Surface integrity inspection on gears using Barkhausen noise analysis

B. Karpuschewski\textsuperscript{a*}, O. Bleicher\textsuperscript{b}, M. Beutner\textsuperscript{a}

\textsuperscript{a} Institute of Manufacturing Technology and Quality Management, University of Magdeburg, Germany
\textsuperscript{b} ZF Friedrichshafen AG, Friedrichshafen, Germany

Abstract

Hard finishing of gears is the last step in the process chain and it is mostly responsible for the properties and performance of the workpiece. A grinding process basically offers the possibility of high temperatures in the cutting zone, possibly resulting in tensile residual stresses, reduced hardness and in metal structure. Thus the control of physical properties of the workpiece is of utmost importance for quality assurance. This paper shows the testing of finished gears in industrial production with a non-destructive, ecological and micro-magnetic method called Barkhausen noise analysis. The strength of Barkhausen signal is influenced by the elastic stresses and the micro structure. So, changes in residual stresses and material structure are measurable. Moreover they are indicators for improvement of the used grinding process. This paper focuses on the possibility to substitute other more hazardous methods by Barkhausen noise analysis. In addition process advantages and drawbacks factors influencing measurements industrial applications and options for measuring automation are also discussed.

© 2012 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of Prof. E. Brinksmeier

Keywords: Manufacturing, Grinding, Gear, Thermal error, Surface integrity

1. Introduction

It is quite common that gears in high performance gearboxes are exposed to extreme loads, which requires assuring high production quality. At the end of the process chain grinding is used to produce high
quality gears. Therefore the most important final characteristics of the workpiece are provided by grinding [1]. However manufacturing processes are working at the edge of their capacity, including grinding, which may result in thermal errors (also known as grinding burn) on the surface of the workpiece. Due to the nature of process kinematics nearly the whole consumed energy is frictional, which is the cause of heat generation in the work zone [2, 3]. As a result surface properties can deteriorate [4], e.g. tensile residual stress, tempering, re-hardening and micro cracks can occur in the surface layer [5]. The possibility of these errors to happen calls for robust quality and process control. In industry there are a number of methods available to observe these damages in the external zone. In order to get detailed information about the surface condition it is often necessary to destroy the workpiece, which obviously cannot be used on every workpiece. The non-destructive method of nital etching is currently the most popular in industry for detecting grinding burns. Unfortunately this is a very subjective and should be avoided in green manufacturing. In attempt to remove these disadvantages new testing methods and monitoring systems (Figure 1) have been analysed [6, 7].

![methods to detect damages of the surface integrity](image)

Fig. 1. Methods to detect damages of the surface integrity [15]

Of the new methods only the micro-magnetic methods are used in industrial environment [8]. This paper presents a micro-magnetic method, which offers an objective, fast and non-destructive measurement of ground gears, based on Barkhausen noise analysis.

2. The Barkhausen effect

2.1. Characteristics of ferromagnetic materials

Ferromagnetic materials offer particular magnetic characteristics. In microscopic dimensions, at lower than the curie-temperature and without external magnetic field, there are areas with uniformly oriented magnetic moments. These areas are called ferromagnetic domains or Weiss domains, as shown in Fig.2 upper right, with a dimension about 10 µm [9]. The homogeneous adjustment is caused by the interaction between interconnection forces and the disoriented heat motion [9, 10]. The bottom right hand side of Fig. 2 illustrates two adjacent domains, which are separated by a small wall, called Bloch wall, which
rotates the magnetic vector of the domains. The rotation is fluent from one area to another and it is performed orthogonally in the plane of the wall. The changeover areas encase the domains like a shell. Another property of ferromagnetic materials is the hysteresis loop. This curve characterises the relationship between the magnetic field \( H \) [A/m] and the magnetic flux density \( B \) [T], as shown in Fig. 2 upper left. An external magnetic field initiates an alternation of the orientation of the Weiss domains in the line of least resistance, where the unfavorable magnetic orientation increases over areas with an unfavourable orientation [10, 11, 12].

