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USE OF SILICON STEEL FOR LOW-HYSTERESIS D.C. ACCELERATOR ELECTROMAGNETS

by

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Abstract

Industrial series production of tightly toleranced, low hysteresis magnetic circuits for accelerator electromagnets has required thorough investigation and provided statistical information on d.c. magnetic properties of standard high-grade non-oriented silicon steel sheet.

1. Introduction

Although the use of high-grade silicon steel in the magnetic circuits of electromagnets for particle accelerators is not new, it has, however, mostly been confined to rapid cycling machines, e.g. electron synchrotrons operating at network frequency. In that case, the rationale for magnetic material selection follows very closely that of more widespread uses, such as transformers and a.c. rotating machines.

Very different is the field of application discussed here, essentially based on the low coercivity, a d.c. magnetic property corollary, although not specific, to the low a.c. core loss which characterizes high-grade silicon steels. The excellent, though less thoroughly documented d.c. magnetic properties of this class of materials make them an interesting alternative, for some specific types of d.c. or slow-cycling electromagnets, to the more generally used decarburized steel.

2. Requirements of the magnetic circuits

2.1 Magnet design characteristics

The magnetic system of LEP, the high-energy electron-positron collider under construction at CERN, is composed of about 4700 bending and focusing electromagnets [1], regularly distributed in a 26.7 km circumference ring tunnel. Successful operation of the accelerator sets tight requirements on the magnetic fields, which can only be achieved by imposing close mechanical tolerances on the magnetic circuits and tight control of the magnetic properties of the steel.

In addition to the above requirements, which apply to all components of the magnetic system, the 616 bipolar, individually powered dipoles for orbit correction [2] demand good linearity and low hysteresis of the excitation curve. In view of their moderate field levels and small dimensions, magnetic circuits made of glued stacks of silicon-steel laminations were soon envisaged as an alternative to decarburized steel or commercially pure ("Armco") iron.

The 64 "weak-field" dipoles, excited in series with the main bending magnets, have to produce a field ten times lower in order to reduce the emission of synchrotron radiation at the ends of the accelerator arcs [3]. To preserve the field ratio with the main dipoles throughout the excitation range, as well as the field homogeneity in the useful aperture, low hysteresis and high permeability at low field (i.e. below 0.3 T) is essential.

The main design characteristics of these electromagnets are summarized in the table below.

Type of dipole		Orbit correction				Weak-field
		MCV	MCH	MCVA	MCHA	MBW
Number		176	248	88	104	64
Maximum field	(mT)	38	58	62	72	10
Gap	(m)	0.2	0.1	0.2	0.1	0.1
Length	(m)	0.4	0.4	0.4	0.4	5.75
Setting accuracy	(mT)	0.04	0.04	0.04	0.04	0.01

2.2 Material selection

In order to match the above requirements, the magnetic circuits must exhibit in all directions low coercivity with little dispersion, while induction at saturation is less critical due to the moderate field levels. This naturally led to consider high-grade, non-oriented silicon steel, a technical material with reproducible magnetic properties, covered by international standards, and well known to the manufacturers of electrotechnical equipment [4]. Magnetic steel sheet, however, is normalized with respect to a.c. properties, particularly core loss at 50 Hz; thus, the main issue was to achieve controlled coercivity while procuring material with guaranteed a.c. core loss. A preliminary investigation, conducted on samples of cold-rolled, non-oriented magnetic steel sheet supplied by several European producers, indicated that coercivity values below 40 ± 5 A m^{-1} could reproducibly be obtained on grade FeV 135-50 according to EURONORM 106-71, which was consequently selected. As the standard was updated (EURONORM 106-84) by referring to core loss at 1.5 T instead of 1.0 T, the equivalent grade became FeV 330-50.

2.3 Technological and economical aspects

High-grade silicon steel sheet is among the few metallurgical products with very low and controlled impurity contents (typically N, O and C below 50 ppm), readily available even in small quantities. In comparison, the use of decarburized steel exhibiting the same range of coercivity calls for special fabrication and production control techniques [5], and therefore can only be considered for large tonnage.

Moreover, the punching of laminations with dimensional tolerances down to 0.02 mm is easier and the techniques and tooling are more commonly available for standard 0.5 mm silicon steel sheet than for 1.5 mm decarburized steel. Despite the small thickness, very high stacking factors (around 0.99) can be achieved, thanks to the flatness and surface quality of silicon steel sheet.

