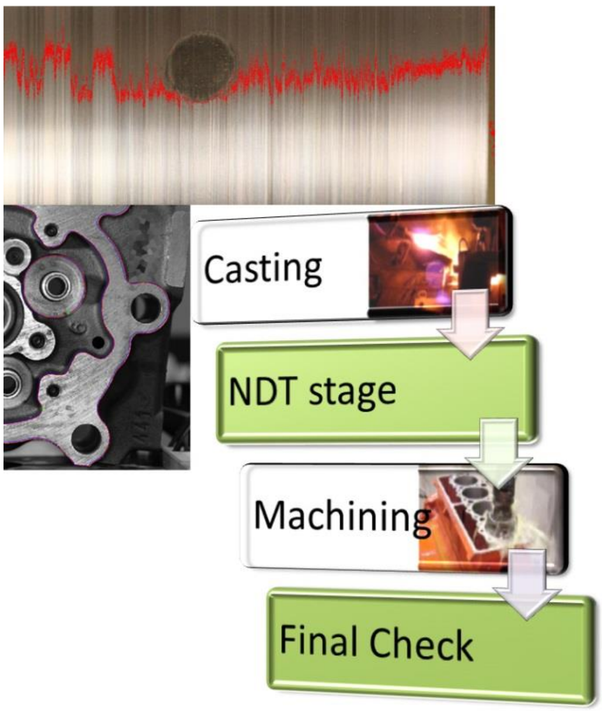
Non Destructive Testing methods: Development of innovative solutions for in-line applications



Project within FFI sustainable production

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

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1 Executive summary

Product quality in automotive manufacturing relies on minimization or elimination of defects (irregularity, discontinuity, flaw or imperfection) induced in various components during production. Auto industry still relies heavily on destructive testing techniques for identifying such defect and producing components conforming to the quality requirements.

The project goal is to develop NDT methods in order to be able to implement them as an in-line solution for early detection of defects on all the parts produced allowing to avoid further value adding activities on a part that eventually should be discarded and obtaining 100% quality check.

The project is covering four cases, namely, cast components, heat treated components, hard turned components and ground components. Several NDT-methods have been employed for the different cases, some of these have been successfully implemented as prototype and others have shown good potential but require further studies and successive development.

The project's major results can be summarized as it follows:

Cast components: a low cost vision system prototype has been developed and tested for surface and contour defect detection. A method based on impact acoustic testing has been found effective for characterization of material properties.

Heat treated components: several interesting correlations between different signals given by Barkhausen Noise (BN) and material properties have been found, opening for a wider use of this technique. More studies have to be carried out to fully understand the BN phenomena and make this method useful as a quality assurance tool for hardened components.

Hard turned components: The major conclusion from this work package is that BN signals should be integrated with other techniques in order to be able to characterize the parts. An approach has been suggested. Further investigation is nevertheless needed.

Ground components: the investigation of BN for control of thermal damage in grinding of crankshafts was successful and useful. The results of the FFI NDT projects are being used as inputs to the development of new strategies for grinding of crankshafts. Last but not least a more detailed insight into the nature of the BN phenomena would be useful to optimize the BN magnetizing parameters for robust in-line measurements and quality control.

Overall, the project results contribute to the FFI programme goals as the techniques implemented by this project allow the industrial partners to:

1- Improve the existing NDT-stations and NDT-procedures for obtaining more detailed information about the produced part.
2- Check 100% conformity at early stage in the production line, avoiding to waste material and energy on parts that would eventually be discarded.
3- Improve their own insight in the technologies employed and/or implemented.

Another important result of the project has been the creation of a consortium of experts in the area of industrial NDT that did not exist before.

2 Background

Automotive manufacturing in Europe is experiencing unprecedented competition due to both new players in the market and higher demands on performance to cost ratio. To be competitive in the global market, European manufacturers need to cut costs, reduce time to market and improve quality, simultaneously.

Product quality in automotive manufacturing relies on minimization or elimination of defects (irregularity, discontinuity, flaw or imperfection) induced in various components during production. Typical defects, for example in powertrain components may include porosity, inappropriate microstructure, cracks, uneven case hardening, insufficient hardness, undesired residual stresses, grinding burns etc. Auto industry still relies heavily on destructive testing techniques for identifying such defect and producing components conforming to the quality requirements.

However, this probability based testing, where a certain number of parts from each batch have to be selected in a way that they represent the entire production batch, for destructive analysis has serious drawbacks such as:

- Expensive and time consuming
- Probability of producing components with non-conforming quality

Risks and costs associated with non-conformance- including scrap, rework, material procurement costs, and complaints out of warranty, product service, product liability, product recall and loss of reputation- call for economical and reliable strategies to identifying defects at early stage in the manufacturing processes. 100% quality check i.e. each component being tested fully for defect identification instead of sample based inspection is one alternative to avoid costly non-conformances. This approach however is impractical in the context of destructive testing and therefore necessitates the use of Non Destructive Testing (NDT) methods. Also referred as non destructive inspection (NDI) or non destructive examination (NDE), several NDT methods are being used in the automotive industry for process improvement and the quality assurance purposes; they are a feasible alternate to destructive testing especially, for 100% quality check approach. However, efficient and economical implementation of the NDT methods requires that they are brought out of the lab and installed in-line. In other words, these methods should be developed in a way that they can be used (either in an automated or a manual setup) at appropriate stages of production processes for testing components produced at desired frequency but without disturbing the production flow. Reliability, robustness and practicability should be the driving design parameters in the development of these industrial solutions.

