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MAGNETIC ANISOTROPY IN SILICON IRON

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Abstract. — The first anisotropy constant for Fe$_1-x$Si$_x$ is determined by torque measurements, for $x$ up to 10 atomic per cent, in the temperature range 21-300 K. The values, as extrapolated to 0 K, vary linearly with silicon content. Using the expressions obtained by Kef-fer and Oguchi it is shown that $K_1$ at 0 K should vary as $(1 - (a + 2)x)$ where $a$ is the ratio of dipole contribution to the total value of $K_1$ and equal to 1.6.

1. Experimental. — Single crystals of silicon iron were shaped spherically by spark erosion and subsequent polishing [1] till the departure from perfect sphericity was less than 0.002. Anisotropy measurements, in fields of 14 kOe, were performed by a torsion magnetometer along the lines developed by Aldenkamp et al. [2] and modified by Van Wyk [3]. Two perspex discs, separated by phosphor bronze torsion vanes, provides a mechanism that twists easily but resists lateral movement. The angular displacement is measured by altering the capacity between parallel metal sheets, each fixed to a disc. The capacitor is part of a stable oscillator’s tuning circuit and the frequency change provides an extremely sensitive method for torque measurements. The results for $K_1$, from measurements performed in the [100] plane of the crystal are depicted in the figure 1 together with the values as extrapolated to 0 K. Both the peak and the slope values of the torsion curves were employed to determine the values of $K_1$. The methods gave comparable values that were well within the limits of experimental accuracy. Some values due to Graham [4] and Arajs et al. [5] are also shown for purposes of comparison.

2. Theory. — The expressions developed by Keffer and Oguchi [6, 7], from spin wave theory, for magnetic anisotropy in a material such as pure iron, lead to the following values for the pseudo dipolar and quadrupole terms $K_{1D}(0)$ and $K_{1Q}(0)$ at 0 K:

$$K_{1D}(0) = -\frac{15}{16} N S J z D S_4;$$

$$K_{1Q}(0) = \frac{5}{3} N S D Q S^2 \left( S - \frac{1}{2} \right)^2$$

(1)

where $N$ is the number of magnetic atoms; $z$ is the number of nearest neighbours; $J$ is the exchange integral; $D$ and $Q$ the dipole and quadrupole coupling constants; $S$ the spin value per atom;

$$S_4 = \sum_i \left( x_{ij}^2 y_{ij}^2 + \cdots - \frac{1}{5} \right)$$

where $x_{ij}, y_{ij}, z_{ij}$ are the direction cosines, relative to the cubic axis, of $r_{ij}$, the displacement vector from the $i^{th}$ to $j^{th}$ atom; $S_4 = \frac{2}{15} z$ when nearest magnetic neighbours are considered in a b.c.c. crystal.

Assuming that the alloy Fe$_1-x$Si$_x$ may be represented by a homogeneous b.c.c. lattice, with $(1-x)$ iron atoms on each site, the quantities $N, z$, and $S_4$ are simply multiplied by $(1-x)$ when applying the above expressions. From saturation magnetisation measurements [8] it is known that the magnetic moment per iron atom remains virtually constant for the range of alloys dealt with here i.e. $S$ remains unaltered. The effects of alloying on the values of $J$, $D$ and $Q$ are very difficult to estimate and it is assumed, to first approximation that they remain constant.

We have thus from equation (1)

$$[K_{1}(0)]_{Fe_{1-x}Si_x} = [K_{1D}(0)]_{Fe_{1-x}Si_x} + [K_{1Q}(0)]_{Fe_{1-x}Si_x} = (1-x) [K_{1D}(0)]_{Fe} +$$

$$+ (1-x)^2 [K_{1Q}(0)]_{Fe}$$

![Fig. 1. — Anisotropy constant $K_1$ for iron-silicon alloys at different temperatures. The inset shows the linear relation between $K_1$ and silicon content (%) as extrapolated to 0 K.](image-url)

- Present measurements
- Graham’s values for 6.17 % Si
- Graham’s values for 9.65 % Si
- Arajs et al. values for 6.89 % Si
Putting

\[ \left[ K_{1a}(0) / K_{1}(0) \right]_{Fe_{1-x}Si_{x}} = a \]

we get

\[ \left[ K_{1}(0) \right]_{Fe_{1-x}Si_{x}} / \left[ K_{1}(0) \right]_{Fe} = 1 - (a + 2) x + \cdots \tag{2} \]

in which higher powers of \( x \) are discarded.

Equation (2) is derived for the case of a lattice parameter that remains constant. In practice the lattice contracts with the addition of silicon [9] and the experimental values for \( K_{1} \) are corrected by utilizing its pressure dependence as given by Veer-1dK,man and Rathenau [10]. It is

\[ \frac{dK_{1}}{dp} = 0.42 \times 10^{-2} \text{ per kilobar per unit mass.} \]

Using this value and the bulk modulus for iron the lattice contraction due to the silicon addition can be equated to an effective applied pressure which alters the anisotropy by an amount \( \Delta K_{1} = -0.5 x \) where \( x \) is again the atomic percentage silicon content. Note that the above value is given for room temperature but employing it down to 0 K introduces only an error of second order of magnitude.

On applying the experimental results, as presented in the figure, to equation (2) one finds the value for \( a = 1.6 \). According to Joenk [11], Buslik finds a value of 2.5 from work on paramagnetic resonance line widths. Joenk [11] using experimental values of \( K_{1} \) and \( K_{2} \) for pure iron calculates a to be 4.6 but this value is not reliable because of the experimental inaccuracy associated with the value of \( K_{2} \). It could in fact be comfortably reduced by half if Graham’s [12] value for \( K_{2} \) is employed.

It is not possible to sensibly predict to what extent \( J, D \) and \( Q \) will be affected by the addition of silicon. Since Curie point measurements [13] indicate only a slight deviation from a linear relationship, as for instance predicted by a molecular field calculation, one concludes that \( J \) is not altered appreciably.

It should be mentioned in passing that the temperature dependence of \( K_{1} \) does not obey any simple power law, the power index increasing as the temperature rises. This is somewhat in qualitative agreement with Van Vlecks [14] earlier work wherein different power indexes are assigned to the dipolar and quadrupolar terms and the power indexes themselves are temperature dependent. It also varies with silicon content. For instance, from measurements of magnetisation taken on the same specimens that were used for the anisotropy measurements it was found, for a specimen containing 2.3% silicon, the expression

\[ K_{1}(T) / K_{1}(0) = \left[ M(T) / M(0) \right]^{2.6} \]

holds at low temperature, whereas the corresponding index for a 8.6% silicon specimen is 4.3.

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