NON DESTRUCTIVE EVALUATION OF SURFACES AFTER HARD MILLING

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Grinding operations are sometimes replaced with hard turning or milling cycles. Mechanism of chip separation during grinding and the corresponding surface integrity remarkably differs from hard turning or milling. For this reason, this paper deals with application of Barkhausen noise for evaluation of surface anisotropy after hard milling. Experiments were carried out on hardened bearing steel 100CrMn6. The analysis contains comparison of RMS values for the different hardness and tool wear after hard milling and also discusses the specific mechanism of BW motion in the case of cyclic magnetization. The paper also discusses significance of surface state after hard milling from the point of view of the consecutive technological operations.

KEYWORDS

Barkhausen noise, milling, surface integrity, white layer, wear

1 INTRODUCTION

Cyclic magnetization in a ferromagnetic material produces magnetic pulsation as a result of irreversible and discontinuous Bloch Walls (BW) motion. Discontinuous BW motion is due to interference of BW with microstructure features such as precipitates, dislocation cells, grain boundaries and other lattice defects. This phenomenon is named Barkhausen noise (BN). BN technique has found high industrial relevance mainly for monitoring surfaces loaded near their physical limits. This technique is usually adopted for monitoring of surfaces after grinding cycles due to strong correlation among thermal over tempering and some BN features [Karpucheewski 2002] [Micuch 2014] [Moorthy 2001] [Rosipal 2012]. Thermal over tempering decreases dislocation density, could transforms carbides shape and morphology as well as produces tensile stresses [Micuch 2014] [Rosipal 2012]. All these aspects contribute to the higher BN emission. Being so, surface overtempering can be easily revealed by the use of the BN technique.

Nowadays, hard machining can substitute grinding cycles. However, hard turning or milling can suffer from formation of white layers (WL) or unexpected tool failures. Suitable and reliable concept for nondestructive monitoring of hard turned or milled surfaces based on BN technique has not been established yet. Machined surface after hard machining is mainly a function of VB and cutting speed. Tools of high VB produce relative thick WL as well as the corresponding heat affected zone (HAZ) [Brandt 1995] [Guo 2004]. On the other hand, grinding cycles can suffer from thermal over tempering. Ground surface can sometimes exhibit HAZ whereas WL occurs randomly. On the other hand, thickness of HAZ and WL after hard milling is about 1 order lower than that induced by grinding. Compared to bulk, HAZ produces richer BN emission (due to tensile stresses, reduced dislocation density and modification of carbides – their size and morphology) whereas WL induced by grinding cycle in the near-surface region emits poor BN due to existence of higher volume of retained austenite, compressive stresses and very fine grain [Brandt 1995] [Guo 2004]. Contradictory effects (layers) contributing to the BN received on the free surface make application of BN for hard machined surfaces a debatable issue. It is also worth to mention that the ratio between WL and HAZ thickness after hard machining is much higher as opposed to grinding [Guo 2004] [Neslusan 2011] [Neslusan 2012]. Moreover, hard machined WL is denser, more uniform with severely strained matrix whereas ground WL retains in their original appearance [Guo 2004]. This study is mainly focused on 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.

2 EXPERIMENTAL CONDITIONS

Experiments were conducted on samples made of bearing steel 100Cr6 (chemical composition as follows - 1.1% C, 0.5% Mn, 0.35% Si, 1.35% Cr, 0.25% Cu). 10 pieces of dimension 120x40x15 mm were prepared for long term test. Bearing steel was heat treated (HT) on hardness 62 HRC (austenitizing temperature 830 °C – oil 62 °C, followed by tempering for 2 hours, 62 HRC – at temperature 160 °C). Cutting process was monitored as a long term test where such aspects as flank wear VB, structure alterations and corresponding surface integrity expressed in 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 50mm with 2 inserts of variable flank wear VB (in the range 0.05 to 0.8 mm, see Fig. 2), a_p = 0.25 mm, v_f = 112 mm.min^{-1}, n = 500 min^{-1}. Flank wear was measured for both cutting inserts and VB values indicated in the paper represents their average value. Inserts of variable *VB* were prepared before the experiments and measured by microscope BK5 as well as measured and analyzed via SEM technique. Tool wear were considered as a key factor affecting the surface integrity in the real industrial practice whereas other parameters are usually kept constant. Flank wear affect the mechanical and thermal load of machined surface as well as the time period within the machined surface is exposed to severe plastic deformation at elevated temperatures which in turn affect degree of surface structure transformations.

