MAGNETIC AND STRESS ANISOTROPY OF MACHINED SURFACES WHEN HARD TURNING AND GRINDING

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Abstract

This paper deals with the pronounced magnetic and stress anisotropy found in a hard turned surface as well as the recovery of magnetic isotropy obtained after grinding operation, both made on bearing steel. The high magnetic anisotropy of the steel surface after hard turning operation occurs due to the significant plastic deformation and due to the temperature exposure exceeding the Curie temperature in the cutting zone followed by rapid cooling. The transformed microstructure of the material in a conjunction with the uniaxial residual stresses near the surface causes the magnetic anisotropy and magnetic domains reconfiguration. On the contrary, the residual stress state is more balanced after grinding operations and the temperatures in the grinding wheel (workpiece contact) do not exceed the Curie temperature. Therefore, smaller mechanic and magnetic anisotropy after grinding operations is obtained. The magnetic properties of the studied surfaces are analyzed by Barkhausen noise emission as well as magneto-optical methods. The results of these two techniques are compared from the point of view of the studied magnetic anisotropy. Better understanding of the processes can be achieved due to the very different physical background of these methods.

Key words

Barkhausen noise, grinding, turning, milling

Introduction

Magnetization in a ferromagnetic material is due to the nucleation and reconfiguration of domains which result from the movement of magnetic domains and corresponding Bloch Walls (BW) with increasing external magnetic field. Motion of BW and domains is usually pinned by precipitates, carbides, dislocations and other lattice defects as well as the magnitude and nature of residual stresses, and result in their discontinuous movement.

Pulsating magnetization can be then obtained, and the corresponding discontinuous jumps of the BW occur due to the rapid magnetic flux, see Fig. 1. This phenomenon is named as Barkhausen noise (1).

Micromagnetic investigation of machined surface based on Barkhausen noise (BN) has found a high industrial relevance. The main advantages of the Barkhausen noise (BN) method are associated with a very fast surface response (in seconds), portability of BN systems and ability to be easily integrated into automatic cycles and robotic cells. BN techniques are mainly applied in monitoring surface integrity of parts loaded near their physical limits. Then, surface integrity expressed in terms of residual stresses, hardness alterations or structure transformation are correlated with the BN values obtained from surface, as well as associated functionality of produced parts. Bearings are usually critical components in machines structures. The role of BN technique is usually connected with variable surface integrity though the constant cutting and other conditions are kept (2, 3).

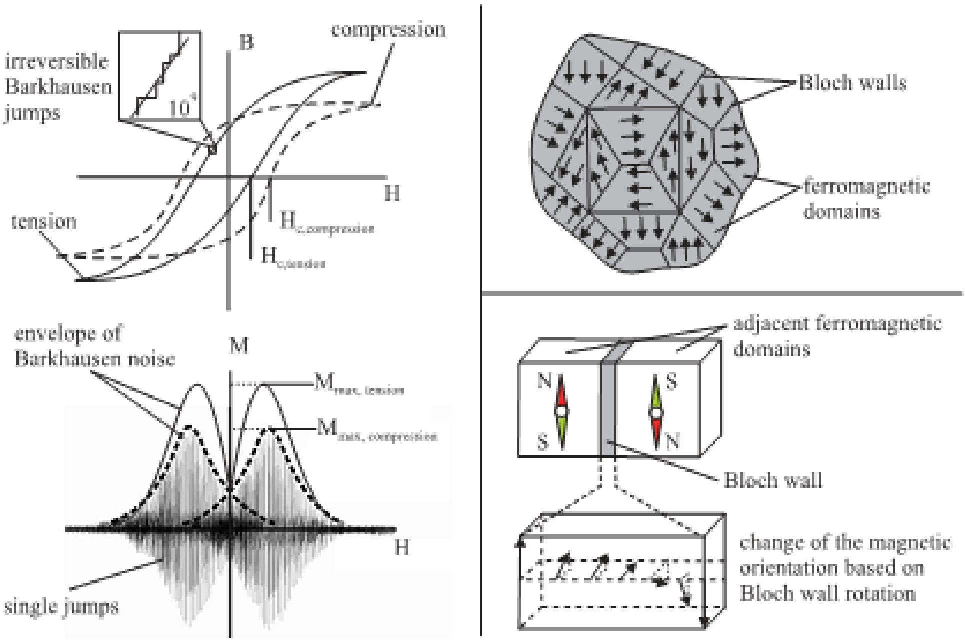


Fig. 1 *Discontinuous changes of hysteresis loop and influence of stress on Barkhausen noise (left side), domain configuration in ferromagnetic material with the detail of Bloch Wall (right side), (4, 5, 6)*

