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Influence of grinding burn and dissolution of carbides on MBN

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The study is dealing with Barkhausen noise in the roll bearing steels after grinding. Two different concepts of roll bearing steel are compared. The first one represents the matrix (100Cr6) containing large carbides which are formed directly from the melt during solidification. The second one represents case-carburised (CC) concept as a result of chemical surface enrichment followed by quenching. The study investigates the potential of Barkhausen noise for monitoring components with respect of their thermal damage as a result of thermal softening initiated by elevated temperatures during grinding.

It was found that Barkhausen noise is growing due to progressive grinding wheel wear as a result of increasing temperatures in the grinding zone. This growth is linked with the thermal softening due to reduction of dislocation density expressed in term of microhardness. The study demonstrates that also the magnitude of the tensile residual stresses is increasing along with growing MBN. Lorentz microscopy carried out with transmission electron microscope (TEM) was used to study the magnetic domain wall structures of the two studied steels. It was revealed that the refinement of the domain size takes place especially in CC steel material with higher temperature output from the grinding.

The study also reports about significance of carbides, their stability and their role in the proposal of suitable threshold for rejection or approval of components after grinding. Large primary carbides in the case 100Cr6 were noticed to be unchanged compared to the CC steel where changes were more visible. One reason for this might be the higher Cr content and its effect on the carbides of the 100Cr6 steel compared to CC steel. The hypothesis is that carbides in the CC steel matrix near the surface tends to dissolve at elevated grinding temperatures during heating followed by formation of very fine precipitates during rapid self-cooling. Whereas the carbide coarsening takes place below the surface in CC steel. The pinning strength of these fine precipitates seems to be more than the initial one and increase the magnetic hardness of the surface layer. Therefore, MBN envelops tend to be shifted to the higher magnetising fields along with increasing envelope height.

Carbides dissolution in the case of CC concept provides opportunity to propose the Barkhausen noise critical threshold for components rejection in a reasonable manner. On the other hand, this threshold should be set more or less arbitrary in the case of 100Cr6 concept.

Production quality monitoring with Barkhausen noise on lamellar graphite cast iron cylinders

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Fabrication processes like welding, machining, embossing, heat treatment, or service operation of mechanical components may create residual stresses, welcome or not. Knowledge of the residual stress level helps guarantee the smooth operation of components, their fatigue behaviour, and their geometric stability with time.

A case of production quality monitoring of lamellar graphite cast iron cylinders has been explored. The stress state is evaluated at different fabrication steps of the parts: before stabilisation heat treatment, after stabilisation heat treatment, and after the final machining step. The test currently implemented is destructive, by cutting the part along a line, lengthwise, and measuring the deformation induced by stress relaxation. The difference between the stress state of the inner and outer surface of the cylinder is correlated with the deformation.

The goal of this project was to find a replacement method for testing the quality of the process which would be non destructive. Such a non destructive method is the Barkhausen Noise (BN). BN is an electromagnetic method applicable to ferromagnetic materials, which is sensitive to material microstructure and residual stress [1, 2]. The penetration of BN signal is of the order of 300 µm, so BN is a surface method.

Barkhausen Noise measurements were thus taken on the inner and outer surface of the cylinder and compared to the reference stress profiles obtained by X-Ray diffraction, for the surface evaluation, and hole-drilling, up to 1 mm depth, also taken on the inner and outer surface of the parts. Signal analysis and data processing were then made. Representative BN and stress indicators were found in order to monitor production quality of the cast iron cylinders.

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Demonstrators for automatic quality control of gears by electromagnetic NDT methods

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Thermal and thermochemical treatments are commonly used in industry to optimize the mechanical properties of materials and ensure both high hardness and contact fatigue, particularly on mechanical transmission parts. Fabrication processes also induce residual stress, which must be compliant with smooth component operation. Quality control of these parts is paramount to guarantee production. The aim is to be able to control 100% of the production fast and reliably. The commonly used methods are destructive. Non-destructive electromagnetic methods, like Barkhausen noise and incremental permeability, can also be used to characterize residual stress, surface and case hardening depths, nitriding layers, carburizing layers, grinding burns, etc.

Three automated systems using NDT electromagnetic methods will be presented on this poster. Firstly, an automated system, based on 3MA, has been developed to test the case-depth and hardness simultaneously on mechanical transmission parts and to automatically sort them depending on the compliance of each of the followed characteristics. Electromagnetic methods applied with the 3MA are sensitive to various microstructural parameters and stress simultaneously which complexifies the analysis of signals. A calibration was made with thirteen parts of same geometry, same material and obtained with the same process, covering the expected variability range of case-depth and hardness, with compliant and non-compliant values included. Electromagnetic parameters were extracted from the electromagnetic signals and combined with multiparameter statistical approaches and machine learning data processing to define a calibration function for each characteristic. These functions were then applied to measurements made on similar unknown parts to estimate the value of the tested characteristics and used for sorting the parts.

The second automated demonstrator developed was designed to test residual stress, induced by shot peening on helicoidal gears, with Barkhausen noise. Multiparameter statistical approaches and machine learning data processing of measurements made with a pool of representative parts, were applied to calibrate the test. The third automated demonstrator was designed to detect grinding burns on each tooth flank of a gear. All these systems demonstrate the potential of electromagnetic methods for implementation in industries to improve production rate and reliability.

Magnetic Barkhausen noise and magneto-optical Kerr effect analyses in property-controlled flow forming of austenitic steel AISI 304L

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The production of rotationally symmetrical workpieces by flow forming allows the manufacture of a wide range of components with applications in industries such as transportation and aerospace, due to the manufacturing flexibility, resource optimization and the possibility to produce components with specific mechanical properties [1]. The use of metastable austenitic steel as raw material makes the production of high-performance products possible. During flow forming of these steels, plastic deformation not only reduces the wall thickness of the workpieces but also changes the microstructure. In particular, phase transformation from metastable austenite to martensite occurs, changing the magnetic and mechanical properties of final products [2]. The implementation of online closed-loop control within the production process enables an application-oriented and efficient production of components. This requires the development of optimal measurement systems for in-process detection of the amount of α'-martensite, transmission and processing of the data within the controller. The application of measurement systems operating under the magnetic Barkhausen noise (MBN) principle is promising due to their high sensitivity to changes in magnetic properties during the forming process [3].

This investigation focuses on the evaluation of a MBN measurement system to detect the amount of deformation-induced α'-martensite to implement a property-controlled flow forming of metastable austenitic steel AISI 304L (1.4307, X2CrNi18-9) tubes. Microstructural investigations by means of electron backscatter diffraction (EBSD) (Fig. 1a) and magnetooptical Kerr effect (MOKE) (Fig. 1b) analyses were carried out to correlate the evolution of microstructure and the magnetic response [4].

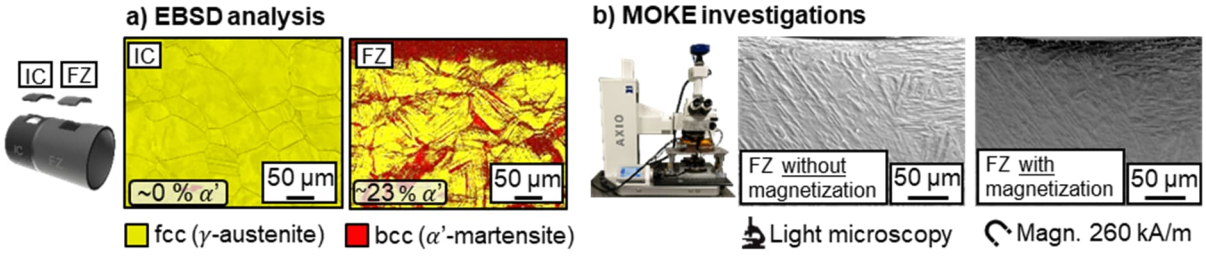

Figure 5. Microstructural investigations of phase transformation of flow formed workpieces by means of: a) electron backscatter diffraction (EBSD), and b) magnetooptical Kerr effect (MOKE) analyses. Modified version of [4].

The detection during flow forming of α'-martensite in tubular workpieces using non-destructive MBN sensors (Fig. 2a), requires calibration models to transform the measured signals of maximum amplitude of MBN (M_{max}) into α'-martensite amount [5]. The calibration models are based on experimental data recorded from specimens produced of seamless tubes, using different infeed depths and feed rates of the forming tool. Thickness reductions between 0.1 and 1.0 mm, and specimens with α'-martensite contents up to 80% were produced, characterized and correlated with the MBN data (Fig. 2b). The MBN-based measurement system was implemented within the control system and validated under real production conditions. Signals recorded online with the MBN sensor were compared with offline measurements taken as a reference with a Feritscope. Three different test conditions (feed rates of 0.1 mm/s in Test 1, 0.3 mm/s in Test 2 and 0.5 mm/s in Test 3) were analysed and the maximal deviation was around 5% of α'-martensite (Fig. 2c). This controlled flow forming process enables manufacturers to adjust geometries and properties, to produce high-added-value components, based on well-understood process-microstructure-property-relationships.

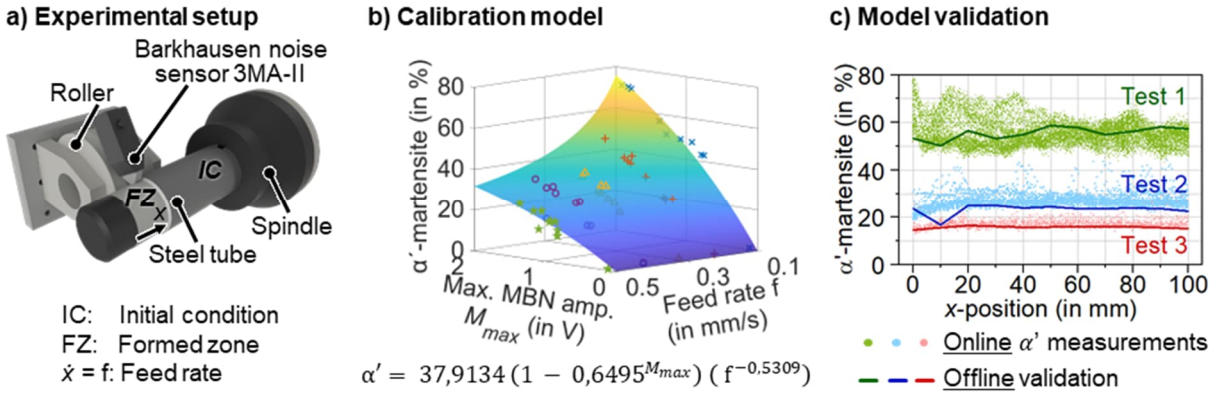

Figure 6. Implementation of a MBN sensor for detection of α'-martensite amount during flow forming of metastable austenitic steel tubes: a) experimental setup; b) calibration model of the MBN sensor, and c) model validation using offline measurements with a Feritscope.

