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In-process measurement of Barkhausen noise and resulting productivity increase potential in grinding of case hardened steel

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ABSTRACT

The micromagnetic Barkhausen Noise (BN) measurements bear the capability of providing non-destructively information about the condition of the surface integrity of ground workpieces. No unambiguous statements about the surface and subsurface area state can be made by evaluating single measured micromagnetic values if a superposition of different effects in the microstructure as a consequence of high thermomechanical loads occur. Especially for highly stressed components in automotive industry or in wind energy systems, case hardenend steels are deployed. These steels are often finished at the end of their process chain by a grinding process. At this point, the workpieces to be ground have already achieved enormous created added value. For productivity reasons, grinding should be carried out close to the process limit. To avoid undesirable phase transformations in the microstructure, process models such as the process model from Malkin can be used. If a grinding process consists of several process steps it must be ensured that the final process step leads to the intended surface and subsurface properties. In order to make the process design as productive as possible, an in-process measurement signal which correlates to the current state of the surface and subsurface area can help to achieve this result. Ideally this signal is applicable to generate an adaptive grinding process.

Such a signal is investigated in this paper by application of BN as an in-process measurement technology. The paper shows the reliability of BN measurements as well as that there are different maximum BN amplitudes for different material removal rates. It is expected that these BN values correlate particularly to the residual stresses in the surface and subsurface area since Malkin's grinding burning limit was used to exclude (strong) phase transformations. Considering a micromagnetic parameter measured in-process a reduction of process time of 37% and thus a significant process improvement was achieved.

Introduction and state of the art

Especially for highly stressed components in automotive industry or in wind energy systems, case hardenend steels are deployed. Steel workpieces are often finished at the end of their process chain by a grinding process [1]. At this point, the workpieces to be ground have already experienced enormous created added value. For productivity reasons, grinding should be carried out on the verge of the process limit [2–5]. Besides geometric parameters like shape accuracy and microtopography the grinding process determines surface and subsurface properties due to its thermomechanical load impact on the workpiece surface. Consequently the functional properties, like the residual stresses or the hardness of the workpiece are essentially influenced by the final grinding process step [6,7]. Today often destructive testing methods, e.g. X-ray depth profile measurements are used for selected testing to prove if the workpiece fulfills the requirements. In order to achieve a 100% non-destructive testing procedure, micromagnetic testing methods are subject of research.

BN measurements

The micromagnetic BN measurements bear the capability of providing non-destructively obtained information about the condition of the surface integrity of ground workpieces [2,4,5]. This method works with an alternating magnetic field $H(t)$, which is generated in the material due to an excitation coil. A receiving coil or Hall sensor detects the resulting magnetic flux density $B(t)$. Discontinuous, stepwise displacements of the Bloch walls, when

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Nomenclature

a_e	depth of cut (μm)
a_{ed}	depth of dressing (μm)
B	inclination factor of Malkin (J/(mm^2 s$^{0.5}$))
$B(t)$	magnetic flux density (T)
d_{eq}	equivalent wheel diameter (mm)
e_c	specific grinding energy (J/mm^3)
$e_c{}^*$	critical specific grinding energy (J/mm^3)
e_w	basis value of the specific grinding energy (J/mm^3)
F_n	normal force (N)
F_t	tangential force (N)
f_a	analyzing frequency (kHz)
f_r	nominal radial feed per revolution (μm)
H(t)	magnetic field strength (A/m)
M_{max}	maximum BN amplitude (V)
$M_{max,av}$	maximum BN amplitude (average) (V)
mp-value/RMS-value	magnetoelastic parameter (mV)
P_S	grinding power (kW)
Q_{MWF}	metal working fluid flow rate (l/min)
Q_w	material removal rate (mm^3/s)
Q'_w	specific material removal rate (mm^3/(mm s))
q	speed ratio (grinding) (–)
q_d	speed ratio (dressing) (–)
t	time (s)
U_d	dressing overlap ratio (–)
V_{BN}	BN ratio (–)
V''_w	specific material removal volume (mm^3/mm)
v_c	cutting speed (m/s)
v_{fr}	radial feed speed (mm/min)
v_w	workpiece velocity (m/s)
δ	analyzing depth (μm)
μ_0	magnetic field constant (N/A^2)
μ_r	relative permeability (H/m)
σ	residual stresses (MPa)
σ	standard deviation (–)
σ	conductivity (1/(Ω m))

the respective remagnetization field strength is exceeded, affect the remagnetization of individual so called Weiss micromagnetic domains [8]. By the stochastical distribution of the orientation and the remagnetization energy of these domains a superimposition of the continuous field strength progression in the material by a noisy signal occurs, the so-called BN signal resulting from the displacement of the Bloch wall displacement [8]. The BN is attenuated exponentially as a function of the depth reached in the material. This attenuation is mainly caused by the eddy current attenuation of electromagnetic fields [9–11] that are generated around the moving Bloch walls. The depth δ of the BN measurement can be estimated as follows (Eq. (1)) [10]:

$$\delta = \frac{1}{\sqrt{\pi \cdot \mu_0 \cdot \mu_r \cdot \sigma \cdot f_a}} \tag{1}$$

Essentially, the depth δ therefore depends on the analyzing frequency f_a, the electrical conductivity σ (material parameter), and the permeabilities μ_r (material parameter) and μ_0 (in vacuum).

