The magneto-X-ray Kerr effect in ferritic steel

1989 J. Phys.: Condens. Matter 1 9261

(http://iopscience.iop.org/0953-8984/1/46/017)

J. Phys.: Condens. Matter **1** (1989) 9261–9266. Printed in the UK

The magneto-x-ray Kerr effect in ferritic steel

Jan Bonarski and Jan Karp
Academy of Mining and Metallurgy, Department of Physical Metallurgy, al. Mickiewicza 30, 30-059 Krakow, Poland

Received 5 July 1988, in final form 23 February 1989

Abstract. Magneto-x-ray rotation of polarised radiation arising from ferritic steel has been observed. The application of this phenomenon to x-ray quantitative phase analysis and, in particular, to the analysis of textured steel is proposed. The details of the proposed method need further study.

1. Introduction

The polarisation capability of electromagnetic waves is one of their characteristic features. This phenomenon is fairly well known in the optical range of spectrum (λ = 4000–7500 Å), which is still not known in the x-ray range (λ = 0.5–2.5 Å). If linearly polarised light falls on a ferromagnetic substance placed in a magnetic field, its plane of polarisation will be rotated as a reflection to the primary beam. This is known as the magneto-optical Kerr effect [1]. The radiation which has passed through the investigated material is a valuable information source about its structure, degree of perfection, thickness, etc. If the beam which has crossed the material (or has been reflected) is plane polarised and additionally Bragg's condition is fulfilled, this is more advantageous from the viewpoint of detailed information.

Optical activity caused by the external magnetic field of some ferromagnetic metals (Fe, Co and Ni) and other substances (e.g. Fe_3O_4, $CuOFe_3$, Fe_3C and MnS) has been found to occur [2, 3]. A schematic diagram of the Kerr effect is shown in figure 1.The magneto-optical Kerr effect for alloys such as Fe–Mn, Fe–Co, Co–Cr and Cu–Mn–Al (Hausler's alloy) is already known [4]. The result of the Kerr effect is rotation of the plane of vibration ($\boldsymbol{E}$ vector) in the reflected beam when compared with the incident beam. The magnitude of this rotation is proportional to the magnetisation vector $\boldsymbol{M}$ for the material [5]:

$$\Delta\varphi = KM \tag{1}$$

where K is a scale factor and $\Delta\varphi$ is the angle of rotation. The Kerr effect for ferritic steel has also been observed in the x-ray range. This is a very important result for practical applications. For a suitable strength of the magnetic field the rotation of the polarisation plane is independent of the steel texture. Then the observed effect can be applied to the x-ray quantitative phase analysis (XQPA) of textured steel. The problem of XQPA of textured material is still the subject of much discussion because the methods already known have not been successful.

0953-8984/89/469261 + 06 $02.50

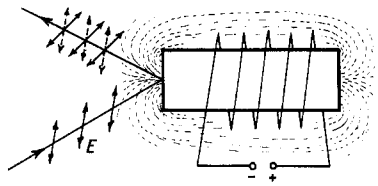

Figure 1. Schematic diagram of the Kerr effect.

2. Experimental details

In order to detect magneto-x-ray rotation in the Bragg-reflected beam for the sample under study, the experimental set-up shown in figure 2 was used. An x-ray tube with a Mo anode was employed. The polariser–monochromator was an LiF crystal with its face parallel to the (100) planes. The 800 reflection has a Bragg angle θ near 45°; so 2θ is approximately equal to 90° and the Bragg-reflected beam would have a high degree of polarisation. Cu Kα radiation has been similarly polarised by a KCl crystal (440 reflection) [6].

The polariser crystal LiF mounted on the Fedorov table was fixed to a horizontal goniometer. The sample was placed on the axis of the goniometer but also in the aperture of an electromagnet which provided a collimated magnetic field of about 1.8 T. An analyser crystal (also LiF) was mounted on the other arm of the goniometer. The scintillation counter was mounted on a special device fixed to a movable arm which rotated about the same axis as the analyser crystal. Both the analyser and the counter were rotated together and thus the angle between the plane of polarisation of the plane-polarised x-rays and the plane of reflection (denoted as the azimuth φ of polarisation could be varied. The azimuth could also be read from a graduated circle by means of a mark on the counter arm (figure 3).