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Advanced utilization of microscopy for Barkhausen noise studies

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The origins of Barkhausen noise (BN) signal can be revealed with special assistance of electron microscopy. Transmission electron microscope (TEM) provides both the information of the microstructure and the magnetic substructure, called as magnetic domains. Magnetic domains represent the magnetic substructure similar to the grain structure of the sample defining the magnetic properties of material. The origin of the BN signal is the indirect information of the motion and interactions of these magnetic domain walls (DWs) in the applied magnetic field in ferromagnetic structure. The visualisation of the microstructural pinning sites (e.g., grain boundaries, dislocations, carbides) which hinders the DW motion can be performed with TEM. In addition, the interactions of the pinning sites with DWs in varying magnetic field can be captured frame-by-frame and processed with special image processing protocols. The sections which are studied from TEM samples are, however, in micrometer scale and thus linking these to the actual BN measurements needs also parallel research methods. The magnetic force microscopy (MFM) technique provides the domain wall information from micrometer to millimeter scale providing a link from the TEM analyses to the actual BN measurements. Microscopic observations, as presented in Fig. 1, were also connected with micromagnetic simulations to deepen our knowledge on the magnetic behavior of ferromagnetic materials. Here, we present a characterization methodology to combine indirect (BN measurement), direct (microscopy) studies and micromagnetic simulations to better understand how microstructural features affect the BN signal [1], [2].

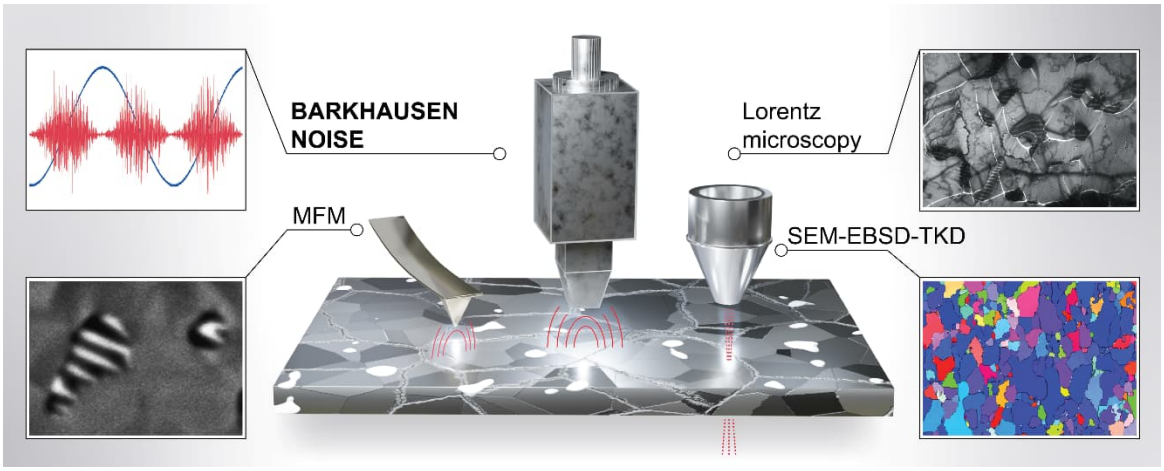

Figure 1. Characterization methodology [2]

Example of the multi-instrumental characterization work is the detailed characterization of magnetic and non-magnetic carbides and dislocation structures from low-alloyed steel materials. To study the bulk structure more related to BN sensor size, MFM studies were done to capture the appearance of DW structures in larger scale. The micrometer scale domain structures altogether with the grain structures were captured with TEM in Lorentz mode. The scanning electron microscopy (SEM) together with electron backscatter diffraction (EBSD) technique will provide information of the dislocation distribution which can be also evaluated with scanning transmission electron microscopy (STEM) technique. The experiences show that linking the different characterization techniques and micromagnetic simulation together will bring valuable information to interpret the BN signal even better.

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Microstructural evolution in the subsurface of quenched and tempered steels during deep hole drilling determined by magnetic Barkhausen noise

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The Boring Trepanning Association (BTA) deep hole drilling process is a particularly effective method for machining bores with large diameters and high lengths. The process is frequently employed for machining complex and costly high-performance components, such as double screw extruders, tube sheets for steam generators and landing gears of aeroplanes [1]. Since such parts need to withstand high thermomechanical loads throughout their entire service lives, ensuring favourable surface integrity (SI) is a crucial task in drilling.

Given the strong interrelations between the design of machining processes, the resulting SI, and the properties and performance of components, targeted subsurface conditioning in machining is currently at the centre of research in academia and industry [2]. For BTA deep-drilled components, however, assessing SI is particularly challenging, as the severely hindered accessibility of the borehole walls prevents the application of most conventional non-destructive approaches like X-ray diffraction. Since magnetic Barkhausen noise (MBN) analysis allows for a holistic characterization of SI based on sensors which are composed of relatively small surface-mounted coils that fit inside boreholes, it is a particularly promising approach for characterizing deep-drilled surfaces in ferromagnetic materials [3].

A phenomenon in the field of SI, which is particularly detrimental to the performance and life of components, is the formation of machining-induced hard and brittle white etching layers (WEL). In the past, evidence has been provided that MBN analysis can be employed for reliably detecting such white etching layers (WEL) in steels [3,4]. However, research into the underlying WEL properties and their effect on MBN generation is limited.

In this study, the inherent properties of WEL are elucidated, using the example of BTA deep-drilled specimens made of the quenched and tempered steel AISI 4140 (1.7225, 42CrMo4). MBN analysis is performed using the instruments FracDim by Fraunhofer IKTS and Rollscan 350 by Stresstech (Fig. 1). In addition to multipurpose sensors, a custom-designed slim drill head sensor is employed. The inherent properties of WEL are analysed by in-depth microstructural analyses, using optical microscopy, as well as advanced approaches in scanning electron microscopy.

Magneto-optical Kerr effect (MOKE) microscopy is used for assessing the evolution of the magnetic structure in the subsurface under external magnetic fields.

It is found that WEL can be detected by lower MBN amplitudes. By means of the microstructural analyses evidence was provided that WEL are composed of nanocrystalline grains with a high dislocation density. These aspects result in a particularly large number of pinning sites, which pose obstacles to domain wall motion. In MOKE microscopy it is observed that the external magnetic field for relatively low field strengths mostly affects the material below the WEL. It is only with higher field strengths that the magnetization inside of the WEL is altered.

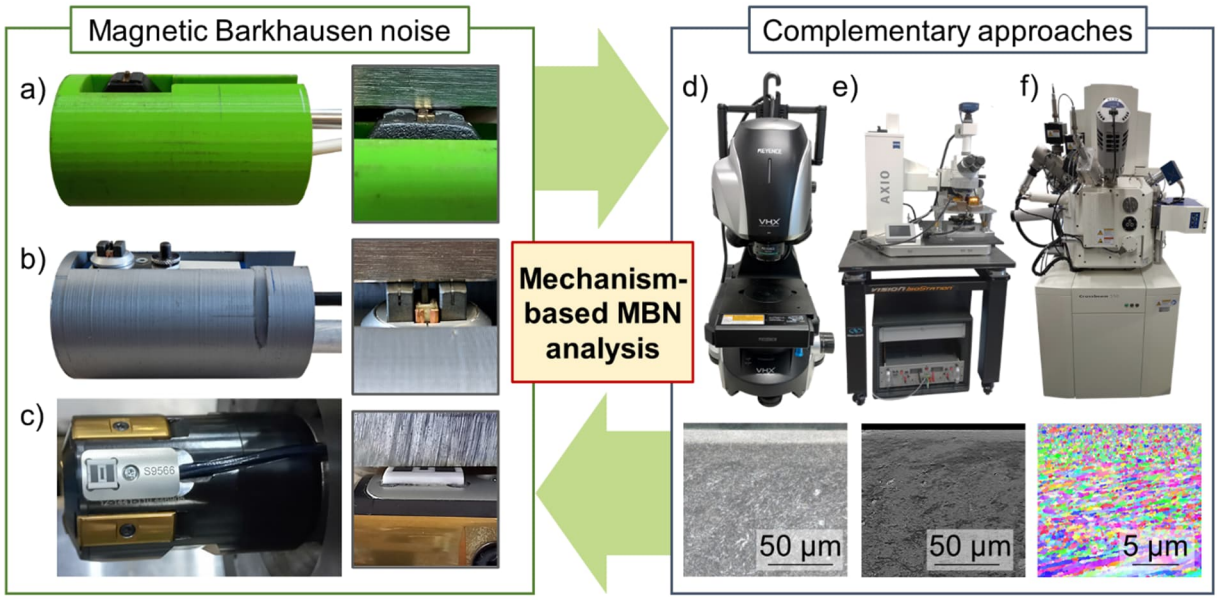

Figure 7. Setup employed for a mechanism-based magnetic Barkhausen noise (MBN) analysis, using the MBN systems: a) FracDim with a multipurpose sensor, b) Rollscan 350 with a multipurpose sensor and c) Rollscan 350 with a custom-designed drill head sensor. The mechanisms governing MBN were elucidated by d) optical microscopy, e) magneto-optical Kerr effect microscopy and f) electron backscatter diffraction (EBSD) and scanning transmission electron microscopy (STEM), using a scanning electron microscope (SEM) in combination with a focused ion beam (FIB). Modified version of [3].

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Magnetic incremental permeability for stress assessment

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Abstract

Magnetic Incremental Permeability is an electromagnetic non-destructive testing (NDT) method used to characterize industrial ferromagnetic parts and evaluate surface properties and treatments like cementation depth, hardness, or residual stress. Residual stress is a determining property for the performance, integrity, and service life of structural steels. A precise assessment of internal stress makes it possible to anticipate possible breakdown and degradation with disastrous consequences. This study explores the magnetic incremental permeability response of a single crystal of Grain-Oriented Iron-Silicon steel under the influence applied uniaxial stress. The experimental observations are confronted to theoretical results predicted with a multiscale model.

