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Magnetic and metallurgical properties of high-tensile steels

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An investigation into the relation between magnetic and metallurgical properties of 26 types of high-strength constructional steel is reported. Correlation between chemical composition and coercive field was found. An independent correlation between coercivity, grain size and relative pearlite and ferrite fractions was also found. The coercivity and initial permeability varied with ultimate tensile strength but Vickers hardness measurements were not found to be a reliable method of predicting coercivity over the hardness range found in the sample set. For a larger hardness range, produced by heat treating one steel type, an excellent linear relationship was found between hardness and coercivity.

1. Introduction

In recent years, the use of magnetic techniques for non-destructive testing has increased rapidly. Magnetic particle inspection (MPI) is of great importance in the early identification of cracks, particularly at welds in massive off-shore structures, and the cost of performing such inspections off-shore is considerable. It is, therefore, surprising that little is known about both the magnetic inks used and the magnetic properties of the steels being inspected. This lack of basic knowledge means that the power of finite element programs developed to study the leakage of flux above cracks during MPI inspections cannot be exploited reliably.

We have begun an investigation into the properties of a range of magnetic inks [1] and have undertaken a detailed study of the inter-relation between the metallurgical, mechanical and magnetic properties of a range of high-tensile steels. In this paper we report the metallurgical, mechanical and magnetic properties of these steels.

Relations between the various measured parameters have been sought with the aid of a BMDP (Biomedical Data Programs) statistical software package on the VAX II computer at Cramlington and we also report certain relationships derived empirically from this study. Using these, it is possible, within certain limitations, to predict the coercive field from a knowledge of the chemical, mechanical and metallurgical parameters.

2. Metallurgical properties

The steels chosen for study were all X56, X60 or X65 pearlitic steels with carbon concentrations shown by spark emission spectroscopy to be between 0.16 and 0.22% and with manganese content in the region of 1%. Within the 26 steel types examined were semi-killed (SK), fully killed (FK) and controlled rolled (CR) steels from various origins. A combination of metallographic and chemical analyses was used to identify the three classes of steel. Semi-killed steels had low silicon and aluminium contents and a relatively large grain size, in contrast to the fully killed steels which had a silicon content above 0.1% and an aluminium content of about 0.04%. Controlled rolled steels have a reduced carbon equivalent (CE) value to improve weldability, the carbon content itself being typically 0.05% less than that of the fully killed steels.

Inclusion of aluminium, vanadium and niobium in the fully killed steels results in a reduced grain size in comparison with the semi-killed steels. Fig. 1 shows a typical micrograph taken following a nital etch to reveal ferrite (white) and pearlite (black) grains. This reduction in grain size results in a generally higher yield stress and ultimate tensile stress for fully killed steels. The controlled rolling process gives rise to less banding of the pearlite and even smaller mean grain size.

Throughout this paper, reference will be made to a mean grain size. It is important to stress from the outset that this represents an average of quite a wide distribution. Fig. 2 gives examples of the ferrite grain size distribution for SK, CR and FK steels, respectively. Further, the grain size varies considerably with position on the sample and considerable care and patience was required in order to obtain a statistically significant value for each specimen. There is also an anisotropy in the grain shape, or equivalently, grain-boundary density, which has been treated mathematically elsewhere [2]. This anisotropy was relatively small and is not important in the context of the results presented here.

2.1. Mechanical properties and the relation to chemical and metallurgical properties

Uniaxial tensile tests were performed on standard Instron testing machines at the British Gas Engineering Research Station at Killingworth. Hardness measurements were made with a Vickers indentor at Durham, and as the pearlite contains cementite (Fe_3C) which is

