TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

MURAT DEVECI

NONDESTRUCTIVE DETERMINATION OF CASE DEPTH BY BARKHAUSEN NOISE METHOD

Master of Science Thesis

Examiner: Prof. Minnamari Vippola
Examiner and topic approved by the Faculty Council of the Faculty of Engineering Sciences
on 13th of January 2016

ABSTRACT

MURAT DEVECI: Nondestructive Determination of Case Depth by Barkhausen Noise Method
Tampere University of Technology
Master of Science Thesis, 60 pages, 0 Appendix pages
May 2016
Master's Degree Programme in Materials Engineering
Major: Materials Technology
Examiner: Professor Minnamari Vippola

Keywords: case depth, case hardening, case depth measurement, case hardening measurement, Barkhausen noise, magnetic Barkhausen noise, Barkhausen noise measurement, nondestructive testing, surface hardening

Demands for better products and more environmentally friendly manufacturing advance the technological developments in quality control applications. Especially car manufacturers which mostly use steel components strive to produce higher quality components with cost efficient ways. In order to improve the quality of steel components, raw material needs to be processed with special methods.

One of the common methods to increase the quality characteristics of steel components is surface hardening process which also increases the service life and fatigue properties of components. There are different methods available to harden the surfaces of steel components to increase their strength. In principle, surface hardening provides a case of hardened layer on top of the soft core which also prevents the crack initiation and propagation.

The quality control of the produced case can be made by measuring the thickness of the hardened layer which is called case depth measurement. Case depth needs to be measured because it verifies the quality of the hardening process as well as the thickness left for re-grinding operations. There are various methods available for case depth measurements. However, industries seek a reliable nondestructive method which could possibly be applied to entire volume of manufacturing, be fast, environmentally friendly and possibly cheap. Currently, hardness profiling is the most common technique for quality control of the surface hardening process. However, this method is destructive, expensive and slow. In order to develop a nondestructive technique to overcome this problem, many methods have been tried so far. Barkhausen noise (BN) has been one of the promising methods to success this.

In this thesis, BN is investigated by using newly developed sensors, software and other hardware to measure the case depth of various hardened steel components. In the thesis, it was indicated that recently developed method of using BN for nondestructive case depth measurement is promising although it still requires further testing period.

The main conclusion of the research was that the method works case by case. Challenge with the research was the lack of suitable sample sets and measurement systems. BN measurements are sensitive and any change in the system and samples, dramatically change the results and affect the correlations. The improvements and ideas to develop the current methodology are also given in this study.

PREFACE

This study has been conducted at Stresstech Oy, Jyväskylä, Finland.

I would like to thank my supervisor Prof. Minnamari Vippola and D.Sc. Suvi Santa-aho for their support, review and comments on this research.

The idea of the thesis was proposed by Lasse Suominen, the president of Stresstech Oy who was also one of the supervisors of the thesis. I would like to use this opportunity to thank him for his valuable support, contributions and being available for discussions.

I also would like to express my gratitude to especially Samuli Savolainen and many others who helped me with the all technical issues and problems throughout the thesis at Stresstech Oy.

In addition, special thanks to Lassi Karvonen and Tiina Suuronen from Sampo-Hydraulics Oy, for helping me to arrange samples and using their laboratory for the measurements.

Finally, I would like to thank my family for their continuous encouragement and ever-lasting support.

Murat DEVECI

Vaajakoski, 20.05.2016

TABLE OF CONTENTS

1. INTRODUCTION 1
2. THEORETICAL BACKGROUND 3
 2.2 Methods to Produce Case Hardening 4
  2.2.1 Induction Hardening 4
  2.2.2 Carburizing 4
 2.3 Case Depth Measurement 5
  2.3.1 Destructive Case Depth Measurements 6
  2.3.2 Nondestructive Case Depth Measurements 7
 2.4 Barkhausen Noise 10
  2.4.1 Case Depth Measurements with Barkhausen Noise 19
3. EQUIPMENT, SOFTWARE AND SAMPLES 22
 3.1 Barkhausen Noise Analyzer 22
 3.2 Magnetizing Power Amplifiers 23
 3.3 Sensors 24
  3.3.1 Existing Sensors 26
  3.3.2 New Sensors 28
 3.4 Software 29
  3.4.1 ViewScan 29
  3.4.2 MicroScan 30
  3.4.3 PCCaseDepth 30
 3.5 Samples 33
4. RESEARCH AND RESULTS 37
5. DISCUSSION AND CONCLUSIONS 52
REFERENCES 55

LIST OF FIGURES

Figure 1 Time of flight responses of ultrasonic waves from hardened steel shafts with varying case depths. [27] 8
Figure 2 Case depth profile of a hardened steel shaft measured using ultrasonic backscatter technique. [32] 8
Figure 3 Case depth measurement results with MFCE system. [28] 9
Figure 4 Domain wall types: a) 180^0 Domain wall. b) 90^0 Domain wall. [41] 11
Figure 5 a) Domains before magnetization. b) Domains after magnetization. [43] 11
Figure 6 Growth of a domain due to external magnetic field a) before the magnetic field, b) after applied magnetic field. [44] 12
Figure 7 Hysteresis loop. [41] 12
Figure 8 Hysteresis loops of different materials. [47] 13
Figure 9 Original Barkhausen set up from 1919. [52] 14
Figure 10 A typical Barkhausen noise measurement scheme is shown. [51] 14
Figure 11 BN signal from device. [51] 15
Figure 12 BN signal response to stress. [51] 16
Figure 13 Alteration of the domain structure due to external influence. [52] 17
Figure 14 BN signal of unhardened steel. [5] 17
Figure 15 BN signal of hardened steel. [5] 18
Figure 16 Response of BN with residual stress of hardened/unhardened steel. [5] 18
Figure 17 BN signal response to hardness. [51] 19
Figure 18 Different BN amplitude by different hardness. [54] 19
Figure 19 The Rollscan 350 device. [59] 22
Figure 20 Measurement view of Rollscan 350 device. [59] 22
Figure 21 Magnetizing frequency and voltage sweep views. [59] 23
Figure 22 External magnetizing power amplifier MA-100. (Courtesy of Stresstech Oy) 23
Figure 23 External magnetizing power amplifier RMX 4050HD. [60] 24
Figure 24 (a) Sketch of a sensor and sample set-up. (b) Detailed view of a spring loaded- pick-up mechanism. [61] 24
Figure 25 Flat Barkhausen noise sensor. (Courtesy of Stresstech Oy) 25
Figure 26 Camshaft sensor (SNO1) and its sketches. (Courtesy of Stresstech Oy) 26
Figure 27 High power OD sensor (SNO2) and its sketches. (Courtesy of Stresstech Oy) 26
Figure 28 Special sensor (SNO3) and its model pictures. (Courtesy of Stresstech Oy) 27
Figure 29 Bearing pick-up sensor and its sketches. (SNO4) (Courtesy of Stresstech Oy) 27
Figure 30 Pot-core general purpose sensor (SN1 and SN2) and its sketches. (Courtesy of Stresstech Oy) 28

Figure 31 The model picture of new pot-core sensors. (Courtesy of Stresstech Oy) 28
Figure 32 Pot-core bearing sensor (SN3 and SN4) and its sketches. (Courtesy of Stresstech Oy) 29
Figure 33 Current sweep measurement view. (Courtesy of Stresstech Oy) 29
Figure 34 MicroScan results overview. (Courtesy of Stresstech Oy) 30
Figure 35 An overview of PCCaseDepth. (Courtesy of Stresstech Oy) 31
Figure 36 Session settings in PCCaseDepth. (Courtesy of Stresstech Oy) 31
Figure 37 General settings in PCCaseDepth. (Courtesy of Stresstech Oy) 32
Figure 38 Samples for trial measurements. 34
Figure 39 Induction hardened samples. 34
Figure 40 a) The first and b) The second set of case carburized samples. 35
Figure 41 Repeatability test for sensor SN3. 39
Figure 42 Sweep comparison of SN1 and SN2. 39
Figure 43 Selecting the voltage interval in software. 41
Figure 44 PCCaseDepth measurement which shows the max. derivative points. 41
Figure 45 PCCaseDepth measurement with low MP values. 42
Figure 46 PCCaseDepth measurement with modified voltage interval. 43
Figure 47 PCCaseDepth measurements of a point with different low frequencies. 44
Figure 48 PCCaseDepth measurement result of different samples. 45
Figure 49 Measurement location of the sample. 46
Figure 50 a) Set-up for current and voltage sweep measurements. b) Connections on the MA-100 magnetizing amplifier. c) Modified sensor. 47
Figure 51 Different envelope shape problem. 48
Figure 52 Random “knee” shape on low frequency sweep. 49
Figure 53 Hardness profile of a case carburized sample. (Courtesy of Sampo Hydraulics Oy) 50
Figure 54 Hardness measurement location. (Courtesy of Sampo Hydraulics Oy) 50
Figure 55 Influence of the operator on measurement results. 51

LIST OF SYMBOLS AND ABBREVIATIONS

3MA	Micromagnetic Multiparameter Microstructure and Stress Analysis
BN	Barkhausen Noise
FWHM	Full width half maximum
HRC	Rockwell C Hardness
MBN	Magnetic Barkhausen Noise
MFCE	Multi-frequency eddy current system
MP	Magneto-elastic parameter
MVS	Magnetizing voltage sweep
MFS	Magnetizing frequency sweep
NDT	Non Destructive Testing
PEC	Pulsed eddy current
RMS	Root mean square
XRD	X-ray Diffraction
f1	Low frequency [Hz] for the sweep measurement
f2	High frequency [Hz] for the sweep measurement
H_c	Coercivity
H_s	Saturation field
M_s	Saturation magnetization
M_r	Remanence
Vmin	Minimum voltage [V] for the sweep measurement
Vmax	Maximum voltage [V] for the sweep measurement
Vstep	Step voltage (increment) [V] for the sweep measurement
σ	Electrical conductivity

δ	The penetration depth of BN signal
f	The frequency of the alternating magnetic field
μ	Magnetic permeability

1. INTRODUCTION

Higher demands on performance to cost ratio leads the manufacturing industries to a global competition. In order to be competitive in the market, manufacturers like the automotive industry companies, try to manufacture higher quality and defect free components at low costs. To meet the customers' quality requirements, companies try to eliminate problems such as, uneven case hardening, harmful residual stresses, and grinding burns. Most of the companies still use many destructive techniques for quality control purposes. The destructive techniques are expensive and time consuming and it is not possible to apply them to all of the manufactured components. The desired quality control should represent 100 percent of the components in order to guarantee defect free and fully tested manufacturing. This desire makes Non Destructive Testing (NDT) a vitally important approach.

Case hardening is a method to create a surface layer for wear resistance and fatigue strength thus for providing longer service life. The thickness of the hardened layer needs to be measured to control the quality of the hardening process and to verify the left over layer thickness for machining operations. Nondestructive evaluation of case hardening depth is a long known asset of many industries since the current destructive but reliable methods are time consuming and causes a big deal of material and capital loss. In order to find a reliable nondestructive method, a few approaches have been made with several different techniques such as, ultrasonic waves, eddy currents, Barkhausen noise and photo-thermal methods. Even though, each method has shown success for specific applications, so far none of them yet has been accepted as a reliable method. [1,2] There have been many previous trials [2-18] especially with Barkhausen noise since its characteristics are promising for case depth measurements.

INTELBARK (Implementing Intelligent Systems on Multiparameter Barkhausen Noise Measurement) was one of the previous Barkhausen noise projects which was conducted by Tampere University of Technology and Oulu University. During INTELBARK, different mathematical procedures were used to model the BN signal to study the utilization of the BN method for case depth determination. In this study, different BN data parameters were used for correlations for the first time. With this project, it was seen that prediction of material related properties such as the thickness of the hardened layer could be possible with using different parameters of Barkhausen noise. [19]

In order to develop the ideas generated during INTELBARK project a new research project called NOVEBARK (Novel Barkhausen Noise System for Induction Hardened Components and Material Defect Identification) has conducted by Tampere University of Technology and Oulu University.

During NOVEBARK, the utilization of the BN method for case depth determination of the hardened components has been achieved. The most important outcome of the project for case depth evaluation was the realization of the effectiveness of using magnetizing voltage sweeps. This new method has suggested the possibility of correlation of different frequencies with different case depth values. The method of using magnetizing voltage sweeps has been further developed as using both low and high frequencies together to detect the thickness of the hardened layers on the components. [20]

The aim of this thesis will be to test this new method of using both low and high frequencies together for case depth determination. The main idea behind of this proposed method is to have information from material's different layers with different frequencies. The low frequencies are used to get more information from subsurface layer of the material while the high frequencies are used to get more information from surface layer of the material. Moreover, the ratio of these two frequencies' maximum slopes is a value which is correlated with the case depth values (in mm) of the samples. By now, magnetizing frequency sweep method has been tested with some samples and it worked well in some cases.

In this research, the method will be tested to prove it as a reliable nondestructive method of case depth evaluation. During this research, the method of using two frequencies at the same time will be tested with a new software and new sensors.

For this purpose, a new software, PCCaseDepth was made by Stresstech Oy which enables to calculate the ratio of maximum slopes of low and high frequency sweeps. Since, Barkhausen noise is the base of this research work, there is a need for suitable sensors to conduct the research. For this purpose, Stresstech Oy has developed new sensors and provided some of their existing sensors. During the research work, even some more modifications have been made on the sensors and their details will be given in the upcoming chapters.

To conduct the measurements, a set of 8 induction hardened bar samples were used. To support the research outcomes, two set of case carburized and some other such as nitrided samples also were used. More than 10000 single measurements were made during this research which took more than 6 months.

To analyze the measurements, all features of the software were used such as the different calculation parameters and different measurement parameters. In addition to them, standard Barkhausen noise measurements, current and voltage sweeps have been made to support the existing data. During the study, shapes of the sweep curves have been also investigated and they were used to explain some of the results and behavior of the repeated signal features.

2. THEORETICAL BACKGROUND

This chapter provides the knowledge for case depth, its measurement methods and Barkhausen noise which are the main subjects of the thesis.

2.1 Case Hardening

Machinery components are subjected to high surface loads and wearing conditions during their service life. To increase the service life, fatigue and wear properties need to be improved by creating a hardened layer in the surface while keeping the core in its original structural condition which prevents the crack propagation by plastic deformation.

Any treatment which causes an increase in the surface hardness is called surface hardening. The hardened layer created by surface hardening processes is called the case. The case hardened layer can have a depth between 0.0025 mm to 10 mm. Case depth term is used to describe the hardened layer. [1,2]

Total case depth and effective case depth are the other terms used to define the case depth more specifically. Total case depth term is used to describe the perpendicular depth location from the surface where the hardness no longer decreases and becomes steady since the core hardness has been reached. It can also be defined as the perpendicular depth location where the carbon content is 0.04% above the carbon content of the core. The effective case depth term is used to describe the distance (in mm) between the surface and the region where the Vickers hardness is equal to 550 under a load of 9.81 N. In U.S, it is defined as perpendicular depth location from surface where the hardness drops to 50 HRC. [1]

Throughout the case, both microstructure and hardness indicate a change. If the case is produced by a diffusion based method, chemical composition will also show a change. The degree of these changes depends on the surface treatment process. As an example, induction hardened components’ hardness suddenly drops in the case depth while case carburized component’s hardness shows a transition. [2]

2.2 Methods to Produce Case Hardening

There are many different methods available to form a hardened layer on steels. These can be categorized as diffusion based which are thermochemical methods and localized heating based which are thermal methods.

In this study, different sample sets were used. These samples were processed by carburizing case hardening which is a thermochemical process and induction hardening which is a thermal process. Some details of these two processes are given below.

2.2.1 Induction Hardening

Induction hardening process is one of the most common methods to increase the hardness on the surface and near surface layer of the components. During induction hardening, the microstructure of the surface and near surface layer of the component changes and after induction hardening, surface has a compressive stress state while the core remains in its original stress state. [21]

Induction hardening is a rapid method to harden the surfaces of the medium carbon content steels. Surface hardening is applied through high frequency induction coils which cause rapid heating. The frequency of the induction coils depends on the aimed case depth in which high frequencies are used for the shallow case depths and vice versa. Characteristics of the induction coils such as diameter and number of turns are also important to reach the aimed case depth. Rapid heating causes the austenization which is followed by quenching and after that tempering to adjust surface layer toughness by changing the hardness and residual stress. [22]

2.2.2 Carburizing

Carburizing is a thermochemical diffusion treatment which enriches the surface layer of the component with carbon. Since it is a diffusion process, carbon content decreases with the distance from the surface layer. Carburizing is the most common method to harden the surfaces of the low carbon content steels and some biomedical titanium alloys. [1,23]

Carburizing is performed between 850 ºC and 1050ºC. Components are heated until the austenization process is completed. During carburizing, double quenching can be applied to create a better hardness profile for deeper cases. Quenching process may cause cracking and distortion. [24] Carburizing is widely applied to gears and other transmission components.

There are different techniques to perform the carburizing process such as pack carburizing, salt bath carburizing, gas carburizing, vacuum carburizing and plasma carburizing on which details are given below.

Pack carburizing

Components are packed in a box where the external carbon source such as coke and catalyst such as barium carbonate are heated together for the diffusion process. The process is inefficient in terms of the energy usage and is not environmentally friendly thus, it is no longer commonly used. [4,24,25]

Salt bath carburizing

Components are placed in a molten salt bath of sodium cyanide and barium chloride which produce the case. Environmental problems due to cyanide limit the application of this method. [22,24,25]

Gas carburizing

Gas carburizing is a fast and continuous process in which the furnace atmosphere carries the carburizing gas. Carburizing gas is generated outside of the furnace. This method provides a good control of case depth. [22,24,25]

Vacuum carburizing

Vacuum carburizing is like the gas carburizing which is carried out at sub-atmospheric pressures (0.1 Torr). This method provides the best process control and the fastest continuous process. [22,24,25]

Plasma carburizing

Plasma carburizing is like the vacuum carburizing which is modified to use glow-discharge technology. This method can produce deeper cases than any other methods at faster production rates. [22,24,25]

2.3 Case Depth Measurement

Hardness and case depth measurements are vital parts of quality control of surface hardening treatment. Assessment of case depth is an important quality control tool since it will determine the remaining case thickness for after processes. Even though they are application specific, there are both destructive and nondestructive methods available for case depth measurements.

Since there is no reliable and fast nondestructive measurement method available, many companies and researchers work to develop a method for this purpose. In addition, the market potential of this kind of application is big. [3]

2.3.1 Destructive Case Depth Measurements

Case depth measurement can be made with different destructive methods. Since these methods are destructive, they cannot be applied to all of the components hence the results do not represent the entire production. Destructive methods are also expensive, slow and sampling is made by random selection from the batches.

There are a few different methods available as mechanical, chemical and visual methods.

The mechanical method also called hardness profiling is the most precise and common method for case depth determination. The method uses either Vickers or Knoop microhardness test technique to determine the case depth by measuring micro hardness profile of randomly selected samples. [1]

This method requires a metallographic surface preparation and analysis which includes cutting, grinding, etching, polishing and analyzing the cross sectional sample with a microscope. Even though it provides precise case depth determination, mechanical method is time consuming, expensive and requires many devices. In addition, it is not a suitable method for mass production but only for laboratory applications. The mechanical method is known as the most precise destructive method for effective case depth determination. [1,26]

The chemical method also called carbon gradient method is another way of measuring the case depth. This method is especially very precise to measure the total case depth of hardened layers which are produced by diffusing techniques such as carburizing or nitriding. In chemical method, chips from the machining process are collected and analyzed with an elemental spectroscopy to determine their carbon content. [1,26]

There are microscopic and macroscopic visual methods available. With the macroscopic method, under low magnification, etched surfaces are analyzed to determine their total case depth. With microscopic method, polished and etched samples are analyzed under 100X magnification to determine their total case depth. Microscopic method is mostly applied to nitrided samples since their case depth is shallower. [1,26]

2.3.2 Nondestructive Case Depth Measurements

The ideal solution for a case depth measurement should be cheap, applicable to entire production and fast which can be only possible with an efficient nondestructive method.

However, nondestructive measurement of case depth is not an easy task while it involves both process issues and material science issues taken into consideration. Several nondestructive methods such as Barkhausen noise, eddy current, ultrasonic inspection, magneto-acoustic emission have been tried to determine the hardened layer's thickness. [2,27,28,29,30] Each of the tested nondestructive methods has their own advantages and disadvantages compared to each other. However, a reliable solution has still not been found.

Many industries such as energy, aviation and especially the automotive industry constantly seek for a reliable and cheap solution for case depth measurements. It is possible to save a lot of capital and avoid huge amount of material loss with a reliable nondestructive technique. A method which could provide a 100% inspection with a nondestructive determination will have a big impact in the advancement of the quality control inspections of the steel parts.

Nondestructive determination of the case depth is based on measuring the differences between the core and hardened layer's material properties such as anisotropy, residual stresses and hardness. [31] Some of the recent developments of nondestructive case depth measurement are given below.

