Miroslav Neslušan
Jozef Majerík
Pavel Kejzlar
Mária Čilliková
Anna Mičietová

ISSN 1333-1124
eISSN 1849-1391

BARKHAUSEN NOISE EMISSION IN HARD MILLED SURFACES OF STEEL C55

Abstract

This paper deals with the application of the Barkhausen noise technique in the nondestructive monitoring of hard milled surfaces. The paper discusses strong magnetic anisotropy linked with microstructural transformations of a machined surface with regard to variable flank wear of cutting inserts. Effective values of Barkhausen noise, peak positions derived from the raw Barkhausen noise signals, the shape of hysteresis loops as well as the Barkhausen noise envelopes are compared with metallographic observations and theoretical background regarding the magnetic domains configuration in the near surface region. A possible concept by which hard milled surfaces could be monitored in real industrial conditions in a non-destructive manner is driven by the specific surface state of the microstructure as well as by the magnetic point of view.

Key words: *Barkhausen noise, hard milling, surface integrity*

1. Introduction

Cyclic magnetization in a ferromagnetic material produces magnetic pulsation as a result of the irreversible and discontinuous Bloch Walls (BW) motion. Discontinuous BW motion is a result of the interference of the BW with the microstructure features such as precipitates (Kameda and Ranjan 1987) [10], dislocation cells (Buttle *et al.* 1991) [3], grain boundaries (Ranjan *et al.* 1987) [15] and other lattice defects (Gaterier-Rothea *et al.* 1998) [8]. This phenomenon is named Barkhausen noise (Barkhausen 1919) [1]. The Barkhausen noise (BN) technique bears great industrial relevance mainly for monitoring surfaces loaded near their physical limits. The BN features usually correlate with residual stresses, microhardness or structural transformations. This technique is mostly adopted for the monitoring of surfaces after grinding due to a strong correlation among overtempering, associated surface burn and the corresponding BN features (Rosipal 2014) [16]. The effect of thermal softening after grinding due to overtempering decreases dislocation density (and the corresponding surface hardness), transforms the carbides shape and their morphology and produces tensile stresses (Mičúch *et al.* 2014) [12]. The above mentioned aspects contribute to the greater magnitude of BN; thus surface overtempering can be easily revealed by the use of the BN technique. Nowadays, hard machining (mainly turning and milling) can substitute grinding cycles. The development of machine tools (especially CBN and ceramics) and of the process technology increased the industrial relevance of hard machining (Tonshoff *et. al.* 2000) [17]. Numerous experimental investigations have been carried out over the years to study the effect of cutting parameters (Cardoso *et al.* 2012) [4] and tool geometries (Cus *et al.* 2011;) [6] on the surface integrity (Krolczyk *et al.* 2014) [11] using several types of cutting and workpiece materials. However, hard turning cycles can suffer from formation of white layers (WLs) induced at the low flank wear *VB* or unexpected catastrophic tool failures. A suitable and reliable concept for nondestructive monitoring of hard turned or milled surfaces based on the BN technique has not been established yet due to complicated relations between BN and the obtained surface (its stress state and microstructural features). The state of the machined surface after hard machining is mainly a function of *VB* and the cutting speed. Inserts of high *VB* produce a relative thick white layer (WL) as well as a corresponding heat affected zone (HAZ) (Brandt 1995) [2]. On the other hand, grinding cycles can suffer from overtempering. Ground surface can sometimes exhibit thermally softened zones (HAZs) whereas the WL represents heavily damaged surface (overheated) due to the violation of the grinding discipline. However, the thickness of the HAZ and the WL after hard milling is about 1 order lower than that induced by grinding. Compared to bulk, the HAZ produces higher BN emission (due to tensile stresses, reduced dislocation density and modification of carbides – their size and morphology) whereas the WL induced by the grinding cycle in the near-surface region emits low BN due to the existence of a higher volume of retained austenite, compressive stresses and very fine grain (Guo and Sahni 2004) [9]. Contradictory effects (layers) contributing to the BN received on the free surface make the application of the BN technique to hard machined surfaces a debatable issue. It is also worth mentioning that the ratio between the WL and the HAZ thickness after hard machining is much higher than after grinding (Neslušan *et al.* 2012) [13]. Moreover, the hard machined WL is denser and more uniform with a severely strained matrix whereas the ground WL retains its original appearance (Guo and Sahni 2004) [9]. This study mainly focuses on the evaluation of surface integrity after hard milling with inserts of variable *VB*. Specific aspects of such surfaces as very high BN responses and strong magnetic anisotropy are discussed. Besides conventional BN values (representing the effective value of the raw BN signal) additional BN features are extracted such as BN envelopes and the corresponding peak position. The BN measurement is compared with metallographic observations and the appearance of hysteresis loops.