In the past, micromagnetic parameters were used to find correlations with the residual stress state, hardness, dislocation density, and chemical homogeneity of the microstructure [2,5,12,13].

BN in grinding

In grinding burn detection especially the level of the BN signal was investigated in order to predict reduced hardness or tensile stresses due to thermal damage by an increasing BN value [4,14–17]. Further research is described in [7], where two micromagnetic methods were used to perform a grinding burn test and quantitative hardness and residual stress measurements after grinding. The investigations show that a correct interpretation of the BN signal as well as other micromagnetic parameters requires calibration on the basis of good and bad parts, even for a qualitative evaluation. The surface and subsurface condition of these parts must be exactly defined with alternative test methods and assigned to the respective BN level [18]. The reason for this is the fact that the surface and subsurface state is defined by different surface and subsurface properties (e.g. residual stress state, hardness, microstructure), so that changes in several properties simultaneously cause overlapping micromagnetic effects. Thus, the measurement result of the BN amplitude cannot be clearly assigned to the change of a certain surface and subsurface property.

In order to obtain meaningful results based on the non-destructive measurement of micromagnetic parameters two approaches were investigated:

1. Micromagnetic multiparameter approaches
2. Combination of one single micromagnetic parameter with parameters from the grinding process itself

For both BN systems that are currently used in industry and academia, the BN device technology 3MA, test equipment from the Fraunhofer Institute for Nondestructive Testing (IZFP), Saarbrücken, Germany, and the Rollscan device technology of the company Stresstech, it has been shown in the past that a reliable non-destructive grinding burn detection is possible by the combination of different micromagnetic parameters. Post-process (outside the grinding machine), stationary (no relative movement between sensor and workpiece) noise measurements were performed [4,10,19–21]. In addition to the investigation of multiparameter approaches, Karpuschewski et al. [22,23] also tried to detect BN in-process that means during the grinding process. They implemented a BN sensor in a grinding machine. Due to the lack of protective layers, the sensor showed serious signs of wear and impairment in the ground workpiece surface after the in-process measurement trials. As a result of the development of sensor technology and the application of a wear protection layer on the BN sensors on the one hand and the idea for a contactless BN measurement set-up on the other, this approach is now being revisited. In order to enable in-process monitoring the significance of soft-sensors in machining processes is rising [24]. A soft-sensor means a combination of one or more physical measurement techniques with a process model to describe for example subsurface characteristics in machining. An exemplary soft sensor development for in-process evaluation of sub surface modifications during cryogenic turning of metastable austenitic steels is presented in [25]. Especially in grinding the non-destructive BN testing method has a high potential to be part of such a soft-sensor, describing surface integrity and in particular the residual stress state.

By BN measurements in combination with the analytical approach of Malkin [26,27] for the thermal influence on surface and subsurface area, which is based on the process parameters of the grinding process, a distinction between good and rejected ground parts can be achieved. In [28] the potential of the combination of one single, post-process measured, micromagnetic parameter with parameters from the grinding process itself (Malkin's process model) could be shown. The findings indicate the dependency of the BN on the residual stress state in the material if a phase transformation can be avoided. The BN level is rising with an increase of the residual stresses in tensile direction. The avoidance of phase transformations can be achieved by using Malkin's grinding burn limit (equation (2)), which is explained in detail in [26–28].

$$e_c^* = e_w + B \cdot d_{eq}^{0.25} \cdot a_e^{-0.75} \cdot v_w^{-0.5} \tag{2}$$

Here it just should be mentioned that the critical specific grinding energy e_c* is the ratio of the grinding power P_s and the material removal rate Q_w and depends on the grinding parameters equivalent grinding wheel diameter d_{eq}, the depth of cut a_e and the workpiece velocity v_w. e_w can be approximated for steel at least as 6.2 J/mm^3 [26] and describes the proportion of specific energy, which is not dissipated in the workpiece. Grinding burn occurs if the specific grinding energy e_c is larger than, or equal to, e_c*.

According to Malkin's burning limit workpieces are regarded as rejects if a typical coloration is visible after nital etching, which indicates annealing effects or rehardening layers at the workpiece surface. It should be mentioned that not only a beginning phase transformation, but also the occurrence of even small tensile residual stresses in the surface and subsurface area can lead to rejects. These workpieces might also not fulfill the required functional properties as a consequence of the negatively influenced residual stress state caused by an excessive thermomechanical stress during the grinding process.

Research approach and motivation

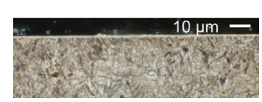
Both, in single-part production, where experience values are lacking and/or very expensive and complex workpieces are machined, and in series production, where every second counts, the BN as an in-process measuring technology enables new possibilities. In this paper the application of BN in-process measurements is targeted to investigate the potential of this technology for an in-process monitoring in combination with the analytical approach of Malkin. An in-process measurement signal, which correlates to the current state of the surface and subsurface area could be used for an adaptive grinding process layout with increased productivity. In order to achieve this an experimental set-up for in-process usage of BN measurements is presented for cylindrical outer diameter grinding tests. Multi-step grinding processes with different thermomechanical influences on the surface and subsurface area are performed. A productivity increase in multi-step grinding based on in-process BN measurements considering that no grinding burn occurs is focus of the experimental investigations.

