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Magneto-Structural Anisotropy of Hard Milled Surface

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This paper deals with investigation of hard milled surface as a surface undergoing severe plastic deformation at elevated temperatures. This surface exhibits quite remarkable magnetic anisotropy (expressed in term of the Barkhausen noise) and differs from ground surfaces. The main reason can be viewed in specific structure and the corresponding domains configuration formed during rapid cooling following after surface heating. Domains are not randomly but preferentially oriented in the direction of the cutting speed at the expense of feed direction. The Barkhausen noise signals (measured in two perpendicular directions such as cutting speed and feed direction) indicate that the mechanism of the Bloch wall motion during cyclic magnetization in hard milled surfaces differ from surfaces produced by grinding cycles or the raw surface after heat treatment.

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1. Introduction

Magnetic Barkhausen noise (MBN) technique is widely employed for monitoring ground surfaces in the real industrial applications. The low MBN values for untouched surfaces are in contrast with the high MBN emission due to thermal overtempering during grinding. MBN is a product of irreversible discontinuous Bloch walls (BWs) motion during cyclic magnetization. BWs interfere with stress state as well as microstructure features (such as dislocations, carbides, grain boundaries, non-ferromagnetic particles, etc.) which pin BWs motion. The high MBN magnitude of over tempered surfaces after grinding is mainly associated with reduced dislocations and carbides density thermally initiated by elevated temperatures which in turns correspond with the decreased pinning strength [1].

Nowadays, hard machining (mainly turning and milling) can substitute grinding cycles. Development in machine tools as well as in process technology raised industrial relevance of hard machining [2]. However, the mechanism of chip separation during grinding significantly differs from hard machining. For this reason, the states of surface produced by these competitive operations are different. The main distinctions can be found as follows [3]: (i) much longer time period during which higher temperatures penetrate beneath free surface at grinding (several times greater tool– workpiece contact), (ii) the average stress over the entire contact in grinding is less than in hard milling, (iii) deeper penetration of compressive stress in hard milling.

Very high heating rates and rapid cooling during hard milling generate the specific state of surface integrity expressed in many terms. Very high MBN values and strong magnetic anisotropy can be found on the milled surface despite limited structure transformations and high hardness [4]. Being so, these aspects should be explained to develop a reliable concept based on MBN for monitoring surfaces after hard milling.

2. Experimental part

The experimental study was carried out on bearing steel 100Cr6 heat treated (HT) on hardness 61±1 HRC. Hard milling was carried out using 050Q22 - 12M 262489 milling cutter of diameter Ø50 mm with 2 inserts of flank wear (VB) 0.05, 0.2, 0.4, 0.6, and 0.8 mm. Cutting conditions: cutting depth $a_p = 0.25$ mm, feed speed $v_f = 0.11$ m/min (feed direction corresponds with the axial direction on the milled surface), cutting speed $v_c = 78.5$ m/min (cutting speed direction corresponds with the tangential direction on the milled surface), see Fig. 1.

MBN was measured using μScan 500 (mag. voltage 10 V, mag. frequency 125 Hz, 10 bursts, frequency range of MBN from 10 to 1000 kHz). MBN refers to the rms (effective) value of the signal. "T" refers to the tangential direction whereas "A" refers to the axial direction. Residual stresses (RS) and volume of retained austenite were measured via X-ray diffraction technique (XRD) ({211}, α-Fe, Cr K_α, GID technique, sensing depth approximately 1 μm, X'Pert PRO). To reveal the microstructure transformations induced by hard milling the 10 mm long pieces were prepared for SEM observations (etched by 5% Nital for 8 s). Microstructure was observed in the direction of cutting speed.

3. Results of experiments

Hard milling initiates very high temperatures and superimposing hydrostatic pressure ahead the cutting edge.

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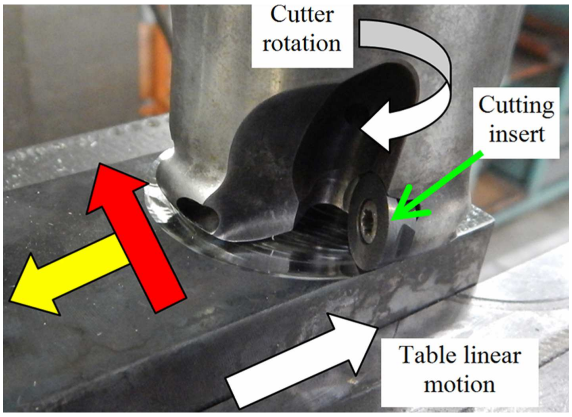

Fig. 1. Illustration of hard milling process (red arrow — direction of v_c, tangential; yellow arrow — direction of v_f, axial).

