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Barkhausen noise,
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NON DESTRUCTIVE EVALUATION OF SURFACE INTEGRITY PRODUCED BY MILLING AND GRINDING USING BARKHAUSEN NOISE SIGNALS

This paper deals with investigation of hard milled and ground surfaces via non destructive Barkhausen noise (BN) technique. The paper compares the raw BN signals, extracted BN features such as effective (rms) values and appearance of hysteresis loops produced by grinding and milling cycles. Information about surface state is correlated and confronted with metallographic observations, SEM readings as well as residual stress state. The paper also discusses the specific character of BN signals (and the corresponding BN features) produced by hard milled surface as a result of the magnetic shape memory effect when the machined surface undergoes severe plastic deformation at elevated temperatures.

1. INTRODUCTION

It is well known that near surface is a critical region of components in use. Grinding cycles are very often employed to achieve acceptable precision and surface integrity of hardened parts. Hardened parts are components loaded near their physical limits and unacceptable surface state can significantly affect their functionality. Ground surfaces can suffer from overtempering or/and overheating as a product of elevated temperatures in the cutting zone [9]. Overtempered surfaces usually exhibit quite thick heat affected zone (HAZ) as a thermally softened region due to thermally induced decreased dislocation density and carbides coarsening. HAZ usually appears dark in metallographic observation and can be easily contrasted against thermally untouched structures [15]. Overheated surfaces contain (except HAZ) also white layer (WL) as a product of excessive temperature exceeding austenitizing temperature followed by rapid cooling [6],[15]. Both, overtempered and overheated surfaces are considered being detrimental to the component life time. For this reason, a non destructive technique should be employed to reveal such surfaces and avoid early crack initiation and premature failures under cyclic load.

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Barkhausen noise (BN) technique is very often employed for such purpose. BN is a physical phenomenon associated with Bloch Wall (BW) motion in a ferromagnetic material. When the ferromagnetic structure is exposed to the cyclic magnetization irreversible and discontinuous BW motion produces electromagnetic pulses which can be detected on the free surface [1]. BW motion, thus magnitude of BN is sensitive to the stress state as well as microstructure features [3],[5],[8],[14]. BW interferes with dislocations tangles, carbides and other non ferromagnetic particles, grain boundaries as well as all crystalline defects [3],[5],[8],[14]. Being so, monitoring of ground surfaces is based on contrast between low BN emitted by thermally untouched structure and HAZ producing richer BN due to lower dislocation density, carbides modifications as well as tensile stresses [10],[15]. All these aspects contribute to BN emission in a synergistic manner. Nowadays, BN technique is widely employed in a variety of industrial applications as automated cycles or robotic cells.

Nowadays, grinding is very often substituted by hard turning or milling cycles. However, mechanism of chip separation during grinding significantly differs from hard machining. For this reason surface state produced by these competitive operations are different. The main distinctions can be found as follows [6]:

- much longer time period during which higher temperatures penetrate beneath free surface at grinding (several times greater tool – workpiece contact),
- the average stress over the entire contact in grinding is less that in hard milling,
- deeper penetration of compressive stresses in hard turning or milling.

It is worth to mention that concepts for non destructive monitoring of hard turned or milled surface based on BN has not been developed yet due to more complicated surface state as opposed to grinding. Stress profile as well as microstructure features of hard machined surfaces are often contradictory; evolution of BN versus *VB* is not always monotonous, thus making application of BN for such purpose a debatable issue [13]. Being so, this paper discusses specific aspects of hard milled surface (as a comparative study against grinding) from the point of BN, corresponding magnetic domain theory and BW motion.

2. EXPERIMENTS

Experiments were conducted on samples made of bearing steel 100Cr6 of hardness 62 HRC. 10 pieces of dimension 60x43x25 mm were prepared for long term test. 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. Cutting and other conditions: milling machine - FA4 AV, dry cutting, cutting tool made of cemented carbides R300-1240E-PM, R300-050Q22 - 12M 262489 of diameter Ø 50 mm with 2 inserts of variable flank wear *VB* (in the range 0.05 to 0.8 mm, rake angle 0º), a_p = 0.25 mm, v_f = 112 mm.min^{-1}, v_c = 78.5 m.min^{-1}. Flank wear *VB* was measured for both cutting inserts and *VB* values indicated in the paper represents their average value. Ground samples were machined at a_p = 0.01 mm (as overtempered) and 0.04 mm (as overheated) samples (10 passes), v_f = 8 m.min^{-1},

v_c = 35 m.s^{-1} (dry grinding to induce a certain degree of overtempering or overheating, grinding wheel A9860J9V, single crystal diamond dresser, grinding machine BPH 20).