1 Introduction

Residual stress can significantly reduce the lifespan of industrial parts. Many methods have been developed to estimate residual stresses, like X-ray diffraction, the hole drilling and the contour method, but these methods are expensive and time-consuming. An alternative option for ferromagnetic materials is the indirect observation of residual stresses through their magnetic signatures [1]. In the first part of the study, we investigate the change of magnetic properties of a specific type of steel as a function of stress. The second part introduces a model to predict these changes.

2 Incremental permeability measurements on FeSi GO steel sheets

2.1 Incremental permeability

As defined by German standard [2], the Magnetic Incremental Permeability (MIP) corresponds to the slope of the inner asymmetric hysteresis loops (Figure 8). These loops, also called minor cycles, are obtained when the tested material is exposed to the superimposition of two magnetic contributions:

1. A low-frequency (quasi-static), high amplitude magnetic excitation that provides a bias magnetization.

2. A high-frequency, low amplitude magnetic excitation, allowing the measurement of the relative magnetic incremental permeability μ_{MIPr}.

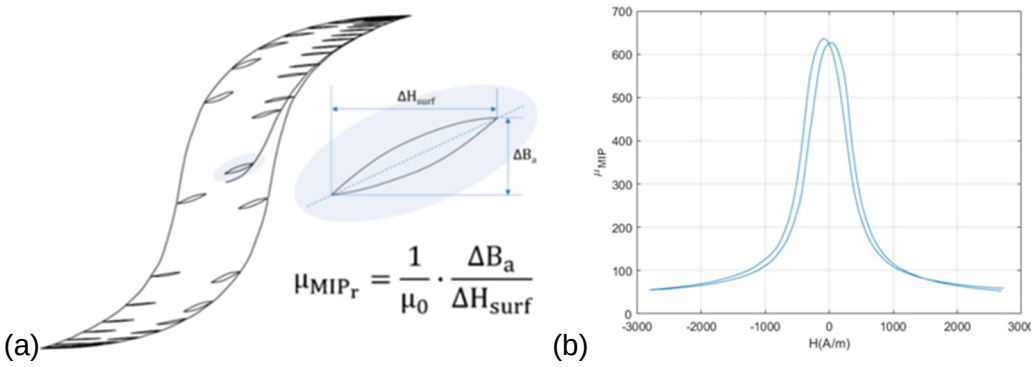

Figure 8. a) MIP illustration and definition and b) example of incremental permeability measurement.

2.2 Experimental set-up

Single crystal of Iron-Silicon Grain Oriented sheets (FeSi GO) was tested in this study. All specimens were extracted from the same batch and cut by electrical discharge machining (EDM) at different orientations from the rolling direction (0°, 30°, 60°, and 90°). For each orientation, MIP measurements have been performed at various levels of applied tension stress. MIP was measured along the specimen in the direction of stress application. The setup measured the impedance of the MIP sensor (wrapping coil around the single crystal). MIP is obtained from the following relation [1]:

$$\mu_{MIP} = \frac{Z'' \cdot l}{\mu_0 \cdot N^2 \cdot A \cdot \omega} \quad (1)$$

Where l the yoke inter-leg length, μ0 the vacuum permeability, N the number of turns of the coil, A the cross-section of the specimen, and ω the frequency.

3 Numerical model

The development of an accurate model for the magneto-mechanical effect is crucial to predict residual stress from magnetic measurements. In this study, a multiscale model [3] was designed to model MIP. For this purpose, it was assumed that stress impacts MIP and differential permeability in similar ways.

Conclusion

Magnetic Incremental Permeability (MIP) is contingent upon both the orientation and magnitude of stress. A multiscale model has been formulated to predict the surface stress distribution from MIP characterization.

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More complex evaluation of surface integrity using residual stress depth profile testing

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Abstract

In many segments of industry, preciously machined hardened steels are used. In addition to hardness and geometrical parameters like shape, dimensions and surface roughness, some other parameters are also important which indirectly describes fatigue properties. These are summarized below by the term “Surface integrity”. This term is very wide, complex and sometimes too arbitrary. For these purposes, parameters mined from Barkhausen Noise Analysis (BNA) and from Residual Stress (RS) measurements such as residual stress profiles can be created. The measured RS profiles can be used for calculation of Sum of Effective Residual Stresses (SERS). This paper introduces new parameter called Effective Residual Stresses Integral (ERSI) which describes plot of residual stress below the surface. This approach of smoother ERSI allows to describe surface integrity as the surface damage physically reasonable scale. In experimental part based on carburized steel samples some comparison of parameters based on BNA, RS tests, SERS and ERSI is presented.

***Keywords*:** ground steel, surface integrity, fatigue, Barkhausen Noise Analysis (BNA), Residual Stress (RS), Sum of Effective Residual Stresses (SERS), Effective Residual Stresses Integral (ERSI)

1 Introduction

The surface status of machined steel is very important. There are many approaches to evaluate and describe it. Classical engineering point of view requires that a part and its surface must fulfil prescribed geometrical parameters expressed in terms like size, shape, roughness and hardness. Earlier, terms like grinding burn were used for only visible grinding damage. Later it was noticed that not all grinding burns were visible and needs Non-destructive testing methods for revealing them. Chemical method-based grinding burn detection can be done with Nital etching where different structures from metallographic point of view are etched in different way with different colours or shades. This method is standardized and conservative but risky. Along microstructure, we can describe surface damage in terms which can be interpret in physics such as residual stresses (RS) coupled to volume changes in the surface and subsurface area of ground part. In addition, magnetic methods based on the movability of magnetic domain walls, expire which can be measured as parameters obtained from Barkhausen Noise Analysis (BNA). Mainly these two

methods; RS and BNA for surface integrity evaluation are discussed below. For Barkhausen Noise Analysis (BNA), the intensity of the signal (root-mean-square, RMS) which also is called as the magnetoelastic parameter (mp) describes the level of the surface damage. Many papers since 1980, when such a method was strongly introduced to industrial practice, describes this fact [1]. The origin of this method is the movability of domain walls which can be disturbed in ferromagnetic materials similar way as movability of dislocations by plastic deformations. Different imperfections in the lattice works such a way. Similar concept is magnetoelastic interaction showing tensile stress to increase the level of BNA signal in steels. Summarizing the effect of hardness and residual stress it is said that RMS value reflects the level of surface damage for temper burn where the austenitizing temperature has not been exceeded. Whereas, for re-hardening grinding burn, the evaluation based on the RMS value might be more complicated. The BNA is used for distinguishing between faulty and valid ground parts while residual stress (RS) profile is used for identifying the level of surface damage. The most common way to compare the BNA outcome is to compare it to another destructive or semidestructive methods to find out accepted/rejected level of RMS. From the RS profile, indexes such as the sum of effective residual stresses (SERS) and effective residual stresses integral (ERSI) can be computed to better describe the level of surface damage. These are also introduced in this paper.

2 Materials and methods

2.1 Surface integrity evaluation using RS measurements

For this study, several samples of gears with small modulus from carburized and tempered steel with final machining and grinding were used. For residual stress determination, X-ray diffraction (XRD) method was utilised with CrKα radiation yielding penetration depth less than five microns. For material removal, samples were etched with ATM Kristall 650 etching machine with ATM K1 etchant with area of 5 mm diameter with depth up to 0.3 mm simultaneously along with the XRD measurements. The BNA measurements with Rollscan 350 (Stresstech) were used for distinguishing between the faulty and valid parts while the residual stress (RS) profiles are used for identifying the level of surface damage. From the RS profile, indexes such as the sum of effective residual stresses (SERS) [2] and effective residual stresses integral (ERSI) can be computed to better describe the level of surface damage.

From this gear sample set, two samples N4 (good) and N3 (bad) were used for more detailed study. Table 1 shows the measured RMS and surface residual stress values for the samples. Figures 5 and 6 show the residual depth profiles. The quantification of the samples was done based on the slightly increased RMS value but also with the residual stress depth information. In terms of RS, for well ground surface typically compressive stress is on the surface smoothing to some value close to zero in depth of fifty microns. Receiving surface RS_0 on the level 300 or 400 MPa compressive, sounds to be proper as shown in Fig.1a for carburized steel. Part ground different way, not so well, in Fig. 1 b shows that the surface value RS_0 is negative but below the surface some tensile residual stresses are noticed. In this case surface RS_0 value could be almost equal to a well ground part, but the general situation is much worse (Fig.1b).

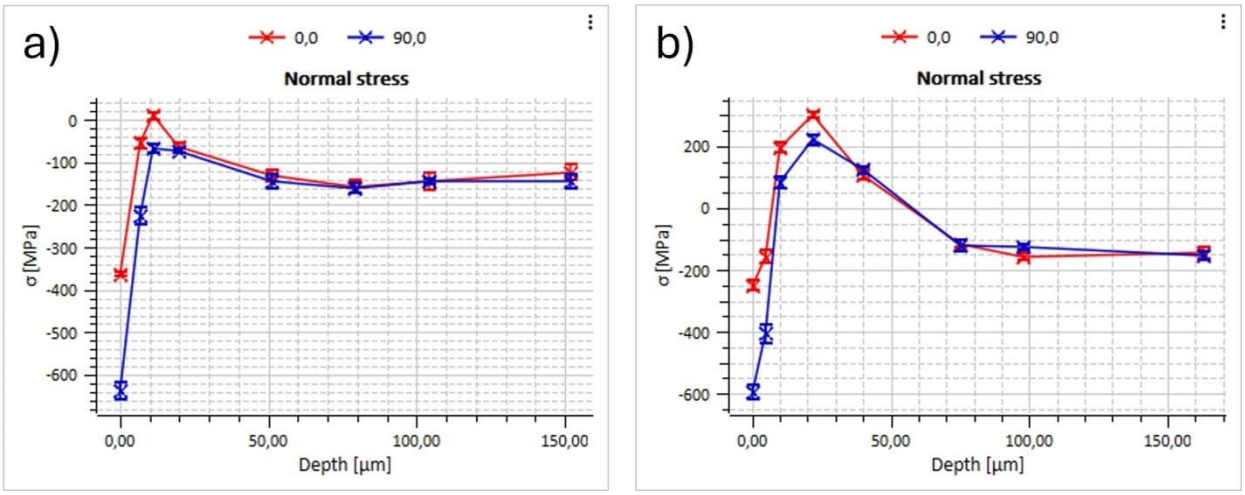

Figure 1. a) Plot of residual stress depth profile on well ground part, b) Plot of residual stress depth profile on not so well ground part.