3 Objective

The main objectives of the project are:

1. Industrial application of existing and new NDT methods with a wider scope in terms of defect identification and components being tested.
2. Reliable and robust NDT solutions for in-line implementation on the production lines for each case study
3. A strong and effective platform for collaboration among the research and industrial partners for successful developments both within the project and future R&D endeavours

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4 Project realization

The project was divided in five work packages:

- WP1 Project coordination and result dissemination
- WP2 In-line NDT of Cast components
- WP3 In-line NDT of Heat Treated components
- WP4 In-line NDT of Hard Turned components
- WP5 In-line NDT of Ground components

5 Results and deliverables

5.1 WP2 In-line NDT of Cast components

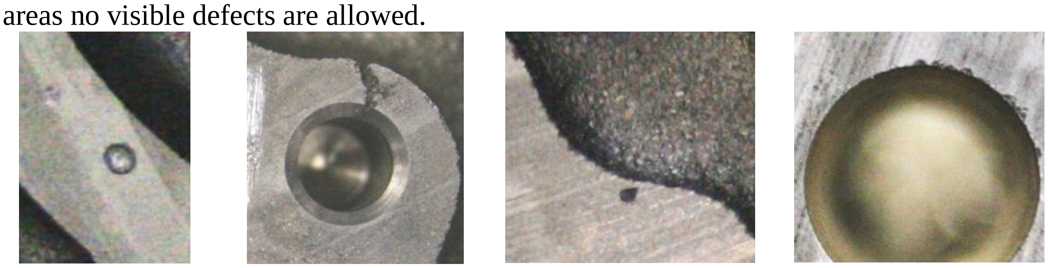
Cast components, such as cylinder heads, undergo a large number of manufacturing operations before reaching the product status. It is therefore important to identify as soon as possible defects that could cause possible problems to the coming operations and/or even the final rejection of the part.
The WP focused on the case study based on real production of cylinder head.
The classes of defects that are wished to be identified by the in-line NDT in the case of cast components are basically two:

1. Presence of pores.
2. Unfavorable microstructure.

The goal was to implement the identification of such defects as soon as possible in the production line, possibly after casting and before the machining operations.

5.1.1 Identification of pores through vision system

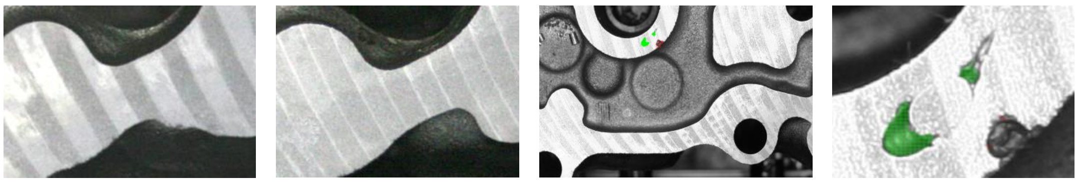
The defects in the cast iron components are mainly caused by gas porosity and traces of sand left from casting. The nature of defects is very broad starting from small cavities and chipped edges with a length of few tenths of a millimeter ending with large portions of missing material. Thus the methods used in the algorithm must guarantee the successful detection of very different types of defects (see Fig. 1). The part is divided into regions with varying tolerances for allowed defect size. For an example, in some areas defects up to 5mm long and 1,5mm deep are approved while in other areas no visible defects are allowed.



(a) (b) (c) (d)

Fig. 1 Various defects (a,b), Plastic contamination (c), chipped edges (not considered defects) (d)

The vision system is designed to enable on-line inspection of parts on a conveyor. The conveyor is not continuously moving thus enabling the use of a simple still camera. With the goal of designing a low cost vision system comes the inevitable drawback of having less possibilities to control the environment and having to cope with uncontrolled environmental factors. The algorithm obtains the contours and eliminates false edges, noise and non-important contours. The surface pores are then measured and compared to the standard to decide if part is approved or not. Thereafter the contours of the part are checked if deviations caused by porosity are present. Self-intersections and occasional parallelism of the contour segment and distance vector (see Fig. 2) are sometimes hard to compensate for. The problem was solved by using multiple points around the part for creating signatures. Test system using a DSLR with 50mm lens and a ring light has shown that the algorithm is able to reliably detect various type of pores but the used methods are better suited for finding smaller defects. System estimates the size of pores and compares with a standard to reach a final decision.



(a) (b) (c) (d)

Fig. 2 Natural variations in contour (a,b). Detected defects (c,d)

5.1.2 Characterization of microstructure

Compacted Graphite Iron (CGI) is a class of materials that can allow higher combustion pressure and lighter design, but material and mechanical properties may largely vary within the given specification for CGI. The microstructure determines the material physical properties which also affects the machinability parameters. Estimating the frequency response (FRF) can be a powerful method for classification of mechanical and material properties.

This estimation can be carried out using resonant inspection techniques such as Impact Acoustic Testing (IAT, also known as Resonant Acoustic Method, RAM). IAT is basically experimental modal analysis simplified for application to high volume production manufacturing and quality control testing. This technique performs resonant inspection by impacting a part and "listening" to its acoustic spectral signature with a microphone. The controlled impact provides broadband input energy to excite the part and the microphone allows for a non-contact measurement of the structural response. The material types and properties of the test specimen are summarized in Table 1.