Preliminary considerations

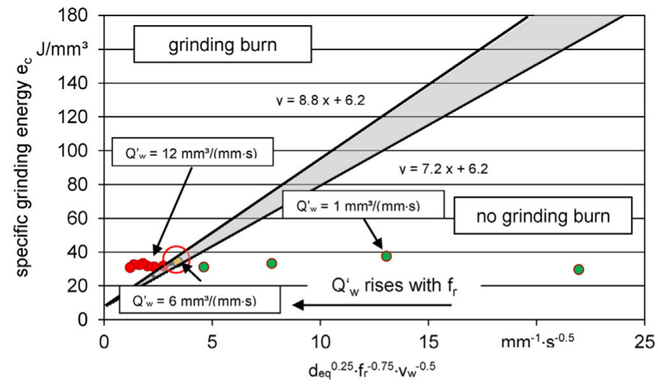
For the layout of the multi-step external cylindrical grinding tests, preliminary considerations were made on the basis of empirical values from single-step external cylindrical grinding tests already carried out with similar system and process parameters. The residual stress depth curves and metallographic inspection of ground AISI4820 workpieces from previous work were used to estimate the depth of influence of the respective process (Table 1 according to [20]). This depth was determined by comparing the measured residual stress depth curves with the residual stress state after heat treatment without processing. In addition, the increase in Barkhausen noise (mp-value, also called RMS-value) compared to a reference with minor thermomechanical influence according to [20] was noted. This value is called ratio V_{BN}. The measured RMS values are based on magnetization parameters of 300 Hz and 9 V.

In addition, Fig. 1 shows the corresponding experimental points from [20] in Malkin's grinding burn diagram according to [28]. Thus, the grey area is a transition area between the occurrence of no grinding burn and grinding burn according to Malkin's publications. Malkin's analytical approach is used in this work to exclude intense phase transformations. In [28], stronger phase transformations were accompanied by a decrease of the BN level, although higher residual tensile stresses were present. These ambiguities shall be avoided in this work when testing the BN technology in-process. Since only slight tempering zones at a specific material removal rate of 12 mm^3/(mm s) was determined, a maximum specific material removal rate of Q'_w < 12 mm^3/(mm s)

Table 1
Results of destructive testing methods for the evaluation of the surface and subsurface area compared to the BN ratio V_{BN} according to [20].

Specific material removal rate Q'_w	Depth of influenced residual stresses	Max. residual stresses σ	Min. residual stresses σ	Metallographic inspection	Ratio $V_{BN,mp}$
0 mm^3/(mm s)[a]	>200 μm	−120 MPa	−250 MPa	–	–
0.5 mm^3/(mm s)	<10 μm	−180 MPa	−250 MPa	–	1
4 mm^3/(mm s)	<60 μm	−50 Mpa	−180 MPa	–	1.25
6 mm^3/(mm s)	<70 μm	150 MPa	−190 MPa		1.6
12 mm^3/(mm s)	<110 μm	260 MPa	−170 MPa		2.1

[a] Material state after case hardening.



Workpiece	Machine, process and wheel	Process parameters	Dressing parameters	Cooling
18 CrNiMo7-6 (AISI 4820), case-hardened	Studer S41 external cylindrical grinding Tyrolit A80CC5V	v_c = 35 m/s q = 90 v_{fr} var. Q'_w var.	a_{ed} = 2 x 20 µm U_d = 4 q_d = 0.8	Q_{MWF} = 40 l/min

Fig. 1. Experimental points of outer diameter grinding test in Malkin's diagram [28].

was chosen for the main tests in this work. According to Malkin's approach, the test point with a Q'_w of 12 mm^3/(mm s) lies already slightly above the grinding burn limit according to Malkin, which seems plausible as slight tempering zones occurred. Based on these preliminary considerations, this paper deals with the potential of BN as an in-process measuring technology in order to increase the productivity of a multi-step grinding process.

Experimental set up

For this work cylindrical case-hardened 18CrNiMo7-6 workpieces (152 mm × Ø67.7 mm) are machined by a cylindrical outer diameter grinding process with variation of relevant process parameters. The process specific influenced material states are evaluated by the micromagnetic BN method.

The grinding tests were carried out on a Studer S41 cylindrical grinding machine tool. The workpieces were clamped between centers. Oil (Rhenus EG 10) as metal working fluid was supplied with conventional nozzle. The grinding experiments were carried out by use of a vitrified corundum grinding wheel 54A120 H15VPMF904 W (500 mm × 36 mm × 203.2 mm) in uphill grinding with a constant metal working fluid flow rate of Q_{MWF} of 40 l/min. The grinding wheel was dressed with a CVD form roller (form roller diameter: 120 mm, dressing radius: 0.5 mm) with a speed ratio q_d of −1 and a dressing overlap ratio U_d of 3. During the grinding process, process forces (tangential force F_t, normal force F_n) were recorded by a piezoelectric measuring system integrated in the workpiece spindle and tailstock. In addition, the effective power of the grinding spindle was documented. The maximum stock that was removed of the grinding process was 300 µm, which corresponds to a specific material removal volume V'_w of approx. 63.5 mm^3/mm. Due to variation of the radial feed speed v_{fr} the nominal radial feeds per revolution f_r vary and correspondingly the specific material removal rate Q'_w amounts to 1, 6 and 10 mm^3/(mm s) (Table 2). Due to the width of the grinding wheel of 36 mm three undependent trials from each other could be done on one workpiece by the cylindrical outer diameter grinding process.