2.2 Concept of SERS

The RS depth profile meaning the dependence of RS on the depth seems to be the most complex method to describe the surface integrity [3]. To obtain the RS depth profile requires some work and is not non-destructive method. Therefore, it is reasonable to use and utilize more complex computational methods. Layers of steel closer to the surface have stronger effect for example to the fatigue properties. That is why a parameter called Sum of Effective Residual Stresses (SERS) was introduced [4]. SERS is interesting not only to summarize the set of discrete values RS(t) but because this parameter can have some physical meaning to describe surface damage in energy per surface area, in units Joule per square metre (Jm^{-2}). Figure 2 shows an example of a RS profile and the distinct RS values with varying depth (*t*). The figure also shows the idea how SERS is calculated as the sum of the areas between the RS profile and the baseline (RS_B). The value of SERS is calculated from (see Figure 2 for notations):

$$SERS = \sum_{i=1}^{n} F_i \left(\frac{RS_i + RS_{i-1}}{2} - RS_B \right) (t_i - t_{i-1}) \tag{1}$$

Factor F_i expresses the weight of the i:th layer. It is desired that the weight for the layers closer to the surface have higher values emphasizing that they have a greater contribution towards surface integrity. The values of the weights in respect to the depth is normalized as

$$\int F(t)dt = 1. \tag{2}$$

Expressing the SERS value as Joule per square metre (Jm^{-2}) shows potential that there exists some critical value mainly for well ground steel (good part) on the level of –1 kJm^{-2} which could guarantee reasonable lifetime of part in use. Still, it is questionable and needs further studies if this limit can be identical for different types of steel. This needs further experimental work.

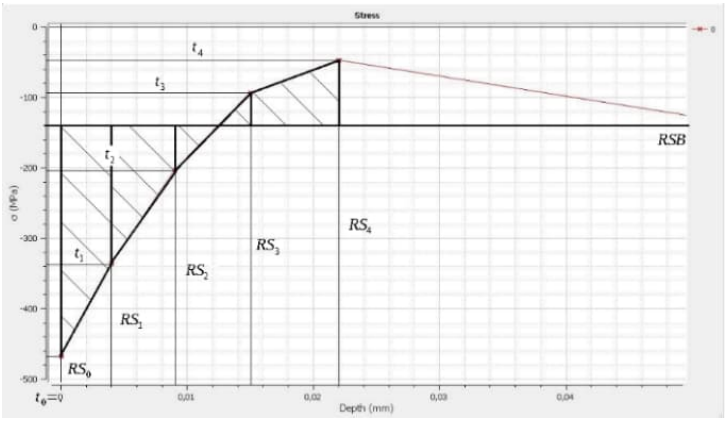

Figure 2. Schematic plot of RS values and design of SERS.

3 Results: Concept of Effective Residual Stress Integral

Typical plot of the residual stress depth profile on ground and shot-peened surface can be shown schematically in Figure 3. In the figure, the green curve shows a typical residual stress depth profile of a good part, blue curve shows a minor grinding burn and brown demonstrates major burn at a machined part. Grey plot shows a typical example of the residual stress depth profile on shot-peened surface with higher compressive stresses deeper below the surface.

Properly ground part typically has compressive stress on the surface gradually reaching some asymptotic value in the depth of 100 µm or more. A minor burn residual stress depth profiles usually start with compressive stress on the surface changing into tensile stress deeper below the surface. The worst situation, the major burn, comes with surface residual stress value already tensile with a stress peak strongly in tensile stress values in depth of about 50 µm.

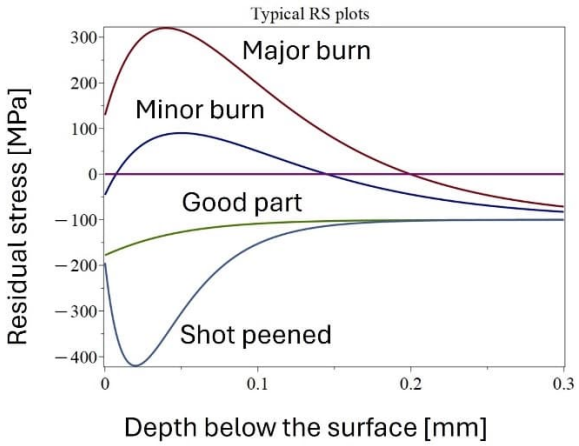

Figure 3. Schematic plots of residual stress depth profiles.

To obtain a smooth RS profile, some function may be fitted to the experimental data. One promising alternative is a four parameter Morse function shown in Figure 4. The figure shows also, how the fitting parameters *a*, *b*, *c* and *d* are calculated. The Morse function is given by:

$$RS=c-d[exp(b-at)-1]^2 \quad (3)$$

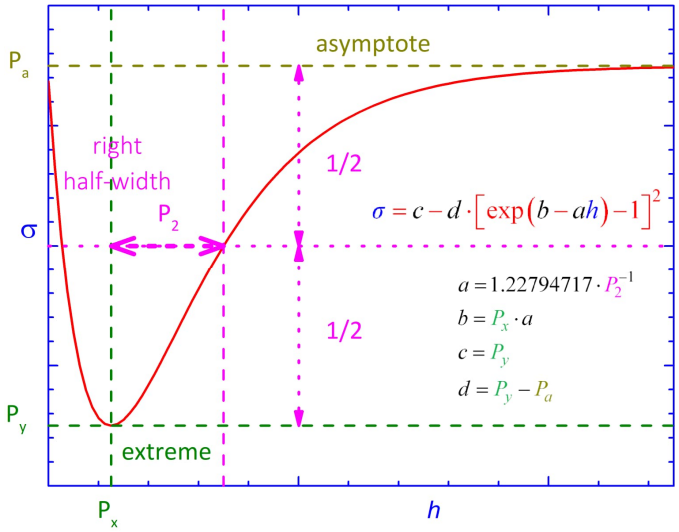

Figure 4. The Morse function and description of parameters for (3).

The four parameter Morse function is observed to approximate experimental data points well with a smooth curve for example if seven RS values from depths of 0, 5, 10, 20, 50, 100 and 200 µm are available. Some RS value in the depth of 155 µm may also be needed for calculation purposes. Figures 5 and 6 show two examples of measured RS values and the fitted Morse functions for samples N4 (good) and N3 (bad), respectively. With the smooth RS depth profile, the effective residual stresses integral (ERSI) can be calculated as the area below the weighted profile. Table 1 shows SERS and ERSI values together with the surface RS and Barkhausen noise RMS value for two samples, called N3 (bad) and N4 (good). It is seen that both SERS and ERSI are more sensitive to surface damage than the other two parameters, RMS and surface RS as Table 1 indicates.

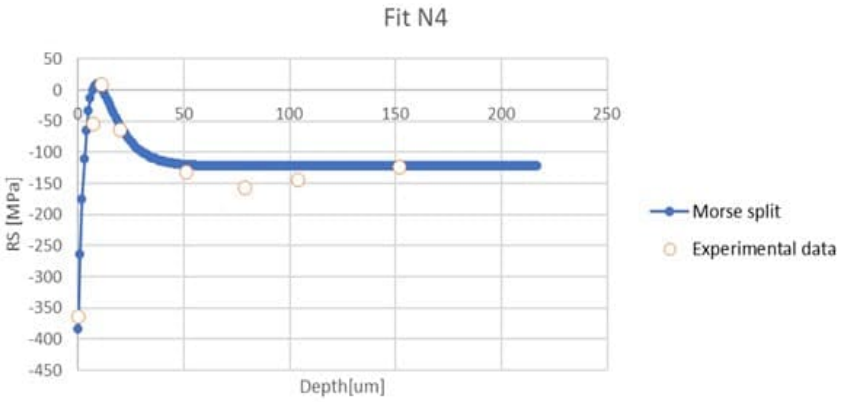

Figure 5. Experimental data with Morse split on good sample N4.

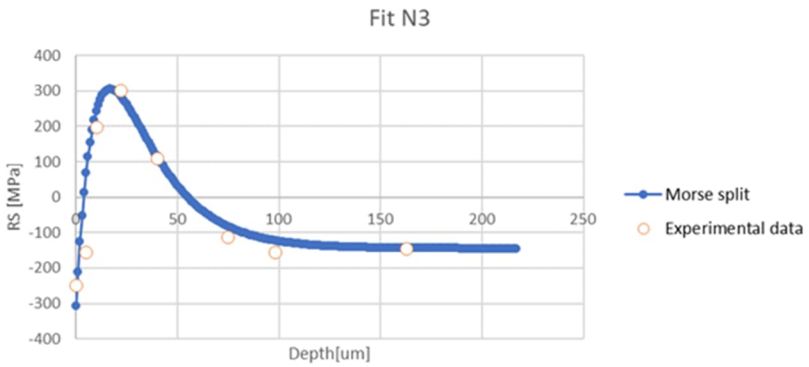

Figure 6. Experimental data with Morse split on bad sample N3.

Table 1. *Main characteristic of samples N3 and N4.*

Sample	RMS [mV]	RS surface stress [MPa]	SERS [kJm^{-2}]	ERSI [kJm^{-2}]
N3 (bad)	41.3	-251	4.08	5.42
N4 (good)	26.4	-363	0.25	0.88

4 Conclusions

Even though the surface residual stress condition is vital for the surface fatigue assessment of the component, it is difficult to use only the surface value of residual stress RS_0 for surface integrity evaluation as the studies show with the examples of tensile stress peaks just below the surface. Indexes based on the RS(t) depth profile can suit better for this. It is expected that fitting a function to RS profile is beneficial to obtain a more robust index. A Morse function is a promising candidate for such a function. The morse function is a four-parameter function and thus less than ten discrete data points can give good reliable approximation of the profile. This approximation can be used for computing the ERSI index giving the level of surface damage in the units of Joule per square metre. The SERS and ERSI indexes based on the RS(t) profile can be used for determination of physically reasonable accepted-rejected levels for tests of surface integrity in the field. This research should continue as experimental work to determine critical values of SERS or ERSI based on fatigue tests.

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Usage of Barkhausen noise analysis for detection of surface integrity properties in different grinding steps

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Abstract

Heavily loaded components are subjected to targeted heat treatment and ground to the specified contour in the final process step to produce high-quality surfaces with high dimensional accuracy. The induced thermo-mechanical load during grinding has a significant influence on the final properties of the subsurface layer. Incorrect process design bears the risk of unfavorable or detrimental thermo-mechanical modifications, such as tensile residual stresses or tempering zones (grinding burn) in surface layer.