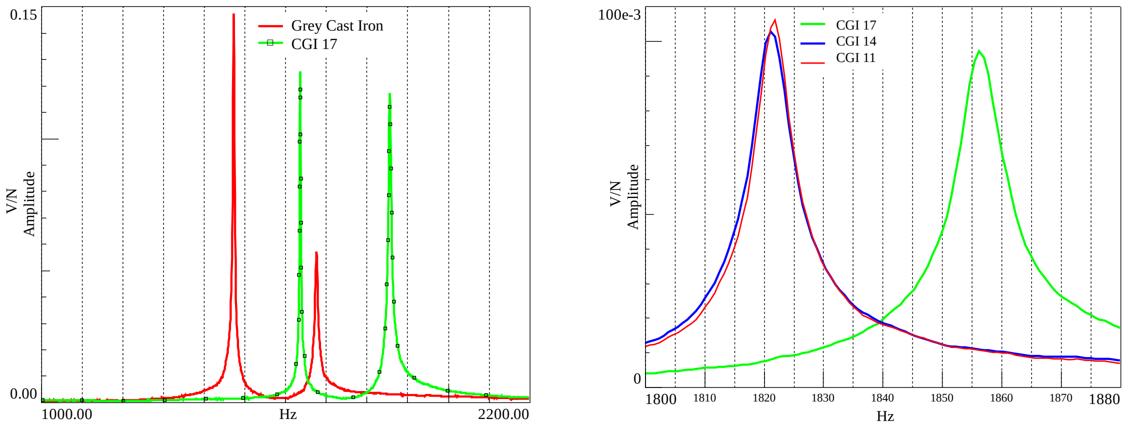
Table 1 Material and mechanical properties of the tested specimens.

Material type	Nodularity	Pearlite content	Interlamellar distance in pearlite [nm]	E	Yield strength	ε	UTS
	[%]	[%]		[GPa]	[MPa]	[%]	[MPa]
Gray Cast Iron	n.a.	n.a.	n.a.	105[1]	182	1.3	222
CGI 11	26	85	274	131	330	2.4	471
CGI 14	6	95	248	132	334	2.6	434
CGI 17	29	95	261	143	353	1.6	505

The IAT could easily distinguish grey iron and the different CGI specimen as expected since the mechanical properties are largely different (see Fig. 3 (a)).

[1] Typical value for Grey Iron.

The differences in mechanical properties between the given CGI specimens are more subtle (see Table 1) and this is shown by the extracted FRF as well (see Fig. 3(b)).
Nevertheless, IAT was able to distinguish CGI 17 from CGI 11 and CGI 14. The two latter resulted undistinguishable from each other.



(a) (b)

Fig. 3 (a) IAT result. Frequency response of Grey cast iron (red) and CGI 17 (green). (b) IAT result. Frequency response of CGI 11 (red), CGI 14 (blue) and CGI 17 (green).

Machinability of CGI is strongly dependent on its material properties and studies conducted in previous research projects (OPTIMA) have been showing that tool life may vary between 30 to more than 180 minutes depending on the material and mechanical properties. A classification method such as IAT can be therefore employed to optimize the cutting process parameters, contributing to higher productivity (by avoiding unexpected stoppages due to sudden tool life end) and lower environmental impact as tools could be used to their optimal life.

5.2 WP3 In-line NDT of Heat Treated components

In this work package the main focus has been to investigate three different non-destructive testing (NDT) methods possibilities as a quality assurance tool in order to verify a heat treatment process. The different NDT methods are at different stages of maturity in order to be used as an in-line method for verification of the heat treatment process induction hardening. The main goal of this work package has been to evaluate the technologies deeper in order to detect improper microstructure, case depth and residual stresses. Within this work package different sample of Volvo Powertrain camshafts has been used as a case study. These camshafts are designed with six individually of cam-lobes sets containing three different cam lobes that each serve with a specific function to operated the engines combustion. For one of the studied camshaft, each cam lob set has been changed where the applied power for induction hardening process has increased or decreased. This has generated a hardening result that changes in the microstructure correspondingly which is also could be seen in the material parameters such as surface hardness, case depth or residual stress.

5.2.1 Measurements with the Barkhausen noise method

The NDT method Barkhausen noise has been the main focus for this work package. This method has several different output parameters some of which has been reported in literature to correlate both the hardness and the hardening depth. Initially the Barkhausen noise method repeatability was explored in order to investigate how stable the different Barkhausen noise parameters were. The results showed high degree of reputability if the proper sensor settings were used.

In order to investigate the BN sensitivity for different microstructures three different materials where measured, induction hardened (SS2244), casehardened (SS2511) and a through hardened steel (SS2260). The results showed great differences in how the BN burst and the magnitude as well as the shape of the hysteresis loop. The initial BN measurements on the camshafts were measured around the cam lobes. The results showed that each cam lobe has a maximum in the BN signal for one position around the cam lobe which was interpreted to be an effect of a secondary heating from the neighboring cam lobes. It was also shown that the different cam lobes had different magnitude of the BN signal. For further analysis it was determined that only two positions around the cam lob should be measured, the top and bottom position. In parallel with these measurements the material characteristics where determined for the cam shaft. This includes measurements of the hardness, hardening depth, residual stress, and grain size. All of these data along with all the BN parameters resulted in a quite large result matrix, xx columns and xx rows. The initial analysis of the results shows no clear correlations. However, in order to study these results further a statistical tool called multivariate analysis was used. This is a tool that makes it easier to find trends in large data sets such as this. This analysis separates the material properties from the BN signal. After some analysis of the data a correlation was revealed for the BN RMS signal and the hardening depth showing that the BN RMS increased with increasing hardening depth according to Fig. 4. This and other results showed a great potential for the BN technique but it also showed the limitations. It was clear that it was possible to find useful correlations to the material properties but it was not understood why these correlations could be detected by a NDT method that only has a limited penetration depth and still it could detect a hardening depth of several millimeters. This and other results show that further and more in depth study of the BN phenomena is needed in order to fully make this method useful as a quality assurance tool.

