

ANISOTROPY OF MAGNETIC PROPERTIES IN TEXTURED MATERIALS

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A short survey is presented of techniques and methods used to correlate the texture with the magnetic anisotropy of various properties of soft and hard magnetic materials. Also, examples of magnetic materials are discussed with emphasis on techniques of processing which optimize the texture.

KEY WORDS Hard magnetic materials, soft magnetic materials, ferrofluids, crystal anisotropy, magnetostriction, torque curves, AlNiCo, NdFeB, FeSi.

All polycrystalline magnetic materials can be broadly classified into two categories, hard and soft. Soft magnetic materials are used for a variety of diverse applications, the most important of which are pole pieces of generators, electric motors and transformer cores. Highest efficiency power and distribution transformers are made from Fe–Si sheets having in the rolling direction a low core loss and a high permeability at low inductions; such properties are associated with the Goss texture. Steels used in making generators or stators should have a good permeability at low and intermediate inductions for which the $\{100\}\langle hkl \rangle$ texture is optimum.¹ Texture influences, as well, the magnetic properties of hard magnetic materials as indicated by the texture dependant qualities of NdFeB, SmCo or Alnico permanent magnets, and separately by a continuing problem of the orientation of magnetic particles in Co–Cr and Co–Ni recording films. The origin of the anisotropy of soft and hard magnetic materials is the same, that being a microscopic magnetic anisotropy of a grain and particle. A microscopic anisotropy of the grain and the particle is either dictated by the constants of the magnetocrystalline energy or by the shape of the particle. The effective magnetic anisotropy of a polycrystalline specimen must therefore be obtained by averaging the grain anisotropy over the grain orientation distribution function i.e. over the texture. The meaning of the word texture, in magnetic studies, is however not the same as the meaning used normally in metallurgical research. For studying the anisotropy of magnetic properties of hard magnetic materials, one needs to know the crystallographic texture and also, quite often, the distribution of the particle orientation.

While, the crystallographic texture can be determined using standard X-ray and neutron diffraction measurements, the information about the grain shape and the distribution of the orientation of particles have to be obtained from optical observations or from small angle scattering data; thus, knowing texture, one may proceed with an averaging of the magnetic properties over the texture function. In general, this is a very difficult problem and it's solution involves making several simplifying assumptions.

AVERAGING THE MAGNETIC PROPERTIES OVER THE TEXTURE FUNCTION

If the local magnetic anisotropy is defined in the reference frame of the grain or the particle as $E(\vec{h})$, then the mean average value of magnetic anisotropy of polycrystalline specimens is calculated from the following formula:²

$$E(\vec{y}) = \frac{1}{4\pi} \int E(\vec{h})A(\vec{h}, \vec{y}) d\vec{h} \quad (1)$$

where $A(\vec{h}, \vec{y})$ is the general axis distribution function of crystals having their direction \vec{h} in the sample direction \vec{y} . Since a relationship, between the magnetization and the field is complex, such an averaging procedure is applied normally to the value of magnetocrystalline energy or magnetostriction which is measured at saturation. Averaging the magnetic properties at a field strength which is lower than the saturation field requires simplified assumptions on the continuity of the magnetization and the field strength across the grain boundary. To obtain realistic results, it is therefore necessary to propose a model of the magnetic interaction between grains. Such modelling is rather difficult because the magnetostatic and magnetoelastic interactions are very complex. Therefore, the assumption is often made that the field strength is the same in the whole specimen and that the magnetization is averaged over the texture function.

TEXTURING OF HARD MAGNETIC MATERIALS

In order to improve the magnetic characteristics of hard magnetic materials a suitable texture can be developed for various applications. The development of such a texture is usually not so well understood as the development of the rolling and the annealing textures in metals. There are a variety of techniques which are applied to produce the required texture.^{3,4} The NdFeB magnet is produced by powder sintering or melt spinning in which case rather isotropic microstructure is obtained leading to the maximum energy product ($BH_{\max} = 8-12 \text{ MGOe}$). If however, during manufacturing, the grains are aligned by the magnetic field one can obtain an anisotropic magnet which has superior energy product of the order of 30–45 MGOe. This property can be explained knowing that during sintering, the growth of the crystal occurs along the “a” axis and therefore the easy magnetic direction, “c”, is being oriented automatically. Pressing can be done in the direction either parallel or perpendicular to the magnetic field, because it serves only to orient the material.