2. Experimental procedure

The experiments were conducted on samples made of hardened steel C55 exhibiting a hardness of 58 HRC. Ten pieces of 120×40×15 mm in dimension were prepared for a long term test. The cutting process was monitored as a long term test where such aspects as flank wear *VB*, structure alterations and corresponding surface integrity expressed in magnetoelastic responses (BN) of the hard milled surface were investigated. The cutting and other conditions were as follows: milling machine - FA4 AV, dry cutting, cutting tool made of cemented carbides R300-1240E-PM, R300-050Q22 - 12M 262489 (rake angle 0°) of 50 mm in diameter with 2 inserts of variable flank wear *VB* (in the range of 0.05 to 0.8 mm), a_p = 0.25 mm, v_f = 112 mm.min^{-1}, n = 500 min^{-1}. Flank wear was measured for both cutting inserts and the *VB* values indicated in the paper represent their average value. The BN measurement was performed by the use of the RollScan 300 and software package. The scan was carried out in the frequency range of 10 to 1000 kHz (magnetizing frequency 125 Hz, magnetizing voltage 10 V). Each BN value was determined by averaging 10 consecutive BN bursts (5 magnetizing cycles). Due to strong surface anisotropy, each surface was measured in two directions - tangential and axial as illustrated in Fig. 1. The BN values indicated in the paper represent the effective (rms) value of the BN signal. To reveal the microstructural transformations induced by milling 10 mm long pieces were sectioned and routinely prepared for metallographic observations (etched with 5% Nital for 10 s).