Besides early saturation, which excludes its use for high-field applications, the main argument against the use of silicon steel is economical: the smaller thickness increases the number of laminations to be punched, and the cost per unit mass is about 20 % higher. The relevance of both arguments to the applications considered here is weakened by the small overall tonnage involved.

3. Magnetic properties of the steel sheet

3.1 Measurement methods and instruments

The procurement of the 140 t silicon steel sheet spread over three years. Every one of the 23 one-meter wide coils constituted a "test unit" in the sense of EURONORM 106 and was characterized by sample lengths taken from both ends. The 3.5 m sample lengths were subsequently cut into adjacent samples for Epstein-frame testing at the steel plant, as well as ring permeameter and sheet coercimeter measurements at CERN. After acceptance of the steel by CERN on the basis of complete assessment of the samples, the coil was cut into sheets, packed and sent to the punching firm.

The Epstein-frame measurements conducted at the steel plant are quite straightforward and will not be further discussed. The reference instrument used at CERN for the evaluation of the steel quality is the ring-sample permeameter [6]; each sample consists of twelve 114 mm o.d., 76 mm i.d. rings, cut at low speed in the sheet, and stacked with their rolling direction aligned. Following complete demagnetization of the sample, magnetic permeability readings are taken at excitation levels ranging from 20 A m^{-1} up to 24 000 A m^{-1}, while the coercivity is measured after magnetization to saturation.

Whereas ring sample measurements physically average magnetic properties over all directions, the directional coercive field was measured on full-size samples of sheet in a coercimeter [7] recently developed and built at CERN for industrial inspection of magnetic steel sheet. This instrument makes it possible to investigate the variations of coercivity, averaged over a minimum sample area of 120 x 100 mm^2, at different orientations with respect to rolling direction and positions in the sheet.

The influence of previous magnetization on the coercive field is compared in Fig. 1 for silicon and decarburized steels; in both cases, asymptotic values of coercive field are reached after magnetizing the material above 1.5 T.

The mean values of coercivity measured in the rolling and transverse directions on the sheet coercimeter correlate well with ring-sample measurements (Fig. 2). For future applications, and provided appropriate sampling procedures are established for averaging the local variations of coercivity, the sheet coercimeter could become a secondary reference instrument, thus avoiding the manpower-intensive fabrication of ring samples.

3.2 Coercivity variation patterns

Although the material is rated as "non-oriented", the most striking feature of its coercivity is strong anisotropy: in all cases, the coercive field in the rolling direction is significantly lower than in the transverse direction, with anisotropy ratios ranging from 1.5 to 2.0. Typical variations of coercivity with orientation are shown in Fig. 3, both for silicon and decarburized steel sheet.

Besides anisotropy, inhomogeneity of the coercivity was also observed across the sheet width (Fig. 4), showing a marked edge effect, particularly for the measurements performed along the transverse direction.

3.3 Coercivity versus core loss

Despite a rather large scatter, Fig. 5 definitely shows a positive correlation between coercivity and core loss at 50 Hz, 1 T; procuring the formerly standard grade FeV 135-50 (EURONORM 106-71) effectively yields values of coercivity below 45 A m^{-1}. Unfortunately,the correlation with core loss at 50 Hz, 1.5 T, which now defines the standard grades (EURONORM 106-84), is less clear. In fact, there does not seem to be a one-to-one correspondence between the present and previous standards, as can be seen from the comparison of core loss at 1.0 T and 1.5 T in Fig. 6.

In spite of this difficulty, specification of a standard grade of magnetic steel sheet and good understanding of the customer's requirements by the steel producers permitted to obtain an average coercive field of 34 A m^{-1}, with a dispersion (standard deviation) of 3 A m^{-1}, without rejecting any batch throughout the production.

3.4 Permeability

The variation of d.c. magnetic permeability with induction in the material appears in Fig. 7, showing an average curve and standard-deviation bands for the silicon steel studied, as compared to an average curve for decarburized steel. The observed behaviour corresponds to current knowledge: silicon steel shows almost twice the initial permeability and a somewhat higher maximum permeability, but saturates earlier.

