X-RAY TEXTURE ANALYZING SYSTEM FOR THE ON-LINE PREDICTION OF MAGNETIC ANISOTROPY

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INTRODUCTION

The global competition for the production of high quality oriented Fe-Si steel and other magnetic materials is increasing, and therefore, there is demand for the characterization of the materials' properties and crystallographic texture. Because it is important to minimize down time in any manufacturing process, it is logical that these demands should be met with on-line systems using non-destructive evaluation techniques. To this end, we have been designing on-line NDE systems for use throughout the manufacturing process to quantitatively understand the affects of different processing conditions on the texture of the material. As the texture is one of the most dominant characteristics of both steels and the new hard magnetic materials, the information can be used to tune the processing conditions to attain optimum end result material properties. Ultimately, the on-line texture analyzing systems will be used in a feed back loop for the on-line control of material properties.

After having thus calculated the texture, correlations can be developed so that the anisotropy of important magnetic properties can be calculated. A description of the on-line system is being published elsewhere [1], and so this paper concentrates mainly on those aspects related to the correlation of the crystallographic texture and the anisotropy of such magnetic properties as magnetization energy, magnetic torque, relative permeability and hysteresis losses.

CORRELATION OF THE ANISOTROPY OF MAGNETIC PROPERTIES WITH TEXTURE

It is well known that iron and iron-silicon single crystals exhibit anisotropy in their magnetic properties as is attested to by the difference in the magnetization curves as a function of crystal direction. The fact that, for the same value of magnetizing field, the magnetocrystalline energy for the [100] direction is the lowest and that for the [111] direction is highest is responsible for terming these the 'easy' and 'hard' magnetic directions, respectively. For some magnetic properties of single cystals, it is possible to express their anisotropy

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in the crystallographic reference frame, by a polynomial series expansion of the form

$$P(\bar{h}) = A'_0 + A'_4\Phi'_4(\bar{h}) + A'_6\Phi'_6(\bar{h}) + \ldots \quad (1)$$

where the function Φ_i are invariant with respect to any relevant cubic crystal symmetry operations. Following a derivation Bunge [2] specifically uses for the anisotropy of magnetocrystalline energy, if magnetic texture can be unambiguously related to the crystallographic texture, then the anisotropy of the magnetic property of a polycrystalline material can be exactly calculated by averaging the single crystal anisotropies of that property over each crystallite as it is described by the ODF. Such averaging produces new functions Φ_i which contain the influence of the texture on the bulk magnetic properties. The bulk anisotropy can thus be written

$$F(\alpha,\beta) = A_0 + A_4\Phi_4(\alpha,\beta) + A_6\Phi_6(\alpha,\beta) + \ldots \quad (2)$$

where

$$\Phi_4(\alpha,\beta) = \frac{1}{9n_4\sqrt{\pi}}\frac{1}{5}F_4(\alpha,\beta)$$

and

$$\Phi_6(\alpha,\beta) = \frac{\Phi_4(\alpha,\beta)}{11} + \frac{1}{13n_6\sqrt{\pi}}\frac{1}{231}F_6(\alpha,\beta)$$

and

$$F_4(\alpha,\beta) = \frac{1}{\sqrt{2}}C_4^{11}\bar{P}_4^0(cos\alpha) + C_4^{12}\bar{P}_4^2(cos\alpha)cos^2\beta + C_4^{13}\bar{P}_4^4(cos\alpha)cos^4\beta$$

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In Equations 2, α and β , respectively, are the polar and azimuthal angles, respectively, of a spherical polar coordinate system describing the direction in which the property is being measured. The symmetrized spherical surface harmonics describing the polycrystalline anisotropy, has been represented as a series of symmetrized associated Legendre polynomials, P, the magnitude of each being determined bythe appropriate coefficient, C, of the ODF. If Equation 2 was used to describe the anisotropy of magnetocrystalline energy, the material's anisotropy constants A_i would usually be called K_4 and K_6, which for a silicon content of 3% have the values of 350,000 and 100,000 ergs/cm^3 respectively. In this case a similar expression for the anisotropy of magnetic torque can easily be derived because torque is related to magnetization energy by the expression

$$\tau(\beta) = -\frac{dE(\beta)}{d\beta} \quad ;\alpha = \pi/2 \quad (3)$$

Equation 2 can be used in two distinct ways: in the case where the material's anisotropy constants A_i are known, as in the case of magnetocrystalline energy in Fe-Si steels, it can be used to calculate the anisotropy of those magnetic properties knowing the lower order coefficients of the ODF. However, it can also be used in a reverse

fashion, such that it and a least squares fitting routine can be combined to calculate A_i provided that the anisotropy of a magnetic property has been measured and that it is strongly related to the crystallographic texture.