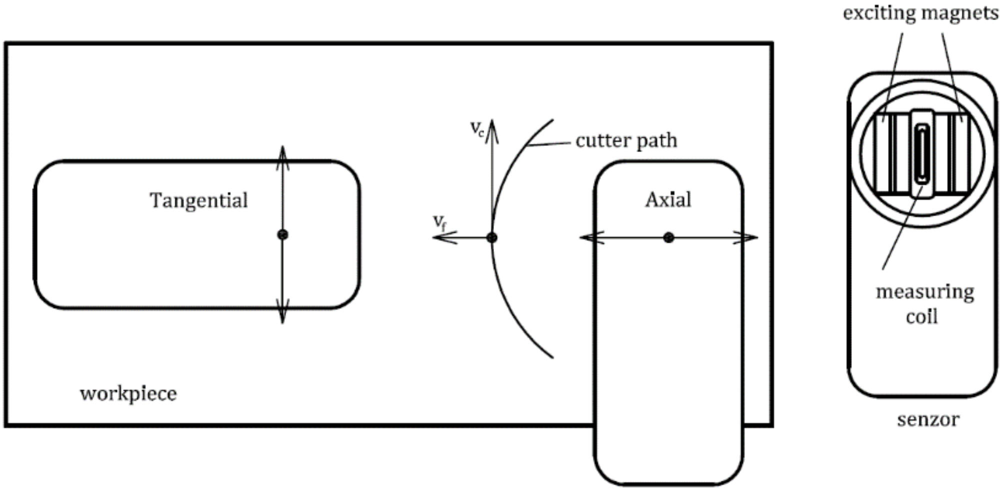


Fig. 1 Orientation of BN sensor

3. Results of experiments

3.1 Tool wear and microstructure of machined surface

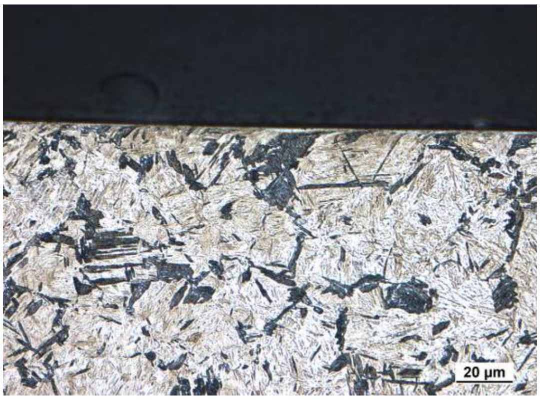


Fig. 2 Microstructure of hard milled surface, *VB* = 0.05 mm

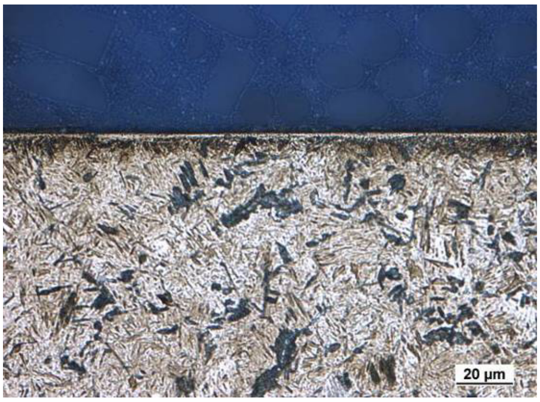


Fig. 3 Microstructure of hard milled surface, *VB* = 0.4 mm

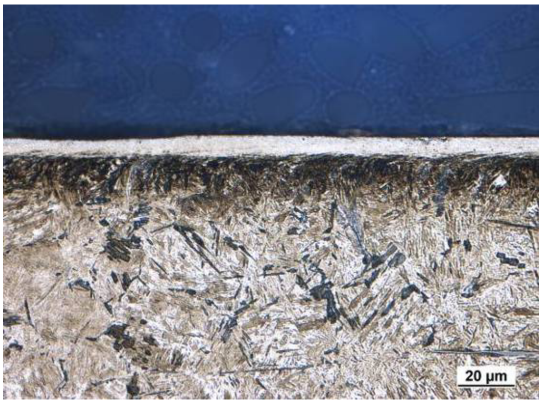


Fig. 4 Microstructure of hard milled surface, *VB* = 0.6 mm

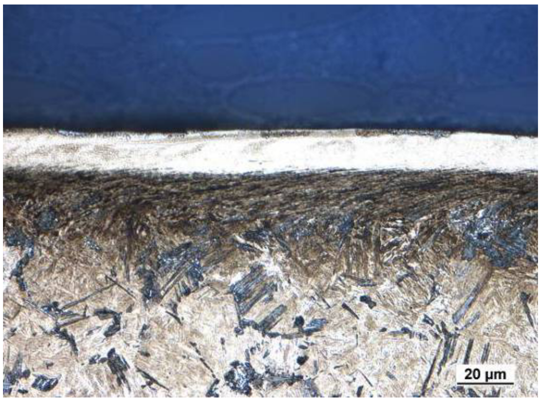
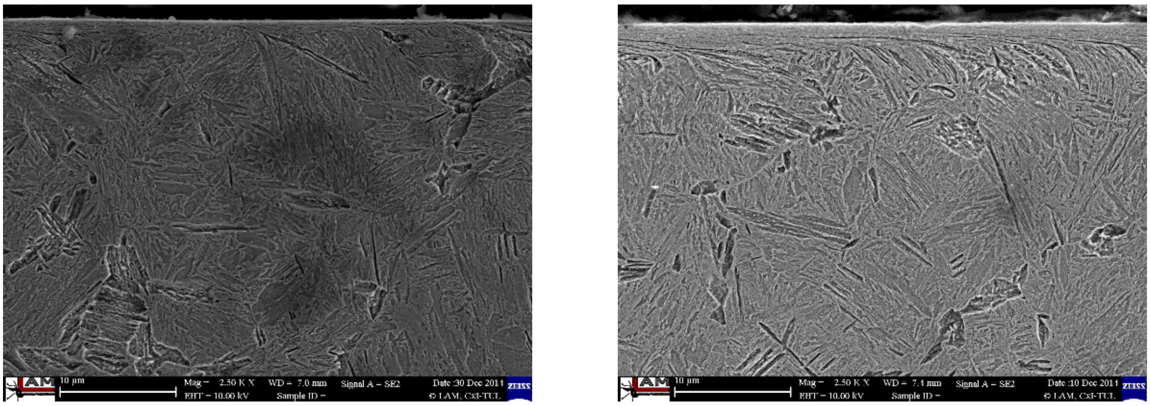
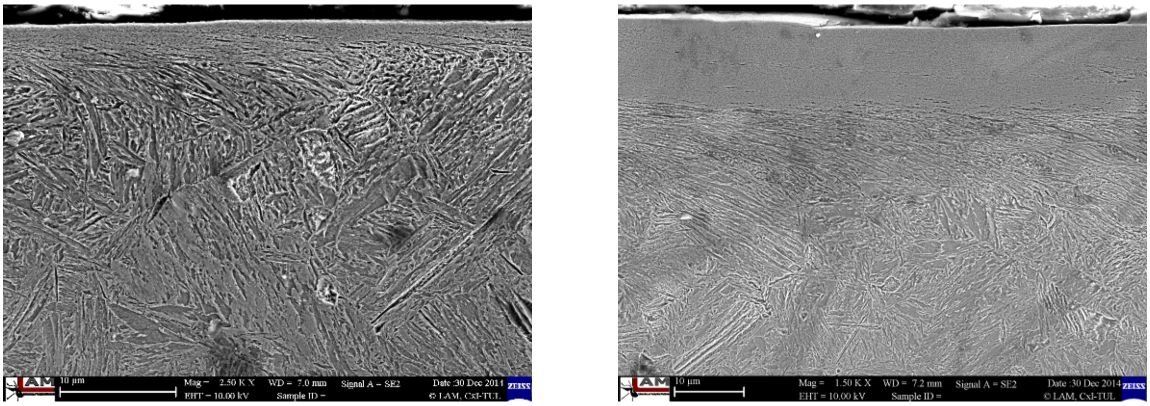