In this study the identification of thermal damages during single-stage surface grinding of differently case-hardened workpieces made of steel grade AISI 1.7131 (16MnCr5) using two different Barkhausen noise measurement methods is evaluated and compared. Barkhausen noise measurements with a 3MA-II (Fraunhofer IZFP) and Rollscan 350 (Stresstech GmbH) devices are carried out on the initial states after heat treatment as well as on ground workpieces to compare the measurement devices and evaluate the influence of different heat treatment states. To induce varying thermal loads leading to grinding burn, depth of cut is increased stepwise, and cutting forces are simultaneously recorded. Surface integrity modifications are evaluated by metallographic cross sections, suitable for the detection of tempering zones. Additionally, residual stresses, FWHM, and hardness depth profiles are measured to obtain additional information about the introduced depth modification. The assessment of the thermal load introduced by the process into the workpiece is done by calculating the contact area-specific grinding power. Finally, it is demonstrated to what extent Barkhausen noise is capable of detecting various thermo-mechanical damages during different grinding steps.

Keywords: Barkhausen noise, Non-destructive testing, Grinding burn, Surface integrity, Depth modification

1. INTRODUCTION AND MOTIVATION

Components subjected to high loads underlie strict requirements regarding dimensional tolerances, shape and surface integrity. Consequently, following heat treatment, hard finishing by grinding is employed as the final step in the process chain to eliminate hardness distortions and fluctuations in the material [1]. Ground surfaces of hardened components, apart from geometric properties, are characterized by surface and subsurface characteristics such as microstructure, hardness, and residual stresses, significantly influencing the functional properties of the workpiece [2]. Grinding induces a thermo-mechanical load in the surface layer of the workpiece. Disturbances during grinding, such as incorrect process parameter design or fluctuations in the material, can lead to tensile residual stresses, tempering zones and even rehardening zones, which can significantly reduce component life time [1,3]. If a critical temperature is exceeded during the grinding process thermo-mechanical damages on surface and subsurface occur [4]. An initial estimate of the thermo-mechanical load (heat impact intensity) can be obtained using the specific grinding power P_c''. The specific grinding power P_c'' for surface grinding can be calculated using the tangential forces F_t, cutting speed v_c and the contact area A between the grinding wheel and workpiece or the width of cut a_p, depth of cut a_e and grinding wheel diameter d_s (equation 1) [4]. Various effects are summarized under the term grinding burn, depending on the extent of the thermal damage, characterized by tensile residual stresses, metallurgical phase transformations, formation of tempering or rehardening zones, and the occurrence of grinding cracks [5].

$$P_c'' = \frac{F_t \cdot v_c}{A} = \frac{F_t \cdot v_c}{a_p \cdot \sqrt{a_e \cdot d_s}} \quad (1)$$

Since thermo-mechanical surface damages cannot be entirely avoided, there is considerable interest in methods for their detection. Destructive measurement techniques (e.g., X-ray residual stress depth measurements and metallographic analysis) are widely used for inspecting surface and subsurface properties after grinding but cause workpiece rejection, which is why nital etching remains the most common method for detecting grinding burns in industrial applications [1]. Workpieces are chemically treated until discoloration indicates surface condition, classified by ISO 14104 into damage-free (A), light tempering (B), heavy tempering (D), and rehardening (E) [6]. Micromagnetic methods such as Barkhausen noise (BN) have been increasingly utilized in industry for non-destructive detection of thermo-mechanical surface damage caused by grinding in recent years [7]. These methods enable the detection of grinding burn without the significant disadvantages associated with the established nital etching method, such as subjectivity, safety and environmental risks [6]. However, tensile or decreasing compressive residual stresses without a decrease in hardness are not detectable by nital etching, whereas BN already exhibits high sensitivity to these changes [8].

The BN analysis relies on the periodic magnetization of ferromagnetic material volumes by an alternating magnetic field [9]. Ferromagnetic materials consist of unidirectionally magnetized domains, known as Weiss domains, separated by Bloch walls [10]. When the material is subjected

to an external magnetic field, domains align approximately parallel to the external field under shift of the Bloch walls [11]. These Bloch wall movements are impeded by obstacles such as dislocations or grain boundaries and are also influenced by residual stresses. The stepwise overcoming of these obstacles is termed Barkhausen jump and is detectable as a voltage pulse in a transmitter coil [11, 12]. After pre-processing the voltage pulses of one hysteresis loop (Figure 1 a) can be plotted against the magnetic field strength H, resulting in a profile curve (Figure 1 b). The peak positions of the profile curve correspond to the coercive field strength H_C [13]. Different measurement parameters such as the root mean square (*RMS; Rollscan, Stresstech*) or the maximum amplitude of the Barkhausen signal (*M_{MAX}; 3MA, Fraunhofer IZFP*) are derived from this curve, depending on the device manufacturer [13]. The coercive field strength H_{CM} increases with hardness and with compressive or decreasing tensile stresses [13] while the peak height decreases [14].

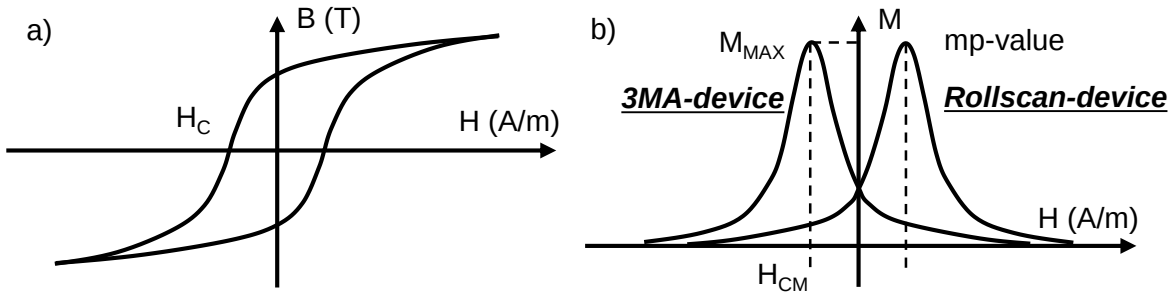

Figure 1: a) Schematic representation of the hysteresis curve b) and the profile curve of the Barkhausen noise

Using BN for detection of thermo-mechanical surface damages from grinding the amplitude of BN typically rises with increasing thermo-mechanical load [15] and hence change of residual stress and microstructural states [7, 12]. This allows the reliable detection of (light) tempering. With severe thermo-mechanical damage, the signal often reaches a maximum, and in the realm of heavy tempering [7] or rehardening [15], the signal decreases again, sometimes dropping below the initial values without damage. Besides the properties generated by grinding, the signal ratio between different surface states is influenced by material and heat treatment condition as well as by process-related factors such as grinding methods and measurement parameters [16]. From a materials engineering perspective, e.g. material properties like case hardening depth or surface carbon content affect the BN amplitude [17, 18]. Overall, there are few systematic investigations about the influences of heat treatment conditions on the detectability of thermo-mechanical surface damages using various testing methods through BN analysis.

The focus of this study is the identification of thermal damage during single-stage surface grinding of differently case-hardened workpieces made of steel grade AISI 1.7131 (16MnCr5) using BN measurements. BN measurements using a 3MA-II (Fraunhofer IZFP) and a Rollscan 350 (Stresstech GmbH) were carried out on the initial post heat treatment conditions and on ground workpieces in order to evaluate the influence of different heat treatment conditions. In order to induce different thermal loads leading to grinding burn, the depth of cut is gradually increased. Simultaneously, grinding forces are recorded and changes in surface integrity are assessed by

metallographic micrographs suitable for detecting tempering zones. In addition, residual stresses, FWHM and hardness depth profiles are measured to provide additional information on the depth modification introduced. The thermal load introduced into the workpiece by the process is assessed by calculating the specific grinding power. Finally, the ability of BN to detect different thermomechanical damage during different grinding steps is demonstrated.

2. EXPERIMENTAL SETUP AND METHODS

2.1 Material and heat treatment

The workpieces were cuboids with dimensions of 80 mm x 18 mm x 20 mm (length x width x height) made from steel grade AISI 1.7131 in different case-hardened states. The heat treatment was varied by three different surface carbon contents and tempering temperatures. After the heat treatments the final carbon contents were measured with a Spark Optical Emission Spectrometer (SOES) SPECTROLAB LAS01 (SPECTRO Analytical Instruments GmbH) in a depth of 50 µm. Hardness depth profiles were conducted on metallographic cross-sections of the specimens using a DuraScan 70 G5 hardness measurement machine (EMCO-TEST Prüfmaschinen GmbH). An overview of the various heat treatment conditions is provided in Table 1. For better comprehension within the study, the heat treatment variants are designated by specifying the carbon content followed by the tempering temperature. For example, Heat treatment 1: *0.57/190*.

Table 1: Heat treatment variants of AISI 1.7131 (16MnCr5)

Heat treatment	Carbon content (wt.-%)	Tempering temperature (°C)	Hardness at 150 µm depth (HV1)	CHD $_{550\ HV}$ (mm)	mp-value (-)	$M_{MAX\ 35\ A/cm}$ (V)
I	0.57	190	672	1.1	245.1	0.297
II	0.66	190	710	1.2	153.5	0.271
III	0.75	190	706	1.2	178.2	0.271
IV	0.67	160	722	1.2	165.2	0.271
V	0.67	220	648	0.8	176.3	0.251

2.2 Surface Grinding process

The surface grinding experiments were performed with a vitrified bonded corundum grinding wheel with the specification CFA60L15VS3CF (Saint-Gobain Abrasives GmbH) on a flat and profile grinding machine, Blohm Profimat 412 HSG (Blohm Jung GmbH). The workpieces were clamped on a magnetic chuck, connected to the force measurement plate Type 9225B (Kistler Instrumente AG) for capturing the tangential force F_t. The experimental setup is shown in Figure 1 a. The fluid supply with CUT-MAX 906-10 oil (Quaker Houghton) was provided through a flat jet nozzle oriented tangentially to the contact zone with Q_{MWF} = 50 l/min. The fluid supply conditions remained constant for all experiments. To ensure identical conditions, the workpieces were pre-ground before each surface grinding operation (v_{ft} = 500 mm/min, a_e = 4 x 25 µm). Following the pre-grinding process, the grinding wheel was dressed using a stationary single-grain diamond dresser (Riegger GmbH). The experimental and dressing parameters are presented in Table 2. Different thermo-mechanical impacts were achieved by variation of depth of cut a_e.