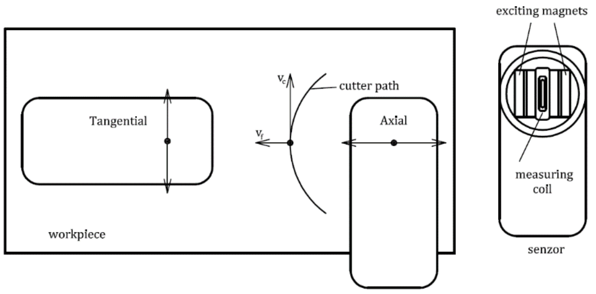
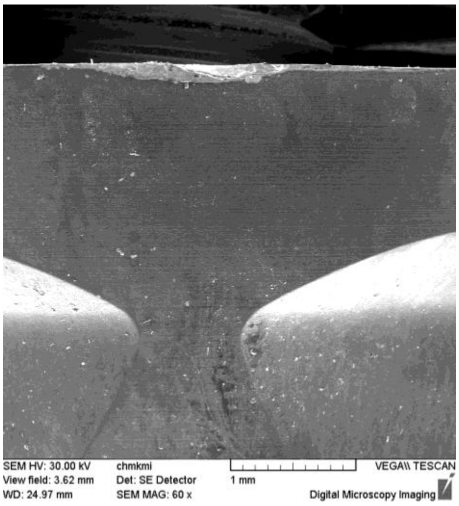
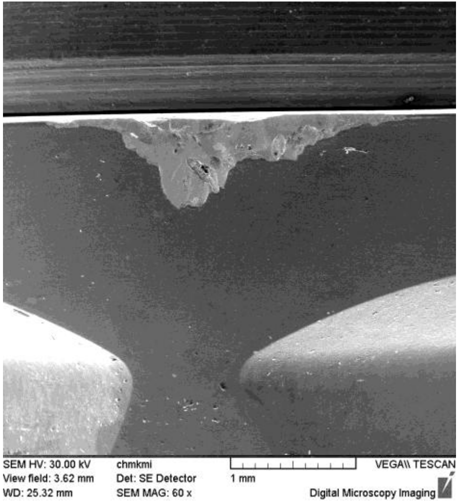


Figure 1. Sensor positioning

BN measurement was performed by the use of RollScan 300 and software package µScan in the frequency range of 10 to 1000 kHz (magnetizing frequency 125 Hz, magnetizing voltage 10 V). Each BN value was determined by averaging of 10 consecutive BN bursts (5 magnetizing cycles). Due to strong surface anisotropy, 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. To reveal the microstructure transformations induced by milling 10 mm long pieces were sectioned and routinely prepared for metallographic observations (etched by 5% Nital for 10s). Except metallographic observation also SEM images were taken from the surfaces.