BN techniques are mostly adopted for inspection of ground surface since strong correlation between the heat generated in the grinding wheel – workpiece contact (its dissipation by workpiece), associated surface burn and corresponding magnetoelastic responses expressed in BN values can be found. Capability of BN technique considering the reliable and very sensitive detection of grinding burn results from thermal softening of the surface as well as subsurface layers and stress state (compressive stresses beneath the surface are shifted towards tensile stresses). It is well known that surface of high hardness gives the poor BN values, whereas softer structures emit higher BN values. Further, magnetoelastic responses are suppressed when compressive stresses occur while more pronounced BN values can be detected for surface containing mainly tensile stresses due to increasing domains and corresponding BW parallel with the direction of magnetic field (while the domains perpendicular to the load are reduced) (4, 5, 6).

Steels of low hardness usually emit strong magnetoelastic pulses and corresponding high level of BN signal expressed in such terms as rms or peak values. Good magnetic response of soft steels is mainly attributed to the microstructural features such as large grain size, low dislocation density or absence of fine carbide precipitates. However, steels and other materials are heat treated to impart good wear and frictional resistance associated with high hardness. Unfortunately, high hardness of steels after heat treatment, mainly hardening, results in poor magnetic response (7). Case – hardened steels is carburized to enrich the carbon content in the near surface layers and hardened afterwards to obtain the surface of high hardness and mechanical strength. However, high hardness and good magnetic response are mutually exclusive characteristics. Poor magnetic responses of case hardened surfaces are affected by microstructural features and stress state. BW are either pinned in their position or the average free path of their motion is significantly reduced due to high dislocation density, fine martensite grain, fine carbide precipitates as a barriers for BW movements as well as compressive stresses induced during rapid cooling. BW motion can be enhanced when microstructure as well as stress state are altered. Grinding operation can cause thermal burn damage when surface is mainly thermally loaded. Then, surface hardness decreases, thickness of heat affected zone (HAZ) extends and residual stresses shift towards tensile stresses (8). On the other hand, in certain cases, such as after hard turning operations, very high BN values can be found on the case hardened surface without any remarkable structure transformations. Therefore, this paper discusses the specific aspects of good magnetic responses and corresponding BN values obtained after hard turning.

Experimental part

The experimental study was carried out on AISI 3412 case hardened bearing steel of hardness varying between 60 ÷ 62 HRC cut from a bearing ring of 1650 mm in diameter. To investigate the ground surface of the variable surface integrity expressed in the different thermal softening, one ring raceway was wet ground while the other raceway was ground without coolant supply. Cutting conditions:

- grinding - A98 80 J9V $v_c = 25$ m.s^{-1}, $v_f = 25$ m.min^{-1},$v_p = 0.003$ mm per rev,
- turning - v_c =150 m.min^{-1}, a_p = 0,5 mm, f = 0.2 mm, dry round ceramics inserts, rake angle 0^o, VB = 0.3 mm.

The surfaces was also characterized with magneto - optical Kerr effect. Residual stresses were measured via X-ray diffraction technique ({211}, α-Fe, CrKα, X'Pert PRO). Tangential measurement residual stresses and magnetic responses correspond with direction of cutting force while axial measurement was carried out in the direction of the ring width. Samples for investigation of the near surface alterations were hot molded and routinely prepared for metallographic observation. Information about BN values, additional BN features as well as burst curves, hysteresis loops, and frequency spectrum on BN records can be found in the standard data set menus of Microscan software. BN values indicated in the paper represent the rms value calculated over the raw BN signal. Micromagnetic testing was performed by use of Rollscan 300 and software package Microscan in the frequency range of 10 to 1000 kHz (mag. frequency 125 Hz, mag. voltage 10 V). Rms values were calculated from the BW pulses in the frequency range of 70 up to 200 kHz. Owing to the strong stress and surface roughness anisotropy, each surface was measured in two directions - tangential and axial (example of a sensor orientation is shown in Fig. 2).