The cutting speed v_c and the workpiece speed v_w were kept constant with v_c = 35 m/s and a resulting speed ratio q = 90. These machining parameters were selected on the basis of empirical values from conventional external cylindrical grinding.

A 3MA II device of Fraunhofer IZfP, Saarbrücken (Germany,) and a Rollscan 350 of Stresstech were used for the micromagnetic workpiece analysis. Both technologies are based on the same principle and enable to detect the Barkhausen noise. For the realization of in-process BN measurements a specially sealed sensor 3MA-WP/HF, which was connected with the 3MA II device, was implemented in the grinding machine. The function of the holder of the BN sensor is explained in the following schematic sketch, Fig. 2. With a micrometer screw a 3D-printed spacer out of plastic can be positioned in such a way that a defined distance between sensor and workpiece can be set to reduce or prevent signs of wear at the sensor and impairment in the ground workpiece surface. The spring force and thus the contact pressure between spacer and workpiece can be set using a linear slide. The current contact pressure can be read out via a strain gauge based force probe. A contact pressure of 10 N was set in the trials. Due to the fact that the hardness of the material of 61 HRC exceeds the

Table 2
Experimental plan.

Material condition	v_{fr} (mm/min)	f_r (µm)	Q'_w [mm^3/(mm·s)]
18 CrNiMo7-6 (AISI 4820) case-hardened, 61 HRC annealing temperature: 150 °C surface carbon content: 0.8% case hardening depth: 2.0 mm	0.28 1.69 2.82	2.54 15.36 25.63	1 6 10

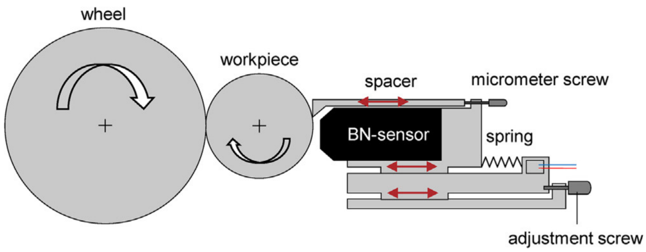


Fig. 2. Schematic sketch of the holder of the 3MA BN sensor for in-process and in situ BN measurements in the grinding machine.

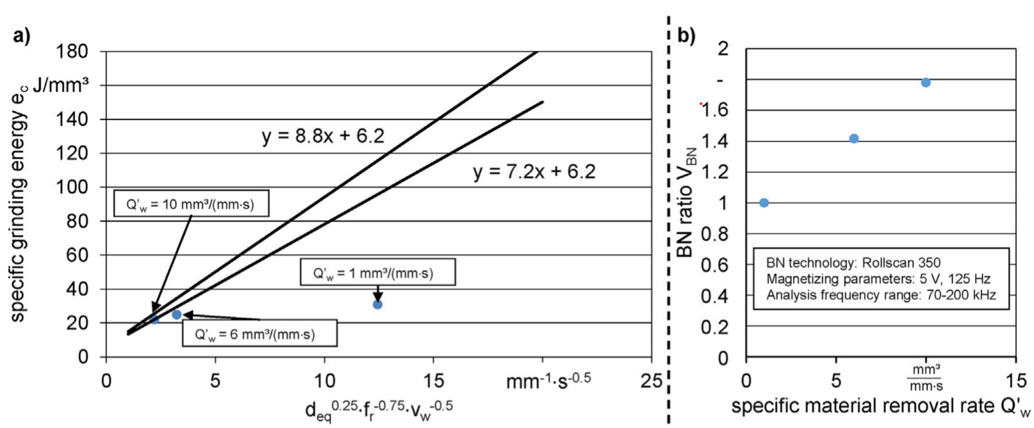
hardness of the plastic spacer, no damage was expected and found by visible inspection and measurements of the surface roughness on the workpiece surface after tests.

For a first check of the in-process and fast post-process (post-process measurements, but inside the grinding machine) BN measurements based on 3MA technology a comparison with post-process measured results from the BN Rollscan technology was made. In previous work [20,28] extensive studies with this BN technology of Stresstech were made and a measurement set-up for a reliable BN detection was found. In order to avoid handling influences a manual usage of the sensor was avoided. Therefore, a Klingelnberg P40 gear metrology center was used, which has an inbuilt interface between the Rollscan 350 device and a specially designed BN sensor S1-14-12-29 [28].