Two types of sheet steel were used as samples (table 1). The intensity of the 311 reflection (00H18N12 steel) and of the 211 reflection (08J steel) were obtained as follows. The analyser crystal was first set at the peak of the Bragg reflection with the x-ray counter in the horizontal plane (azimuth $\varphi = 0°$). Then it was turned away from this arrangement

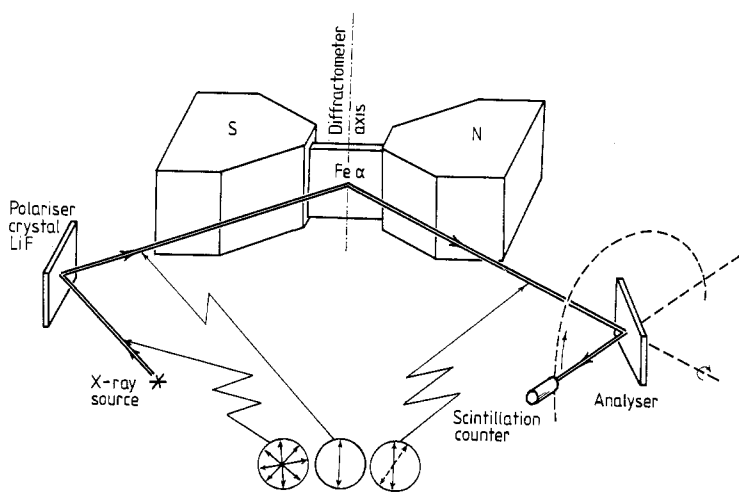

Figure 2. Schematic diagram of the set-up for the magneto-x-ray experiment.

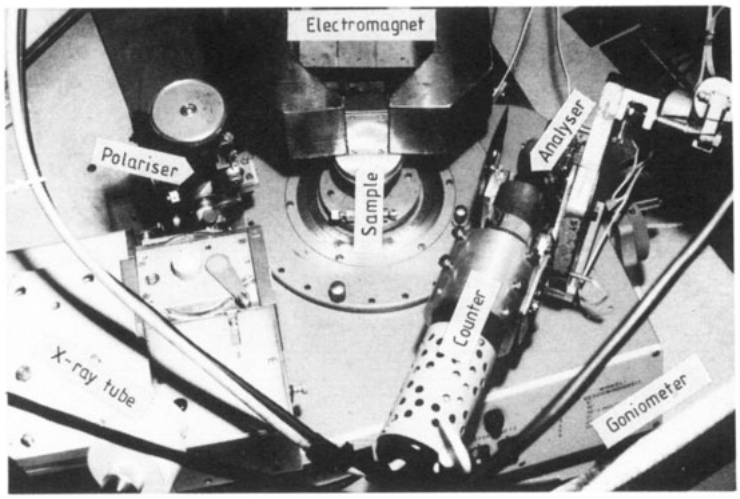

Figure 3. View of the experimental stand.

Table 1. The steels investigated.

	Chemical composition (wt%)								
Designation	C	Mn	Si	P	S	Cr	Ni	Mo	Al
00H18N12, austenitic	0.05	0.95	0.015	—	0.007	17.35	12.70	0.21	—
08J, ferritic	0.04	0.26	0.005	0.007	0.013	—	—	—	0.03

by 0.25° by means of a step motor. The Bragg angle 2θ was fixed. The intensity of the peak was measured for angles φ varying from 0 to 90° in the absence and subsequently in the presence of a magnetic field, five times for each step. The range of the φ-angle could be changed.