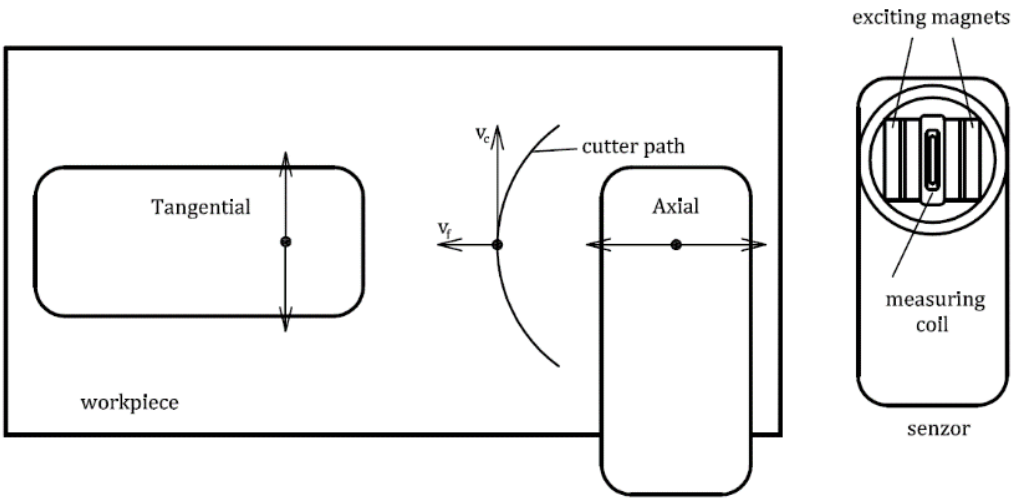


Fig. 2 *Orientation of BN sensor during inspection of milled surfaces*

Results of experiments

The measured residual stresses presented in Fig. 3 indicate strong relation among the stress state of investigated ground surfaces, microstructural features and corresponding BN values shown in Fig. 10. The explanation of higher BN values after grinding is connected with more pronounced thermal softening influencing the microstructure and stress state in a synergistic manner (9). While limited thickness of HAZ (up to 10 μm – nearly untouched surface with the discontinuous dark spots indicated in Fig. 4a) can be found after wet grinding, the dry grinding process produces the surface with the extended thermal softening exceeding 70 μm (dark layer of variable thickness depicted in Fig. 4b).

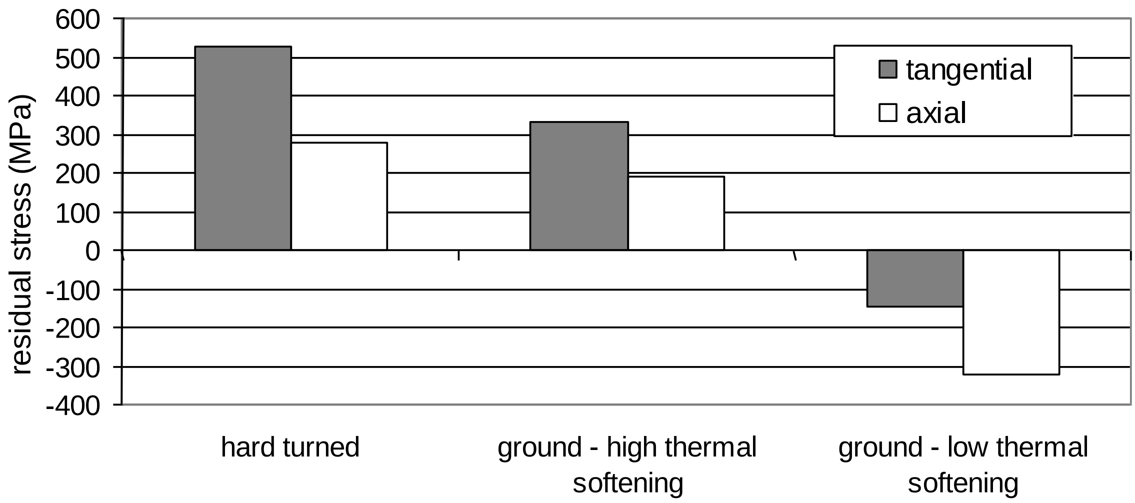
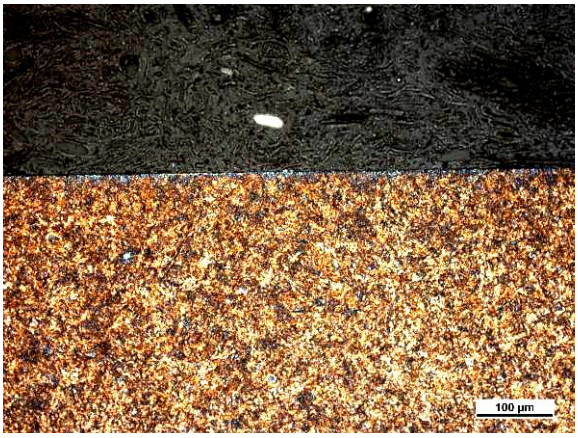