a) VB = 0.2 mm

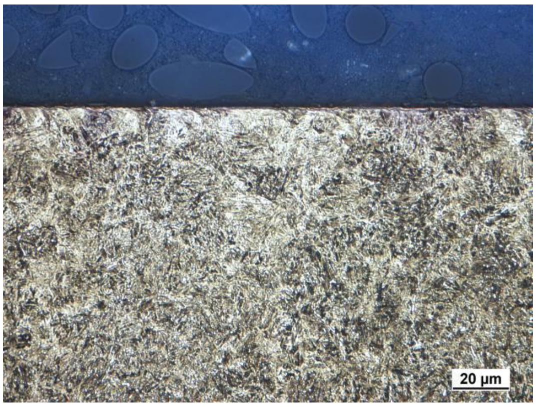


b) VB = 0.6 mm

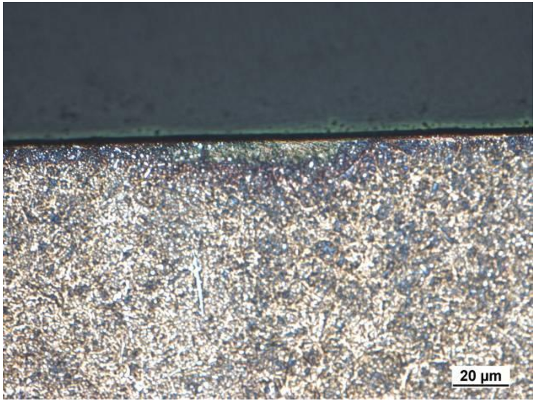
Figure 2. Flank wear of inserts, SEM

3 RESULTS OF EXPERIMENS

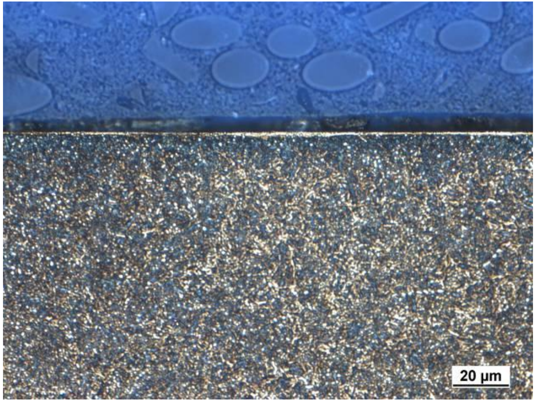
Fig. 2 depicts the different phases of flank wear VB. Hard turning operations are not usually performed with inserts of flank wear VB above 0.4 mm in order to avoid the excessive cutting forces and the corresponding stability of machining. On the other hand, the flank wear is a major factor affecting the thickness of HAZ as well as WL, see Fig. 3. For this reason, quite high VB were used to produce the surface of thick HAZ as well as WL; thus making more remarkable specific aspect of surface integrity investigated via BN. The specific aspects of surfaces after hard milling are associated with severe plastic deformation in the workpiece - tool contact at elevated temperatures. Fig. 4 shows that martensite matrix in the near surface region is preferentially oriented in direction of cutting speed at the expense of perpendicular (axial) direction. Fig. 4 also shows that also brittle carbides behave in a malleable manner. On the other hand, near surface region after grinding stay nearly untouched in terms preferential orientation and martensite needles stay randomly oriented. However, thickness of HAZ after aggressive grinding (as that shown in Fig. 5a) is much thicker than that as hard milled.



