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Anisotropic Magnetic Properties of MilledBearing Steel Surface

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For many reasons, the steel surfaces are machined to obtain required physical properties. Suitable methods are required for the management and control of the manufacturing processes, which are simultaneously sufficiently robust and sensitive. The non-destructive testing methods, sensitive to the magnetic properties of the surface, are very suitable for this purpose. The Barkhausen noise (BN) measurement, which reveals the discontinuous movement of the magnetic domains in the thin surface layer during magnetisation reversal process is very robust, while magneto-optical Kerr effect (MOKE) method, using polarized light for orientation measurements of magnetic domains at the surface, is very sensitive and provides detailed information about hysteresis curves (HC) of the materials. In this contribution our results obtained on the milled 100Cr6 bearing steel are presented. These properties were obtained by MOKE laboratory measurements and bring very interesting facts about the magnetisation reversal process, which depends on the orientation of the magnetic field with respect to the cutting direction. Our results clarify the strong anisotropy of BN, which is observed during the industrial application of this method.

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1. Introduction

To impart desired surface properties, steels can be machined by various methods. Commonly used hard milling strongly affects microstructure and physical properties of material surface. The Barkhausen noise (BN) measurement has a high industrial relevance as a technique suitable for the detection of structural alterations of surfaces, as well as assessment of the residual stress state. The stress fields and microstructure depend on each other and affect the BN in a synergistic manner [1]. BN is associated with the cyclic magnetization of a ferromagnetic material as it is a result of nucleation and reconfiguration of magnetic domains and the corresponding Bloch walls (BWs) motion. The motion of BWs is usually pinned by precipitates, dislocations, grain boundaries, and other lattice imperfections, which cause discontinuous movement of BWs [2–4]. The surface integrity, expressed in terms of residual stresses, hardness alterations or structural transformation, is correlated with BN values obtained from the surface. The residual stress is reflected in anisotropic magnetic properties.

The magneto-optical Kerr effect (MOKE) provides sensitive method for observing the magnetisation processes on the material surface. It relies on the fact, that ferromagnetic media have optical anisotropy that changes the state of linearly polarized light. The polarization direction of incident light is rotated upon reflection by a small Kerr angle. The rotation angle is directly related to the magnetization direction within the probing region of the light. A Wollaston prism can be used to transform the Kerr rotation into a change of intensity of the transmitted beams [5].

Here we report on the detailed study of BN and of magneto-optically measured hysteresis curves (HC), of hard milled surfaces on a frequently used bearing steel. Very strong magnetic anisotropy has been discovered which is related to the residual stress and altered microstructure. The magnetic properties of the layer affected by machining were determined by both methods, MOKE and BN. Comparing these results we reveal the nature of ongoing processes.

2. Experimental materials and conditions

The experimental study was carried out on the OVAKO through-hardened bearing steel 100Cr6 (according to EN 10027-1) on samples of hardness 61 HRC and 45 HRC. See Table for chemical composition.

Chemical composition of the studied material. TABLE

Component	Cr	C	Mn	Si	S	Fe
wt. %	1.50	0.97	0.35	0.25	<0.015	balance

The studied surfaces of material were prepared by hard milling operation. Hard milling (conditions: FA4 AV, dry, cutting inserts made of cemented carbides R300-1240E-PM, tool holder R300-050Q22-12M 262489, $a_p = 0.25$ mm, $v_f = 112$ mm min^{-1}, $n = 500$ min^{-1}) initiates high temperatures and considerable hydrostatic pressure at contact point with the cutting edge. The temperature in the tool-workpiece interface exceeds Currie temperature [6]. Very anisotropic, huge tensile residual stresses remains in surface layer after milling as a result of plastic deformation [7].

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In the article, direction parallel to the cutting direction is considered to be tangential (t) and the normal is perpendicular (p). Defined directions correspond to the principal axes of the tensor of residual stress. Residual stresses after the machining, measured by X-ray diffraction on the X'Pert PRO diffractometer ({211} α-Fe, CrK_α, X'Pert PRO) were $\sigma_t = 528$ MPa in tangential direction and $\sigma_p = 278$ MPa in perpendicular direction.

2.1. Magneto-optical Kerr effect method (MOKE)

In order to investigate the magnetization reversal processes, both components of the surface magnetization, parallel and perpendicular to the in-plane applied field, were measured as a function of the magnetic field intensity. The experimental setup is shown in Fig. 1.