Ultrasonic Method

Ultrasonic analysis is one of the tested methods to determine the depth of a hardened layer. It is reported [27,32] that the technique works well with induction hardened parts with case depth values greater than 1 mm due to method's poor sensitivity to near surface layer. In this method, time of the ultrasonic wave's flight between the sensor and the transition zone are calculated. A calibration is needed to convert the time of flight (TOF) measurement into the case depth in millimeters. [27] For the calibration, at least two parts with known case depths are used. Then the unknown part's time of flight data is plotted and fitted into a straight line to determine the case depth. [27]

As it can be seen in Figure 1, different samples with known case depth values produce different time of flight responses of ultrasonic waves which makes the method a potential way of case depth determination. Figure 1 shows that the transition zone which is linearly correlated with the case depth moves to the right with the increase in case depth values.

With a reliable ultrasonic analysis, case depth measurements can be made without any surface preparation.

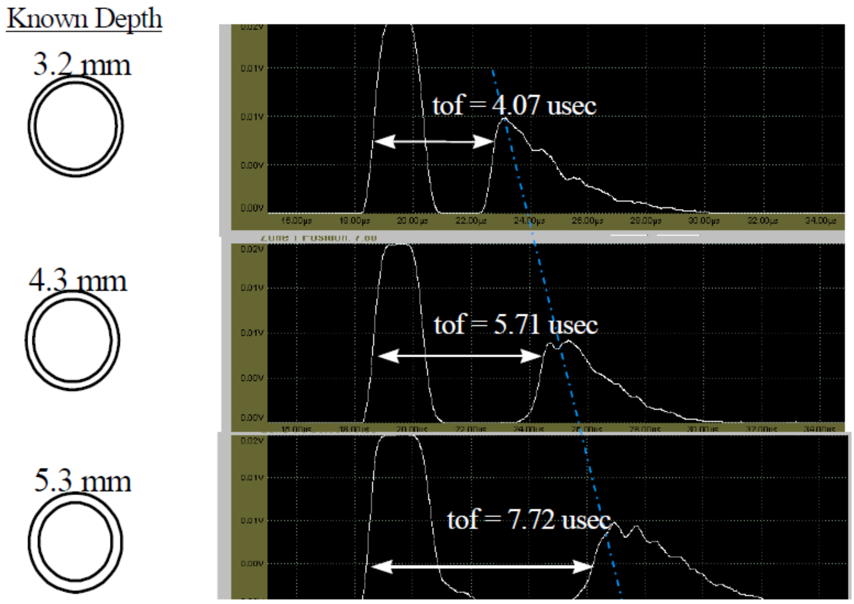


Figure 1 *Time of flight responses of ultrasonic waves from hardened steel shafts with varying case depths.* [27]

One way to determine the case depth is ultrasonic backscattering method. In a study conducted by Baqeri *et al*. induction hardened round bars were used in a special inspection system constructed for the research. [32] As it can be seen in Figure 2, the authors linearly scanned the surface of the sample to measure the case depth nondestructively. They also applied signal filters into their measurement results to smooth their data. For verification of the ultrasonic backscatter results, they also cut the samples and performed a destructive study.

The correlation for the case depth was found to be 0.997 which was of course good but the result only represents these tested samples. [32]

Figure 2 *Case depth profile of a hardened steel shaft measured using ultrasonic backscatter technique.* [32]

Eddy Current

Eddy current method has also been tested for nondestructive evaluation of case depth. Case hardening process induces changes in the magnetic and electrical properties of the sample. Since eddy current is sensitive to these changes, it would be possible to measure the case depth with a multi-frequency eddy current system (MFCE) or pulsed eddy current (PEC) system.

In a study conducted by Cuffe *et al.* [28] special eddy current probes were designed to measure the case depth of induction hardened samples with case depth values between 1-6 mm. They saw that the sensitivity of the measurements was affected heavily by the noise parameters which were originated from the residual stress, surface geometry, probe lift-off and tilt angle. The system's repeatability was good although variations in pulsed eddy current measurements were seen. MFCE system's result is given below in Figure 3 was better than PEC system's.

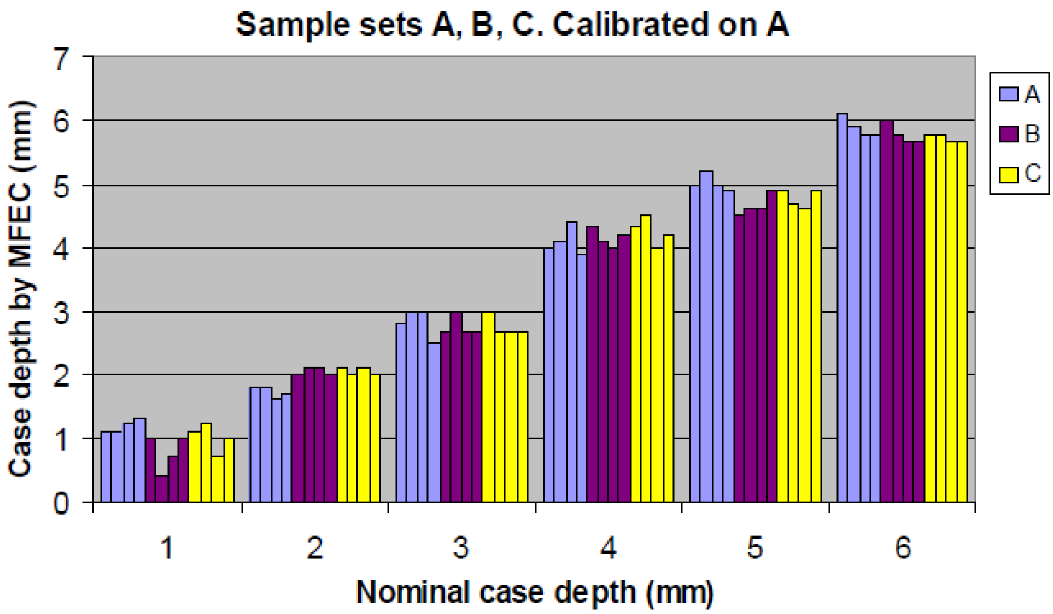


Figure 3 *Case depth measurement results with MFCE system.* [28]

3MA

The 3MA (Micromagnetic Multiparameter Microstructure and Stress Analysis) technology combines different micro-magnetic methods such as Barkhausen noise, incremental permeability, harmonic analysis of the tangential magnetic field strength and multi-frequency eddy current to improve the testing capability. The 3MA simultaneously measures these mentioned phenomena to acquire information about material's hardness, stress state and microstructure. Overall, the 3MA technology provides 41 different parameters as the measurement parameters.

It has been reported that with this technique it is possible to measure the case depth of the components up to 8 mm which is enough for all of the surface hardening processes. [29] The 3MA which is a commercially available nondestructive method from Institute for Nondestructive Testing (IZFP) requires calibration with known case depth samples. The unknown case depths are found with regression analysis. Even though it is tested by IZFP and claimed as a working method for nondestructive testing of case depth, it seems like the 3MA still is not recognized by most of the industries and not preferred over the destructive or other possible nondestructive methods.

Photo-thermal Inspection

Another method which has been tried for nondestructive case depth measurement is photo-thermal inspection. In this method, the sample surface is heated by a laser and material related data is collected after heat is propagated into the material.

The technique first tried for the surface hardness measurements by Jaarinen and Luukkala [33] then Wang *et al.* [30] It was also reported that the carbon content and thermal diffusivity are affecting the material parameters and thus this relation makes the photo-thermal inspection a possible solution for nondestructive case depth measurement. [34]

Photo-thermal method works better with the inspection of hardened layers which are created with diffusion based techniques rather that the localized heating techniques. Photo-thermal inspection remains still as a laboratory based trial method.

2.4 Barkhausen Noise

In this subchapter, Barkhausen noise method will be introduced in detail together with some of its renowned characteristics such as its response to residual stress and hardness, as well as the recent developments in the case depth measurements.

Barkhausen noise (BN) method also referred to as Magnetic Barkhausen noise (MBN) was discovered already in 1919 by a German scientist Prof. Heinrich Barkhausen. [35] However, the method drew the attention for industrial applications in the beginning of 1970s by a Finnish scientist Dr. Seppo Tiitto. [36] Today, it is a recognized nondestructive technique for materials characterization and heat treatment defect testing. [37]

To create the Barkhausen noise, applied magnetic field needs to magnetize the specimen hence MBN is applicable only to ferromagnetic materials. [37] French scientist Pierre Weiss proved that ferromagnetic materials are composed of magnetic domains in 1907. To minimize the magnetostatic energy, material divides itself into magnetic domains.

Magnetic domains may include several small grains or can exist within one large grain. [38] Magnetic domains are separated from each other by domain walls, also known as Bloch walls, named after Swiss scientist Felix Bloch who made the first observations of them in 1931. [39] Hysteresis in ferromagnetic materials is caused by Bloch (Domain) walls.

Domain walls are the borders between the domains in which all magnetic dipoles are aligned in the direction of the easy axis. At the domain wall, magnetic dipoles have to reorient themselves. Depending on their crystallographic arrangement, ferromagnetic materials have different types of domain walls. Domain walls which separate the opposite magnetic moments are called 180^0 walls while walls positioned at 90^0 to each other are called 90^0 walls. [40] The types of domain walls are presented in Figure 4.

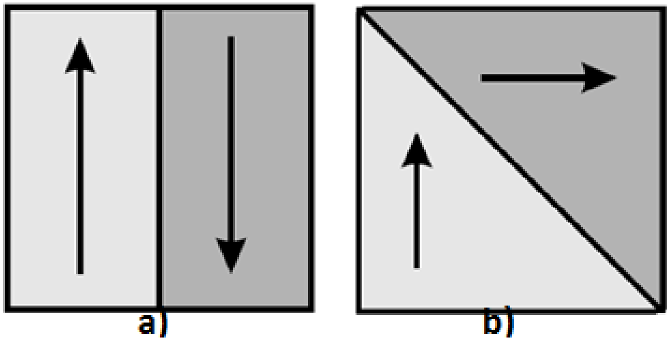


Figure 4 *Domain wall types:* **a)** *180^0 Domain wall.* **b)** *90^0 Domain wall.* [41]

It is known that MBN occurs due to 180^0 domain walls' motion. In the absence of external magnetic field, total net magnetization of the material is zero because the directions of magnetic domains are random which can be seen in Figure 5. [42]

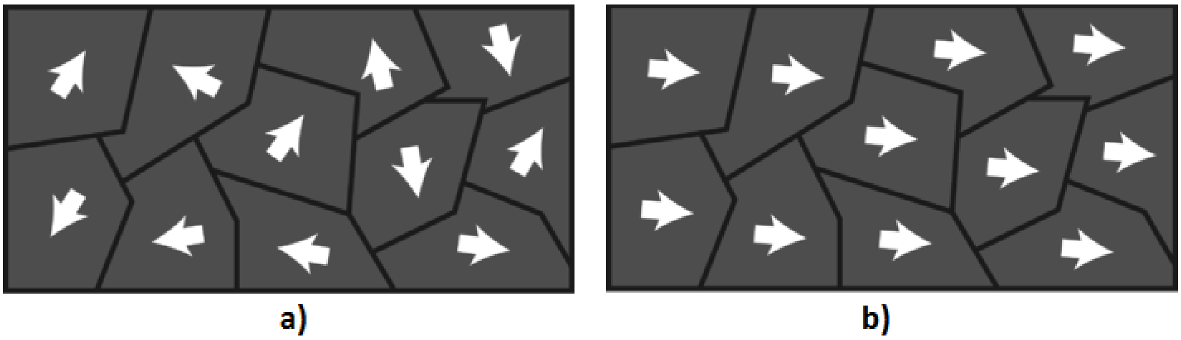


Figure 5 a) *Domains before magnetization.* **b)** *Domains after magnetization*. [43]

When the magnetic field is constantly increased, there is a point where the saturation is observed. In saturation, all of the magnetic domains become parallel to the applied magnetic field by orienting themselves. This orientation increases the magnetostatic energy that depends on the wall positions and the domain orientations. [45]

With an increasing external magnetic field, magnetic domains start to change their sizes which can be seen in Figure 6.

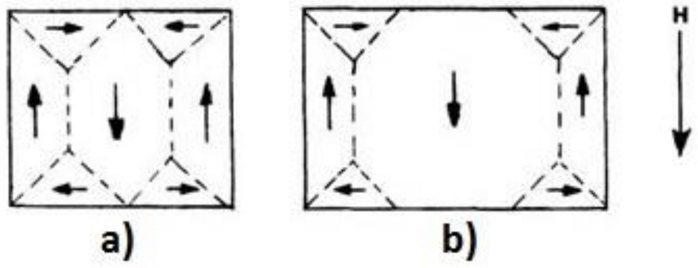


Figure 6 *Growth of a domain due to external magnetic field* **a)** *before the magnetic field,* **b)** *after applied magnetic field.* [44]

Due to the magnetic hysteresis, which is the difference between the magnetizing and demagnetizing paths, decreased magnetization does not follow the same hysteresis curve as increased magnetization. While the demagnetizing field is applied, some of the magnetic domains follow a reversed easy direction to decrease their magnetostatic energy. [46]

When external magnetization becomes zero again, the material will have some remaining magnetization which is called remanence. With an increasing opposite direction magnetic field, the magnetization of the material continues to decrease. To make the net magnetization zero, an opposite external magnetization is required which is called coercivity. The combination of decreasing and increasing magnetization fields form a loop in the hysteresis. [42, 46] The hysteresis loop is the basis of magnetism.

The hysteresis loop which can be seen in Figure 7, gives information about saturation magnetization (M_s), remanence (M_r), coercivity (H_c) and saturation field (H_s). [47]

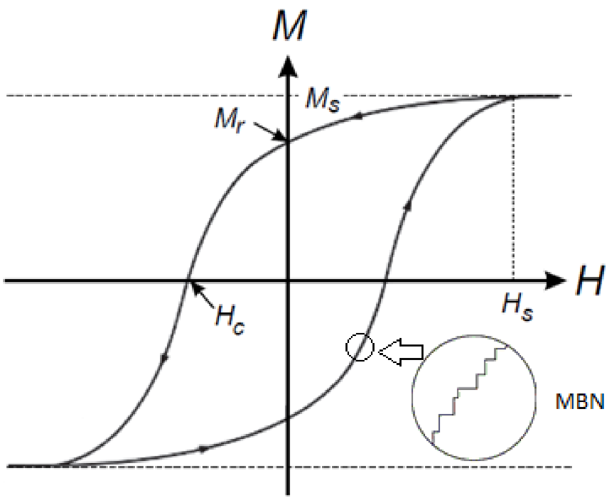


Figure 7 *Hysteresis loop*. [41]

In addition, residual micro-stresses and interactions of different types of domain walls affect the domain wall motions and the shape of hysteresis loop that can be seen in Figure 8. [4,48,49]

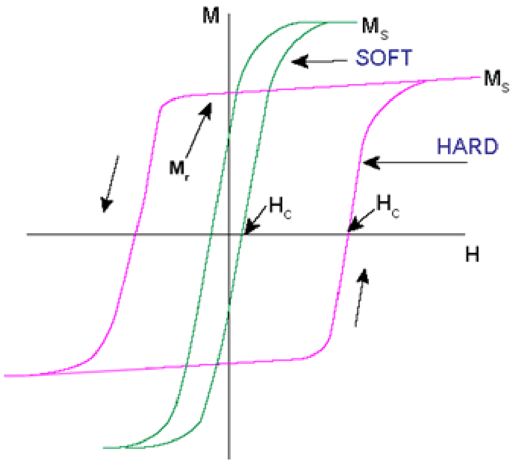


Figure 8 *Hysteresis loops of different materials.* [47]

Under applied alternating magnetic field, domain walls move back and forth because the domain on one side of the wall increases its size while the domain on the opposite side of the wall shrinks. [48]

During their motion, domain walls may spend their energies to consume the less favorable oriented domains in order to move away from the pinning sites. For small external magnetic fields in Rayleigh regime, reversible domain wall movements still may occur. For strong external magnetic field in Barkhausen regime, the energy of the domain walls overcomes the energy of these pinning sites. [48]

This is also the reason why domains may not follow the same path to go back to their original configuration when the magnetic field or stress state changes back. [49]

Pinning sites which are precipitates, grain boundaries, inclusions, dislocations and small volumes of second phase material, slow down the domain wall's movement. The domain walls may be trapped behind these sites. [50]

The abrupt jumps due to energy spending in order to overcome pinning sites lead to sudden changes in the magnetization of the material. Even though the applied external magnetic field changes smoothly, these so-called Barkhausen jumps are the reasons of the discontinuity that is directly observable in the hysteresis loop that is given in Figure 7. Detecting these changes in the magnetization, forms a noise-like signal called the Barkhausen noise. [51]

Barkhausen noise, the irreversible jumps of domain wall over pinning sites, is called "noise" because of the sound heard from the speaker used in the original experiment that can be seen in Figure 9.

It is often called “magnetic” to separate it from “acoustic” Barkhausen noise which is the base for magneto-acoustic emission. [46]

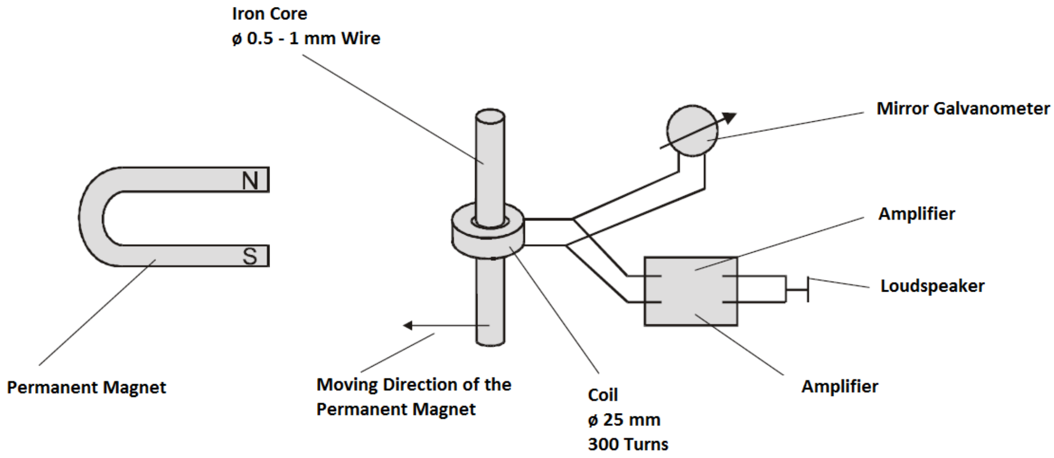


Figure 9 *Original Barkhausen set up from 1919.* [52]

Barkhausen noise is sensitive to the hardness and microstructure of the material because the microstructure determines the domain structure and the distribution of pinning sites. Analysis of Barkhausen noise can give information on the interaction between domain walls and stress configurations, or compositional microstructure. [51,52]

Barkhausen Noise Measurements

Barkhausen noise measurement requires an applied magnetic field which is induced by a sensor.

A sensor consists of a ferrite yoke with coil (magnetizing pole pieces) and a ferrite pick-up (sensing pole piece) to detect the BN signal.

During the measurement, the sensor magnetizes and demagnetizes the sample in a cycle. A scheme of the principle of Barkhausen noise measurement is given in Figure 10.

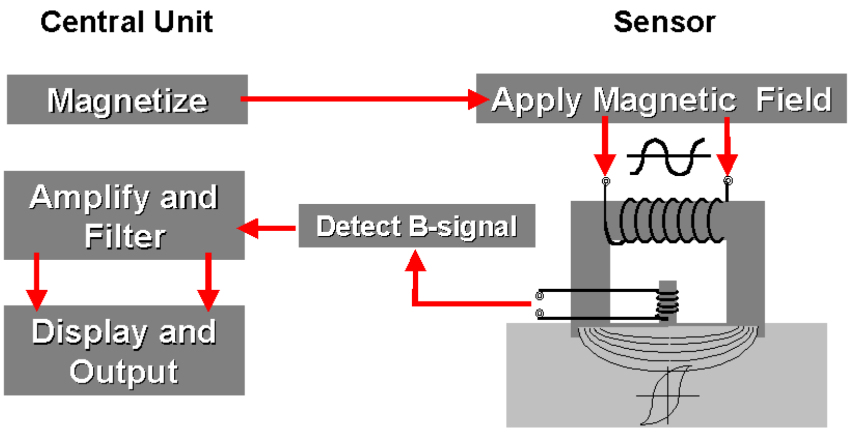


Figure 10 *A typical Barkhausen noise measurement scheme is shown.* [51]

Barkhausen Noise Signal

Characteristic of the BN signal are amplitude, peak and width shape which are affected by the microstructure of the sample and applied magnetizing field. An example Barkhausen noise signal can be seen in Figure 11. The most important aspect of Barkhausen noise signal is its response to changes in stress and hardness in the material.

