NON-DESTRUCTIVE CHARACTERIZATION CONCEPTS FOR PRODUCTION (OFP4p)

Public report

Project within Hållbar produktion – FFI

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Content

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1. Summary

One major challenge in the automotive industry today is given by achievement of necessary material properties (e.g. hardness and hardening depth) of a given component to withstand loads during its use. These properties could be measured by means of destructive or Non-Destructive Testing (NDT) methods. However, until this day the destructive testing methods have been dominating in the industry. The reason for this is that the available NDT-methods have been regarded as too slow and/or less reliable. The lack of fast reliable NDT-methods has several consequences for the automotive industry. The major problem is that to ensure a certain output of a production process (such as heat treatment) one has to rely on destructive testing, which is costly and time-consuming.

Results from the 2010-2013 VINNOVA FFI project *Non-Destructive Testing methods: development of innovative solutions for in-line applications* showed promising results for a variety of Non-Destructive Testing (NDT) methods with respect to the ability to characterize different material properties such as surface hardness and hardening depth. The NDT-methods studied were Barkhausen Noise (BN), Eddy Current Testing (ET) and Ultrasonic Testing (UT) which have been used for many years in the industry mainly for detecting flaws/defects like grinding burns (BN only) and cracks (ET and UT). BN and ET, which basically works with the same physical principle (magnetism), has been proven to be sensitive to material properties (e.g. microstructure) and consequently hardness levels but has, for physical reasons, limited investigation depth (approx. 2 mm from the surface). UT has also been shown to be an effective tool for material characterization but is only effective from a depth of 2-3 mm from the surface down to very high depths (several 100:s of mm in theory). This opened for exploiting the possibility of combining the two types of techniques in order to obtain a complete and in-depth non-destructive characterization of a component's microstructure.

To take a bow mentioned idea step further, a new Vinnova FFI project *Non-destructive characterization concepts for production (OFP4p)* was initiated, in order to allow the combination of the two different NDT methods: magnetic and ultrasound. The NDC concepts were based on the statistical data processing for extracting information from the data set produced by the BN/ET and UT measurements and transform it into an understandable structure. These strategies can be implemented by mechanized solutions within the production line.

The OFP4p project was organized in different work packages where each was dedicated to one heat treatment process: induction hardening, case carburizing, and nitriding. The NDT and traditional destructive testing methods were used to collect data. This procedure was then adopted in chosen different industrial case studies for verification, validation, and implementation.

The outcomes of the project have shown the possibility to use different NDT methods as a tool to characterize the process. The production process variations can be captured especially when combinations of the different NDT methods are in use.

Results from numerous experiments in the project show that:

- The method of ultrasonic testing has shown great potential in measuring the hardening depth. The Barkhausen noise method has also shown to measure the hardening depth and additionally shown to be sensitive to changes in microstructure and especially different microstructures.
- The developed test matrix showed a strong correlation with the hardness depth for both methods, but BN requires a sharp transition zone between different microstructures. The

results from the hardening need to be characterized in new ways, for example, to measure the number of different phases in the BN interaction/measurements volume.
- UT showed a clear correlation to the hardening depth at greater depths of more than 5 mm.
- For case-carburized components the case hardening depth (CHD) is difficult to measure.
- Surface topography (roughness) plays important role in BN testing.
- BN signal level (magneto-elastic parameter value) depends strongly on grinding parameters more than on grain size used for making grinding wheel. Note, that CBN grinding wheels were only tested.
- Magnetic properties of the material didn't change in depth. This topic must be investigated widely in future research.
- Step grinding experiment shows great potential to create a calibration block set for BN equipment calibration.
- Last but not least, thanks to a unified sample shape there is the possibility to perform interlaboratory measurement test (round robin). This will show the stability of the measurement method. The process is ongoing.

One of the most important achievements of this project is the good practice guide for Barkhausen noise measurements. The guide contains fundamental knowledge about Barkhausen Testing method, necessary equipment, parameters, measurement conducting, data evaluation, and decision-making process. One of the parts of this book is dedicated to the standardization of the measurement, with a working example of the Standard Operating Procedure (SOP). That can be very helpful for creating a custom SOP for the production line.

The future research subjects were discussed during the Final Dissemination Workshop, and can be as follow:

- Active control of the machining processes by using non-destructive techniques.
- Investigation of material microstructure effect on Barkhausen noise signal.
- Effective calibration methodology for BNT.
- Machining optimization methods driven by NDT sensors-based data and machine learning.
- Application of non-destructive methods for additive manufacturing.

2. Sammanfattning på svenska

En stor utmaning inom transportindustrin idag är att på ett kostnadseffektivt sätt säkerställa att tillverkade komponenter har de nödvändiga egenskaper (främst ythårdhet och härddjup) som krävs för att de skall klara de laster de utsätts för under den specificerade livslängden.

De nödvändiga egenskaperna (främst ythårdhet och härddjup) kan mätas upp med antingen förstörande eller oförstörande provningsmetoder. Fram tills nu har dock de förstörande provningsmetoderna dominerat inom industrin. Skälet till detta är och har varit att de tillgängliga oförstörande metoderna hittills har ansetts opålitliga och/eller för långsamma.

Bristen på snabba och pålitliga oförstörande provningsmetoder för mätning av kritiska materialegenskaper såsom ythårdhet och härddjup har hittills haft stora konsekvenser för den tillverkande industrin enligt följande:

1. För att säkerställa att tillverkade komponenter från en viss produktionsprocess (ex. vis värmebehandling) uppfyller specificerade krav har det hittills varit nödvändigt att tillämpa förstörande provningsmetoder på ett utvalt antal är både kostnads- och tidskrävande. Ett exempel från de deltagande företagen är att vid varje omställning mellan olika artiklar på en viss produktionslina behöver linan stå stilla nästan en hel arbetsdag i väntan på labresultaten från den förstörande provningen. Omräknat i pengar per år innebär detta cirka 16 MSEK bara för en typ av produkt från en produktionslina.
2. Det faktum att bara en del av den totala produktionen kan provas med oförstörande metoder (stickprov) innebär att statistiska metoder måste tillämpas för att säkerställa att de tillverkade komponenterna innehåller specificerade krav. Detta innebär per nödvändighet komponenterna måste överdimensioneras för att med en viss sannolikhet klara alla postulerade lastfall vilket i sin tur leder till både högre material- och tillverkningskostnader

Tidigare arbeten och studier har visat på stor potential för flera oförstörande provningsmetoder vad gäller karaktärisering av kritiska materialegenskaper såsom ythårdhet och härddjup. Exempelvis används redan idag Barkhausenprovning (BN) i stor utsträckning av flera av projektets deltagande företag som ett verktyg för att detektera oönskade egenskaper i härdade komponenters ytskikt, så kallade ”slipbränningar”.

För att fullt ut kunna utnyttja potentialen för de metoder som redan idag används för oförstörande materialkaraktärisering av tillverkade komponenter kvarstår dock vissa frågor att lösa främst vad gäller signalanalys och identifiering av viktiga variabler samt hur dessa samverkar med varandra.

Inom projektet har de oförstörande provningsmetoderna Barkhausen (BN), virvelström (ET) samt ultraljud (UT) utvärderats främst med avseende på deras förmåga att mäta härddjup på sätthärdade, induktionshärdade samt nitrerade komponenter i stål.

Resultaten från projektet som helhet är mycket tillfredställande och är mest lovande vad gäller mätning av härddjup på induktionshärdade komponenter med hjälp av UT. Med UT har i stort sett samma mätnoggrannhet som vid förstörande provning konstaterats.

Tillfredställande resultat har också uppnåtts vad gäller mätning av härddjup på nitrerade komponenter med hjälp av ET och BN och i viss mån också på sätthärdade komponenter med hjälp av BN.

3. Background

One major challenge in the automotive industry today is given by achievement of necessary material properties (e.g. hardness and hardening depth) of a given component to withstand loads during its use. These properties could be measured by means of destructive or Non-Destructive Testing (NDT) methods. However, until this day the destructive testing methods have been dominating in the industry. The reason for this is that the available NDT-methods have been regarded as too slow and/or less reliable.

The lack of fast reliable NDT-methods has several consequences for the automotive industry. The major problem is that to ensure a certain output of a production process (such as heat treatment) one has to rely on destructive testing, which is costly and time-consuming. The production process has to wait until lab results are ready before starting full-scale production. A recent survey on a camshaft production line (at one of the project partners' site) established that the average lead time for such analysis is 6,5 hours. This process has to be repeated anytime a new article is introduced in the line. The same survey shows that the introduction of NDT would imply a cost cut of 16 million SEK per year for only one type of product on one production line.

Moreover, as the outcome of a process can only be controlled through destructive testing one has to assume the statistical stability of the process, therefore, components are over-dimensioned using safety factors allowing all produced components to withstand all possible loads (Fig. 1). This implies higher production costs.

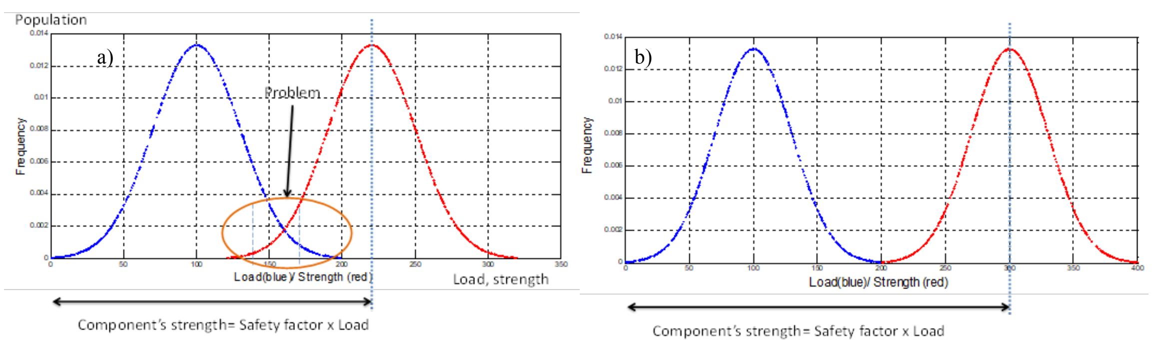

Fig. 1 Distribution of loads during components' lifetime (blue), distribution of components' strength (red). All components should have higher strength than the load they have to withstand. a) Problems occur when some of the components are not able to withstand some of the loads. b) to avoid these components are over-dimensioned by using larger safety factors.

Last but not least, competence on the heat treatment processes and the effect of the process parameters on the properties of the components often resides in the experience of the personnel. In case of turn over this competence may disappear. Having the process parameters effect mapped through NDT secures the process competence from this risk.

The previous VINNOVA-FFI-project "*Non-Destructive Testing methods: development of innovative solutions for in-line applications*" has shown promising results for a variety of Non-Destructive Testing (NDT) methods with respect to the ability to characterize different material properties such as surface hardness and hardening depth. The NDT-methods studied were Barkhausen Noise (BN), Eddy Current Testing (ET) and Ultrasonic Testing (UT) which have been used for many years in the industry mainly for detecting flaws/defects like grinding burns (BN only) and cracks (ET and UT). In order to utilize the full potential of these NDT-methods also for Non Destructive materials Characterization (NDC), there are, however, still some important issues to be resolved which is the background for this project.

BN and ET, which basically works with the same physical principle (magnetism), has been proven to be sensitive to material properties (e.g. microstructure) and consequently hardness levels but has, for physical reasons, limited investigation depth (approx. 2 mm from the surface). UT has also been shown to be an effective tool for material characterization but is only effective from a depth of 2-3 mm from the surface down to very high depths (several 100:s of mm in theory), (Fig. 2).

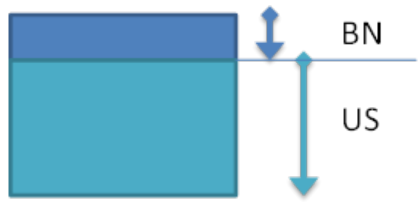

Fig. 2 Effectiveness of BN and UT/US in relation to depth of the specimen.

This opens for exploiting the possibility of combining the two types of techniques in order to obtain a complete and in-depth non-destructive characterization of a component's microstructure.

4. Purpose, research questions and method

The expected results of the project are:

1. NDC-concepts (combination of BN/UT/ET, 3D Vs 2D measurements) for measurement of critical material properties with a special emphasis on the hardening depth.
2. Model for reliable interpretation of test results with given acceptance criteria.

In order to allow a combination of the two of types NDT methods (magnetic/ultrasound), the NDC concepts will be based on data mining for extracting information from the data set produced by the BN/ET and UT measurements and transform it into an understandable structure. The concepts could also make use of 3D mapping for data presentation and analysis. These strategies can be enabled by mechanized solutions within the production line. The experimental activities will be run according to scientific methodology through the design of experiment (DoE) for generating the experiment matrix combining the factors chosen according to literature and experience from the previous project. NDT and traditional destructive testing methods will be used to extract data to be structured through data mining activities in order to generate the appropriate NDC procedure. This procedure will then be adopted in chosen different industrial case studies for verification, validation, and implementation (Fig. 3).

For physical/technical reasons the research activities have been divided into three main parts as follows:

I. Work package 2 (WP 2), Studies focused on Barkhausen Noise Testing (BN) on components with relatively small hardening depths (down to approx. 2 mm), i.e. case–hardened components.

II. Work package 3 (WP 3), Studies focused on Barkhausen Noise Testing (BN)/Ultrasonic Testing (UT) on components with fairly large hardening depths (from 2 up to 8 mm) i.e. induction hardened components.