**Fig. 2. Characteristics of ferromagnetic materials [10,11,12]**

The increase takes place by the movement of the Bloch walls and the increase is stepwise. The amplification shows that the course is discontinuous like stairs. The reason for the stepwise behaviour is the irregular changes of magnetisation in the elementary moments [9, 10] and the discontinuous jumps can be made audible. This phenomenon was discovered by Prof. Barkhausen in 1919 [13]. To honour him the change of magnetisation is called Barkhausen jump. The removal of the exciting field causes all reversible wall movements and rotating processes to return, but some domains are not able to take their original dimension and orientation [11,14]. The difference in magnetisation is measurable and it’s called remanence \( B_r \) and the coercivity \( H_c \) is needed to set this zero.

**2.2. Influences of material properties on Barkhausen**

The behaviour of the Barkhausen noise is substantially influenced by the material microstructure. The impurity atoms, inclusions and vacancies constrain the movement of the Bloch walls. Mechanical stresses
also affect the magnetisation process through the change of the magnetic structure changed by wall movements [11]. The resistance against the mobility of the walls is decreased by the increase of tensile residual stresses causing the Barkhausen signal amplitude $M_{\text{max}}$ to grow.

![Barkhausen technology and influences](attachment:image.png)

This fact is useful because the sensitivity increases with growing tension which is a clear evidence for a thermal damage [15]. Contrary to this, compressive residual stresses produce a lower signal amplitude [15, 16], as seen on Fig. 3. Studies regarding the influence of grain size and grain orientation were done by Tiitto at the end of the 1970s [17]. It was found that increasing carbon content influences the Barkhausen amplitude. However if the higher content is caused by carburizing the signal is decreasing. This can be explained by the fact that martensite has a high mechanical and a high magnetic hardness. The Barkhausen signal increases by tempering because of the transformation of martensite and the reduction of hardness caused by residual stresses [18]. The upper left hand side of the Fig 3 shows the principle and components of a sensory system. Fig. 3 at the bottom left also shows a picture of an industrial sensor for gear measurement. In industrial measurement there are a few more factors to pay attention to. Every group of parts needs a dedicated sensor [19], as shown in Fig. 3 and 5 for gears with a module range of $m_n = 1.5$ mm to 4.0 mm. An accurate fitting on the workpiece surface is required that prevents air gap, which would generate errors in the measurement. But also material properties like deformation, phase composition, and crystallographic texture need to be considered. Other materials and heat treatments cause to change the Barkhausen signal as well, as illustrated in Fig.4. The diagrams are dimensionless because the instruments and measuring parameters are not comparable to each other. Furthermore unpolished areas, cracks, remnant magnetisation of the workpiece and external
electromagnetic fields influence the Barkhausen signal as well, which gives rise the need for signal calibration.

Fig. 4. Qualitative illustration of different influences on Barkhausen noise [15]

2.3. Comparison to nital etching

The current method to detect thermal errors on the workpiece surface is nital etching. This method uses the effect that different components of the material have different vulnerabilities to acids [20]. As a result the damaged areas look differently, mostly darker. However, it is requirement of green manufacturing to remove acids and bases from the production. Another disadvantage of this method is the subjective inspection of the workpieces coupled with the fact that only the top layer of the surface can be tested. This process is not able to detect sub-surface grinding burn. In contrast the measurement using Barkhausen effect is objective. In order to establish limit values for individual workpieces it is necessary to have a critical consideration of the previous processes in process chain. The measurement time of both methods is strongly dependent on the particular workpieces (module, number of teeth, external diameter).

3. Application in gear manufacturing

The first industrial application of this technology was developed in the 1980s [15, 21]. Since then Barkhausen analysis is increasingly used in industry it is more and more in the focus of fundamental
research [22-37]. Nowadays it is possible to adapt solutions to gear surface measurements for gear measurement, like a robot based system, as shown in Fig.5 (upper right). The remaining challenge is a development of a commonly accepted handling instruction together with clearly defined calibration procedures.

The aim of the FVA-project 239/III [8] was the investigation of options, limits and applications of the magnetic Barkhausen noise analysis. It is based on the knowledge of previous researches [33, 34], where the ability of this method for the detection of grinding burns were demonstrated. The operational sequences of the Barkhausen measurement of different gear manufacturers were compared. It was noticed that the users had had a broad knowledge on parameters influencing measurement results. On the other hand the same specimen produced different Barkhausen signals. However, some type of damages could not be detected, and a number of detected damages are underestimated and the measured values had a wide spread. The results made it clear that a standard guideline is needed for measurements, otherwise it leads to different general conditions for calibration. In addition there is no strong argument for clients to accept for quality measurements. Hence the guidelines should comprehend a protocol for calibrating, measuring environment, measurement operation and the evaluation and interpretation of values.