Fig. 3 *Residual stresses measured via X-ray diffraction technique*

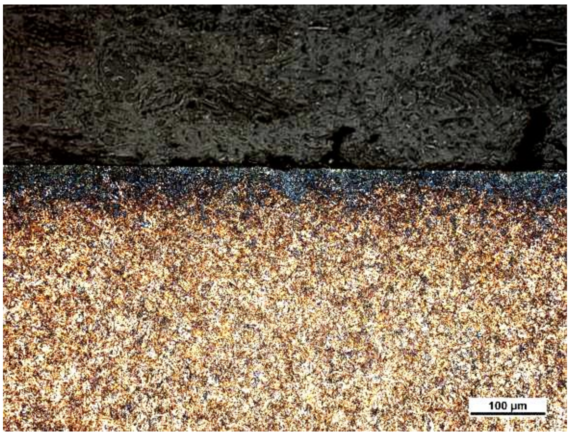
Fig. 4 depicts micrographs where thermal softening in the case of grinding can be indicated as the dark zone clearly distinguished from the untouched bulk structure below. The Figure also indicates the corresponding BN_T values measured in the tangential direction.

When limited thermal load of ground surface is obtained (Fig. 4a), the microstructure is dominated by the high dislocation density, the carbide precipitates and the paramagnetic retained austenite phase, which are strong obstacles to Bloch Wall (BW) motion. The thermal softening (Fig. 4b) enhances BW motion due to the decrease of dislocation density, coarsening of carbide precipitates and transformation of paramagnetic austenite to martensite. Temperature during grinding usually does not exceed critical temperature of the austenite transformation. The absence of a white layer on the ground surface illustrated in Figs. 4a, b indicates that no transformations are induced either by wet or dry grinding. Residual stresses are shifted towards the tensile zone and also contribute to the higher BN values.

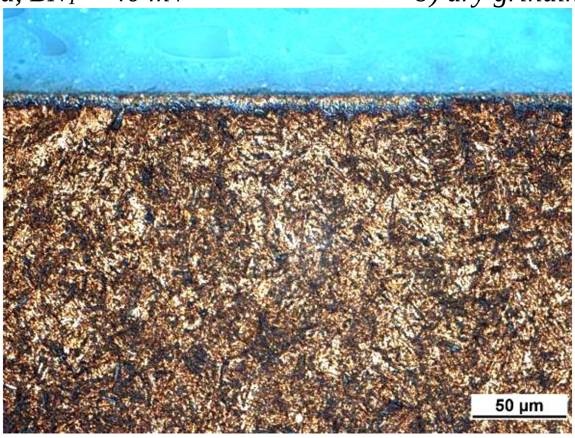
It is well known that BN values depend on BW motion (average of BW motion paths) as well as BW arrangement. BW interferes with microstructural features such as dislocation, precipitates, grain boundaries, other phases and lattice imperfections as well as magnitude and nature of residual stresses. Moorthy et al. (9) reported that microstructural features affect the pinning strength and the mean free path of the BW displacement while stresses affect mainly domain alignment with respect to the stress direction. Variation in microstructure and stress alters magnetoelastic responses through a hysteresis cycle. Explanations of the higher BN values with progressive thermal load during grinding is connected with more pronounced thermal softening influencing microstructure and stress state in a synergistic manner, see Fig. 6. (Fig. 5 and Fig. 6 are compilations of two BN signals. The left side indicates an example of the high BN signal and y-axis shows received BN voltage; the right side illustrates the low BN signal and y-axis shows course of the applied magnetization current).