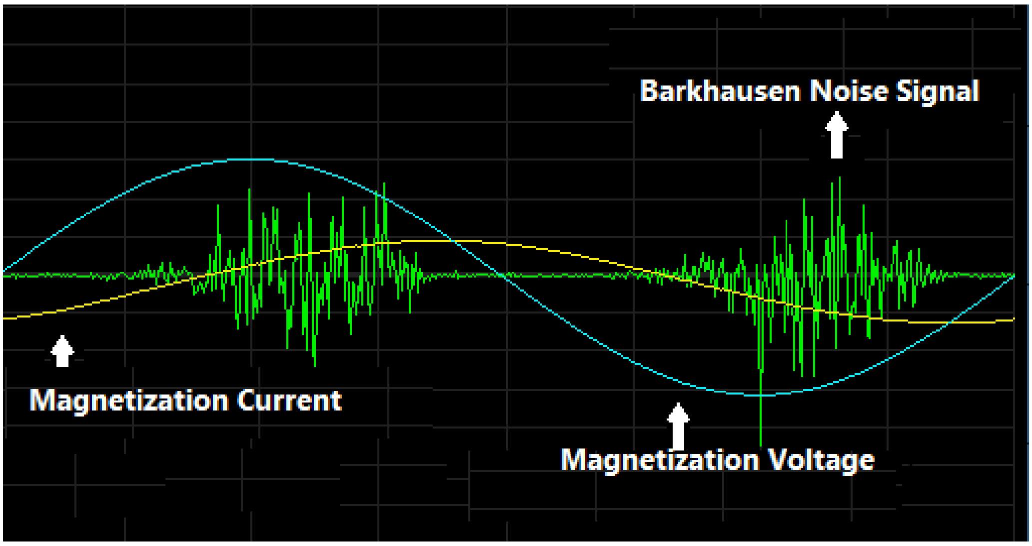


Figure 11 *BN signal from device.* [51]

Barkhausen noise has a wide power spectrum starting from the adjusted magnetizing frequency and ending above 2 MHz in most of the ferromagnetic materials. [56]

Barkhausen noise gives information from the surface and very close area beneath the surface. In order to have more information from beneath the surface (to increase the penetration depth), one possible way is to use low analyzing and magnetization frequencies. Barkhausen noise signal is damped due to skin effect which is caused by the opposing eddy currents induced by the changing magnetic field.

An estimation of the penetration depth of the BN signal can be calculated using the following formula:

$$\delta = 1 / \sqrt{\pi \mu \sigma f}$$

where δ denotes the penetration depth, μ represents the magnetic permeability, σ means the electrical conductivity and f denotes the frequency of the alternating magnetic field. [56] Microstructure of the sample directly affects the shape of the signal output as well. As an example, hard magnetic materials have wider and soft magnetic materials have narrower BN signal envelope shape. [50]

Residual Stresses

Barkhausen noise can be used for the evaluation of stress state of materials. Barkhausen noise gives a response to the stress level of specimens, which can be seen in Figure 12.

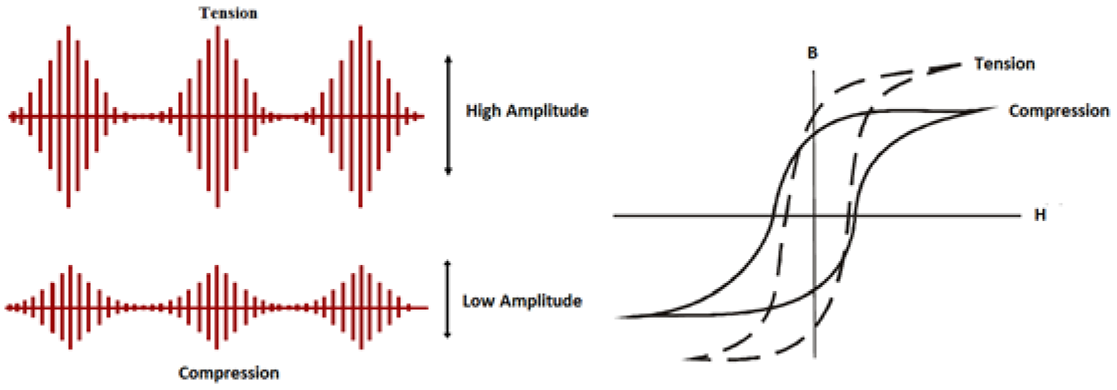


Figure 12 *BN signal response to stress.* [51]

Tensile stress increases the Barkhausen noise signal amplitude and compressive stress decreases Barkhausen noise signal amplitude.

Since Barkhausen noise gives response for both hardness and stress changes, the prediction of residual stress state can be challenging with Barkhausen noise. However, it can be used as a NDT tool for comparison studies of elastic stresses and strains and changes with plastic deformation.

To evaluate the stress state of materials with Barkhausen noise, calibrations need to be made with known stress levels and known signal values. [5] Since magnetic domains are influenced by the presence of stresses and strains, even with the absence of external magnetic field, ferromagnetic materials' bulk magnetization changes with stress changes. [47]

Pinning sites and ferromagnetic domains are also affected by the presence of stress and strain state. This effect is sometimes called "stress-induced volume change" due to the change in elastic energy densities. Both stresses and applied magnetic field change the energy state of the dipoles. All magnetic domain size modification causes a change in Barkhausen noise signal. [6]

Processes as cold rolling and shot peening which are used to create complex compressive residual stress distributions at the surface layer can be characterized by Barkhausen noise. [53] However, for all studies, a calibration is needed since Barkhausen noise does not directly produce any MPa value results for stress state determination. [52]

In order to investigate the effects of stresses on magnetic domains, a stress free demagnetized material should be used.

The relation between the applied magnetization direction and stress state can be seen in Figure 13. [52]

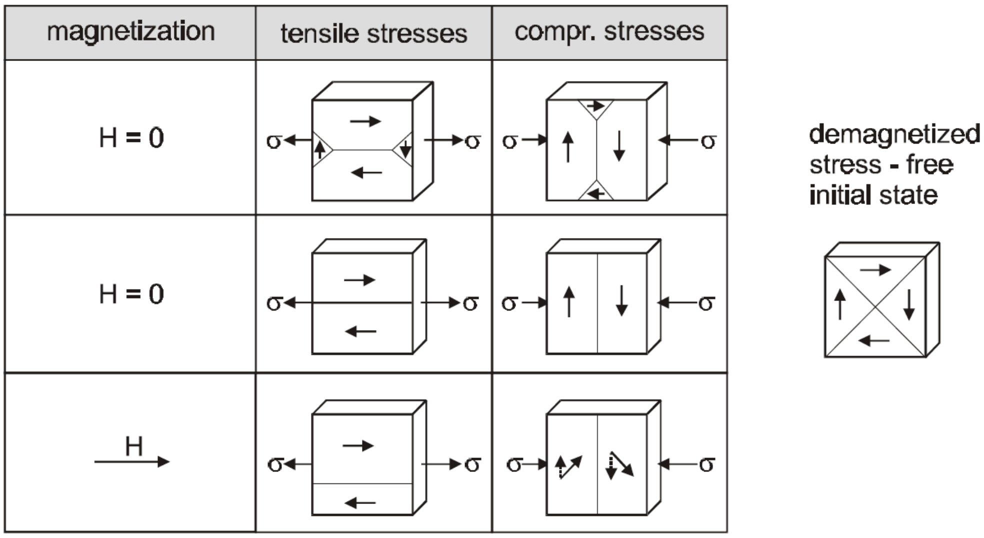


Figure 13 *Alteration of the domain structure due to external influence.* [52]

The effective voltage (root-mean-square, RMS) of the generated signal, also referred to as magneto-elastic parameter (MP), is a strong function of the microstructure and the residual stress state of a material. [52] In a study conducted by Vashista et al. Barkhausen noise was used for the assessment of surface grinding of steels. [5]

For Vashista's study, plunge-roughed hardened and unhardened steels were used to investigate the Barkhausen noise's response to different conditions. Response of Barkhausen noise's amplitude is different for unhardened and hardened steels which can be seen in Figures 14 and 15.

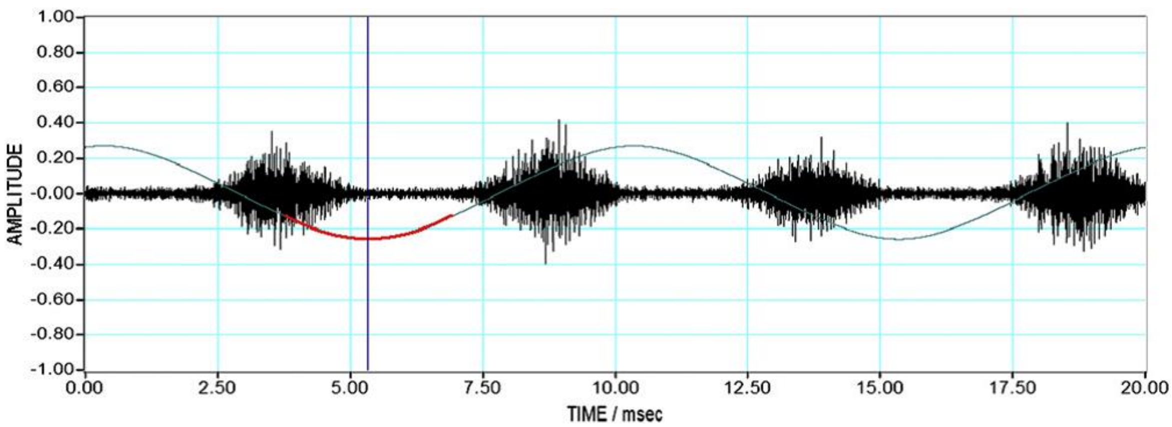


Figure 14 *BN signal of unhardened steel.* [5]

As it can be seen in Figure 15, the Barkhausen noise response to the hardened steel is quite different and weaker than the unhardened steel's response.

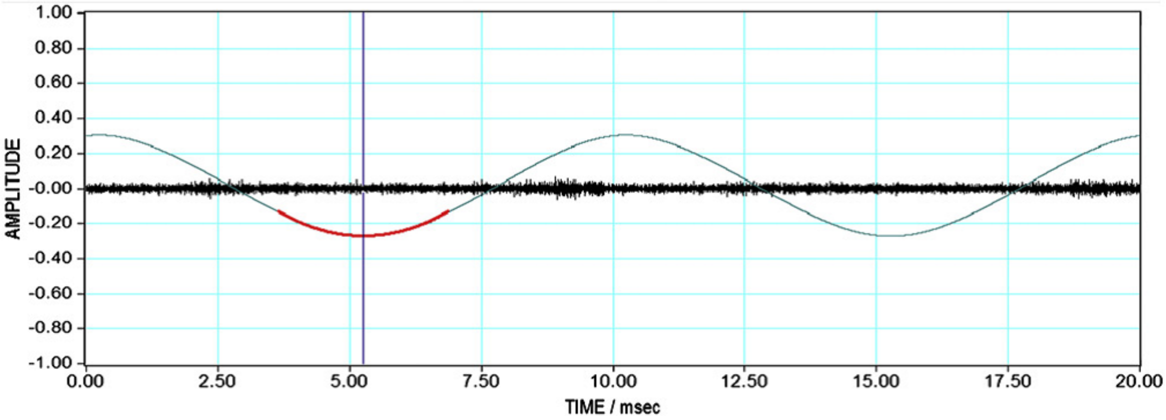


Figure 15 *BN signal of hardened steel.* [5]

In addition, residual stress state of the hardened and unhardened steels gives different Barkhausen noise values which can be seen in Figure 16. For both hardened and unhardened steel, a linear correlation between the residual stress and Barkhausen noise can be seen in Figure 16. In Figure 16 it is again can be seen that the hardened steel's residual stress response is weaker than unhardened steel's residual stress response.

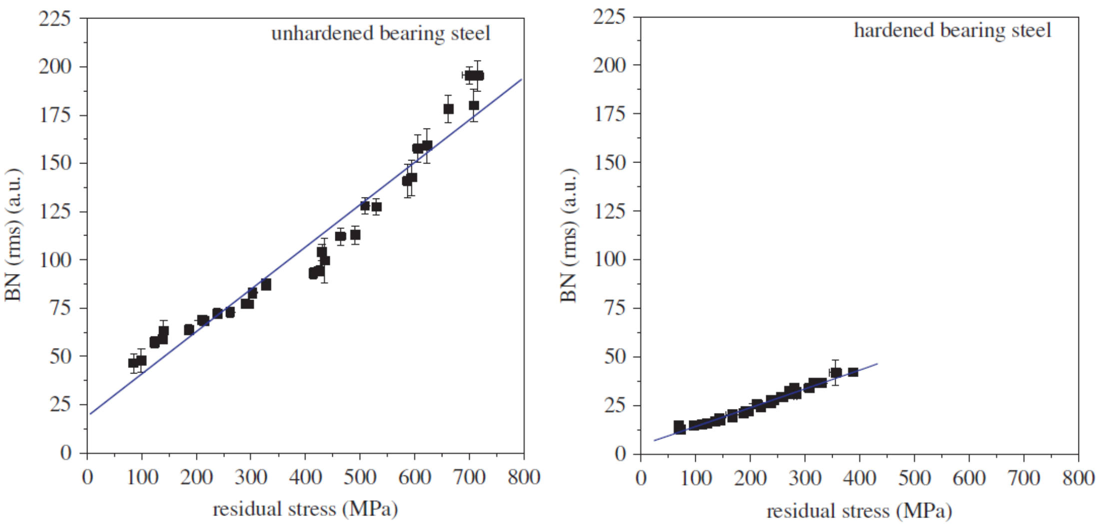


Figure 16 *Response of BN with residual stress of hardened/unhardened steel.* [5]

Hardness

Barkhausen noise can be used for the evaluation of hardness state of the materials. Soft materials increase the Barkhausen noise signal amplitude and hard materials decrease Barkhausen noise signal amplitude.

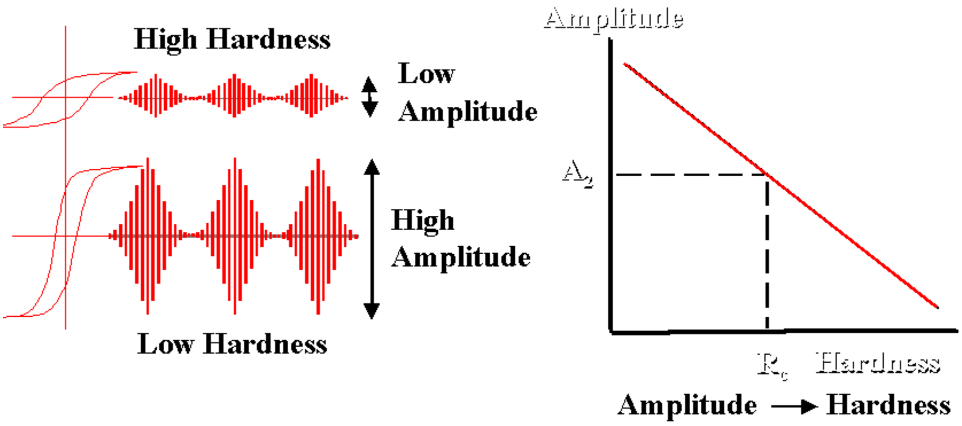


Figure 17 *BN signal response to hardness.* [51]

In a research made by Fix [54] chromium-plated, hydraulic cylinders were tested with BN to control the thermal damages that may have occurred during the service by friction forces. Study found that different hardness levels produce different BN amplitude as it can be seen in Figure 18. It was already confirmed in another study made by Tiitto *et al.* [55] that Barkhausen noise could observe the changes through chromium plating.

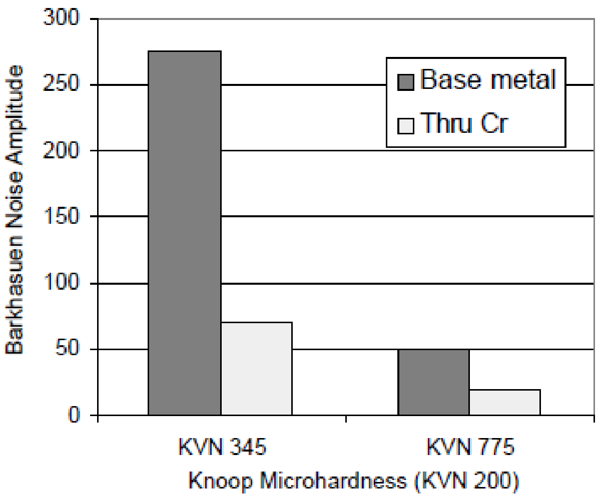


Figure 18 *Different BN amplitude by different hardness.* [54]

2.4.1 Case Depth Measurements with Barkhausen Noise

Barkhausen noise is sensitive to both microstructure and hardness which is why it has always been considered one of the best possible ways to determine the case depth. Barkhausen noise can easily detect the different states of hardness in ferromagnetic materials.

Nondestructive case layer determination is mostly about the detection of the hardness difference in the material.

Barkhausen noise has been used to detect the case depth many times with different approaches. [2-4,6-17,19,20] However, still not an effective and reliable solution has been adapted in practice.

The early attempts were made with using low frequencies to determine the case depth. Since with lower frequency, deeper penetration of the signal into the material is possible hence thicker hardened layers could be detected. The determination of the case depth is also related with the material properties of the samples such as the permeability and anisotropy. [56]

In addition, Barkhausen noise signal is also damped when it is penetrating the material due to eddy currents which are created by the magnetization of the sample. In the first attempts, detection of the case depth has been made up to 1 mm with lower frequencies. [2,9,13] Moorthy *et al*. reported that using high frequency, 1000 kHz, detection of case depth has been made up to 0.15 mm. [14] High frequency measurements were also made by Santa-aho *et al.* [16]

Stresstech Oy has also developed an equipment called CaseMaster which is no longer in use due to newly developed BN methods. The equipment was using low magnetizing frequency, 1-5 Hz, while magnetizing the samples with a high power magnetization yoke. The data was being transferred to a special software, called CaseScan, which was made to analyze case depth. With this equipment, case depth evaluation was made up to 3 mm thickness. [4,13]

It has be seen in several studies that hardened case layer and soft core layer produce separate Barkhausen noise signal peaks. It is generally stated that BN signal peak with lower shift comes from the soft core layer and higher shift comes from the hardened case layer. In addition, it is possible to use the ratio of these two peaks and correlate it with the case depth. [16,17,19,20]

The changes in the coercivity and hysteresis values were also used for case depth evaluation. [11,12,19,20] The study performed in [11] showed that the total saturation magnetization is affected by the thickness of hardened layer but the saturation magnetization of the case and the core is different than each other due to different magnetic properties of these layers. It is reported in [12] that permeability and case depth are inversely proportional. The study made by Kai *et al.* [57] found that magnetic flux density and magnetic field strength could also be used to evaluate the thickness of the hardened layer.

A complete new approach has been introduced by Santa-aho *et al.* [2] as they used different set of samples which were induction hardened and case carburized and each set of samples had a similar residual stress profile. The case depth value of these samples had a range between 0.35 mm and 3.4 mm.

In this approach [2] they used magnetizing voltage sweeps (MVS) and magnetizing frequency sweeps (MFS) in case depth measurements. MVS and MFS were used to optimize the sensitivity of BN measurements by Thomas et al. [17] In their study, the slopes of the sweeps were used for the correlation studies. The steepest slope (the maximum slope value) of the sweep showed good correlation with case depth.

During NOVEBARK project [20], the effectiveness of using magnetizing voltage sweeps in case depth measurements was realized. It has be seen that different frequencies can be correlated with different case depths. It was also reported that using low and high frequencies together gives a better correlation than any other frequency related approaches.

The idea behind of using two frequencies together, is getting information from the material's different layers with different frequencies at the same time. When low frequency provides a better signal from deeper parts of the material, the high frequency provides a better signal from the surface and very near surface parts of the material. Hence, the highest slopes' ratio of these two frequencies gives a value which is correlated with the case depth in millimeters. Most commonly used frequency couple has been 20 Hz and 125 Hz. Since 125 Hz was considered as the standard frequency for normal Barkhausen noise measurements, it was preferred again for the case depth measurements. [17]

The sweep method has performed well to measure the case depth of various hardened components but still more research is needed to announce that this BN based new approach is a reliable and working method for case depth measurement. In this research, the method of using two frequencies at the same time will be tried again with a new software and new sensors.

One of the most important parameters of the magnetizing voltage sweep method is the chosen frequency couple. So far, no meaningful relation has been established between the chosen frequency couple and the case depth determination. However, it has be seen that comparing the ratio of two different frequency sweeps' highest slopes, high correlations could be found with the case depth values. In addition, it could be possible to estimate the case depth values by calculating regression lines from the known correlations.

As both hardness and residual stress affect the magnetic properties of the material, there are meaningful reasons to think that the method could be used to evaluate the residual stress values when the hardness states are known. For this reason, the sweep-slope method has been tested [58] for determination of residual stress values. The study concluded that the found correlations were not so good and it will require further studies to develop the method.

3. EQUIPMENT, SOFTWARE AND SAMPLES

During this study, different equipment and software were used to measure and analyze the samples. In this chapter, these will be introduced in detail.