Quenched NdFeB magnets are microcrystalline and the shreds are polymer bonded. If the magnet is compressed at a temperature 600–700 degrees celsius, its structure is rather anisotropic. Higher temperature produces a strongly anisotropic structure, a possible explanation for which being that, due to pressing only, the grains with “a” and “b” perpendicular to the press direction are allowed to grow at the expense of the other grains. The high temperature favors the growth along “a” axis and therefore the final magnet is oriented having the “c” axis parallel to the press direction.

Both sintered NdFeB magnets and the quenched magnets are therefore

textured and this texture is essential for obtaining the required energy product and remanence. The texture has strong effect on the properties of another important magnet, SmCo, which is widely used in the manufacturing of magnetic devices. The unique properties of this magnet depends on the presence of the $\langle 011 \rangle$ fiber texture, and on texture perfection.

Texture is also essential for application of materials such as a perpendicular magnetic recording medium. In particular, Co-Cr films⁵ crystallizing in the hcp structure show a pronounced texture, *c*-axis (being the magnetic easy axis) tending to be oriented perpendicularly to the film plane. For a good magnetic recording medium one needs a small remanence in the plane of the tape which is achieved by decreasing the film thickness which in turn leads to an increase of texture sharpness. There is a number of parameters which affect the texture formation resulting from the sputtering of Co-Cr films, a few of which are the surface temperature or the film thickness. A rapid reinforcement of texture, measured by low amount of *c*-axis in the plane of the tape, can be achieved at low film thickness by choosing a low substrate temperature, e.g. $T_s = 350$ K. It was demonstrated,⁶ however that certain parasitic textures may appear additionally to the mean *c*-axis texture. The $\langle 10.1 \rangle$ texture, (having the *c*-axis inclined to the surface normal by an angle of $\Theta = 60^\circ$) or the $\langle 110. \rangle$ texture (*c*-axis parallel to the film plane) are often responsible for deterioration of the properties of perpendicular recording media. There is a number of other important applications of texture induced magnetic anisotropy. Specimens are obtained not only by sputtering but also by electro-deposition (i.e. iron-nickel strip films⁷), by cooling powder (MnNiB) suspended in alcohol in a magnetic field⁸ or by annealing the melt spun ribbon.⁹ In this last case the magnetic texture is formed as a result of a combined influence of the demagnetizing field and stresses.

In addition to the already described methods of texturing, magnetic fluids can be textured.¹⁰ The fluid is comprised of magnetically single domain particles dispersed in a carrier liquid and stabilized against segregation by the presence of a particle surfactant coating. Magnetization of a fluid involves the alignment of the independent particle moments, and may be considered to occur by one of two processes. If the particles are small, then the thermal energy may be sufficient to decouple the particle moment from the particle's easy magnetic direction. In this case the magnetization occurs by moment rotation alone. For large particles, the particle moment and the crystallite are essentially locked together and magnetization must now involve the bulk rotation of the particle in the carrier liquid. Whilst the fluids, in a magnetized state will exhibit texture, the randomizing effect of thermal energy ensures that this is rapidly lost when the field is removed; the system returns rapidly to the unmagnetized equilibrium ground state in zero field, that is to say that the fluid behaves superparamagnetically. However, when the carrier liquid is frozen or polymerized the magnetization process of the blocked particles now depends upon the particle magnetocrystalline and the shape anisotropy and hence the particle easy axis orientation distribution, or texture within the specimen. Thus, it is apparent that texture may be induced, controlled and preserved in a specimen by solidifying a magnetic fluid in a presence of a magnetic field. Such a specimen will be anisotropic and when blocked particles are present exhibit the magnetic hysteresis. The texture will generate an anisotropy of magnetic energy which can be measured, Figure 1 or conversely measurement of magnetic torque can be used to estimate the alignment of the