a) gently wet ground, BN_T = 40 mV

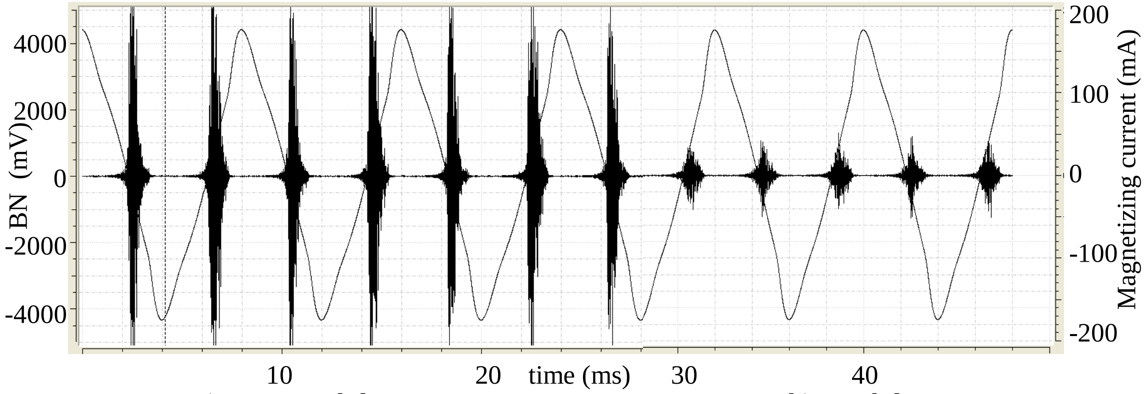


b) dry grinding, BN_T = 123 mV



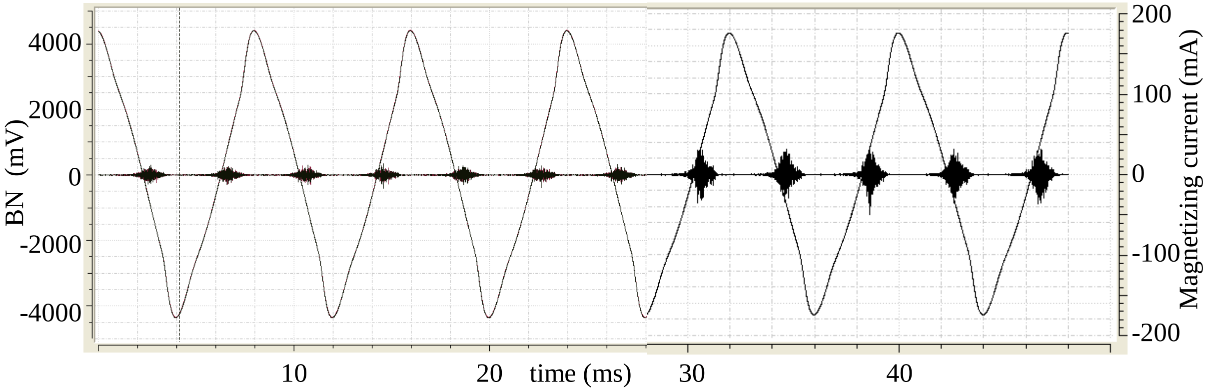
c) hard turned, BN_T = 775 mV

Fig. 4 *Micrographs of machined surfaces, Nital 2% etched*



a) tangential direction *b) axial direction*

