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Laser investigations of surface roughness of cobalt single crystal and its influence on the magnetic domain image observed in SEM

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In this paper, the influence of the roughness on a surface perpendicular to the axis c of a cobalt single crystal on the quality of magnetic domain image recorded with the aid of a scanning electron microscope (SEM) is examined. The basic parameter of the surface roughness, *i.e.* the r.m.s. deviation of the profile σ was determined based on optical reflexometric method (He-Ne laser). From the results obtained, it can be seen that in order to diminish significantly the topographic contrast, in other words, to improve the quality of the magnetic domains image, the examined surface should be prepared in such a way that its r.m.s. profile deviation σ be not less than 0.19 μm.

1. Introduction

The examinations of phase transitions of single crystals of cobalt are carried out via either slow heating (several K/min.) as is the case in conventional methods [1] or quick heating (about 10^6 K/s) with the aid of pulse laser radiation [2]. In both methods, the structure of the magnetic domains is observed (in the plane perpendicular to the c axis) in a scanning electron microscope (SEM). The quality of the domain image observed in this way depends on both the magnetic contrast (of the first type) as well as topographic contrast (surface roughness) [3]. The roughness has also an essential influence on the dynamic effects of its interaction with the nanosecond laser pulses caused, among others things , by the light pressure and the pulse recoil [4], and the processes depending on the effective surface of interaction which, in turn, is a function of roughness [5]. The laser radiation interaction may result in modification of the surface roughness (due to melting or slight evaporation) of the surface layer [6]. Therefore, we should know the parameters of the surface roughness before its irradiation in order to state to what change (modification) they were subject after laser action.

The surface roughness is usually characterized by the r.m.s. deviation of the profile σ and the correlation length T [7]. It is obvious that in this kind of examinations these parameters are best measured (estimated) by a touchless method, for instance, an optical one, based on the light scattering at a rough surface. It is a common view that the theoretical model of electromagnetic radiation scattering of a rough surface is presented in most complete way in work [8] by Beckmann and Spizzichino.

The purpose of this work is to carry out an experimental investigation of the influence of the roughness of the surface perpendicular to the c axis of a cobalt single crystal on the quality of the magnetic domain image recorded with the help of a scanning electron microscope. The basic parameter of roughness (measured most frequently), *i.e.*, the r.m.s. of the profile deviation σ, was determined using the reflexometric optical method (He-Ne laser). A number of surfaces of different roughness were produced in a way it was done in works [3], [9], [10], *i.e.*, by polishing with abrasive papers of different grain gradations, polishing powders and also electrolytically.

2. Principle of measurements

The determination of the dependence of surface roughness on parameters of the field of the reflected electromagnetic wave is a basic task of the theory describing the reflection of the electromagnetic radiation from a rough surface [8]. From the practical point of wiev, the most general and important model of a surface is the one in which the roughness parameters are treated as those of a random process. Then the solution of this problem is reduced to finding the random characteristics of the scattering field of the electromagnetic wave.

Usually, two methods of calculation of parameters of the reflected electromagnetic wave are mentioned: perturbation methods and that of Kirchhoff. The choice of the method is determined by the limiting conditions of its applicability, defined by the microgeometry of the surface roughness. The first method is applied to the surfaces of unevenness that is small compared to the wavelength λ and not changing smoothly (mildly) on distances comparable with the light wavelength. In contrast to this, the other method is used to the surfaces of unevenness comparable to the wavelength λ. It is commonly believed that this kind of metal surfaces is produced using conventional mechanical methods of processing (for example, those used in this work).

The Kirchhoff method, also called tangent surface method, applied to describe the problems of electromagnetic wave diffraction at a rough surface is similar to that known in the light diffraction theory [11]. The equations presented in this work follow from the monograph [8]. In this method, the calculations of the electric field strength vector at the observation point are carried out based on the incident wave vector at the rough surface and the normal derivative of the latter. In these calculations, the Green's theorem and Helmholtz integrals are used. This vector on the surface and its normal derivative are determined under the assumption that the reflection of the wave incident at each point of the surface is the same as that at an infinite surface tangent to this point at the surface. This assumption is justified if the curvature radius of the microunevenness is sufficiently big compared to wavelength λ of the incident wave. This is equivalent to the requirement that the correlation length T and the wavelength λ fulfil the condition $T \gg \lambda$. In the Kirchhoff method it is also assumed that the examined surface of stochastic (normal, stationary, ergodic) roughness is nominally flat and perfectly conducting; the screening (covering) and multiple reflections are neglected; the incident wave is a plane and linearly polarized one of the electric vector **E** being located either in the incident plane or in that perpendicular to the latter. The observation plane is sufficiently far from the surface and therefore the scattered waves can be considered as plane while the area A of the illuminated surface fulfils the condition $A \gg \lambda^2$.