III. Work package 4 (WP 4), Studies focused on Eddy current Testing/Barkhausen Noise testing (ET/BN) on components with very small hardening depths (< 100 µm), i.e. nitrided components.

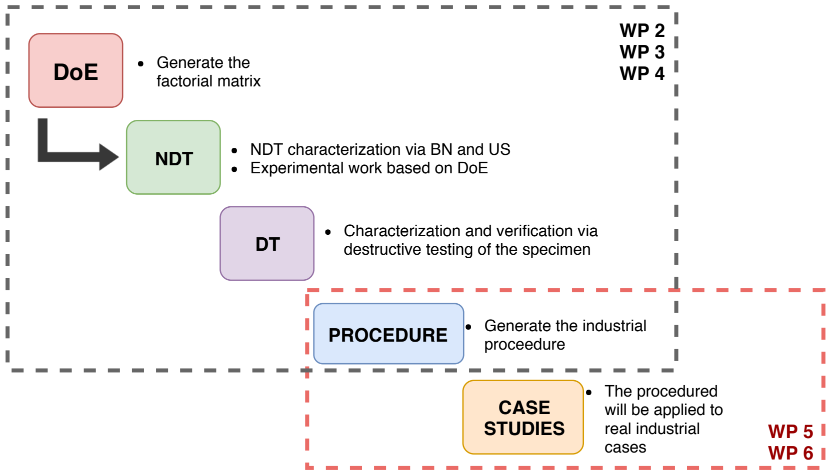

Fig. 3 Schematic representation of the research and implementation methodology applied in OFP4p.

5. Objectives

The development of the NDC methodology will allow addressing the objective of the FFI program and the Sustainable Production subprogram as it follows:

1. Faster and more efficient process control leading to shortening set up times when altering component type in the production line, through introducing innovative concepts for analysis and verification of product quality with special emphasis on the hardening depth.
2. Consequent reduction of scrap ratio resulting in higher Overall Equipment Effectiveness (OEE) as the production line will not have to wait for lab analysis.
3. Further improvement of productivity and competitiveness of Swedish industry thanks to the possibility of narrowing tolerances in terms of material properties and requirements by introducing effective methodologies for follow-up and continuous improvement. NDC can be employed to swiftly characterize all produced components, allowing to feedback data to the process in order to control the process and narrow its outcome allowing a risk-free reduction of the safety factor (Fig. 4) not dependent on statistical stability assumptions but on actual data.

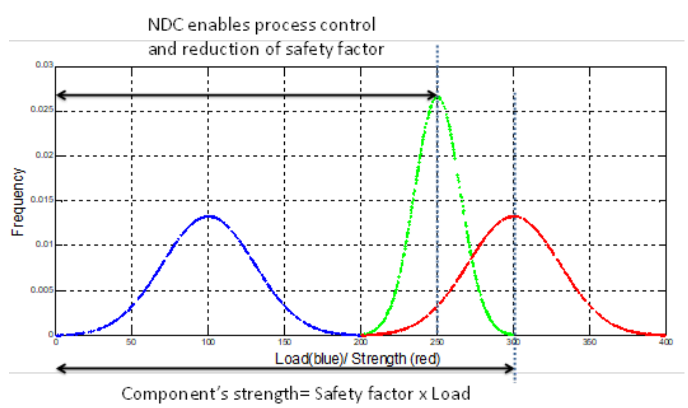

Fig. 4 Distribution of loads during components' life-time (blue), distribution of components' strength (red).

4. The total NDC will allow producing components with a predictable and defined lifetime allowing to a more efficient use of resources, both in terms of material and energy.

In addition to this, the project will contribute to a general lift of competence within the given scope thanks to the constellation of partners contributing all with their own competences in all the necessary fields of science and applications (NDT methods, material science, scientific methodology and heat treatments) both from academia and industry, allowing to create an innovative and knowledge-driven research environment.

The importance of this project in the national research agenda is underlined by the fact that NDT has been identified as a key R&D area by two of the Manufacturing R&D clusters, i.e. Component Manufacturing and Geometry and Quality.

6. Results and deliverables

Presently, the only way to ensure the output of a manufacturing process (such as heat treatment) is destructive testing, which is a costly and time-consuming process. The production process has to wait till the lab results are ready before full-scale production can be started. A recent survey on a camshaft production line (at one of the project partners' site) established that the average lead time for such analysis is 6.5 hours. This process has to be repeated every time when the article in the line has to be changed. This translates into extremely high cost per year, for only one type of product on one production line. Moreover, as the outcome of a process can only be controlled through destructive testing, the statistical stability of the process has to be assumed. Therefore, components are over-dimensioned using safety factors that allows all produced components to withstand all possible loads. This implies higher production costs as well as higher environmental impact in terms of material and energy consumption. The solution for time and money-consuming destructive testing are non-destructive testing (NDT) methods. The NDT of machine parts' surface integrity has greatly enhanced over the last 20 years. There are many methods and techniques, based on different physical effects, that can be used for NDT (Fig. 5). Faster and more efficient process control leading to reduced setup time can be achieved through the introduction of proper methods and innovative concepts for the analysis and verification of product quality, especially for altering the component type in the production line.

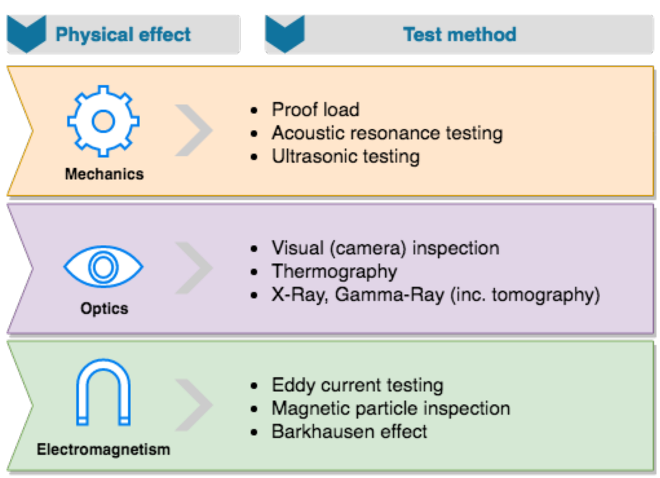

Fig. 5 General overview of the physical effects employed in NDT.

One of these NDT methods is the Barkhausen Noise Testing (BNT) method. The BNT method is utilized to assess changes in the surface layer of ferromagnetic materials, especially to monitor changes in their hardness and residual stresses. The BNT method functions on the interaction between the external magnetic field and ferromagnetic material. The reorganization of the magnetic domains and the formation of an internal magnetic field are registered by the sensor. The magnitude of the registered signal and its parameters depend on many factors. Many of them are non-correlated, while others share a strong correlation. One can easily demonstrate that the set of factors affecting the Barkhausen signal comprises more than 200 components, including interactions between factors (Tab. 1). The combination of all these factors results in the material response of external magnetization.

Table 1 Factors that can affect Barkhausen measurement

Material	Heat treatment	Machining	Surface and shape integrity	Electromagnetic properties	Measurement
Microstructure (ferrite, perlite, martenzite etc.)	Quenching	Magnetic holding - remanence	Roughness	Original domain directions	Gauge type
Grain size (fine, coarse)	Tempering	Count of machining	Waviness	Remanence	Gauge quality
Grain shape (lamellar, spheroidal, sorbitic etc.)	Carburizing	Type of machining	Roundness	Conductance (thermal, electrical)	Surface type & quality
Grid crystallographic defects	Straightening	Parameters of machining	Hardness	Permeability	Temperature
Chemical composition	Annealing		Residual stress	Coercivity	Parameters (voltage, frequency)
Internal cracks	Toughening		Scratches	Susceptibility	Voltage
Internal discontinuities			Cracks		Load force
Non-metallic inclusions			Burns		Calibration

The application of BNT has a technical and economic rationale behind it. The technical reason is shifting from destructive to NDT methods. This will be short-term, which is the money saving aspect, the economic reason. The NDT using BN method could either be considered as a go or no-go supervision method. Nevertheless, it could also be used as a tool for the development or enhancement of a process. An overall benefit of using the NDT method is that it is environmentally friendly, as it prevents the waste of the tested component. The measurements are fast and can be performed statically or dynamically on the component. The part's magnetization creates an interaction with the material that measures typically from the near surface up to a few hundred microns below the surface. The actual measuring depth cannot be easily determined, but the penetration depth could be controlled by the magnetizing frequency.

The limitations of this technique are the sensitivity of the physical condition of the sensor, part integrity (e.g. micro-structure or surface topography) and geometrical specification. For example, an oxide on the surface will influence the measurement. Further, the sensor employs a ferritic material to magnetize the tested surface. This material could wear down, especially if the measurement is dynamic, which may influence the signal. The BNT method is classified as an electromagnetic method of NDT (Fig. 6).

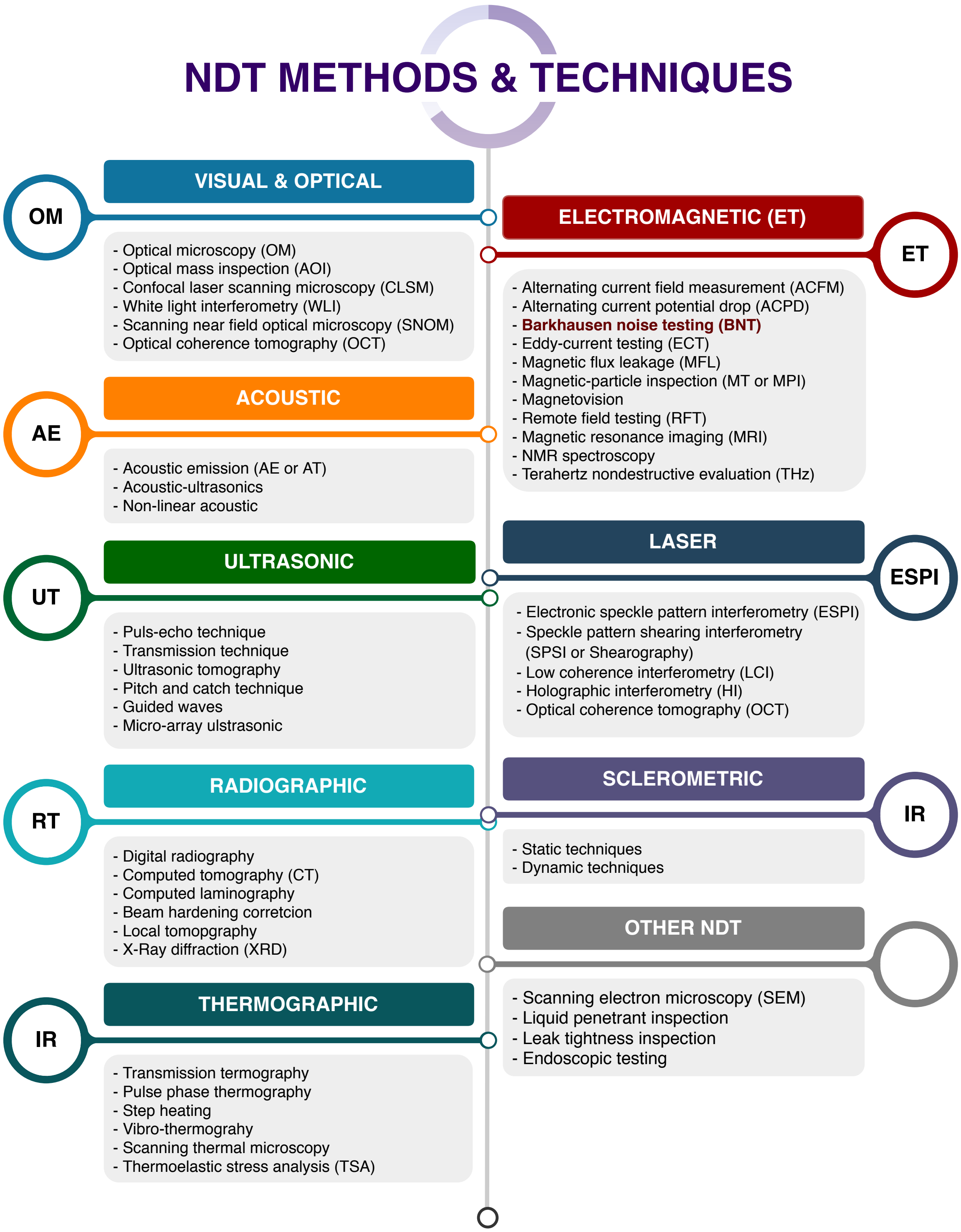

Fig. 6 Classification of NDT methods [Good Practice Guide].

The magnetic BN (MBN) method can be applied in different measurement modes, depending on the investigated material's properties:

- Hardness and residual stresses.
- Microstructure.
- Case depth.
- Other.

The Barkhausen noise method used in the "case depth mode" seeks the total and effective case hardening depth after different types of the heat treatment, such as induction hardening, case carburizing, nitriding and so on. The calculated depth of signal analysis or penetration depth of BN can be made using the skin depth effect formula (1).

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0\mu_r}} \quad (1)$$

This is normally around 40 µm to 100 µm in regular steel. Harder steel will give higher analyzing depth and softer steel slightly lower analyzing depth. There have been several research projects in the last few years concerning the analysis of the case hardening depth using BN.

6.1 WP2 – NDC-concept for case hardened components

The work package 2 (WP2) was dedicated to the measurement of the hardening depth after carburizing (Fig. 7).