Table 2: Process and dressing parameters of surface grinding process

Process parameters		Dressing parameters	
Cutting speed v_c	35 m/s	Overlapping ratio U_d	3
Tangential speed v_{ft}	4,000 mm/min	Depth of cut dressing a_{ed}	0.03 mm
Grinding width a_p	18 mm	Grinding wheel diameter d_s	400 mm
Depth of cut a_e	25/50/75/100/125/150/200 µm		

2.3 Characterization methods of the ground samples

For the preparation of metallographic samples and hardness depth profiles, specimens measuring 18 mm x 15 mm x 5 mm (length x width x thickness) were eroded from the center of the ground samples. The specimens were polished and then etched with 3% alcoholic HNO_3 solution and examined under an optical microscope Zeiss Axioplan 2 (Carl Zeiss AG). Subsequently, hardness depth profiles were conducted on the specimens using a DuraScan 70 G5 hardness measurement machine (EMCO-TEST Prüfmaschinen GmbH). A diffractometer type MZ IV (GE Inspection Technology) with CrKα radiation (beam diameter 2 mm) was employed for measuring residual stresses and FWHM using the $\sin^2\psi$ method using EN15305 standard. For depth profiles, material was stepwise removed using a MoviPol5 with NaCl as electrolyte. The measurements of micromagnetic properties are described in Section 2.4. Figure 2 a) shows the setup in the grinding machine, Figure 2 b) provides an overview of the evaluation methods and measurement positions.

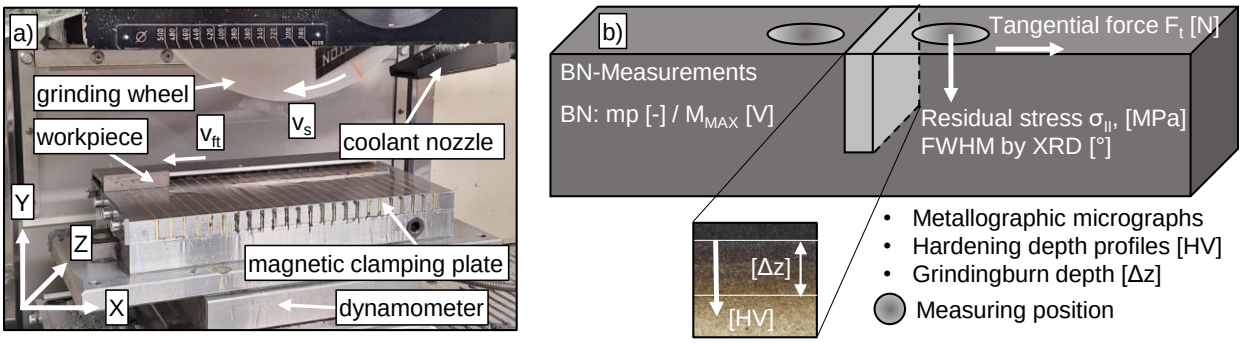

Figure 2: a) Experimental setup of the surface grinding process
b) and sketch of cuboidal sample and measurement positions for characterization methods

2.4 Micromagnetic measurements

In addition to metallographic analysis and residual stress measurements, the ground samples were analysed using two BN Measurement instruments. The BN measurements were performed with a Rollscan 350 device (Stresstech GmbH) and a 3MA-II device (Fraunhofer IZFP, Saarbrücken). In the first step, the samples were demagnetised with a degaussing coil EM12 (Vallon GmbH) to remove the magnetisation introduced from the clamping. For the BN measurements, a sweep of the magnetization amplitude was conducted to determine appropriate measurement parameters. Subsequently, measurements were conducted using the magnetization parameters specified in Table 3 for Rollscan 350 device and in Table 4 for the 3MA-II device. For each sample five measurements were taken in the centre and an average value was calculated.

Table 3: Measurement parameters for Rollscan 350 device

Measurement Parameter	Value
Magnetization Voltage sweep	0…10 V
Magnetization Voltage U_M	5 V
Magnetization frequency range f_M	125 Hz
Analyzing frequency range f_a	70 – 200 kHz

Table 4: Measurement parameters for 3MA-II device

Measurement Parameter	Value
Magnetization amplitude sweep	10/15/20 … 95/100 A/cm
Magnetization amplitude	35 A/cm
Magnetization frequency range f_M	100 Hz
Analyzing frequency range f_a	100 kHz – 1 MHz

3. RESULTS AND DISCUSSION

3.1 Characterisation of thermo-mechanical influence on surface integrity

First, the measured tangential forces F_t during grinding were converted into the specific grinding power P_c'' by using Table 2 and equation 1. The calculated specific grinding power is shown in Figure 3 a. As the cutting depth increases, the values and thermo-mechanical load on the workpiece surface layer rise, and with constant tangential velocity, the time for heat flow to act on a surface point also increases. This applies regardless of the heat treatment variants and the calculated specific grinding power is in the same order of magnitude for all treatment variants. The exemplary surface images of *0.66/190* in Figure 3 b show also a stronger discolouration or burning of the ground workpiece surfaces.

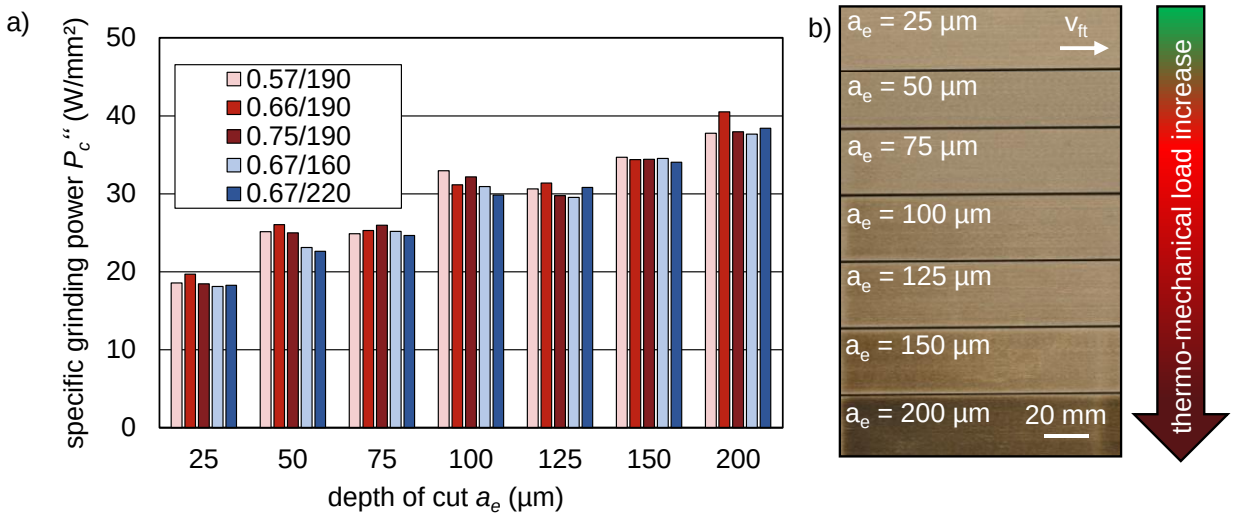

Figure 3: a) Specific grinding power P_c'' for different heat treatments with increase of depth of cut a_e b) and surface images of samples with heat treatment state 0.66/190 with increase of thermo-mechanical load

Between a_e = 50 µm and 75 µm there does not seem to be a large increase in specific grinding power, whereas there is a clear increase at a_e = 100 µm. A drop in specific power at a depth of cut a_e = 125 µm is noticeable. The increase in contact area appears to have a stronger influence in comparison to the increase in measured tangential forces, which is why there is an overall reduction in the thermo-mechanical load. Furthermore, the heat impact intensity appears to be

more pronounced at Heat treatment condition II with 0.66 carbon wt.-% and 190 °C tempering temperature with an a_e = 200 µm. Since results show a comparable thermo-mechanical load, differences in the signals of the BN for different material states can therefore not be attributed to varying grinding behaviour and are thus directly caused by the material state.

Figure 4 a shows the residual stresses and the FWHM determined by XRD (Figure 4 b) on the surface of the samples as a function of the depth of cut and the heat treatment. At the lowest depth of cut a_e = 25 µm, only compressive residual stresses and a high FWHM can be observed for each heat treatment. An increase in depth of cut leads firstly to a decrease in the compressive residual stresses and then to the formation of tensile residual stresses. The reduced thermo-mechanical load between a depth of cut of a_e = 100 and 125 µm, despite the presumed increase, is confirmed by the measured values in Figure 4. Starting from a_e = 100, a reduction in tensile residual stresses and FWHM can be observed. The FWHM is influenced, by residual stresses and lattice defects [19] and correlates well with the hardness after grinding [18]. For the highest depth of cut, the formation of compressive residual stresses can be observed at *0.66/190* and *0.67/220*. For *0.66/190* also an increase in the FWHM can be seen. It is therefore assumed that rehardening zones were generated.

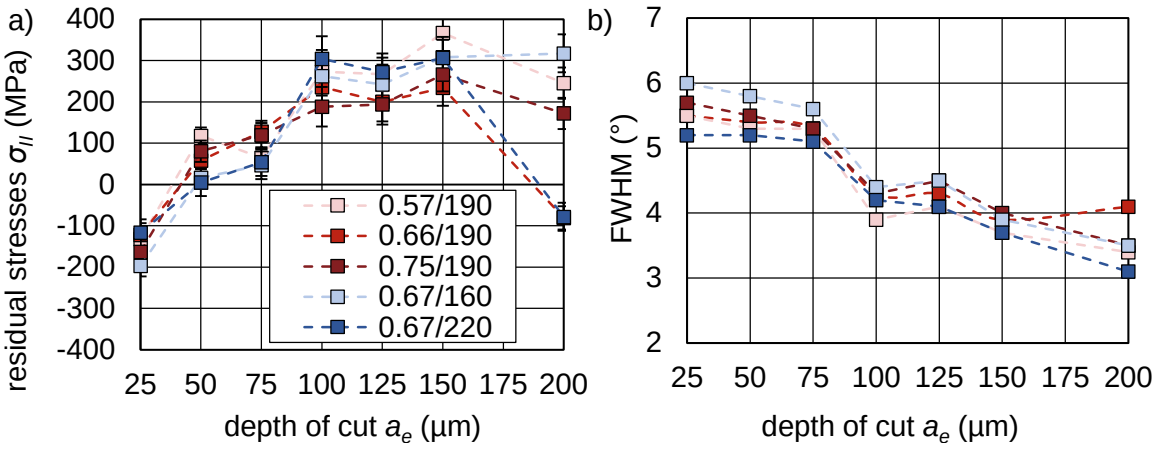

Figure 4: a) Residual stresses on the surface of ground workpieces b) and FWHM with increasing depth of cut for different heat treatments

The generation of different surface states by the grinding process can also be seen in the examplary metallographic micrographs with variation of the tempering temperature (Figure 5). Metallographic micrographs are shown for a_e = 50 µm to 200 µm. Since at a depth of cut of a_e = 50 µm no formation of thermally damaged microstructure can be seen, it can be assumed that the surface layer at a_e = 25 µm also has no tempering zones. At this depth of cut only compressive residual stresses are measured at the surface. An increase in depth of cut to a_e = 75 µm shows the first formation of light tempering zones. A further increase shows the formation of strong tempering zones and an increase in the depth of tempering zones Δz. Also high tensile residual stresses and a reduction of FWHM at the surface is visible there. At a depth of cut of a_e = 125 µm, tempering zones with a lower depth Δz can be seen at the *0.67/160* and *0.67/220* material states. This behaviour comes together with the reduction of surface tensile residual stresses. For *0.67/220*, individual surface areas with separate rehardening zones

became visible. Rehardening zones can be observed at the material states with compressive residual stresses. In the metallographic micrographs for *0.67/160* no rehardening zone is visible and high tensile residual stresses were induced. The depth of the tempering zone and the intensity of the discolouration correlate with the specific grinding power.

