# MAGNETIC CORRELATIONS IN ALUMITE STUDIED BY NEUTRON DEPOLARISATION

W.H. Kraan and M.Th. Rekveldt,
Interfacultair Reactor Instituut, Delft University of Technology
Mekelweg 15, 2629 JB Delft, The Netherlands

Abstract - A polarised neutron beam (λ=0.36 nm) is transmitted both perpendicularly and at skew angles through Alumite films of various geometries. Three-dimensional depolarisation analysis is performed.

A model containing the geometry of the needles in the alumite and a parameter K for the excess correlation between their magnetic moments over the reduced magnetisation is applied to describe the data. It appears that K becomes more negative as the magnetic interaction between the needles increases.

## Introduction

The last few years many perpendicular recording experiments are presented in literature, most of which are carried out on CoCr. Alumite was proposed as a possible medium for perpendicular recording [1,2]. At present alumite is mainly used as a model material for verifying magnetic measurements and studying hysteresis properties of "films" with perpendicular anisotropy.

Such films effectively consist of a 2-dimensional hexagonal lattice of ferromagnetic iron needles of a few µm length and 0.01-0.1 µm in diameter with their axes perpendicular to the film plane. This geometry makes alumite film an almost ideal two-dimensional system to study magnetic correlations between ferromagnetic particles. Such studies may contribute to understanding the recording properties of such media. The neutron depolarisation technique used in this and our earlier papers has proved to be a very valuable technique for such studies [3,4].

In analogy with the correlation theory for domains in a continuous medium, advanced earlier by Rekveldt [5], we introduced [3] the parameter K:

$$K = \langle n_i, n_{i+1} \rangle - m^2. \qquad (1)$$

which describes the excess correlation between the magnetisation directions $n_i$ and $n_{i+1}$ in neighbouring needles over the square of the reduced magnetisation m. Our subsequent paper [4] dealt with one alumite (YS-623) in the remanent states after in-plane and after perpendicular saturation.

In the present paper a number of alumites of various filling fractions and needle diameters was studied by transmission experiments with polarised neutrons, followed by 3-dimensional polarisation analysis. The magnetic correlations between neighbouring needles will be determined as a function of the interaction strength of a specific needle with the magnetic field due to its neighbours.

## Samples

We deal here with the so called "rigid alumites" prepared at Yamaha R&D Laboratory on 1.9 mm thick Al substrates. Details on their preparation are found elsewhere [2]. The relevant properties are given in Table I.

Manuscript received September 5, 1989.

Table I: properties of alumites [6]

| Sample No. YS | thick-ness t [µm] | pore diam δ [nm] | cell size c [nm] | filling fr. f eq.(7) | $H_c$ [Oe] | $U^{*)}$ eq. (12) | $K^{*)}$ |
|---|---|---|---|---|---|---|---|
| -617 | 4.5 | 30 | 62 | 0.21 | 1488 | 17 | -0.2 |
| -618 | 1.5 | 30 | 62 | 0.21 | 1269 | 5.7 | 0.05 |
| -619 | 4.5 | 43 | 91 | 0.20 | 950 | 11 | 0.1 |
| -620 | 1.7 | 43 | 91 | 0.20 | 875 | 4.1 | 0.2 |
| -621 | 4.0 | 58 | 113 | 0.24 | 531 | 9.3 | 0.05 |
| -622 | 1.1 | 58 | 113 | 0.24 | 494 | 2.6 | 0.3 |
| -623 | 4.3 | 43 | 62 | 0.43 | 956 | 33 | -0.3 |
| -624 | 1.0 | 43 | 62 | 0.43 | 838 | 7.7 | 0.0 |
| -625 | 4.7 | 43 | 113 | 0.13 | 1050 | 5.9 | 0.1 |
| -626 | 1.6 | 43 | 113 | 0.13 | 1094 | 2.0 | 0.2 |

*) This paper

The meaning of δ is obvious; t is identified with the length of the needles. The pores are filled with Fe and appear to be arranged in a hexagonal pattern [2] of a cell size denoted c. The values for the coercive force $H_c$ are from magnetisation measurements in perpendicular fields by Tokushima e.a. [6] and checked by Huysmans e.a.[7]. The saturation magnetisation is in accordance (except for YS-623) with the "filling fraction" f calculated for an hexagonal pattern with cell and pore sizes listed in Table I, assuming that the pores are completely filled with Fe.