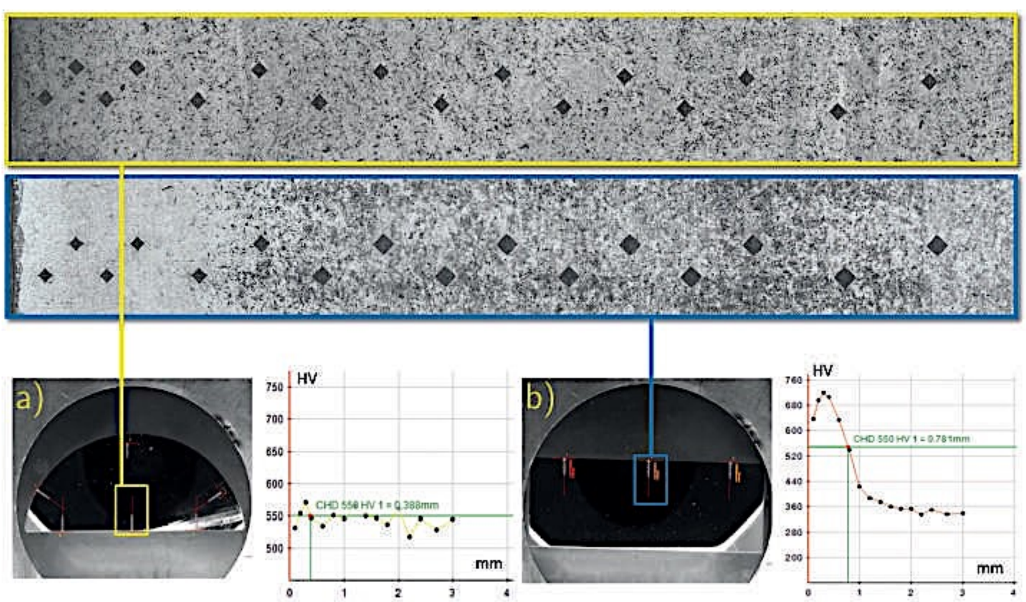

Fig. 7 Example of destructive method of case-depth evaluation through the hardness measurement for case carburized: a) on the surface, b) in depth (profile) with the indication of the "effective case hardening depth".

When a magnetic material is magnetized by an alternating field or time-dependent magnetic field, an effect takes place when the field impinges on an electrically conducting material. Based on the Faraday-Lenz law of electromagnetic induction, time-dependent magnetic flux will generate an opposing electromagnetic field or voltage. In an electrically conducting material, this gives rise to induced currents, commonly known as eddy current, which opposes the penetration of the applied field. Therefore, magnetic field penetration depth into bulk is limited by this eddy current screening. The calculated depth of signal analysis or penetration depth of BN can be made using a so-called skin depth effect. This is normally around 40 µm to 100 µm in regular steel. Harder steel will give higher analyzing depth and softer steel slightly lower analyzing depth.

Investigation on the penetration depth of magnetization signal was made for soft material, before hardening. The magnitude of Barkhausen signal was measured by moving sensor over blind holes. The samples had blind holes were with different depth, from 14.8 mm to 13.2 mm, simulating different thickness of surface, from 0.2 mm to 1.8 mm. The non-hardened material had a ferritic-pearlitic microstructure with non-uniform distributed stresses. It can be observed that recognized penetration depth for the soft material is 0.6 - 0.7 mm (Fig. 8).

Based on the analysis the BN signal value *mp* dependency of the magnetization frequency and the magnetization voltage was determined (Fig. 9). This relation allows concluding that penetration depth is much bigger than sensing depth. There is still need work to be done in according to better signal sensing evaluation in relation to penetration depth since this ratio relies on the material microstructure and sensor capabilities (which can differ).

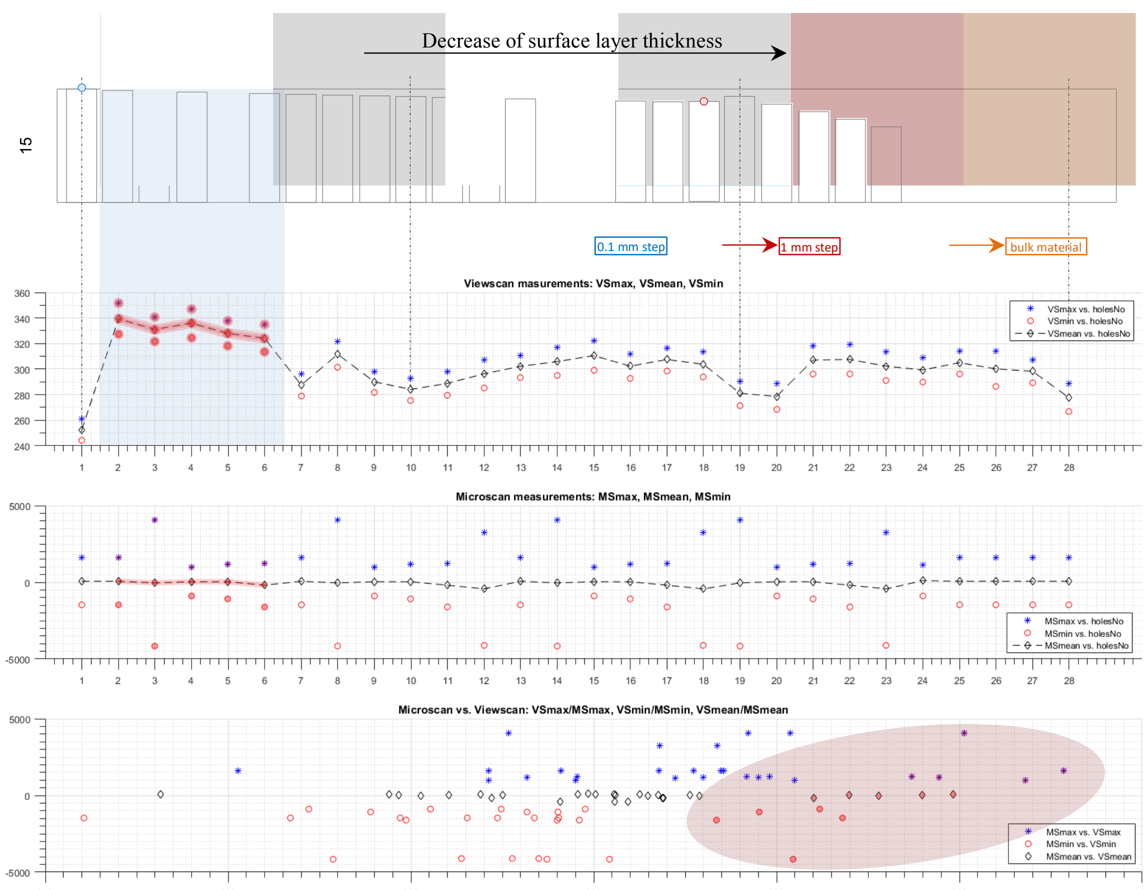

Fig. 8 Penetration depth of magnetic field measurement for soft material.

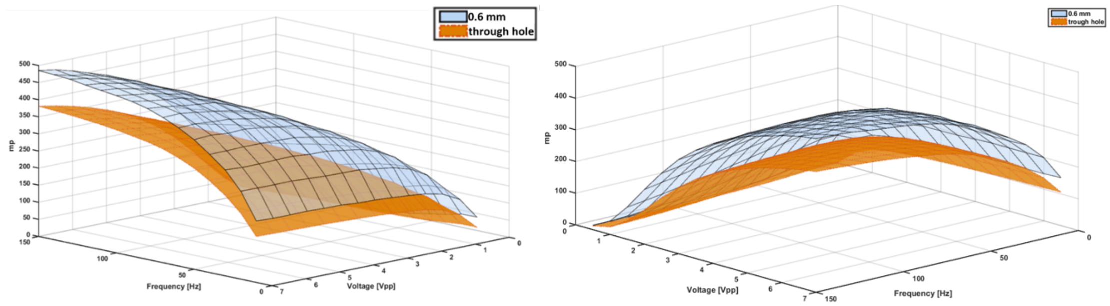

Fig. 9 Evaluation of the penetration depth in the relation to magnetization voltage and magnetization frequency

Penetration depth assessment caused another experiment, where surface topography effect on BN signal was investigated. The chemical composition of the steel used in this study is given in Table 2.

Table 2 Chemical composition of the C38mod (38MnVS6) steel used in this study

Element	***C***	***Si***	***Mn***	***P***	***S***	***V***	***N***
Wt. %	0.34/0.41	0.15/0.80	1.20/1.60	$\leq$0.025	0.020/0.060	0.08/0.20	0.01/0.02

The samples were cut from the crankshaft engine truck in the form of plates with hardness 57HRC on a surface after induction hardening. Before measurements, the samples were etched using Nital (2% NHO3 in ethanol) with different time of exposition, in goal to change surface topography without changing residual stresses in near-surface layer. MBN measurements were made using the Rollscan 300 system and flat surface sensor pick-up coil supplied by Stresstech Oy, Finland with excitation voltage 0–16 V and magnetization frequency of 125 Hz. The MBN signals were acquired at 2.5 MHz sampling rate and analyzed in the frequency range of 10–1000 kHz (70–200 kHz dominant frequency range) using dedicated software Microscan and Viewscan, as well as Matlab™. The MBN signal is averaged over 10 cycles of magnetization and the average MBN level is plotted as a function of the percentage of the excitation voltage applied to the electromagnetic (EM) yoke has been used for analysis of the MBN profile. Surface topography measurement was made using Sensofar 25 system, supplied by Sensofar Metrology, which is working based on confocal laser scanning microscopy method (Fig. 11).

Etching the surface acts as a filter. Peaks are dissolved and the valleys are deepened. It should be noted that the peaks are removed faster. The most sensitive parameters for evaluation changes after etching are *Sk* parameters (Fig. 10).

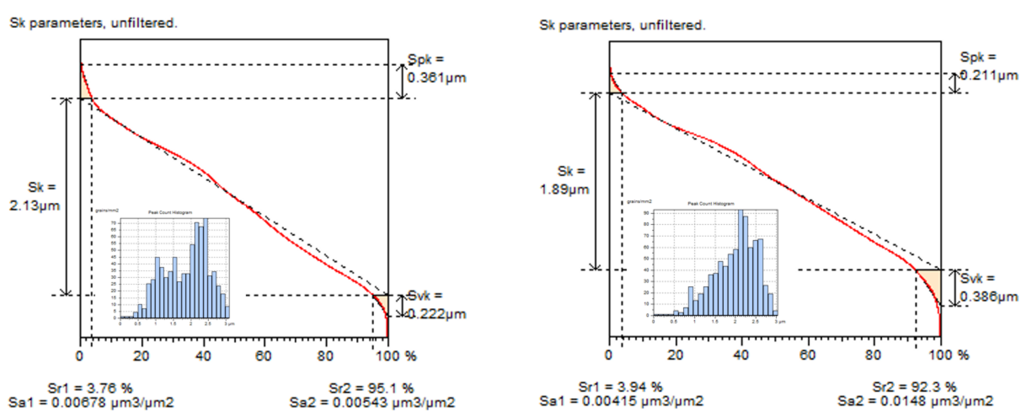

Fig. 10 Sk parameters before (left) and after 60s etching (right).

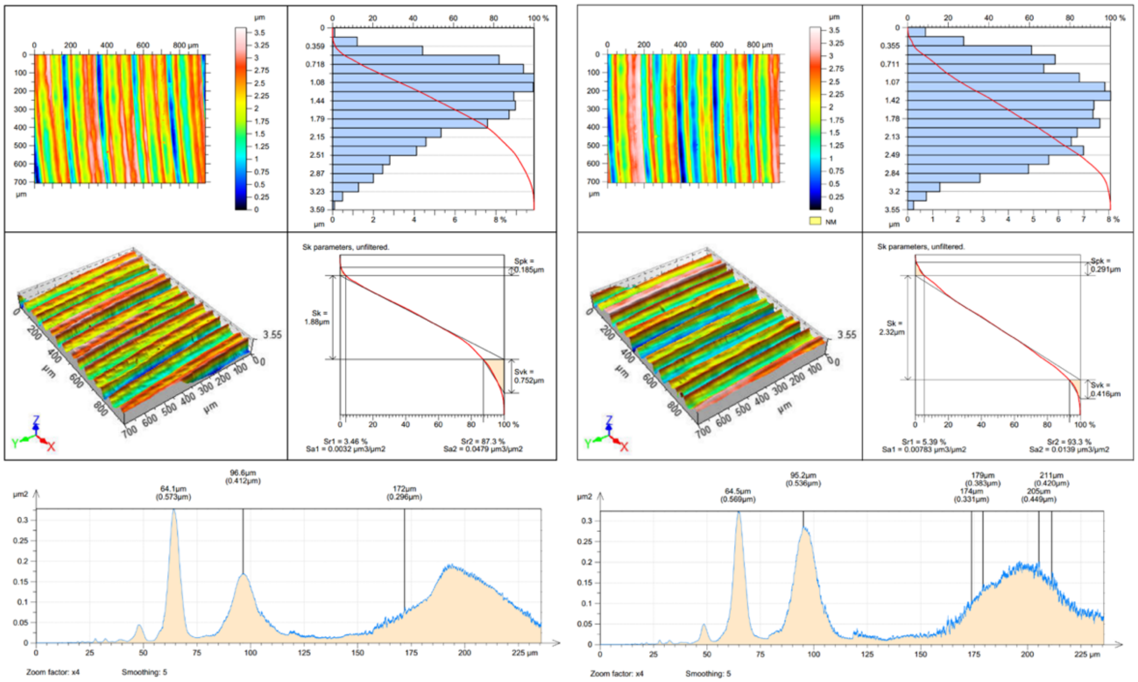

Fig. 11 Surface before etching (left) and after 60s of etching (right).