3. Interpretation of the experimental results

The obtained degree p of polarisation defined by

$$p = (I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp}) \tag{2}$$

where $I_{\parallel}$ and $I_{\perp}$ are the diffracted intensities measured in the reflection (horizontal) plane and in a plane perpendicular to this, respectively, was about 0.82 (figure 4). Figure 5 shows non-smoothed experimental curves. The upper curves in both figure 5(a) and figure 5(b) correspond to the diffraction intensity for the sample in the absence of the magnetic field and the lower curves to that in the presence of the field. This intensity difference in both cases is due to a change in the peak position caused by the magnetostriction effect. In general, the intensity of the 311 reflection for austenite is lower than that of the 211 reflection for ferrite. This difference results from the structure and the geometrical factors of these peaks [7]. In applied experimental geometry some ellipticity of the reflected beam may occur, especially when the angle between the plane

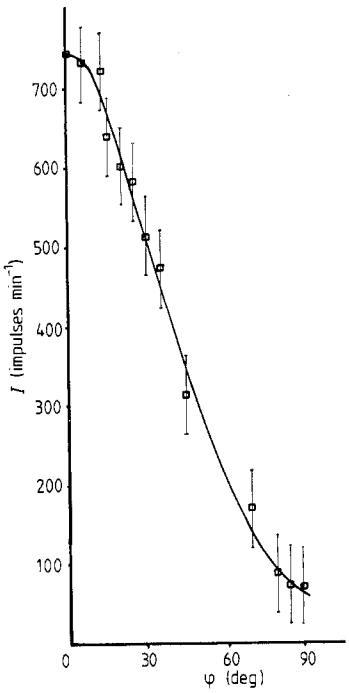

Figure 4. Curve of the intensity of the incident beam against the angle φ ($\varphi = 0°$ when the counter is in the diffraction plane). $p = (I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp}) \simeq 0.82$.

of vibration and the reflection plane is not exactly equal to 90°. This misorientation may visibly increase when the beam is reflected again. The result of this effect is observable in the form of decreased intensity. However, the visible relative lateral shift $\Delta\varphi$ of the curves for ferritic steel is a very important result (see figure 5(*b*)). The evaluated magnitude of the shift is about 1°, i.e.

$$\Delta\varphi_F = 1 \pm 0.25°. \tag{3}$$

For austenitic steel (see figure 5(*a*)) no shift was observed and thus it can be written as

$$\Delta\varphi_A = 0 \pm 0.25°. \tag{4}$$

The shift (rotation $\Delta\varphi$) confirms the theoretical supposition resulting from optics (visible range of spectrum) [8–14].

According to quantum mechanics,

$$\Delta\varphi = m(\lambda, T)d|\boldsymbol{M} \times \boldsymbol{l}|/M \tag{5}$$

where $m(\lambda, T)$ is Verdet's constant, d is the length of the beam in the material, $\boldsymbol{l}$ is the beam direction and $\boldsymbol{M}$ is the magnetisation vector.

However, any analogy to the optical range must be made very carefully, because in the x-ray range the dynamical diffraction in the magnetic field and the interaction between radiation and atoms should be considered.

4. Conclusion

Apparently the magneto-x-ray rotation observed for ferritic steel can be applied to the quantitative phase analysis of two-phase austenitic–ferritic (martensitic) steel and, in