The research project 594 of the FVA which is called Barkhausen dealt with setting up guidelines for the Barkhausen measurements. The final version was completed in June 2011. The guideline has been created for supervisors and it comprehends instructions for appropriate correct adjustments of the measuring device and handling of the Barkhausen method. Another aim of the workgroup was the development of education methods, where the users were taught in measuring methods, techniques, environmental influences and physical basics relevant to the developed guidelines.

Another important compendium for application and research is the international conference on Barkhausen noise and micromagnetic testing (ICBM). By now there are nine proceedings which offer a various amount of literature. Reviewing the articles it is obvious that the University of Newcastle is researching on Barkhausen noise analysis of the external zone of gears. Thereby plenty articles are released by Moorty and Shaw.

In [25, 26] different frequencies and their behaviour to damaged areas in the external zone on En 36 and Ovako 677 steel are analysed. High frequencies had shown a very sensitive behaviour near the surface (<10 μm). If it is necessary to examine the subsurface (<50 μm) or deeper regions of the external zone it is better to use middle or low frequency measurements.

An overall analysis of the experiments of Moorty and Shaw is described in [27]. Most Barkhausen analyses are based on the high, middle and low frequencies in agreement with [25, 26]. The results show that the magnetic Barkhausen analysis is a robust instrument to monitor heat treatment processes and different heat treatments could be distinguished clearly by the Barkhausen signal. When testing large parts it is advisable to use high frequency to increase the measurement speed. It is possible to detect the effective hardening depth up to 1 mm, where a change of >50 μm could be detected reliably. In terms of distortion caused by heat treatment it is possible that the grinding process leaves a reduced effective hardening depth or in a worse case to expose the core hardness. Because of the importance of the hardened layer affects material it is necessary to detect the effective hardened depth after grinding.

3.1. Investigation in industry

The experiment was conducted on case hardened planetary gears (BNA0-BNA7) made of 20 MnCr5 material, a module of \( m_n = 2.88 \) mm, helix angle of 20° and 28 teeth. The gears were ground with a single layer CBN grinding worm for roughing and a profile grinding wheel for finishing. In order to obtain signals up to thermal damage the material removal rate was continuously increased. After grinding the
gears were inspected using nital etching. To give a clear view in Fig. 6 the data points of the workpieces BNA 1-3 were removed. The results of these workpieces almost matched the reference piece (BNA0).

A slight burning at gear BNA7 was detected. All workpieces were inspected by Barkhausen noise analysis. The measurement was done by a 7 axis robot to guarantee repeatability. For surface scanning a spring mounted trapezoidal sensor was used, as shown in Fig. 5 bottom left. The sensor is touches the tooth flank at the middle of the profile in the contact line. The emission of the magnetic field offers a detection that is a slightly broader than the contact line. For larger areas the measurement strategy has to be adapted.

Fig. 5. Fully automated Barkhausen measurement

The results of the Barkhausen measurement are shown in Fig. 6 on the bottom left hand side. When analysing the signal several options are available. First the maximum value can be used as well as the average size. Equally the ratio of max/min can be evaluated. The result shows that the maximum value clearly increases contrary to the minimum value. When compared to the material removal rate the Barkhausen signal increases in the same way. Another indication for a change of surface properties is the spread of the max/min values. To verify and also to classify the results of Barkhausen measurement several teeth were analysed for residual stresses and surface hardness, as illustrates in Fig. 6 right. The stress state at the surface was measured by a fully automated 7 axis 4 cycle goniometer (Seifert XRD 3003 PTS). To get a residual stress profile in depth the material was removed by etching. The residual stresses were detected in the profile direction. Due to the kinematic of the grinding process the compressive residual stresses are higher than in the direction of the flank line. It can be stated that on the
surface all specimens have nearly the same compressive residual stresses. But in a depth of 0.01-0.02 mm to surface the values diverge. The nital etching has detected a slight burn on the surface of specimen BNA7, which explains the unexpected values obtained. The damage may have been caused during the roughing process and the following finishing induces new compressive residual stresses in the external zone. This is also known as sub-surface grinding burn. The compressive residual stresses of BNA 0 to BNA 5 were decreasing slowly and getting closer to the stress-free state. In contrast, the residual stresses of BNA 6 and BNA 7 changed suddenly under the surface into tensile residual stresses. To get values of hardness the full width at half maximum (FWHM) was measured by the 4 cycle goniometer at the \{211\} peak of martensite. Due to the correlation between the FWHM and the hardness it is possible to get information close to the surface. It appears to be that the surface hardness decreases from BNA 0 to BNA 7. The obtained value shows that the hardness is only low at the surface and 0.02 mm below the values approach to the core hardness. The surface softening in combination with the tensile residual stresses can lead to a reduction of the workpiece life time. The investigation shows a good correlation between the Barkhausen signals, the results of the nital etching and values measured in the laboratory.