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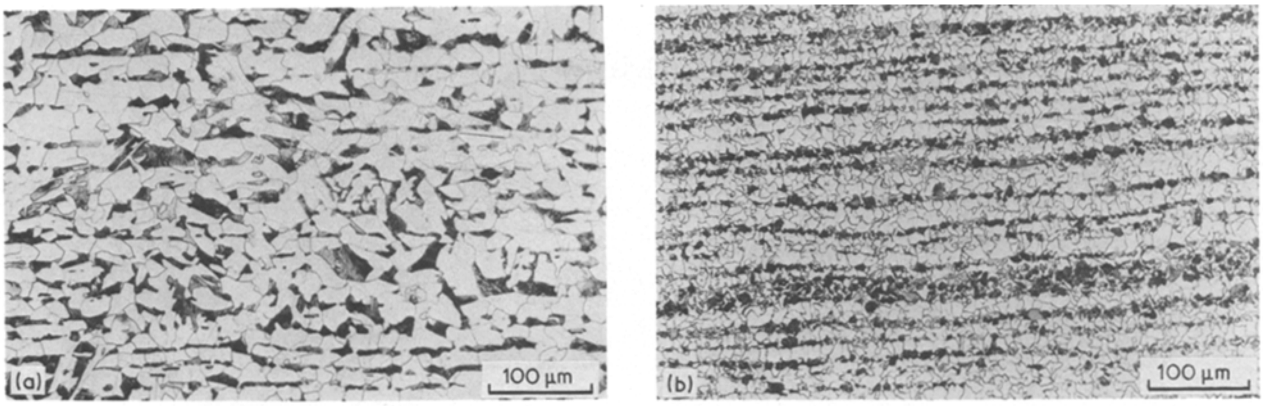

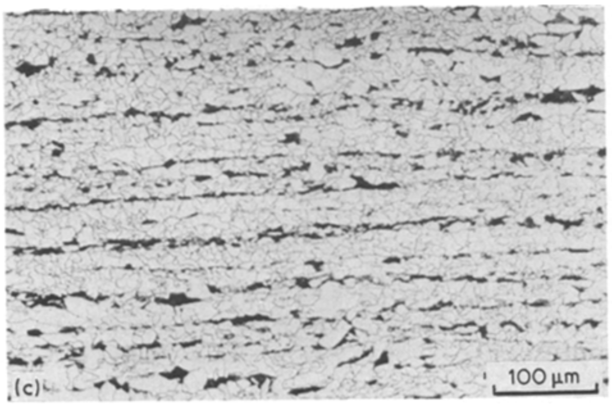

Figure 1 Comparison of the microstructures of typical steel types studied: (a) semi-killed (b) fully killed, (c) controlled rolled.

very much harder than pure iron (ferrite), a number of readings were taken from random points across the sample to average out the effects of banding of the pearlite (see Fig. 1b and c).

The ultimate tensile stress (UTS) varied linearly with the yield stress (YS), as found by previous authors studying similar steels [3], although the scatter on the data points was rather larger than we had expected. We found, with UTS and YS expressed in $\mathrm{MN\,m^{-2}}$,

$$\mathrm{UTS} = 0.79\ \mathrm{YS} + 211 \qquad (1)$$

having a correlation coefficient of 0.83. This wide spread reflects the variations in microstructure within the massive samples used for the tensile tests. Similarly the Vickers Hardness VH varied with UTS according to

$$\mathrm{UTS} = 1.93\ \mathrm{VH} + 206 \qquad (2)$$

with a similar correlation coefficient of 0.82.

It proved difficult to find a direct relationship between steel chemistry and mechanical properties, although the steels can be categorized into classes with respect to UTS and silicon content (Fig. 3). The CR steels all have higher UTS values than the FK steels while most of the SK steels have relatively low UTS values. Only the manganese content showed an upward trend with UTS, and here the correlation coefficient was only 0.72. Similarly, attempts to fit the yield stress to a Hall–Petch relation [4] were unsuccessful and it is clear that the impurities act both to control grain size and also to alter the lattice friction by solid solution and precipitation hardening.