Fig. 5 *Raw BN signals after hard turning*



a) low BN *b) high BN*

Fig. 6 *Raw BN signals after grinding*

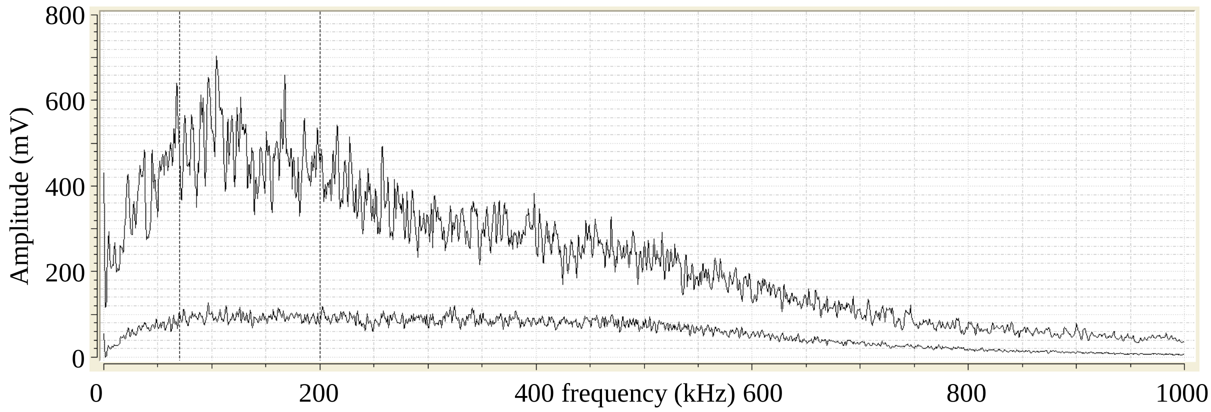


Fig. 7 *FFT spectrums of BN signal in the tangential and axial direction, hard turned*

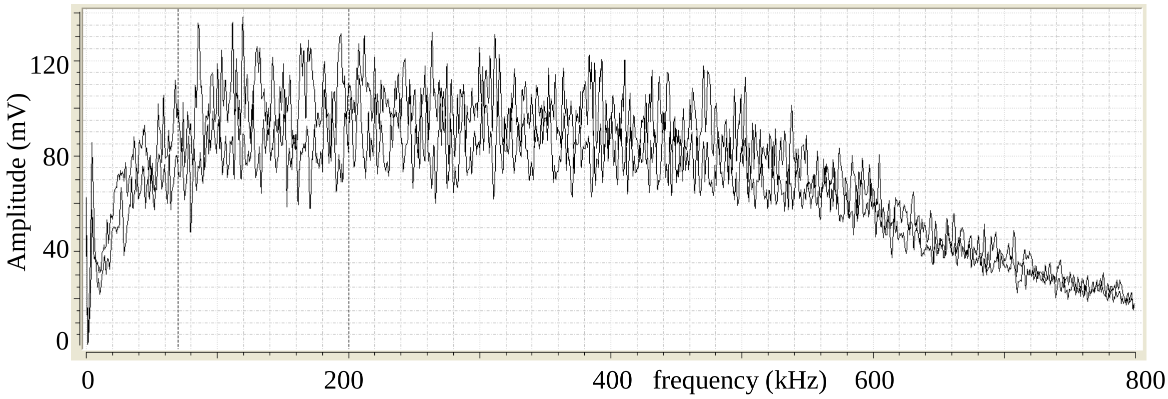
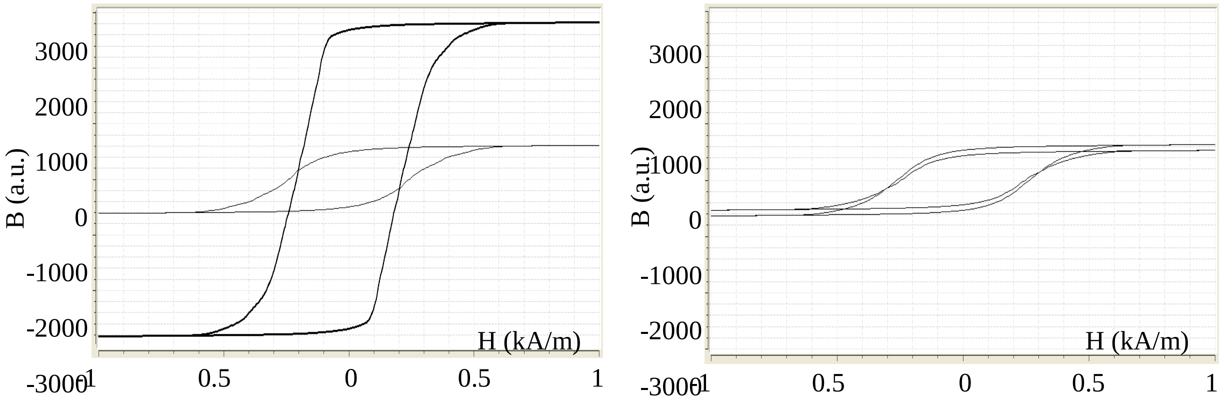