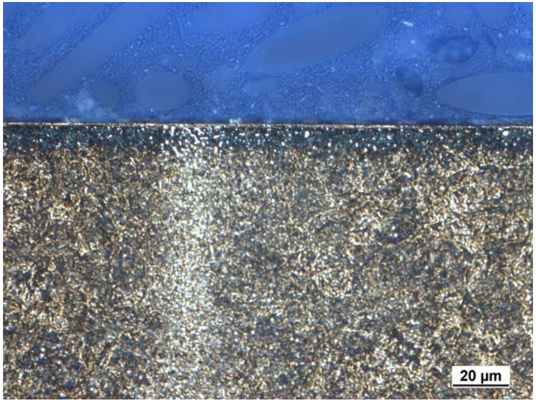
a) VB = 0.05 mm



b) VB = 0.4 mm



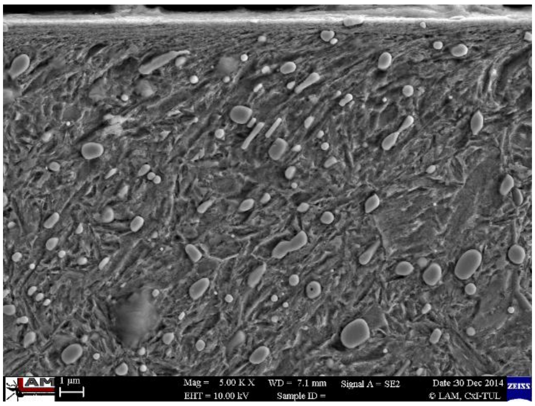
c) VB = 0.6 mm



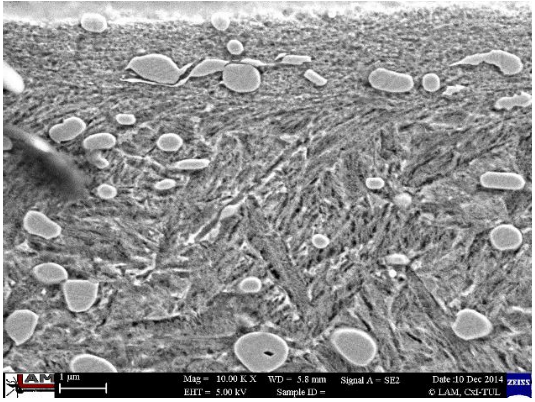
d) VB = 0.8 mm

Figure 3. Optical images of milled surface

Thermal softening of surface initiated by over tempering during grinding can increase BN values approximately 2 or 3 times (compared to as HT state), see Fig. 5a. Such increase is associated with occurrence of quite thick HAZ [Micuch 2014] [Neslusan 2011]. On the other hand, hard milling produces quite thin HAZ as well as WL. Being so, very high BN values obtained in the tangential direction (BN_T) for surfaces after hard milling for a certain degree of VB can not be explained due to thermal softening effect.