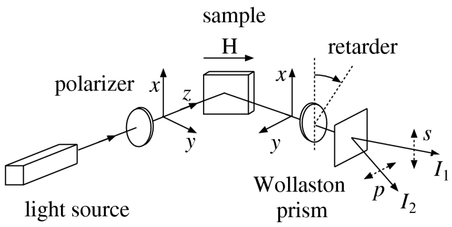

Fig. 1. The MOKE experimental setup.

A laser beam with the wavelength of 650 nm and power of 5 mW, amplitude modulated at the frequency 50 kHz was used. The incident angle was 45° and the MOKE was measured at the reflection angle 45° (zero order of diffraction). The component of magnetization, parallel to the incident plane, was measured as a consequence of the linear dependence of the conversion reflection coefficients $r_{sp} = r_{ps}$ on the longitudinal magnetization [8]. The light penetration depth is less than 100 nm. The component of magnetization, measured when the field is parallel to the incident plane, will be named longitudinal and when the field is perpendicular to the incident plane it will be named transversal. For each sample four hysteresis curves (HC) (tangential longitudinal and transversal and perpendicular long. and trans.) were measured in the same experimental conditions.

2.2. Measurement of Barkhausen noise

The BN was measured with Microscan 500 device with the standard probe. The affected area is about 1 cm^2. Magnetizing coil was powered by harmonic voltage with amplitude 10 V in the frequency range 10 Hz–1 kHz. The penetration depth of magnetic field depends on frequency, but is still large compared to the thickness of altered surface. Presented results were measured at the frequency of 100 Hz due to the highest signal to noise ratio. The sampling frequency was 2.5 MHz. The BN magnitude was calculated from RMS value adjusted for noise. Depending on the probe orientation the BN in tangential or perpendicular direction is obtained.

3. Experimental results

The hard milled surfaces were prepared on the 61 HRC and 45 HRC materials. Details of these surfaces captured by stereomicroscope are presented in Fig. 2a for 61 HRC and in Fig. 2b for 45 HRC steel. The roughness of the surfaces is of the order of 10 μm with evident periodicity in the perpendicular direction.

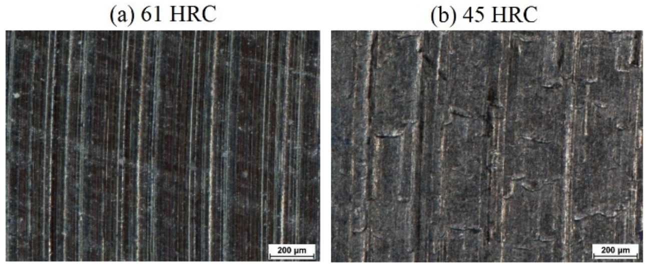

Fig. 2. The examined hard milled surfaces, 61 HRC (a) and 45 HRC (b).

The BN was measured on both samples at the magnetisation frequency of 100 Hz and adjusted from the thermal noise. The mean BN magnitudes obtained on the 61 HRC samples were 200 mV and 46 mV in tangential and perpendicular direction respectively (4:1 anisotropy ratio). The example of measured signal is shown in Fig. 3a,b. The magnitudes obtained on 45 HRC were 251 mV and 46 mV in tangential and perpendicular direction respectively (5:1 anisotropy ratio), see Fig. 3c,d. It should be noted that the BN values, anisotropy ratio and signal to noise ratio are frequency depended in general.

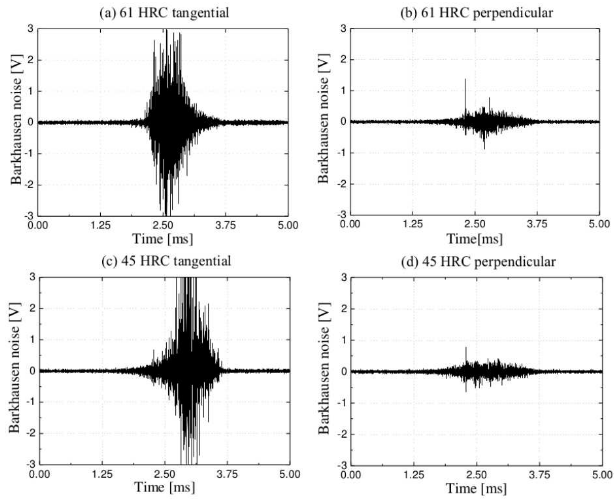

Fig. 3. The measured BN signals on the hard milled surface. 61 HRC sample tangential (a) and perpendicular (b) direction. 45 HRC sample tangential (c) and perpendicular (d) direction.