Results and discussion

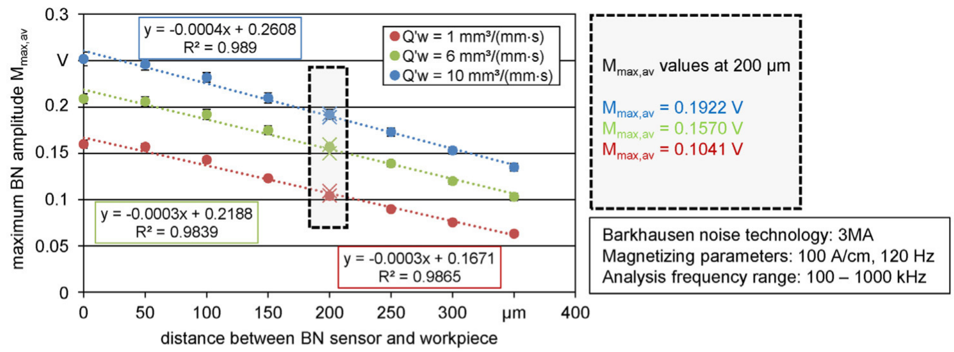
Fig. 3 shows the specific grinding energy e_c of single step external cylindrical grinding tests plotted versus the product $d_{eq}{}^{0.25}\, a_e{}^{-0.75}\, v_w{}^{-0.5}$ according to Malkin. The product was varied by the adjustment of different radial feed speeds v_{fr} and the resulting different nominal radial feeds per revolution f_r, which correspond here to the depth of cut a_e. It can be seen that the two chosen specific material removal rates 1 mm³/(mm s) and 6 mm³/(mm s) lead to experimental points, which are located below the grinding burn limit determined by Malkin [26,27]. The specific material removal rate of 10 mm³/(mm s) is in the area of the grinding burn limit (between the two black lines). After the preliminary considerations and the experience of previous work the aim of no (strong) phase transformation seems to be achieved. Nevertheless tensile residual stresses up to depths <100 μm with the consequence of undesirable material states are expectable. Measurement results of post process measurements of BN with the Rollscan device technology indicate the displacement of the residual stress state in the tensile area. A ratio V_{BN} up to 1.8 could be measured (c. f. Table 1). Thus, an in-process measurement of the BN during grinding without phase transformations excluded by application of Malkin's process model should show mainly the change of the residual stress state.

Subsequently this different thermomechanical influenced material states after grinding with different material removal rates were measured by BN in-situ (stationary) under variation of the distance between probe and workpiece. The contact pressure between spacer and workpiece was kept constant at 10 N. Fig. 4 shows the average values of 30 magnetization cycles per distance and their standard deviation in error bars, which is usually under 3% of the measured value. The magnetizing parameters of the 3MA device were chosen iteratively whereby attention was paid to a similar magnetizing frequency which was applied during post-process measurements with the BN Rollscan technology. Also the lower limit of the analysis frequency range was chosen in a similar order of magnitude for reaching similar analyzing depths (equation (1)). It can be seen that there is a decrease of maximum BN amplitude, M_{max}-signal, with increasing distance. Nevertheless it is possible to distinguish the different thermomechanical influenced material up to a distance of more than 300 μm. To prevent signs of wear at the BN sensor and on the workpiece surface a distance of 200 μm was chosen in the following for the in-process-measurement set up. To check the reliability of the



Workpiece	Machine, process and wheel	Process parameters	Dressing parameters	Cooling
18 CrNiMo7-6 (AISI 4820), case-hardened	Studer S41 external cylindrical grinding 3M 54A120	v_c = 35 m/s q = 90 v_{fr} var. Q'_w var.	a_{ed} = 2 x 20 μm U_d = 3 q_d = -1	Q_{MWF} = 40 l/min

Fig. 3. (a) Comparison of experimental results with the limits for the thermal influence on the surface and subsurface area according to Malkin. (b) Results of post-process BN measurements obtained with Rollscan technology.



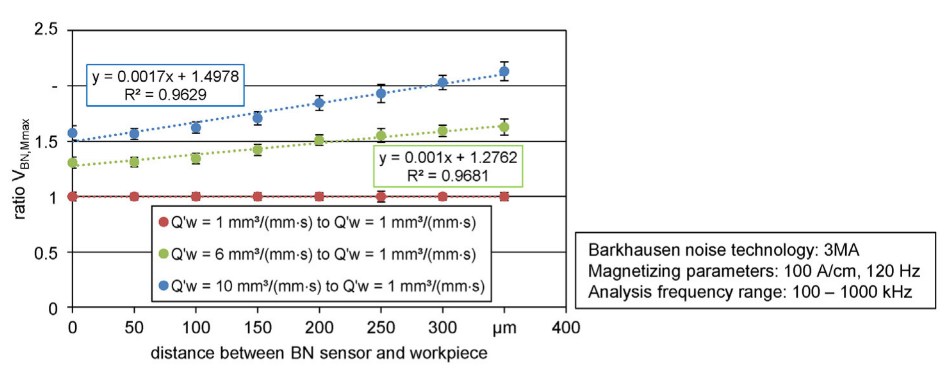
Workpiece	Machine, process and wheel	Process parameters	Dressing parameters	Cooling
18 CrNiMo7-6 (AISI 4820), case-hardened	Studer S41 external cylindrical grinding 3M 54A120	v_c = 35 m/s q = 90 v_{fr} var. Q'_w var.	a_{ed} = 2 x 20 µm U_d = 3 q_d = -1	Q_{MWF} = 40 l/min

Fig. 4. Dependency of in situ measured maximum BN amplitude, $M_{max,av}$ values, by varying the distance between BN sensor and workpiece for different Q'_w.

measurement setup, the in situ measurements at a distance of 200 µm were repeated three times. Thereby the distance was reset again for each repetition. These experimental points are also plotted in Fig. 4 (colored crosses). Due to the occurrence of minor deviations the measurement conditions seem to be reliable.