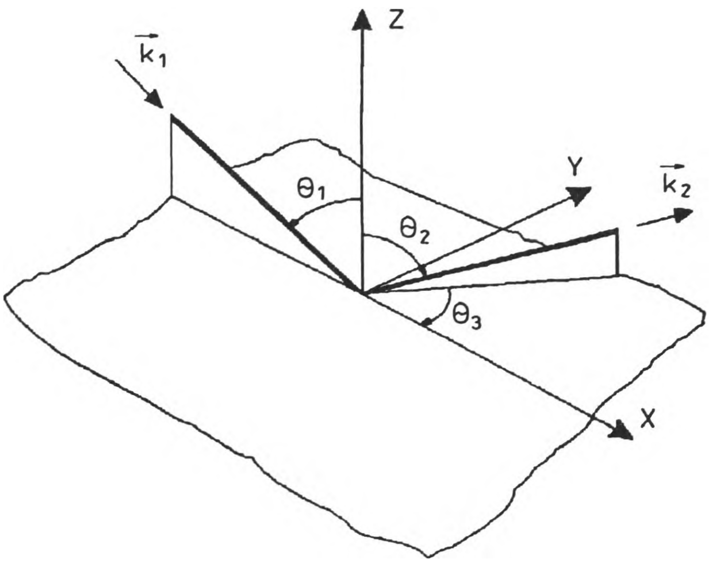

Fig. 1. Geometry of scattering, $\mathbf{k}_1$, $\mathbf{k}_2$ — wave vectors of the incident and scattered waves, respectively

Under the above conditions the authors of the monograph [8] obtained the following expression for the light intensity I reflected in the direction of mirror reflection (Fig. 1) from a two-dimensional rough surface (for $g \ll 1$):

$$I(\theta_1 = \theta_2,\ \theta_3 = 0) = r(\theta_1) I_0 \exp(-g)\left[1+\frac{\pi T^2}{A}\right] \tag{1}$$

where

$$g = \frac{16\pi^2\sigma^2\cos^2\theta_1}{\lambda^2}, \tag{2}$$

and $r(\theta_1)$ is a reflection coefficient.

In order to determine the r.m.s. deflection σ the experiment was carried out in geometry allowing the photodetector to record the light energy flux confined in a small solid angle (about 0.0001 srd, [12]). Then it can be assumed that $I = \text{const}$ within this angle and that only the light energy flux corresponding to the "mirror component" I_z is recorded. If, in addition to that, the field A of the illuminated surface and correlation length T fulfil the condition $A \gg T^2$, equation (1) will take the form

$$I_z = r(\theta_1) I_0 \exp\left[-\frac{16\pi^2\sigma^2\cos^2\theta_1}{\lambda^2}\right]. \tag{3}$$

The recording of I_z for different angles of light incidence θ_1 (if λ, I_0, $r(\theta_1)$ are known or when it is assumed that $r(\theta_1) = \text{const}$) makes it possible to determine σ on the basis of (3). The measure of σ is then the tangent of the slope angle for the straight line: $\ln I_z = f\left(\frac{\cos^2\theta_1}{\lambda^2}\right)$.

3. Experiment

3.1. Measuring apparatus

The scheme of the apparatus used in the investigations is shown in Fig. 2. The light source was a He-Ne laser ($\lambda = 0.6328$ μm) of HNA-188-S type, 60 mW power and plane-polarized light (the electric vector of the wave was perpendicular to the incidence plane). The incidence angle of the laser beam illuminating the sample was

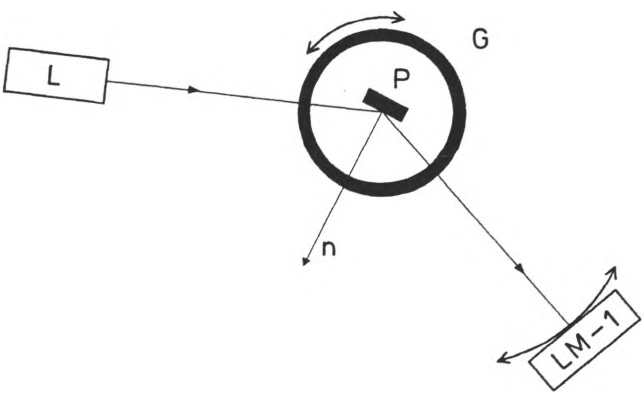

Fig. 2. Scheme of the measuring system (L — He-Ne laser, P — sample, G — goniometer ZRG-3, LM-1 — laser radiation power meter)

established (changed) with the aid of the ZRG-3 goniometer on which the sample was fixed. The intensity (power) of the light reflected was recorded on LM-1 laser power meter. The diameter of the irradiated area was 2 mm. The applied geometry of examination made it possible to record the intensity of the light scattered within a small solid angle (about 0.0001 srd).