Fig. 5 Microstructure of hard milled surface, *VB* = 0.8 mm



a) $VB = 0.05$ mm b) $VB = 0.4$ mm



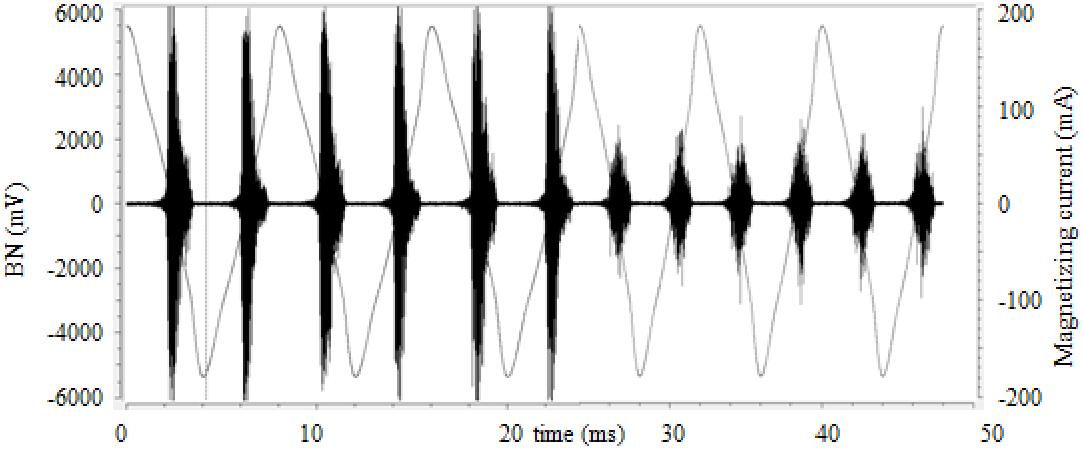
c) $VB = 0.6$ mm d) $VB = 0.8$ mm

Fig. 6 Micrographs of machined surface, SEM

Hard turning operations are not usually performed with inserts of flank wear *VB* above 0.4 mm in order to avoid the excessive cutting forces and the corresponding stability of machining. On the other hand, the flank wear is a major factor affecting the thickness of the HAZ as well as the WL, see Figs. 2, 3, 4 and 5. For this reason, quite large *VB* was employed to support the surface of the relatively thick HAZ and WL; thus creating more remarkable specific aspect of surface integrity, which is investigated via BN. Microstructural observations show that milling with inserts of low *VB* (0.05 and 0.2 mm) produces a surface containing a thin HAZ (which appears blue in the deeper layers) and a thin WL (which appears white in the near surface region), see Fig. 2. The higher *VB* is employed, the thicker HAZ and WL can be produced (see Fig. 3, 4 and 5). The microstructure also exhibits strong preferential orientation in the cutting direction. For this reason, SEM micrographs (as those illustrated in Fig. 6) were analyzed. SEM micrographs clearly show that the martensite matrix is severely strained and the thickness of preferentially oriented layer increases along with the progressively developed flank wear VB.

3.2 BN emission

Fig. 7 illustrates the BN signals obtained for the tangential direction and two different *VB*. This figure also shows that the surface containing thin WLs (obtained at low *VB*) emits higher BN than that machined by the insert of more developed *VB*. The cumulative relationship is indicated in Fig. 8. This figure also shows that when *VB* is kept low the BN emission in the tangential direction is higher than that in the axial direction. On the other hand, as soon as *VB* and the corresponding WL thickness become more developed the BN in the axial direction becomes higher at the expense of the tangential direction. Strong magnetic anisotropy (as a ratio of BN in the tangential to BN in the axial direction) is strongly reduced. It is worth mentioning that such high BN emission (especially for low *VB*) and remarkable magnetic anisotropy of the hard machined surfaces have been previously reported (Neslušan *et al.* 2014) [14]. The main reason can be seen in the cutting temperature exceeding the Curie temperature needed to disturb the domain configuration of ferromagnetic steel. The domain configuration of the near surface during heating is disturbed and the new domain alignment is configured during rapid cooling. The domains are not randomly but preferentially oriented in the cutting direction (tangential direction).



(a) *VB* = 0.05 mm (b) *VB* = 0.6 mm

Fig. 7 BN signals in the tangential direction

Fig. 8 shows that BN in the tangential direction drops along with the progressively developed *VB*. However, the axial direction exhibits a remarkable increase which in turn results in a progressive decrease in magnetic anisotropy expressed in the ratio of BN in the tangential to BN in the axial direction (see the ratio indicated in Fig. 8). The progressive decrease in BN versus *VB* in the tangential direction is linked with the structural transformations in the near surface layer as a region mostly contributing to the BN signal obtained on the free surface. It is well known that a surface produced by hard turning or milling consists of a WL in the near surface region followed by the HAZ in the deeper region. While the HAZ after grinding cycles is a region producing higher BN due to reduced hardness (and the corresponding lower density of dislocations), coarsening carbides and stresses shifted to the tensile stresses, the WL usually produced by grinding cycles emits quite low BN as a result of a higher volume of retained austenite (Brandt 1995) [2], compressive stresses, very fine grain, high dislocation density and carbon in a supersaturated state (Guo and Sahni 2004) [9]. The interpretation of the WL as a region contributing to BN after milling cycles is more complicated. Surface rehardening is a product of rapid selfcooling (when the temperature in the cutting zone exceeds the austenitizing temperature). On the one hand, the WL contributes to the high BN emission due to realignment of magnetic domains and the corresponding BW (as it is mentioned above). On the other hand, as WLs increase in thickness, the volume of retained austenite as a non ferromagnetic phase also increases (Brandt 1995) [2]. Both effects affect BN in a synergistic manner. Thickness of a WL is a function of *VB*. Flank wear land represents the time interval during which machined surface undergoes a severe plastic deformation at elevated temperatures. Two basic aspects of more developed *VB* should be discussed. The first one is associated with the longer time interval when the machined surface undergoes severe plastic deformation at elevated temperatures. The second one is associated with the increasing temperature in the tool/workpiece interface along with more developed *VB* due to the increase in normal and shear stresses – forces (Dubec 2014) [7]. On the other hand, the previously performed study reported that the chemical composition within the WL or the HAZ after hard machining stays nearly untouched due to quite rapid selfcooling of the machined surface (Brandt 1995) [2]. For this reason, the microchemical analysis was not employed in this study.