3. Measurement of magnetic properties

Magnetic measurements were performed in a closed

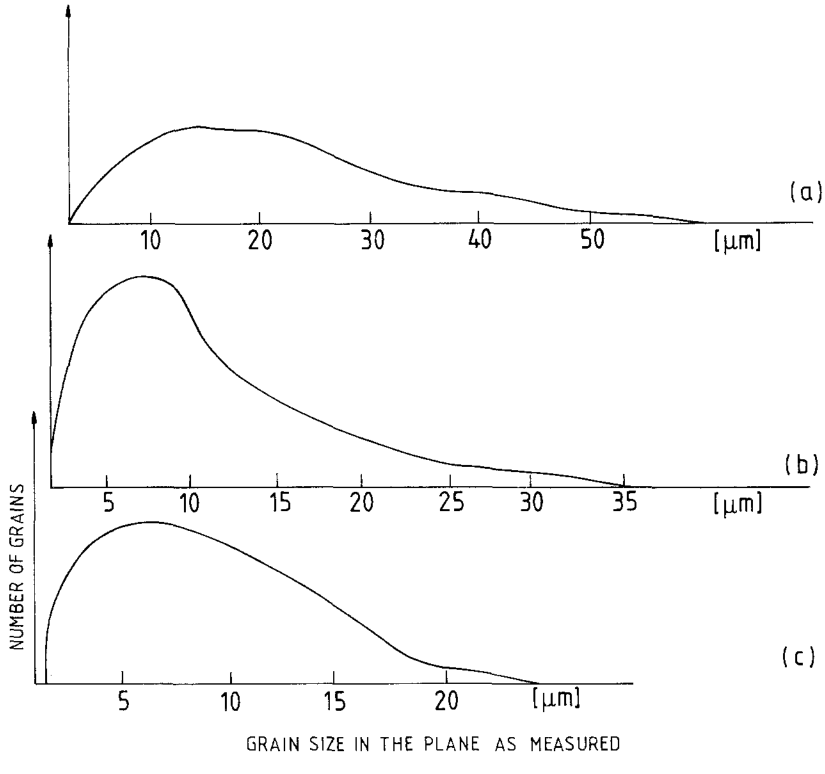

Figure 2 Ferrite grain size distribution for three of the samples: (a) semi-killed, (b) controlled rolled, (c) fully killed steel.

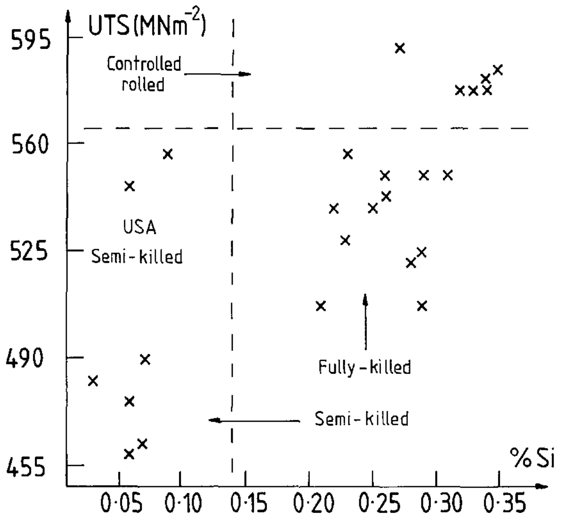

Figure 3 Categorization of steels by UTS and silicon content.

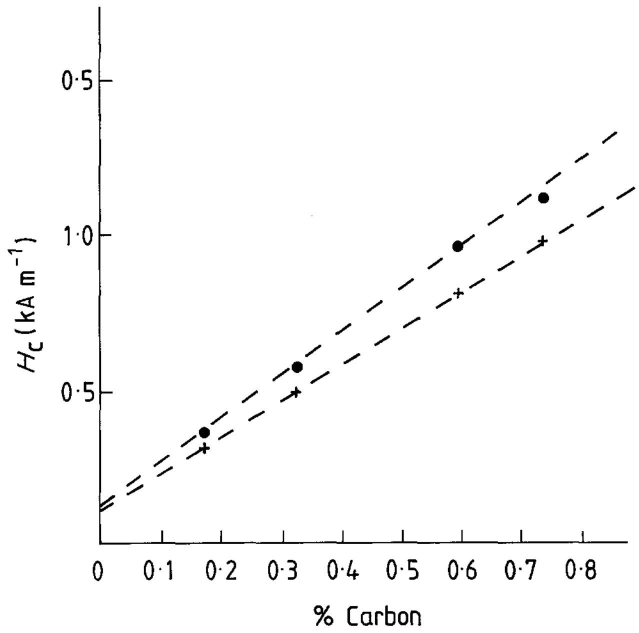

Figure 4 Variation of H_c with carbon concentration in specially prepared steels with only carbon concentration varying.

yoke magnetometer in a magnetizing field up to 5.6 kA m^{-1}. The technique used was essentially that given in BS5884 (Determination of Magnetic Materials). The field applied to the bar-shaped sample was measured with a Hall probe adjacent to the sample surface and the magnetic induction in the bar was measured by integrating the e.m.f. from a tight fitting multi-turn coil wrapped around it. A long solenoid, the axis of which is coincident with the central line of the sample, provided the magnetizing field and the current in this was controlled remotely by an M.I.N.C. minicomputer. Data from the Hall probe and integrating voltmeter were also logged by the computer.