Even the metallographic examination has shown an increasing tempered zone. In BNA 7 the tempered zone evolved at 300 µm from the surface. Unlike at nital etching the Barkhausen signal increases at changing residual stresses. Due to the sensitivity of Barkhausen method it could also be used to control the manufacturing process by interrupting the process to avoid errors.
4. Conclusion

This paper shows that the Barkhausen analysis is an effective measurement method to detect thermal damages on workpiece surface. But on the downside it is important to know the influences to interpret the values correctly. However, it must be realize that changing values are caused by a combination of all influences. When compared to nital etching the objectivity and the sensitivity of Barkhausen signals are significant advantages. Unfortunately this is offset by the cost of calibration and referencing. To establish the system in industry the first step must be to set limit values based on preliminary investigations. Different limits are needed for changing heat treatments, materials and manufacturing processes due to the sensitivity of this method. This has to be followed by a reasonable cost reduction to substitute nital etching.

References

[1] Karpuschewski B, Knoche HJ, Hipke M, Gear finishing by abrasive processes, Annals of the CIRP 57 (2), 2008, 621-640
[2] Salje E, Begriff der Schleif- und Konditiniertechnik, Vulkan-Verlag, Essen, 1991
[3] Tönshoff HK, Denkena B, Spanen – Grundlagen, 2. Aufl. SpringerVerlag, Berlin, 2004
[4] Gorgels C, Entstehung und Vermehrung von Schleifbränd beim diskontinuierlichen Zahnflankenprofilschleifen, Diss. RWTH Aachen, 2011
[5] Karpuschewski B, Residual Stress Generation in Grinding Processes, in Lu J, (Ed.) Handbook on Residual Stress, Society for Experimental Mechanics (SEM), USA,2005, 56–69
[6] Jawahir IS, Brinksmeier E, R’Saoubi M, Aspinwall DK, Outeiro, Meyer, D, et al., Surface integrity in material removal processes: recent advances, Annals of the CIRP 60 (2), 2011, 603-626
[7] Karpuschewski B, Inasaki I, Monitoring systems for grinding, in Condition and Monitoring Control for Intelligent Manufacturing, Springer Verlag, London, 2006, 83-107
[8] Denkena B, Stimpel, F, Richtlinie zum Einsatz der magnetischen Barkhausen-Rauschanalyse in der Antriebstechnik (REmBRAnt) – Möglichkeiten, Grenzen, Einsatzgebiete, Abschlussbericht FVA-Vorhaben Nr. 239/III, FVA e.V., Frankfurt, 2006
[9] Peiter A, Eigenspannungen I.Art, Michael Tritsch Verlag, Düsseldorf, 1966
[10] Heptner H, Stropp H, Magnetische und magnetinduktive Werkstoffprüfung, 3. Auflage,VEB Verlag, Leipzig,1973
[11] Kneller E, Ferromagnetismus, Springer Verlag Berlin, Göttingen, Heidelberg, 1962
[12] Willmann W, Untersuchung zur messtechnischen Ausnutzung des magnetischen Barkhaueneffektes, Freiberger Forschungshefte, Leipzig, 1969
[13] Barkhausen H, Zwei mit Hilfe neuer Verstärker entdeckte Erscheinungen, Phys. Zeitschrift, XX, 1919, 401-403
[14] Seeger A, Moderne Probleme der Metallphysik, Springer Verlag, Berlin, 1966
[15] Karpuschewski B, Mikromagnetische Randzonenanalyse geschliffener einsatzgehärteter Bauteile, Diss., University Hanover,1995
[16] Theiner WA, Altpeter I, Kern R, Determination of sub-surface microstructure states by micromagnetic NDT, 2nd International Symposium on Non-Destructive Characteristics of materials, Montreal, 1986