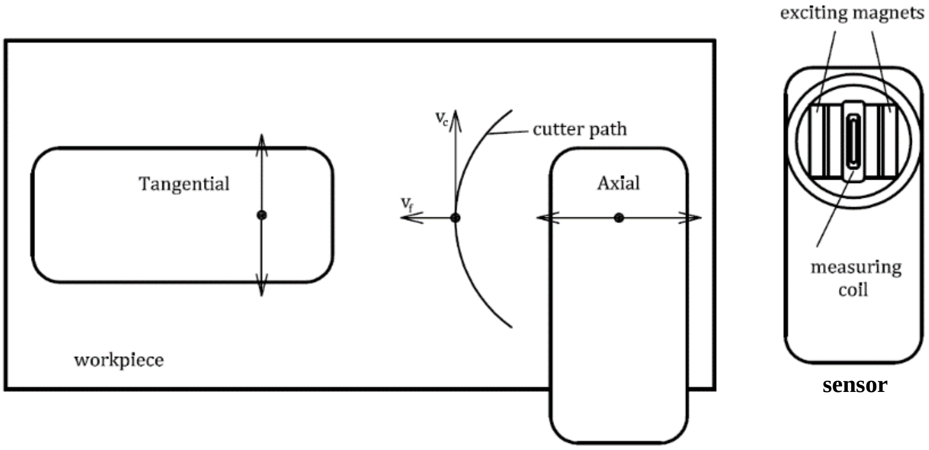
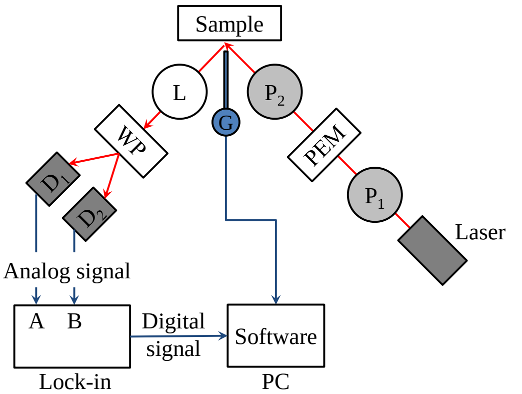


Fig. 1. Orientation of BN sensor

BN measurements were performed by the use of RollScan 300 and software package µScan in the frequency range 10 – 1000 kHz (mag. frequency 125 Hz, mag. voltage 10 V). Each BN value was determined by averaging of 10 consecutive BN bursts (5 magnetizing cycles). Due to strong surface anisotropy of milled surfaces, each surface was measured in two directions - tangential and axial as Fig. 1 illustrates. BN values indicated in the paper represent the effective (rms) value of BN signal (obtained from µScan software). To reveal the microstructure transformations induced by milling 10 mm long pieces were sectioned and routinely prepared for metallographic observations (etched by 2% Nital for 8 s).



P_1, P_2 – Frank-Ritter polarizers PEM – Photoelastic modulator
G – Gaussmeter L – Converging lance
WP – Wollaston prism D_1, D_2 – Detectors
Lock-in – Signal amplifier

Fig. 2. Brief illustration of MOKE

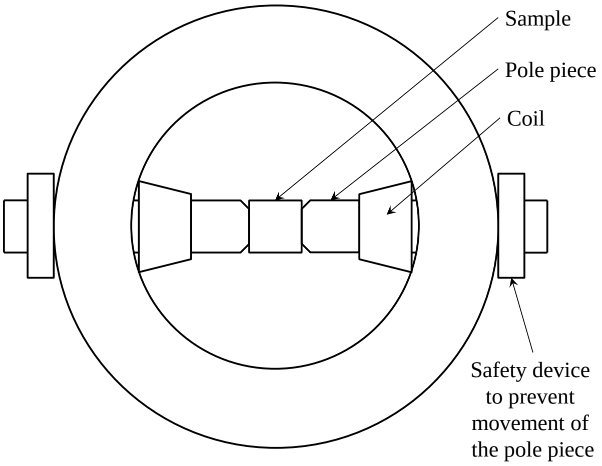


Fig. 3. Position of a sample between poles

Microstructure was observed in the direction of cutting speed. Residual stresses were measured by mechanical method based on electrolytic etching (2 hours, 20 % concentration of H_2SO_4 – electrolyte, 5 V and 6 A) of machined surface and simultaneous measurement of a sample deformation. The details about principle, mathematic apparatus and device can be found in [11].