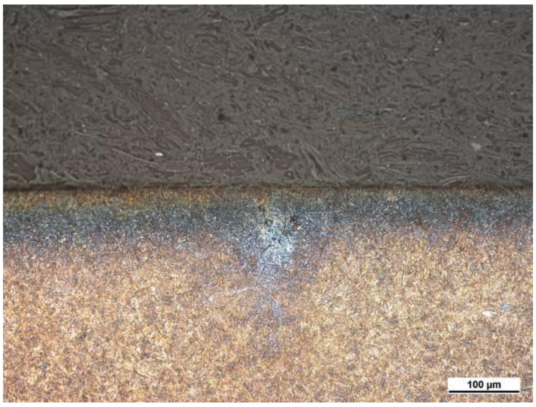


a) VB = 0.4 mm

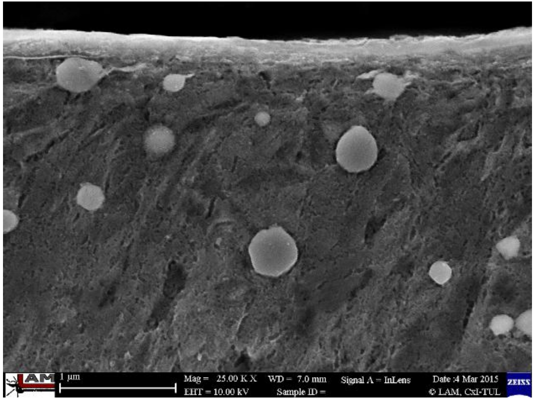


b) VB = 0.8 mm

Figure 4. SEM images of milled surface

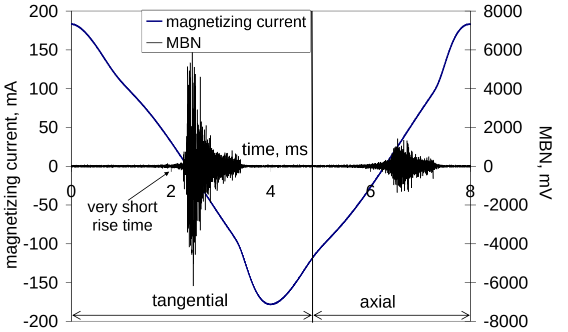


a) optical image of ground surface, BN = 300 mV, infeed 0,01 mm.s^{-1}

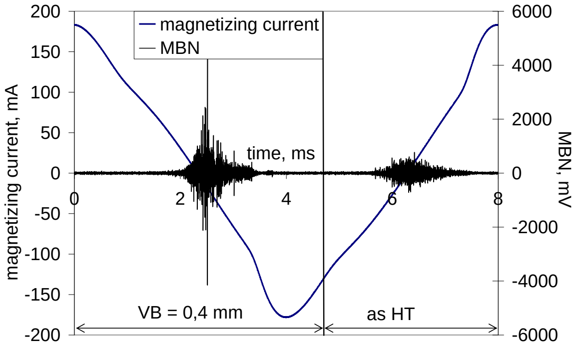


b) SEM image of ground surface

Figure 5. Optical and SEM images of ground surface



a) BN signal in tangential and axial directions for VB = 0.05 mm



b) BN signal in tangential directions - milled surface (VB = 0.05 mm) and for surface after HT

Figure 6. Raw BN signals for different directions and variable VB

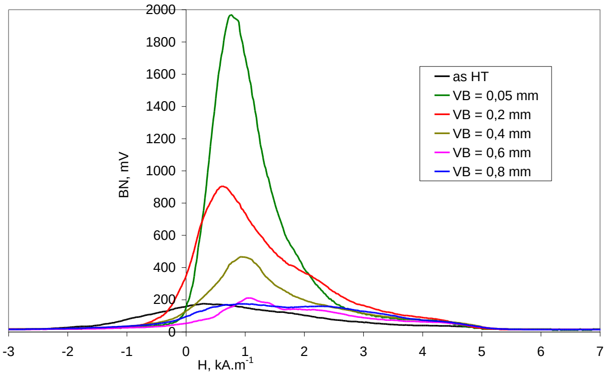


Figure 7. BN envelopes in the tangential direction

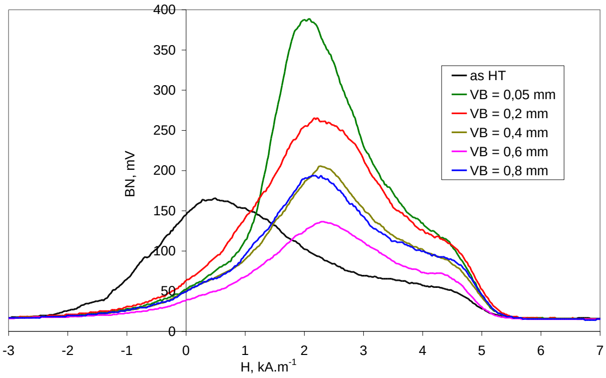


Figure 8. BN envelopes in the axial direction

Fig. 6 illustrates that BN emission is driven by VB and the corresponding structure transformations initiated by temperature cycle. This figure also reveals that hard milling produces surface of remarkable magnetic anisotropy, see also Fig. 9. Fig. 6 also show that shape of BN burst for surface produced by insert of VB = 0,05 mm is remarkably different than those obtained for the axial direction or higher flank wears. Immediate increase of BN pulses for VB = 0.05 mm (very short rise time) is due to specific alignment of BW in the near surface region. BWs oriented in the direction of cutting speed jump to the opposite direction in the form of one jump (or few jumps). On the other hand, axial direction of presence of higher volume of retained austenite in the matrix results in gradual increase of BN pulses magnitude along with increasing magnetic field, see Fig. 6. This quite specific mechanism of BW motion can be evidenced by the BN envelopes as that illustrated in Fig. 7. The BN envelope for VB = 0.05 mm exhibits steep increase along with increasing magnetic field whereas increasing VB results in more gentle increase of BN envelopes. On the other hand, BN envelopes in the axial direction are shifted to higher magnetic fields with moderate increase of BN envelopes for all VB (this is the hard axe of magnetization). This aspect is also associated with different character of BWs motion. BWs tend to rotate at lower magnetic fields and discontinuous jumps occur as soon as the magnetic field attains the critical (quite high) value.