Measurements were made for a quite rough surface to an observation of visible changes in surface roughness, but further investigation is needed, especially for smooth surfaces. Change of surface topography even in a small field causes a change of signal measure behavior. That may be caused by better contact between measured surface and sensor. Almost all parameters of BN signal increase with time exposition of etching, which was changed from 0s to 60s with the 15s step. More different surfaces with similar hardness and residual stresses value are needed, to investigate in deep surface roughness effect on the BN signal, especially after abrasive machining processes.

Table 3 Parameter values of BN signal for sample set

Etching	RMS avg	Peak avg	Peak pos avg	FWHM avg	Coercivity	Remanence	Permeability	Integral area	Spectrum area
Before	**65.3**	**108.5**	**0.5**	**51.9**	**0.0501**	**50.04**	**1034.0**	**102.10**	**10350**
15s	47.9	80.8	3.8	46.1	0.0621	46.75	767.7	85.09	7617
30s	54.8	94.8	0.2	45.5	0.0220	18.71	898.7	45.81	8679
44s	73.9	138.4	10.6	30.1	0.1303	185.60	1413.0	192.30	11480
60s	**81.7**	**146.3**	**14.7**	**43.1**	**0.1423**	**196.30**	**1464.0**	**224.70**	**12870**

As an effect the wider hysteresis of measured Barkhausen signal after etching was obtained, which means that is harder to magnetize and demagnetize of the test material (Fig. 12).

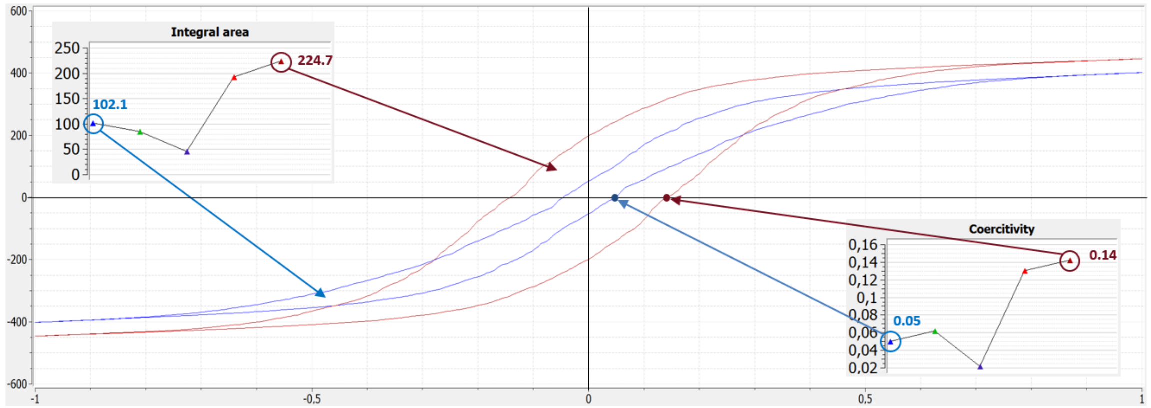

Fig. 12 Integral of Barkhausen noise signal before (blue) and after 60s of etching (red).

Another experiment for the well-parametrized grinding procedure has shown a tremendous effect on BN and residual stress level. The grinding procedure was done for the case carburized samples (made by Bodycote, project partner), where half of the batch was normalized in 180 C degrees for 1.5h after carburizing. Also, two grinding wheels with different size of grains and two feed rates were tested. It's clearly visible that the most significant effect on the BN signal has feed rate (Fig. 13).

Grain size as well as normalizing (even if hardness was slightly changed) has less effect on BN signal values. Nevertheless, in the different groups, it was observed that the variation of the parameters is bigger for bigger grain size.

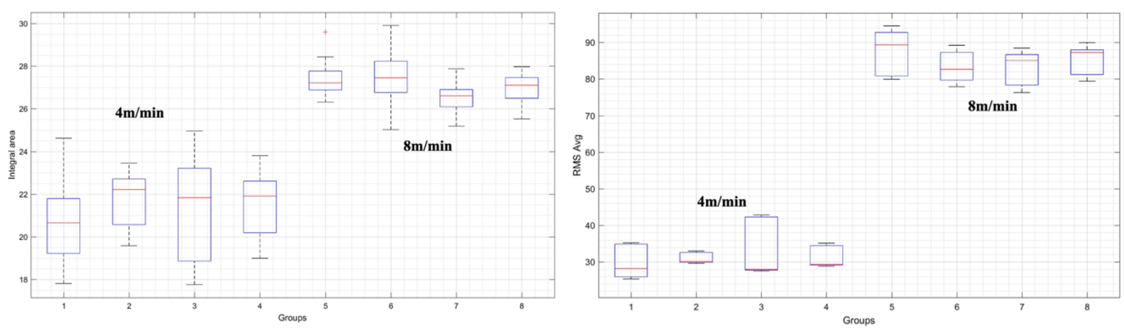

Fig. 13 (a) Integral area depended on the feed rate, (b) RMS avg. values depended on the feed rate.

Despite the good and promising results, it's worth mention that case carburized components are difficult to investigate in the terms of the case hardening depth with BNT (Barkhausen Noise Testing). This difficulty has the origin in the very long carburizing transition zone, where the carbon content is changing non-linear (Fig. 14). The depth of the measurement is also a result of the eddy current shielding effect experienced by the propagating electromagnetic field and is strongly dependent on the electric and magnetic properties of the material.

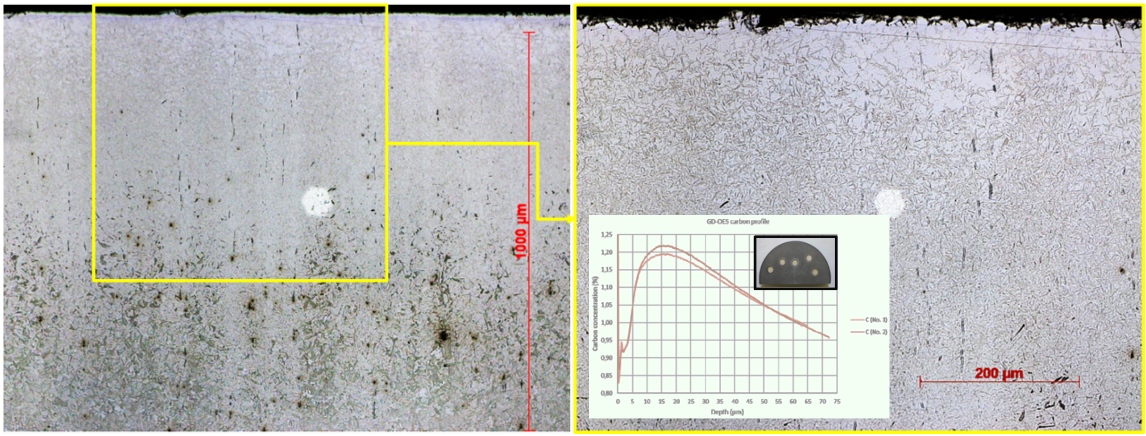

Fig. 14 Cross-section of the carburized material with non-linear carbon profile in the first 75 micrometers of the material depth (in communication with P. Nerman, Scania CV AB).

Therefore, there is a need for more sophisticated modification of BN method to measure effective or total hardening depth after carburizing. This can be done e.g. by using so-called focused sensors or low-frequency sensors. Both types are in the experimental phase of development, but they have unique features which could be probably used for CHD measurement. The work in the FFI-OFP4p project demonstrated an extremely good correlation with the hardening depth of nitrocarburized steel material as well as for induction-hardened steel. However, the case-carburized steel did not exhibit such a good correlation.

6.2 WP3 – NDC-concept for induction hardened components and BN-modelling

The main focus of this work package was to develop a predictive model that correlates the characterized features of the tested results from the NDTs and traditional destructive techniques to the actual induction hardening products. An experimentally determined testing procedure, tailored for existing and future process demands will be established. New types of data collection, signal analysis and simplified physical modeling of BN will be targeted and integrated into this predictive model.

The major challenge in the automotive industry is given by achievement of necessary material properties (e.g. surface hardness, microstructure, and hardening depth) of a given component to withstand loads during its use. Therefore, it is essential to verify that these properties are within specifications from manufacturing, as below shown with the data from destructive testing in induction hardened components.

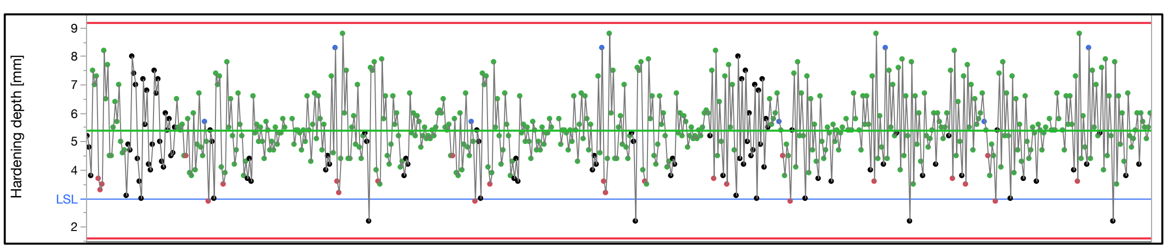

Fig. 15 SPC for production hardening depth.

The average hardening depth during a production period is 5,3 mm (green line), but even though this production sequence was stable and predictable (no observation beyond the ±3 sigma limits – red lines), will the large variation of the hardening depth result in a naturally random variation between 1,6 and 9,3 mm. The irony in this situation is that the 2% waste with shallow hardening below the lower spec limit of 3mm, has no explanation except as a consequence of large random noise level. The standard procedure to improve a stable predictable process, according to Robust Engineering principles, is to rebuild it in order to decrease the common noise level in the process. This total noise is the sum of the noise from two independent sources: process part-to-part variation and measurement imprecision ($\sigma^2_{total} = \sigma^2_{process} + \sigma^2_{measurement}$) that cannot be separated without a measurement system analysis (MSA).

Today manufacturing verification is done solely by destructive testing where manufactured parts are sectioned to smaller pieces and the properties are verified relative the tolerances. For the case of camshafts, this is necessary every time the production is reset or after other planned or unplanned interruptions. The verification process is very costly since production stands still for several hours.

The prior project "Non-Destructive Testing methods: development of innovative solutions for in-line applications" showed great potential for a variety of NDT methods for characterization of a microstructure, hardness and hardening depth of steel components. Two of the most promising methods for this application were Barkhausen noise (BN) and Ultrasound (US), which already are widely used in industrial environments for similar objectives, e.g. detection of grinding burns, structural defects etc. BN is sensitive both to the magnetic response from the surface layers of the material (e.g. hardness of different microstructures), and the residual stress state. Recent research has also advanced the analyzing methodology of the response signal for sub-surface microstructural characterization. The US is also known to be effective for material characterization. One of the major differences between the two technologies is the analyzing depth range. In theory, BN is only effective within few tenths of millimeters below the surface, whereas the UT is sensitive to both surface and sub-surface characteristics depending on the configuration.

It is not yet fully unfolded how the information from BN and US overlap (or gap) and could be utilized to detect the variation that needs to be detected in the specific hardening process – that is, relative the process robustness.

- Literature shows that the methods have potential in this field, but it is not known if the resolution is sufficient to detect variation in hardening depth for this combination of heat treatment and alloy in this industrial application – by themselves and/or in combination.
- Influence of microstructure variation and component geometry on data/decision quality is not fully understood:
    - Optimal parameter settings.
    - Optimal monitoring procedure.
- The recent development of BN-analytics has shown that there is a correlation between the case hardening depth of steel and the MVSS-method. Many reports and articles have shown a good correlation for the MVSS method for different surface hardening methods. Looking at the maximum slope of the magnetizing voltage sweep, it can be compared with the permeability component of the magnetic hysteresis BH-curve. If we have two different magnetizing frequencies, we can assume that we get two different penetration depths of the magnetizing field. This should give a hint of the gradient of the magnetic permeability of the material at two different depths. Permeability is correlated to the microstructure, which is correlated to hardness. Therefore one can expect a correlation between the ratio of the maximum slope of the sweep to the gradient of the hardness. If the material has a constant gradient of the decreasing hardness, one should be able to correlate the sweep slope ratio to the case hardening depth. This means that the analyzing depth of the Barkhausen noise signal doesn't need to be in the range of the case hardening depth. The use of MVSS method needs to find the start of the gradient of the hardness curve quite close to the surface. At higher case depth, the gradient will start at the higher depth, out of range of the BN analyzing depth, and by that limiting the analyzing depth of the MVSS-method.