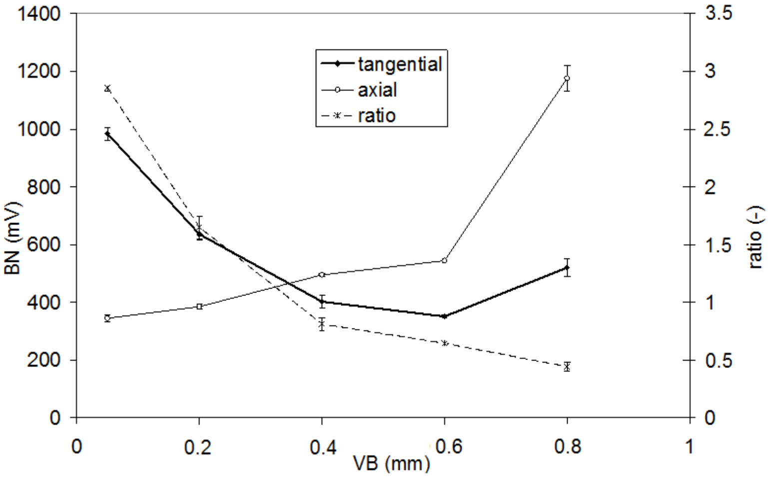


Fig. 8 Influence of flank wear *VB* on BN values in the tangential and axial direction

Both aspects contribute to the thicker WL (as well as HAZ) along with *VB* because the austenitizing temperatures penetrate deeper beneath the surface. As it was reported, a thin WL produced by the early phase of *VB* produces high BN emission due to the domain re-alignment. However, increasing the volume of the retained austenite and a higher magnitude of compressive stresses for the surface produced by an insert of higher *VB* causes BN to drop in the tangential direction (see Fig. 8) at the expense of the axial direction. Decreasing BN values in the tangential direction together with a higher BN emission in the axial direction results in a decrease in the degree of magnetic anisotropy expressed in the parameter ratio (see Fig. 8) along with more developed *VB*. The BW in the thicker WL becomes hard to unpin; the strong stray magnetic fields around carbides and the retained austenite as well as negative magnetostriction (associated with the stress state, compressive stresses) contribute to the higher BN in the axial direction. The relation between the investigated directions is inverted above *VB* = 0.4 mm, Fig. 8. The weaker BN signal produced by the inserts of higher *VB* corresponds with the shape of the BN envelopes and peak positions found on the envelopes.

3.3 Peak position

The BN envelopes in the tangential direction give two characteristic peaks (except the BN envelope for *VB* = 0.05 mm). The primary peak originates from heat treatment (or/and the HAZ) whereas the secondary peak originates from the re-hardened WL in the near surface region. Fig. 9 shows that the peak position in the axial direction stays nearly constant along with *VB* whereas the peak height (see Fig. 10) corresponds to the BN values indicated in Figure 10. On the other hand, the BN envelope for *VB* = 0.05 mm and the tangential direction exhibits only the primary peak corresponding to the nearly untouched surface, see Figs. 2 and 11. As *VB* is more developed and the WL becomes thicker the Peak Height of the primary peak falls and disappears for higher *VB*. Furthermore, the primary Peak Position is shifted to the lower magnetic fields (see Fig. 9) due to more remarkable thermal softening in the HAZ. On the other hand, the remarkable secondary peak (originating from the WL) appears in the BN envelopes as soon as *VB* attains 0.4 mm. The peak position of the secondary peak can be found at a much higher magnetic field than those associated with the HAZ due to much higher pinning strength of the WL produced at higher *VB*. Fig. 9 also shows that the primary peak disappears and the secondary peak appears when the ratio of the tangential BBN to the axial BN is inverted. The values (as well as their scatter plot) indicated in Figs. 8 and 9 were obtained by averaging 10 consecutive BN bursts (5 magnetizing cycles).