It is shown in Fig. 4.a,b that HC measured in the tangential direction is widened, while the HC measured in perpendicular direction, is extremely narrowed to the zero coercivity and remanence. This behaviour may be explained by presence of the strong magnetoelastic uniaxial easy axis in the tangential direction. The magnetisation reversal tends to occur in two distinct steps if the magnetic field is applied in the perpendicular direction.

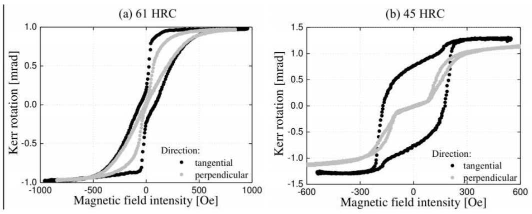

Fig. 4. The measured MOKE hysteresis curves on the hard milled surfaces of the 61 HRC (a) and 45 HRC (b).

3.1. The magnetic reversal of 45 HRC hard milled

The above presented results demonstrate that magnetic reversals processes are principally different, depending on the direction of the applied magnetic field. To clarify ongoing process, both longitudinal and transversal components of magnetization were measured by MOKE on both samples. Bigger differences were obtained on the 45 HRC.

The results presented in Fig. 5a,b show that the magnetic reversal process in the case of the tangential magnetic field consists of the switch by 180°, with a negligible transversal component. During this continuous nucleation and growth of opposite-oriented domains, the sample passes through the demagnetized state. In the case of perpendicular magnetic field, (shown in Fig. 5c,d) the reversal process consists of the coherent rotation of magnetization, followed by two-step 90° switches, and completed by coherent rotation. The magnetization never drops below 25% of the saturated value, which is the reason why the sample cannot be demagnetized by alternating perpendicular field. These results are consistent with those obtained on epitaxial Fe film [9].

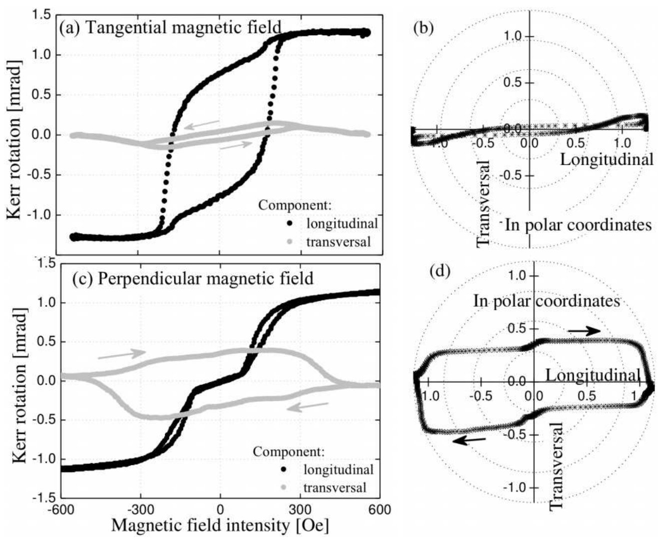

Fig. 5. The magnetization reversal process measured by MOKE on the milled 45 HRC. Both components of magnetization, longitudinal and transversal, are presented as a function of magnetic field intensity (a,c) as well as in polar coordinates (b,d).

4. Conclusions

The magnetization reversal of the hard milled bearing steel OVAKO 100Cr6 has been studied by MOKE and Barkhausen noise emissions. The observation of both magnetization components allows us to investigate the reversal process and reveal the nature of measured BN. We demonstrated that MOKE method can be successfully used on polycrystalline surface with roughness of the order of 10 μm.

The measured results show that the uniaxial magnetic anisotropy, parallel to the cutting direction, is an important controlling factor that affects the nature of magnetic reversal processes. From transversal MOKE measurements, it is obvious that uniaxial anisotropy promotes domain nucleation and magnetic reversal in one step, if the magnetic field was applied in tangential direction and contrary, it supports the rotation of magnetization in the plane, combined with two-step switching, if the magnetic field was perpendicular to the machining direction. It can be deemed that the reversal process in tangential direction is performed using 180° domain walls, while in perpendicular direction it is performed using 90° domain walls. The very anisotropic BN can be explained by the assumption of the 90° domain walls being bad sources of BN in contrast to 180°, which are significant sources of BN. As a result of mentioned factors, the stronger uniaxial anisotropy is reflected in very anisotropic BN, with measured ratio up to 5:1 in orthogonal directions.

Acknowledgments

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