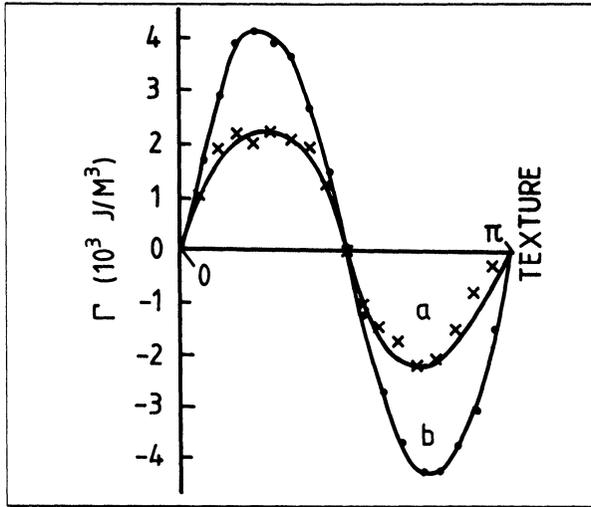


Figure 1 Magnetic torque as a function of angle β for ferrofluid specimens textured in (a) 0.4 T and (b) 1.4 T fields.¹⁰

magnetic particles. It has been demonstrated¹¹ that the hysteresis loops and the magnetization curves of a field induced textured system of fine Cobalt particles can be explained by a general equation for the magnetization of a textured fine particle system containing a mixture of superparamagnetic and ferromagnetic blocked particles.

CORRELATION OF TEXTURE AND MAGNETIC PROPERTIES IN TEXTURED FINE PARTICLE MAGNETS

In spite of its importance the texture of single domain magnets has not been studied extensively.¹²⁻¹⁵ Recently there has been more interest in studying their texture, the reason being, a strong influence of texture on properties of rare earth transition metal permanent magnets and materials used for magnetic recording. The mean deviation angle has often been used to classify differences in texture.^{12,13} However, this measure of texture is not always sufficient and therefore, a more quantitative description of texture must be used.¹⁴ In many practical cases it is enough to describe the texture using the series expansion of Legendre's polynomials, since in the majority of technical magnets, the orientation of the magnetic particles is symmetrical about the direction of the external magnetic field. Such texture description can be used therefore to predict the magnetic properties of the fine particle magnets. We would like now to discuss shortly a model which has been previously used for calculation of the texture influence on these properties.¹⁴ The model is based on several assumptions. We start by assuming that the particle is a single domain at zero field and it will stay saturated at any field. Also the assumption will be made that the magnetic particles are dispersed, thus the interaction between them can be neglected. The magnetic anisotropy of the particle is therefore either defined by the constants of

the magnetocrystalline anisotropy or by the shape of the particle. The particle shape is ellipsoidal. The total energy of the particle is then expressed in the specimen reference frame as a sum of the energy of the magnetocrystalline anisotropy, demagnetization energy and the energy of interaction of magnetization with the magnetic field. Minimizing this energy we obtain the projection of the magnetization onto the external magnetic field. From there we can proceed with the calculation of the average magnetization. The value of the magnetization averaged over the orientation distribution is used in the calculation of the remanence and the initial susceptibility. The calculation of the value of the mean coercivity has been made by averaging the coercivity of the particle over the texture function. This assumption is less strongly justified than the one used to calculate the remanence and the susceptibility but leads to similar expression. Final results of the calculation using this model can be summarized as follows. The initial susceptibility in textured materials is given by

$$\chi = \frac{M^2}{2T} \sum_{l=0}^L t_l \lambda_l; \quad T = \frac{1}{2} M^2 (N_T - N_0) + K \quad (2)$$

where M is the magnetization, N_T and N_0 are demagnetizing coefficients for a particle of an ellipsoidal shape and K is the constant of magnetocrystalline anisotropy. λ_l are constants listed in Table 1 (see Ref. 14 for details). t_l are the series expansion coefficients of the texture function given by the expression.

$$g(\alpha) = \sum_{l=0}^L t_l \bar{P}_l(\alpha) \quad (3)$$

where α being the angle between the direction of the magnetic field and the easy direction of magnetization and $P_l(\alpha)$ are Legendre functions.