To obtain information about shape of hysteresis loop in the near surface region (of several nanometers) MOKE (magnetic Kerr rotation) technique was employed for such purpose. Brief illustration of MOKE equipment is indicated in Fig. 2 and Fig. 3. Measurement was carried out in longitudinal (tangential) and transversal (perpendicular) directions with incidence angle of laser beam 45° (the difference between the second harmonic components was measured). Other conditions: $\lambda = 670$ nm, $f = 50$ kHz, $I = 10$ A, 2000 samples per hysteresis loop.

3. RESULTS OF EXPERIMENTS

Milling operations are not usually performed with the inserts of flank wear *VB* above 0.5 mm in order to avoid the excessive cutting forces and catastrophic tool failures. On the other hand, the flank wear is a major factor affecting the thickness of WL and HAZ, see Figs. 4 and 5. For this reason, quite large *VB* values were employed to facilitate surface of relative thick WL; thus making more remarkable specific aspect of surface integrity investigated via BN. Microstructure observations show that milling with inserts of low *VB* (0.05 and 0.2 mm) produces surface containing thin HAZ which appears dark in the near surface region (see Fig. 4) together with thin WL (appearing white). HAZ and WL are not continuous of variable thickness below 2 μm. As soon as *VB* becomes more developed thickness of HAZ and WL progressively increases. The higher *VB* is employed, the thicker HAZ and WL can be produced (see Fig. 5).

On the other hand, ground surfaces exhibit much remarkable thermal softening or rehardening, see Figs 6 and 7. Thickness of HAZ as well as WL is several times greater as a result of much longer time period during which excessive heat (originating from cutting process) and the corresponding temperature penetrate beneath the free surface. Hardened bearing steels emit poor BN due to high dislocation density and presence of fine carbides. Decreased dislocation density as well modification of carbides shape, their density and dimensions in the HAZ also decrease the pinning strength (pinning strength is equal to the magnetic field needed for irreversible BW motion hindered by a variety of lattice imperfections) of such structure and contributes to the higher magnitude of BN (since BW interfere with dislocations, carbides and other non ferromagnetic particles or lattice imperfections). As opposed to thermally untouched surfaces, ground overtempered surfaces produce higher BN. BN of overheated surfaces depend on HAZ/WL thickness ratio versus BN sensitive layer. Compared to the thermally untouched samples, surfaces containing thin WL (a few micrometers in thickness) usually emit 4 times richer BN due to predominating effect of reduced pinning strength of HAZ. As the WL increase in thickness BN emission falls down [4] due to increasing effect of WL as a zone containing untampered fine martensite, compressive stresses, higher volume of retained austenite and carbon in supersaturated state [6] (see Fig. 14).

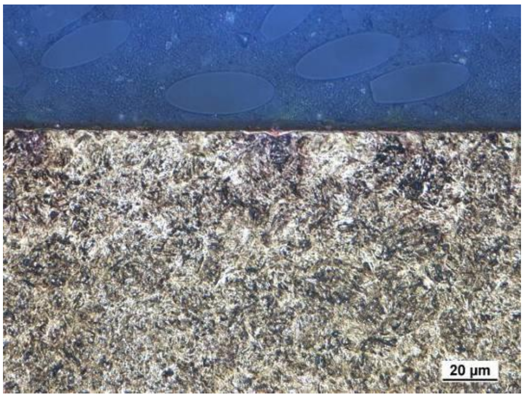


Fig. 4. Microstructure of the milled surface, *VB* = 0.05 mm, HAZ and WL below 1 μm