A typical *B–H* loop of an initially demagnetized sample consisted of 200 pairs of magnetic induction and field values and consequently quite lengthy run times of up to 45 min were encountered. In order to eliminate amplifier drift, three readings of the magnetic induction at consecutive half cycles of the B–H loop were taken in sequence. Over the period required for three measurements the drift was found to be linear and the appropriate correction made in the software. When care was taken to machine accurate flats on the specimen where it made contact with the yoke, thus minimizing demagnetizing effects due to air gaps, excellent consistency was achieved. Independent measurements at the National Physical Laboratory showed agreement to within 2% throughout the loop.

In order to quantify loop shape, as well as record-crossing parameters such as B_r, H_c and μ_{max}, *B–H* loops were parameterized by means of the harmonic analysis technique described by Willcock and Tanner [5, 6]. Both odd and even harmonic coefficients, determining principally loop shape and width, respectively, were recorded up to the ninth order and correlated with metallurgical and mechanical parameters.

4. Inter-relationship of magnetic and metallurgical properties

Many studies have been conducted over the years into the variation of the coercive field, H_c, with carbon content and grain size in steels. Previous workers have found a linear dependence of H_c with carbon concentration [7] and we also found such a relation in

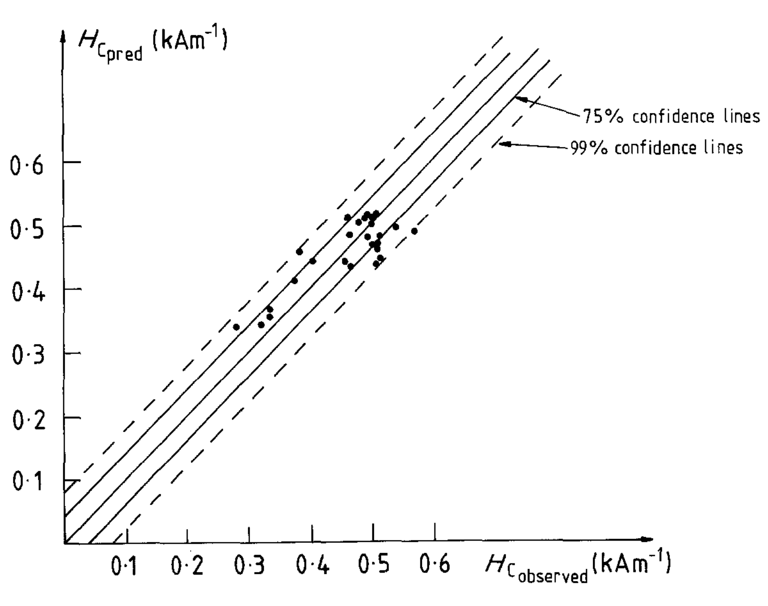

Figure 5 Measured value of H_c plotted against the value predicted from the carbon and manganese concentration below.

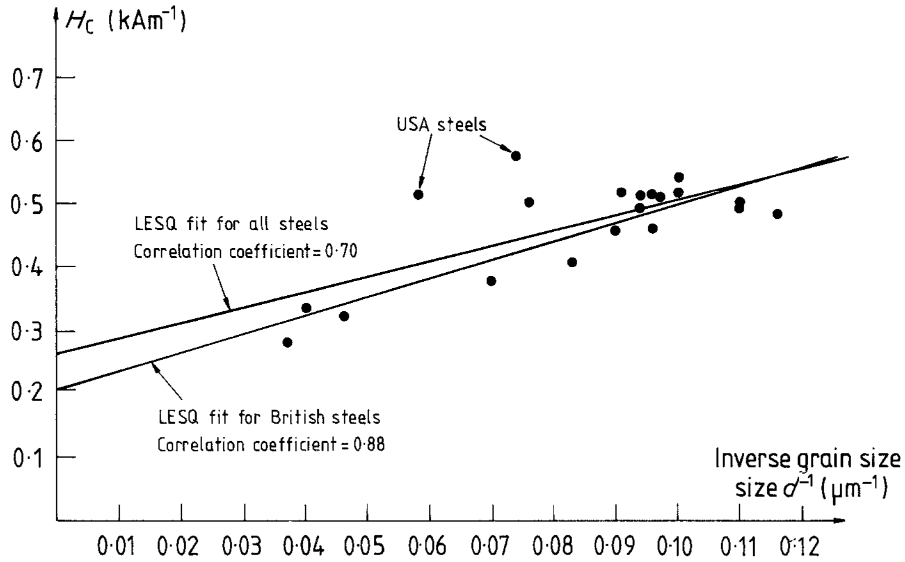

Figure 6 Coercive field H_c plotted against inverse ferrite grain size, d_F.

steels prepared specially for us within which only the carbon concentration varied (Fig. 4). These steels had a much higher carbon concentration than our main sample set and no such simple relation could be discerned within the constructional steels. Use of the multiple linear regression option on the BMDP program did, however, reveal that H_c was related to the total manganese and carbon content. We found that, with H_c in (kA m^{-1}),

$$H_c = 1.186\,(\%\,\mathrm{C}) + 0.237\,(\%\,\mathrm{Mn}) \tag{3}$$

with a correlation coefficient of 0.81.