3.1 Barkhausen Noise Analyzer

The Barkhausen noise measurements were conducted using a Rollscan 350 system which is manufactured by Stresstech Oy (Vaajakoski, Finland). Rollscan 350 system consists of a main analyzer unit and a sensor. Rollscan 350 is a digital Barkhausen noise processor which is used to detect the near-surface defects involving changes in hardness, microstructure and stress state of the ferromagnetic materials. Rollscan 350 which can be seen in Figure 19 is a fast and easy to use NDT quality control tool. Rollscan 350 uses a Linux-based user interface. [59]

Figure 19 *The Rollscan 350 device.* [59]

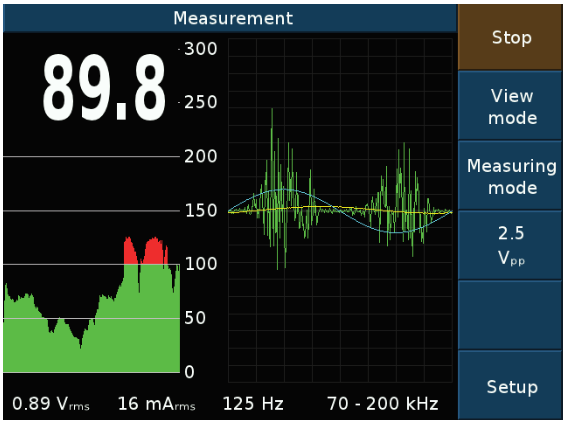


Figure 20 *Measurement view of Rollscan 350 device.* [59]

The measurement data can be transferred into a PC via Ethernet or USB connection and analyzed with software called ViewScan and MicroScan. To make a Barkhausen noise measurement, a magnetizing voltage and frequency need to be chosen. The optimal magnetizing voltage and frequency can be chosen with built-in functions which their interfaces can be seen in Figure 21.

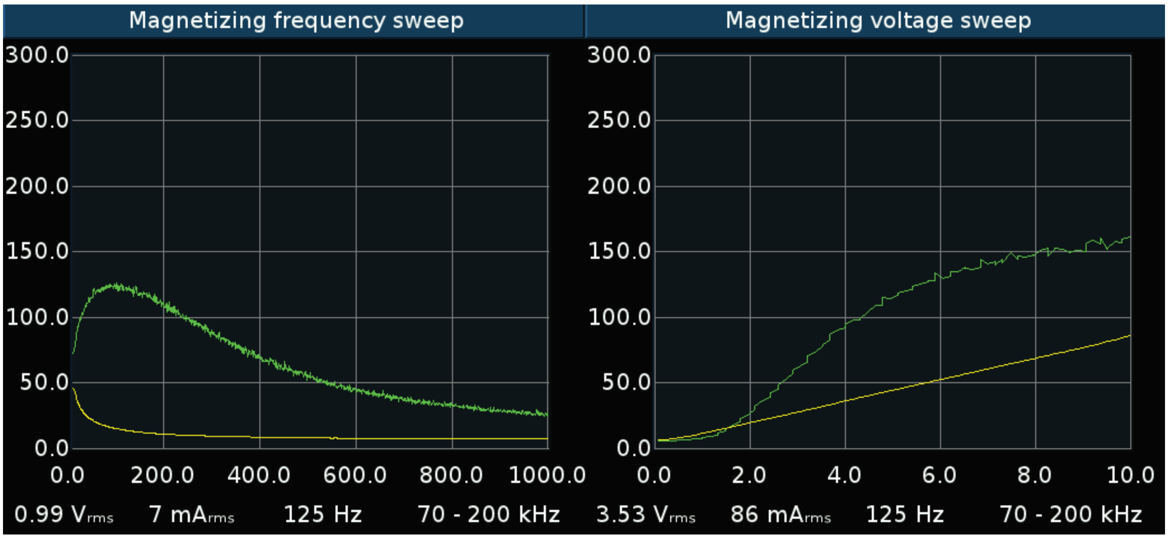


Figure 21 *Magnetizing frequency and voltage sweep views.* [59]

3.2 Magnetizing Power Amplifiers

Magnetizing power for Barkhausen noise measurement is produced by the integrated magnetizing power amplifier with Rollscan 350. However, for some cases, integrated amplifier of Rollscan 350 cannot produce high enough magnetizing power. In these kind of cases, it is possible to magnetize the sample with an external magnetizing power amplifier. During this study, MA-100 which can be seen in Figure 22 and RMX 4050HD which can be seen in Figure 23 were used to take the magnetizing power externally.

Figure 22 *External magnetizing power amplifier MA-100.* (Courtesy of Stresstech Oy)

MA-100 which is manufactured by Stresstech Oy has a power output of around 100 Watt and it was used during the current and voltage sweep measurements where this level of power was enough. RMX 4050HD which is manufactured by QSC Audio Products, Inc. has a power output of around 4000 Watt and it was used during some of the case depth measurements.

Figure 23 *External magnetizing power amplifier RMX 4050HD.* [60]

3.3 Sensors

A sensor can magnetize the sample internally, pick-up the signal from the sample surface and even amplify the received signal with the built-in pre-amplifier. This type of sensor's scheme is given in Figure 24 a).

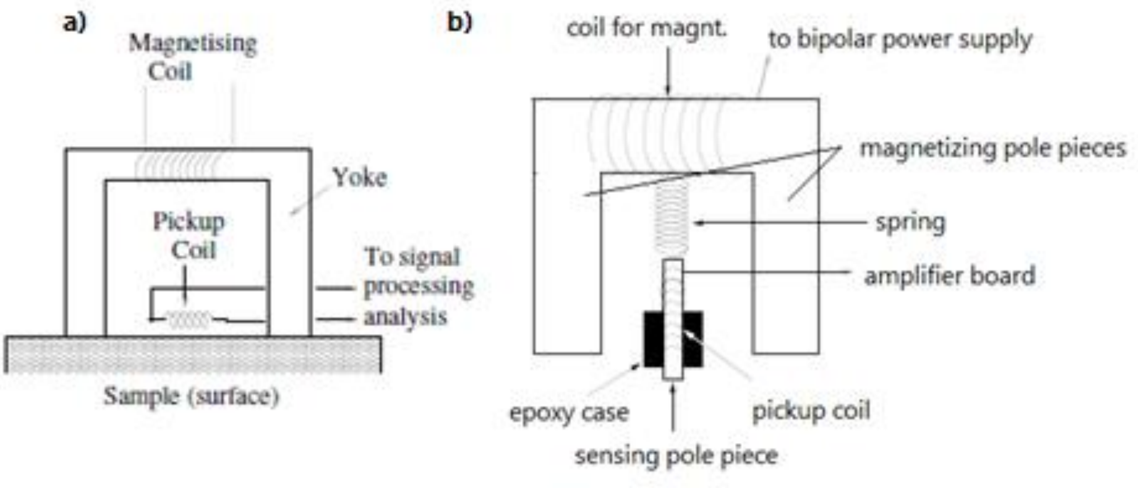


Figure 24 a) *Sketch of a sensor and sample set-up.* **b)** *Detailed view of a spring loaded-pick-up mechanism.* [61]

A sensor consists of a pick-up pole piece, two magnetizing pole pieces, a case, a potentiometer, a cable connection and a connector. Pick-up and magnetizing pole pieces are made of ferrite. A detailed sketch of a spring loaded pick-up can be seen in Figure 24 b). Pick-up also called sensing pole piece is fixed and its surface geometry depends on the geometry of the sample's surface.

For example, for round surface samples, a round shaped pick-up pole piece and for flat surfaces, a flat shaped pick-up pole piece is used. As an example, a flat sensor is given in Figure 25. Magnetizing pole pieces are not fixed instead they are removable and they can be changed with different shaped pole pieces which again depend on the sample's surface. With this flexibility, same sensor can be used in different applications.

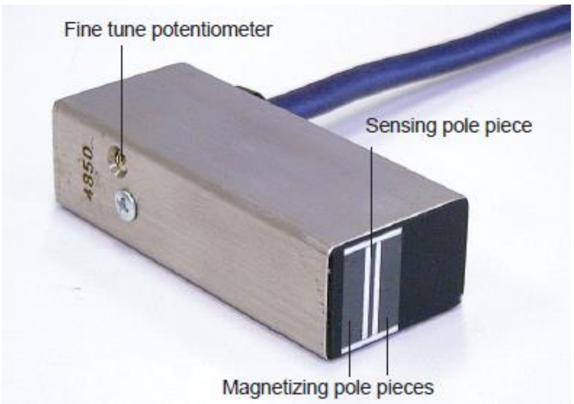


Figure 25 *Flat Barkhausen noise sensor.* (Courtesy of Stresstech Oy)

The case of the sensor is made of either stainless steel or aluminum. The empty gaps between the parts and the case are filled with epoxy to make the sensor sturdy. Especially for commercial applications where the sensors are being used more than 6 hours per day, sensors can wear out after some point. To avoid this, tungsten carbide pieces are inserted into the magnetizing pole pieces and aluminum oxide pieces are inserted between the magnetizing and pick-up pole pieces. Sensors, depending on the application can be in many different types, shapes and sizes. This is one of the main advantages of Barkhausen noise method.

In addition, sensors can be divided into two categories, one is active and the other is passive sensors. An active sensor includes a pre-amplifier and passive sensor uses the hardware's amplifier. Passive sensors are not used for magnetization of the sample but just for picking-up the signal. For this kind of sensors, an external magnetization yoke is needed to magnetize the sample.

A normal frequency band for a Barkhausen noise sensor is 70-200 kHz while a wide band means that the sensor can work between 3 and 1000 kHz analyzing frequency range. A normal frequency band sensor has higher rounds of copper winding in its magnetizing pole pieces than a wide frequency band sensor. A higher round of copper winding means that higher self-capacitance and lower self-resonance frequency. In general, a normal frequency band sensor provides a better signal to noise ratio even though it is more affected from the noise than the wide frequency band sensor. In addition, for high voltage demanding applications, generally a normal frequency band sensor is used. In this study, many different types of sensors were used.

In addition, some sensors were specially manufactured just for this study. Some of the details of the used sensors will be introduced in the following subchapters.

3.3.1 Existing Sensors

In this chapter, sensors which are commercially available and used during this study will be introduced.

Sensor: SNO1

This sensor and its basic sketches can be seen in Figure 26 and it has a built in amplifier and is used for measuring outer diameter (OD) surfaces of camshafts (lobes and bearing journals). It is an active wide band sensor and its magnetization direction is axial. It was used in this study because it allows measurements with different contact angles.

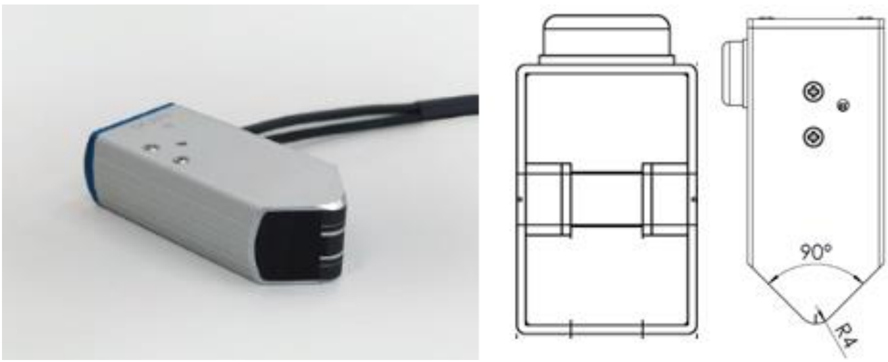


Figure 26 *Camshaft sensor (SNO1) and its sketches.* (Courtesy of Stresstech Oy)

Sensor: SNO2

This spring loaded sensor and its basic sketches can be seen in Figure 27. It has a built in amplifier and used to measure OD surfaces (e.g. camshafts, crankshafts, gears). This sensor was chosen for this study because spring loaded pick-up pole piece makes the sensor self-aligning which was very beneficial while measuring the rod samples.

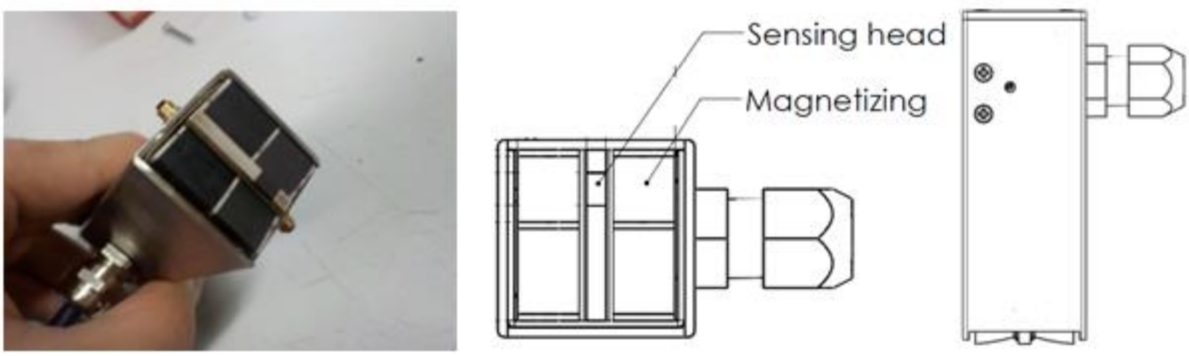


Figure 27 *High power OD sensor (SNO2) and its sketches.* (Courtesy of Stresstech Oy)

Sensor: SNO3

This spring loaded active band sensor and its design model which can be seen in Figure 28 has an amplifier outside of the case and is used for measuring OD and inner diameter (ID) surfaces. This sensor was chosen for this study because it is easy to align and has small pick-up which was very beneficial while measuring various types of samples.

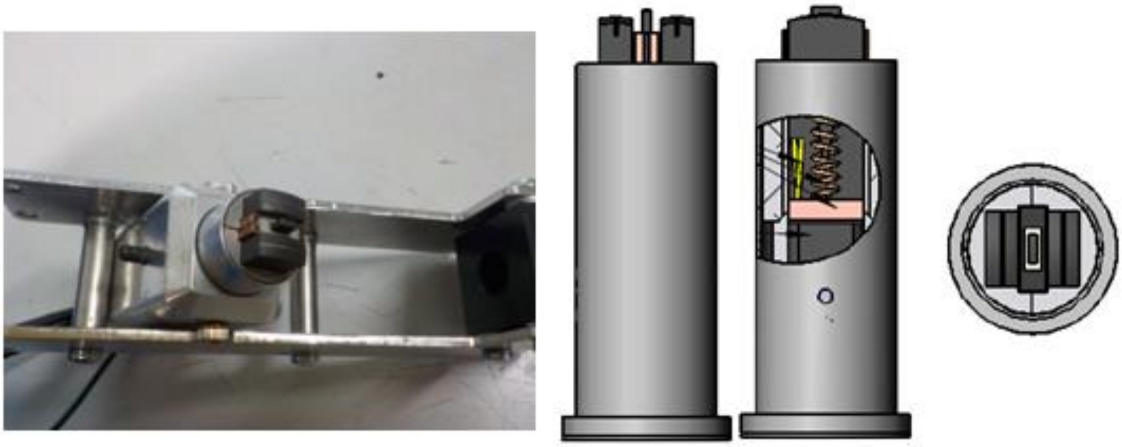


Figure 28 *Special sensor (SNO3) and its model pictures.* (Courtesy of Stresstech Oy)

Sensor: SNO4

This active band pick-up sensor has no magnetizing piece and thus it needs an external magnetizing unit. This sensor is used to measure various forms of metal parts (e.g. plug taps, drill bits and bearing surfaces).

This sensor was chosen for this study because it has a similar design with one of the new-manufactured sensors and has a small pick-up which was very beneficial while measuring the small areas. The sensor and its sketches can be seen in Figures 29.

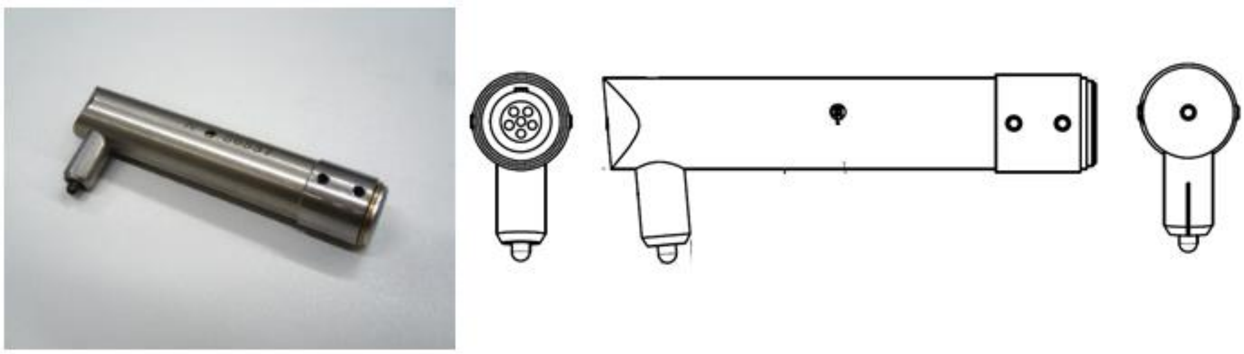


Figure 29 *Bearing pick-up sensor and its sketches. (SNO4)* (Courtesy of Stresstech Oy)

3.3.2 New Sensors

The new sensors were made with a new pot-core design and their pick-up pole piece design was inspired with the research made by Steven Andrew White in his PhD thesis. [18] For this study, two general purpose type and two pen type sensors were manufactured. The details of the sensors are given below.

Sensors: SN1 and SN2

These sensors are identical and their sketches and model pictures are given in Figures 30 and 31. Sensor consists of a brass shield as the outermost layer, ferrite core as the innermost layer and between them a sheath, a bare coil ring and another bigger coil ring. The idea of sheaths is to focus the sensing (pick-up) in a smaller area to get more signal from possibly deeper parts of the sample.

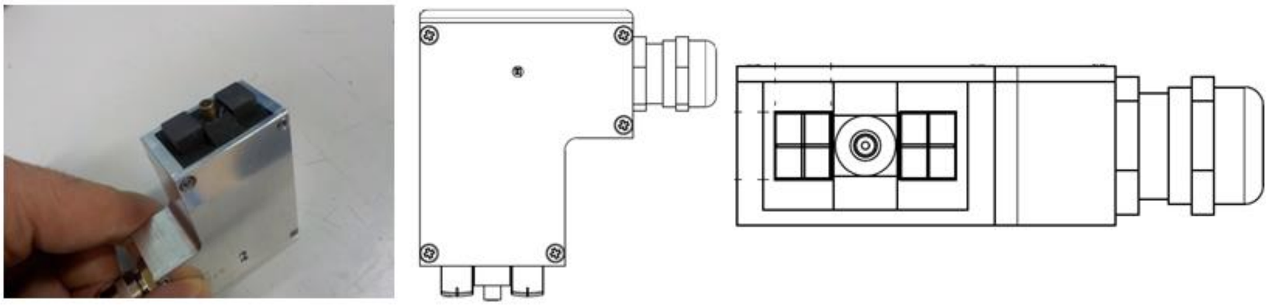


Figure 30 *Pot-core general purpose sensor (SN1 and SN2) and its sketches.* (Courtesy of Stresstech Oy)

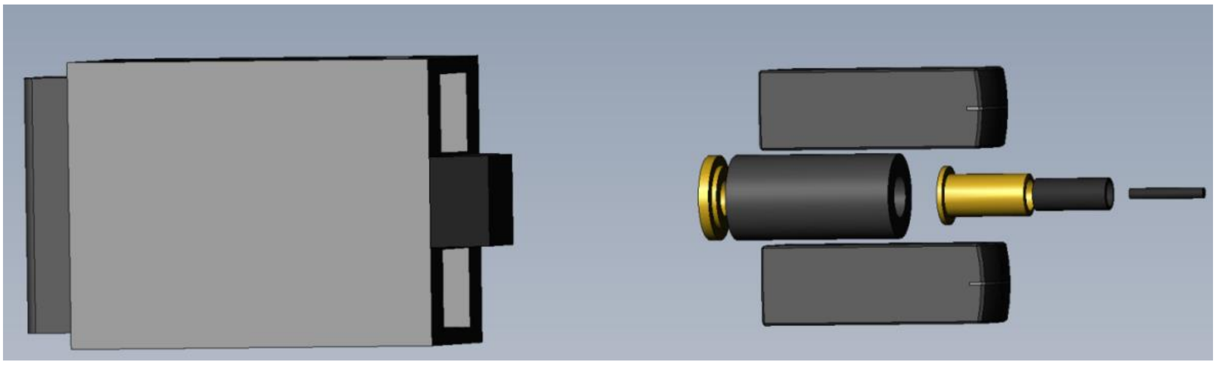


Figure 31 *The model picture of new pot-core sensors.* (Courtesy of Stresstech Oy)

Sensors: SN3 and SN4

These sensors are also identical and their sketches and pictures are given in Figure 32. The only difference between SN1&SN2 and SN3&SN4 is that these sensors do not have magnetizing capability just like SNO4, and they require external magnetization. The sensors as SNO4 and SN3&SN4 are called pen-type sensors.

