The Effect of the Anomalous Absorption on the Diffraction Contrast on 90° Bloch Walls

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Dedicated to Prof. Dr. G. Borrmann on the occasion of his 65th birthday

The diffraction contrast produced by 90° ferromagnetic domain walls in X-ray transmission topographs is calculated. Two cases are considered: very low and very high normal absorption. The results indicate that the difference in contrast on walls having opposite signs of lattice tilt is due to the anomalous absorption and depends on the magnitude of normal absorption. These theoretical results are in agreement with the contrast observations in X-ray transmission topographs taken from Fe–3 wt%Si single crystal samples using different plate thickness and different radiations.

1. Introduction

The X-ray diffraction contrast on ferromagnetic domain walls was observed by several authors using different topographic techniques and different materials (e. g. Refs. [1–3]). The contrast is caused by the change of magnetostrictive deformation across the walls. It was shown that a 90° domain wall is visible only if

$$(\boldsymbol{m}_2 - \boldsymbol{m}_1)\,\boldsymbol{g} \neq 0\,, \qquad (1)$$

where $\boldsymbol{m}_1$ and $\boldsymbol{m}_2$ are unit vectors parallel to the magnetization in the two adjacent domains and $\boldsymbol{g}$ is the diffraction vector [4]. In order to explain theoretically the origin of the contrast, it was supposed that the 90° domain wall can be considered as a coherent twin boundary. This model is consistent with observed effects and it was directly proved in Reference [5]. A quantitative comparison between the calculated and observed contrast was performed for a special case of 110 diffraction on a (001) plate containing domain walls parallel to the $(1\bar{1}0)$ planes [6]. It was shown that the wall appears as a dark band if the product (1) is positive and a white one if it is negative. The contrast increases with the change of the glancing angle across the wall $\delta\,\Delta\vartheta$, i. e. with the effective tilt of the diffracting planes. The calculations were simplified supposing the absorption to be so high that only the waves with lower anomalous absorption can traverse the crystal, but the magnitude of the absorption was not taken into account. However, it was observed [7] that, while the visibility condition (1) remains valid, the rules determining the contrast are more complicated. In particular, the contrast was found to be dependent on the absorption, i. e. on the value of μt (μ is the linear absorption coefficient, t is the sample thickness). The aim of this paper is to calculate the theoretical dependence of the contrast on the absorption and to compare the results with experiments.

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2. Theory

A special case will be considered: 110 reflection on a plate cut from a Fe-3 wt% Si single crystal with surfaces parallel to the (001) plane, the sample being tilted around the $\boldsymbol{g}$ vector (Figure 1). The boundary conditions are that of a symmetrical Laue case with respect to both the surface and the inter-

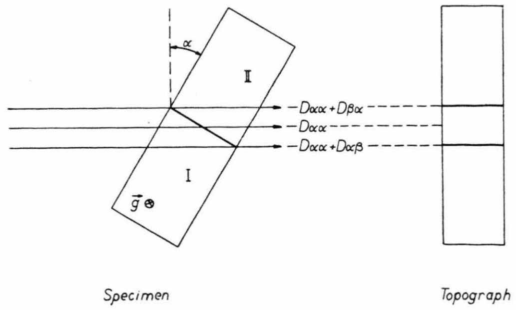


Fig. 1. Scheme of the experimental arrangement. The sample is tilted from its usual vertical position around the $\boldsymbol{g}$-vector. The wall between the domains I and II, normal to the surface, is visible as a band in the X-ray transmission topograph. The band width depends on the sample thickness and on the angle of tilting α.

face between the domains. At the interface, a tilt of diffracting planes appears:

$$\delta \varDelta\vartheta = \pm 3\,\lambda_{100} \sin\alpha\,, \qquad (2)$$

λ_{100} being the magnetostrictive constant and α the angle of tilting [8]. The sign of $\delta\varDelta\vartheta$ is that of the product (1) irrespective of the sense of tilting [8]. Using the dynamical theory of diffraction of a plane wave on a perfect crystal (e. g. [9]), the amplitudes of the four waves D'_{hi}, $h=0$, H, $i=\alpha,\beta$ existing in the domain I can be found for each polarization direction.