Within the range of steels studied here, one is thus able to predict H_c from a knowledge of the steel chemistry alone. At a confidence level of 99%, the error in H_c estimation is 20% (Fig. 5). It must be stressed that this will not be a universal relation applicable to all steels and the numerical constants are, therefore, sensitive to exact alloy composition and manufacturing process. By the way of example, we also plot in Fig. 4 the predicted values (crosses) of coercivity for the specially prepared high-carbon steels using the coefficients given in Equation 3. While the intercept at zero carbon content of the experimental points is in excellent agreement with that predicted for the measured manganese content of 0.45%, the slopes of the two lines differ significantly. Use of this relation as a predictive tool must, therefore, be viewed with caution. No other simple relationship emerged between the steel chemistry and magnetic parameters.

Variations in remanence induction, B_R, between samples of the same steel type were greater than the variations between the steels, and to our disappointment, no pattern emerged for the odd order harmonic coefficients, even though we have shown elsewhere that they determine the loop shape [5, 6]. The first and third even-order coefficients correlated with carbon and manganese but as these are linearly related to H_c both experimentally [5, 8] and theoretically [6], little new information is obtained from this result. Throughout the study no correlation was found between odd-order coefficients and any other parameter suggesting that the loop squareness varies very little across the sample range. This conclusion should, however be treated with caution as we find that for the particular loop shapes encountered in these steels, the individual odd-order harmonic coefficients are rather insensitive to small changes in loop squareness [8].

There have been many reports of studies of the variation of coercivity H_c with grain size, d, in iron and

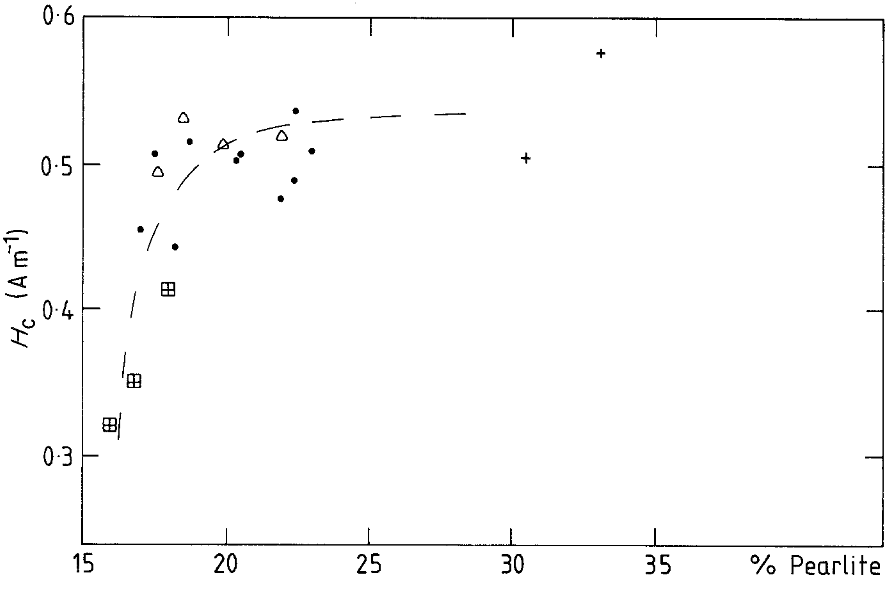

Figure 7 Coercive field H_c plotted against pearlite fraction, c_P.