## Experimental

When a polarised neutron beam passes through an alumite film, the polarisation vector **P** performs a Larmor precession about the magnetic induction inside the ferromagnetic needles. The vector **P** can be adjusted in a polarisation turner along any one of the (x,y,z) axes of the laboratory system. By means of a second polarisation turner after transmission the component of **P** - as it emerges out of the sample - along any one of these axes can be analysed. Thus, a (3x3) depolarisation matrix $D_{ij}$ (i,j=x,y,z; Fig.1) can be measured.

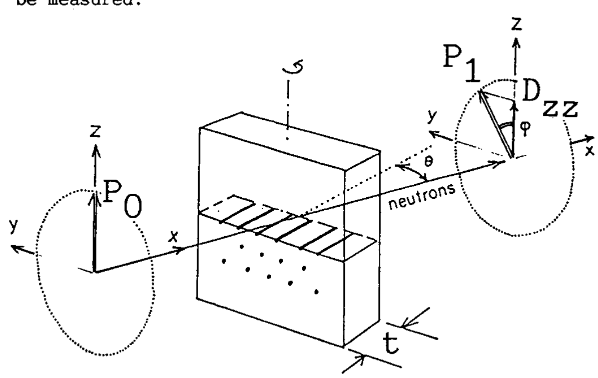


**Fig.1** Schematic view of the angle dependent neutron depolarisation experiment.

0018-9464/90/0100-0219$01.00 © 1990 IEEE

The angle $\theta$ between the normal to the film and the transmission direction is an additional variable.

For all alumites in Table I the complete depolarisation matrix was measured in the magnetic states:

(i) "as received" .

In addition, for YS-619, -623 and -624 data were taken in the remanent states:

(ii) after magnetisation to 10 kOe in-plane //z and
(iii) idem perpendicular to the plane.

To enhance the signal to be measured, data were taken from stacks of 4 substrates, each carrying an alumite film on both faces, instead of a single film. As a consequence, the outcome of the simulations outlined below must be raised to the power 8 before comparing with the experimental data.

In states (ii) and (iii) the samples were stacked with their remanence alternately parallel with +/-z and +/-x, respectively to cancel stray fields due to the remanence of the individual films. If not, the vector P will precess in this field before and after transmission through the films. This leads to a rotation of the (x,y,z) coordinate system, which becomes apparent as a non-zero value for the non-diagonal elements. From the outcome of these elements it was checked that these fields actually canceled.

## Model description

The model to interpret the data consists of Fe cylinders (needles) with length t and diameter $\delta$ with their axes perpendicular to the plane of the film, arranged in a hexagonal lattice with cell size c. The effect of the stray field outside the needles is neglected as appears from a schematic field calculation.

Since the transmission direction is varied by rotating the film about the z-axis, $D_{zz}$ for each $\theta$ equals the average cosine (taken over all trajectories) of the total precession angle $\Phi(\theta)$:

$$D_{zz} = \langle \cos\Phi(\theta)\rangle. \quad (2)$$

Formulas for the other diagonal elements follow from $D_{zz}$ by geometry.

$\Phi(\theta)$ is the sum of the precession angles $\phi_i$ through the individual needles along a trajectory:

$$\phi_i(\theta) = \pm\, 5.72 \times 10^8\, M_s \ell(\theta)\, \lambda = \pm\, \gamma\, \ell(\theta). \quad (3)$$

$\ell(\theta)$ [m] is the length of the trajectory through the needle, $M_s$[A/m] is the saturation magnetisation of Fe and $\lambda$[nm] is the neutron wavelength.

In the absence of magnetic correlations we may write

$$\langle \Phi^2(\theta)\rangle = \langle N(\theta)\rangle \, \langle \phi_i^2(\theta)\rangle, \quad (4)$$

where $\langle N(\theta)\rangle$ is the average number of needles along the trajectory. To account for correlations between the magnetisation directions of the needles along the trajectory, we multiply $\langle \phi_i^2\rangle$ in eq.(4) by (1+K)/(1-K), with K defined by eq.(1). In general $\phi_i(\theta)$ and hence $\Phi(\theta)$ are small, so the small angle approximation for the cosine is valid. Now, eq.(2). takes the form:

$$D_{zz}(\theta) = 1 - \langle N(\theta)\rangle \frac{\langle \phi_i^2(\theta)\rangle}{2} \left(\frac{1+K}{1-K}\right) . \quad (5)$$