At the interface, each wave excites four new waves, the diffraction conditions being slightly changed in the domain II. No phase change is supposed to appear at the interface. The waves have different wave vectors so that a phase shift between them appears at the exit surface resulting in interference fringes. As we are interested in the mean total intensity, we shall not consider the interference. (The fringes visible on domain walls in the topographs are due to zig-zaged walls, as shown in [10].) The amplitudes of the eight waves with wave vectors in the reflected direction are:

$$\begin{aligned} D_{\alpha\alpha} = D'_{0\alpha} D''_{\mathrm{H}\alpha} + D'_{\mathrm{H}\alpha} D''_{0\alpha} = &-\tfrac{1}{4}\{1-\eta(\eta^2+1)^{-1/2}\}\,[(\eta+\delta\eta)^2+1]^{-1/2} \\ &-\tfrac{1}{4}(\eta^2+1)^{-1/2}\{1+(\eta+\delta\eta)\,[(\eta+\delta\eta)^2+1]^{-1/2}\}\,, \end{aligned} \qquad (3.1)$$

$$\begin{aligned} D_{\alpha\beta} = D'_{0\alpha} D''_{\mathrm{H}\beta} + D'_{\mathrm{H}\alpha} D''_{0\beta} = &\tfrac{1}{4}\{1-\eta(\eta^2+1)^{-1/2}\}\,[(\eta+\delta\eta)^2+1]^{-1/2} \\ &-\tfrac{1}{4}(\eta^2+1)^{-1/2}\{1-(\eta+\delta\eta)\,[(\eta+\delta\eta)^2+1]^{-1/2}\}\,, \end{aligned} \qquad (3.2)$$

$$\begin{aligned} D_{\beta\alpha} = D'_{0\beta} D''_{\mathrm{H}\alpha} + D'_{\mathrm{H}\beta} D''_{0\alpha} = &-\tfrac{1}{4}\{1+\eta(\eta^2+1)^{-1/2}\}\,[(\eta+\delta\eta)^2+1]^{-1/2} \\ &+\tfrac{1}{4}(\eta^2+1)^{-1/2}\{1+(\eta+\delta\eta)\,[(\eta+\delta\eta)^2+1]^{-1/2}\}\,, \end{aligned} \qquad (3.3)$$

$$\begin{aligned} D_{\beta\beta} = D'_{0\beta} D''_{\mathrm{H}\beta} + D'_{\mathrm{H}\beta} D''_{0\beta} = &\tfrac{1}{4}\{1+\eta(\eta^2+1)^{-1/2}\}\,[(\eta+\delta\eta)^2+1]^{-1/2} \\ &+\tfrac{1}{4}(\eta^2+1)^{-1/2}\{1-(\eta+\delta\eta)\,[(\eta+\delta\eta)^2+1]^{-1/2}\}\,. \end{aligned} \qquad (3.4)$$

The parameter η can be expressed in the form

$$\eta = \varDelta\vartheta / d\,D \qquad (4)$$

where $\varDelta\vartheta$ is the deviation from the exact Bragg angle, d is the interplanar distance and D is the diameter of the hyperbola forming the dispersion surface. The variation of this parameter at the interface is

$$\delta\eta = \delta\,\varDelta\vartheta / d\,D\,. \qquad (5)$$

Two cases will be considered:

1. The absorption is very low, i. e. $\mu t = 0$. Then the mean intensity is

$$I = \sum D_{hk}^2\,. \qquad (6)$$

From the integration over the total diffraction range it follows

$$R = \pi[(\delta\eta)^2+2]/[(\delta\eta)^2+4]. \qquad (7)$$

2. The normal absorption is so high that the waves with higher anomalous absorption have no significant intensity at the exit surface. If the wavefield crosses the interface approximately in the middle of the sample, only the waves with the amplitudes $D_{\alpha\alpha}$ are important. If the wavefield crosses the interface near either the entrance or the exit surface, the waves with the amplitudes $D_{\alpha\beta}$ or $D_{\beta\alpha}$ become significant as well (see Figure 1).

Supposing that the waves pass half their way in the domain I and the other half in the domain II, the intensity may be written in the form

$$\begin{aligned} I = D_{\alpha\alpha}^2 \exp\{-\tfrac{1}{2}\mu t\,[2-|P|\,\varepsilon(\eta^2+1)^{-1/2} \\ -|P|\,\varepsilon((\eta+\delta\eta)^2+1)^{-1/2}]\}\,, \end{aligned} \qquad (8)$$

where P is the polarisation factor and $\varepsilon = F_H''/F_0''$ is the ratio of imaginary parts of the H and 0 components of the structure factor. The integrated intensity

$$R(\delta\eta, \mu t) = \int_{-\infty}^{\infty} I(\eta, \delta\eta, \mu t)\,\mathrm{d}\eta \qquad (9)$$

was calculated for $\mu t = 0$, 4, 10, $P=1$ and supposing $\varepsilon = 1$. For a wall with $\delta\eta = 0$, the intensity equals that of the ideal crystal. Therefore the ratio $R(\delta\eta, \mu t)/R(0, \mu t)$ represents the contrast on the wall and is plotted as a function of $\delta\eta$ in Figure 2.