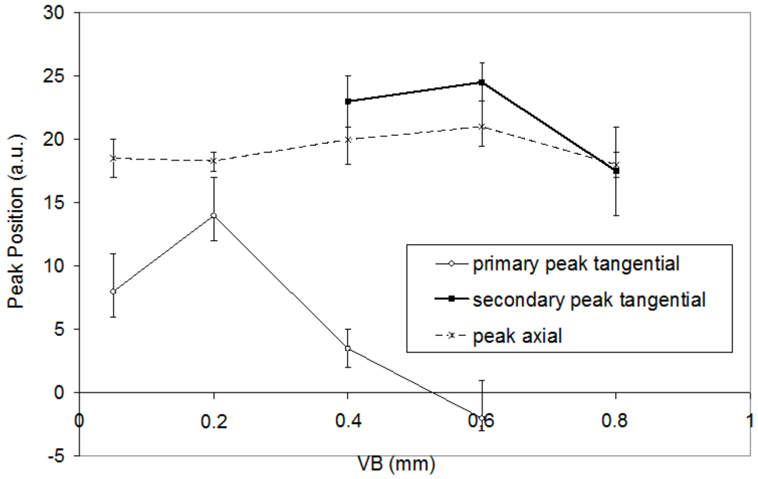


Fig. 9 Peak Position versus *VB*

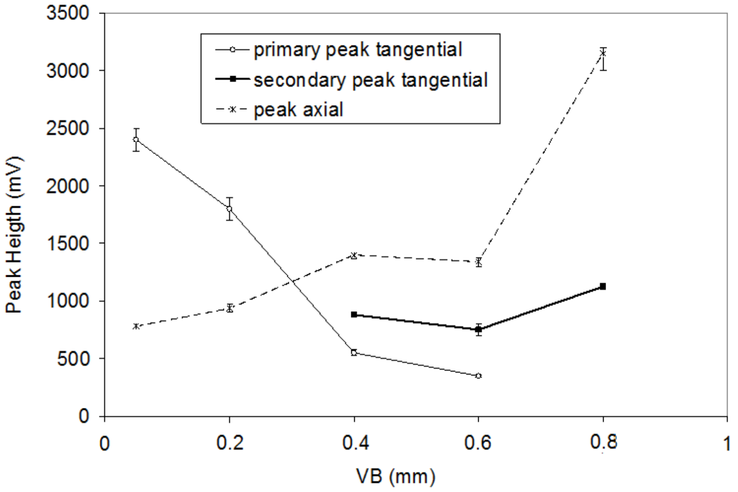


Fig. 10 Peak Height versus *VB*

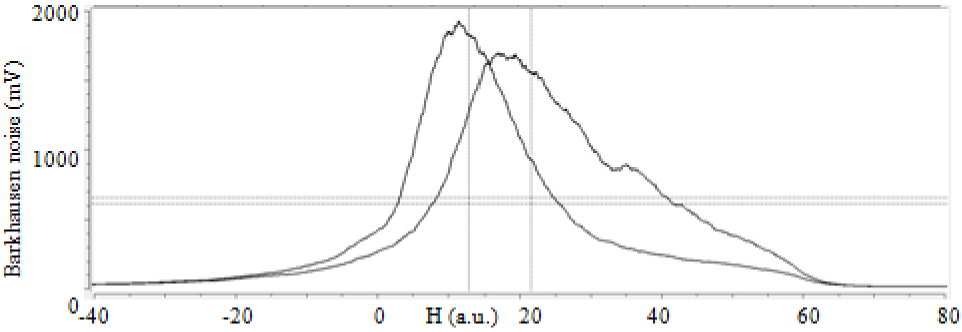


Fig. 11 BN envelope in tangential direction, *VB* = 0.2 mm

The secondary Peak Position and the Peak Height are less sensitive to the *VB*. Figs. 12 and 13 also show that the secondary peak becomes more apparent in the BN envelopes at higher *VB*. For instance, the primary and the secondary peaks are more balanced for

VB = 0.4 mm whereas the secondary peak originating from the WL dominates in the BN envelope when *VB* attains 0.6 mm due to increasing the WL thickness and limited BN skin depth. As the WL thickness increases, the re-hardened region increasingly contributes to the BN emission which in turn means lower BN due to high pinning strength of the WL.