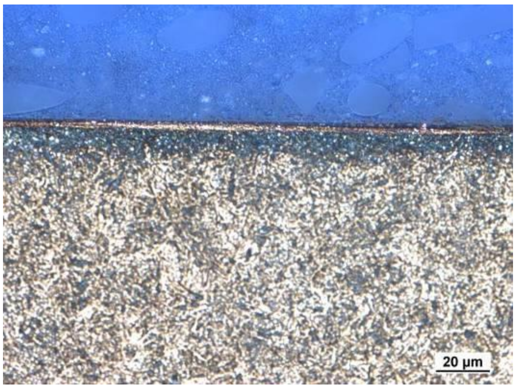


Fig. 5. Microstructure of the milled surface, *VB* = 0.8 mm, HAZ ≈ 8.5 μm, WL ≈ 4.5 μm

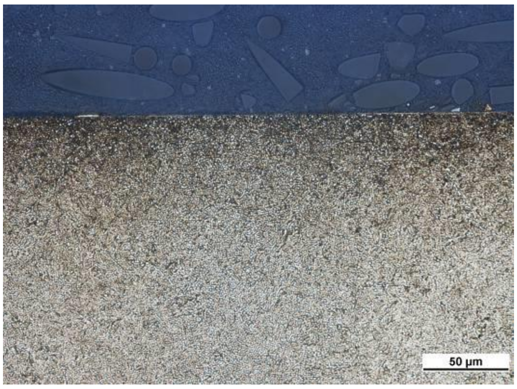


Fig. 6. Microstructure of ground, surface – over tempered, HAZ ≈ 18 μm, WL below 1 μm

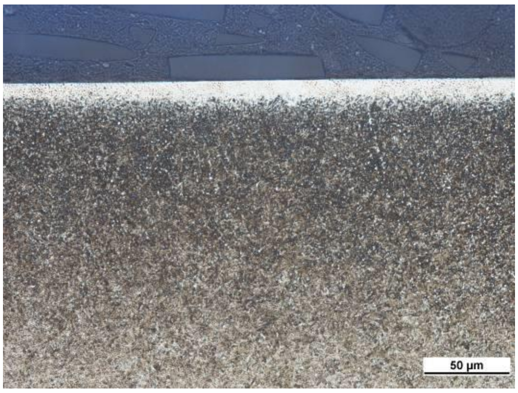


Fig. 7. Microstructure of ground, surface - over heated, HAZ ≈ 110 μm, WL ≈ 18 μm