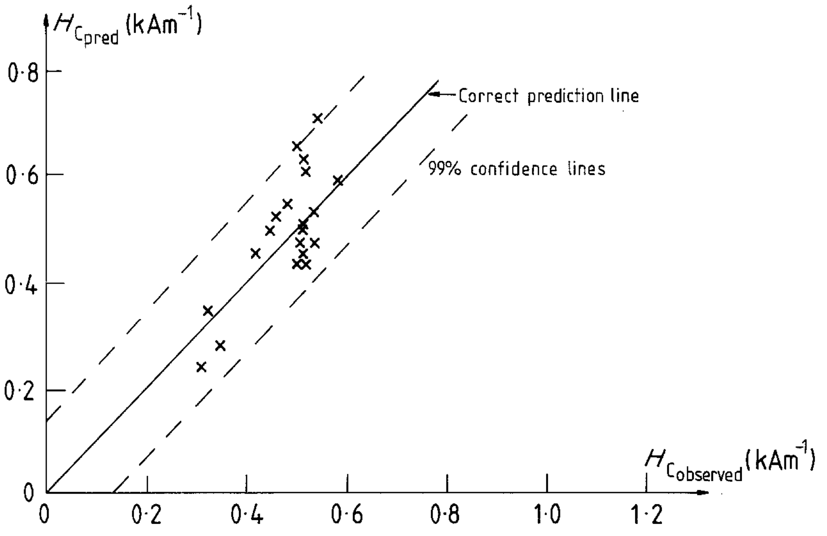

Figure 8 Coercive field H_c as a function of pearlite fraction, c_P, ferrite fraction, c_F, pearlite grain size, d_P, and ferrite grain size, d_F.

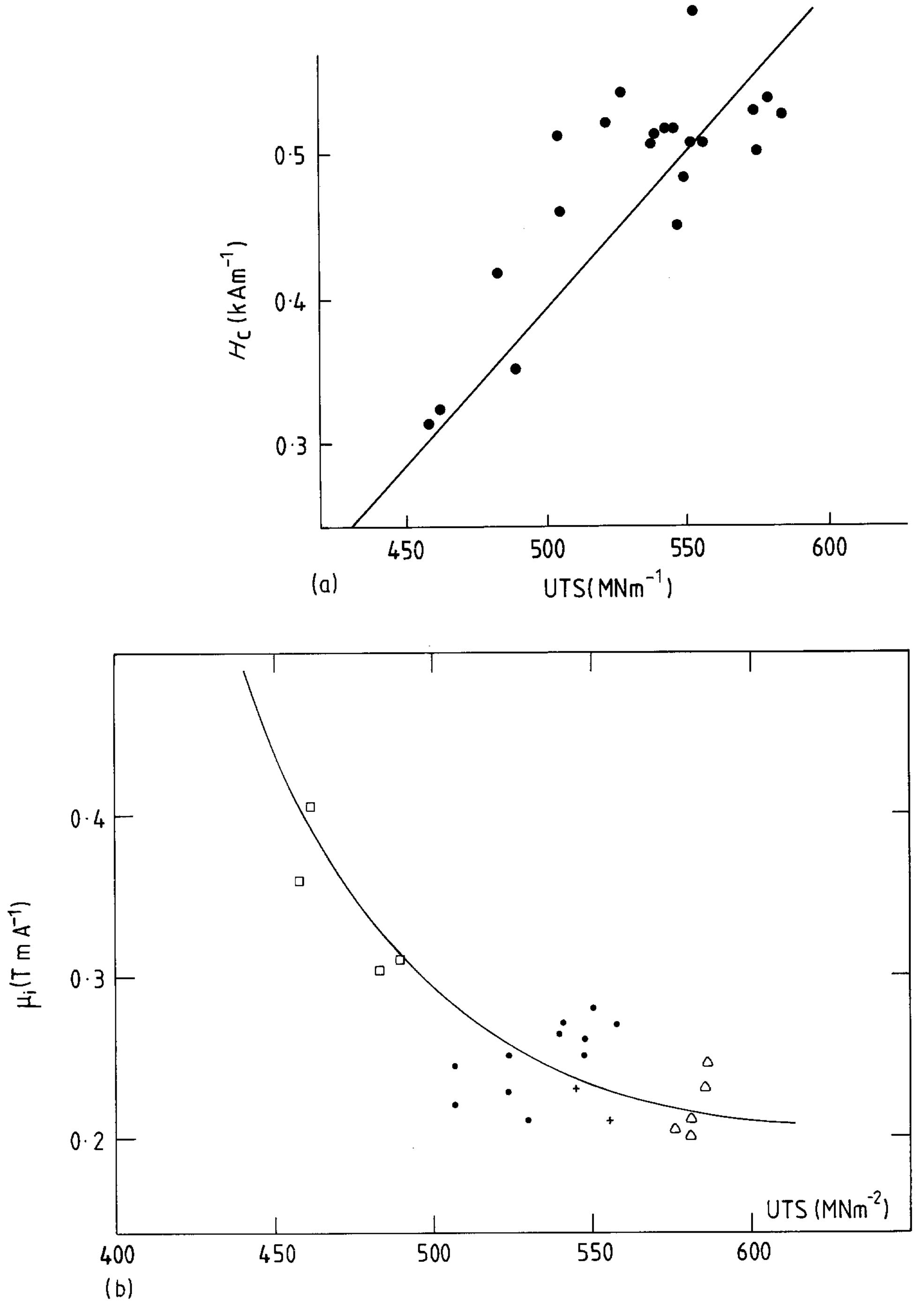

Figure 9 Variation of ultimate tensile stress (UTS) with (a) H_c and (b) μ_i.