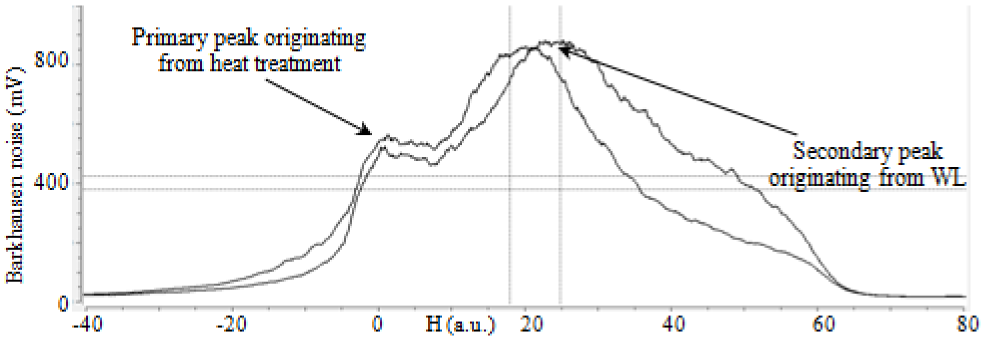


Fig. 12 BN envelope in tangential direction, *VB* = 0.4 mm

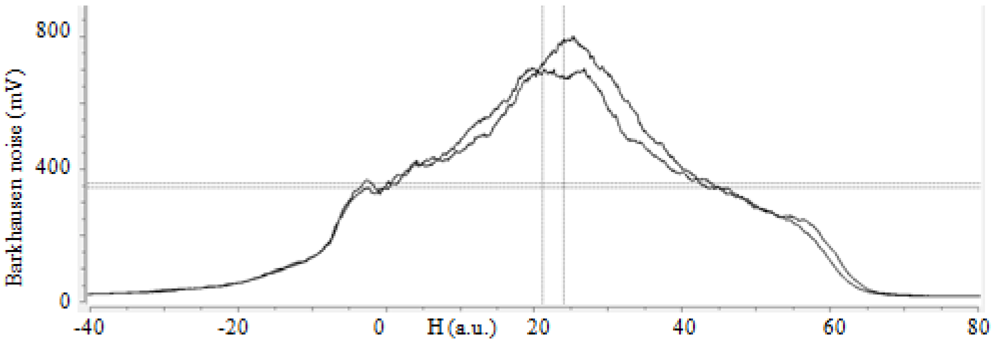


Fig. 13 BN envelope in tangential direction, *VB* = 0.6 mm

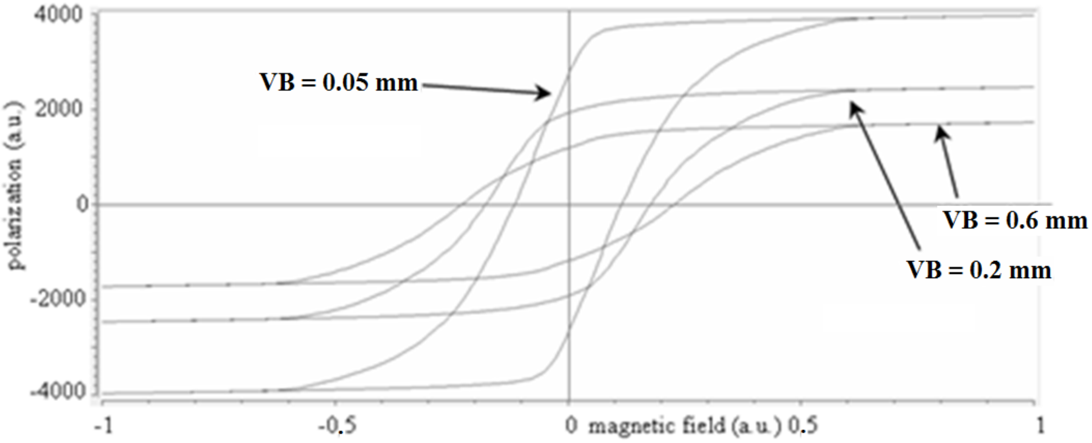


Fig. 14 Influence of VB on the shape of hysteresis loop in tangential direction

The appearance of hysteresis loops (extracted from the raw BN signals) proves the indicated BN values as well as the appearance of BN envelopes. The high BN emission at low *VB* (0.05 mm) is typical of soft magnetic structures producing a quite narrow hysteresis loop of high saturation (as well as a low coercive force and high remanence) whereas the low BN emission is connected with the thick hysteresis, low saturation, high coercive force and low remanence, see Fig.14.

4. Discussion of results

The BN emission of hardened steels is usually studied on ground surfaces (Rosipal 2014) [16] as a function of cutting conditions (Mičúch *et al.* 2014) [12], stress state (Čilliková *et al.* 2014) [5] and microstructure. However, hard milling or turning operations produce quite a different state of surface due to the different mechanism of chip removal (Tonshoff *et al.* 2000) [17]. Being so, the character or the BN emission from surface after hard milling is quite specific. The specific alignment of magnetic domains and the corresponding BW (preferentially oriented martensite matrix) produce very high BN not only after hard milling but also after the hard turning operation (Neslušan *et al.* 2012) [13]. However, the high BN emission is not driven by pure stress anisotropy (stress anisotropy occurs in hard machined as well as ground surfaces) and should be considered as a temperature dependent quantity in relation to the Curie temperature (Neslušan *et al.* 2014) [14]. Being so, stress and temperature load of a hard milled surface strongly affect the magnetic behavior in a synergistic manner. For this reason, the possible concepts for monitoring hard milled surfaces are far away from those adapted for grinding cycles and seem to be more closely linked with turning cycles (Dubec 2014) [7].

5. Conclusions

Further research focused on the BN emission after hard turning cycles should be carried out and discussed in the near future. Additional observations, not covered in this paper, indicate a strong asymmetry in the magnetization process as well as sensitivity to magnetizing conditions. However, the state of the art in the field has already proved the relevance of the suggested concept. Thus, the following conclusions can be drawn:

- the martensite matrix is preferentially oriented in the direction of the cutting direction,
- the domain alignment corresponds with the microstructure of the near surface WL,
- the preferentially oriented domains explain very high BN emission at low *VB* in the tangential direction,
- hard milling operations produce surfaces of strong magnetic anisotropy,
- as *VB* increase (and the WL increases in thickness) the BN emission and the degree of magnetic anisotropy decreases,
- the BN envelopes exhibit peaks either originating from heat treatment (or the HAZ) or/and the WL,
- the shape of hysteresis loops corresponds with the specific character of the BN emission.