The remanence is given by a similar expression.

$$\frac{M_R}{M_S} = \sum_{l=0}^L t_l \gamma_l \quad (4)$$

Table 1 Constants used in the calculation of the influence of the texture on the magnetic properties.

<i>Legendre polynomials</i> $\bar{P}_l(\alpha)$	<i>Texture-susceptibility coefficient</i> λ_l	<i>Texture-remanence coefficient</i> γ_l	<i>Texture-coercivity coefficient</i> δ_{Cl}	<i>Texture-anisotropy field</i> δ_{Al}
$\bar{P}_0(\alpha)$	0.943	0.707	0.530	1.672
$\bar{P}_2(\alpha)$	-0.422	0.395	0.215	-0.145
$\bar{P}_4(\alpha)$	0	-0.088	-0.082	0.223
$\bar{P}_6(\alpha)$	0	0.040	0.077	-0.061
$\bar{P}_8(\alpha)$	0	-0.023	-0.011	0.032
$\bar{P}_{10}(\alpha)$	0	0.015	0.020	-0.035
$\bar{P}_{12}(\alpha)$	0	-0.010	-0.005	0.051
$\bar{P}_{14}(\alpha)$	0	0.008	0.013	-0.023
$\bar{P}_{16}(\alpha)$	0	-0.006	-0.002	0.033
$\bar{P}_{18}(\alpha)$	0	0.005	0.007	-0.017
$\bar{P}_{20}(\alpha)$	0	-0.004	-0.002	0.024

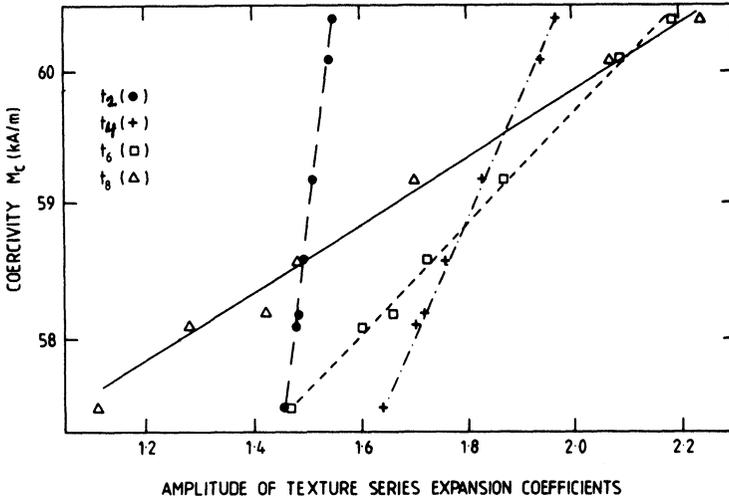


Figure 2 Experimental coercive force as a function of the amplitude of the texture series expansion coefficients for Alnico 5.

Finally the coercive force can be estimated using

$$H_C = \frac{2T}{M} \sum_{l=0}^L t_l \delta_{cl} \quad (5)$$

The constants γ_l and δ_{cl} are listed in Table 1. The results of theoretical prediction of the influence of texture on the coercivity are compared with the experimental results obtained for Alnico 5 magnets having various degrees of texturing (see Figure 2). The results listed in Table 1 demonstrate that different magnetic properties are sensitive to texture to various degrees. The initial susceptibility is most sensitive to texture changes and it can be calculated from only two texture coefficients. The coercive force is more strongly dependent on the shape of the crystal orientation distribution. According to Figure 2, texture changes in the investigated specimen illustrate the relation between the experimental value of the coercive force and the amplitude of the series expansion texture coefficients. Changes in the amplitude of the higher order series expansion coefficients contribute significantly to the value of the coercive force.

The remanence is affected mostly by low l series expansion coefficients of texture, because the γ_l constants for higher l values are small (see Table 1).