This sensor also consists of a brass shield as the outermost layer, ferrite core as the innermost layer and between them a sheath, a bare coil ring and another bigger coil ring.

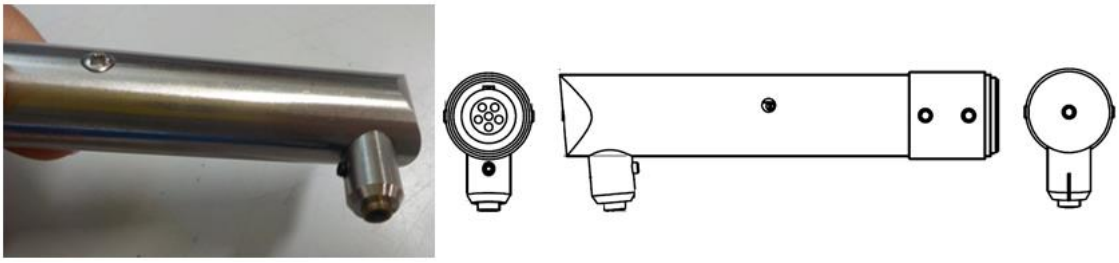


Figure 32 *Pot-core bearing sensor (SN3 and SN4) and its sketches.* (Courtesy of Stresstech Oy)

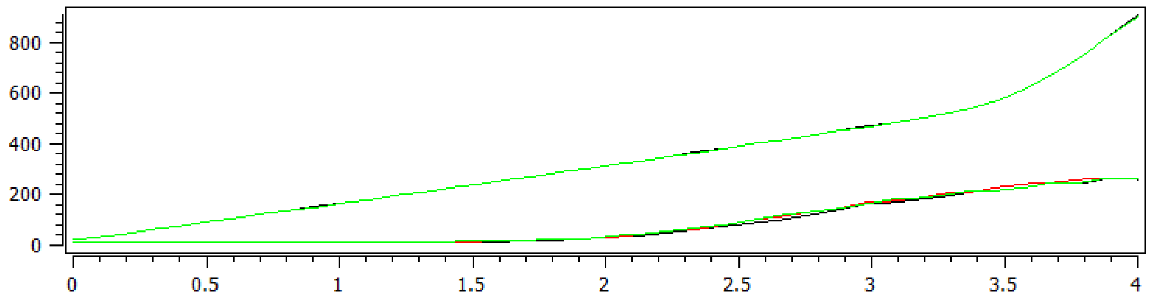
3.4 Software

During this study, different software solutions were used to investigate and analyze the measurement results and the details of the used software are given in this chapter.

3.4.1 ViewScan

ViewScan is a software for data acquisition and analyzing of Barkhausen noise measurements. It is a product of Stresstech Oy. It is used for current sweep measurements during this study. An example of a current sweep measurement view can be seen in Figure 33. Data collection is made with a Barkhausen noise analyzing instrument, Rollscan 350 together with SN1 sensor which was modified to get the magnetization through the MA-100 (magnetizing amplifier).

Data transferred to ViewScan via a network (TCP/IP) connection.



Meas Id	Name	S	Max	Limit	At	Min	Avg	Dev	Npts	Max/Min	Max/Avg	Min/Avg	Max-Min
1	MP 1	M..	265.10	-	3.90	9.30	81.75	88.93	40	28.51	3.24	0.11	255.80
2	Current 1	M..	900.80	-	4.00	20.60	336.99	219.70	40	43.73	2.67	0.06	880.20
3	MP 2	M..	266.40	-	4.00	10.30	86.19	90.97	40	25.86	3.09	0.12	256.10
4	Current 2	M..	900.30	-	4.00	21.10	336.38	219.63	40	42.67	2.68	0.06	879.20
5	MP 3	M..	266.80	-	4.00	11.00	86.16	89.33	40	24.25	3.10	0.13	255.80
6	Current 3	M..	900.50	-	4.00	19.10	336.26	219.65	40	47.15	2.68	0.06	881.40

Figure 33 *Current sweep measurement view.* (Courtesy of Stresstech Oy)

3.4.2 MicroScan

MicroScan is an advanced Barkhausen noise signal analyzing software. MicroScan system is used for correlation of different microstructural parameters with Barkhausen noise and it is a product of Stresstech Oy. An example of analyzing view is given in Figure 34.

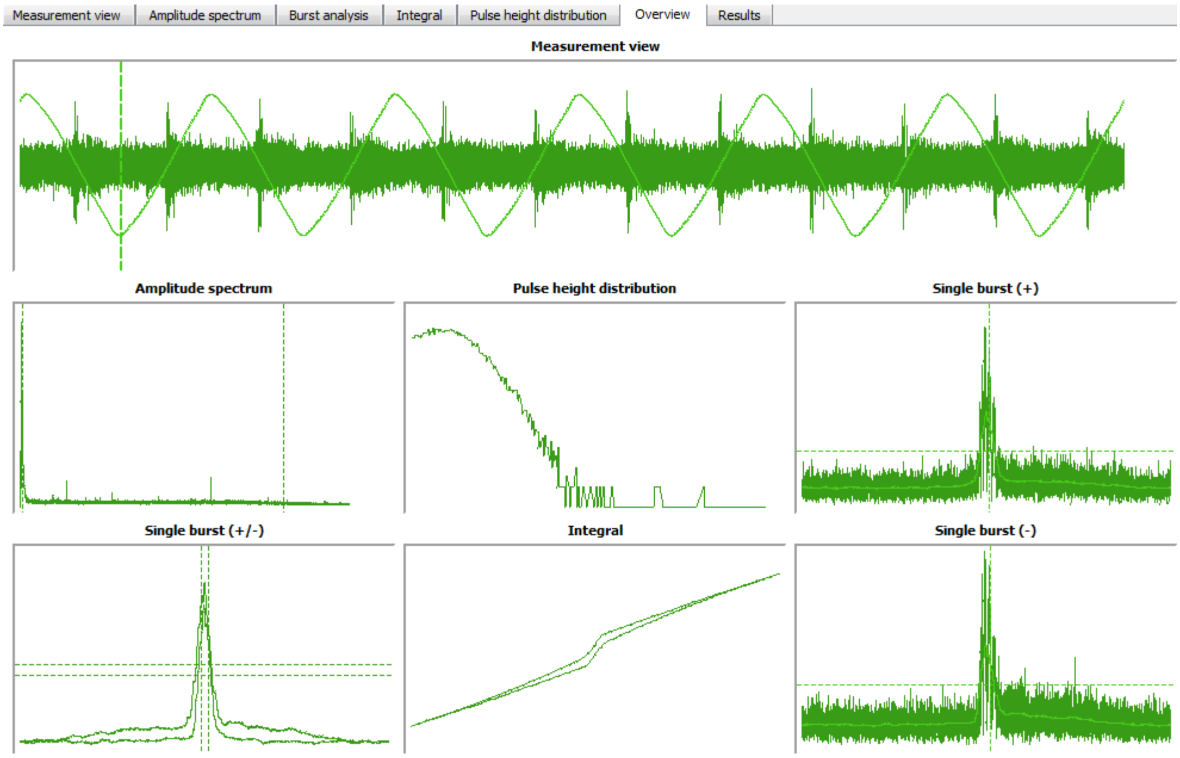


Figure 34 *MicroScan results overview.* (Courtesy of Stresstech Oy)

During this study, MicroScan was used to investigate the Barkhausen noise signal which was collected from different samples. With MicroScan, it is possible to record the other values than RMS i.e. the peak values and peak positions.

3.4.3 PCCaseDepth

PCCaseDepth is a software specifically made for case depth studies by Stresstech Oy. One of the main purpose of the thesis work was to investigate the usefulness of the software for the case depth measurements. During the study, software was used for over 5 months and more than 10000 measurements were made with it.

PCCaseDepth was developed to make case hardening depth measurements using the ratio of sweep slopes method. The software works with a Barkhausen noise analyzer and a suitable sensor to collect the data. Data transferred to the software via a network (TCP/IP) connection.

A general overview of the software is given in Figure 35.

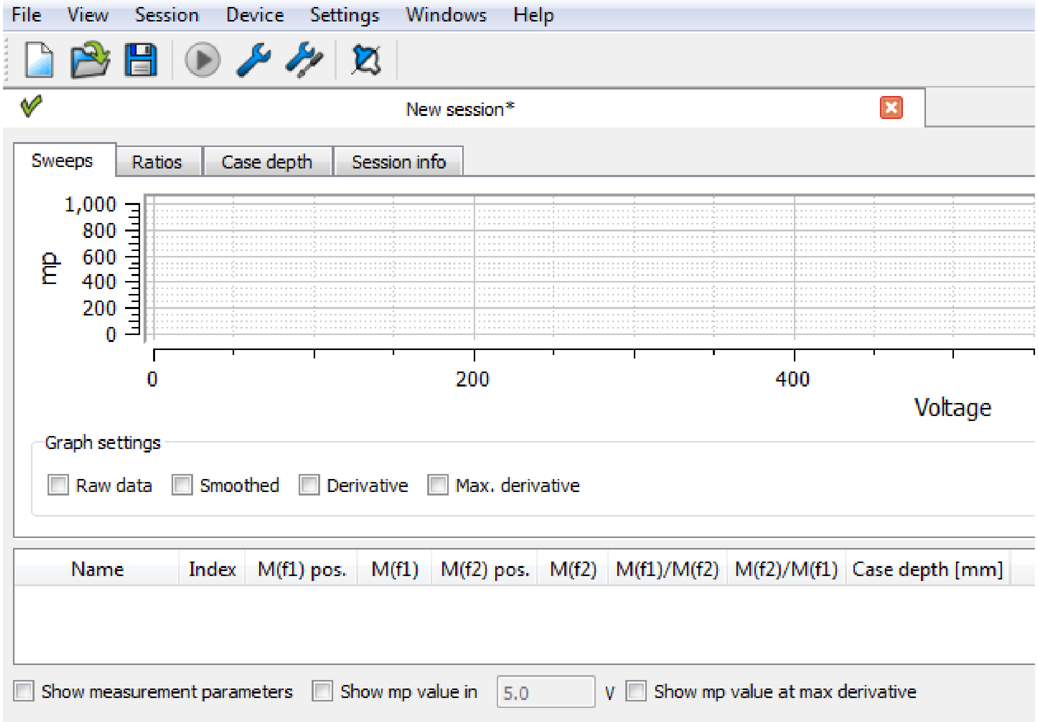


Figure 35 *An overview of PCCaseDepth.* (Courtesy of Stresstech Oy)

Measurements with PCCaseDepth

A measurement starts with choosing a new session into which the measurements are recorded. Measurement parameters must be defined from the session settings which can be seen in Figure 36.

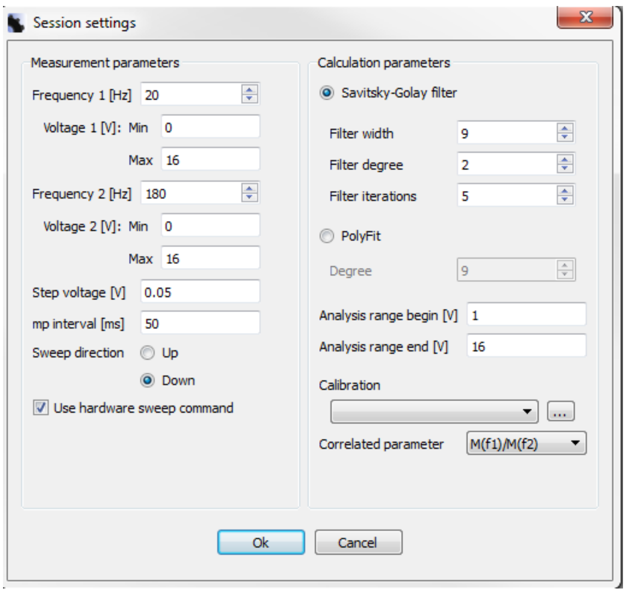


Figure 36 *Session settings in PCCaseDepth.* (Courtesy of Stresstech Oy)

In session settings, measurement parameters f1 [Hz], f2 [Hz], respectively as low and high frequencies must be chosen together with minimum voltage Vmin [V], maximum voltage Vmax [V], step voltage Vstep, [V], MP interval [ms], and sweep direction as up and down. There is an option to use built-in hardware sweep as well. When hardware sweep option was chosen, PCCaseDepth sends all the sweep commands to Rollscan at once hence the sweep is faster, and measurement time is significantly shorter.

In addition to measurement parameters, calculation parameters can be chosen in session settings. Analysis range which is in default between 0 and 16 Volt can be defined and the beginning and the end of the sweeps can be chosen. Some sensors cannot perform higher than some certain voltages which can be experimentally found. In addition, for some measurements, there is no need to increase the voltage up to 16 Volt or it is not necessary to start from 0 Volt. So with these settings, this kind of arrangements can be made to calculation parameters. Apart from the analysis range, smoothing settings which is by far the most important settings of the calculation can be made in session settings.

The Barkhausen signal is extremely noisy, even after averaging several bursts together. To make the analysis easier, it needs to be filtered and smoothed. There are two smoothing options available as Savitzky-Golay and PolyFit. It is difficult to define the smoothing parameters for all of the situations: there is no right or wrong parameters and parameters may affect the correlations drastically. [62]

The other settings such as the connection type and units can be chosen from the general settings which can be seen in Figure 37.

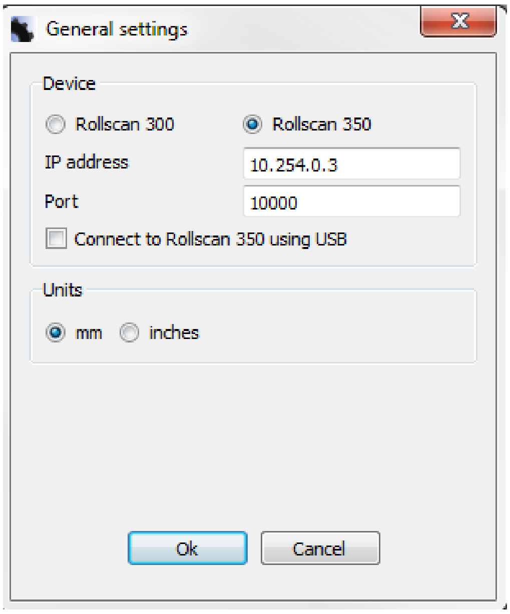


Figure 37 *General settings in PCCaseDepth.* (Courtesy of Stresstech Oy)

PCCaseDepth measurements follow these steps:

1. Set magnetizing frequency f1 (low frequency).
2. Do magnetizing voltage sweep. Collect sweep data.
3. Set magnetizing frequency f2 (high frequency).
4. Do magnetizing sweep and collect sweep data, as in step 2.
5. Demagnetize the part by stepping the voltage down to 0 Volt with Vstep increments. [62]

The most frequently used frequency couples are 20/125Hz and 40/250Hz. However, frequencies are directly related with the conditions of the samples and many other different frequencies were tried in this study such as 20/20, 10/500 and 30/180. When low frequencies such as 10 Hz or 5 Hz are applied, they may vibrate the sensor and thus affect the measurement results. It is recommended to use a sensor holder for all the measurements. In this study, many different sensor holders were developed and used with care. It is also possible to use external equipment such as a foot pedal as the triggering mechanism to start the measurement. The usual practice to start the measurement is to use the keyboard of the computer in which the software is installed.

Calculation

The software first smooths each sweep curve (low and high frequency) using the chosen filter which is either Savitzky-Golay or PolyFit. After smoothing, derivatives are calculated and the maximum value of the derivative M(f) is found. After maximum derivatives of each curve has been found, the ratio of them is calculated and the values are displayed separately as M(f1), M(f2), M(f1)/M(f2), M(f2)/M(f1). The voltage values (positions) of the maximum derivatives are also displayed in separate columns as M(f1) pos. and M(f2) pos. [62]

After calculation, PCCaseDepth plots the raw and smoothed sweep curves as well as the smoothed sweep derivatives and the ratio of the maximum slopes.

3.5 Samples

In this study, many different samples with case depths varying between 0.70 to 5.10 mm have been used. For the first trial measurements, nitrided, induction hardened and carburized samples were used.

In addition, some samples with artificial thermal defects also were used to test the sensitivity of the sensors.

In order to understand the software and the measurement procedure, many samples with different geometries and properties have been tried.

Some of them are given in Figure 38. The main samples of this study were induction hardened bars and the details of them are given below.

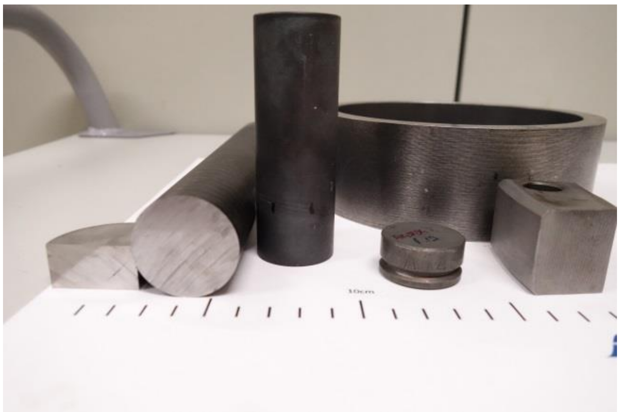


Figure 38 *Samples for trial measurements.*

Main samples of this study which can be seen in Figure 39 were also used previously by Santa-aho in her research [2]. This induction hardened rods with a steel grade 34CrNiMo6 were heat-treated by Bodycote Värmebehandling AB (Malmö, Sweden).

The original length of these samples was 300 mm but the length of the samples during this study was between 290 and 260 mm, and the diameter 45 mm. The length difference was due to cutting process which took place before this study for sample preparation but this should not have any effect on the study. The induction hardening case-depth was between 0.65 mm and 2.2 mm. The list of the samples and case depths are given in Table 1.

Figure 39 *Induction hardened samples.*

Table 1 *The case depths of the induction hardened rods.*

Sample number	Case depth (mm)
1	1.45
2	1.3
3	1.15
5	0.95
6	0.9
7	0.75
8	0.65
9	0.7

These rod samples were first measured with Rollscan 350 to identify the Barkhausen profile of the samples. Then four locations according to their BN signal intensity which were chosen 90 degrees apart from each other for the study. These four locations on eight samples were the study points of sweep measurements.

To supplement the research, two sets of case carburized samples were provided by Sampo-Hydraulics Oy which are shown in Figure 40.

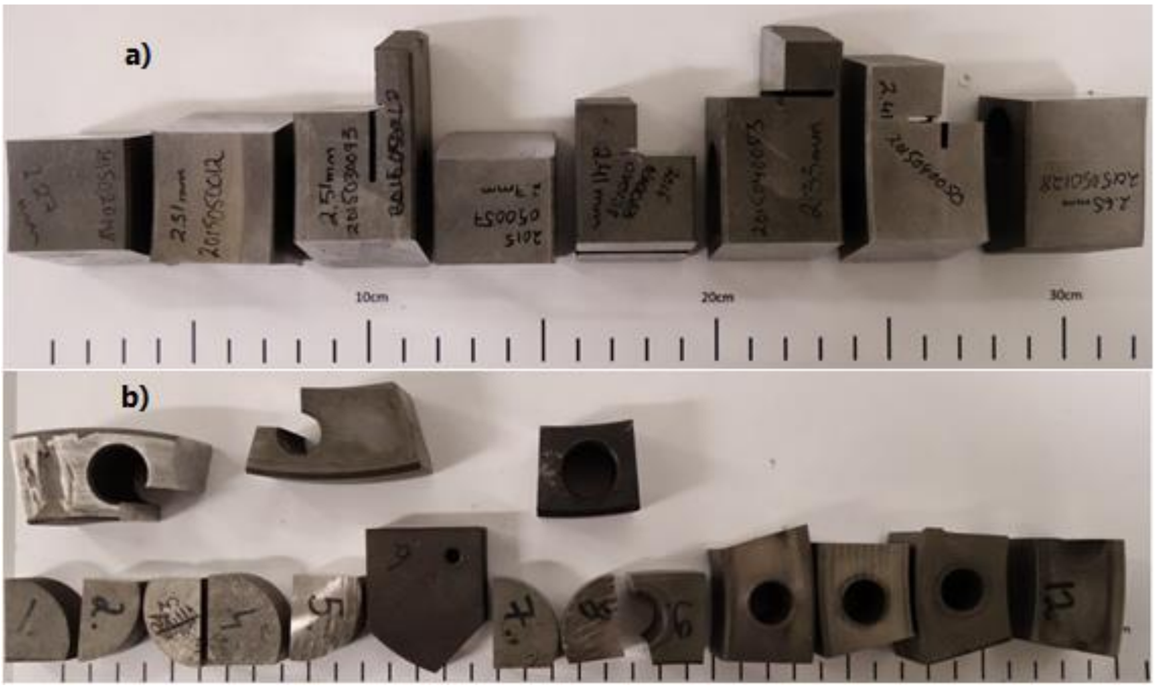


Figure 40 a) *The first and* **b)** *The second set of case carburized samples.*

These samples with a steel grade 18CrNiMo7-6 (EN10084) +HH (high Jominy band) were heat-treated by Bodycote Lämpökäsittely Oy (Vantaa, Finland). These case carburized steel samples had varying geometries and it was very challenging to measure them.

