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TEMPERATURE DEPENDENCE OF INDUCED MAGNETIC ANISOTROPY IN FERROMAGNETIC ALLOYS

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Résumé. — La dépendance de la température de l’énergie d’anisotropie magnétique induite est donnée pour plusieurs alliages ferromagnétiques de fer. La température de mesure varie entre l’azote liquide et les valeurs auxquelles les processus de diffusion commencent. Les résultats expérimentaux sont comparés avec les données des théories de Zener et de Taniguchi. On trouve que quelques alliages (Fe-Ni, Fe-Cr, Fe-V) suivent la loi de Zener, c’est-à-dire $K_u$ diminue pour température croissante proportionnellement à la troisième puissance de la magnétisation de saturation, tandis que d’autres alliages (Fe-Si, Fe-Al, Fe-Co) montrent de grandes déviations de cette loi. La loi puissance deux prouvée par la théorie de Taniguchi n’est suivie par aucun des alliages examinés.

Abstract. — Results are reported for the temperature dependence of field induced magnetic anisotropy $K_u$ in several iron-rich ferromagnetic alloys. Temperature ranges from liquid nitrogen up to values at which diffusion begins to take place. The experimental results are compared to the ones given by the Zener’s and Taniguchi’s theories. It is found that some alloys (Fe-Ni, Fe-Cr, Fe-V) follow Zener’s law, i.e. $K_u$ decreases with temperature according to the third power of the saturation magnetization $I_s$, while other alloys show strong deviations from this law. None of the examined alloys was found to obey Taniguchi’s $I_s(T)$ law.

1. Introduction. — As is known, ferromagnetic alloys generally show a uniaxial induced magnetic anisotropy energy $K_u$ after annealing in a magnetic field.

When the temperature is varied but is kept below the value at which atomic diffusion becomes effective, the induced anisotropy $K_u$ changes reversibly.

Taniguchi [1] worked out a theory of the temperature dependence of $K_u$ based on Van Vleck theory [2] of the crystalline anisotropy. According to this theory $K_u$ should decay with increasing temperature proportionally to the square of the saturation magnetization $I_s(T)$.

A different approach to the study of crystalline anisotropy due to Zener [3] may be also used to find the temperature dependence of $K_u$. With some assumptions we obtain an $I_s(T)$ law.

Obviously the theories of Zener and Taniguchi are based on different assumptions and approximations, which will be later discussed. By an extension of some arguments due to Keffer [4] one should actually conclude that these theories can be considered as limiting cases, valid respectively at low and high temperatures.

The very few available experimental data refer to Ni-Co (Chikazumi et al. [5]), Fe-Ni (Taniguchi [1]), and Fe-Si (Ferro et al. [6]). The first alloy shows a temperature dependence of the induced anisotropy which is in good agreement with Taniguchi’s theory, while the results of the second alloy better agree with Zener’s one. In the case of Fe-Si there is a strong disagreement with both theories.

In this paper many experimental results will be given on several ferromagnetic alloys. It is found that in some alloys, like Fe-Cr, Fe-Ni, Fe-V, the experimental dependence of $K_u$ on $T$ is in good agreement with Zener’s law, while in other alloys, like Fe-Si, Fe-Al, Fe-Co, strong deviations occur with respect to this law.

These results will be compared with the theoretical ones derived from the mentioned theories.

2. Experimental results. — Measurements of $K_u$ were performed by means of a very sensitive torque magnetometer on small disks of polycrystalline material suitably treated to obtain a good compensation of the crystalline anisotropy.

The induced anisotropy $K_u$ was always measured for each temperature value as the difference between torque curves obtained after annealing the specimen along two mutually perpendicular directions. This eliminates errors due to residual crystalline anisotropy, form anisotropy, etc., as suggested by Ferguson [7] and Barbier et al. [8], and allows a measurement accuracy of about $±2\%$.

The temperature dependence of the saturation magnetization has been measured on ellipsoidal specimens of the studied alloys by means of the same torque magnetometer.

Results are shown in figures 1, 2 and 3, where the

Fig. 1. — Experimental $K_u$ dependence on temperature for Mumetal, Fe-Ni, Fe-Cr, Fe-V alloys (squares and triangles). Full lines represent the cube saturation magnetization vs. $T$ for same alloys. Reduced coordinates are used.
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Re. 2. - Same as figure 1 for Fe-Co alloys.

Fig. 3. - Same as figure 1 for Fe-Al and Fe-Si alloys.

The main influence of temperature increase on the induced anisotropy is reasonably due to the following effects:

1) local spin direction do not coincide with the average magnetization direction, but fluctuates because of thermal motion;

2) the spin-orbit interaction energy of magnetic electrons is changed by thermal expansion and lattice vibrations;

3) solute atom pair axis fluctuates with respect to its rest direction, and thus with respect to the average magnetization direction, owing to lattice vibrations.

Both in Taniguchi and Zener theories only the effect relative to point 1) is taken into account. In Taniguchi theory the anisotropy arises from a term \( \sum_{i<j} w_{ij} \) which appears in the free energy of the alloy, and represents the thermal average of the Van Vleck's pseudodipolar energy:

\[
\sum w_{ij} = \sum_{i<j} C_{ij} [S_i S_j - 3 r_{ij} \cdot (S_i \cdot r_{ij}) (S_j \cdot r_{ij})],
\]

where \( S_i \) and \( S_j \) are the spin operators for atoms \( i \) and \( j \). While in a pure b. c. c. or f. c. c. metal this term does not give rise to any anisotropic effect, in alloys an anisotropy arises from the fact that the dipole-dipole coupling constants \( C_{ij} \), which appear in the summation, differ for different kinds of atoms pairs. The assumption that these coupling constants are independent of temperature corresponds to disregarding point 2) effects.

An equivalent assumption about the invariance of spin-orbit interaction energy with temperature is explicitly made by Zener, whose theory assumes that the specimen can be divided into small regions of highly correlated spins, where one can define a local magnetization direction. The decay of \( K_u \) with temperature is simply due, in this case, to the increasing spread of the magnetization directions relative to different regions, which behave as independent small crystals.

While point 3) seems to have a little influence on \( K_u(T) \), except presumably at extremely low temperatures, the failure of taking into account point 2) effects might explain the strong discrepancy between experimental and theoretical results observed in some alloys. Typical cases are:

a) Fe-Co 20% which shows an extremely small temperature dependence of \( K_u \);

b) Fe-Si and Fe-Al in which, on the contrary, \( K_u \) varies strongly with temperature, approximately according to a \( T^{-6} \) law.

It may be noted in fact that the effects described in point 2) may give either a positive or a negative contribution to the ones relative to points 1) and 3).

There is another important aspect of the problem which has not been taken into account when Van Vleck theory on crystalline anisotropy has been applied to describe induced anisotropy of alloys: the thermal average of spin operators relative to the atoms localized in the neighbourhood of a solute atom pair has been implicitly assumed to be the same as the macroscopic average taken on all the atoms of the same type in the crystal. An equivalent assumption has been made in extending Zener's theory to alloys.

If one takes into account that, particularly in diluted alloys, there is a sort of local change in the Curie temperature because of the modified electron exchange interaction right in the region where anisotropy originates, some of the observed discrepancies could also be qualitatively explained: in fact cobalt strongly increases the Curie temperature, while Si and Al strongly depress it.

Finally it must be also remarked that Taniguchi's theory assumes that the spin quantum number is the same for all the atoms in the alloy. This probably further limits its application to only few of the studied alloys.
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