[17] Tittoto S, On the Influence of microstructure on magnetization transistions in steel, Acta Polytechnica Scandinavia, Applied Physics Series, 1977, No.119
[18] Donath A, Untersuchungen zum Einfluss ausgewählter Wärmebehandlungsverfahren auf den Barkhausen-Effekt und den magnetostriktiven Effekt bei Stählen, Diss., TU Dresden, 1989
[19] Karpuschewski B, Sensors for Physical Properties, in Sensors for Manufacturing, Wiley-VCH, Weinheim-New York, 2001, 123-142
[20] ISO 14104:1995, Surface Temper Etch Inspection after Grinding, International Standardization Organisation, 1995
[21] Karpuschewski B, Sensoren zur Prozessüberwachung beim Spanen, Habil., VDI Verlag, Düsseldorf, 2001
[22] Dapprich D, Schleifbrandprüfung mittels Barkhausenrauschen, Seminar Feinbearbeitung von Zahnradern, Vol. 19, RWTH Aachen, 2007
[23] Dapprich D, Anwendung des Barkhausenrauschens - Verzahnungen, Aachener Kolloquium Anwendungstechnik Verzahnung, 2005
[24] Dapprich D, Sattelberger K, Robot Controlled Grinding Process Inspection by Barkhausen Noise Analysis on Spiral Bevel Gears, ICBM-4, 2003, 199-209
[25] Moorthy V, Shaw BA, Magnetic Barkhausen Emission Measurement for Evaluation of Depth of Grinding Damage, ICBM 7, 2009, 1-12
[26] Moorthy V, Shaw BA, Bennet, W, Hopkins P, Assessment of depth of Grinding damage on gear teeth using Magnetic Barkhausen noise Measurement, ICBM 6, 2007, 1-4
[27] Moorthy V, Shaw BA, Magnetic Barkhausen Emission Measurement for Evaluation of Depth of Material properties in gears, NDT&E, 2008, 317-347
[28] Desvaux S, Duquennoy M, Gualandri J, Ourak M, The Evaluation of surface residual stress in aeronautic bearings using the Barkhausen noise effect, NDT&E, 2004, 9-17
[29] Höhn BR, Oster P, Tobie T, Schwinbacher S, Koller P, Indicating Grinding Burn on gears – Comparison and Evaluation of Different Testing Methods, ICBM 7, 2009, 1-10
[30] Klocke F, Gorgels C, Influence of the Process on Material Properties in Gear Profile Grinding and its Detection using Barkhausen Noise Analysis, ICBM 5, 2005, 123-132
[31] Kendrish SJ, Rickert TJ, Fix RM, Using Barkhausen Noise Analysis for Process and Quality Control in Production of Gears, ICBM 6, 2005, 1-7
[32] Ceurter J, Smith C, Ott R, The Barkhausen Noise Inspection Method for detecting Grinding Damage in gears, ICBM 2, 1999, 1-12
[33] Tönhoff, HK, Regent, C, Erkennung und Vermeidung von Schleifbrand beim Verzahnungsschleifen, Abschlussbericht FVA-Vorhaben Nr. 239/I, Heftnr. 469, FVA e.V., Frankfurt, 1996
[34] Tönhoff, HK, Regent, C, Mandrysch, T, Industriefähiges Überwachungssystem zur Schleifbrandanalyse, Abschlussbericht FVA-Vorhaben Nr. 239/II, Heftnr. 578, FVA e.V., Frankfurt, 1999
[35] Moorty V, Shaw BA, Magnetic Barkhausen emission measurements for evaluation of material properties in gears, NDT&E, 2008, 317-347
[36] Blaow M, Evans JT, Shaw BA, The effect of microstructure and applied stress on magnetic Barkhausen emission in induction hardened steel, Journal of material Science, 2007, 4364-4371
[37] Blaow M, Evans JT, Shaw BA, Effect of hardness and composition gradients on Barkhausen emission in case hardened steel, Journal of magnetism and magnetic materials, 2006, 153-159