While the axial direction exhibits low BN_A values within all applied VB, BN_T values are a function of VB. It is worth to mention that BN_T values are very high taking into consideration hardness of the samples after HT. The high degree of magnetic anisotropy and the high BN_T values are due to new alignment of BWs in the near surface region. Such remarkable magnetic anisotropy of the hard machined surfaces was previously reported [Neslusan 2014]. Main reason can be viewed in cutting temperature exceeding the Curie temperature needed to disturb domains configuration of ferromagnetic steel [Neslusan 2014]. 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). Fig. 9 depicts that the high BN_T values and the corresponding high anisotropy expressed in term of BN_T/BN_A ratio can be found for VB = 0.05 mm followed by progressive drop of BN_T values as well as the BN ratios.

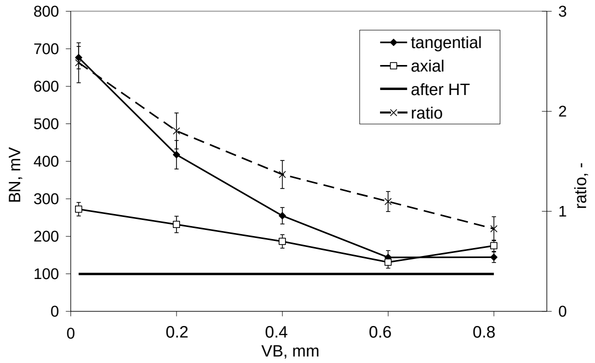


Figure 9. Influence of VB on BN and BN ratio

One might argue that BN_T values as well as degree of magnetic anisotropy would increase along with the more developed VB. Such statement is associated with increasing WL thickness and the corresponding layer in which BW are aligned in direction of cutting speed (BN_T direction). Thickness of WL along with more developed VB is due to 2 effects: (i) increasing contact temperature along with more developed VB, (ii) longer time interval within the machined surface undergoes severe plastic deformation at elevated temperatures. Fig. 4 shows that martensite matrix (and some carbide precipitates) is preferentially oriented in the tangential direction at the expense of the axial direction. Along with more developed VB preferential alignment penetrates deeper beneath the free surface. Such microstructure observations would associate increasing BN_T values as well as ratios. However, BN_T values and BN ratios are decreasing along with VB since increasing WL thickness is connected with increasing volume of retained austenite in the surface [Brandt 1995] [Guo 2004]. Retained austenite is the matrix is referred as a non ferromagnetic phase strongly hindering BWs motion which in turn means lower magnitude of BN. Volume of retained austenite in the matrix increases from 15% for surfaces produced by inserts of VB = 0.05 mm up to 45% for surfaces produced by inserts of VB = 0.6 mm.

4 CONCLUSIONS

Concept in which hard milled surfaces could be monitored is quite different from that applied for ground surfaces. As it was mentioned above, increasing BN values on the ground surfaces can be easily linked with increasing degree of thermal softening. On the other hand, hard milling process produces remarkably different state of surface integrity expressed in many terms. On the one hand, surface should be monitored in two perpendicular directions. The high BN values as well as ratios usually indicate the low surface damage expressed in terms of WL thickness a vice versa.

Industrial experience indicates that the high BN emission after hard milling or turning (when hard turning or milling is performed as a roughing cycle before grinding) can result in certain difficulties when surface after finishing grinding is monitored via BN technique. As it was mentioned, the high BN emission after grinding is associated with surface burn due to overtempering. Typical thickness of the layer ground off by finishing grinding is about 0,2 ÷ 0,3 mm. However, in production large bearings (or large components) some areas affected by previous hard milling or turning are not fully removed by grinding and retain below the ground surface. Being so, it could be difficult to distinguish between the high values originated from hard milling or overtempering during grinding. As a consequence of this some parts after grinding could be referred as thermally damaged despite correctly performed finishing grinding.

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