The number $\langle N(\theta)\rangle$ equals the product of the area of the projection of a needle on the plane of the alumite film (taken along the neutron trajectory) and the 2-dimensional density $1/A_c$ of the needles:

$$\langle N(\theta)\rangle = (t\delta\sin\theta + A_p).(1/A_c), \quad (6)$$

where $A_c = \frac{1}{4}c^2\sqrt{3}$ is the cell area and $A_p = \frac{\pi}{4}\delta^2$ is the pore area. From this follows the filling fraction f:

$$f = A_p/A_c. \quad (7)$$

$\langle \phi_i^2(\theta)\rangle$ in eq.(5) is the average square of the precession angle in one needle. We take $\phi_i$ equal to $\gamma$ (eq.(3)) times the volume of a needle divided by its projection upon the plane perpendicular to the transmission direction. Hence:

$$\langle \phi_i^2(\theta)\rangle = \gamma^2 \left(\frac{A_p t}{(t\delta\sin\theta + A_p\cos\theta)}\right)^2. \quad (8)$$

To account for the non perfect alignment of the needles, we introduced in [3] a normalised gaussian distribution $W(\alpha_1,\alpha_2)$ of half width $\Delta$, $\alpha_1$ and $\alpha_2$ (insert of Fig.2) being the deviations of the orientation of a needle from the normal in two orthogonal directions. An average of eq.(5) weighed by $W(\alpha_1,\alpha_2)$ was taken over $\alpha_1$ and $\alpha_2$. For this average the quantity $\langle N(\theta)\rangle\langle \phi_i^2(\theta)\rangle$ in eq.(5) is transformed into an expression including $\alpha_1$ and $\alpha_2$. The result is written:

$$D_{zz}(\theta) = \iint d\alpha_1 d\alpha_2 \; W(\alpha_1,\alpha_2)\; D^*_{zz}(\theta,\alpha_1,\alpha_2). \quad (9)$$

Here the quantity $D^*_{zz}(\theta,\alpha_1,\alpha_2)$ results after substitution of eqs.(6) and (8) into (5):

$$D^*_{zz}(\theta,\alpha_1,\alpha_2) = 1 - \frac{\phi^2(\theta)}{2} \frac{f}{\cos^2\theta} \frac{1}{1+Q} \left(\frac{1+K}{1-K}\right) \quad (10)$$

with

$$Q = \frac{4t}{\pi\delta} \tan\left[(\theta-\alpha_1)^2 + \alpha_2^2\right]^{1/2}. \quad (11)$$

and f given by eq.(7).

This averaging is performed numerically, using the geometrical quantities t, $\delta$, c and $\Delta$, together with the magnetic correlation K as parameters. For the given values of t, $\delta$ and c (see Table I) the outcome hardly depends on $\Delta$ for $|\theta|>15°$. So in this $\theta$ region the correlation K remains the only parameter to be fitted to the experimental data.

Around $\theta=0$ on the other hand, the outcome appears to be extremely sensitive to the choice of both K and $\Delta$.

## Results and Interpretation

comparison between states (ii) and (iii)

Fig.2 contains the data for YS-619 in states (ii) and (iii). Around $\theta=0$ the element $D_{zz}$ in state (iii) appears to be dramatically lower than in state (ii). This is presumably due to the fact that in state (ii) half of the needles is "magnetically broken" as we suggested in [4]. Beyond $|\theta|=5°$ the difference in $D_{zz}$ between both states reverses.

The same is found in YS-623 and 624. This effect may also be expressed in terms of the parameter K. For this purpose, $D_{zz}$ obtained following the procedure in the previous section is plotted in Fig.2 for the sets of values {K=0,Δ=0}, {K=0.2,Δ=0} and {K=0,Δ=0.025}. For the first and last set, the results coincide for $|\theta|>3°$, illustrating that Δ has no influence for θ far away from 0. The influence of Δ around θ=0, on the other hand, is evident from the results around θ=0.

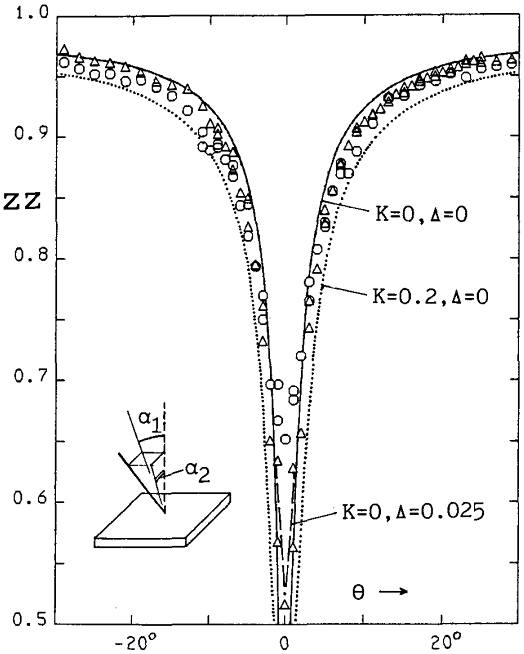


**Fig.2** Measured (symbols) and simulated (full and interrupted lines) result for YS-619:
o : remanent state after 10 kOe in-plane (ii);
Δ : idem after 10 kOe perpendicularly (iii).