Fig. 8 *FFT spectra of BN signal in the tangential and axial direction, ground – high thermal softening*

When limited thermal load of ground surface is obtained, the microstructure is dominated by the carbide precipitates and the paramagnetic retained austenite phase, which can be considered as strong obstacles to the BW movements. In addition, BW also interferes with the high dislocation density. As soon as more pronounced thermal softening takes place, BW movement is enhanced due to the decrease of dislocation density, coarsening of carbide precipitates and transformation of paramagnetic austenite to martensite. Being so, thermal softening induced by grinding strongly correlates with BN values, frequency spectrums of BN responses (see Fig. 8 – thermal softening in grinding operations contributes to higher BN responses in both direction and frequency spectra are nearly the same) as well as more extended HAZ thickness (shown in Fig. 4a, b). Furthermore, residual stresses shifted towards the tensile zone also contribute to the higher level of generated BN signal level (see Fig. 3).

Hard turning significantly differs from grinding. The tool–workpiece contact area is restricted, being several times lower than that found in grinding. Severe plastic deformation of hard tuned surface is superimposed with high temperature in the tool–chip and tool–workpiece interface. Further, cutting speed is performed by workpiece (instead of the grinding wheel in the case of grinding) and the processes altering surface integrity are accelerated. Immediate heating of incoming material is followed by rapid cooling. Being so, thermal softening is reduced and found thickness of HAZ is low as illustrated in Fig. 4c. Therefore, the high BN values obtained from hard turned surface in tangential direction (see Fig. 5 and 10) cannot be attributed to the microstructural feature alteration. Furthermore, neither high tensile stresses found on the hard surface can fully explain extremely the high BN magnetic response. Essential role is played by the temperature in the cutting zone. Temperature in the grinding wheel – workpiece contact usually dos not exceed critical temperature above which structure transformations are initiated. Absence of a white layer on the ground surface illustrated in Figs. 4a, b indicates that no phases transformations are induced either by wet or dry grinding. Increasing heat flux in dry machining only enhances thermal softening extending deeper beneath the surface and alteration of residual stresses state.

On the other hand, hard turning operation needs initiation of high temperatures and superimposing hydrostatic pressure ahead the cutting edge to induce hard and brittle structure behaving in the malleable manner (10, 11).



a) hard tuned *b) ground – high BN values*

Fig. 9 *Hysteresis loops for hard turned and ground surfaces*

Simulations (10) as well as the experimental measurement studies (9) reported that temperature in the cutting zone exceeds 1000 ºC in the tool–chip interface. Since the tool–workpiece interface temperatures depend on flank wear, they still exceed the Curie temperature needed to disturb domains configuration of ferromagnetic steel. When hard turning is performed with low flank wear VB, the restricted tool–workpiece interface area and superimposing fast heating up and rapid cooling rates do not induce structure transformation. On the other hand, domain configuration of the near surface during heating up phase is disturbed since the tool–workpiece interface temperature exceeds the Curie temperature. Owing to the high temperatures and rapid cooling rates, white layers can be found on the near surface (12). New domain alignment is configured during rapid cooling. However, the new configured domains are not randomly oriented, but preferentially oriented in the direction of the cutting speed as the direction of the main stress vector, which is due to the magnetostriction effect. The new domain alignment corresponds with the different magnetoelastic responses in the tangential and axial directions as shown in Fig. 5, and the corresponding frequency spectrum is illustrated in Fig. 7. Reconfiguration of the domain alignment can be also evidenced by frequency spectra appearance. Axial direction gives flatter frequency spectrum whereas the low frequency pulses in the frequency zone 50÷300 kHz dominate in tangential direction. Strong magnetic anisotropy is indicated in Fig. 9a where significant differences in their appearance in the different measuring direction evidence anisotropy of domains configuration. While ground surface emits nearly the same shape of hysteresis loop in different direction, hard turned surface indicates strong anisotropy and significantly larger area of hysteresis loop as well as magnetic saturation.