Returning to the discussion of the assumptions made, we should mention, that unison rotation of the magnetic vectors is not a unique mechanism of magnetization and the incoherent processes of magnetization reversal can also be considered using this model.

The averaging of the magnetic properties over the texture function is complex. Usually¹⁵ the magnetization is considered as an intrinsic property and is averaged over the texture function assuming a zero field from the neighboring particles. This approach seems to be fully justified in most materials. Another extreme approach is to assume, that the magnetization is homogeneous throughout the magnet and the magnetic field strength is not. Such method of averaging gives for

certain materials better agreement with the experimental value of the coercivity¹⁴ and was used as the foundation of the analytical theory of a behavior of ferromagnetic materials.¹⁶

TEXTURE IN MAGNETIC STEELS

Controlling the texture is important in both, oriented and non-oriented Fe-Si steels. Oriented steels are used mainly in the manufacture of transformers. The $\{110\}\langle 001 \rangle$ texture provides the required magnetic anisotropy and lowest losses in the direction of magnetization. The iron loss can not only be reduced by increasing the perfection of the $\{110\}\langle 001 \rangle$ texture, but also by reducing the sheet thickness, increasing the Silicon content, applying external stresses and influencing domain nucleation by domain refining at the surface of the steel.¹ Texture influences the magnetization processes in steels both through the domain wall movement and the rotation of the direction of magnetization. The alignment of an easy magnetic direction along the direction of the applied magnetic field generates, through the movement of the 180 degree domain walls, a large change in magnetization. Also, the total energy required for rotation of the magnetic moments along the direction of the magnetization is small. A number of studies have been done concerning the production of sharp Goss texture. For example, a method was proposed where a temperature gradient enhances the alignment of the axis with the rolling direction.¹⁷ It was demonstrated that when the secondary recrystallized grains grow under a temperature gradient, grains with orientation nearer $\{110\}\langle 001 \rangle$ grow preferentially. The minimum losses were observed for the average misorientation angle of 2.5 degrees.

So called "non-oriented steels" are also textured. The ideal texture for these steels is $\{100\}\langle 0vw \rangle$ because such texture gives a minimum rotational power loss in the plane of steel sheet.¹⁷ This texture is usually accompanied by $\{110\}$, $\{112\}$ and $\{111\}$ textures which are known to be responsible for a deterioration of the desired magnetic properties. Therefore, major efforts are being devoted to maximize the $\{100\}\langle 0vw \rangle$ component of texture. Considerable improvement, for example, was obtained¹⁸ by hot band annealing steels with small amounts of Sb.

TEXTURE AND ANISOTROPY OF PROPERTIES OF SOFT MAGNETIC MATERIALS

Magnetic steels used to build transformers or generators have anisotropic magnetic properties. Properties, like the power loss or the permeability are of major importance for application of these materials in various magnetic equipments. Other properties, like magnetostriction and magnetoresistance are usually less important. As we have already described, the influence of texture on properties is calculated by averaging the properties over the orientation distribution function. As examples, we will discuss the correlation between the texture and magnetocrystalline energy and magnetostriction. Both properties will be compared to experimental data obtained at saturation. For the magnetic field strength lower than the saturation field the theory of the averaging of properties

over the texture function is much more complex since the grain orientation, magnetostatic and magnetoelastic interaction between grains contributes to a fluctuation of the magnetization and the field strength at the grain boundaries. The magnetocrystalline energy, defined as the energy required to rotate the magnetic moments towards the direction of an external magnetic field is, for a single crystal, usually expressed by the following formula:

$$E(\vec{h}) = K_4\phi_4(\vec{h}) + K_6\phi_6(\vec{h}) \quad (6)$$

with

$$\begin{aligned} \phi_4(\vec{h}) &= h_1^2h_2^2 + h_2^2h_3^2 + h_3^2h_1^2 \\ \phi_6(\vec{h}) &= h_1^2h_2^2h_3^2 \end{aligned}$$

where h_1, h_2, h_3 are the direction cosines of crystallographic directions. For Silicon steel, two anisotropy constants K_4 and K_6 describe the energy with sufficient accuracy. By averaging the energy over the ODF, we obtain in the reference frame of the specimen direction α, β the expression:

$$E(\alpha, \beta) = \frac{1}{9n_4\sqrt{\pi}} \left[\frac{K_4}{5} + \frac{K_6}{55} \right] F_4(\alpha, \beta) + \frac{1}{13n_6\sqrt{\pi}231} \frac{K_6}{55} F_6(\alpha, \beta) \quad (7)$$