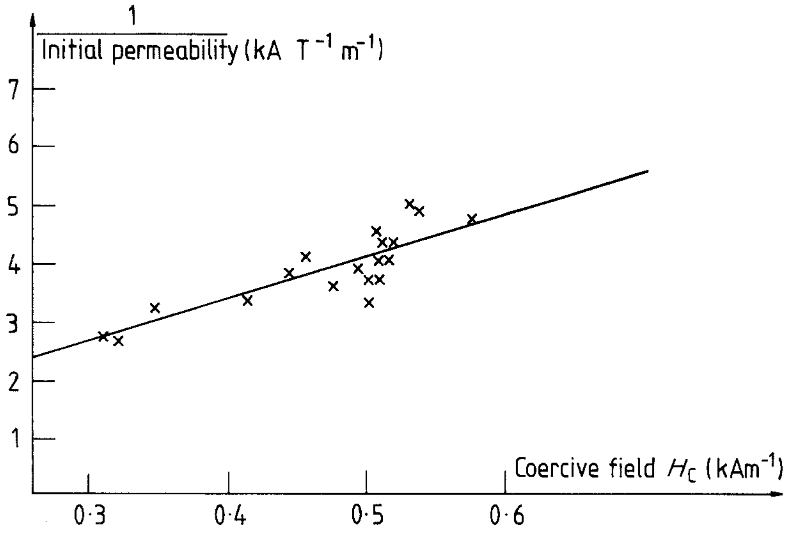

Figure 10 Variation of H_c with μ_i^{-1}:

steel [9–11], and relationships of the form

$$H_c = Ad^{-1} + B \qquad (4)$$

occur repeatedly; A and B are coefficients with a complex relation to the degree of alloying and the nature of the alloying elements. In the steels examined here, a rather poor fit was found to such a relation when H_c was plotted against ferrite grain size d_F (Fig. 6). The pearlite content has clearly a major influence on the coercivity and although a simple relation does not emerge, this dependence is confirmed in Fig. 7 where H_c is plotted against pearlite fraction c_P.

Several theoretical treatments predict a variation of H_c with inverse grain size [12–14], and all the models suggest that the impedance to domain wall motion determines the coercive field rather than the difficulty in nucleating reverse domains. High-voltage Lorentz electron microscopy has been used on these steels to identify pinning sites [15]. Boundaries between cementite lamellae and ferrite within the pearlite grains act as strong pinning sites and these appear to be about an order of magnitude greater than the sites associated with ferrrite–ferrite boundaries. On the basis of this, a relation of the form

$$H_c = (Ac_P/d_P) + (Bc_F/d_F) \qquad (5)$$

was derived [15]. Fig. 8 shows that this relation gives a very much better fit to the experimental data than Equation 4.

5. Inter-relationship between mechanical and magnetic properties

A good correlation was found between the UTS and both coercivity H_c (Fig. 9a) and initial permeability, μ_i (Fig. 9b). The hyperbolic variation of μ_i with UTS suggested that an inverse relationship existed between μ_i and H_c. A linear relation between H_c and μ_i^{-1} is indeed found (Fig. 10) and this was one of the early pointers to a domain wall pinning mechanism determining the value of the coercivity.

Tensile tests on massive samples are difficult to do reproducibly due to variations in material properties along a sample. Therefore, we sought a correlation between H_c and hardness using a Vickers profile indentor, averaging a number of results taken at random from different locations on the sample. A relation between Vickers hardness, VH, and H_c of the form

$$\mathrm{VH} = 166H_c + 93 \qquad (5)$$

was found by a least squares fit to the data (H_c is again in kA m^{-1}). However, although the correlation