As it was previously reported [5] the main reason can be viewed in the specific structure and the corresponding domains configuration formed during rapid cooling followed after surface heating. Domains are not randomly but preferentially oriented in the direction of the cutting speed (tangential direction) at the expense of the perpendicular feed direction (axial direction), see Fig. 2. Strong magnetic anisotropy originates from the corresponding stress anisotropy (see Table I) and superimposing rapid heating/self-cooling temperature cycle. Constrained time period within machined surface undergoes severe plastic deformation at elevated temperatures avoids deeper penetration of structure transformations initiated by hard milling (especially at the low degree of flank wear $VB = 0.05$ mm). Therefore, the unexpected very high MBN after hard milling in the tangential direction cannot be associated neither with the thermal softening nor the stress state (compressive stresses would decrease MBN).

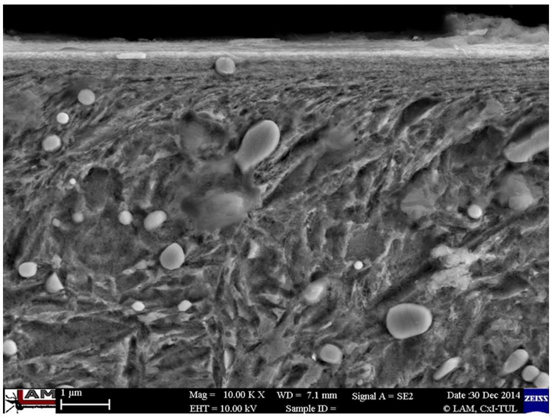

Fig. 2. SEM micrograph of milled surfaces, VB = 0.4 mm.

The high MBN in the tangential direction is driven by the nucleation magnetic field $H_n > H_g$ (field of growth). The high H_n is due to strong surface texture after hard milling — small missorientation of neighboring grains decreasing the density of magnetic dipoles. The domains in the near surface region stay aligned parallel with the machined surface. Cyclic magnetization only changes their alignment to the opposite direction. MBN in this layer occurs in the form of single massive MBN event (or a few MBN jumps). The specific mechanism of BWs motion exhibits Fig. 3 in which steep increase in MBN magnitude during magnetization can be found without previous remarkable nucleation phase (as contrasted with the MBN for the axial direction.

TABLE I

MBN and RS.

VB [mm]	RS_T [MPa]	RS_A [MPa]	MBN_T [mV]	MBN_A [mV]
0.05	–775±3	–485±8	592±26	155±17
0.2	–1137±9	–863±30	334±19	125±18
0.4	–804±10	–337±18	255±11	92±13
0.6	–732±3	–556±34	87±15	64±12
0.8	–686±64	–419±37	98±12	174±14

MBN for $HT = 87 \pm 12$ mV and $RS = 24 \pm 12$ MPa.

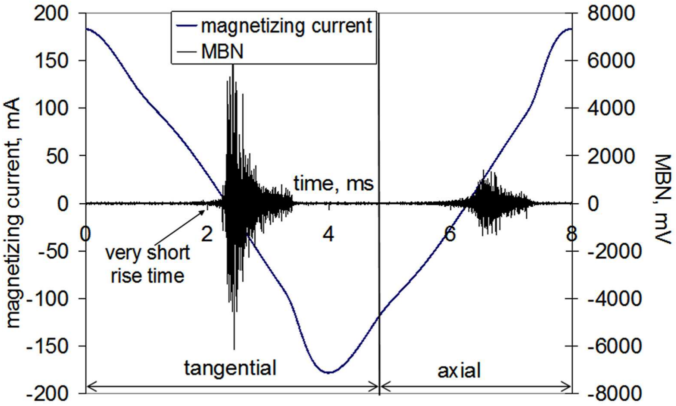

Fig. 3. MBN signals for tangential and axial directions, $VB = 0.05$ mm.

Table I indicates that MBN is a function of VB. MBN values (especially MBN_T) and the corresponding degree of magnetic anisotropy (expressed in the ratio MBN_T/MBN_A) decrease along with the more developed VB. It is well known that preferential orientation of the martensite matrix penetrates deeper along with more developed VB. One might expect that MBN would increase along with increasing VB. However, BW motion is strongly pinned by retained austenite whose volume in the surface increases with VB (for instance 14% for $VB = 0.2$ mm and 45% for $VB = 0.6$ mm).