The above formula is similar to one given for the single crystal; however, the functions F_4 and F_6 are now expressed in terms of the ODF coefficients $C_i^{\mu\nu}$ as follows:

$$F_4(\alpha, \beta) = \frac{1}{\sqrt{2}} C_4^{11} \bar{P}_4^0(\cos \alpha) \cos 2\beta + C_4^{13} \bar{P}_4^4(\cos \alpha) \cos 4\beta$$

and

$$\begin{aligned} F_6(\alpha, \beta) &= \frac{1}{\sqrt{2}} C_6^{11} \bar{P}_6^0(\cos \alpha) + C_6^{12} \bar{P}_6^2(\cos \alpha) \cos 2\beta \\ &+ C_6^{13} \bar{P}_6^4(\cos \alpha) \cos 4\beta + C_6^{14} \bar{P}_6^4(\cos \alpha) \cos 6\beta \end{aligned} \quad (8)$$

which gives for $\alpha = 90^\circ$, i.e. in the surface plane of the specimen, an expression for the magnetic torque:

$$M(\beta) = -\frac{dE(\beta)}{d\beta} \quad (9)$$

Several authors^{19,20,21} have demonstrated that the above expression predicts the magnetic torque which agrees well with the experimental data. All investigations were done for Fe–Si steel and therefore texture uniquely was responsible for the magnetic anisotropy. An example of the correlation between the texture and this anisotropy is given in Figure 3 and Figure 4 for the Goss texture in oriented Fe–Si steel. In Figure 4 the energies are referred to a minimum energy set equal to zero.²² Equally good correlation was obtained for various other recrystallization textures.

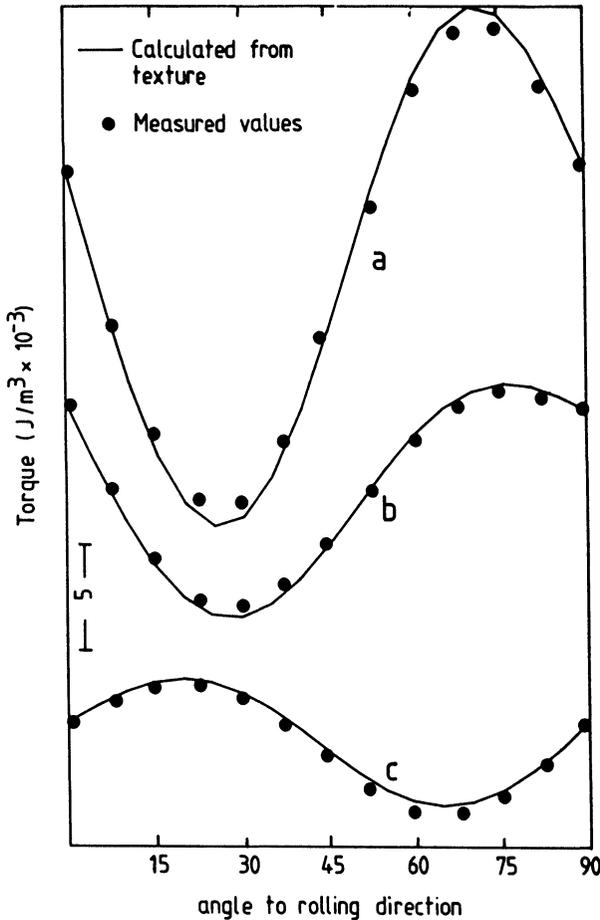


Figure 3 Magnetic torque curves for specimens of Fe-Si oriented steel (line ____-torquemeter measurements, points • calculations from texture data).