Correlating the Anisotropy of Magnetic Torque with Texture

The least squares fit method of calculating the anisotropy constants A_i was used on magnetic torque measurements obtained for a strongly Goss oriented Fe-3%Si steel. The coefficients of the ODF used were calculated from pole figures that were measured previously using neutron diffraction in order to alleviate the problems of poor statistical symmetry in the pole figures due to the large secondary recrystallized grains. Figure 1 presents the results of a number of fits run using Equation 5

The two fits differ from one another in that Figure 1a is the result of a fit which assumes that the sixth order anisotropy coefficient A_6 is zero while Figure 1b does not. Evidently, within the estimated error, the truncation of the order of the fit does not appreciably alter the fit quality for this strongly oriented magnetic steel. As the constants A_i have been calculated, a surface representing the anisotropy of the magnetization energy can be created using Equation 2. The axes marked in Figure 2 are the polar (α) and azimuthal (β) angles described previously.

Correlating the Anisotropy of Permeability with Texture

From the same oriented Fe-Si steel, magnetization curves from Epstein strips cut at 10 degree increments from the rolling direction to the transverse direction were obtained for a range of driving fields from 0 to 100.0 Oe. Of a number of magnetic properties obtainable from these curves, the anisotropy of relative permeability is the most used in practical applications. A series of least squares fits were done with the data and the anisotropy constants were calculated. Similar to that which occurred with the torque measurements, suitably accurate fits were obtained using a truncated expansion up to the fourth order, allowing that the property values be plotted directly against the texture anisotropy function $\phi 4$.

Figure 3 contains results for relative permeabilities measured at 0.5 and 100.0 Oe.

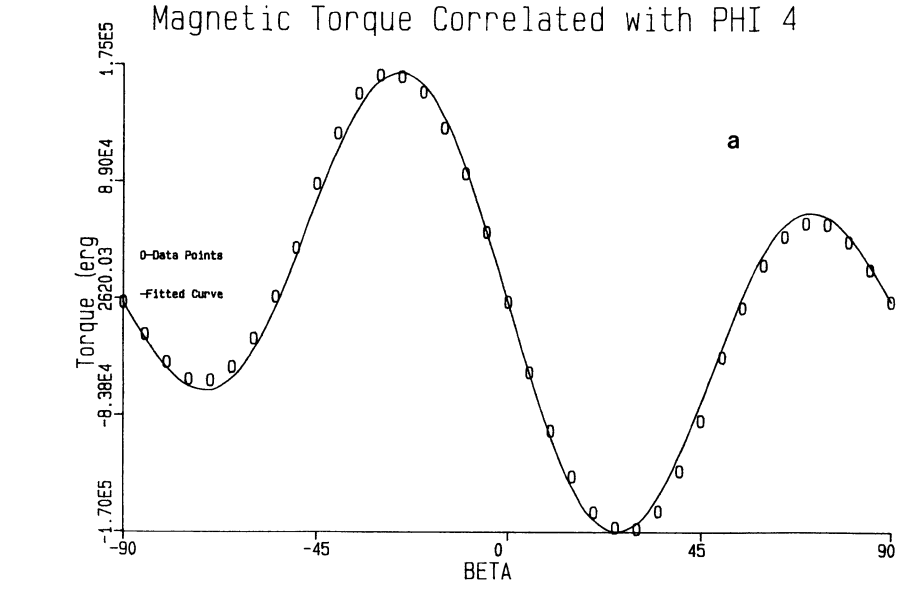
In general, the quality of the correlation between the anisotropy of the permeability increases with increasing magnetic field, the major discrepancies occurring for the β=0 and β=10 degree data which tend to be too high.