3.2. Methodology of examinations

A sample of cobalt single crystal of thickness 4.0 mm was the subject of examinations. Different roughness of the surface (0001), *i.e.*, that of different values of σ was produced by successive grinding and polishing with the help of abrasive papers and polishing pastes of different sizes of grains, including electrolytic polishing. After each kind of treatment the sample was subject to optical examinations by both measuring I_z for different angles of incidence θ_1 within the interval 84.5–86.0 degrees and investigating the sample through a BS301 SEM and recording the image of the magnetic domain structure on the (0001) surface for the same working parameters of the microscope (current intensity of the electron beam was equal to 100 pA, the inclination angle of the Everhart–Thornley detector with respect to the sample surface was 25°).

3.3. Results of optical investigations

The results of optical investigations are presented in Figure 3 and the table. In Fig. 3, the plots can be seen illustrating the relation $\ln Y = \sigma^2 X$ which results from tranforming Eq. (3), where Y and X are respectively equal to:

$$Y = \frac{r(\theta_1) I_0}{I_z}, \tag{4}$$

and

$$X = \frac{16\pi^2 \cos^2\theta_1}{\lambda^2}. \tag{5}$$

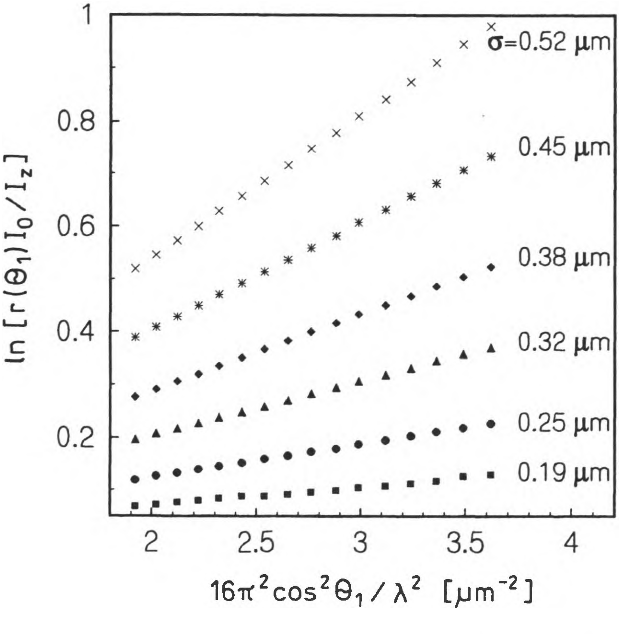

Fig. 3. $\ln Y$ as a function of X $\left(Y = \frac{r(\theta_1) I_0}{I_z},\ X = \frac{16\pi^2 \cos^2\theta_1}{\lambda^2}\right)$

The values of the reflection coefficient $r(\theta_1)$, necessary to calculate the profile deviation σ, were calculated (within the examined range of angles) based on the corresponding data (the refractive indices n and absorption k as dependent on the incidence angle of the wave of the length 0.6328 μm), which are presented in papers [13], [14]. Additionally, in the calculations has been assumed that $r(\theta_1) = r_s(\theta_1)$.

Table. Values of the parameter g dependent on σ and θ_1

$[\sigma \pm S_\sigma]$ (μm)	r	θ_1(°)	g
0.19 ± 0.018	0.8031	84.5	0.08
		86.0	0.04
0.25 ± 0.023	0.8342	84.5	0.14
		86.0	0.08
0.32 ± 0.029	0.8235	84.5	0.23
		86.0	0.12
0.38 ± 0.034	0.8142	84.5	0.33
		86.0	0.17
0.45 ± 0.041	0.8104	84.5	0.46
		86.0	0.25
0.52 ± 0.047	0.8754	84.5	0.62
		86.0	0.33

Analogously to the case considered in paper [15], a linear dependence of the $\ln Y$ on the parameter X was obtained. This means that in the examinations carried out the contribution of the diffusion reflection to that in the mirror direction can be neglected. From the results obtained it is also visible (Table) that the value of parameter σ determined in this way (σ^2 being an average empirical coefficient of linear regression of standard deviation S_σ [16]) changes within the interval from 0.19 μm to 0.52 μm. Experimental value of the correlation coefficient r (Table) is greater than the critical value of the correlation coefficient $\rho = 0.6226$ (at the significance level $\alpha = 0.01$).