Another example is for magnetostriction. Averaging the magnetostriction tensor λ_{ijkl} over the texture function is rather straight forward since the magnetostriction of a single crystal is defined by a 4-rank tensor.² In polycrystalline materials, the magnetostriction defined in the specimen reference frame can be described as a tensor which has components expressed as a function of the Euler angles describing the orientation of the crystal reference frame in the reference frame of the specimen.

$$\frac{dl}{l} = \sum_{i,j,k,l} b_i b_j \lambda_{ijkl}(g) a_k a_l \quad (10)$$

where $a(a_1, a_2, a_3)$ is a unit vector in the direction of the magnetization and $b(b_1, b_2, b_3)$ is a unit vector in the direction in which dl is measured. The exemplary calculation of the magnetostriction for Fe-Si steel made according to this formula

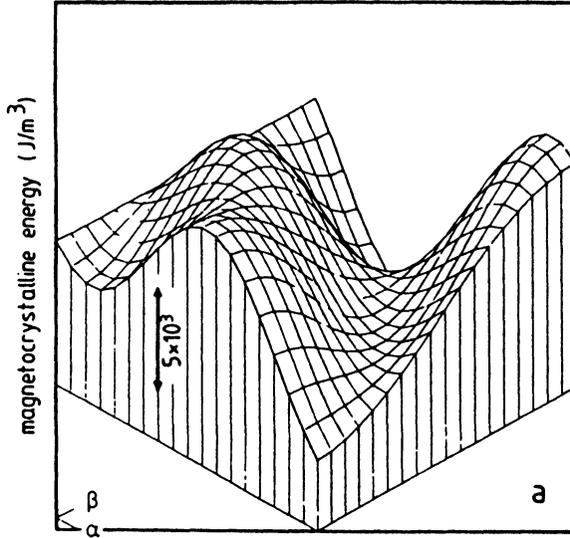


Figure 4 Graphical representation of the anisotropy of magnetocrystalline energy, $E(\alpha, \beta)$, for specimens of Fe-Si.

are presented in Figures 5 and 6. In Figure 6, the magnetostriction is referred to a minimum magnetostriction set equal to zero; the direction of magnetization and the direction in which Δl is measured coincide.

Averaging $\lambda_{ijkl}(g)$ over the orientation distribution function one obtains the average value for a component of the magnetostriction tensor:

$$\overline{\lambda_{ijkl}} = \lambda_{ijkl} + \bar{a}_0^{11}(ijkl) + \lambda_\alpha[\bar{a}_4^{11}(ijkl)C_4^{11} + \bar{a}_4^{12}(ijkl)C_4^{12} + \bar{a}_4^{13}(ijkl)C_4^{13}] \quad (12)$$

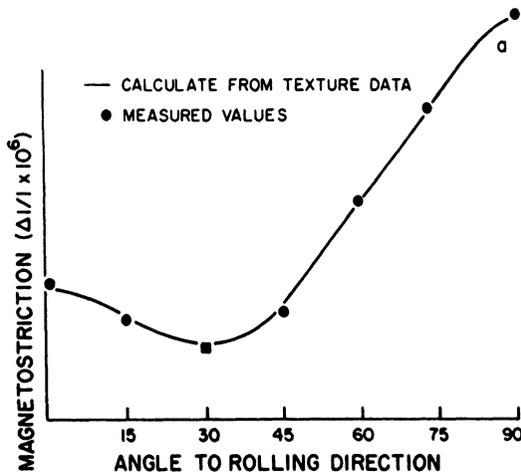


Figure 5 The changes in the magnetostriction strain calculated in the plane of the sheet for Fe-Si oriented steel. Experimental points shown for comparison.²²