Due to their small sizes, complex geometries and lack of suitable measurement set-ups the measurement of case carburized samples could not be performed as it was planned.

Carburization case depth of the first set was between 2.27 mm and 2.70 mm and the case depth of the second set was between 2.00 and 3.20 mm which can be seen as a list in Table 2.

Table 2 *The case depths of first set of case carburized samples.*

	Sample Number	Case Depth (mm)
First Set	1	2.27
	2	2.33
	3	2.41
	4	2.41
	5	2.51
	6	2.51
	7	2.65
	8	2.70
Second Set	3	2.00
	11	2.40
	9	2.50
	10	2.50
	13	2.55
	15	2.60
	16	2.66
	1	2.70
	7	2.70
	12	2.70
	2	2.80
	14	2.90
	5	3.00
	6	3.10
	4	3.20
	8	3.20

4. RESEARCH AND RESULTS

Before starting the measurements, residual magnetism of the samples was measured. The samples which had higher residual magnetism than 10 Gauss were demagnetized. The residual magnetism levels were controlled frequently during the study and the necessary actions (demagnetization etc.) were taken according to measurement procedure.

All of the measurements were taken from four locations of the surface area. These four locations provided the highest MP values. Even though the induction hardening process should have created a uniform hardened layer, almost each of these four locations gave quite different MP values. Any defect, crack or corroded location can easily increase the MP values. Therefore, these kind of problematic locations were tried to be avoided as much as possible.

The solution for nondestructive measurement of case depth with BN should provide a uniform result without depending on the location. It is assumed that the hardened layer's depth was uniform throughout the surface. However, almost all of the eight rod samples gave different slope ratios from different points. Sometimes entire surface area was tried to measure so that the average value will provide a uniform result. However, without an automation, manually these kind of measurements are extremely hard. BN itself is very sensitive to contact and within case depth measurements the same problems with operator dependency and contact area have be seen.

As previously explained, two pen-type sensors, SN3 and SN4 were designed and produced for this study. By design and pre-defined settings, they are identical and they are expected to produce the same results. Two measurements were made with these two sensors. The measurement and calculation parameters which are given in Table 3 were the same for both measurements.

Table 3 *Measurement and calculation parameters of the measurement.*

Measurement Parameters						Calculation Parameters		
minV,maxV	StepV	mp int.	Sweep dir.	Hw sweep	SG-Filter	SG-Filter Degree	SG-Filter width	SG-Filter iterations
0-16 / 0-16	0.1	50	Up	Disabled	X	4	21	7
0-16 / 0-16	0.1	50	Up	Disabled	X	4	21	7

Measurements were taken from the same four locations on each of the 8 induction hardened bars.

The set-up of the measurement was adjusted so that, the contact between the sensor and the sample was same during all of the measurements. A special measurement arm was used to hold the sensor and the sample was fixed with a vice. In total, approximately 250 measurements were taken only with these two sensors and with these parameters.

Then the average of the measurements was used for the evaluation of the measurements and the percentage of correlation with case depth values (%) which can be seen in Table 4. Two different calculation filters were also applied to understand their effects on the results.

Table 4 *Correlations of the identical sensors with Savitzky–Golay and PolyFit.*

		Correlation with Case Depth *%*					
Sensor	**Filter**	**M(LOW) pos.**	**M(LOW)**	**M(HIGH) pos.**	**M(HIGH)**	**M(LOW)/M(HIGH)**	**M(HIGH)/M(LOW)**
SN3	S.G	93	77	90	9	92	89
SN3	S.G	79	77	72	56	81	78
SN4	PolyFit	91	60	95	20	43	43
SN4	PolyFit	82	72	62	60	54	48

It was seen that when Savitzky–Golay was used as the smoothing filter, the correlation of the slope ratios (M(LOW)/M(HIGH) and M(HIGH)/M(LOW) were significantly better than when PolyFit was used as the smoothing filter. On the other hand, positions of the slopes (M(LOW) pos. and M(HIGH) pos.) gave better correlations with case depth. When all of the measurements were taken into account, statistically M(HIGH) gives the lowest correlations which can be seen again in Table 4.

PolyFit smoothing filter, regardless of its degree gives lower correlations with case depth than Savitzky–Golay smoothing filter. PolyFit smoothing filter of the PCCaseDepth software allows us to change the degree of the smoothing function. The results were investigated with different degrees and 9 was found to be a suitable one for most of the cases. Smoothing degree should be chosen according to the best fit scenario.

For the specific measurements when the degree of Savitzky-Golay smoothing filtering increased about 50%, the correlations reduced about 10% meanwhile when the width of the filter reduced about 50%, the correlations reduced about 5% and when the number of iterations reduced about 50%, the correlations reduced about 20%.

In order to evaluate he repeatability of the case depth measurements with PCCaseDepth and new sensors, 4 measurements were taken from each of the 4 chosen locations of each of the 8 samples. After first measurements of all of the samples were completed, residual magnetism of the samples was controlled again. Then, with the same sensor, another measurement was made. The highest difference in slope ratios was about 6%.

The repeatability test result which was made with SN3 sensor is given in Figure 41.

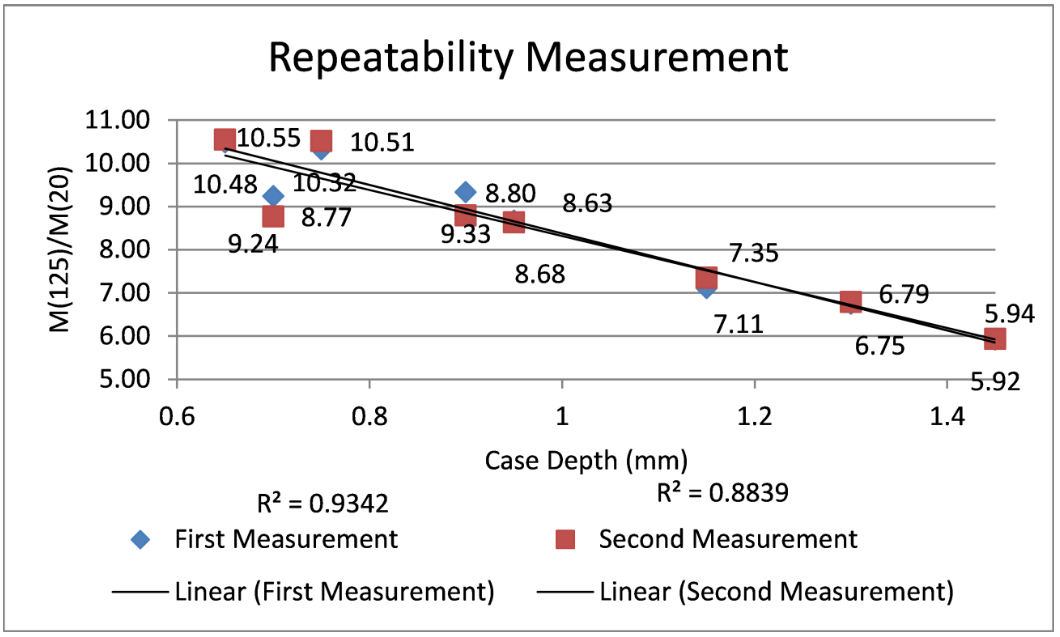


Figure 41 *Repeatability test for sensor SN3.*

In addition, two examples of four continuous PCCaseDepth measurements of the same measurement location are given in Figure 42. As it can be seen, there are visual shape differences between the sweeps and SN2 sensor's sweeps have wider gaps than SN1 sensor's sweeps. For both of the sweep measurements, sweep curves follow a hierarchy with their numbers and their positions as 1st measurement is located in lower position and 2nd measurement is a bit higher than the 1st measurement and it continues like that for both of the sensors. There was no change in any of the parameters during these measurements. They were made non-stop and continuously.

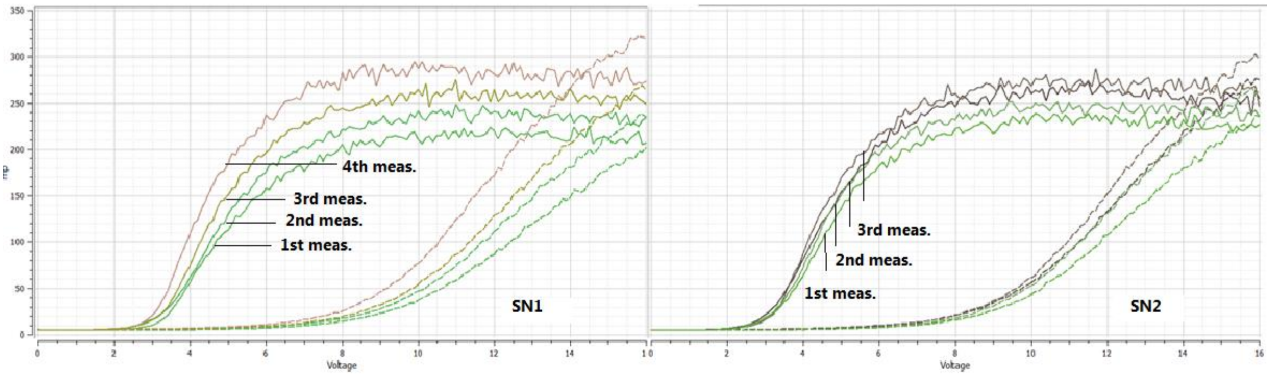


Figure 42 *Sweep comparison of SN1 and SN2.*

Barkhausen noise measurements were repeatable. When the same measurement procedures are followed for the case depth measurements, it has been seen that they are also repeatable with some small degree of deviation. The difference between two measurements may be caused by many different reasons. Many different parameters can affect the results. The most important ones are, the contact between the sensor and the sample which should be same as all the time and it was same for the measurement in Figure 42. Any vibration and any misalignment can cause big differences as well.

On the other hand, the pressure which can be applied by the sample, meaning the fixture which is used to hold the sample or sensor itself, can affect the results dramatically. When it is unavoidable to apply pressure to provide a better contact for the sensor on the sample, it should be applied evenly on the sample since it was seen that the signal value is affected due to this.

However, differences in the repeatability measurements can be also caused by the remanence. After the first measurement, there could be still some residual magnetism left in the material even though the software automatically demagnetizes the sample. The continuous measurements as one example is given in Figure 42 could be especially affected by this phenomenon. It is possible that during the second measurement perhaps material had a different hysteresis and magnetism character than during the first measurement. It could be possible that material accumulates some magnetism and is unable to demagnetize itself so that for continuous measurements, the latter measurement shifts upward which could explain the reason of the visual difference.

As it was previously mentioned, PCCaseDepth has an option for how to perform the voltage sweep. The first option is to use the hardware sweep mode. In this mode, PCCaseDepth sends all the sweep commands to Rollscan all at once and the sweep is faster. The other option is that PCCaseDepth receives and sends commands one by one. With this option, the process takes longer time. In order to see the effectiveness of two modes on the results, some comparisons have been made. For around 300 measurements, hardware sweep was used as the chosen option, and for another 300 measurements, this option was not used. The faster method, hardware sweeps enabled mode, showed about 10% less correlation with case depth values than the slower method.

During the measurements, it is possible to define the voltage interval between 0 and 16 Volt. Saturation occurs at different voltage levels according to used sensor and frequency couple. For most of the measurements, defined interval was chosen between 0 to 16 Volt.

Figure 43 shows an example of 0 to 16 Volt measurement. For this specific measurement, maximum derivative points where the highest slopes occur were located below 4 Volt so there was no reason to increase the voltage up to 16 Volt, for this measurement.

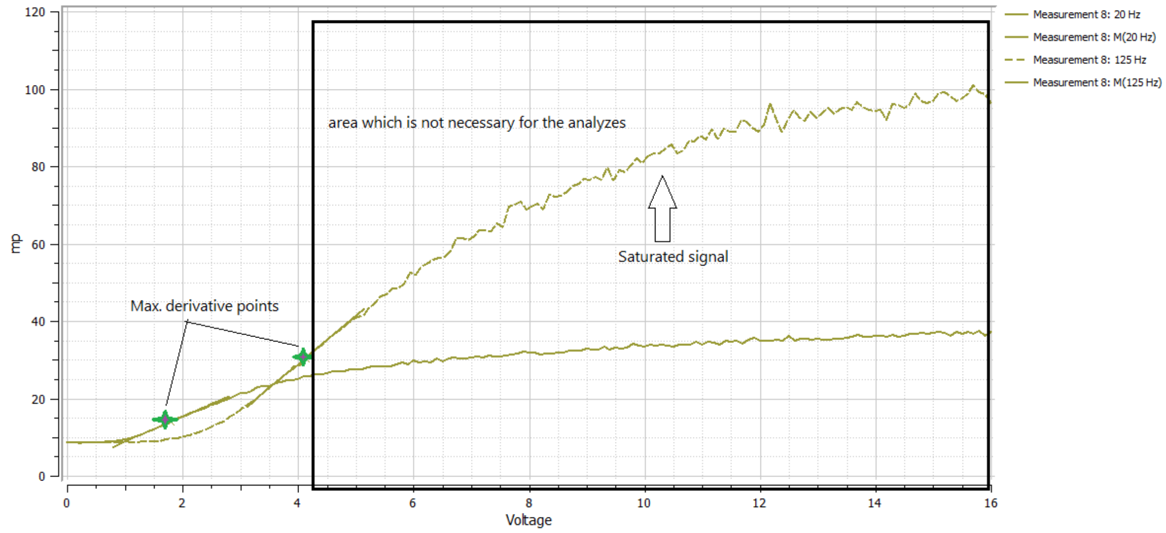


Figure 43 *Selecting the voltage interval in software.*

In addition, sometimes saturation occurs after the highest slope's location which can be seen again in Figure 43. This possibly means that due to chosen parameters of the software and capabilities of the hardware, the obtained signal exceeds the maximum value which can be managed on the system. With the current system, it is not possible to correct the distorted signal or convert the saturated data into useable signal levels. This was the reason why the saturated signal was avoided and not added to the calculations.

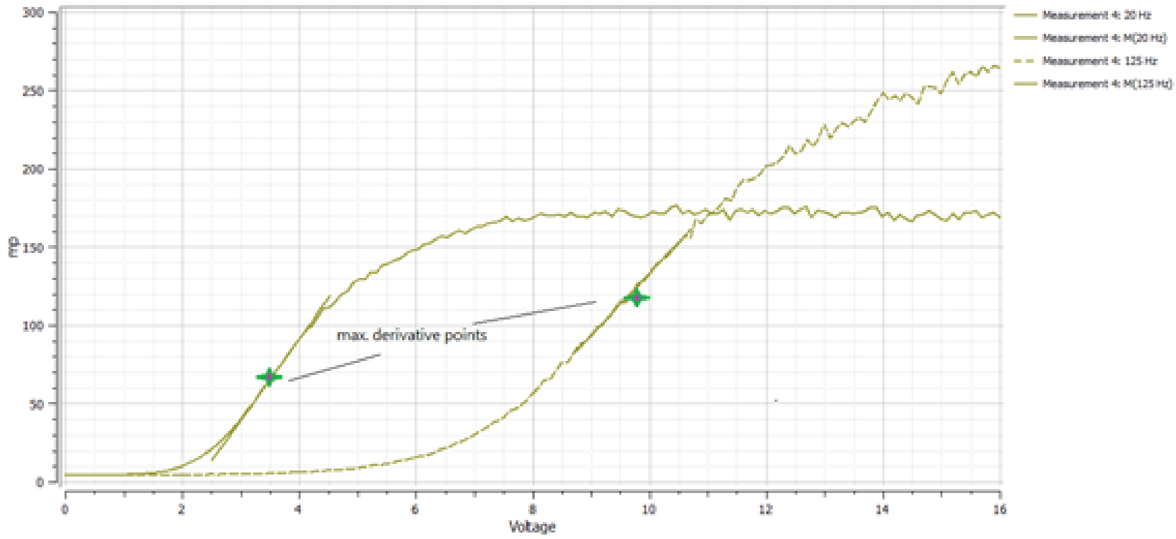


Figure 44 *PCCaseDepth measurement which shows the max. derivative points.*

The shape of the MP vs. Voltage curves also depends on the character of the sensor. For example, Figure 43 shows an example of different shape than Figure 44.

Figures 44 and 45 also show that the same frequency levels can create different shape of voltage sweep curves. Figure 44 shows almost a perfect shape and the positions of the maximum derivative points are well located.

Even though with low frequency it is possible to see the saturation and flat shape, high frequency curve still shows an increase in the MP values. So it could be possible that the location of the maximum derivative point for the high frequency may be wrong due to the calculations made by the software.

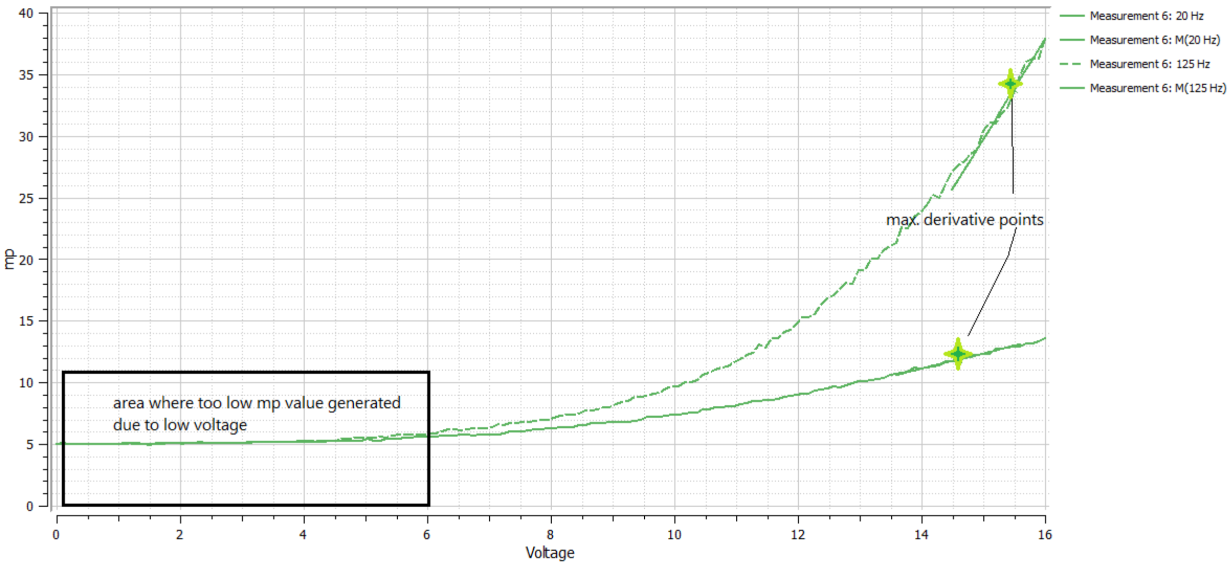


Figure 45 *PCCaseDepth measurement with low MP values.*

For some cases, it is possible to think that the highest slope may be seen in a higher voltage level than 16 Volt which was not possible to see and confirm with the existing hardware since 16 Volt is the absolute maximum in terms of the given magnetization voltage. In Figure 45, the maximum derivative points were seen very near to the 16 Voltage which can be explained by low MP values. This kind of shape generally means there is not enough voltage for magnetization. This was the reason to use an external magnetization for this specific case.

Observing only the shape of the signal is not enough to decide to use an external source for magnetization. In addition, the signal level is also directly related with the material, Barkhausen noise measurement parameters and contact between the sample surface and the BN sensor.

For some sensor and frequency combinations, it was not possible to use higher magnetization voltages due to high heat production and vibration which both affect the signal outcome and lifetime of the components.

An example of this case is given in Figure 46. Usually the low frequency created the problems by causing too much vibrations.

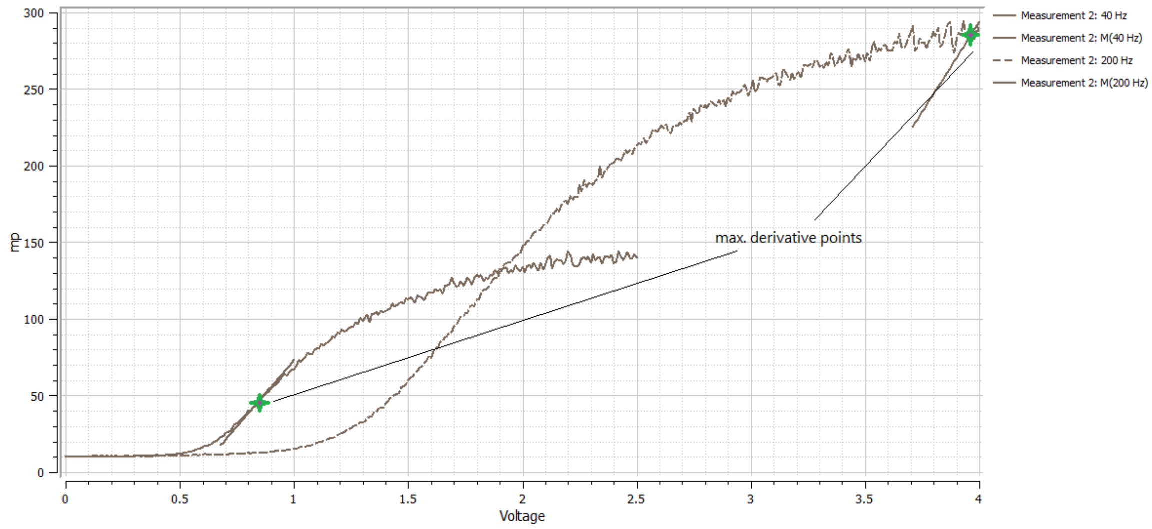


Figure 46 *PCCaseDepth measurement with modified voltage interval.*

In addition, a step voltage can be defined with the software. The default step voltage is 0.05 Volt. The lower step values for voltage increase were used when lower minimum and maximum voltage values were used as the interval. In an example case in which 0 - 2.5 Volt was used for minV and 0 - 4 Volt was used for maxV, the stepV was chosen as 0.01 Volt which provided more data in return. To avoid the overheating of the sensor, this kind of modifications were needed time to time. Excessive magnetizing voltage may damage the sensor and can give higher noise to signal ratio.