The quantitatively very similar decrease of the measurement signal $M_{max,av}$ at different specific material removal rates with higher distances leads to varying relations between the different processed material states. Fig. 5 reveals the rising relations from $Q'_w = 6\ mm^3/(mm\ s)$ to $Q'_w = 1\ mm^3/(mm\ s)$ and $Q'_w = 10\ mm^3/(mm\ s)$ to $Q'_w = 1\ mm^3/(mm\ s)$. Thus the ratio V_{BN} and thus the sensitivity is dependent on the distance between sensor and workpiece. Due to the reason that the material and batch specific measured micromagnetic values and ratios indicate that the processed surface and subsurface area states could be distinguished, the magnetizing parameters and analyzing frequency range were kept constant for the following trials.

These investigations built the basis of the in-process-measurement trials. Main advantage of the in-process measurement is the possibility to get hints by the stress dependency of the BN about the current effective stresses in the workpiece surface and subsurface area. In particular in multiple step grinding processes with continuous contact between grinding wheel and workpiece this might prevent negative influences on the finally finished surface. At first, grinding tests were performed with a Q'_w of $1\ mm^3/(mm\ s)$ and BN was measured in-process. Fig. 6 shows the M_{max} values of in-process measurements of a three times repeated process with a total removed stock of 100 µm. It is visible that the



Workpiece	Machine, process and wheel	Process parameters	Dressing parameters	Cooling
18 CrNiMo7-6 (AISI 4820), case-hardened	Studer S41 external cylindrical grinding 3M 54A120	v_c = 35 m/s q = 90 v_{fr} var. Q'_w var.	a_{ed} = 2 x 20 µm U_d = 3 q_d = -1	Q_{MWF} = 40 l/min

Fig. 5. Ratio dependency on distance of the sensor from the workpiece surface.

measurements are repeatable and in the same size of magnitude like the results of the post-process measurements (Fig. 4).

In order to obtain results, which verify the potential of this measured signal for an in-process monitoring and on long term for an in-process control further experiments were done. The ability of the BN measurement technology to detect differences in the thermomechanical influence within one process was investigated. Therefore, a three step grinding process with continuous contact between grinding wheel and workpiece and varying radial feed speeds and thus varying specific material removal rates was designed. This was achieved by the definition of positions in radial direction, where the radial feed speed v_{fr} and thus the specific material removal rate Q'_w are switched (reduced). These positions were chosen at first in 100 μm removed stock steps, which should be high enough to remove the negatively influenced material layer of the former process step (Table 1): In previous work a maximum depth of influenced residual stress state of <110 μm was found for a specific material removal rate Q'_w of 12 mm^3/mm s. After the three step grinding process a total removed stock of 300 μm is reached. Fig. 7 shows the in-process measurement signals of M_{max} of a three step grinding process. At first a material removal rate Q'_w of 10 mm^3/(mm s) leads to a strong increase of the M_{max} value. At the first switching positon the M_{max} value amounts to 0.175 V as a consequence of Q'_w = 10 mm^3/(mm s) and subsequently decreases when a specific material removal rate Q'_w of 6 mm^3/(mm s) and thus a lower thermomechanical influence is applied on the workpiece. At the second switching position a value of about 0.154 V is measured which is in line with the results of the post-process measurements in Fig. 4. Finally a specific material removal rate Q'_w of 1 mm^3/(mm s) leads to a further decrease down to a M_{max} level, which was measured in post-process measurements at material states, which were processed by the same Q'_w = 1 mm^3/(mm s).

Afterwards, this knowledge shall be used in a next step to achieve a much more productive process with a final stock to be removed of 300 μm with the investigated specific material removal rates of 1, 6 and 10 mm^3/(mm s), which meets the condition of a final surface and subsurface area state which corresponds to the one before grinding. Thus, in a multi-step process with continuous contact between workpiece and grinding wheel the first step of grinding process has been carried out in such a way that the part is strongly thermally affected. By means of the continuous in-process BN measurement the following grinding steps can be set in a way that the negatively influenced surface and subsurface layers of previous process steps are removed in order to finally generate a good part. To estimate the depth of the influenced residual stress state in comparison with the heat treated but not machined state of the workpiece the results of previous work in Table 1 were used. Therefore, the depth of influenced material with major tensile residual stresses and without phase transformation due to a grinding process of 10 mm^3/(mm s) was estimated to approx. 100 μm. Lower tensile residual stresses could be estimated for the area of influenced material up to a depth of approx. 70 μm as a consequence of a process step of 6 mm^3/(mm s). For a specific material removal rate of 1 mm^3/(mm s) the depth of influenced material was assumed to 20 μm with compressive residual stresses and just slight differences to the heat treated and not machined state. With these estimations a new multi-step process was performed in a much more optimized manner with regard to reduced process time keeping the surface layer impact on a desired level. Fig. 8 shows the measured tangential force of this process. The first switching position of the radial feed speed v_{fr} was set in a way that material is removed with a specific material removal rate of 10 mm^3/(mm s) and a radial feed speed of 2.82 mm/min up to a depth of 160 μm. Caused by the fact that the depth of influenced material in the surface and subsurface area was estimated to approx. 100 μm the following process steps should remove the negatively influenced material if a final stock to be removed of 300 μm is targeted. After the first switching position was reached the radial feed speed decreased to 1.69 mm/min, which leads to a specific material removal rate of 6 mm^3/(mm s). This second step was performed up to a second switching position in a depth of 250 μm. At this depth the main part of the influenced material by the first step is removed, so it is assumed that the current material state in the surface and subsurface area corresponds with the one, which is described in Table 1. The influenced residual stress state up to a depth <70 μm as a consequence of the second process step (Q'_w = 6 mm^3/(mm s)) should be removed finally by a finishing process. Thus, the third process step was designed with a specific material removal rate Q'_w = 1 mm^3/(mm s) up to a total removed stock of 300 μm. In Fig. 8 also the results of the BN in-process measurements are plotted. These results confirm the procedure for the process design. At first the BN signal of the rotating, case hardened, unprocessed workpiece is measured for a short time up to the moment where the first contact between grinding wheel and workpiece is achieved. Consequently a shift of residual stresses in tensile direction has occurred by the process (Q'_w = 10 mm^3/(mm s)) and leads to a strong increase of the M_{max} values. These results fit to the measured signal level from the investigations with