Research questions and aims addressed in WP3

- Procedures how to quantify part-to-part variation relative measurement uncertainty
- Exploration of the microstructure variation over the profile of the case-hardened layer
- Estimation of the specific physical properties of individual microstructure layers, e.g. the relative permeability, which can be used:
  - to determine the relationship between microstructure and the corresponding more advanced BN signal characteristics
  - as input to modelling and simulation
- Continuum Mechanic parametric numerical model for prediction of BN response behavior
- Development of test sample set embracing relevant process variation
- BN-analysis refining
  - Investigating and verifying the different BN parameters and the MVSS-method on induction hardened material, i.e. ratio of the maximum slope of the magnetizing voltage sweep curve at two different magnetizing frequencies.
  - Definition of range of the analyzing depth of MVSS on induction hardened material
  - Approaching a theoretical explanation why the MVSS method experimentally seems to work even though it contradicts the expected behavior reaching an analyzing case depth of several millimeters when the expected theoretical analyzing depth of BN only is few tenth of a millimeter.
  - Influence of the homogeneity of the hardened region under the sensor.
- US-analysis refining
  - Does the existing ultrasonic system for hardening depth measurement (QNet) have a good enough resolution and precision for hardening depth evaluation of cam shaft inspection?
  - Can the existing US based hardening depth measurement procedures be modified to work also for LUS?
- Exploration of the limitations of how to triangulate the hardening depth utilizing both theoretical and empirical methods (BN, QNET and LUS).

The specific knowledge gained

- BN-analysis refinement
  - The BN MVSS signal show potential of measuring hardening depth down to 3 mm. For greater depths the transition between different microstructural features becomes too vague, which might contribute to the loss of correlation.
  - Promising results indicate high precision of prediction of induction hardening depths from 1,8 to 7 mm on a test sample series have been observed, using a model based on input data from dual separate BN scanning techniques with the same sensor. The precision of this technique needs to be quantified relative the actual process variability and resolution requirements before validated.

- Microstructure layers have different physical properties that leads to different behaviors when come to different analyzing technique. The microstructure has shown to influence the BN signal a great extent. This could be seen in the Barkhausen burst in terms of magnitude, peak position, width of the burst and skewness of the burst.
- Simulations
    - Linear FE-model predicting the BN RMS (mp) response, containing sensor and material parameters for harmonic excitation. Some numerical configuration predictions experimentally verified, and some experimental deviations explained by numerical results.

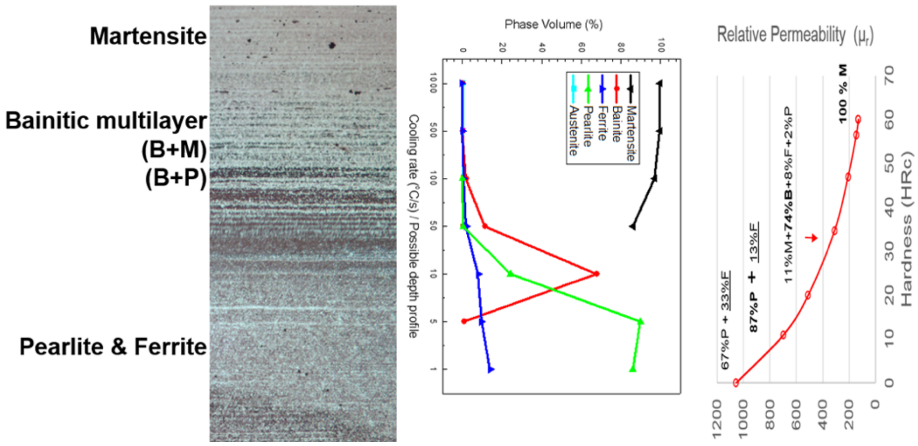

Fig. 16 The cross-section image and the middle graph show that the microstructure gradually shifts from the hard Martensite at the surface to softer structures below resulting in gradually changing magnetic properties.

- BN-analysis refinement
    - BN could measure hardening depth down to 3 mm by using the BN MVSS signal. For greater depths the transition between different structure becomes too vague, which results in unclear distinctions with BN could not be made.
    - The selection of frequencies in the MVSS has great impact on the measured result. The lower frequency has the greatest influence on the signal which causes a shift of the signal toward higher amplitude of 0.6 MVSS when the frequency decrease from 40 to 20 Hz. The lower frequency also results in slightly higher slop of the regression line improving the sensitivity of the signal for the hardening depth. The higher frequency is instead causing a shift in penetration depth which in this case was 0.2-0.35 mm when increasing the frequency from 125 to 200 Hz.
- US-analysis refinement
    - Both US methods (conventional QNET and LUS) have shown to measure case hardening depth down to 5 mm.
    - It was verified in one sample set (crankshaft) that the ultrasonic based system from QNet had a high enough resolution and low enough variation in the hardening depth measurements when measured in a lab environment.
    - It was indicated that laser ultrasound could be utilized for hardening depth measurements on the selected industrial cases.

What is the consequence of the new knowledge?

- By knowing the difference of different microstructures, the parametric study on BN data become sounded, e.g. peak position. Microstructure can be identified (by BN)
- Hardening depth can be evaluated with both methods; however, precision requirements needs to be determined relative the monitoring objective in each case.
- The conventional ultrasonic based procedure, and system from QNet, has been shown to be promising for the evaluation of hardening depths in steel; however, at this stage we cannot put it in production and take decisions on its evaluations, further explorations of its limitations are required.
- Simulations results in better parameter choice in practical test situations supporting the procedure development
- Triangulation is necessary – more than one monitoring system needs to be synchronized supported by simulations and estimated physical parameters.

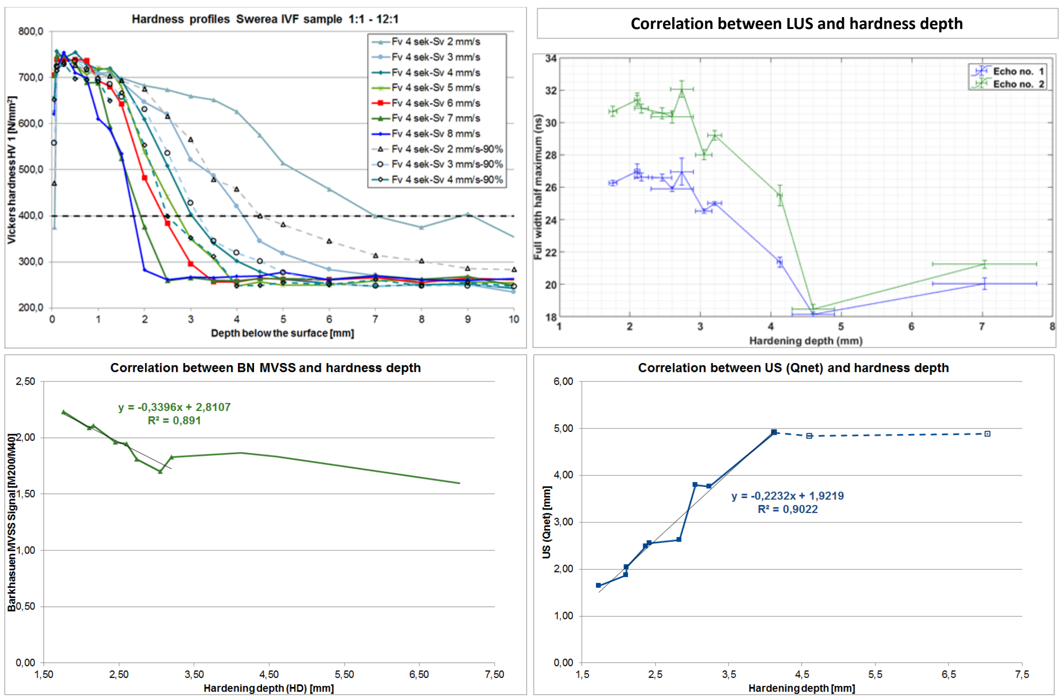

Fig. 17 Illustrates how the three investigated NDT techniques measures the hardening depth for induction hardened steel samples with hardening depth in the interval 1.87-7 mm. the result for induction hardened steel samples.

Recommendations for the next step

- Decomposing and quantifying process variation – how much of the part-to-part variation of the hardened component comes from variations in the incoming material relative the heat treatment process variation, e.g. quantifying the robustness of the case hardening process that sets the basic resolution requirements on the monitoring methods.
- Explore how the physical properties profile vary (in parallel with the gradually shifting microstructure in the hardened layer) within the acceptable alloying range and heat treatment process window of the specific material as part of the NDE monitoring procedure set-up process using simulations and meta-modelling, corresponding to Figure 16.
- BN measurement/monitoring
  - Use other parameters together with RMS in the monitoring process, such as: peak position, peak width etc.

  - Further development of the MVSS-method and correlation to other features of the hardness profile its corresponding microstructure characterization.
- Simulations:
  - Can be further developed with non-harmonic excitation and nonlinear material models to increase the usability of the model
- US-monitoring
  - Further analysis of US-signals from microstructural interfaces deeper than 5mm below the surface
    - QNet gauge r&R studies relative process variation to quantify reproducibility and repeatability. The resolution and variation in a production environment was not explored, e.g. only single/few operators; need a better understanding of the limitations of the method, e.g. why a low resolution and high variation is present for some of the sample sets and not for other, as well as resolution at larger hardening depths above some 5 mm.
  - Laser ultrasound: the variation and resolution were not explored enough in order to conclude if the method was suitable for a production environment or not. In addition, the same procedure and idea as for the conventional ultrasonic system from QNet was more difficult to generalize to laser ultrasound, further optimization is required. There was a limited theoretical understanding of the results, this needs to be improved.
  - Correlation between physical properties of the material and ultrasound wave propagation need to be advanced
- Triangulation practices needs to be developed; how to sample, process data, visualize variation and take decisions.

6.3 WP4 – Development of NDC concept for nitrided components

The purpose of this work package has been to evaluate a non-destructive method to measure the results from the heat treatment process nitriding and nitrocarburizing of steel components. These processes are “low temperature” processes, compared to for example case hardening. Therefore are nitriding processes commonly employed for components that have high demands on dimensional accuracy after heat treatment.

Typical components that are nitrided are gears and rotating or sliding shafts of heavy-duty engines. The heat treatment transforms the surface of the steel into a hard and wear resistant layer. This heat treatment is performed in an atmosphere of nitrogen and carbon at temperatures of 550-580°C, much lower than the austenite temperature of the steel which minimizes dimensional growth.

The nitriding process creates an outer compound layer (CL) and a diffusion zone (DZ) that that has excellent wear properties. The composition and extension of these two zones depend on steel grade and nitriding process parameters such as gas mixture, process temperature and time. The compound zone is a rather thin layer consisting of ε (Fe3N) and γ’ (Fe4N) nitrides, this layer has a typical extension 5-30 µm. The diffusion zone has both good wear and fatigue properties and is consisting of nitrides corresponding to the steel alloying elements. The diffusion zone has a typical extension of a few hundreds of microns up to 0.5 mm.

It is of great importance to evaluate these layer thicknesses in order to secure that the desired properties are attained. Today the process is verified both by destructive measurements using hardness measurements and to some extent by non-destructive testing (NDT) using magnetic techniques such as eddy current. However, the only existing NDT method today is a dated equipment called Nortest. However, there is a strong demand for replacing the Nortest measurement equipment since it is outdated and could stop working at any time, and today there exists no new commercial alternative. Hence, the aim of this work is to develop a methodology for characterizing and non-destructively measure the compound layer and the diffusion zone, using Barkhausen noise. Recent work has shown a good possibility of the Barkhausen noise parameter MVSS that will be further evaluated to verify the heat treatment process of nitriding.

In order to evaluate the BN method a test matrix of three different steel grades, 42CrMo4, Ovako 280 and 46MnVS3, was heat treated using three different recipes. The aim was to generate compound layer thickness of 5, 15-20 and 25-30 µm. For each steel grade, ten test coupons were heat treated and evaluated. In figure 2 an overview of the samples after heat treatment is illustrated.

Fig. 18 Overview of samples of the three different steel grades.

The heat treatment was carried out in a furnace in an atmosphere of nitrogen and carbon. The samples were preheated to 400°C and then heated to 580°C during the heat treatment. In order to generate three different compound thicknesses, the samples were heat treated during three different holding times, 80, 130 and 240 min. After heat treatment, the samples were quenched oil bath in a 60°C, and then cleaned.

The heat treatment generated the expected result of the different thickness of the CL and DZ which also, as expected, differed between the three steel grades. The different steel grades have entirely different microstructures after heat treatment. The 42CrMo4 shows a fully quench and tempered martensitic structure below the compound layer while the Ovako 280 and 46MnVS3 show a ferritic/pearlitic structure instead. The two later also show similar growth of CL while the 42CrMo4 steel grade is much thinner for all heat treatments. Figure 19 shows the microstructures for the different samples and the porosity of the CL. The measured results of the CL and DZ are presented in Table 4.

Table 4. Resulting material properties after nitriding.