Correlating the Anisotropy of Hysteresis Losses with Texture

The Epstein strips mentioned previously were used in a series of hysteresis tests from which the hysteresis losses as a function of the angle from the rolling direction could be measured. Figure 4 contains the results of the attempted correlation for losses measured for maximum applied fields 5.0 Oe, assuming that A_6 is zero. The presented results show that the correlation is poor, a contradiction with results published by Morris and Flowers [3].

DISCUSSION

According to the assumptions made in their derivation, Equation 2, and thus also Equation 3, should only be used in certain magnetically 'clean'



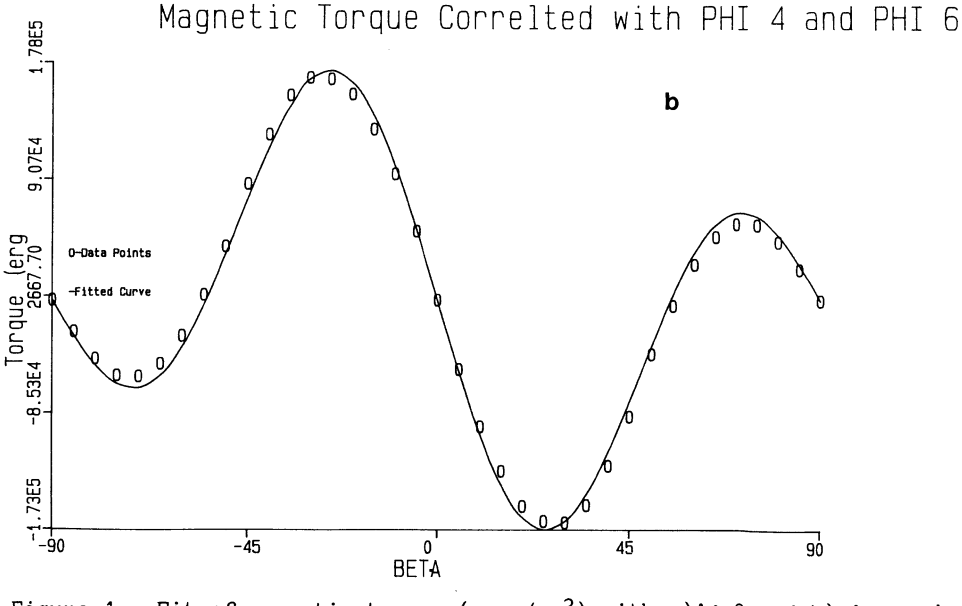


Figure 1. Fit of magnetic torque (ergs/cm3) with a)A_6=0 and b) A_6 used.
Legend:_- least square fit, •- data points