Appearance of MBN envelopes (see Fig. 4 and Fig. 5) strongly corresponds with MBN values indicated in Table I. MBN envelope peak maximum falls down with more developed VB and position of the peak is shifted to the higher magnetic fields. Compared to the tangential direction, envelopes for the axial direction are shifted to the higher magnetic field and exhibit lower magnitude due to the specific preferential domains alignment perpendicular against the axial direction. Moreover, comparing the different directions remarkable distinctions can found in the appearance of the MBN envelopes; especially in the ascending part of the MBN envelopes.

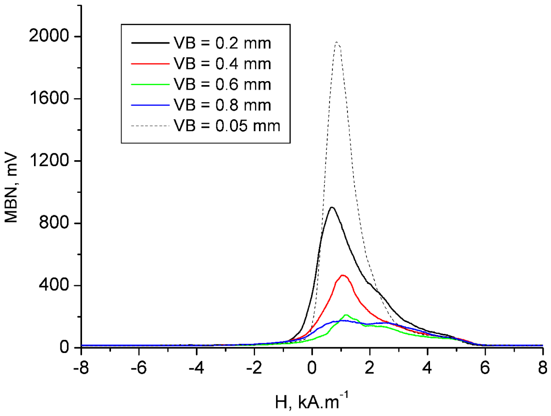

Fig. 4. MBN envelopes for tangential direction.

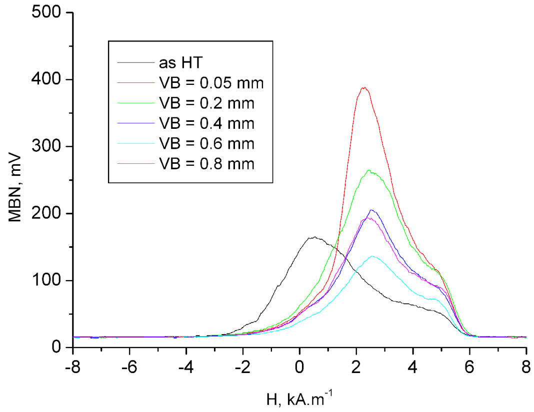

Fig. 5. MBN envelopes for axial direction.

Martínez-Ortiz et al. [6] reported that MBN events nearby the main peak in the MBN envelope are associated with the pure 180° BWs motion. Authors define that the width of this region (dH_{180}) is 25% of the entire magnetic fields (dH_e) in which any MBN events occur and name this region R^{180} [6]. The width (and position) of this region is defined as the MBN envelope maximum $\pm 12.5\%$ of dH_e. Authors attribute the region (dH_{90}), between the first point in which MBN envelope grows above the background noise to the R^{180} region, to the nucleation (and the motion) mainly reversed (90° BWs) domains. This region can be named R^{90} hereafter. The MBN energy in a certain region (defined by the width dH) can be calculated using

$$E = \sum_{\text{events}} \int mV^2 \, \mathrm{d}H,$$

where mV is the induced voltage in the pick up coil originated from MBN jumps.

As opposed to the axial direction or as HT surface, Table II shows remarkably reduced R^{90} and dominating R^{180} region (and the corresponding MBN energy) for the tangential direction due to specific mechanism of BWs motion in the near surface region originating from strong magnetic anisotropy (explained in the previous text). On the other hand, the large area of R^{90} region and the corresponding E_R^{90} energy (see Table II) indicates that the unmilled surface (as HT) or the axial direction favors nucleation process ($H_n < H_g$) when magnetic field is reversed during cyclic magnetization. Furthermore, R^{90} and R^{180} regions and the corresponding E_R^{90} and E_R^{180} energies become more balanced along with the gradual increase of VB and the decreasing degree of magnetic anisotropy.

TABLE I

MBN energies extracted from MBN envelopes.

VB	E_R^{90}		E_R^{90}	
[mm]	tangential	axial	tangential	axial
0.05	21.1	106.9	2024	572
0.2	54.9	157.4	1019	440
0.4	60.1	107.5	609	299
0.6	31.3	78.4	251	188
0.8	54.9	116.7	285	28

$E\_R^{90} = 60.3\ mV^2$ for HT and $E\_R^{180} = 272\ mV^2$.

4. Conclusions

The possible concept in which hard milled surface would be monitored is driven by relation between MBN and thickness of the near surface region altered by cutting process. As opposed to grinding, the high MBN values and degree of anisotropy should be linked with the low thickness of altered layer whereas progressive decrease of MBN produces thicker region of near surface undergoing severe plastic deformation at elevated temperatures.

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