Ferromagnetic resonance in polycrystals
Ernst Schlömann

To cite this version:

HAL Id: jpa-00236043
https://hal.archives-ouvertes.fr/jpa-00236043
Submitted on 1 Jan 1959

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
FERROMAGNETIC RESONANCE IN POLYCRYSTALS

Ernst SCHLÖMANN,
Raytheon Mfg. Comp., Waltham, Mass., U. S. A.

Résumé. — On développe la théorie de la résonance ferromagnétique en milieu polycristallin dans le cas d’un champ d’anisotropie, soit très grand, soit très faible par rapport à l’aimantation à saturation. Les résultats expérimentaux obtenus pour des ferrites fortement anisotropiques à réseau cubique et hexagonal sont en accord satisfaisant avec la théorie.

Abstract. — The theory of ferromagnetic resonance in polycrystalline material is developed for the two cases in which the anisotropy field is either very large or very small compared with the saturation magnetization. Experimental results obtained with cubic and hexagonal ferrites of large anisotropy agree reasonably well with the theory.

1. Introduction. — Most of the phenomena of ferromagnetic resonance in single crystals are at present fairly well understood. The location of the absorption line is dependent on the shape of the sample, the orientation of the dc field with respect to the crystalline axes, and the effective gyromagnetic ratio which may differ appreciably from the value expected for free electrons. On the other hand, it has been rather difficult to explain the observed width of the absorption line. Many loss mechanisms have been considered in the literature, but good agreement between theory and experiment has been achieved only in very few cases.

In this situation it may seem presumptuous to try to understand finer details of the resonance behavior as observed in polycrystalline material. It may appear that such an understanding would require a detailed knowledge of the origin of the linewidth in single crystals. Closer inspection of the problem shows, however, that this is not necessarily true. In polycrystalline material an additional linebroadening mechanism is present, which, in many cases, so far outweighs all other mechanisms that they can be neglected in comparison. This additional linebroadening mechanism arises from crystalline anisotropy in conjunction with the polycrystalline character of the sample. It was first mentioned in the literature by Van Vleck [1] and later by Kittel and Abraham [2]. In the present paper this mechanism will be considered in detail.

Since polycrystalline material is much more readily available than single crystals, many of the experiments on ferromagnetic resonance have been performed with polycrystals. It is hoped that the present investigation will aid in interpreting such experiments and in extracting from them the physically significant data.

The theory of ferromagnetic resonance in poly-crystals is made difficult by the fact that an interaction exists between the various crystallites of the sample. One contribution to this interaction arises from exchange forces. Because of their short-range character, however, exchange forces are not very important and can usually be neglected. The major part of the interaction arises from dipolar forces. The strength of the coupling is, therefore, proportional to the saturation magnetization $M_s$. On the other hand, the anisotropy field $H_a (= 2|K_i|/M_s$ for cubic materials) is a measure of the tendency of the grains to behave independently. It is convenient to distinguish between the case of strong coupling, in which $M_s \gg H_a$ and that of weak coupling, in which $M_s \ll H_a$. Different theoretical methods have to be used in the two cases.