The BN technique has high industrial relevance for the detection of mainly grinding cycles when unacceptable thermal softening and tensile stresses contribute to the high BN values. This study demonstrates and proves the potential of the BN technique for monitoring surfaces of high anisotropy. The industrial implementation of the BN technique for real needs would avoid the implementation of components with unacceptable surfaces; and thus prevent early crack initiation of the surface and premature machine failures.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the KEGA agency (Projects No: 005ŽU - 4/2014 and 009ŽU - 4/2014).

REFERENCES

[1] H. Barkhausen: *Phys. Zeitschrift 20.* 1919.

[2] D. Brandt: *Randzonenbeeinflussung beim Hartdrehen.* PhD. Dissertation. Universität Hanover, Germany. 1995.

[3] D. J. Buttle, C. B. Scruby, J. P. Jakubovics, G. A. D. Briggs: *Magneto-acoustic and Barkhausen emission: their dependence on dislocations in iron.* NDT & E Int. **24**, 47 – 54 (1991).

[4] P. Cardoso, J. P. Davim: *Micro milling of metallic materials – a brief overview.* Transactions of Famena. **36**, 79 – 85 (2012).

[5] M. Čilliková, M. Neslušan, K. Kolařík, M. Mičúch: *Detection of Surface Damage after Grinding of Large Case–hardened Bearing Rings*, Key Engineering Materials. **581**, 205-210 (2014).

[6] F. Cus, U. Zuperl: *Merged neural decision system and anfis wear predictor for supporting tool condition monitoring*. Transactions of Famena. **35**, 13 – 26 (2011).

[7] J. Dubec: *Multiparametric analysis of Barkhausen noise for investigation of surface integrity.* PhD. Dissertation. University of Žilina, Slovakia. 2014.

[8] C. Gatelier-Rothea, J. Chicois, R. Fougeres, P. Fleischmann: *Characterization of pure iron and carbon-iron binary alloy by Barkhausen noise measurements: study of the influence of stress and microstructure.* Acta Mater. **46**, 4873 – 4882 (1998).

[9] Y. B. Guo, J. Sahni: *A comparative study of hard turned and cylindrical ground white layers.* International Journal of Machine Tools and Manufacture. **44**, 135 – 145 (2004).

[10] J. Kameda, R. Ranjan: *Nondestructive evaluation of steels using acoustic and magnetic Barkhausen signals – II. Effect of intergranular impurity segregation.* Acta Metall. **35**, 1527 – 1531 (1987).

[11] G. Krolczyk, S. Legutko: *Investigations into surface integrity in the turning process of duplex stainless steel.* Transactions of Famena. **38**, 77 – 82 (2014).

[12] M. Mičúch, M. Čilliková, M. Neslušan, A. Mičietová: *Micromagnetic study of cutting conditions and grinding wheel wear influence on surface integrity.* Manufacturing Technology. **14,** 66 – 71 (2014).

[13] M. Neslušan, M. Rosipal, K. Kolařík, V. Ochodek: *Application of Barkhausen noise for analysis of surface integrity after hard turning.* Manufacturing Technology. **12,** 60 – 65 (2012).

[14] M. Neslušan, D. Blažek, D. Hrabovský, M. Bukovina: *Magnetic anisotropy in hard turned surfaces.* Acta Physica Polonica. **124**, 188– 189 (2014).

[15] R. Ranjan, D. C. Jiles, P. Rastogi: *Magnetic properties of decarburized steels: An investigation of the effects of grain size and carbon content.* IEEE Trans. Magn. **23/3**, 1869 – 1876 (1987).

[16] M. Rosipal: *Application of Barkhausen noise for study of surface integrity of machined surfaces*. PhD. Dissertation. University of Žilina, Slovakia. 2012.

[17] H. K. Tonshoff, C. Arendt, R. Ben Amor: *Cutting of hardened steel.* CIRP Annals Manufacturing Technology. **50**, 547 – 567 (2000).

Submitted: 09.4.2015

Accepted: 14.10.2015

Prof. Dr. Ing. Miroslav Neslušan
Faculty of mechanical engineering
Univerzity of Žilina
Univerzitna 1
010 26 Žilina Slovakia
Ing. Jozef Majerík, PhD.
Faculty of special technology
A. D. University of Trenčín
Pri Parku 19,
911 05 Trenčín Slovakia
Ing. Pavel Kejzlar, Ph.D.
Institute for Nanomaterials, Technical
University in Liberec, Studentska 1402/2,
46117 Liberec, Czech Republic
Assoc. Prof. Ing. Mária Čilliková, PhD.
Faculty of mechanical engineering
Univerzity of Žilina
Univerzitna 1
010 26 Žilina Slovakia
Prof. Ing. Anna Mičietová, PhD.
Faculty of mechanical engineering
Univerzity of Žilina
Univerzitna 1
010 26 Žilina Slovakia