3. Comparison with Experiments and Discussion

In Fig. 2, the value of μt appears as a parameter of the curves $R(\delta\eta)/R(0)$. The curve for $\mu t = 0$ has no exact physical meaning and is shown for

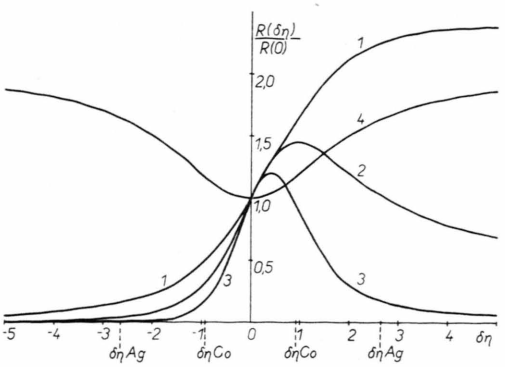
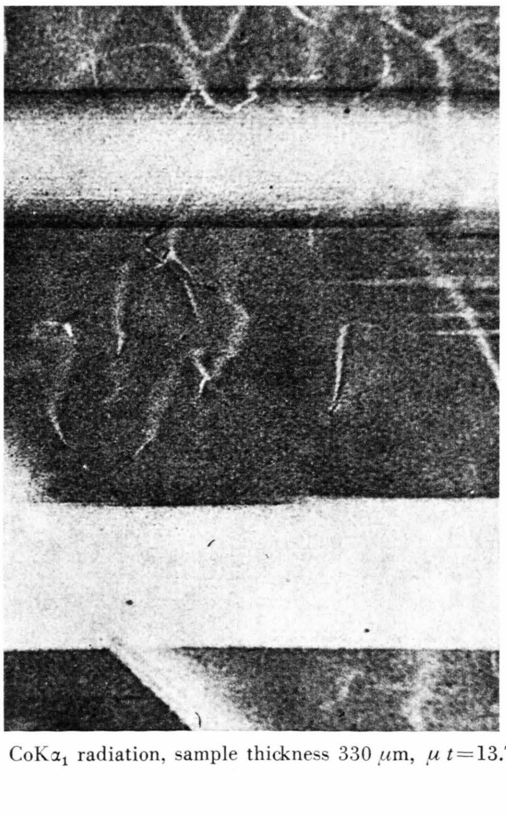


Fig. 2. Calculated contrast vs. $\delta\eta$. Curves 1, 2 and 3 ($\mu t=0$, 4 and 10 respectively) are calculated from Eq. (8), curve 4 from Equation (7).