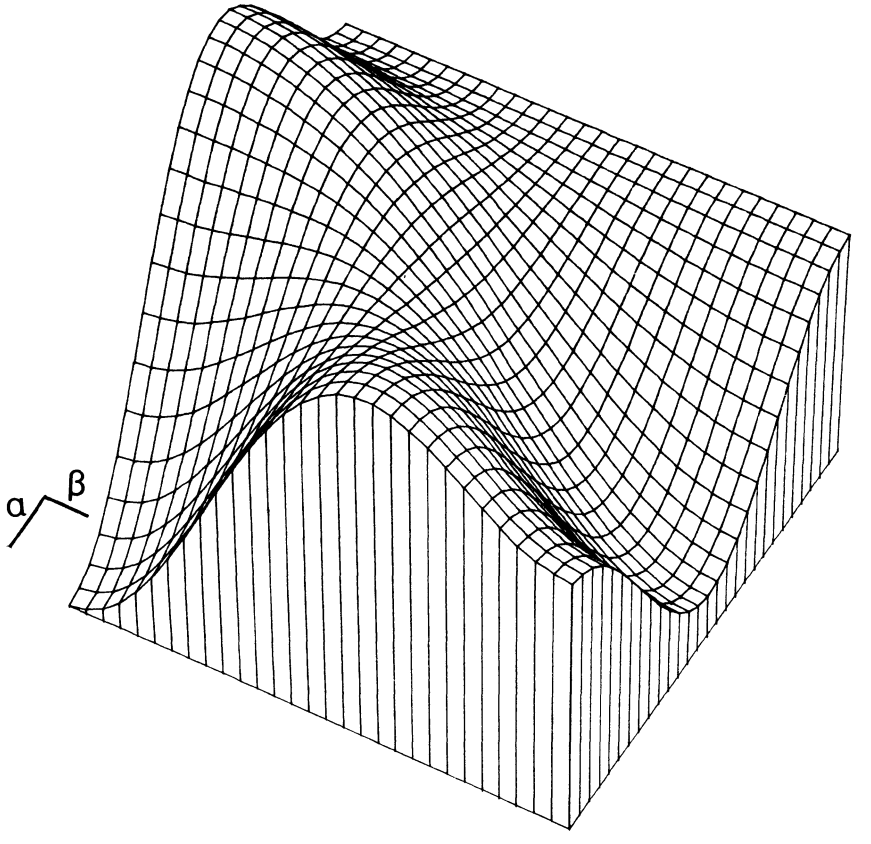


Figure 2. Magnetocrystalline energy calculated from anisotropy constants calculated from least squares fit of magnetic torque data.

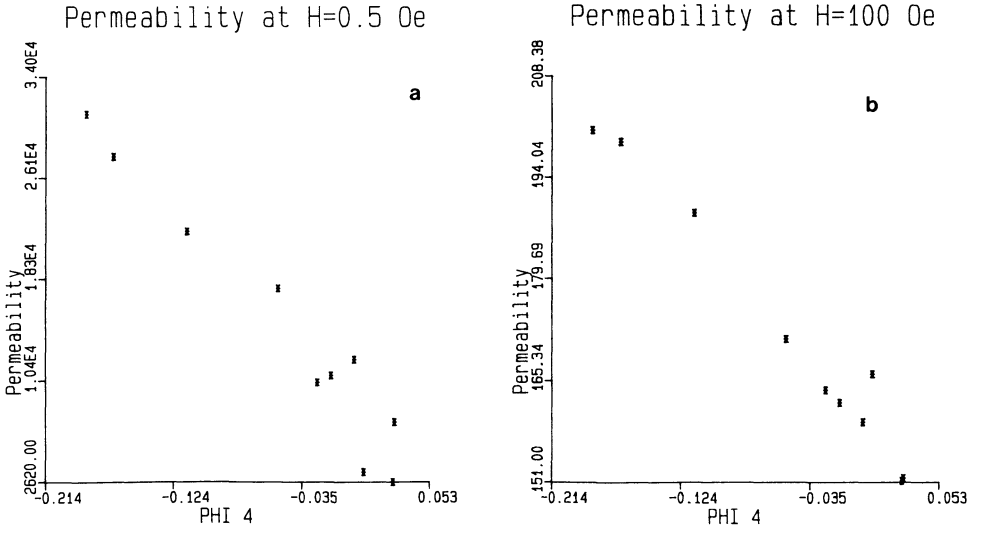


Figure 3. Correlation of relative permeability measured at a) 0.5 Oe, b) 100.0 Oe, assuming $A_6=0$