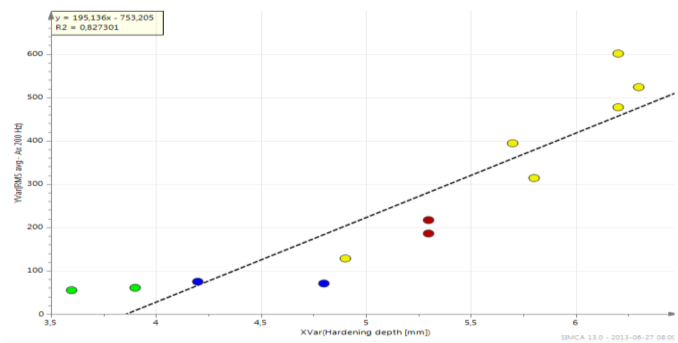


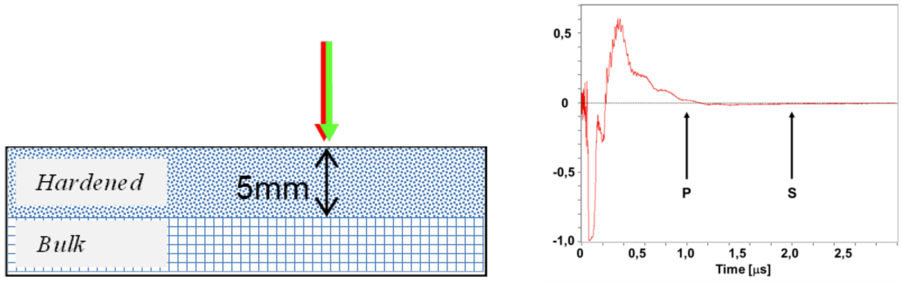
Fig. 4 Results from the analysis of data for all five cam shafts showing a good correlation between the hardness depth of the cam lobes and the Barkhausen noise signal RMS.

5.2.2 Modelling of ultrasonic NDT method

A second NDT method that was evaluated in this work package was the modeling of ultrasonic method in order to investigate whether this method could be a potential alternative to determine the hardening depth none destructively. In pure scattering, the energy of motion is not converted to heat; instead, it is diverted into waves traveling in directions other than the main wave. These diverted waves appear as random noise and the amount of wave energy that is scattered depends mainly on the size of the scattering particles compared to the wavelength of the ultrasonic wave. An ultrasonic method to measure hardness depth has previously been available commercially and was based on applying conventional UT probes and instrumentation (QNET, Sonix). In the near future the intention is to implement the technology in process integrated measurements complemented with information about e g surface hardness and grain size. Previous experiences indicated on good correlation between measured depths and actual depths found by destructive examinations. It is obvious that if the method is to be applied for in-line measurements it must be based on better theoretical knowledge of the ultrasonic wave propagation in the surface hardened components.Based on previous experience, initial simulation has been conducted in order to illustrate how this concept could be used in the development of a non destructive characterization technique (NDC). By using a thorough validated model of the transmitter and receiver the beam spreading can be simulated and thus be singled out from the parts that actually are related to the material. Since both absorption (i.e. viscous damping) and grain scattering have the same kind of impact ($e^{-\alpha x}$) on the amplitude it will be important to develop an ultrasonic procedure that distinguishes between these both phenomena. One hypothesis is to use the backscattered information in an estimation of the grain sizes and use this as a presumption in the analysis of ultrasonic energy that has been reflected against the back wall one or at a number occasion. The latter is a conventional technique known as transfer damping measurement and the number of decibels between two adjacent signals is measured and the value is then divided by the time interval between them. This calculation produces an attenuation coefficient in decibels per unit time. In order to validate whether the spherical inclusion could be used as ultrasonic scattering representatives to individual grain scattering in a statistical perspective a control volume (10x10x10 mm) was implanted with randomly distributed inclusions of different sizes (i.e. $Ø = [0.9Ø_0, 1.1Ø_0]$). Four different sizes of inclusions was used ($Ø_0$ = 20, 50, 100 and 200 μm) and two different pulse echo probe with different frequencies were scanning the surface above the volume. A spherical cavity (Ø = 0.1 mm) was introduced as a calibration object. The results from the simulations indicate on the possibility to use simulation in the development of a ultrasonic procedure that estimates the hardening depth. The next would be to experimentally validate the model and use the model in order to identify possible probe techniques and optimize such set-up.