2. Strong coupling : $M_s \gg H_a$. — This case was first investigated by Geschwind and Clogston [3]. The theoretical procedure appropriate under these conditions can be described as follows: At first the normal modes of the sample are investigated for the limiting case in which $H_a = 0$. Aside from the homogeneous mode, which is usually excited in resonance experiments, higher modes exist, which are not excitable by a homogeneous microwave field. The general calculation of the frequencies of these higher modes is rather complicated [4], but simple results are obtained for the limiting case in which $H_a = 0$. Aside from the homogeneous mode, which is usually excited in resonance experiments, higher modes exist, which are not excitable by a homogeneous microwave field. The general calculation of the frequencies of these higher modes is rather complicated [4], but simple results are obtained for the limiting case in which the wavelength of the mode is very small compared with the sample dimensions. Under these conditions the physical boundary conditions can be replaced by periodic boundary conditions which are mathematically much more convenient. The normal modes in this limit are the so-called spinwaves. The presence of crystalline anisotropy introduces a small coupling between the homogeneous mode and those spinwaves whose wavelength is of the order of or larger than...
the average linear grain size. In this way energy is transferred from the homogeneous mode to the spinwaves and the resonance line is broadened. For the wavelengths of interest, exchange forces are much smaller than dipolar forces and can usually be neglected. Energy can be transferred only to those spinwaves which have the same frequency as the homogeneous mode. The additional linebroadening is, therefore, critically dependent on the number of long wavelength spinwaves that are degenerate with the homogeneous mode. In this connection it is important to notice that the frequency of the homogeneous mode may lie outside the band of frequencies of the long wavelength spinwaves. Under these conditions no significant additional linebroadening should occur. On the other hand, the additional linebroadening should be very large if the frequency of the homogeneous mode is just below the upper boundary of the spinwave band, because the density of normal modes is very large there. Figure 1 demonstrates the dependence of the spinwave frequencies on wave number and magnetic field. It is evident that for spheres the frequency of the homogeneous mode lies above the spinwave band if the internal field is smaller than \( 4\pi M_s/3 \). The additional linebroadening mechanism is, therefore, practically inactive if the measuring frequency is smaller than \( \gamma 8\pi M_s/3 \). A detailed calculation [5] shows that at frequencies just below this value the upper edge of the spinwave band can appear as a separate absorption peak in addition to the usual peak associated with the homogeneous mode. Figure 2 demonstrates the frequency dependence of the linewidth as expected for spherical samples. (1)

3. Weak coupling : \( M_s \ll H_0 \). — In this case it is reasonable to neglect the coupling altogether.


The individual grains then go through resonance independently, and the absorption as a function of field-strength is essentially proportional to the number of grains that have their resonance in a given interval (between \( H \) and \( H + dH \)) of applied field. This distribution has been calculated with the assumption that the only significant forces are those arising from Zeeman energy and anisotropy energy, and that the grains are orientated at random. The mathematical method used in this calculation is described elsewhere [6]. It can be shown generally that the distribution starts and ends with a finite step and that it has a logarithmic singularity, which corresponds to the saddle points of the resonance field surface. Figure 3 shows a set of such distributions. The calculation is based on the following assumptions ; 1) cubic symmetry, 2) first order anisotropy constant is negative, 3) higher order anisotropy constants are negligible. The distributions are plotted on a reduced scale, such that their width is not dependent on the dimensionless anisotropy parameter \( k = \gamma H_0/\omega \). It should be noticed that for \( k \geq 0.5 \)
Fig. 2. — Theoretical frequency dependence of the anisotropy contribution to the linewidth in spherical samples. The ordinate is the linewidth divided by $2.07 \frac{H_B}{4 \pi M_a}$. The full line is obtained neglecting exchange effects and intrinsic dissipation. The broken line is obtained with the exchange correction.

Fig. 3. — Reduced distribution for various values of the anisotropy parameter $k = \gamma H_a/\omega$.

Fig. 4. — Absorption curves for NiFe$_{1.5}$Al$_{0.5}$O$_4$ quenched from 1200 °C. Measurements at various temperatures.

A secondary absorption maximum is predicted which corresponds to resonance in the easy direction. Figure 4 shows a set of experimental absorption curves obtained at X-band with a nickel-ferrite-aluminate [7]. It is seen that the line is comparatively narrow at high temperatures and that the structure at lower temperatures can be understood, if one assumes that the anisotropy
field increases with decreasing temperature. Figures 5-8 show examples of resonance curves in

Fig. 5. — Measured and calculated absorption line for NiFe$_{1.3}$Al$_{1.7}$O$_4$ at 104 °C. \( H_a = 620 \) Oersted, \( g = 3.88 \), \( k = 0.33 \).

Fig. 6. — Measured and calculated absorption line for NiFe$_{1.3}$Al$_{1.7}$O$_4$ at 36 °C. \( H_a = 1030 \) Oersted, \( g = 3.85 \), \( k = 0.55 \).

which a detailed comparison of experiment and theory has been made. The theoretical curves are normalized in such a way that the areas under the curves agree. For the purpose of this normalization the experimental curves have been slightly modified in the range of very small fields (broken lines), where the theory can not be expected to be applicable. Reasonably good agreement is obtained in all cases, if one assumes that the first

Fig. 7. — Measured and calculated absorption line for NiFe$_{1.3}$Al$_{1.7}$O$_4$ at 0 °C. \( H_a = 1410 \) Oersted, \( g = 3.83 \), \( k = 0.75 \).