Recipe	Steel	CL [µm]	DZ [mm]
1	46MnVS3	11.7	0.192
2	46MnVS3	23.8	0.377
3	46MnVS3	29.3	0.500
1	42CrMo4	5.8	0.143
2	42CrMo4	16.4	0.291
3	42CrMo4	20.9	0.306
1	Ovako 280	10	0.251
2	Ovako 280	19.3	0.448
3	Ovako 280	25.4	0.506

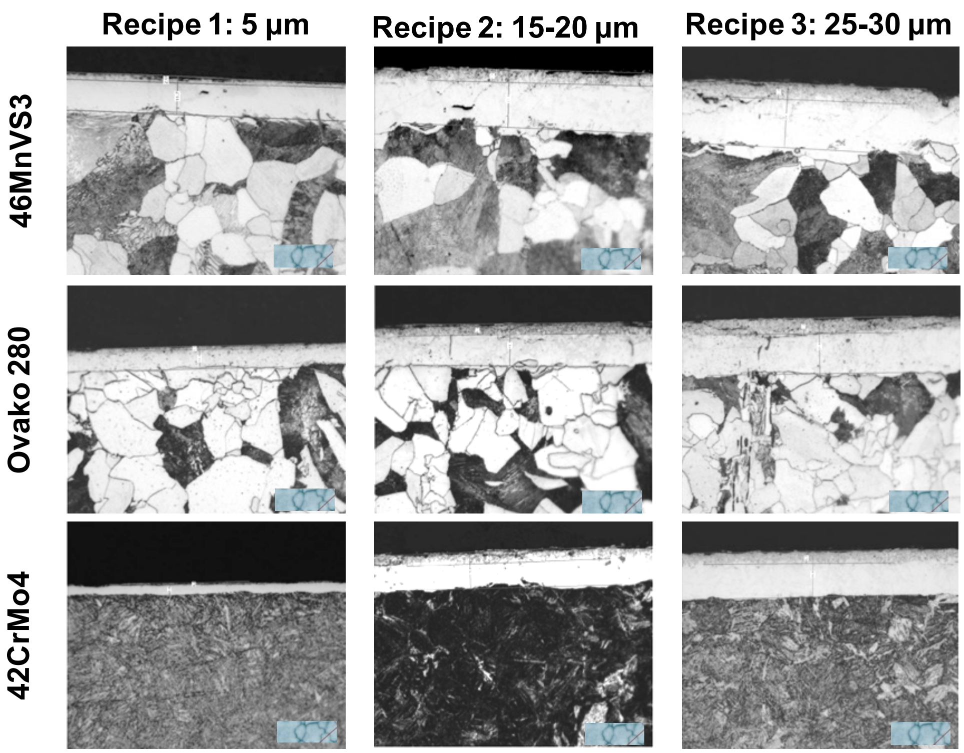

Fig. 19 Micrographs of the three different steel grades and heat treatment recipes.

The eddy current (Nortest equipment) measurements show a good correlation to the CL according to Figure 20. The results show that an increasing CL increase the eddy current signal respectively. It could further be observed that the curves for the three different steel grades are strongly related, especially for the Ovako 280 and 42CrMo4 steel grades, which implies that the Nortest equipment could measure CL with similar calibration curves.

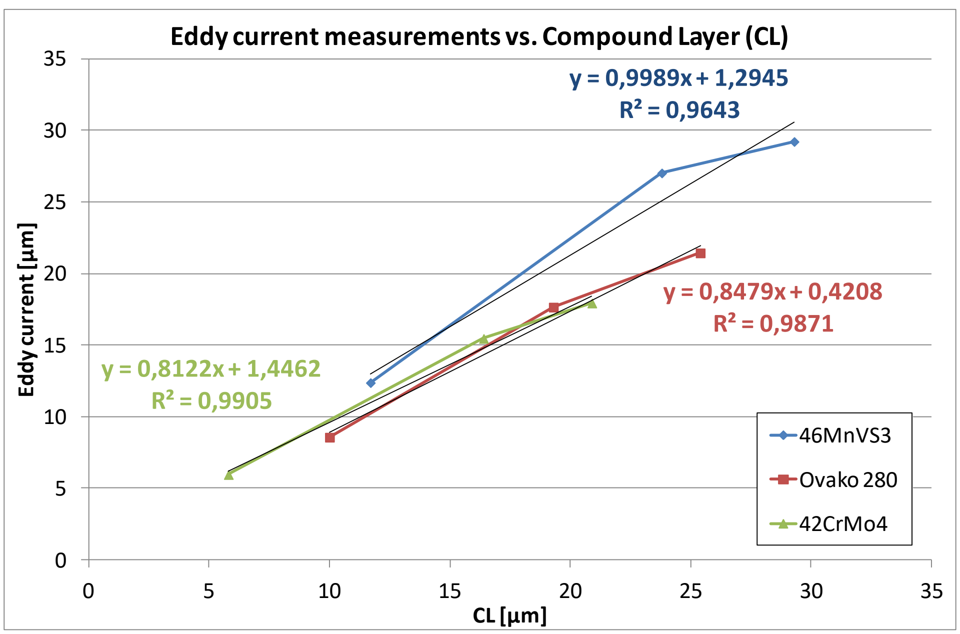

Fig. 20 Eddy current measurements versus CL the three different steel grades.

The results from the BN measurements showed good correlation to two different BN signal parameters and the nitrocarburized layers characteristics according to Figure 21. The MVSS was measured using a T-core sensor and the results show that the signal increases with increasing CL and DZ. Since the MVSS measurements interval is relatively small the curves for the three different steel grades are closely related for the CL but differs more for the DZ. Additionally, the BN signal FWHM also showed a good correlation to the CL/DZ thickness.

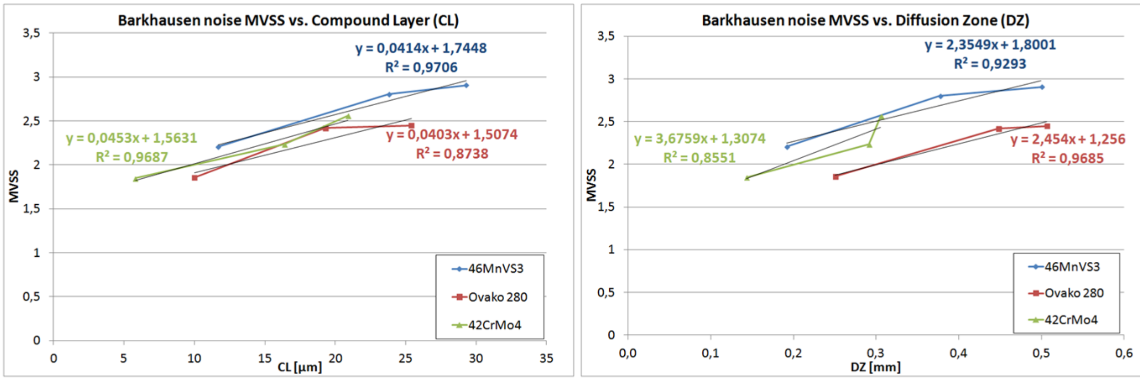

Fig. 21 Barkhausen noise MVSS measurements versus CL and DZ for heat treated steel grades.

In order to compare the different signal parameters, the normalized signals are presented in Figure 22. This result clearly visualizes that the Nortest equipment has a much steeper slope compared to BN which makes it less sensitive for variations between different samples with similar layer thickness, but the BN MVSS parameter is also showing good potential.

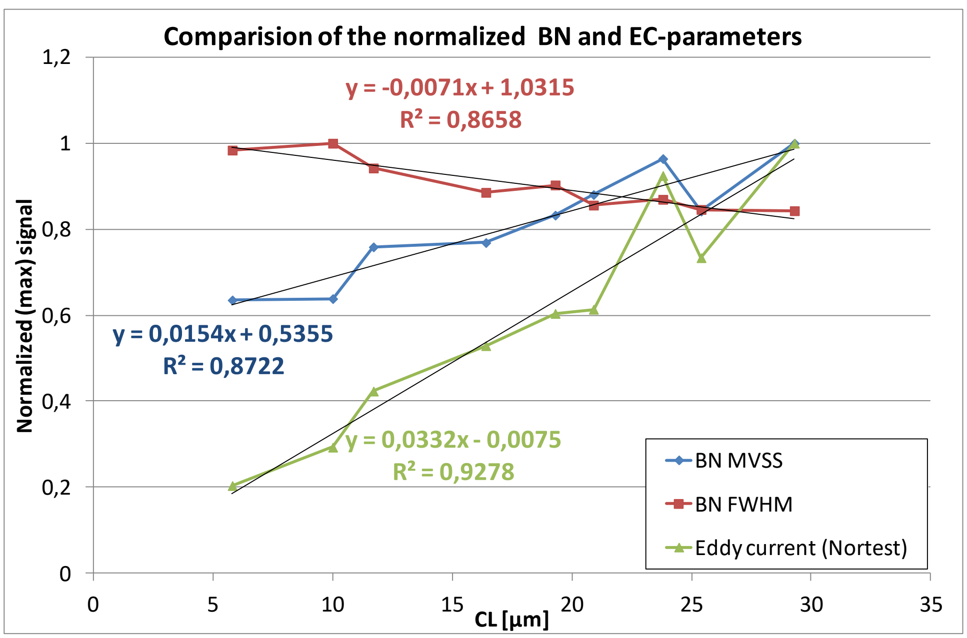

Fig. 22. The normalized signal for measuring the compound zone after nitriding.

To determine if the BN MVSS signal measures the compound layer or the diffusion zone thickness measurements was performed on samples without the compound layer (electropolished). These measurements showed the same result which indicated, as expected, that BN instead measures the deeper diffusion zone (nitride hardening depth) instead.

Conclusions

- Both the Barkhausen noise measurements and eddy current measurements show potential of measuring the layer thickness of nitrocarburized steel samples.
- The eddy current (Nortest) shows very good correlation to compound layer thickness and measurements showed a greater output signal interval which makes it less sensitive for variations compare to the Barkhausen noise signal.
- Barkhausen noise signal showed that both the MVSS and burst FWHM parameter correlates well with diffusion zone thickness.

The Barkhausen noise signal output parameter need to be optimized in terms of magnetizing settings in order to widen the signal output interval and make it less sensitive for variations.

6.4 WP5 – Industrial case studies

The purpose of this work package has been to evaluate the different Non-Destructive Characterization (NDC) concepts that have been developed within WP2-4. This will be done by performing measurements on real components and then verify the results by destructive measurements. It is worth to mention, that each Work Package had a different focus even if the final goal was case hardening depth investigation. This is due to the variety of components, materials and different heat-treatment procedures.

6.4.1 Camshaft (WP2)

This case study was performed in order to see an effect of surface hardness change regarding case hardening depth on the camshaft. The idea was to grind the camshaft journals to the nominal value and thereafter grind material off radially with steps, in total ten steps (Fig. 23). The requested diameters on each step-in axial direction were as follow:

Step 1: J1 – J7 Ø85.0

Step 2: J1 – J7 Ø84.4

Step 3: J1 – J7 Ø84.0

Step 4: J1 – J7 Ø83.6

Step 5: J1 – J7 Ø83.2

Step 6: J1 – J7 Ø82.8

Step 7: J1 – J7 Ø82.4

Step 8: J1 – J7 Ø82.0

Step 9: J1 – J7 Ø81.6

Step 10: J1 – J7 Ø81.2

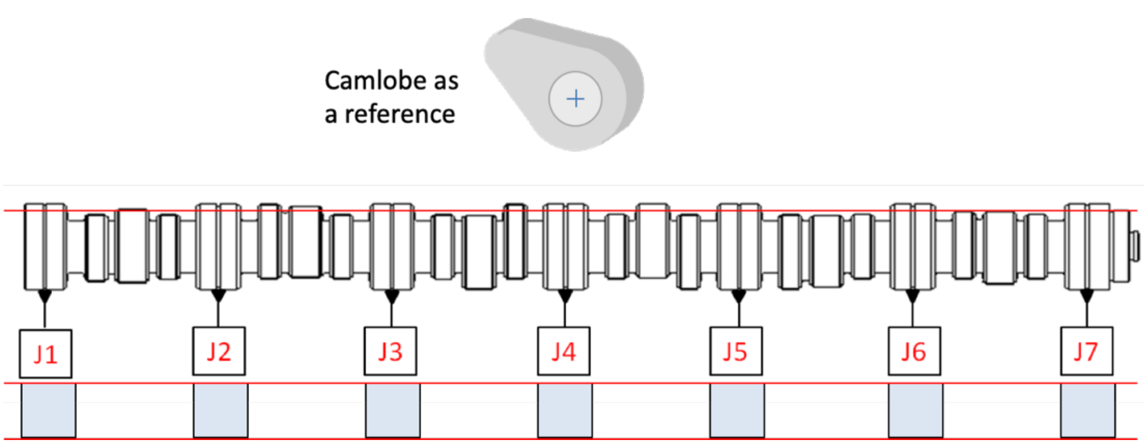

Fig. 23 Graphical representation of the camshaft main journals grinding.

The measurements were done on the production equipment Rollscan 1000 SV-91989. The reference for the radial starting position of measurements was the dowel hole D in the position (Fig. 24). For axial reference, the position of each sensor will be programmed through the NC to the middle position of the bearing surface.

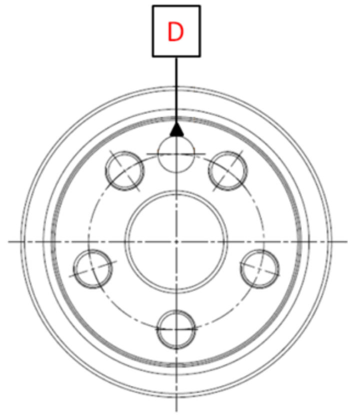

Fig. 24 The measurement position on the bearing surface.

All journals were measured with the same sensor and parameters. Before the start of measuring the equipment was calibrated according to the actual routine.

Table 7 Measurement parameters

Unit	Rollscan 200
Gain	50
Magnetization frequency	50 Hz
Measuring speed	2 rpm

Hardness change was registered after each grinding step and is presented on the Fig. 25.