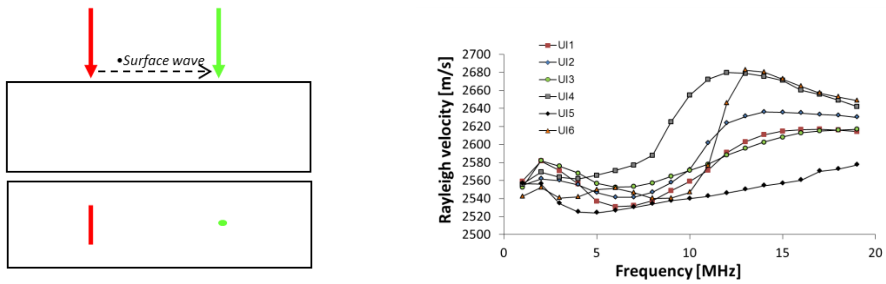
5.2.3 Measuring with LUS method

The hardened camshafts were investigated by laser ultrasonic. This technique has the advantage that it can access and measure relatively irregular geometries. The ultrasound can also be induced in the material on a very small area, down to 200 × 200 μm, permitting local variations on small scales to be investigated. The idea was to see if the laser ultrasound can be used to measure both the depth of cure and also say something about the quality of the hardened layer. Two experimental methods were investigated and developed in the project. One method was to try to detect the ultrasonic reflection from the interface between the cured and the uncured portion of the surface (Fig. 5a) . In theory, the small grains in the hardened section should in principle be transparent to the ultrasound, while the larger grains in the bulk reflect/diffract ultrasound back to the surface. Unfortunately, we could not detect any echo from the interface (Fig. 5b). A second method was to measure the ultrasonic velocity of a wave traveling along the sample surface. These Rayleigh waves also penetrate the sample with a depth of about one wavelength (Fig. 6 a). A clever detail with laser ultrasound is that the short generation pulse means that a wide range of ultrasonic frequencies from about 1-100 MHz is generated instantaneously in each measurement. With the help of wavelet analysis, ultrasonic velocity at different frequencies can be extracted from the raw signal. It is known that ultrasound velocity is affected by material parameters like hardness, internal stress and microstructure. As different frequencies penetrate the sample more or less, information from several different layers of the sample can be compared. Fig. 6b shows the first results of this method on the six cams labeled U1- U6. Although some differences between the cams and the ultrasonic frequency can be distinguished, it was not possible to see clear trends that correlated with process parameters and destructive testing.



(a) (b)

Fig. 5 ***a) Schematic picture of a tempered sample hit by a generation laser (red arrow) and a detection laser (green arrow). The black double arrow shows how an ultrasonic pulse could travel in the sample. b). Ultrasonic signal from a camshaft (A-scan) measured with the experimental setup presented in a). No echo from the interface is visible neither for the longitudinal wave (P) or the transverse wave (S).***



(a) (b)

Fig. 6 a). Test set-up for surface wave analysis. The top picture shows the sample from the side with the generation laser (red arrow) and the detection laser (green arrow) hit the surface from above. The bottom image shows the sample from above. The generation is focused as a line for the ultrasonic wave to cover up a larger volume. b). Results of "wavelet analysis" of the surface waves. The figure shows the speed of sound as a function of ultrasound frequency for the six cams U1-U6.

5.3 WP4 In-line NDT of Hard Turned components

In-line non-destructive evaluation (NDE) of the surface microstructural alteration on the hard-turned steel components is the case of interest. On these machined surfaces, depending on the cutting condition, surface and subsurface microstructure alteration are occasionally observed. The undesirable machine-induced surface “white layer” is on focus. Whilst it is important to know how to avoid this layer, the knowledge of applying appropriate NDT techniques to conduct this monitoring is of the same importance.

AISI 52100 steel was the studied material. Two sets of samples were prepared to have tempered martensitic structures (M-series) and bainitic structures (B-series). In each sample set, machining conditions were applied to create the surface integrity of different conditions in accordance with the experimental design matrix shown in Fig. 7. The flank wear length on the cutting inserts (V_B) and the cutting speed (v_c) were chosen as the variable factors. The cutting inserts used were PCBN. The wear of the inserts was introduced by using the inserts on other samples with a comparable diameter prior to the final cut. Emulsion was applied during machining.

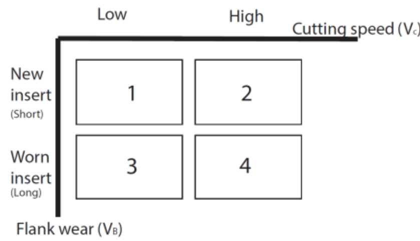
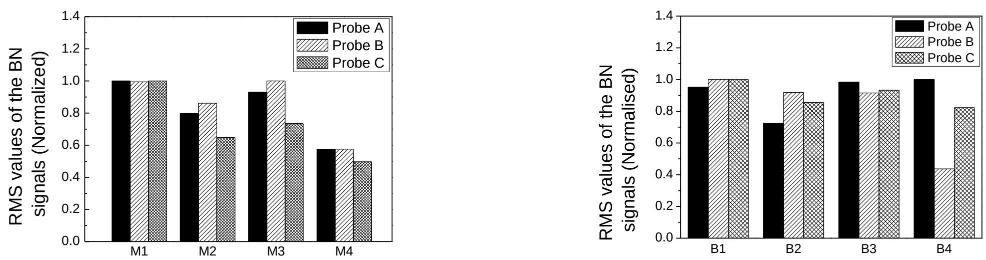


Fig. 7 . The varied testing parameters and the corresponding sample numbering.

The NDT methods applied in this study include Barkhausen noise (BN) and light scattering (LS) techniques.

5.3.1 Barkhausen noise (BN) technique

The application of Barkhausen noise (BN) for material characterisation is by making use of the magnetic domain movement in the material when an external magnetic field is applied on the tested sample. The instrument used was a Stresstech Rollscan 300 Digital Barkhausen Noise Analyser. To achieve "white layer" measurement, 3 probes of different magnetizing power were used and the magnetising frequency and magnetising voltage were adjusted at a relatively high level, e.g. 1000 Hz and above 12 V, in order to acquire the BN signal from the uppermost surface. Other parameters including analysing filter range, number of analysed bursts and sampling frequency were set at 25-600 kHz, 20 and 2.5 MHz, respectively. To enhance the reliability, every reported data was obtained by measurements from at least 3 times at 4 different positions.



(a) (b)

Fig. 8 The normalized RMS values of the investigated samples from three different probes (1000 Hz).

Among all the possible parameters generated from a single measurement, only the RMS value is studied.