There is a strong correlation between low-field permeability and coercivity, as shown in Fig. 8. In fact, permeability and coercivity remain well correlated up to an induction of 0.9 T. Besides academic interest, this correlation is of great practical importance, since the control of coercivity also serves to limit the spread in permeability, thus improving the reproducibility of the magnetic circuits.

3.5 Ageing

Influence of ageing on coercivity was investigated by submitting all samples to an accelerated ageing procedure (100 h at 150 °C). In most cases, very little or no variation is observed, whereas a few samples exhibit greater ageing. This difference in behaviour remains unexplained.

4. Conclusion

Controlled d.c. magnetic properties within specified tolerances were obtained through the procurement of 140 t high-grade non-oriented silicon steel sheet meeting industrial standards. This was a key factor in matching economically the tight requirements of field quality, reproducibility and low hysteresis, throughout the production by European industry of several hundred electromagnets for the LEP collider.

Acknowledgements

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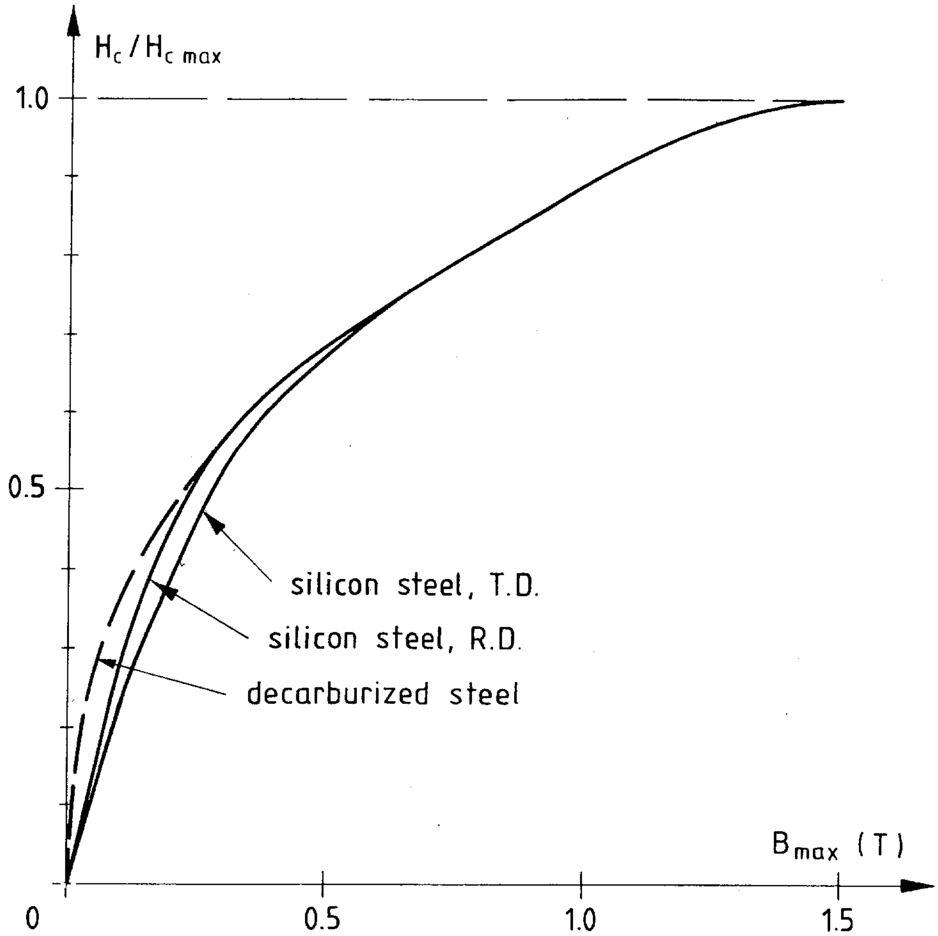

Fig. 1 Coercive field versus maximum induction for silicon steel (rolling and transverse directions) and decarburized steel sheet.