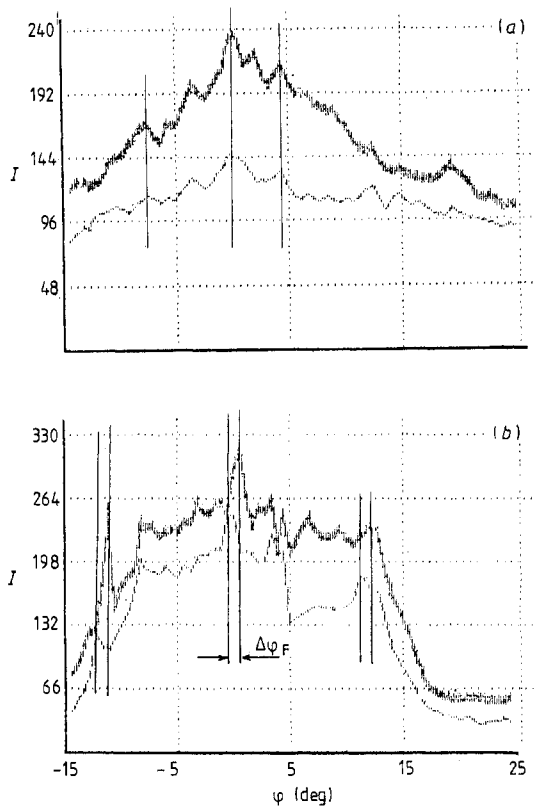

Figure 5. Experimental curves of magneto-x-ray rotation for (*a*) austenitic steel (00H18N12) (311 reflection) and (*b*) ferritic steel (08J) (211 reflection): ——, specimen in magnetic field; ——, specimen without magnetic field.

particular, textured steels. This problem is still under discussion, because the x-ray methods are based on the integrated intensity of the diffraction peaks which varies for any particular material depending on whether the material is textured or non-textured. However, no single, relatively simple and simultaneously correct universal method exists for the analysis of textured materials [15–17].

Consequently, the following formulae based on the magneto-x-ray rotation are proposed for the quantitative phase analysis of textured steels;

$$\Delta\varphi_{F(M)} \simeq V_{F(M)}. \tag{6}$$

Assuming that $V_A + V_{F(M)} = 1$, we can write

$$V_{F(M)} = C\Delta\varphi_{sample}/\Delta\varphi_{F(M)} \tag{7}$$

where V_A is the volume fraction of austenite, $V_{F(M)}$ is the volume fraction of ferrite(martensite), $\Delta\varphi_{sample}$ is the measured magneto-x-ray rotation, $\Delta\varphi_{F(M)}$ is the rotation arising from pure ferrite(martensite) in the same conditions (Bragg's angle, magnetisation vector and sufficiently strong magnetic field) and C is an unknown scale factor.

The proposed method is based on the measurement of one diffraction peak only. Because the rotation $\Delta\varphi_{F(M)}$ is not usually large, the applied magnetic field in the experiment must be sufficiently strong. According to equation (5), the rotation depends

on the material constant $m(\lambda, T)$; therefore, studies of this dependence should be continued. For more accurate investigations, another strong source of radiation is needed initially. Completely linearly polarised synchrotron radiation and about 1000 times stronger than the Mo Kα radiation used here is the best x-ray source for further investigations.

Acknowledgments

The authors are grateful to Professor Stanisław Gorczyca for his support for the experiment and to Docent Zdzisław Obuszko for his valuable assistance during the construction of the special electromagnet.

References

[1] Kerr J 1877 *Phil. Mag.* **3** 321; 1878 *Phil. Mag.* **5** 161
[2] du Bois 1890 *Phil Mag* **29** 253
[3] Loria St and Martin P 1912 *Ann. Phys., Paris* **38** 889
[4] Barker S G 1917 *Proc. R. Soc.* **29** 1
[5] Loria St 1953 *Postepy Fiz.* **5** 2
[6] Ramaseshan S and Ramachandran G N 1954 *Proc. Indian Acad. Sci.* A **39** 20
[7] Cullity B D 1978 *Elements of X-ray Diffraction* 2nd edn (Reading, MA: Addison-Weseley)
[8] Voigt W 1908 *Magneto- und Elektrooptik* (Leipzig: Teubner)
[9] Hirsch E 1893 *Wien. Ann.* **48** 446
[10] Klitzing K H 1933 *Z. Phys.* **85** 240
[11] Darwin C G 1935 *Proc. R. Soc.* **151** 512
[12] Sokolow A W 1953 *Zh. Eksp. Teor. Fiz.* **50** 161
[13] Moriya T 1968 *J. Appl. Phys.* **39** 1042
[14] Balanda M and Niziol S 1975 *Postepy Fiz.* **26** 3
[15] Karp J and Pofelska I 1979 *Hutnik* **46** 253
[16] Karp J 1984 *Hutnik* **7–8** 267
[17] Karp J, Bonarski J and Klimanek P 1989 to be published