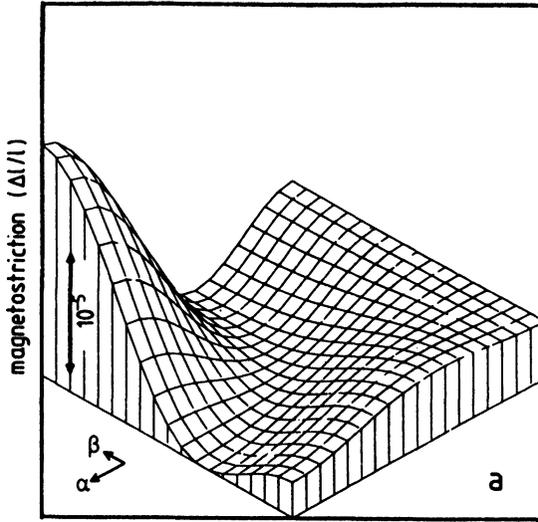


Figure 6 Graphical representation of the anisotropy of magnetostriction $\Delta l/l(\alpha, \beta)$, for the specimen of Fe-Si oriented steel.

The magnetic loss and the permeability are more important technological parameters than the magnetocrystalline energy and magnetostriction. It is also well known that there is a direct relationship between the texture and these properties. However, the calculation of the properties cannot be selfconsistently determined without fully quantitative modelling of the magnetization changes in the polycrystalline materials. Such modelling is very difficult and the results cannot be obtained without drastically simplifying assumptions. As a result of such difficulty, attempts were made to establish semi-empirical correlations between the texture parameters and the power loss and permeability.²¹ In order to predict the anisotropy of these properties the following expression was used.

$$F(\beta) = A_0 + A_4\phi_4(\beta) + A_6\phi_6(\beta)$$

The functions ϕ_4 and ϕ_6 are defined in Eq. (8). The constants A_0 , A_4 and A_6 are determined by fitting the experimental results obtained at various angles to the rolling direction with the formula given above. Hutchinson and Swift¹⁹ fitted the power loss in 1.8% Fe-Si steel using ϕ_4 functions; also, Morris and Flowers obtained good correlation between the core loss and the fourth order texture parameter (see Figure 7). In both cases, however, the texture was not as strong as the texture usually present in Fe-Si oriented steels. Morris and Flower also correlated the permeability at field strengths of about 10 Oe with the ϕ_4 texture function.²¹ These fits could not be improved by correlating the data with a linear combination of texture functions ϕ_4 and ϕ_6 . At present, there is not enough evidence to demonstrate that such correlation is valid for a variety of textures existing in the same material. In particular, it is not known whether it can be applied to the very sharp textures observed in oriented Fe-Si steels. Also there is

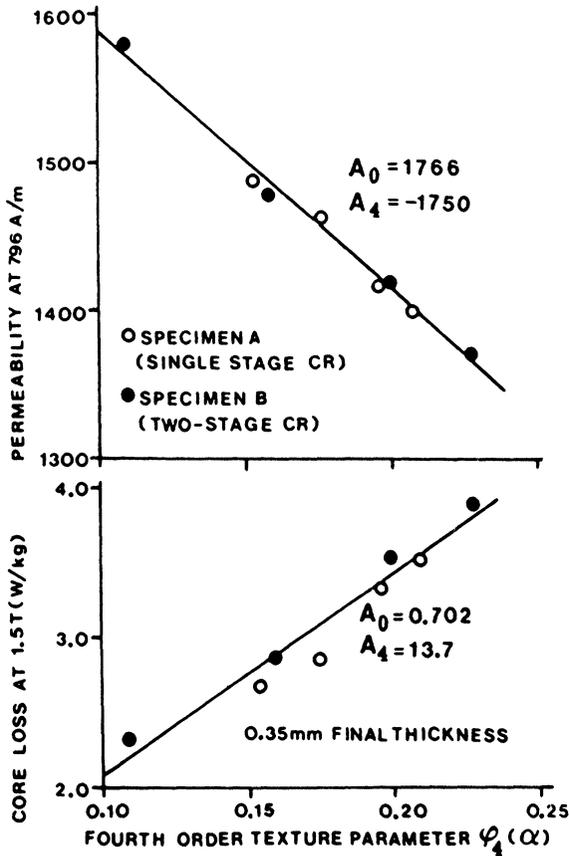


Figure 7 Permeability and core loss versus the fourth-order texture parameter.

an indication that other metallurgical factors such as the grain size and stress, affect the core loss and permeability. These non textural factors are most likely included in the constant A_0 .

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