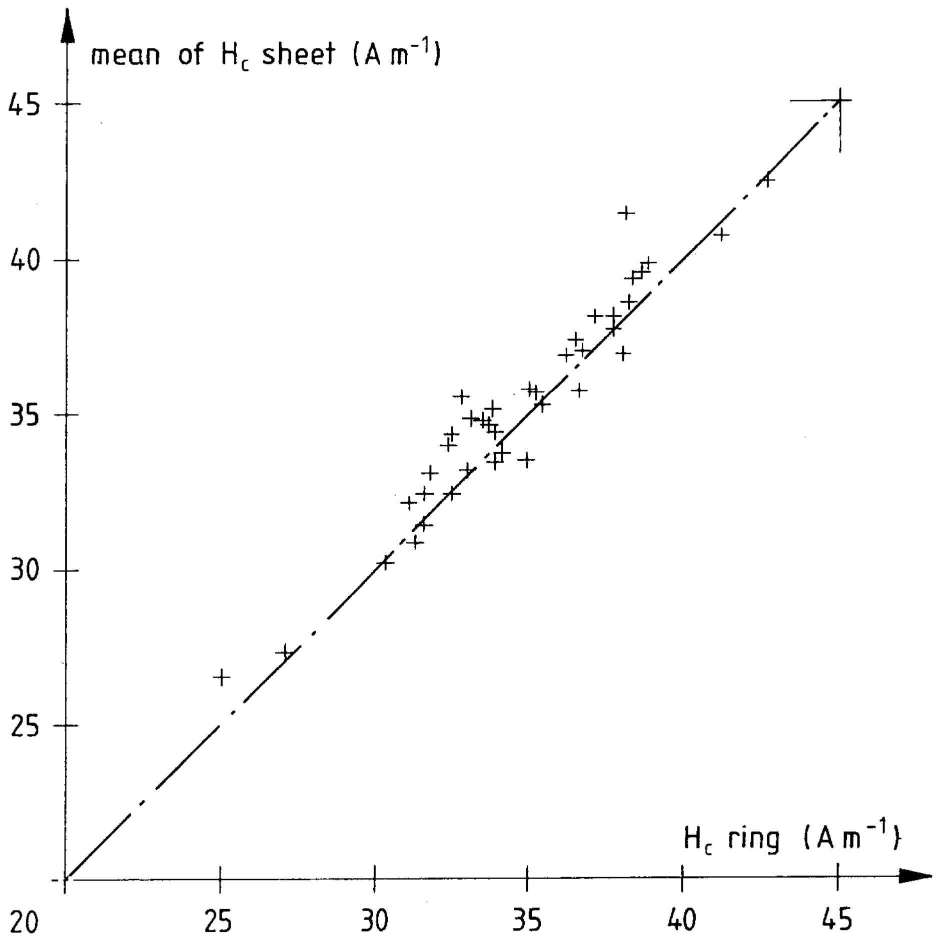

Fig. 2 Correlation of mean coercivity in rolling and transverse directions with ring-sample measurements (FeV 330-50, 40 samples, correlation coefficient 0.94).