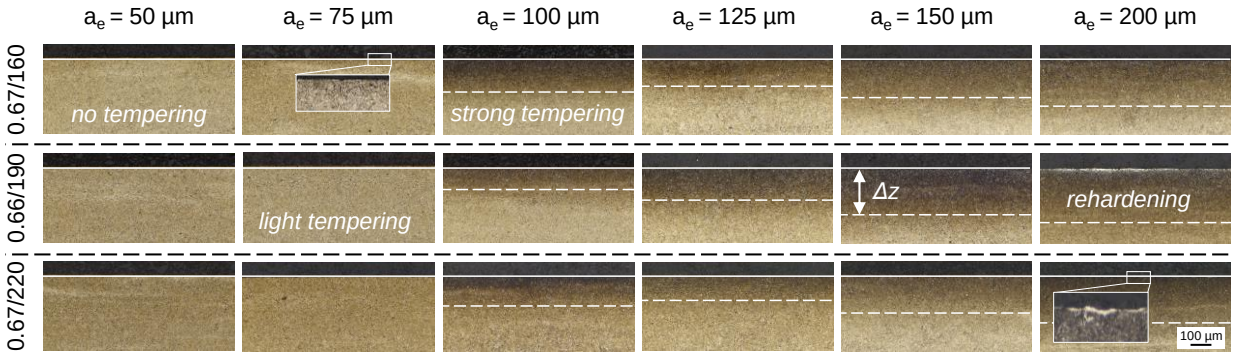

Figure 5: Metallographic micrographs of samples ground with different cutting depths and tempering temperatures

Figure 6 shows the depth modifications of residual stresses (6 a) and hardness (6 b) for *0.66/190* with increase of depth of cut. Grinding with the lowest depth of cut of a_e = 25 µm shows a more pronounced mechanical effect. Compressive residual stresses were induced. An increase of a_e shows a light formation of compressive and also slight tensile residual stresses at a comparatively high hardness. The depths of cut a_e = 100 and 150 µm initially show a similar pattern in the residual stress depth curves. The lower depth of cut results in an earlier reduction of the tensile residual stresses. At a_e = 200 µm the tensile residual stresses remain in the same order of magnitude to a depth of 200 µm. The formation of the rehardening zone is an indication of high thermal loading of the workpiece and is indicated by the formation of compressive residual stresses in the surface layer before the formation of high tensile residual stresses. In general, increase of thermo-mechanical loading goes along with hardness reduction.

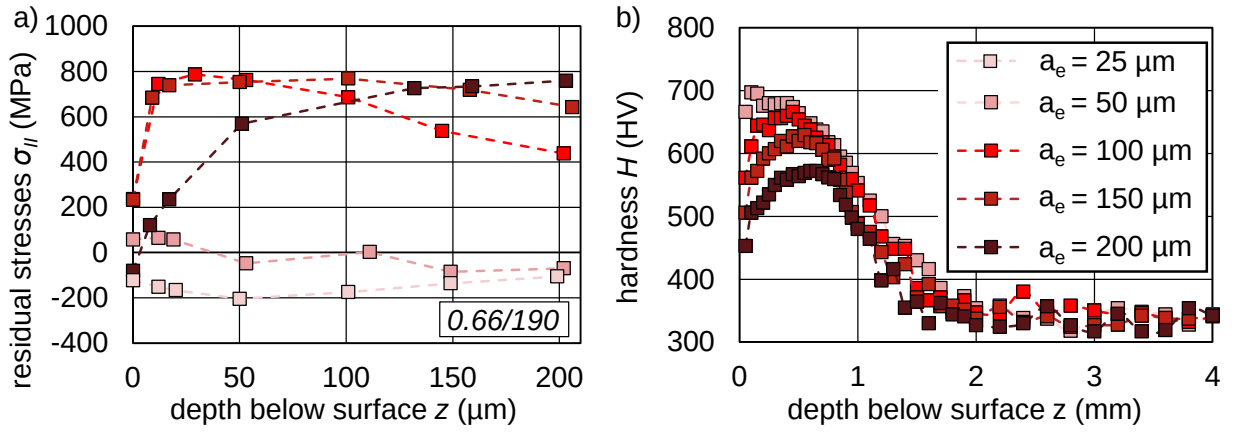

Figure 6: a) Residual stress depth profile of ground samples of heat treatment 0.66/190
b) and hardness depth profiles of ground samples with different depth of cuts of 0.66/190

3.2 Evaluation of influences on Barkhausen noise signal

The investigations in section 3.1 have shown that the thermo-mechanical load applied to the surface layer correlates very well with the specific grinding power. Uninfluenced surface layer,

light and heavy tempering zones and even certain rehardening zones were generated on samples with different heat treatments. In the following results section, the influence on the Barkhausen noise (BN) is analysed. For this purpose, two measurement methods are used and evaluated.

In order to determine suitable magnetization parameters for the 3MA-II device, the magnetization amplitude was incrementally increased during measurements of three samples in different thermo-mechanically influenced states. Figure 7 shows the development of BN-amplitude M_{MAX} and the slope for three surface states. The optimum setting is assumed to be the magnetization amplitude with the maximum slope. For further measurements, therefore, amplitudes of 35 A/cm were chosen for the BN measurements. The same procedure was used to setup the Rollscan 350 device. Here a magnetization volatage of 5 V was determined as optimum.

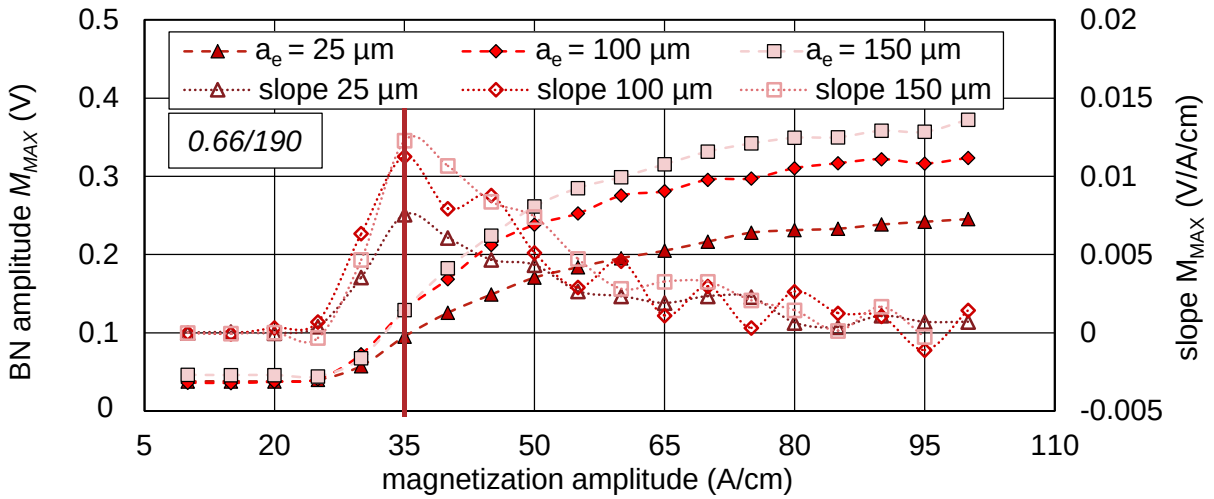

Figure 7: Development of the BN amplitude M_{MAX} and slope with increasing magnetization amplitude for 0.66/190

Figure 8 shows the BN amplitudes using the Rollscan 350 device (a) and the 3MA-II device (b) with an increase in the depth of cut for all heat treatment variants. Measurement of the BN (mp-value) for the Rollscan shows an increase from the undamaged reference condition (a_e = 25 µm) up to a maximum at a_e = 75 µm. Until this depth of cut the formation of light tempering zones and decrease in hardness and formation of tensile stresses occur. The initial increase corresponds to the increase in thermo-mechanical load caused by the grinding process, which is confirmed by the formation of tensile residual stresses. As the carbon content increases, a reduction in BN amplitudes can be seen within the individual depth of cuts. It is assumed to be due to the simultaneous increase in retained austenite, which leads to a reduction of the signal. This behavior can also be seen in [20]. There is no trend in the variation of the tempering temperature. The values remain almost constant for *0.67/160* and *0.67/220*. At a depth of cut a_e = 100 µm, the values drop rapidly as the thermally induced load continues to increase for all heat treatment variants (Figure 8 a). The associated metallographic micrographs illustrate the formation of heavy tempering zones in the microstructure, which is linked to the decrease in the signal. A further increase in depth of cut leads to a further reduction in the BN amplitude. The rehardening zone for *0.66/190* can be seen from the significant decrease in the signal. For *0.67/220*, rehardening zones could also be seen at a few spots on the surface. However, these are not apparent from

the BN amplitude. It is assumed that the measurements were carried out at a location with a strong tempering zone instead of a rehardening zone. Apart from the influence of the rehardening zone, the reduction of the BN amplitudes within the same depth of cut for the different surface carbon contents can still be seen. The areas of the four different damage types are also highlighted in colour in Figure 8.