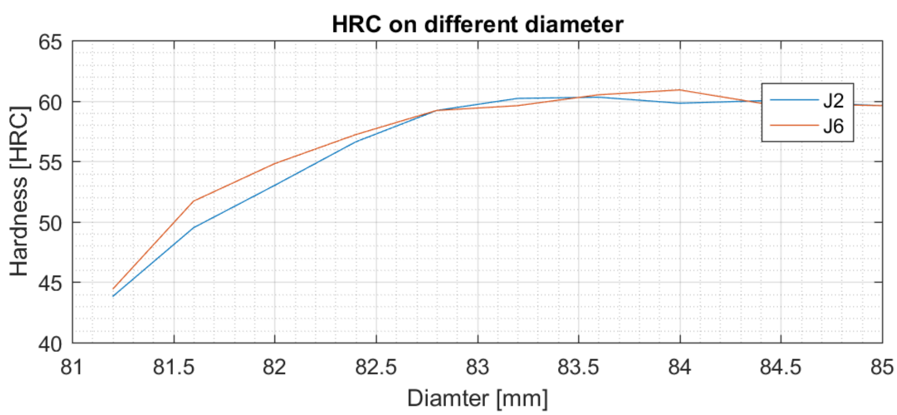

Fig. 25 Hardness change after each grinding step.

Surface roughness change was registered after each grinding step and polishing step and is presented on the Fig. 26.

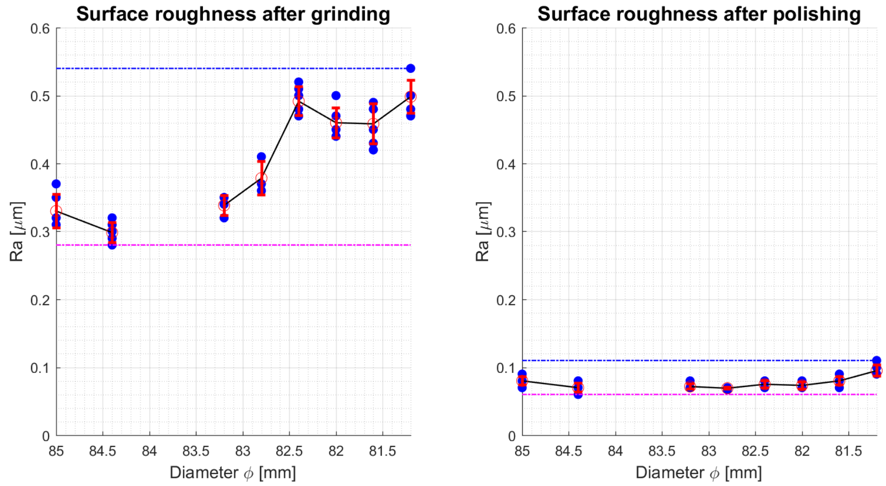

Fig. 26 Surface roughness change after each grinding and polishing step.

Surface roughness changed after grinding as expected, due to material hardness change. Nevertheless, roughness is more stable and the *Ra* values are less spread after polishing than grinding.

The Barkhausen noise values were also changing as expected together with diameter change (Fig. 27). There is only a small variation between journals. It was discovered that in this case study more influential was material hardness change than surface roughness.

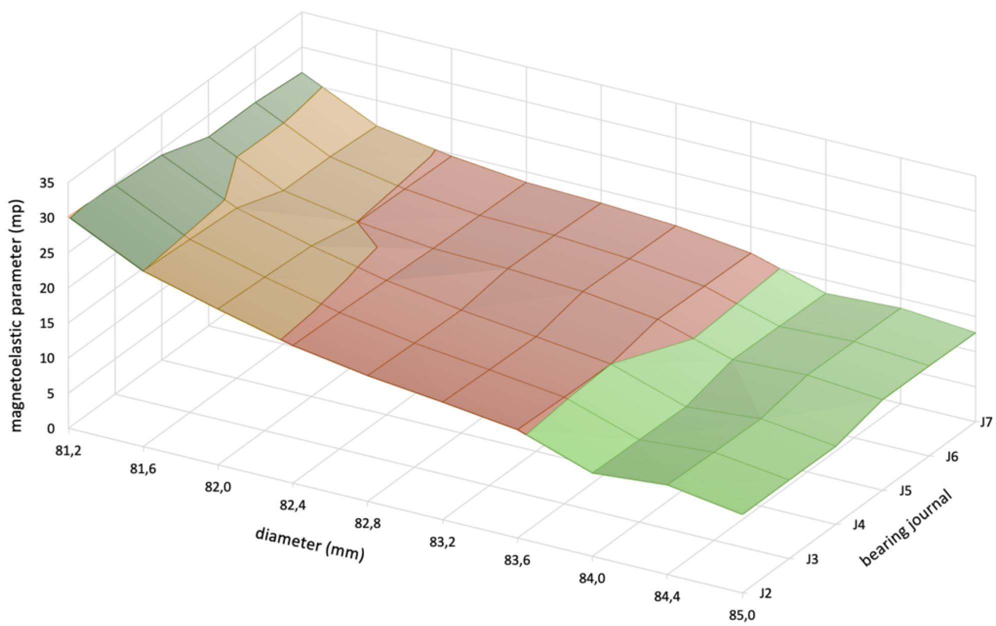

Fig. 27 Magneto-elastic parameter values in relation to the diameter change after grinding.

Conclusions

The grinding process is stable and it allows to identify hardness changes of the materials, e.g. grinding burns. Nevertheless, there is no correlation between BN and case hardening depth after carburizing This difficulty, can be solved by using modern sensors for low-frequency measurements, which can penetrate material up to several millimeters.

6.4.2 Crankshaft (WP3)

The case depths on induction hardened C38 crankshafts were measured using Case Depth Tester P3121 by Quality Network Inc. The ultrasonic search unit consists of a polystyrene wedge with an ultrasonic transducer mounted on it. The ultrasonic sound wave propagates through the surface with an angle of 28.3º and it uses a fixed frequency of 20MHz. The apparatus is suited for case depths ranging from 1.5 mm up to approximately 12.0mm.

The results from the destructive testing (DT) and the ultrasonic testing (UT) can be seen in Figure 28a. The case depth varies from approximately 3.2 up to 5.8 mm. The trend from these measurements can be seen to be orientated along a straight line, with some spread, slightly offset against the destructive testing. The differences between the DT and the UT have a mean value of 0.39 mm and a standard deviation of 0.20 mm (Table 5).

Table 5. The mean value of the differences between DT and UT and the standard deviation for the differences. These values are for the standard HDE-11 crankshaft.

Crankshaft	**Mean value difference (DT-UT)**	**Standard deviation for the differences**
Standard HDE-11	0.39 mm	0.20 mm

Figure 28b illustrates the corrected values from the UT, i.e. where the average difference of 0.39 mm is added. The red line is the 1:1 ratio an as can be seen the corrected case depth values are oriented along that straight line. This correction can be arranged by the software by moving the second cursor.

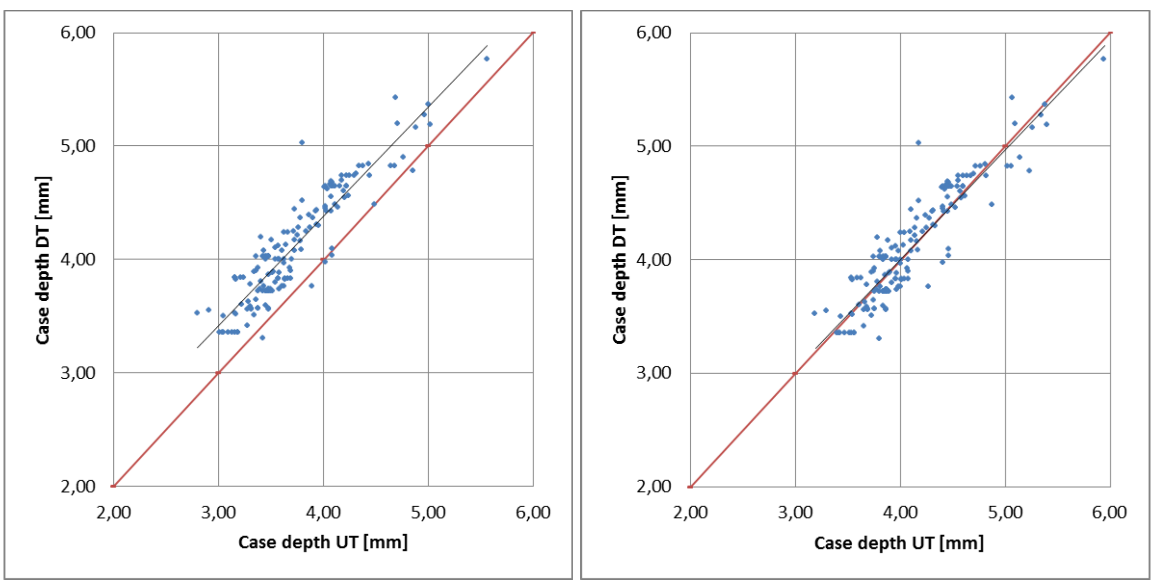

Fig. 28 a) Measured case depth by both DT and UT. The differences between the values for the DT and UT have a mean value of 0.40 mm and a standard deviation of 0.21 mm, b) Corrected case depth values for the UT.

A study to determine the reproducibility of the method was also done on induction hardened crankshafts. The standard deviation for the reproducibility of this ultrasonic method was determined as 0.074 mm.

Conclusions

- The correlation between the DT and the UT methods is good for determination of case depths, ranging from 3.2 mm up to 5.8 mm, on induction hardened crankshafts with a C38 steel composition. The standard deviation for the difference between DT and UT was 0.20 mm and the reproducibility of the method has a standard deviation of 0.074 mm.
- The ultrasonic measurements with P3121 are suitable for case depths above 2 mm which will make the measurements on case depths smaller than 22 mm less accurate. The correlation between the DT and the UT will then not be fully applicable at such small case depths.

6.4.3 Nitrocarburized gears (WP4)

The gears for this case study are tested camshaft gears in material STEEL V-2906-95. These gears are a part of the engine transmission and drive over-head camshaft and are about 240 mm in diameter with 84 teeth.

Fig. 29 Overview of the measure gears.

The results from the destructive measurements showed a variation of the compound layer of 7.6 µm – 13.1 µm and the correspondingly nitrided hardness depth (NHD) of 0.28 mm – 0.47 mm, (Table 6).

Table 6 Result from the destructive measurements of the nitride layers.

Gear wheel ID	NHD [mm]	CL [µm]	CL porosity [%]	Flank surface hardness [HV1]	Flank core hardness [HV1]
1711160012	0.37	13.1	24.4	424	261
1711170005	0.34	8.9	0	417	271
1801210004	0.4	12.4	16.9	422	268
1802050001	0.4	13.1	22.3	430	308
1705262055	0.38	9.5	0	390	301
1705240546	0.47	7.6	0	448	306
1705262108	0.28	7.9	0	361	278

However, the nitriding process is also sensitive for among others the geometry and surface finish which might cause a variation of the layer thickness. To illustrate this plot of the measured results for different positions on the gear wheel, side plane/flank/root, has been plotted in Figure 30. These results show that the measured thickness of both the NHD and CL varies for the same component at different positions.

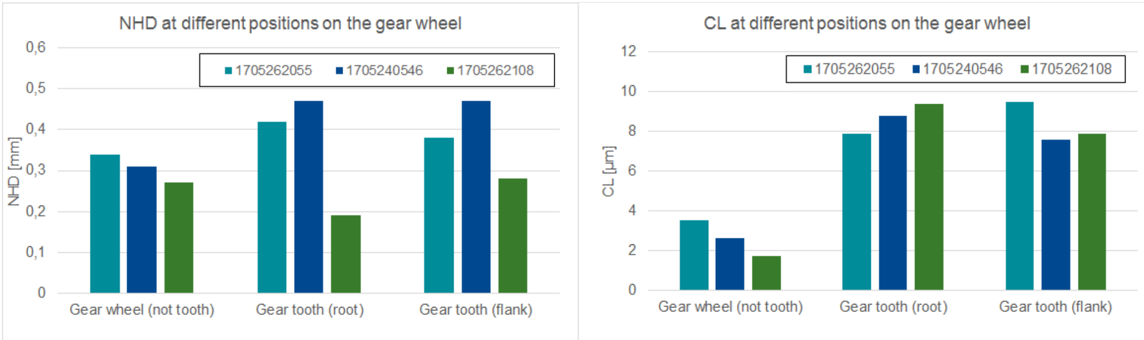

Fig. 30 Results from destructively measured NHD and CL for three different gear wheels.

The gear was measure using the Barkhausen Magnetic Voltage Sweep Slope method with the settings that were employed in WP 4, 125 Hz and 40 Hz. The gear tooth flange was measured according to Figure 1 using a gear sensor. For each of the gears three positions was measured, at 0, 120 and 240 °. The sensor was handheld during the measurements where the flat surface of the sensor was pressed against the gear tooth flank (Fig. 31).

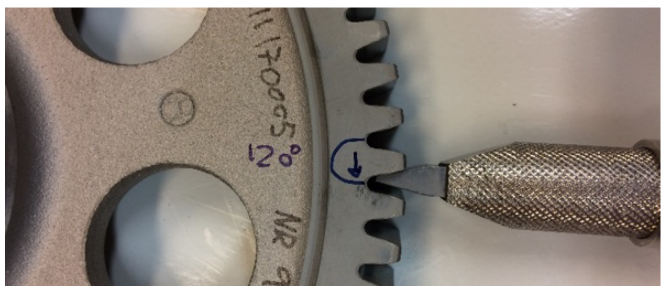

Fig. 31 Overview of the measurement setup for gear tooth flange measurements.