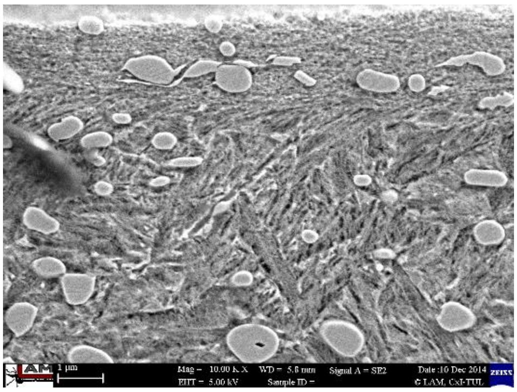


Fig. 8. Microstructure of the milled surface, *VB* = 0.8 mm, SEM

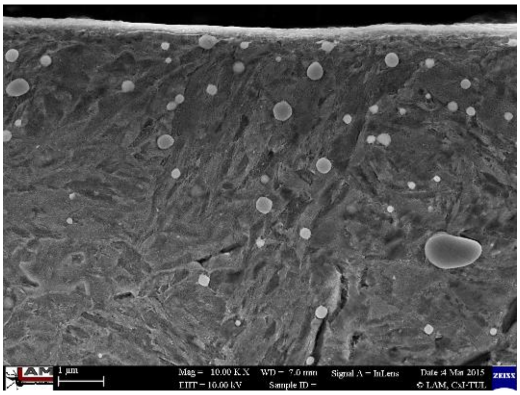


Fig. 9. Microstructure of ground surface, overheated, SEM

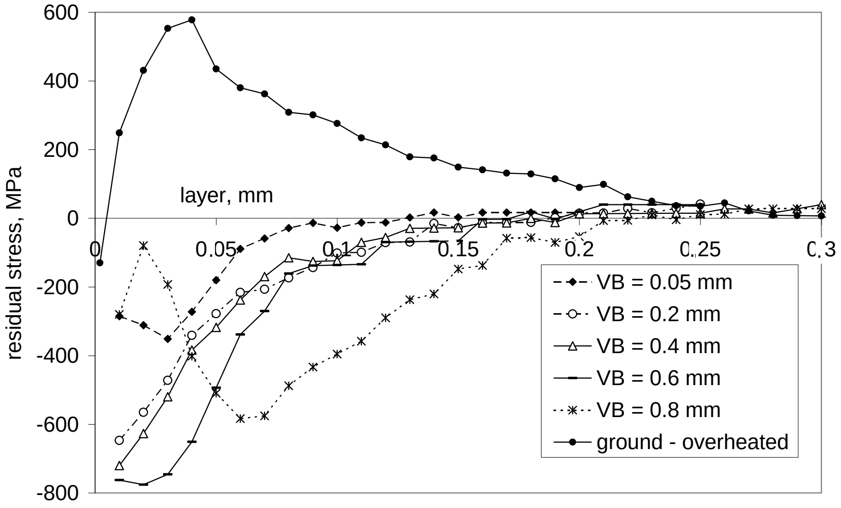


Fig. 10. Profiles of residual stresses as hard milled of various *VB* as well as ground (overheated)

From the stress point of view, ground surfaces usually contain very thin near surface region with compressive stresses followed by much thicker HAZ in deeper regions containing tensile stresses. Compressive stresses produce low BN whereas tensile stresses contribute to richer BN. For this reason, high magnitude of BN for over tempered surface could be also linked with thick HAZ containing tensile stresses dominating over thin plastically deformed (or rehardened layer in the case of overheated samples) containing compressive stresses, see Fig. 10.

On the other hand, hard milled surface produced by inserts of variable *VB* contains mainly compressive stresses as well as quite thin HAZ (as well as low HAZ/WL ratio). Being so, one might expect quite poor BN in hard milled surfaces. Extremely high BN emission (see Figs. 11 and 13), strong magnetic anisotropy as well as the specific charact of magnetic domains and the corresponding BW. Predominating thermal effect during grinding cycles produces surfaces containing randomly oriented martensite matrix (Fig. 8)

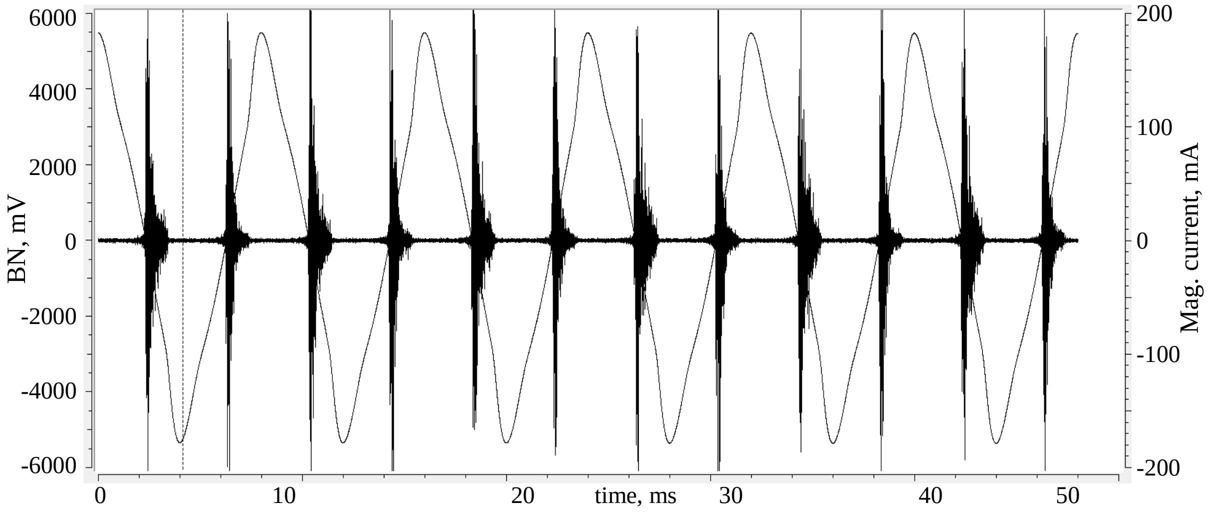
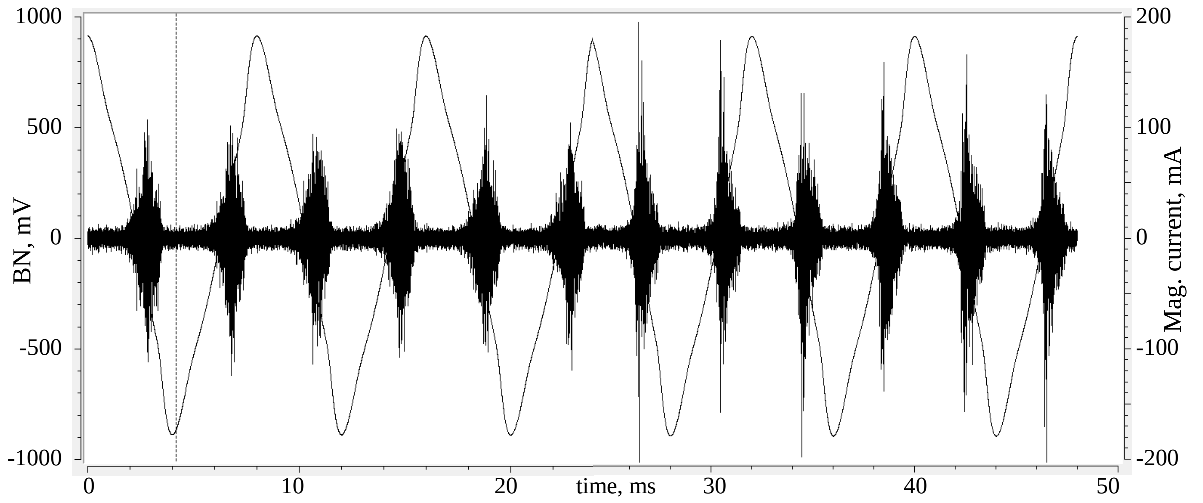