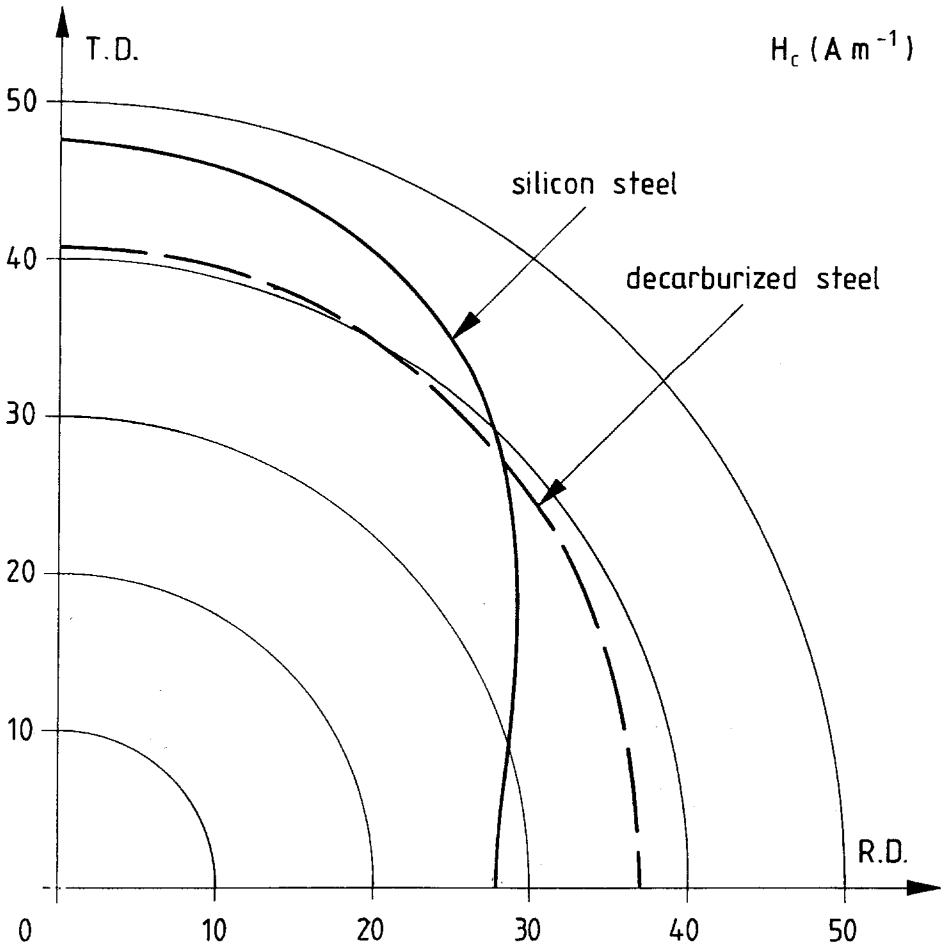

Fig. 3 Typical anisotropy of coercivity in silicon and decarburized steel sheet.

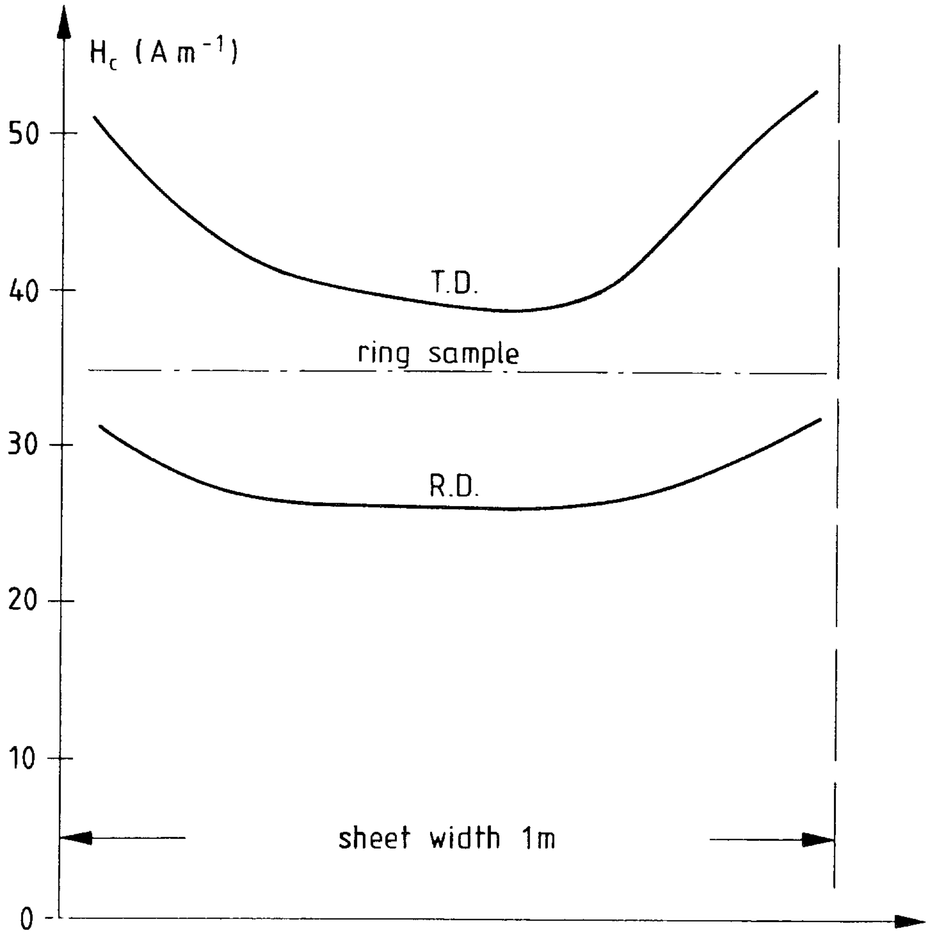

Fig. 4 Typical inhomogeneity of coercivity across width of silicon steel sheet.