The results for the measurements on the six different gears at the positions (0, 120 and 240°) are presented in Figure 32. These results show that there is some variation around the gear and that the different gears only have a slight difference in the MVSS signal.

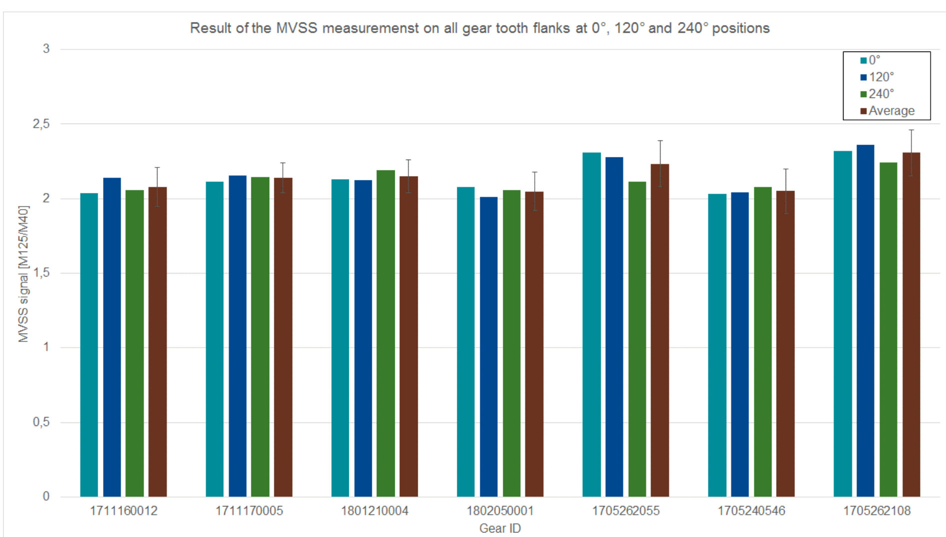

Fig. 32 BN MVSS results for all gear wheels measured on the flank of the gear tooth at three different positions around the gear 0°, 120° and 240°.

The correlation between the MVVS signal and the compound layer thickness is shown in Figure 33. However, there does not appear to be any clear correlation in this case.

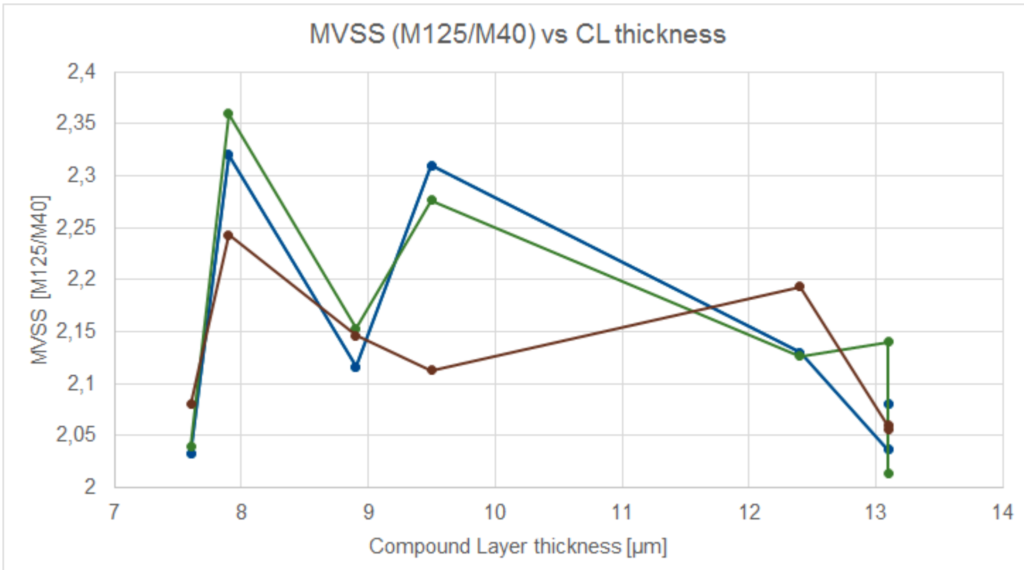

Fig. 33 Correlation between BN MVSS and the compound layer thickness for the gear samples.

The correlation between the BN MVSS and the Nitriding Hardness Depth does however show some interesting correlation according to Figure 34. If the two gears with 0.38 and 0.4 mm NHD are considered as outliers an even more clear trend appears where the MVSS signal decrease with increasing NHD.

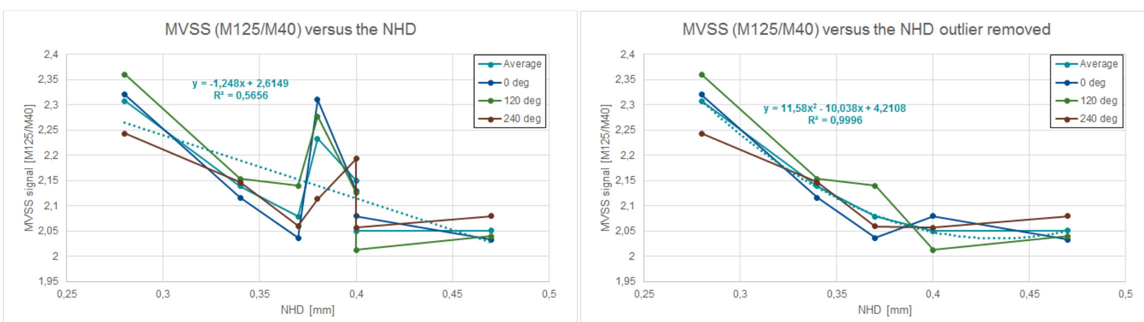

Fig. 34 Correlation between BN MVSS and the nitride hardness depth (NHD) for the gear samples.

Conclusions

- These results show a possible correlation between the nitriding hardness depth and the MVSS signal. However, there are some outlier that causes a scatter in the results which need to be further investigated in order to understand the correlation better.
- The sensitivity connected to the handled measurements performed for these gears might cause some scatter in the measurements.
- The destructive measurement of the nitride hardness depth showed that the layer thicknesses varied at different locations around the wheel which also might cause a variation in the correlation to the measured MVS result.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The knowledge gained during the project period raised significantly the level of the understanding measurement process. Based on that knowledge further development through new scientific projects will be continued. Developed new Barkhausen noise signal analysis techniques can be implemented in the industry in the near future.
Be passed on to other advanced technological development projects	X	Based on the finding there is ongoing discussion in the consortium for continuation of the scientific research and preparing a new project proposal for future development.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

Publications

1. Holmberg, P. Lundin, J. Olavisson, S. Sevim," *Non destructive testing of surface characteristics after nitrocarburizing of three different steel grades*", 2017, ICBM12 conference proceedings
2. R. Tomkowski et. al, *Penetration depth investigation of Barkhausen noise signal for case-hardened components*, 2017, ICBM12 conference proceedings
3. Pui Lam Tam et. al, *Preliminary Study: Barkhausen Noise Evaluation on the Hardening Depth of an Induction-hardened Carbon Steel*, 2017, ICBM12 conference proceedings
4. R. Tomkowski et. al, *Impact of surface integrity on the Barkhausen noise measurements.* Met&Props 2017, Book of abstracts
5. R. Tomkowski et. al, *Effect of surface roughness on Barkhausen noise parameters*, ICSM 2016

Master Thesis

1. S. Sirén, *Case Depth Measurements on Induction Hardened Crankshafts by Using Ultrasonic Backscattering Method*. Master Thesis. Uppsala University. 2017

Seminars and Conferences

1. *5th International Conference on Surface Metrology*, April 4-7, 2016, PUT Campus Poznan, POLAND
2. *SSF & VINNOVA Conference: Bringing New Materials to Market*, April 25, 2017, Stockholm, Sweden
3. *ICBM12 - the 12th International Conference on Barkhausen Noise and Micromagnetic Testing*, September 24-26, 2017, Dresden, Germany
4. *21st International Conference on Metrology and Properties of Surfaces,* 26 – 29 June, 2017, Gothenburg, Sweden
5. *Barkhasuenbrusdag i Arboga,* November 8, 2017, Arboga, Sweden
6. *Final Dissemination Workshop of the VINNOVA FFI OFP4p project*, 9th and 10th of October 2018, SCANIA Tekniskt Centrum, Södertälje

Book

1. R. Tomkowski *ed.*, *The Barkhausen Noise Measurements. Good practice guide.* ISBN: 978-91-7729-978-3, KTH Royal Institute of Technology, Stockholm, 2018

The results have also been presented at different occasions to the Swedish Värmebehandlings Centrum Network (VBC).

8. Conclusions and future research

8.1 Conclusions

Developing non-destructive methods to improve the production is very admirable. The reason is that it enables to qualify the outcome from the process and in this project three different cases have been studied in detail. Today each of these processes requires time consuming and costly efforts to verify the outcome by destructive means. However, the outcome from this project has shown the possibility to use different NDT methods as tools to both test and characterize the process and especially if combinations of methods are used different process variations could be captured.

Concerning the induction hardening process, it has been shown that different NDT methods need to be employed to capture the characteristics from the hardening process. The method of ultra-sonic testing has shown great potential in measuring the hardening depth. The Barkhausen noise method have also shown to measure the hardening depth and additionally shown to be sensitive to changes in microstructure and especially different microstructures.

The developed test matrix showed a strong correlation the hardness depth for both methods, but BN requires a sharp transition zone between different microstructures. However, it has also be shown that BN instead is more sensitive to capture the effects from improper hardening which cause alterations in the microstructure. Within this field more work need to be done. The developed matrix could be used as a starting point but where controlled alterations of the microstructure is realized through controlled hardening. Then the results from the hardening need to be characterized in new ways, for example to measure the number of different phases in the BN interaction/measurements volume. Modeling of this may then become an important tool to further understand and interpret the BN signal.

UT on the other hand showed an even clearer correlation the hardening depth but at greater depths than 5 mm the correlations stops. The reason for this has not been fully understood but it might be connected to features in the microstructures of this material.

For case carburized components the case hardening depth (CHD) are difficult to measure. This is due to continuous transition zone of the carbon content, formed during hardening process, where microstructure is changing slowly in depth. Since BNT is strongly dependent on material microstructure it is hard to distinguish exact layer of CHD.

Nevertheless, the knowledge about measurement itself was broadened. Numerous experiments show that:

- Surface topography (roughness) plays important role in BN testing.
- BN signal level (magneto-elastic parameter value) depends strongly on grinding parameters more than on grain size used for making grinding wheel. Note, that CBN grinding wheels were only tested.
- Magnetic properties of the material didn't change in depth. This topic must be investigated widely in the future research.
- Step grinding experiment shows great potential to create calibration block set for BN equipment calibration.
- Last but not least, thanks to unified sample shape there is possibility to perform interlaboratory measurement test (round robin). This will show stability of the measurement method. The process is ongoing.

One of the most important achievements of this project is the good practice guide for Barkhausen noise measurements. The guide contains fundamental knowledge about Barkhausen Testing method, necessary equipment, parameters, measurement conducting, data evaluation, and decision-making process. One of the parts of this book is dedicated to the standardization of the measurement, with a working example of the Standard Operating Procedure (SOP). That can be very helpful for creating a custom SOP for the production line.

8.2 Future research

The future research subjects were discussed during the Final Dissemination Workshop, and can be as follow:

- Active control of the machining processes by using non-destructive techniques.
- Investigation of material microstructure effect on Barkhausen noise signal.
- Effective calibration methodology for BNT.
- Machining optimization methods driven by NDT sensors-based data and machine learning.
- Application of non-destructive methods for additive manufacturing.

9. Participating parties and contact persons

PARTNER	REPRESENTATIVE (contact person bolded)	ROLE IN PROJECT
KTH Royal Institute of Technology	Lorenzo Daghini, **Andreas Archenti,** Stefan Jonsson, Robert Tomkowski, Theodoros Laspas	Project coordination, responsible for all activities in WP2, case study responsible in WP5 and dissemination coordinator (WP6).
Chalmers University of Technology	Eric Tam, **Peter Hammersberg,** Gert Persson	WP3-leader, responsible for activities in WP3, participating in dissemination (WP6), supporting case studies (WP5) as experts in BN-modelling and DoE
Swerea IVF (RISE IVF)	**Jonas Holmberg,** Eva Troell, Hans Kristoffersen	WP4 and WP5 leader. Supporting WP3,4 and 5 with expertise in BN measurements of hardened components.
Swerea KIMAB (Swerim)	Peter Lundin, **Eric Lindgren**	UT expert, supporting WP3 with UT-measurements
Scania CV AB	Sven-Eric Stenfors, **Peter Nerman,** Jan Linder	Supporting WP2 with manufacturing of samples, BN-measurements and equipment. Supporting WP5 with case study.
AB Volvo	**Danfang Chen,** Jarri Olavison, Kenneth Åsvik	Supporting WP3 with manufacturing of samples, BN-measurements and equipment. Supporting WP5 with case study.
Stresstech	**Per Lundin**	Supporting WP2 through WP5 with expertise on BN and residual stress measurements, supplying BN equipment for measurement.
Parker Hannifin	**Hossein Ghotbi**	Production of samples in WP4, provide case study in WP5.
EFD Induction	**Kristian Berggren**	Production of samples and measurements in WP3.
Technoheat	**Lars Ullmark**	Production of samples and measurements in WP3.
Atlas Copco, Secoroc	Mattias Lejon, **Richard Johansson,** Jan Andersson	Production of samples and measurements in WP4.