The greatest value of the parameter g (Eq. (2)) calculated for $\sigma = 0.52$ μm and the incidence angle $\theta_1 = 84.5$ degrees is equal to about 0.62, while the smallest value (for $\sigma = 0.19$ μm and angle $\theta_1 = 86.0$ degres) is about 0.08. Thus, in the examinations performed the condition $g < 1$ is surely fulfilled and in part of them we have even $g \ll 1$ (Table), which justifies the application of Eq. (1).

3.4. Results of SEM examinations

The most characteristic results of examinations carried out with a scanning electron microscope (SEM) are presented in Fig. 4. These are four photos of the surface (0001) of the sample examined. These photos were made while keeping the working parameters of the microscope the same (sample inclination, beam current). Each surface was prepared (polished) in a way allowing us to obtain surfaces of different values of the parameter σ. Thus, the best readable image of the magnetic domain is visible on the photo A ($\sigma = 0.19$ μm). Such a clear and bright image of the domains means that the contribution of the topographic contrast to the effective contrast is negligible. In this case, the magnetic contrast is mainly responsible for the image quality. At the same time, the image recorded on the photo C ($\sigma = 0.52$ μm) is an

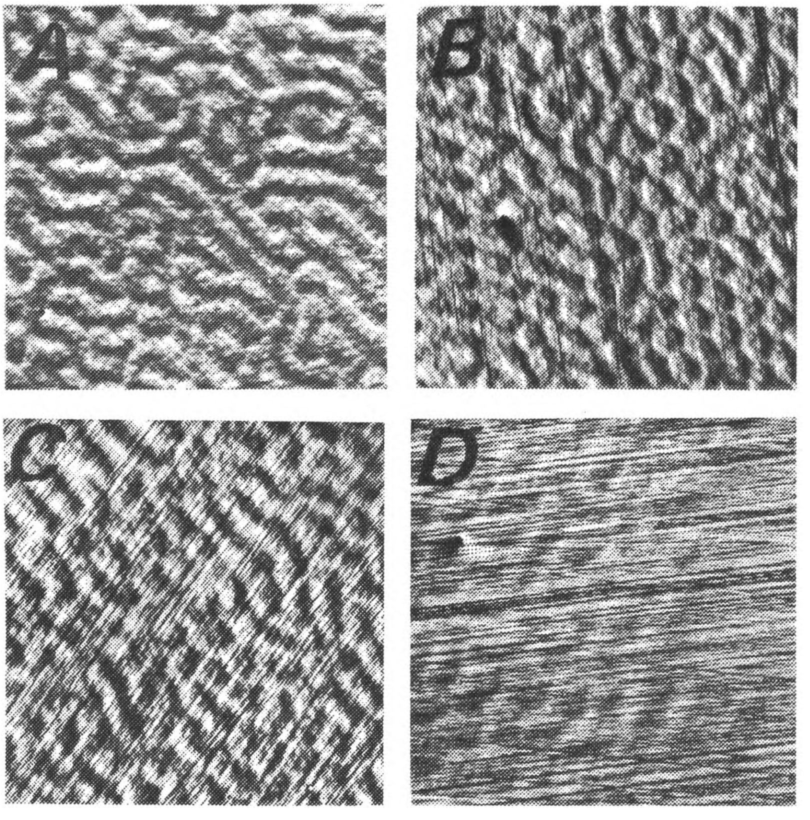

Fig. 4. Photos (A, B, C, D) illustrate the domain image as a function of the value of parameter σ: A – $\sigma = 0.19$ μm, B – $\sigma = 0.25$ μm, C – $\sigma = 0.38$ μm, D – $\sigma = 0.52$ μm

illustration of the opposite situation, here the magnetic contrast is small. In this case, the high surface roughness has the main influence on the effective contrast characterized by high surface roughness. In this situation, the magnetic phase transition (martensiting transition) will be difficult to observe.

4. Summary

The results obtained here can be very useful in the examination (by the SEM method) of magnetic phase transition between the domain (open and closed) structures. It is just then that small values of magnetic contrast (of first kind) appear. This means that in order to eliminate (or significantly diminish) the topographic contrast the surface of the examined sample should be sufficiently smooth (small r.m.s. value of the profile deviation σ).

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