Measurement of BN amplitudes with the 3MA-II instrument at a magnetisation amplitude of 35 A/cm shows an increase in BN amplitudes M_{MAX} with thermo-mechanical surface changes and a decrease with severe damage (Figure 8 b). Compared to the other material states, *0.67/220* shows significantly higher M_{MAX} values for all depths of cut. The 3MA-II operates at a much higher analysing frequency range, bringing the depth of analysis closer to the surface. It is assumed that this is due to the reduced hardness (Table 1). A reduction in amplitudes can be seen as the carbon content increases. This is consistent with the findings of the Rollscan instrument. There is no explicit trend within the tempering temperatures. Although *0.67/160* and *0.67/220* show a clear increase in BN amplitude, *0.66/190* cannot be integrated into the behaviour shown. The reduction in BN amplitudes only occurs at greater depths of cut compared to the Rollscan. Other criteria must therefore be identified and defined for the detection of tempering zones.

The differences in the behaviour of the measurement results are probably due to the evaluation methods of the two instruments. Different depths of the thermo-mechanically influenced material structure are included in the evaluation due to different analysing frequencies. It is also questionable to what extent the peak height of the mp-value and the averaged value M_{MAX} can be compared. It is also unknown how the two instruments process and filter the recorded signals and make them available to the user.

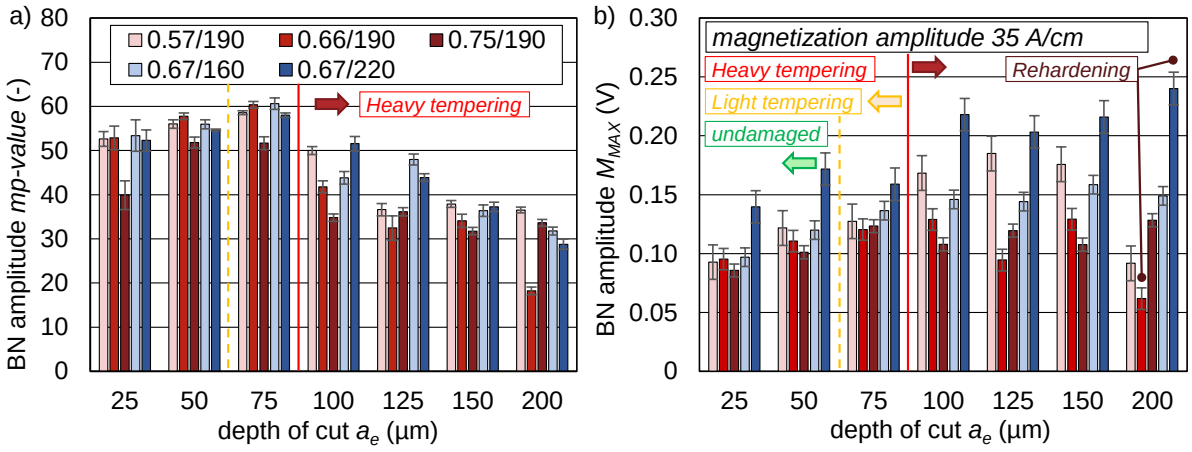

Figure 8: a) BN amplitude value – mp (Rollscan 350) of samples ground with different depth of cuts b) and BN amplitude – M_{MAX} (3MA-II) of samples ground with different depth of cut

4. CONCLUSION

In the investigations presented, the influence of different material states in terms of surface carbon content and tempering temperature on the BN amplitudes as a function of the surface integrity was evaluated. Different surface integrity conditions were generated by surface grinding and

characterised in terms of stress-, hardness-, and FWHM depth profiles, metallographic micrographs and specific grinding power. Two different instruments were used to measure BN and the results were then interpreted and discussed.

It has been shown that the specific grinding power P_c'' correlates very well with the applied thermo-mechanical load. This has been demonstrated in terms of surface residual stresses, FWHM and depth of tempering zones. Both Rollscan and 3MA-II show the ability to detect light, heavy tempering and rehardening zones. However, the Rollscan signal starts to drop off much earlier with the formation of light tempering zones, whereas the 3MA-II signal starts to drop off with the formation of heavy tempering zones. The effect of carbon on the BN signal can be seen better than that caused by tempering temperature. For better comparability between the instruments, it is recommended that individual criteria are defined to detect changes in surface integrity.

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Academic studies of Barkhausen noise at Tampere University

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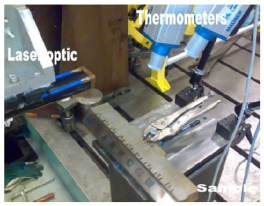
The Materials Characterization research group at Tampere University started the Barkhausen noise (BN) related studies in 1997. During the years, different aspects of the magnetic measuring method has been studied by the group in several projects in collaboration with other academic institutes and companies like BN system manufacturer Stresstech Oy or other ones utilizing the BN. The main role of the research group has been in the BN measurements and structural characterization of the studied materials. The academic collaborators have provided their expertise in the field of data analysis, modelling, simulations, and special characterization techniques. Industrial collaborators have provided the expertise on BN measuring system and provided the actual practical research questions arising from the daily use on the BN.

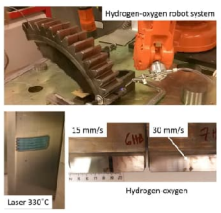
Early years

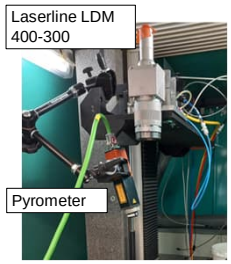
1997- 2002

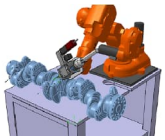
ICBM3 – 2001, TAMPERE

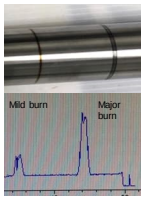
The first phase of the BN research in the group headed by Prof. Lepistö concentrated on the utilization of BN in residual stress measurements and fatigue damage estimations. Fundamental effects of e.g. **prestrain and biaxial stress on the stress vs. Barkhausen noise** relation were studied [1]. At that time, the scientific work provided background knowledge for industrial applications. The 3rd ICBM (International Conference on Barkhausen Noise and Micromagnetic Testing) conference was held at Tampere on 2–3 July 2001.

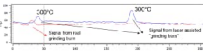


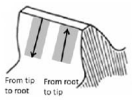












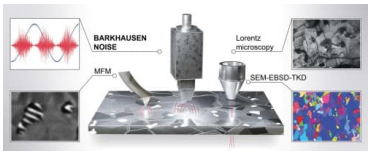
2nd phase

2007 - 2013

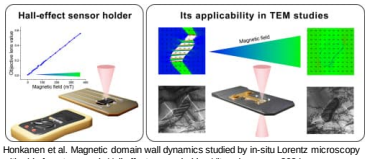
The second phase of BN research continued after few years of break in 2007. Group headed by Prof. Lepistö got acquainted with the novel data processing method called neural networks which was studied at University of Oulu and soon a research project (INTELBARK**, Implementing intelligent systems on multiparameter Barkhausen noise measurements**) covering both BN measurements and data processing with this novel technology was started. The research work of the utilisation of Barkhausen noise (BN) for characterization of hardened component surfaces with neural networks in the INTELBARK project funded by Academy of Finland (2007–2009) was continued in a Finnish funding agency for technology and innovation (TEKES) -funded research project NOVEBARK (**Novel Barkhausen Noise System for Induction Hardened Components and Material Defect Identification**) during 2010–2013. INTELBARK focused on the gear grinding burns and the first novel data processing with neural networks of the multiparameter BN data captured with Microscan software (Stresstech Oy). Close collaboration with data processing and modelling was carried out with Control Engineering Laboratory (University of Oulu, UO) during years 2007–2019 in various projects. One of the NOVEBARK project's highlights was development of the **laser processing system for creating artificial thermal damages** mimicking grinding burns altogether with detailed material characterization work of the calibration samples. The calibration sample preparation for BN method [2] with different methods has been improved and developed since 2009 in various projects involving companies utilizing the BN method. The second highlight of the NOVEBARK project was the development of **Magnetic voltage sweep (MVS) measurement concept** for case depth studies, which also other researchers [3] have utilized and further developed.

3rd phase

2015 -



Santa-aho et al. Multi-instrumental approach to domain walls and their movement in ferromagnetic steels- Origin of Barkhausen noise studied by microscopy techniques, Materials and design 2023



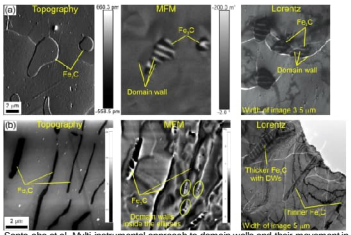
Honkanen et al. Magnetic domain wall dynamics studied by in-situ Lorentz microscopy with aid of custom-made Hall effect sensor holder, Ultramicroscopy 2024

The 3rd phase of BN research started along the change of group leader from Prof. Lepistö to Prof. Vippola. Continuing work was acquired in Academy of Finland funded project FUNBARK (**Fundamentals of Barkhausen noise and magnetic field modelling – Multidisciplinary approach to implement sweep measurements for industrial quality control**) which was performed during 2015–2019. The highlights of this project were sophisticated magnetic field modelling related to the BN sensors, grinding quality control actions with data driven models and detailed characterization work related to Jominy end quench samples studied with BN. After this, the focus of the BN-related projects moved towards the basic fundamental understanding of the magnetic domain walls and domain wall interactions in different structures during Research council of Finland funded project BarFume (**Magnetic Barkhausen Noise: From Fundamental Physics to Non-Destructive Testing**, 2021–2025). The new transmission electron microscope (TEM) at Tampere Microscopy Center provided the use of **Lorentz microscopy** which allows the observation of the **magnetic domain structures**. The BN studies now, with **link to the origins of the signal connected to micromagnetic simulations,** offer a new perspective for microstructural characterization and understanding the complex interactions of material, stress, and BN measurement results [4].

ICBM15 – 2024, TAMPERE

FUTURE

We continue Barkhausen noise studies at Tampere University with our collaborators to investigate further the complex details affecting to the BN signal. The ultimate goal is to characterize magnetic domains in 3D and link them to microstructural features.



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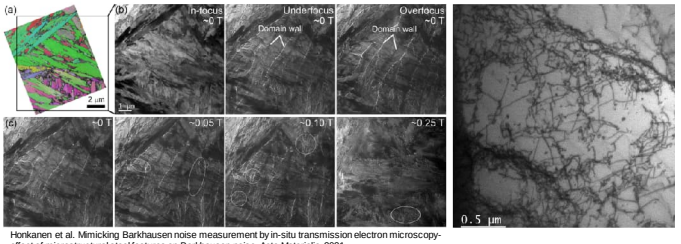

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