Fig. 11. Raw BN signal in the tangential direction, *VB* = 0.05 mm



a) ground - overheated b) hard milled – VB = O.6 mm

Fig. 12. Raw BN signals for hard milled and ground (overheated) surfaces

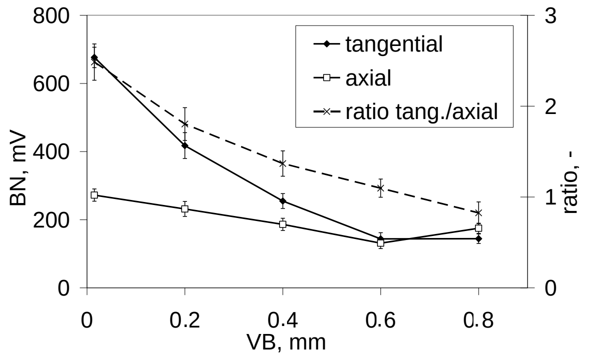


Fig. 13. BN values for hard milled surfaces

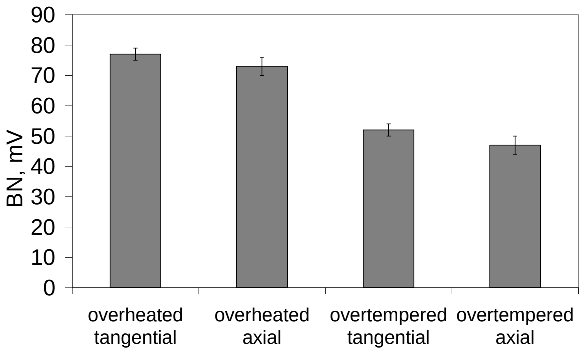


Fig. 14. BN values for ground surfaces

of low magnetic anisotropy (Fig. 14). On the other hand, machined surface during hard milling is exposed to very high compressive stresses over entire tool – workpiece contact at elevated temperatures (usually exceeding austenitizing temperature). Being so, martensite matrix is preferentially oriented in direction of cutting speed together with carbides severely strained in the same direction, see Fig. 9.