To investigate the effect of the low frequency for the shape difference of the curves, different frequencies such as 20, 25, 30 and 35 Hz were used while high frequency was kept as 125 Hz. As it can be seen in Figure 47, when the low frequency was increased the position of the maximum derivative which is the highest slope's position was also steadily increased.

A movement to the right can be observed in Figure 47, as well as the increasing M(LOW) pos. and M(LOW) values can be seen in Table 5. While this change has been observed in low frequency values, a small change in the position of the high frequency slope was also observed which can be seen in Figure 47 as well.

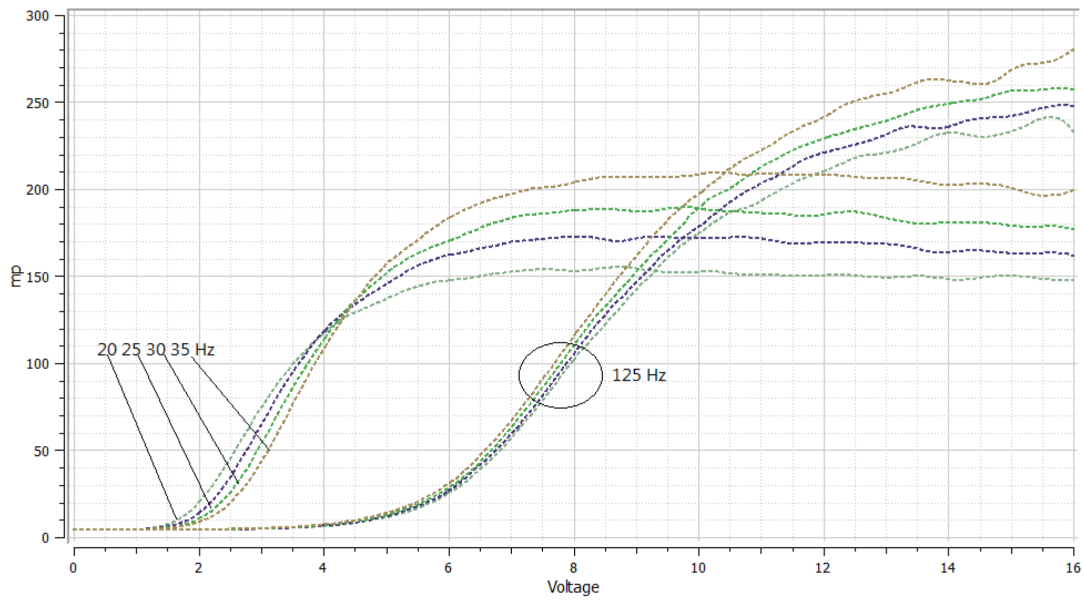


Figure 47 *PCCaseDepth measurements of a point with different low frequencies.*

Table 5 *Changes in the PCCaseDepth values with different low frequency measurements.*

f1,f2	minV,maxV	StepV	mp int.	Sweep dir.	Hw sweep	M(LOW) pos.	M(LOW)
20-125	0-16 / 0-16	0.05	50	Down	Enabled	2.72	58
25-125	0-16 / 0-16	0.05	50	Down	Enabled	2.97	62
30-125	0-16 / 0-16	0.05	50	Down	Enabled	3.22	64
35-125	0-16 / 0-16	0.05	50	Down	Enabled	3.5	66

As it was explained in the Chapter 3, two smoothing filters were used to smooth the raw data. PolyFit was one of the filters in which its degree can be changed. To understand the effect of the degree on the correlations, couple of raw measurement data files was smoothed with different PolyFit degrees.

Table 6 *Effect of different PolyFit degrees on the raw data.*

Correlation with Case Depth *%*						
M(LOW) pos.	M(LOW)	M(HIGH) pos.	M(HIGH)	M(LOW)/M(HIGH)	M(HIGH)/M(LOW)	PolyFit Degree
95	77	87	25	41	4	9
94	80	84	22	10	10	12
95	82	82	19	13	10	15

It has be seen that the change in the PolyFit degree can affect the correlation of the sweep measurement with the case depth values. Table 6 shows the percentage of the correlation with case depth. However, it was not possible to define a straight forward relation with change in the PolyFit degree and change in the correlation values.

Other changes such as the change in the shape of the sweep or change in the position of the maximum derivative also did not help to define a relation between the degree change and the correlation change. However, it is clear that there is a minimum and maximum degree values which could be used.

In the experiment which results are given in Table 6, it can be seen that the positions of the slopes (M(f1) pos. and M(f2) pos.) give a better correlation with case depth than slope ratios (M(f1)/M(f2) and M(f2)/M(f1). These kind of results were seen with both PolyFit and Savitzky-Golay smoothing filters so it is not possible to say that this happens only with one of the filters.

In addition to PolyFit, Savitzky-Golay smoothing filter was also tested with several different parameters as it can be seen in Table 7.

Table 7 *Effect of different Savitzky-Golay degrees on the raw data.*

Correlation with Case Depth *%*								
M(LOW) pos.	M(LOW)	M(HIGH) pos.	M(HIGH)	M(LOW)/M(HIGH)	M(HIGH)/M(LOW)	SG-Filter Degree	SG-Filter width	SG-Filter iterations
90	77	6	23	0	1	**8**	**21**	**9**
66	82	35	25	5	0	**3**	**21**	**9**
50	69	8	15	6	2	**8**	**15**	**9**
96	78	46	45	0	0	**8**	**21**	**5**

It has be seen that Savitzky-Golay parameters do not cause too much change in the correlation levels of slope ratios which are already too low to make any comment. Each correlation value on the Table 7 represents around 100 measurements. For these specific measurements, Savitzky-Golay was not the suitable filtering. This means that without analyzing the raw data the filtering cannot be chosen directly. The issue of higher correlation with the positions of the slopes (M(f1) pos. and M(f2) pos.) was again seen.

To understand the effect of the measurement location on the correlations, one example is given in Figure 48.

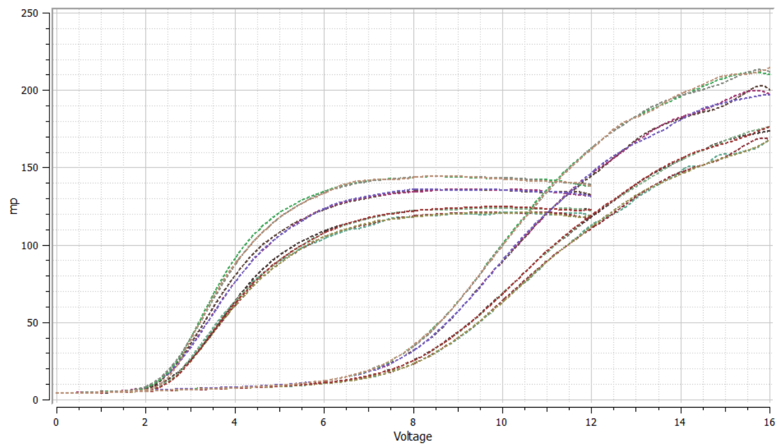


Figure 48 *PCCaseDepth measurement result of different samples.*

Figure 48 shows the voltage sweep measurement result of the exact same point of one of the induction hardened samples.

In this example, four points were chosen on an induction hardened sample's surface. Each of the four point is located 90 degrees apart from each other. From each point, three measurements were taken. Figure 49 shows the measurement location and information. Table 8 shows the measurement results in which index number 1,2,3 are from point A 4,5,6 are from point B 7,8,9 are from point C 10,11,12 are from point D. The values highlighted with green colors are the lowest and red colors are the highest values for each of the measured value. As it can be seen, there is no trend followed and variations can be seen. One side can provide the highest value for one test result as well as the lowest for another test result.

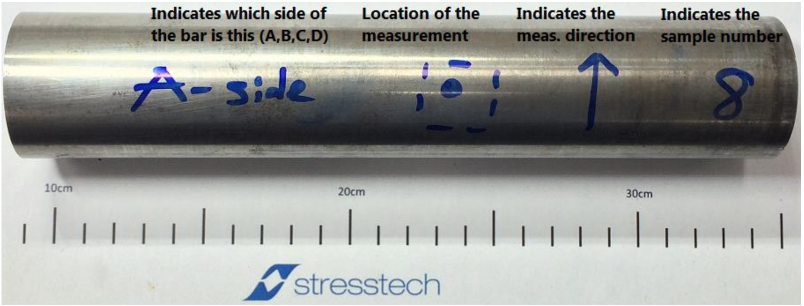


Figure 49 *Measurement location of the sample.*

The idea of this test was to emphasize the importance of several point measurements. If we have chosen point B for the case depth measurement, the correlation would be so much different from point C. Figure 48 also shows clear difference between the measurement points. It is either the induction hardening process which is not uniform or the proposed theory needs to be developed further.

Table 8 *Measurement results of the location test.*

Index	M(20) pos.	M(20)	M(125) pos.	M(125)	M(20)/M(125)	M(125)/M(20)
12	3.23	55.24	9.26	36.94	1.5	0.67
4	3.73	40.7	10.26	27.72	1.47	0.68
10	3.33	56.22	9.66	37.98	1.48	0.68
3	3.43	38.27	10.57	26.55	1.44	0.69
7	3.33	47.63	9.36	33.21	1.43	0.7
5	3.43	38.93	10.06	27.6	1.41	0.71
2	3.63	36.98	10.26	26.75	1.38	0.72
6	3.43	39.33	10.36	28.39	1.39	0.72
11	3.33	50.77	9.66	37.42	1.36	0.74
1	3.43	39.45	10.87	29.6	1.33	0.75
8	3.43	44.82	9.66	33.93	1.32	0.76
9	3.43	44.2	9.96	34.33	1.29	0.78

Another example was also made to see the effect of the measurement location. In this example, again four locations were chosen on a surface of the sample bar which were located 90 degrees apart from each other. The average of these four locations and each side's own average are given in Table 9. As it can be seen in the table, the average and individual sides may have quite different values. This means that there is no point of making measurements from one location and not even four locations.

This kind of measurements should represent the entire surface area of the sample. What has been done in this study, was not an effective approach in terms of the measurement procedure. However, it was better that these kind of results were seen at this point. In addition, an interesting outcome of this test was to see the consistency of the slope ratio with the case depth.

Table 9 *Correlations of the case depth measurements.*

	Correlation with Case Depth *%*					
Measurement	**M(20) pos.**	**M(20)**	**M(125) pos.**	**M(125)**	**M(20)/M(125)**	**M(125)/M(20)**
Average of 4-side	77	47	64	2	85	89
Side-A	76	5	56	18	88	87
Side-B	69	77	63	19	84	87
Side-C	78	18	65	1	65	70
Side-D	83	50	62	13	80	83

Current and Voltage Sweep Measurement Results

Induction hardened rod bar samples were also used for current and voltage sweep measurements. These sweep measurements were taken with Rollscan 350 together with SN2 sensor which was modified to get more magnetization power through the MA-100 (magnetizing power amplifier). With external magnetizing power amplifier, it is possible to get more magnetizing power than what Rollscan 350 can provide. Each sample was measured from 4 different locations. (90° apart) For each location, 3 sequential measurements were taken. First 40 Hz then 200 Hz measurements were completed. The set up for the sweep measurements is given in Figure 50.

a) b) c)

Figure 50 ***a)*** *Set-up for current and voltage sweep measurements.* ***b)*** *Connections on the MA-100 magnetizing amplifier.* ***c)*** *Modified sensor.*

The expected result of the voltage measurements was to see a clear difference between samples which have clearly different case hardened layer thicknesses. For this purpose, three samples were chosen with the case depths of 1.45 mm, 0.95 mm and 0.65 mm.

During the measurements, voltage was increased until 4 Volt and two different frequencies were used as 40 Hz and 200 Hz. However, for these three case depth values there was less than 1% difference in the voltage levels for 40 Hz and averagely 3% difference in the voltage levels while testing with 200 Hz.

The expected result of the current sweep measurements was also to see a difference between samples which have clearly different case hardened layer thicknesses. The same samples again were used for the current sweep measurements. However, it has seen that current response does not change with the change in the case depth. As the result of voltage and current sweep measurements, it can be said that for the used sensor and frequency couple, voltage sweep as well as the current sweep is not well correlated with the case depth.

When the new and old sensors were compared statistically in terms of their correlation with the case depth, it is not possible to say that the new sensors are better than the old sensors for case depth measurements. Case by case they gave better correlations which is also true for the old sensors.

During the measurements, different problems have also seen, some were mentioned already. For example, when four sequential measurements of the same location were made, regardless of the sample, sensor and measurement parameters, almost 90% of the time, the first case depth sweep gave a different shape than rest of the three measurements. Most of the times, this problem was seen with the low frequency sweep but rarely with high frequency sweep as well. The different shape was not always the same. In fact, perhaps every time, it was different from the others. Some examples of this situation are given in Figure 51.

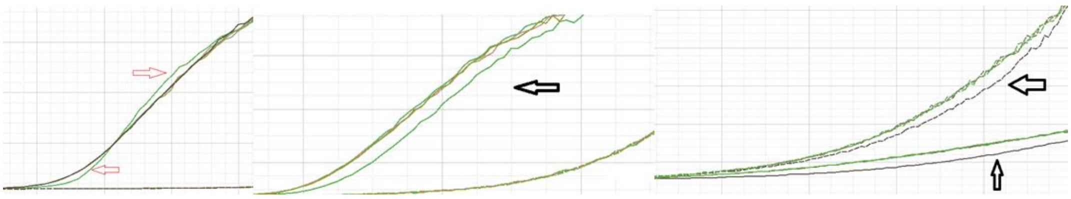


Figure 51 *Different envelope shape problem.*

Another common problem was random “knee” forms on the low frequency sweep measurement shapes. The reason for this is unknown. Several different approaches have been made to avoid this problem but still it has appeared occasionally. One example of the problem can be seen in Figure 52.

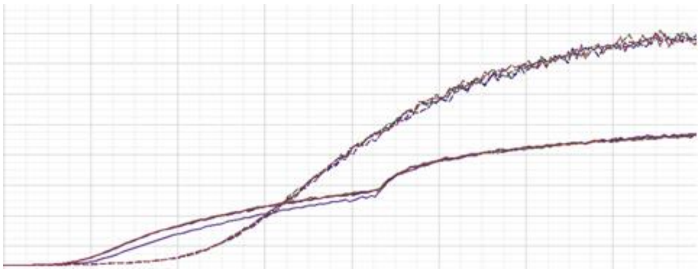


Figure 52 *Random "knee" shape on low frequency sweep.*

So far, all of the mentioned results were about the induction hardened samples. Apart from the induction hardened parts, some case carburized samples also were used. However, due to their complex geometries, these case carburized samples were not used so often. Around 3000 single measurements were made and these limited results are given briefly in the following paragraph.

Statistically, the highest correlation was about 0.4 with the case depth. This has been achieved with one of the old sensors. The new sensors were averagely giving only 0.1 correlation.

There have been different trials with different frequency couples such as 40/200, 50/250, 40/250, 125/250, 20/125 etc. However, no relation was found with the change in the frequencies and the case depth. The calculation parameters were checked and all possible parameters were tried. However, there was no change in the low correlation values.

It was clear that complex geometries of these samples were one of the reasons. The other reason could be that the case hardened layer of carburizing process is hard to detect with this proposed theory. Since, induction hardening process has a completely different surface hardening process than the carburization process which involves also chemical change in the material by diffusing carbon atoms, may be this method has something to do with the presence of carbon atoms. In fact, this idea can be expanded as, the tested method may be affected by the inclusion atoms such as carbon and nitrogen because during the trial period, there were some nitrided parts which also gave quite lower correlation with the case depth.

In order to be sure before making any more claims, another set of case carburized samples were tried again. The sample geometry was again the same. The only difference between these two case carburized samples was that they are from different batches of the production. Again, all possible measurements were made and all possible calculation parameters were tried to use to correlate the data with the case depth. However, the highest correlation ratio was about 0.3. In total, about 25 different case carburized samples were measured with about 10 different sensors.

Due to the low correlations, the correctness of the acquired cased depth values was questioned. To make sure the values were correct, couple of destructive case depth measurements were made at Sampo Hydraulics Oy to verify the correctness of given case depth values. The hardness profiling (destructive case depth measurement) result of one of the samples can be seen in Figure 53. In addition, the microscopic image of the hardness measurement which shows some of the measurement locations can be seen in Figure 54.

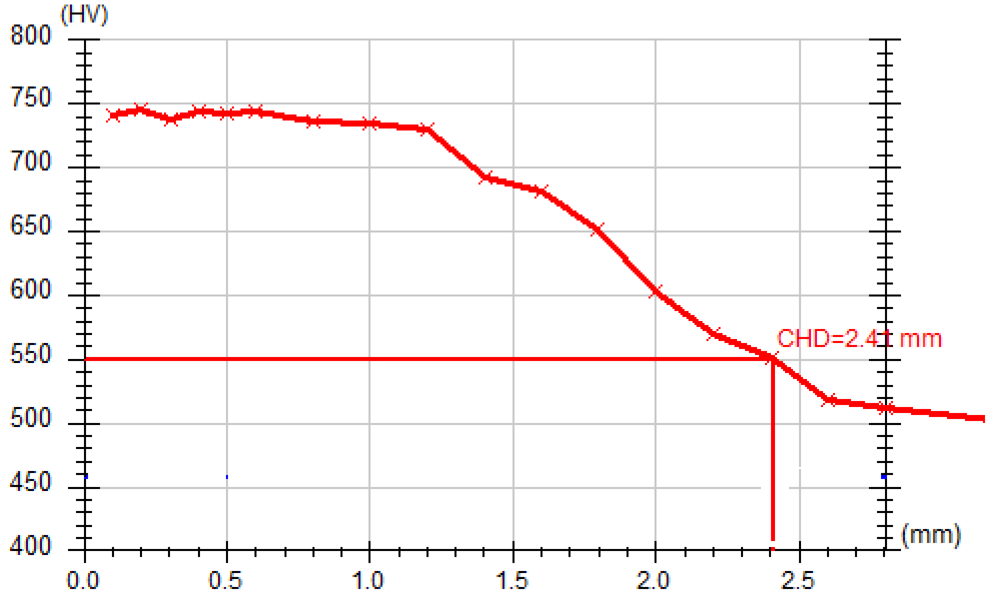


***Figure 53** Hardness profile of a case carburized sample.* (Courtesy of Sampo Hydraulics Oy)

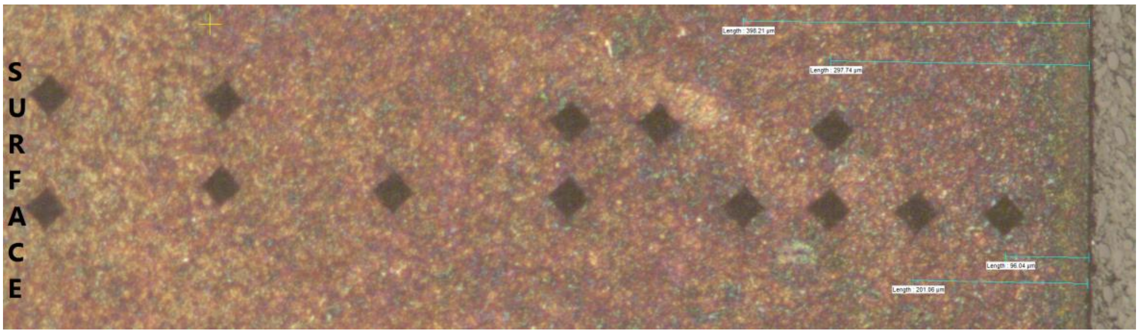


***Figure 54** Hardness measurement location.* (Courtesy of Sampo Hydraulics Oy)

After the destructive case depth measurements, it was seen that the values were correct and the nondestructive method itself was not working for these set of samples. As a result of case carburized samples' measurements, it is possible to say that the proposed theory and existing measurement set up does not provide any new and meaningful solution to detect the case hardened layer' thickness for the tested samples.