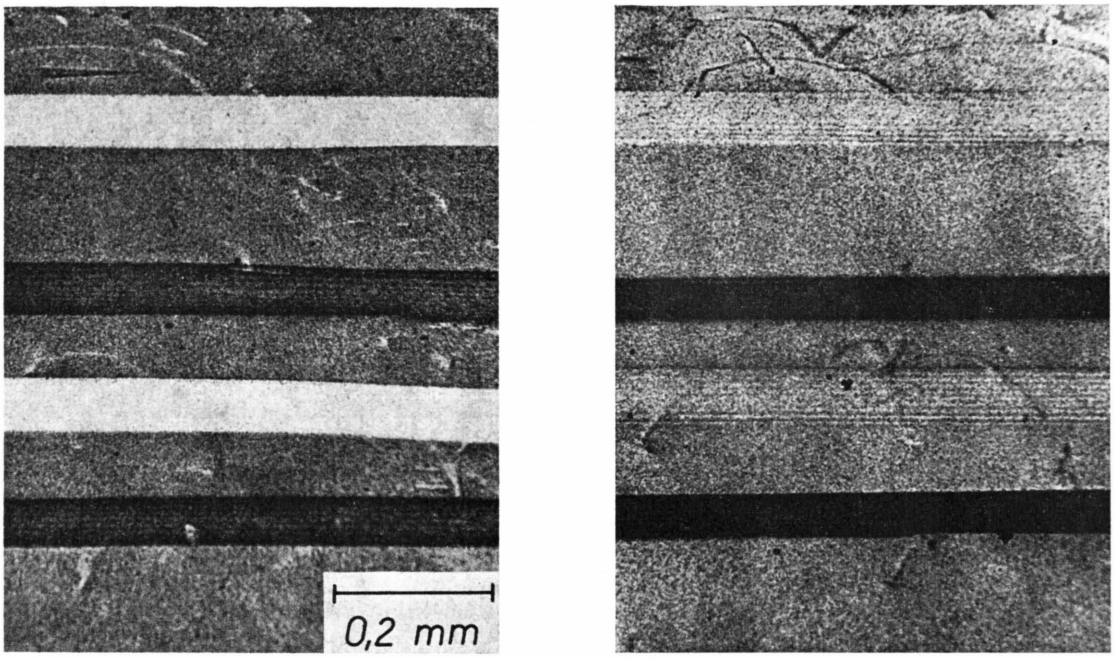
comparison with previous calculations [6]. Nevertheless, it is quite a good approximation for small $|\delta\eta|$ and not too high absorption. It was actually in good agreement with experiments, when $|\delta\eta| < 1$ and $\mu t \sim 5$ was used [6]. For $\mu t = 0$ the Eq. (7) should be used which shows that the contrast grows with $|\delta\eta|$ up to the asymptotic value 2. There is no difference in contrast for opposite signs of $\delta\eta$. This difference appears only if the anomalous absorption is taken into account. This asymmetry decreases with increasing μt and $|\delta\eta|$.

In Fig. 3, four X-ray transmission topographs (Lang's technique [11]) made under similar conditions are shown which differ by the sample thickness and the radiation used. For the same $\delta\Delta\vartheta = 8.25''$ ($\alpha = 30°$, $\lambda_{100} = 2.7 \times 10^{-5}$), $\delta\eta$ depends on the value of D, i. e. on the wavelength, and equals $\delta\eta_{\mathrm{Co}} = 0.93$, $\delta\eta_{\mathrm{Ag}} = 2.65$, respectively (see Figure 2). In the topographs, the darker band corresponds to a wall with $\delta\eta > 0$, the lighter one to that with $\delta\eta < 0$. Comparing the density in the darker bands in Fig. 3 a, b, c, the greatest contrast appears with CoKα radiation, $\mu t = 5.0$ (Figure 3 c). Really, the theoretical contrast is approximately at the maximum of the corresponding curve (Figure 2). With higher absorption ($\mu t = 13.7$), even this darker band has lower density than its surroundings (Fig. 3 a), in agreement with the theory. With AgKα radiation, $\mu t = 5.1$ (Fig. 3 b), the darker band is approximately as dense as its neighbourhood, although the absorption is nearly the same as in Fig. 3 c; this is due to the greater value of $\delta\eta$ (see Figure 2). In all



a) CoKα_1 radiation, sample thickness 330 μm, $\mu t = 13.7$;

b) AgKα_1 radiation, sample thickness 330 μm, $\mu t = 5.1$;



c) CoKα_1 radiation, sample thickness 120 μm, $\mu t = 5.0$; d) AgKα_1 radiation, sample thickness 120 μm, $\mu t = 1.9$.

Fig. 3. X-ray transmission topographs with images of 90° domain walls. 110 reflection, $\alpha = 30°$.

those three cases the lighter band has much lower density than the surrounding crystal, as corresponds to the theory. The density should be compared in the middle of the bands, where the conditions of the calculation are fulfilled. At the edges of the bands, the density is higher due to the contribution of the waves $D_{\alpha\beta}$ and $D_{\beta\alpha}$ to the total intensity. In Fig. 3 d (AgKα radiation, $\mu t = 1.9$), the density in the lighter band is nearly the same as that of the perfect crystal, while the darker band is even denser than in Figure 3 a, b, c. This case forms a transition between the two theoretically considered cases.

4. Conclusions

The calculations based on the dynamical theory of diffraction show that the difference in contrast on 90° domain walls having opposite signs of the product $(\boldsymbol{m}_2 - \boldsymbol{m}_1)\,\boldsymbol{g}$ is due to the anomalous absorption and depends on the value of μt. These results are fully verified by experiments. The greatest difference appears for medium values of μt. The difference is less striking for extreme values of μt: both types of walls appear darker than the perfect crystal if μt is small and lighter if μt is high.

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