Figure 13 illustrates the BN signals obtained for the different directions and *VB*. This figure show that surfaces obtained at low *VB* emit higher BN signals of high magnetic anisotropy. As *VB* and the corresponding WL thickness become more developed BN emission and magnetic anisotropy are strongly reduced due to increased volume of retained austenite [2] (as a non ferromagnetic phase) as well as interference of BW with carbides. Such remarkable magnetic anisotropy of the hard machined surfaces was previously reported [12]. As it was claimed [12], the main reason can be viewed in cutting temperature exceeding the Curie temperature needed to disturb domains configuration of ferromagnetic steel. Domain configuration of the near surface during heating is disturbed and the new domain alignment is configured during rapid cooling. Domains are not randomly but preferentially oriented in the direction of the cutting speed (tangential direction).

Specific appearance of BN for *VB* = 0.05 mm shown in Fig. 11 should be also discussed. Conventional BN signals (as those shown in Fig. 12) demonstrate the gradual increase of BN along with increasing magnetic field. When the magnetizing field is reversed, first BN signal received from BN sensitive layer originates from 90º BW (spike domains around carbides). Magnitude of BN produced by 90º BW is much lower than that 180º BW (lower degree of orientation mismatch between the neighboring domains of 90º BW). Moreover, gradual increase is also connected with the gradual initiation of BW motion in randomly oriented martensite matrix (versus direction of external magnetic field). However, occurrence of 90º BW in hard milled surface is reduced due to the specific above mentioned BW reconfiguration as well as reduced pinning strength of carbides also strained in direction of cutting speed. Being so, extremely high BN magnitude occurs in a very short time period as soon as the magnetic field attains the critical strength. Compared with ground BN bursts (or BN burst for *VB* = 0.6 mm), BN burst for *VB* = 0.05 mm are very thin exhibiting very short rise time (and the corresponding magnetic field).

Irreversible BW motion is a major factor explaining magnetic hysteresis in ferromagnetic materials. Isotropic surfaces usually produces hysteresis loop of the typical S-shape as a product of BW interference with the variable pinning sites represented by different microstructure features (for instance grain boundaries or/and carbides). Being so, mechanically soft structures containing small volume of pinning sites of low pinning strength gives narrow hysteresis loop of high remanence and low coercive force whereas hard structures gives more thick hysteresis loop of low remanence and high coercive force [7] (of typical S – shape). Figure 15 indicates that BN magnitude corresponds with appearance of hysteresis loops.