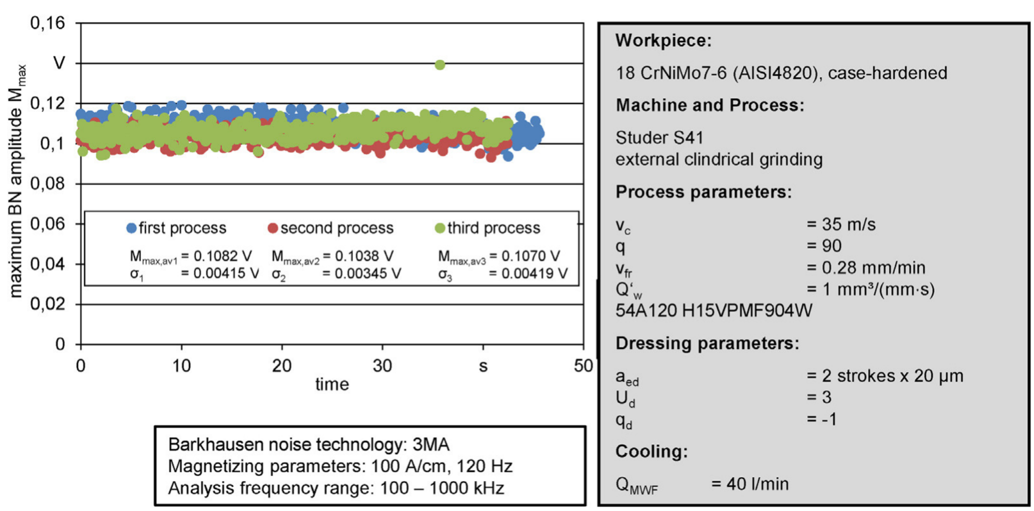


Fig. 6. In-process BN measurements during three grinding processes with constant removal rate Q'_w = 1mm^3/(mm s).

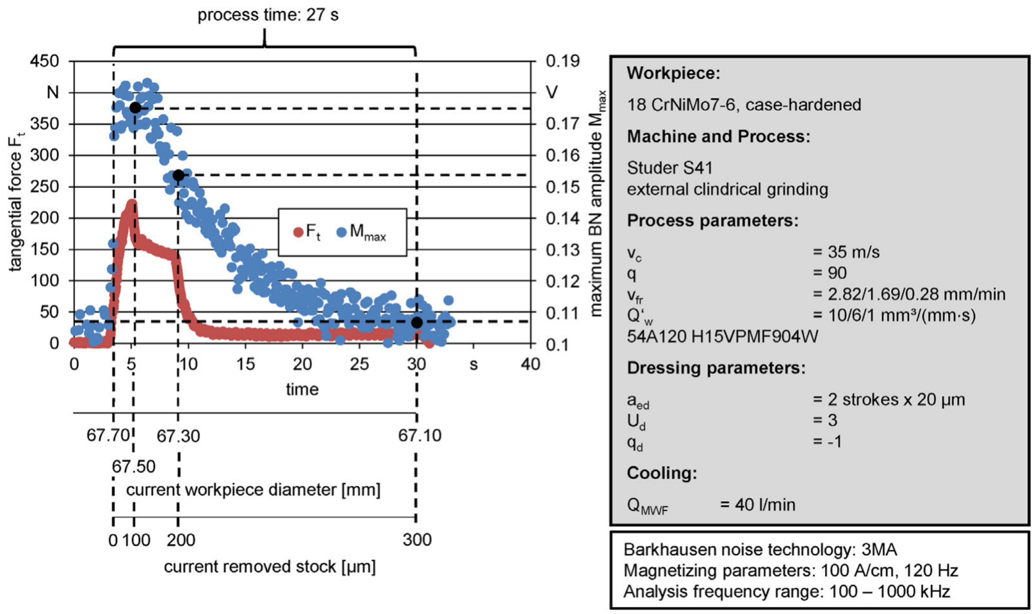


Fig. 7. In-process BN measurements during a three step grinding process with $Q'_w = 10/6/1\ mm^3/(mm\,s)$.