Results of the three probes conclude that higher RMS values are obtained in the B-series and the descending trends in individual series are M1 (B1), M3 (B3), M2 (B2) and M4 (B4), respectively, except Probe A in B-series, as shown in Fig. 8.

The minor RMS difference observed between M1 (B1) and M3 (B3) implies that their surface conditions are similar and relatively lower values in M2 and M4 (B4) imply a more significant impact is given by high speed hard turning than by the flank wear length of the insert.

5.3.2 Light scattering (LS) technique

Surface micro- and nano-topography strongly influences the reflected light distribution and this can be used as a fingerprint of height variations and spatial frequencies in the surface. The photodetector capturing the scattered light was either a Si-photodiode or a digital camera provided with a macro lens. A laser diode operating at 635 nm wavelength was used as the light source, illuminating the surface at an oblique angle An example of the camera captured light scattering from the four M1-M4 surfaces is shown in Fig. 9. For M1, there was almost no scattering, while the M4 surface created a considerable amount of scattering. In order to conclude if this scattering is related to the white layer or just the wear of the insert, more investigations needs to be done. In addition to the light scattering the surface roughness was measured according to the ISO standard with a Zygo white light interferometer at five spots on each sample. It shows no clear relationship among the samples with the Ra range between 0.30 – 0.50 µm. However, the standard deviations in M1 and M2 are smaller than those in M3 and M4. It is then concluded that the worn inserts increase the variation in Ra across the grooves.

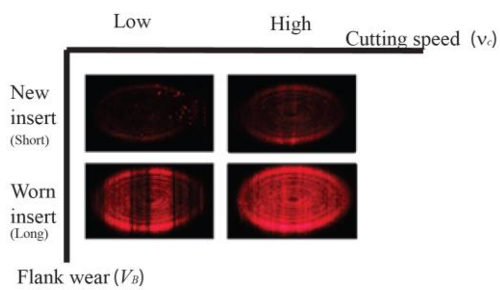
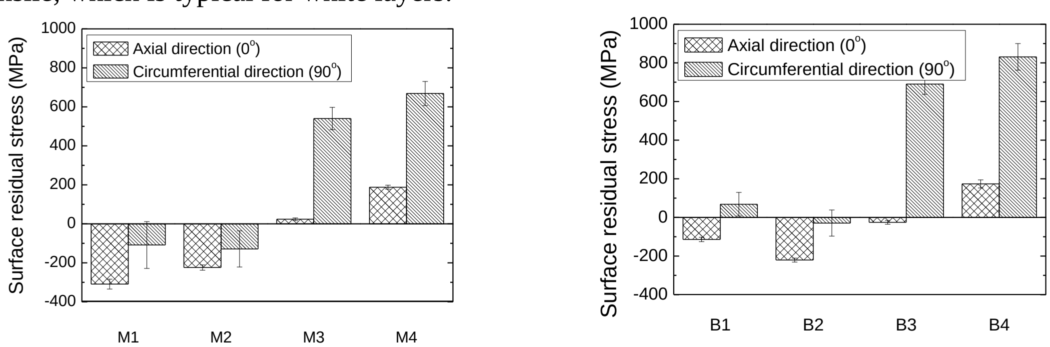


Fig. 9 Images of light scattering of the four martensitic samples. Illumination is obtained from a red laser diode (635 nm) illuminating approximately 5 mm of the surface in the axial direction.

5.3.3 X-ray residual stress measurements

The residual stress analysis was conducted by a Stresstech XStress X3000 G2R equipped with a CrKα source (λ = 2.2897Å). The near-surface residual stress levels on the machined samples (both M-series and B-series) are plotted in Fig. 10. For the fresh insert, independent to the type of materials, cutting speed and the direction of the XRD measurement, compressive residual stresses were determined most of the time. With the worn tools machining, surface stresses became tensile, which is typical for white layers.

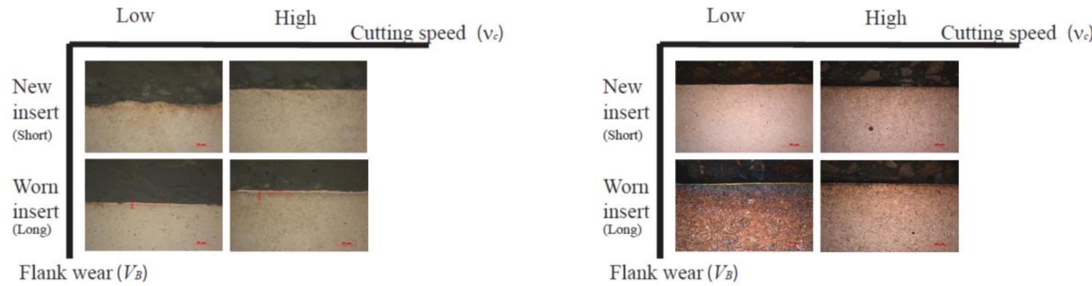


(a) (b)

Fig. 10 Surface residual stress levels determined by means of X-ray stress analyser

5.3.4 Optical microscopy

Optical microscopy was used to examine the cross-sectional microstructure at the machined surface (see Fig. 11). The microscope used was a Leica Letz DMRX equipped with an AxioCam MRC5 camera. In the microstructural examination, the surfaces along the axial (feed) direction were investigated. The microstructural study shows that no white layer (continuous or discontinuous) appears on the samples that were machined by fresh cutting inserts, i.e. M1 and M2, as well as B1 and B2. Meanwhile, uniform and featureless white layers were observed on those surfaces machined by inserts with excessive tool flank wear, i.e. M3 and M4, as well as B3 and B4. Thus, it's proved that microstructural alteration occurs only in the selected machining condition, i.e. inserts with significantly long flank wear. To integrate this information with other characterised properties, it is found that samples without and with discontinuous white layer were characterised to have compressive residual stresses, while surfaces with continuous white layers showed high tensile surface residual stresses. Nonetheless, it is still uneasy to determine the surface characteristics via BN method as it is known that the acquired RMS value consists of several materials characteristics as well as properties such as microstructure (phases and grain size), hardness and residual stress.