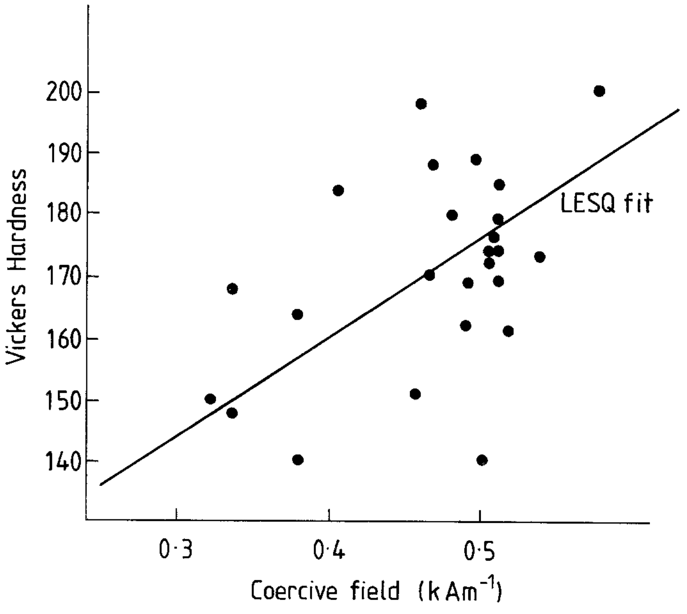

Figure 11 H_c plotted against Vickers hardness on an expanded scale.

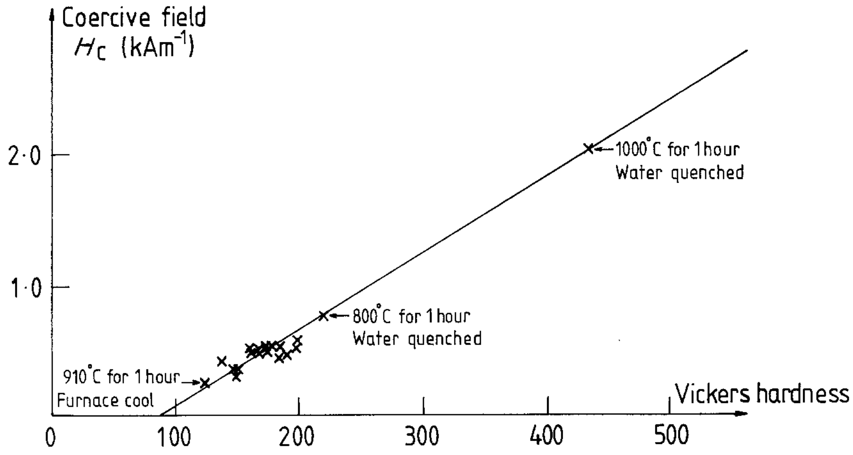

Figure 12 Vickers hardness plotted against H_c for heat-treated steel samples. Note the change of scale compared with Fig. 11.

coefficient was 0.96, plotting the data on an expanded scale (Fig. 11) reveals a very large scatter of data points within the steel set. Vickers hardness varies very little within the sample set and thus as a predictive relation Equation 5 has little value. Probably the large scatter arises from the strong banding of the pearlite in some of the steels studied (Fig. 1). Cementite (Fe_3C) is very much harder than iron and the measured hardness is clearly influenced by the amount of pearlite and hence cementite, under the indentor.

Over a wider hardness range, however, an excellent correlation is found between hardness and coercivity. One of the steel samples was heat treated in three ways: sample A – heated to 910° C for 1 h and slowly furnace cooled; sample B – heated to 800° C for 1 h and water quenched; sample C – heated to 1000° C for 1 h and water quenched. The results are shown in Fig. 12, yielding excellent correlation between hardness and coercivity. All the as-prepared steel sample data points cluster about the least squares fit line through the heat-treated sample data points, but the gradients of the LESQ fit lines for the two sets of data differ. Once again universal coefficients cannot be found, the coefficients being dependent on the detailed microstructure.

6. Discussion and conclusions

The detailed study of metallurgy and magnetic properties of 26 types of constructional steel show that the magnetic properties are related to the grain size, the relative phase composition and the concentration of alloying elements. As the latter factor predominantly controls the former two, the independent variation of H_c with (a) grain size and relative pearlite and ferrite fraction, and (b) carbon and manganese content, is understandable. Our experience with a limited range of high-carbon steels which have closely controlled impurity content suggests that the relations found may be of general validity but that the coefficients in the relationships are sensitive functions of the microstructure and chemical composition of the steel. Outside a specifically defined range of steels, therefore, the coefficients must be determined empirically before use can be made of the relations to predict magnetic properties from metallographs or chemical analysis.

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