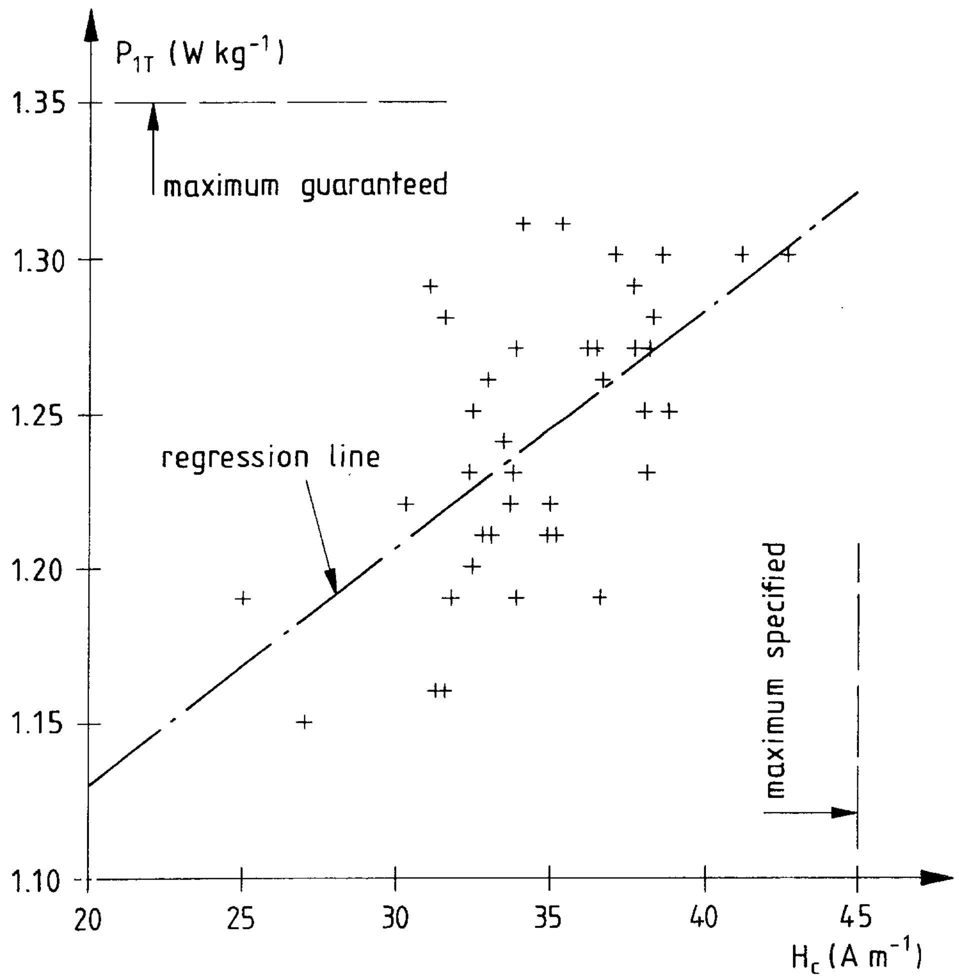

Fig. 5 Correlation of coercivity with core loss at 50 Hz, 1 T
(FeV 330-50, 40 samples, correlation coefficient 0.59).