Lastly, to understand the effect of the operator on case depth measurements with the proposed method, PCCaseDepth measurements were done on two new carburized samples which were not tried before.

Each part was measured on 16 measurement locations which were spread around the outer surfaces of the parts. Both of the measurements were performed with the same frequencies. The results of the two operator's measurements which are shown in Figure 55, showed the effect of different operator. During both of the measurements, the exactly same set-up and sensors were used. Samples were fixed with a suitable vice and the sensor was fixed with a special measurement arm. The only difference with the measurements was the conductor who made the measurements. The ratio values from the measurements followed a general trend even though the values are quite different. The average difference between two operator's measurements was about 20%. These samples were measured also to see the effect of complex surface geometry.

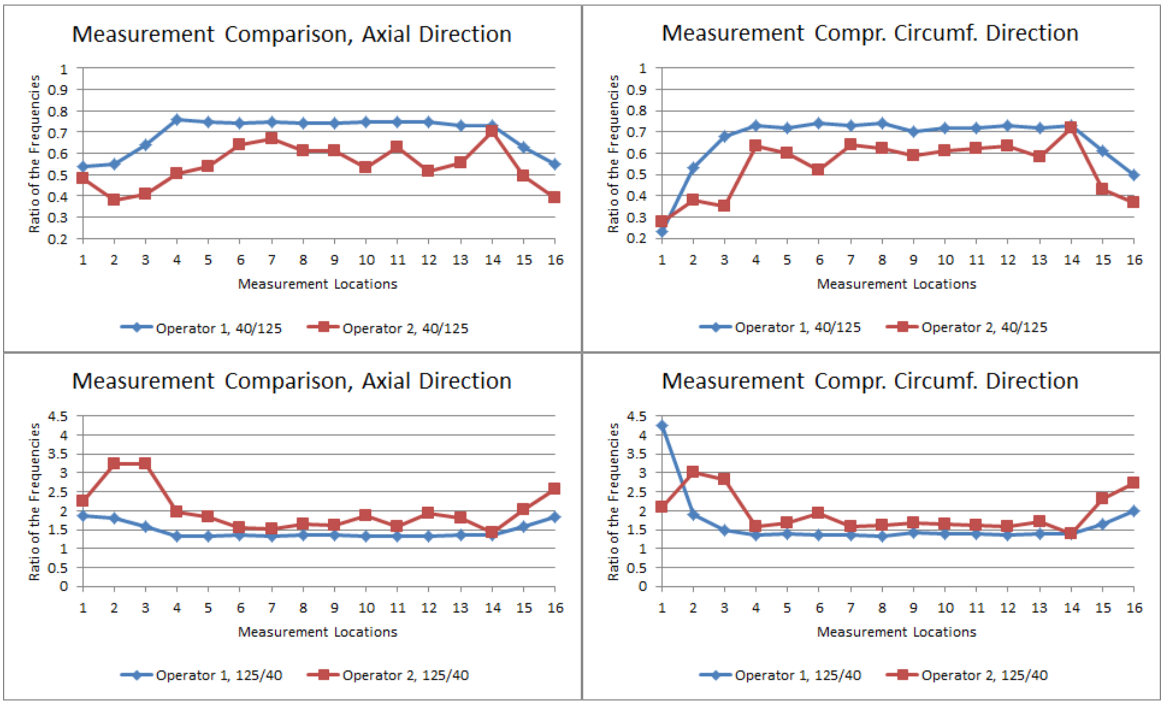


Figure 55 *Influence of the operator on measurement results.*

5. DISCUSSION AND CONCLUSIONS

In an early research [19], it was realized that prediction of material related properties such as the thickness of the hardened layer could be possible with using different parameters of Barkhausen noise. This result, led the researchers to develop the method to investigate the detection of surface hardened layer thickness. It was realized [20] that using magnetizing voltage sweeps in both low and high frequencies together and taking their slope ratios give high correlations with case depth values. [2]

The aim of this thesis was to test the new method of using both low and high frequencies together for case depth determination to prove it as a reliable nondestructive method of case depth evaluation. The main idea behind of the tested method is to have information from material's different layers with different frequencies. The low frequencies are used to get more information from subsurface layer of the material where the hardness is lower than the surface layer while the high frequencies are used to get more information from surface layer of the material where the hardness is higher than the softer core.

For this aim, using the slope ratio of different frequencies for case depth determination was tested with a new software and new sensors and many different samples which were surface hardened by induction hardening, carburizing and nitriding processes.

For the study, a new software, PCCaseDepth which enables the calculation of the ratio of low and high frequency sweeps' highest slopes and new sensors which were designed to focus the sensing in a smaller area to get more signal from possibly deeper parts of the sample were used.

For some of the measurements, it has be seen that the ratio of highest slopes of low and high frequency sweeps can have almost a linear correlation with the case depth values. However, not all of the measurements provided this kind of very good correlations. In some cases, lower correlations such as less than 0.5 were even seen. For some other cases, the ratio of slopes gave no correlation (less than 0.1) but some other measurement parameter such as the position of the slope gave almost a linear correlation (0.97) with the case depth values. This means that magnetizing sweep method works case by case for determining case depth values.

On the other hand, it is difficult to say why other parameters else than slope ratio also give good correlations with the case depth. This area needs further investigation. With the fact that at least some of the parameters are well correlated with the case depth values, the proposed sweep method has still a big potential.

To improve and develop the method further, a study shall be conducted with better samples and a better measurement set-up.

Another interesting result of the study was, the ratio of highest slopes of low and high frequency sweeps always gave a higher correlation with induction hardened samples than with case carburized or nitrided samples. This may be explained by the difference between these surface hardening processes. Both carburizing and nitriding are thermo-chemical processes, which cause changes in the chemical composition of the material by the diffusion process. It could be possible that interstitial atoms (carbon and nitrogen) interfere with the micromagnetic detection mechanism of the method because of their different magnetic characters from the steel which makes the detection of case depth harder for diffusion based surface hardening processes.

It is also found that low and high frequency sweep measurements should be taken from multiple points as single point measurements only represent small regions which could have surface integrity problems to affect the correlation results. One suggestion for this could be, making sweep measurements of the entire surface area of the samples which should be made with an automated system or better with a robotic arm. An automated system or using a robotic arm for this kind of measurements, will avoid the problems originate from the sensitivity of the method, operator dependency and will provide an average value. Manual measurements are one of the biggest challenges of application of this method. If this research could have been made with an automated stand, the results could be significantly different and/or better.

Regardless of the type of it, all Barkhausen noise measurements rely on a good contact with the sensor and the sample. Any misalignment or any applied pressure will make a difference on the results. Since Barkhausen noise is a micro-magnetic method, any magnetic interference from outside could affect the measurement results. This has been experienced during the research as well. The necessary actions should be taken to avoid the interference.

In addition, we can say that the method is quite repeatable but some of the cases it was hard to reproduce the same values in sequential measurements. This was mainly due to complex geometry of the tested samples.

When the new and old sensors were compared according to their correlations with the case depth values, for most of the cases both sensors gave very close results.

However, case by case for some specific frequency couples and some specific calculation parameters, correlation results can be very different as well. In addition, it should be remembered that the correlations are dependent on the chosen measurement and calculation parameters so that they must be the same to make a comparison of any kind that includes sensor comparisons as well.

The concluding remarks of the study are as following:

1. Magnetizing voltage sweeps with fitted maximum slopes method works better with induction hardened samples than carburized and nitrided samples. Therefore, it can be said that method works case by case.

2. The new sensor which has a new pot-core design and consists of a shield and sheath does not work significantly better than the old sensor design. It has be seen that it worked better than the old sensor in some cases although there were some cases it did not give any correlation at all when the old sensor gave very high correlations. Therefore, it can be said that the new sensor also works case by case.

3. The new software, PCCaseDepth worked well with calculation of the slope ratios in most of the cases. However, in some cases it has be seen that it calculated wrong values or it gave wrong locations for the slope positions. Therefore, the software needs an overall check and update.

REFERENCES

[1] R. Meyendorf, “Nondestructive determination of case depth in surface hardened steels by combination of electromagnetic test methods”. University of Dayton, Materials Engineering, Ph.D. Dissertation, 2011, Retrieved from https://etd.ohiolink.edu/!etd.send_file?accession=dayton1303834395&disposition=attachment

[2] S. Santa-aho, M. Vippola, A. Sorsa, K. Leiviskä, M. Lindgren, T. Lepistö, “Utilization of Barkhausen noise magnetizing sweeps for case-depth detection from hardened steel”, NDT&E International, 52 (2012) 95-102.

[3] V. Moorthy, B.A. Shaw “Magnetic Barkhausen emission measurement for evaluation of depth of material properties in gears” NDT&E (2008), pp. 317–347

[4] S. Santa-aho, “Barkhausen noise method for hardened steel surface characterization - The effect of heat treatments, thermal damages and stresses”, Tampere University of Technology. Publication; Vol. 1080, ISBN: 978-952-15-2926-9, Retrieved from https://tutcris.tut.fi/portal/files/1911116/santa-aho.pdf

[5] M. Vashista, S. Paul “Novel processing of Barkhausen noise signal for assessment of residual stress in surface ground components exhibiting poor magnetic response" J. Magn. Magn. Mater. 323 (2011) 2579–2584

[6] M. Dubois, M. Fiset, “Evaluation of case depth on steels by Barkhausen noise measurements”. Mater Sci Technol. 1995;11(3):264-7.

[7] G. Bach, K. Goebbels, W.A. Theiner “Characterization of hardening depth by Barkhausen noise measurements”. Mater Eval. 1988; 46:1576-1580.

[8] A. Vaidyanathan, V. Moorthy, T. Jayakumar, B. Raj, “Evaluation of induction hardened case depth through microstructural characterization using magnetic Barkhausen emission technique”. Mater.Sci. Technol. 2000;16:202-8.

[9] V. Moorthy, B. Shaw, P. Hopkins, “Surface and subsurface stress evolution in case carburized steel using high and low frequency magnetic Barkhausen emission measurements”. J Magn Magn Mater. 2006; 299(2):363-375.

[10] V. Moorthy, B. Shaw, K. Brimble “Testing of case depth in case carburized steels using magnetic Barkhausen emission technique”. Mater. Eval. 2004;62(5):523-7.

[11] C. Zhang, N. Bowler, C. Lo, “Magnetic characterization of surface-hardened steel”. J. Magn. Magn. Mater. 2009; 321:3878-3887.

[12] C.C.H. Lo, E.R. Kinser, Y. Melikhov, D.C. Jiles, “Magnetic non-destructive characterization of case depth in surface-hardened steel components”. In: Thompson DO, Chimenti DE. (Eds.) Review of Progress in Quantitative non-destructive evaluation 25B, AIP Conference Proceedings. 2006; 820:1253-1260.

[13] S. Santa-aho, M. Vippola, M. Lindgren, A. Sorsa, K. Leiviskä, T. Lepistö “Use of low frequency Barkhausen noise for inspection of induction hardened rod samples”. Proceedings of 9th International Conference on Barkhausen Noise and Micromagnetic Testing, June 28-30, 2011, Liberec, Czech Republic

[14] V. Moorthy, B. Shaw, J.T. Evans, “Evaluation of tempering induced changes in the hardness profile of case carburized EN36 steel using magnetic Barkhausen noise analysis”, NDT&E International 36 (2003), 43-49.

[15] J. Thomas, R.M. Fix, “Optimizing magnetization parameters of magnetic Barkhausen noise for more accurate detection of residual stresses and variations in microstructure”, Proceedings of 7th International Conference on Barkhausen Noise and Micromagnetic Testing, July 15-16, 2009, Aachen, Germany

[16] S. Santa-aho, M. Vippola, T. Lepistö, A. Sorsa, K. Leiviskä “The final research report of “NOVEBARK” Novel Barkhausen Noise System for Induction Hardened Components and Material Defect Identification”

[17] J. Thomas, “Using Barkhausen Noise to Analyze Case Depth”, HTPRO June 2015 issue Retrieved from http://amp.digitaledition.asminternational.org/i/518667-jun-2015/40

[18] S. White, “A Barkhausen Noise Testing System for CANDU Feeder Pipes” (Queen’s University, 2009), PhD Thesis) Retrieved from https://qspace.library.queensu.ca/bitstream/1974/1994/1/White_Steven_A_200907_PhD.pdf

[19] S. Santa-aho, M. Vippola, A. Sorsa, T. Lepistö, K. Leiviskä “Implementing Intelligent Systems on Multiparameter Barkhausen Noise Measurement” (INTELBARK) a joint project between Tampere University of Technology and Oulu University which was coordinated by Institute of Materials Science at Tampere University of Technology. (2007-2009)

[20] S. Santa-aho, M. Vippola, A. Sorsa, T. Lepistö, K. Leiviskä "Novel Barkhausen Noise System for Induction Hardened Components and Material Defect Identification" (NOVEBARK) a joint project between Tampere University of Technology and Oulu University which was coordinated by Control Engineering Laboratory at Oulu University. (2010-2012)

[21] G. Fett, "Importance of induction hardened case depth in torsional applications" Heat Treating Progress, vol. 9, no. 7, pp. 15–19, Oct. 2009.

[22] E.F Tyrkiel, P. Dearnley, "A guide to surface engineering terminology", Institute of Materials in association with the IFHT. (London, England). (1995)

[23] A. S. M. A. Haseeb, M. F. Islam, O. Alam, S. A. M. Tofail, "Surface hardening behavior of titanium alloys in carburization" In: B. Misra, G. J. Kipouros, (eds.) Titanium Extraction and Processing, Warrendale: TMS.

[24] "Carburizing steels", Available (accessed on 1.9.2015): https://www.staff.ncl.ac.uk/s.j.bull/mmm452/gears/sld036.htm

[25] J. R. Davis, "Surface hardening of steels: Understanding the basics". Materials Park, OH: ASM International. (2002) ISBN: 978-0-87170-764-2

[26] "Indian standard methods for measuring case depth of steel" (First Revision) IS 6416: 1988

[27] "Ultrasonic Microstructural Analyzer (UMA): Breakthrough in hardness depth measurement", Available (accessed on 1.9.2015): http://www.sonix.com/learning/files/UMAJBreakthrough.pdf,

[28] J. Cuffe, H. Sun, Y. Plotnikov, S. Nath, Sheila-Vadde, A. "Eddy current measurement of case hardened depth of steel components", 17th World Conference on Nondestructive Testing, Shangahai, China. (2008). Accessed online http://www.ndt.net/search/docs.php3?showForm=off&id=6594

[29] 3MA Brochure: "Hardness, Case Depth, Yield Strength, Tensile Strength" by Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren IZFP Retrieved from http://www.izfp.fraunhofer.de/en/FuE/3MA.html

[30] C.Wang, A. Mandelis, "Case depth determination in heat-treated industrial steel products using photothermal radiometric interferometric phase minima", NDT & E International 03/2007; 40(2):158-167.

[31] W. Theiner, R. Kern, M. Stroh, "Process integrated nondestructive testing of ground and case depth hardened parts", ECNDT2002, Barcelona, Spain, June, 17-21, 2002.

[32] R. Baqeri, F. Honarvar, R. Mehdizad, “Case depth profile measurement of hardened components using ultrasonic backscattering method”. In: 18th World conference on nondestructive testing, Durban, South Africa, 16–20 April 2012, pp. 1–8.

[33] J. Jaarinen, M. Luukkala, “Numerical analysis of thermal waves in stratified media for non-destructive testing purposes”. J Phys (Paris) 1983;44:C6–C503.

[34] L. Nicolaides, A. Mandelis, “Physical mechanism of thermal-diffusivity depth-profile generation in a hardened low-alloy Mn, Si, Cr, Mo steel reconstructed by photothermal radiometry”. J Appl Phys 2001; 89:7879–84.

[35] H. Barkhausen, “Two phenomena discovered with the aid of the new amplifier” Phys. Zeits, 20, 1919

[36] S. Tiitto, “On the influence of microstructure on magnetization transitions in steel”, Acta Polytechnica Scandinavica, Applied Physics Series No. 119, Helsinki 1977.

[37] Barkhausen Noise Analysis: “http://stresstech.com/content/en/1034/1113/1113.html” Available (accessed on 10.4.2015)

[38] P. Weiss, “L'hypothèse du champ moléculaire et la propriété ferromagnétique” J. Phys. Theor. Appl., 1907, 6 (1), pp.661-690

[39] R. Hofstadter, Biographical Memoirs V.64 Chapter: Felix Bloch (1994) “http://www.nap.edu/read/4547/chapter/3” Available (accessed on 10.4.2015)

[40] F. Bloch, G. Gentile, “Zur anisotropie der magnetisierung ferromagnetischer Einkristalle” Z. Phys. 1931, 70:395-408

[41] M. Getzlaff, 2008, “Fundamentals of Magnetism” (Springer, Berlin)

[42] D. Jiles, 1991, “Introduction to magnetism and magnetic materials” (Chapman and Hall, London, New York)

[43] Image Source: http://www.ck12.org/user:ZGF2aWRoYXJ0MTAwQGdtYWlsLmNvbQ../book/Mr.-Harts-High-School-Physics/section/19.1/, Available (accessed on 20.4.2015)

[44] Image Source: http://what-when-how.com/electronic-properties-of-materials/magnetic-phenomena-and-their-interpretationclassical-approach-magnetic-properties-of-materials-part-1/, Available (accessed on 20.4.2015)

[45] FVA 594, "Process instruction for Barkhausen noise analysis" by Stresstech Oy Retrieved from http://www.stresstechgroup.com/files/upload_pdf/1072913/FVA%5FBarkhausen%5Fprocess%5Finstructions%5F2010%2002%2011%5FV1%5FEn.pdf

[46] C. Stefanita, 2008, "From bulk to nano the many sides of magnetism" (Springer-Verlag, Berlin, Heilderberg, Germany)

[47] Image Source: http://nptel.ac.in/courses/115103038/5 , Available (accessed on 20.4.2015)

[48] B. D. Cullity, C. D. Graham, 2009 "Introduction to magnetic materials" 2nd ed., John Wiley & Sons, New York, 2009

[49] T. Miyazaki, H. Jin, 2012, "The physics of ferromagnetism" (Springer, London)

[50] A. Sorsa, "Prediction of material properties based on nondestructive Barkhausen noise measurement" 2013, University of Oulu, Acta Universitatis Ouluensis. C, Technica, Issue:442, ISBN: 978-952-62-0068-2, Retrieved from http://jultika.oulu.fi/files/isbn9789526200682.pdf

[51] V. Honkamäki, 2002, "Barkhausen method for non-metallurgist, theory and background" Internal Stresstech Document

[52] B. Karpuschewski, 1996, "Introduction to micromagnetic techniques" Proceedings of 1st International Conference on Barkhausen Noise and Micromagnetic Testing, September 1-2, 1998, Hannover – Germany

[53] Dr. B. Augustyniak, M. Chmielewski, J. Siecinski "Evaluation of Residual Stress Distribution Maps in Shipyard Sheets with Barkhausen Effect Non-Contact Probe" Proceedings of 2nd International Conference on Barkhausen Noise and Micromagnetic Testing, October 25-26, 1999, Newcastle Upon Tyne, UK

[54] R.M. Fix, "Applications of Barkhausen Noise Analysis (BNA), a review of three cases having industrial significance" Proceedings of 1st International Conference on Barkhausen Noise and Micromagnetic Testing, September 1-2, 1998, Hannover – Germany

[55] K. Tiitto, R.M. Fix, “Evaluation of grinding burns, heat treat defects and residual stresses through chrome plating,” Published in 24th Annual Aerospace/Airline Plating & Metal Finishing Forum, April 4-7, 1988, Phoenix, Arizona.

[56] P. Lundin, L. Suominen, M. Hakanen, “New trends in case-depth measurements by Barkhausen noise” in Proceedings of the 4th Scientific and Technological Conference Diagnostics of Material and Industrial Components DMIUT, Gdansk, Poland, May 2012.

[57] Kai Y, Y. Tsuchida, M. Enokizono, “Numerical analysis for non-destructive evaluation of hardening steel taking into account measured magnetic properties depending on depth”. Electromagnetic Nondestructive Evaluation, Takahashi S and Kikuchi H. (Eds.) IOS Press, Amsterdam. 2007.

[58] S. Santa-aho, A. Sorsa, M. Hakanen, K. Leiviskä, M. Vippola, T. Lepistö “Barkhausen noise magnetizing voltage sweep measurement in evaluation of residual stress in hardened components” Measurement Science and Technology, Volume 25, Number 8, 2014

[59] “Rollscan 350 Operating instructions”, Stresstech Oy, V1.0e August 2015

[60] “RMX 4050HD User Manual” Retrieved from http://www.manualslib.com/manual/704794/Qsc-Rmx-4050hd.html

[61] V.A. Yardley, “Magnetic Detection of Microstructure Change in Power Plant Steels”, 2003, University of Cambridge, Retrieved from https://www.repository.cam.ac.uk/bitstream/handle/1810/221825/Yardley_thesis.pdf

[62] “PCCaseDepth Operating Instructions”, Stresstech Oy