(a) (b)

Fig. 11 Cross-section of (a) M-series and (b) B-series after machining.

As a result, an attempt to gather the experimental results obtained from other techniques like light scattering, X-ray stress analysis and optical examination and compared them with this RMS value was done. An empirical function is established as shown in Equation (1).

$$\text{BN signal} = \frac{\text{Tensile stress level}}{\text{Compressive stress level} \times \text{Layer thickness} \times \text{Ra-range}} \quad \ldots (1)$$

Still, much further effort will be needed to establish a more refined physical model to understand how these different aspects of surface integrity of a material correlates with this acquired BN signal, together with a statistical model from experimental data, to map a picture for better understanding of BN technique and achieve the ultimate in-line application purpose.

5.4 WP5 In-line NDT of Ground components

The goals related to this objective was to investigate the feasibility of applying different NDTs to identify and classify different types of thermal damage, such as tempering, onset of tensile residual stresses and rehardening, that can occur in industrial grinding (on the shop-floor, in-line). The result was an improved NDT solution, based on the Barkhausen noise technique that is already implemented in the production line. The main task of WP5 was to run a set of grinding tests to reproduce different types of thermal damage. Using the Barkhausen Noise (BN) technique to identify different types of damage and to develop grinding burn threshold diagrams.

The benefits of the BN technique are the following:

- Equipment available at Scania (integrated in-line with production).
- Measurement time is short, process rather robust, which are the major advantages of this technique for industrial application.
- BN instrument works as a comparator (qualitative values) and requires calibration with the temperatures and different types of thermal damage in grinding.

- As a practical matter, our goal was to directly apply this method for identifying different types of thermal damage (tempering and the onset of tensile residual stresses during grinding of crankshafts.

The investigated factors effecting the process and its outcomes were: (1) workpiece material, (2) feed rate of the grinding process (affecting the removal rate – productivity as well as surface integrity), and (3) overlap ratio of the dressing process (affecting workpiece quality - surface integrity). The grinding process was characterized by measuring the grinding power and calculating the specific energy. These two parameters are the main parameters used in an industrial grinding research. All the grinding tests needed to obtain project results were executed at Scania, using the in-line production equipment and vitrified CBN grinding wheels. The assessment of results were carried out at Scania (BN) and at Stresstech Oy facilities in Finland (analysis of residual stress).

Dressing has a large effect on grinding power and specific energy (which is monitored in parallel). The objectives of this sub-task were the following:

- Analyze the effect of dressing on Barkhausen noise
- Analyze the influence of material charge on grinding results
- Analyze the effect of dressing on grinding power
- Analyze the effect of dressing on specific grinding energy
- Estimate effects of dressing and material on grinding temperature

Different wheel topographies were created by the dressing process, namely by changing the dressing overlap ratio. In this way wheels used for testing ranged from worn to very sharp

We have found out that the dressing process significantly affects the estimated grinding temperatures (calculated by using Jaeger´s moving heat source theory). All the temperatures are likely to cause the onset of tensile residual stresses and in the extreme case (U_d=10) for grinding with a worn wheel a possible rehardening. Interestingly, the material supply was also likely to affect grinding temperatures (and thermal damage). This situation is far from optimal for industrial grinding, therefore the effect of the material was investigated further. In the next step experiments were designed to perform this detailed investigation

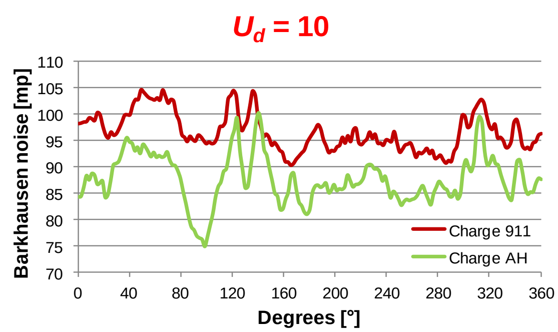


Fig. 12 Effect of material batch on BN measurements.

The results of the BN measurements confirmed that the material charge significantly affects the measurements, shown in Fig. 12. This NDT technique proved very reliable in tracking the changing trends of the BN signal around the ground workpiece circumference.

The following conclusions have been made:

- The BN levels are higher when grinding Charge 991 in comparison to grinding of Charge AH. Significant effect of material charge.

- The increase in BN average values for Charge 991 when we move to dressing with higher overlap ratios could be associated with material softening (normal wheel) and the onset of residual tensile stresses (dull wheel). The lowest observed average BN value is associated with grinding with a worn wheel (possible rehardening).
- The same interpretation cannot be made for the measured average BN values for Charge AH. Readings appear more random. This could be associated with local variations in the material or machining history. Different types of thermal damage could not be identified.
- The standard deviation between the five successive BN measurements on Charge AH was about 4.