**From interpolation between the first two simulations, a best fit with the experimental data corresponding to states (ii) and (iii) for $|\theta|>15°$ is ob**tained for K=0.10(5) and K=0.05(5), respectively.

This could indicate a weak parallel correlation between needles, established after in-plane magnetisation, as a result of their non perfect alignment. In order for this correlation to occur, the axes of the needles in regions of finite area should have a systematic deviation from the normal. After removing the in-plane field, the needles in such a region have parallel magnetisation. The existence of such regions implies K>0, by definition. In the case of perpendicular magnetisation such a mechanism is lacking.

The present results for $D_{zz}$ in state (iii) are not consistent with our earlier results on YS-623 in this state, but more reliable, because stray fields due to the remanence of the individual films were eliminated by proper stacking. In the results given in [4] stray fields were not fully eliminated, so the element $D_{zz}$ had to be corrected. Therefore, a systematic error up to 0.05 may be present in those results.

comparison between different alumites

Although a difference in K between states (ii) and (iii) can be discerned for a single alumite, the fit of K lacks the accuracy to make a distinction between the magnetic states meaningful when comparing different alumites. So for this comparison the outcome of K in state (i) is considered a useful parameter.

In Fig.3 these values for K are plotted as a function of the dimensionless quantity

$$U = t\delta^2/c^3, \tag{12}$$

being proportional to the energy of the dipole moment ($\propto \frac{\pi}{4}\delta^2 t$) of a needle in the resultant field ($\propto c^{-3}$) due to its neighbours.

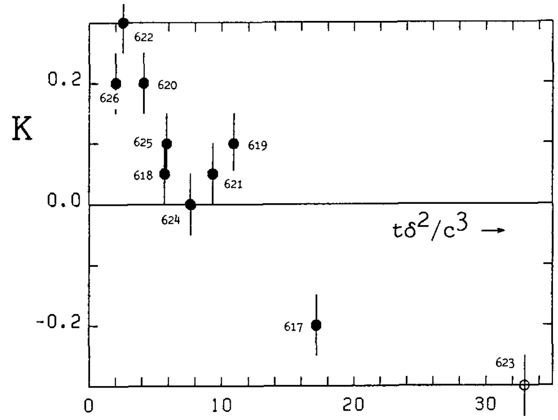


**Fig.3** Correlation parameter K (eq.(1)) determined for the magnetic state "as received" (i) as a function of the quantity U (eq.(12)) representing the energy of a needle in the resultant field due to its neighbours.

K appears to decrease gradually from positive to negative as U increases. This means that the alignment of neighbouring needles tends to be more anti-parallel as their dipolar interaction increases, which can be qualitatively understood.

## Conclusion

Using the 3-D Neutron Depolarisation Analysis it appears possible to quantify the magnetic correlations between the iron needles in Alumites in terms of a correlation parameter K. The value of K depends upon the magnetic history of the alumite.

It is demonstrated that K becomes less positive (i.e. the correlations tend to be more anti-parallel) with increasing interaction between the needles due to their size and distance. The same tendency is shown after perpendicular magnetisation, with respect to in-plane magnetisation.

The authors wish to thank Dr. T.Tokushima from Yamaha R&D Laboratories for providing the samples and the data in Table I. Prof.Dr. J.J.Van Loef is acknowledged for critically reading the manuscript.

## References

[1] M.Shiraki, Y.Wakui, T.Tokushima and N.Tsuya, IEEE Trans. MAG-13 pp 1272-74, 1977.
[2] N.Tsuya, Y.Saito, H.Nakamura, S.Hayano, A.Furoghori, K.Ohta, Y.Wakui and T.Tokushima, JMMM vol. 54-57 pp 1681-82, 1986 and references therein
[3] W.H.Kraan and M.Th.Rekveldt, IEEE Trans. MAG-24 pp 1793-95, 1988.
[4] W.H.Kraan and M.Th.Rekveldt, J.de Physique vol. 49,C8 pp 1985-86, 1989.
[5] M.Th.Rekveldt, JMMM vol. 1 pp 342-50, 1976.
[6] T.Tokushima, private communication
[7] G.T.A.Huysmans, J.C.Lodder and J.Wakui, J.App.Phys. vol. 64 pp 2016-21, 1988.