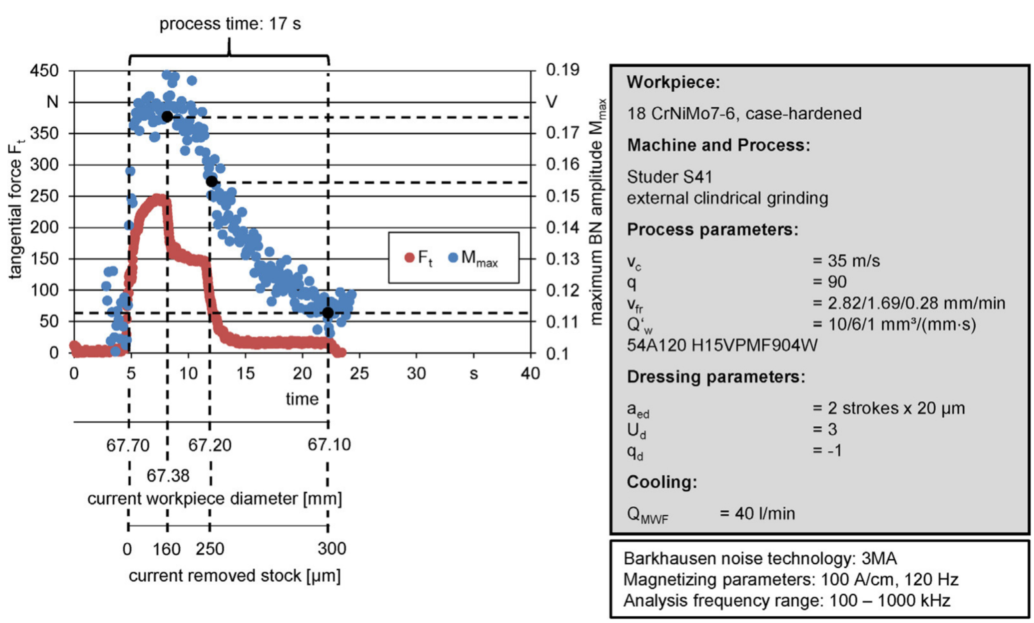


Fig. 8. In-process BN measurements during a three step grinding process with $Q'_w = 10/6/1\ mm^3/(mm\,s)$ and an optimized process design.

the same process conditions, which are presented in Fig. 4 (post-process measurements) and Fig. 7 (just minor deviations). After reaching the first switching position and the reduction of radial feed speed the M_{max} values decrease to similar values corresponding to this specific material removal rate ($Q'_w = 6\ mm^3/(mm\,s)$). This decrease occurs over the whole distance between the first and second switching position caused by superposition of the influenced material of process step one and the current second process step. After the second process step, the third one, the finishing process ($Q'_w = 1\ mm^3/(mm\,s)$), leads at the end of the process to M_{max} values similar to the level measured in a single step process with a specific material removal rate of $Q'_w = 1\ mm^3/(mm\,s)$. By achieving this the process design with these certain process steps is much closer to the verge of maximum productivity. This improvement was achieved by optimizing the set up for the switching positions. The in-process measured BN level indicates no critical residual stress state at the end of the three step grinding process despite a reduction of 37% in time.

Conclusion

Summary and outlook

Barkhausen noise measurements bear the capability of providing non-destructively information about the condition of the surface integrity of a ground workpiece. Ambiguities of single measured micromagnetic values can be present if a superposition of different effects in the microstructure as a consequence of thermomechanical loads occur. For example changes of the residual stress state in combination with phase transformations often followed by changes in hardness, lead to the fact that a separation of the influence of these effects on the measured BN parameter is not possible. To exclude an intense phase transformation the analytical approach of Malkin was used for the estimation of the grinding burn limit. Thus, Malkin's model was used for the process design of the investigated grinding processes. This paper reveals new possibilities for the usage of BN as a non-destructive in-process measurement technology to evaluate the surface and subsurface area during machining. The results show, that it is possible to distinguish different surface and subsurface area states without a direct contact between BN sensor and workpiece, which is ground. With an air gap of 200 μm repeatable measurements were performed. Besides, the potential of BN as an in-process-technology was shown due to the reduction of the process time of 37% in a three step process with continuous contact between grinding wheel and workpiece. Thus, an increase of the productivity of the outer diameter grinding process was achieved. Consequently a high potential of this contactless nondestructive in-process technology is given to enable an adaptive, BN-signal dependent, grinding process.

In the future, the potential of a sensor system for in-process measurements of the BN will be evaluated also for trials in which stronger phase transformations are allowed in the first process steps in order to achieve a highly efficient process. It should be targeted to reach BN-measurement results which correspond to those which were measured at softly processed material, although a phase transformation occurred at the beginning. Besides further process parameters like the cutting speed should be varied to prove the influence on the measured BN and in what kind it corresponds to the residual stress state. Furthermore, the maximum of analyzed depth of the surface and subsurface area due to the BN measurements should be investigated. In order to achieve this, the gradients of the residual stresses and hardness from the surface to the case hardening depth of workpieces should be investigated. A comparison between these properties and in-process BN measurements is expected to clarify the value of this depth. Especially with this knowledge the application of this measurement technology as part of a soft-sensor, describing surface integrity, in particular the residual stress state, in combination with a process model and measured process variables, to enable in-process monitoring and in-process control is promising.

Declaration of interests

None.

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