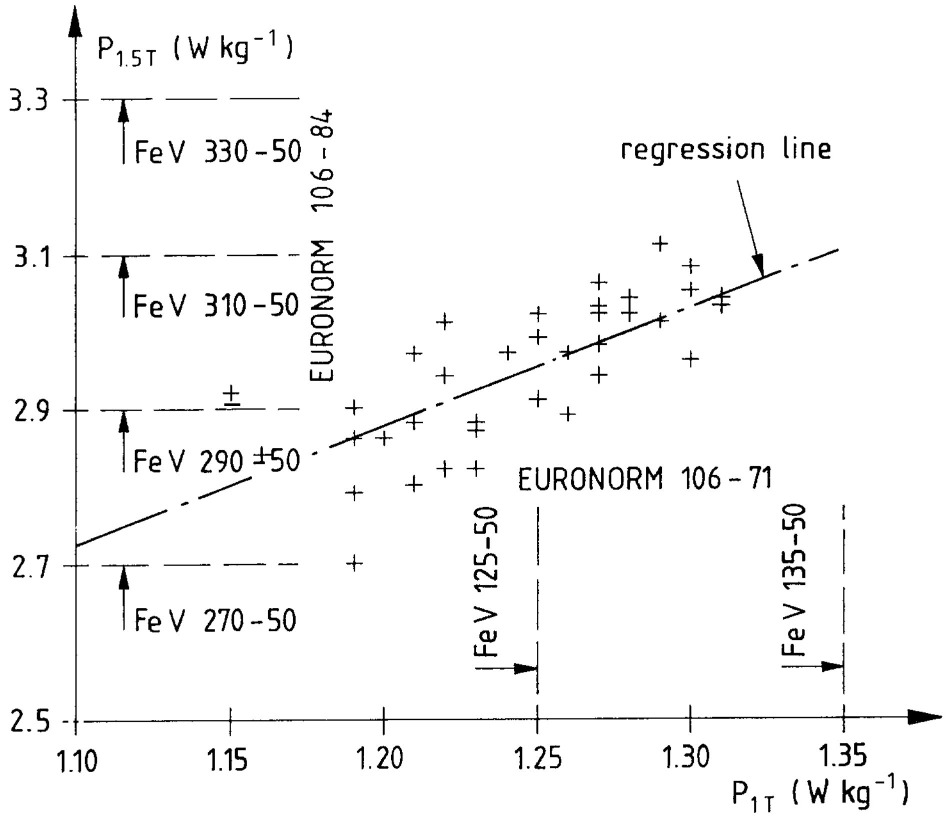

Fig. 6 Correlation of core losses at 50 Hz, 1 T and 50 Hz, 1.5 T (FeV 330-50, 40 samples, correlation coefficient 0.71).