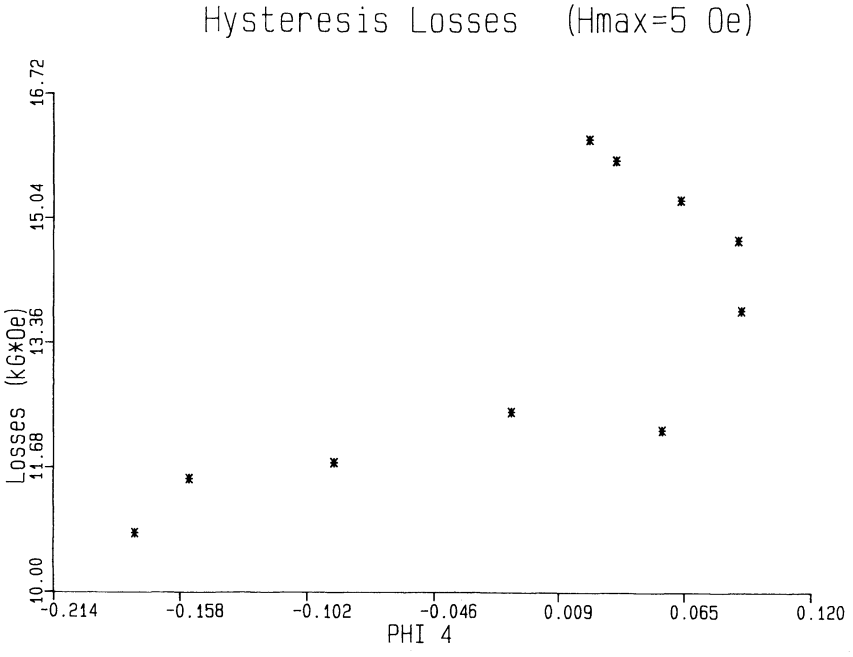


Figure 4. Correlation of hysteresis losses measured at maximum applied fields of 5.0, assuming $A_6=0$

cases, i.e. those in which the domain structure for each grain, and thus their magnetic anisotropy, is related to each grains' crystallographic orientation in an identical manner. At saturation, a very high proportion of the domains inside a specimen are aligned very close to the applied magnetic field, and thus the measured property can be related to the texture through the averaging of those same properties over each of the constituent crystallites.

Equally, upon increasing the applied field strength from near zero values, most of the domain rearrangement is accomplished by domain wall motion; ideally, the energy required to do this varies with the magnetic anisotropy of the crystallites. Because the domain structure within the polycrystal at zero field is random, and that by increasing the applied field the domains would rearrange so as to lie in the closest easy magnetic directions of the grains, the magnetic texture would be related to the crystallographic texture.

However, practically, an otherwise clean magnetic case can be impaired by the interaction of closure domains at grain boundaries and near the sheet surface with the ideal domain structure. Along these lines, metallurgical factors such as the anisotropy of grain size, precipitate distribution and the through thickness variation of texture play roles which can be significant. If the anisotropy of domain evolution and arrangement are affected by these factors, then the bulk magnetic anisotropy will not be strictly related to the weighted sum of the crystallites' anisotropies through the coefficients of the ODF via Equation 2.

In this paper, the texture of the material used was characterized by low order coefficients of the ODF calculated from pole figures measured by neutron diffraction, meaning that the texture used in the correlations were that of the bulk or through thickness averaged texture. Apart from this, the extent to which one expects such a variation in the texture is small due to the fact that the secondary recrystallized grains are very close to being as thick as the sheet itself. However, if the material is not so ideal and the texture measurements are being done by standard reflection X-ray diffraction, as is done in some on-line texture analyzing systems, one must realize that the bulk magnetic properties are not neccessarily described by correlations with the surface measured texture.

CONCLUSIONS

Attempts at correlating the anisotropy of such magnetic properties as relative permeablility, magnetic torque, magnetocrystalline energy and hysteresis losses were made using

$$F(\alpha,\beta)=A_0+A_4\Phi_4(\alpha,\beta)+A_6\Phi_6(\alpha,\beta)+\ldots$$

or its derivative with respect to β. This function presumes that single crystal anisotropies can be described using low order series expansions and that the sum of these terms through the ODF can predict the anisotropies of the bulk specimen. This function is not, therefore, suitable for those anisotropies which are exhibited in the bulk polycrystalline material only.

It was found that the anisotropy of magnetic torque (and thus of magnetization energy) and of relative permeability correlated well with the function assuming that the sixth order term was zero. The constants A_4 and A_6 calculated in the case of magnetic torque were $370{,}000 \pm 10{,}000$

Table 1. Fitting constants A_0 and A_4 for relative permeability.

	0.1 kG	0.2 kG	0.5 Oe	2.0 Oe	5.0 Oe	20.0 Oe	100.0 Oe
A_0	1587	2135	13784	6435	2709	724	170
A_4	-9734	-13486	-96475	-9449	-3769	-1053	-185

and 60,000±10,000 ergs/cm3 respectively, which agree well with accepted values listed previously. Table 1 contains A_0 and A_4 anisotropy constants for the fits of relative permeabilty. However, similar correlations with the anisotropy of hysteresis losses produced poor results.

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