Thermal damage is one of the main factors which affects workpiece integrity and limits the production rates which can be achieved by grinding, so it was especially important to understand the underlying factors which affect the grinding temperatures. This case-study referred to grinding of crankshafts (one material batch). The objectives of the study were the following:

- Analyze effect of the grinding process on thermal damage of crankshaft main bearing
- Investigate variation of BN around the circumference of the mains
- Investigate variation of BN around with respect to material batch
- Estimate correlation between thermal damage and BN values
- Test BN measurements in-line (Rollscan) and off-line (MicroScan) modes

Experiments were carried-out to realize the different grinding burn scenarios. The tested productivity cases, typically used in production, gave similar results of BN measurements. So the technique is not sensible enough to discriminate between the different types of thermal damage. Nevertheless, the most extreme scenario, gave higher values of the BN, which are likely associated with severe tensile residual stresses. The repeatability of measurements was adequate.

Similar results were obtained by laboratory BN measurements using the Rollscan 300 – Microscan software. Only one case (Q'_w=49.6 mm^3/mm s) significantly differs from the others. This confirms the in-line measurements of the BN in real production, on the shop-floor level.

To confirm the obtained BN measurements, residual stresses were measured by Stresstech in Finland. The residual stress profile for the severe grinding case (Q'_w=49.6 mm^3/mm s) reveals a high level of tensile residual stresses reaching up to +680 MPa.

The additional material investigations at Scania´s material lab proved the absence of rehardening. Therefore no significant drop in the BN was observed. Based on this investigation, the following conclusions are offered:

- Grinding tests were designed to generate different types of thermal damage (in quasi temperature ranges between 526-1058 °C).
- The maximum increase in grinding power was 400%. Up to 85% of available spindle power (63 kW) was used to produce the grinding burn scenarios.
- The BN levels for the four grinding tests are similar. Based on the results, the scale of thermal damage is similar.
- The BN level increase for the fifth grinding scenario is 20%. The increase is likely associated with the onset of tensile residual stresses.
- BN bursts were analysed as well using the microscan. Obtained results are the same.
- Additional X-ray measurements were carried out to analyse residual stress and retained austenite. No re-hardening was observed

Overall, the investigation of BN for control of thermal damage in grinding of crankshafts was successful and useful. The results of the FFI NDT projects are being used as inputs to the development of new strategies for grinding of crankshafts. Last but not least a more detailed insight into the nature of the BN phenomena would be useful to optimize the BN magnetizing parameters for robust in-line measurements and quality control.

5.5 Delivery to FFI-goals

- 30 % higher productivity:
  The results of this project are all contributing to such goal. The NDT characterization of material properties beforehand via IAT and or BNT can allow process optimization. In addition to this the early detection of defective parts via vision system allows to not waste production time on parts that would be anyway discarded.
- 30 % mindre miljöpåverkan i tillverkningsprocesserna:
  Not wasting production time on defective parts also means not wasting energy. Having a reliable tool for characterising material properties will drastically cut down the need for destructive testing, reducing material waste.

The knowledge and prototypes developed in this project have great relevance for all Swedish manufacturing industry, small, medium and large enterprise. For instance, the technologies studied and implemented in WP2 give the possibility of using low-cos equipment for defect detection and/or material characterization, enabling fully automated control of the parts at affordable cost. Thanks to the public dissemination of the results a knowledge base is also available.

6 Dissemination and publications

6.1 Knowledge and results dissemination

The project results have been disseminated through seminars within the project consortium and academic publications presented at international conferences.

Seminar 1: 13 April 2011, at SKF Headquarters in Gothemburg, Sweden
Seminar 2: 2-3 September 2013, at Scania Headquarters in Södertalje, Sweden

6.2 Publications

Bergqvist, A. (2011). Oförstörande provning in-line: Säkerställande av produktionskvalitén vid gjutning av cylinderhuvuden. (Master Thesis). KTH.

Daghini, L. & Berglund, A. (2013). Impact Acoustic Testing as NDT Method for Classification of Compacted Graphite Iron. In: Archenti, Andreas; Maffei, Antonio (Ed.), Proceedings of the International Conference on Advanced Manufacturing Engineering and Technologies. Paper presented at NEWTECH 2013, the International Conference on Advanced Manufacturing Engineering and Technologies; Stockholm, Sweden 27-30 October, 2013 (pp. 293-302). Stockholm: KTH Royal Institute of Technology.

Tam, P. L., Hosseini, S. B., Holmberg, J., Lundin, P., Mattsson, L. & Nyborg, L. (2013). A study of the surface integrity after machining by means of non-destructive testing methods. In: A.

Archenti and A. Maffei (Ed.), Proceedings of the International Conference on Advanced Manufacturing Engineering and Technologies. Paper presented at NewTech 2013 conference, Oct 27-30, 2013, Stockholm (pp. 283-292). Stockholm: KTH Royal Inst of Technology.

Eshetu Tefera, Z. (2014). Impact Acoustic Testing for Classification of CGI Mechanical and Material properties. (Master Thesis). KTH.

Kiviorg, A. (2014). Development of a Low-Cost Vision System for finding Contour and Surface Defects on Cast Iron Engine Components. (Master Thesis). KTH

7 Conclusions and future research

The knowledge and experience obtained during the project together with the challenges encountered and new industrial demands have laid the foundation for formulating new challenges in the new project FFI OFP4p ("Oförstörande provning för produktion"). The main goal for FFI OFP4p is to provide a deeper understanding of the physics behind the Barkhausen noise technique BNT (already largely used within automotive industry), allowing the extraction of a greater amount of information about the tested components material properties with higher reliability. The ultimate objectives are to minimise destructive testing of components as well as make possible to swiftly assess the processability of workpieces before they enter the given processes, allowing an optimization of the process beforehand.

8 Participating parties and contact person

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