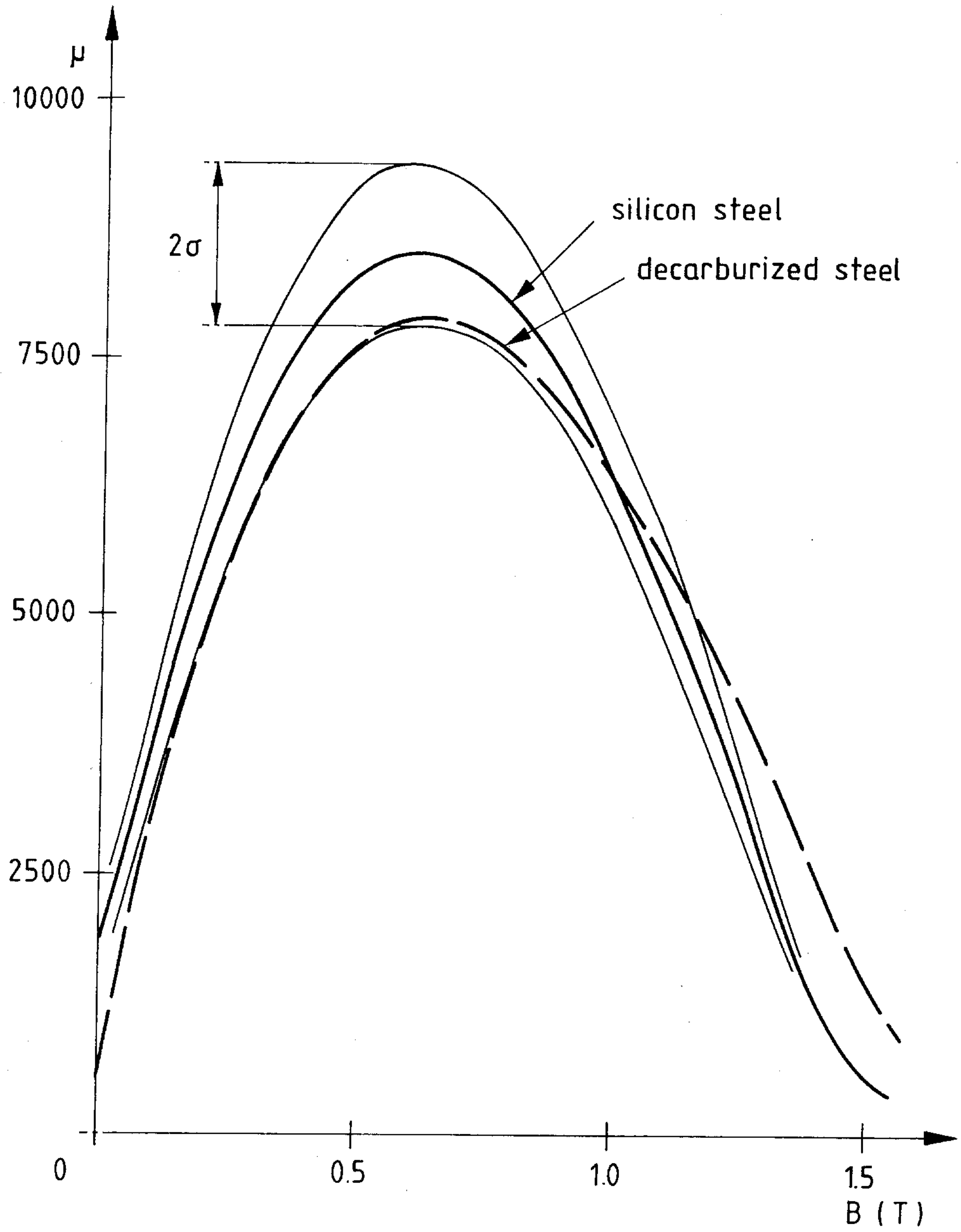

Fig. 7 Permeability versus induction in ring samples of silicon steel (FeV 330-50, 40 samples, average and one standard deviation bands) and decarburized steel (average of 200 samples).

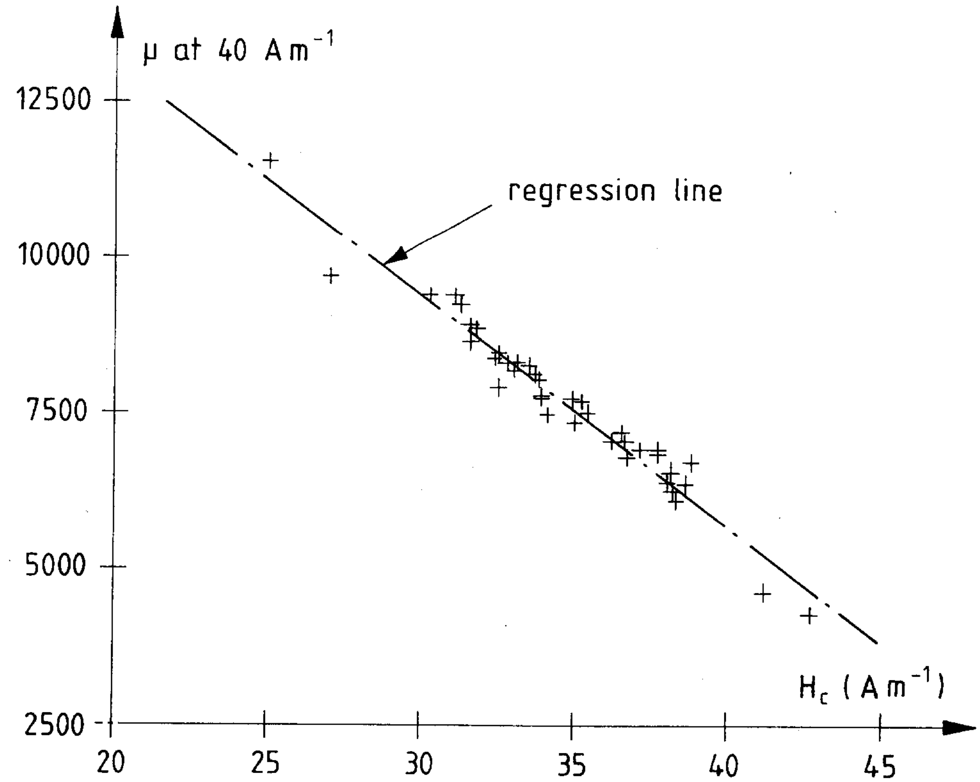

Fig. 8 Correlation of low-field permeability with coercivity (FeV 330-50, 40 samples, correlation coefficient -0.95).