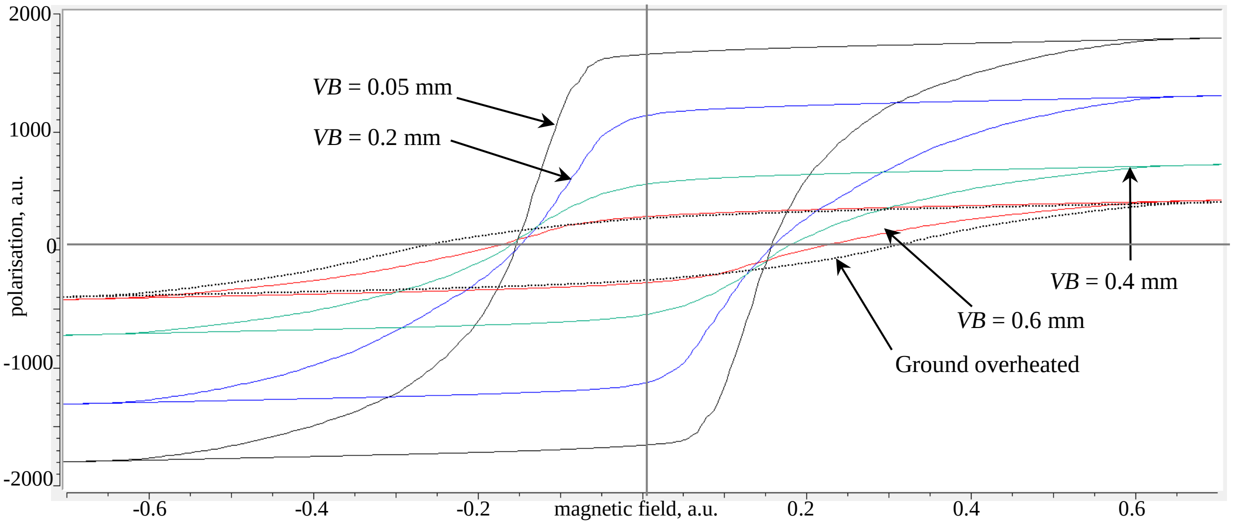
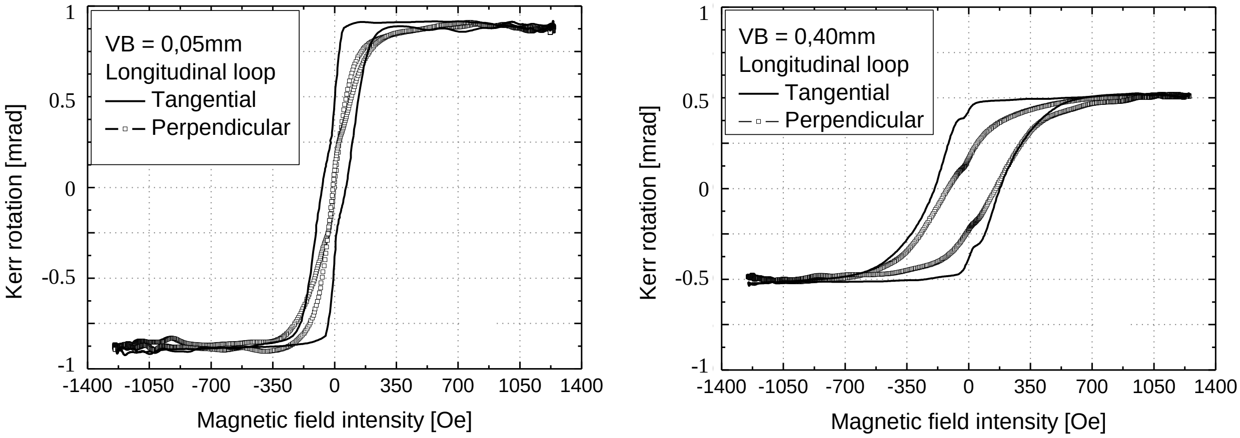


Fig. 15. Hysteresis loops extracted from BN signals

Figure 11 demonstrates that the high initial BN at *VB* = 0.05 mm is followed by BN of lower magnitude since the BN sensitive layer is much deeper that the thickness of the layer



a) *VB* = 0,05 mm b) *VB* = 0,4 mm

Fig. 16. Hysteresis loops – MOKE technique

containing reconfigured domains due to magnetostriction. Expressed in other words, BN signal received on the free surface contains information about BW and domain motion from the reconfigured near surface region as well as less affected or untouched structures in the sub surface regions. Such proposition also explains why the hysteresis loop for *VB* = 0.05 mm derived from the raw BN signal is not clearly narrow but should be characterized as a mixed type. To obtain information about hysteresis loop appearance attributed to near surface region (containing aligned matrix in the cutting direction only) MOKE technique were employed for such purpose. Figure 16 illustrates hysteresis loops for *VB* = 0.05 mm and 0.6 mm. Tangential direction produces very high BN due to domains aligned in this direction and the corresponding transformed shape of hysteresis loop, see Fig. 16a. On the other hand, cyclic magnetization in axial direction produces loop of zero hysteresis, see Fig. 16a. The theoretical models [7] correspond with the shape of real hysteresis loop obtained in these directions via MOKE effect. As soon as *VB* becomes more developed conventional S – shaped hysteresis loops can be obtained as those illustrated in Fig. 16b.

4. CONCLUSION

BN technique has found high industrial relevance for detection mainly grinding cycles when unacceptable thermal softening and tensile stresses contribute to the high BN values. Milling or turning processes form the different state of surface integrity than that after grinding. Grinding cycles usually produces isotropic (from magnetic point of view) surface whereas turning and milling cycles does not. This study indicates that hard milled surface could be monitored via BN technique since BN values fall down along with the progressive developed *VB* and the corresponding WL thickness. However, relation BN versus VB is not always monotonous for surfaces or lower hardness (for instance 45 HRC). The key factors of quite high BN emission are presence of WL and its thickness together with insert geometry. However, this study indicates potential of BN technique for such purpose.

It should be noticed that industrial implementation of BN technique for real needs would avoid implementation of components of unacceptable surface; thus prevent their early crack initiation and machine premature failures.

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