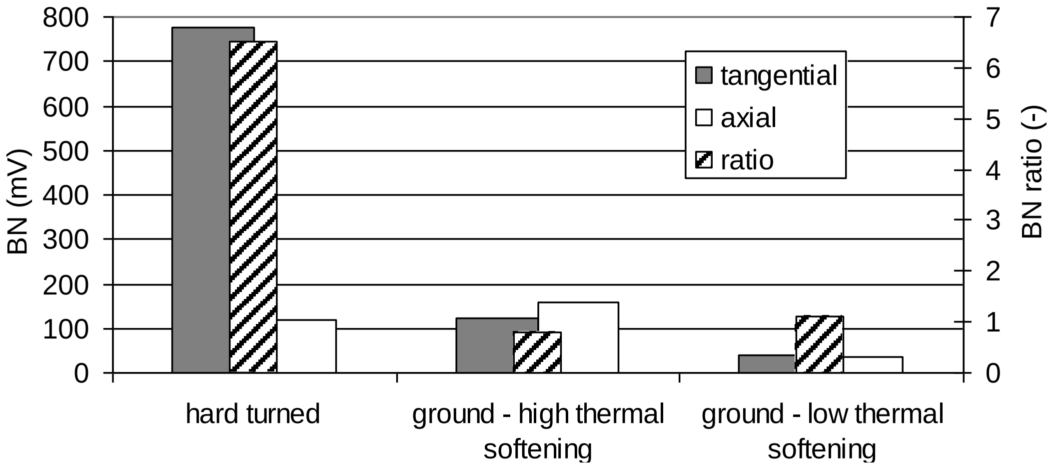


Fig. 10 *BN values and ratio for different surface*

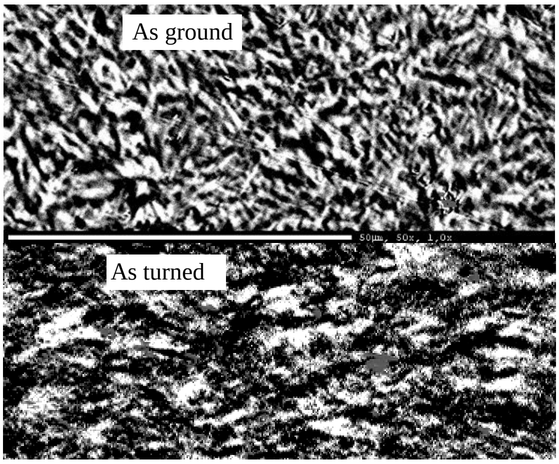


Fig. 11 *Magneto–optical Kerr micrographs of surfaces*

Fig. 11 illustrates the brief sketch of domain alignment for the raw and reconfigured structure. It is well known that BW moves perpendicular against the direction of magnetic field. Therefore, it can be easily understood that the high BN responses of hard turned surface in the tangential direction are associated with the specific domain orientation. Magnetic anisotropy expressed in terms of different BN responses measured in two different directions (see Fig. 10) is then closely connected with the domain reconfiguration as indicated by the BN values or obtained hysteresis loops.

Another aspect the reconfigured domain alignment should be also discussed. Rapid cooling of the surface during hard turning strongly affects the grain size of the near surface where a white layer is usually found (13). It is supposed that grain size is dramatically reduced (crystalline size) to less than BW thickness. Being so, BW is not pinned by the grain boundaries and more or less free BW irreversible movement results into the very high BN responses of the hard tuned surfaces.

Conclusions

The stress anisotropy is found on all machined surfaces. However, the corresponding magnetic BN anisotropy is found only on the hard turned surface. This suggests that the temperature in the cutting zone exceeding the Curie temperature is a key factor. Neither measured BN (see Fig. 6) values nor hysteresis loops illustrated in Fig. 9b, (or other obtained micromagnetic parameters) indicate any remarkable magnetic anisotropy after grinding. As soon as the temperature in the cutting zone exceeds the Curie temperature, stress anisotropy is a decisive factor influencing the domain reconfiguration due to the magnetostriction effect. Despite the affected surface layer after hard turning is very thin (up to 10 μm - compared to the skin-depth about 125 μm), the near surface region considerably contributes to the very high BN values.

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