Fig. 8. — Measured and calculated absorption line for NiFe$_{1.3}$Al$_{1.7}$O$_4$ at -25 °C. \( H_a = 1880 \) Oersted \( g = 3.89 \), \( k = 1.0 \).
order anisotropy constant is negative and that higher order anisotropy constants are negligible. It is seen that the experimental curves are not exact but only smeared out images of the theoretical curves. This is to be expected in view of the approximations involved in the calculation of the theoretical curve. Figure 9 shows the temperature dependence of the g-value and the anisotropy field as inferred from the absorption lines. It is seen that the anisotropy field increases rapidly with decreasing temperature and that the g-value is practically independent of temperature.

The mechanism discussed above is by no means the only one capable of explaining a secondary absorption maximum. It is known that in the vicinity of the compensation point of angular momentum a secondary maximum can occur due to the excitation of the exchange mode of ferromagnetic resonance [8, 9]. The two mechanisms can be distinguished experimentally if circularly polarized radiation is used to excite the resonance. In the present experiments no evidence for the excitation of the exchange mode has been observed. It is felt that resonance experiments on nearly compensated ferrites are liable to be strongly influenced by anisotropy effects, because the effective anisotropy field involves the saturation magnetization in the denominator.

The theory can, of course, also be applied to materials with other than cubic symmetry. Detailed calculations have been made for hexagonal materials with a preferential plane (negative uniaxial anisotropy). In this case it was necessary to take higher order anisotropy into account. The theory appears to be in good qualitative agreement with experiments performed by R. V. Jones [10]. An example is shown in Figure 10. In this case three resolved maxima occur. They correspond to grains in which the dc field is applied along the easy, the intermediate, and the hard direction respectively. The separation of the two lowest peaks is a measure of the anisotropy in the preferential plane. In the present case the neglect of dipolar interaction is less well justified because the material has an appreciable magnetic moment.

4. Conclusions. — It appears that anisotropy broadening is in many cases the dominant line-broadening mechanism in polycrystalline ferrites. If the anisotropy field is very small compared with the saturation magnetization the theory predicts an essentially Lorentzian absorption line, whose width depends quite strongly on the frequency and the shape of the sample. If the anisotropy field is very large compared with the saturation magnetization the absorption line should have a definite structure. From an analysis of this structure detailed information about the various anisotropy constants can be obtained.

Acknowledgements. — A large part of the work reported in this paper was performed in cooperation with J. R. Zeender, who has carried out the resonance experiments on nickel ferrite aluminates described in Sec. 3. The samples for these experiments were provided by Dr. S. Blum and by Mr. J. Zeeimer. I should like to thank Prof. R. V. Jones for making his experimental results available prior to publication. Many stimulating discussions with Dr. M. Sirvetz and Dr. H. Statz are gratefully acknowledged.
REFERENCES


DISCUSSION

Mr. Artman. — I recollect that in your analysis the individual grain resonances have zero line width. Is it mathematically feasible, and if so do you believe it worthwhile, to carry out your calculations for individual resonances of finite line width.

Mr. Schlömann. — I believe that such a calculation is feasible and probably also worthwhile. One should not forget, however, that the theory described in Sec. 3 involves as an essential approximation neglect of dipolar interaction. In many cases it is probably more important to take this interaction into account them to allow for the intrinsic line-width of the individual grains.

Mr. Teale. — I have carefully measured the resonance absorption line shape of polycrystalline spheres of Yttrium iron garnet. The effective g factors calculated using the magnetic field at the resonance peak showed an increase of about 4% between porosities of 7% and 40%. Within the accuracy of its determination (~1%) the g factor calculated using the field at the centre of gravity was independent of the porosity. These observations indicate that the g factor should be determined using the centre of gravity when asymmetric resonance absorption curves are observed.

Mr. Schlömann. — I agree that the determination of the centre of gravity of the absorption line yield reliable g-factors if such measurements can be done sufficiently accurately. It can be shown from the theory described above that the centre of gravity is to first order independent of the anisotropy field. Similar considerations hold for the case of linebroadening caused by porosity (paper presented at the Conference on Magnetism and Magnetic Materials, Boston 1956).