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MAGNETIC ANISOTROPY IN NICKEL AND IRON ; THE EFFECT OF PRESSURE

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Résumé. — On discute les travaux expérimentaux et théoriques sur l'anisotropie magnétique et sur la magnétostriction du nickel et du fer, accordant beaucoup d'attention aux expériences sous haute pression. On essaye d'élucider plus spécialement la situation expérimentale en ce qui concerne l'anisotropie magnétique du nickel. Des arguments sont allégués qui soutiennent un calcul dans le modèle des bandes, dans lequel les contributions principales à l'anisotropie magnétique ont leur origine dans les régions de la zone de Brillouin, où les bandes, en l'absence de l'interaction spin-orbite, sont dégénérées.

Abstract. — The experimental and theoretical work on the magnetic anisotropy energy and the magnetostriction of nickel and iron is reviewed with special attention to the experiments under high pressure. It is attempted to clear up the experimental situation around the magnetic anisotropy of nickel in particular. Arguments are collected that support a band theoretical calculation in which the main contributions to the anisotropy energy of nickel arise from regions in the Brillouin zone, where bands are degenerate in absence of the spin-orbit interaction.

I. **Introduction.** — Discussions on the magnetic anisotropy energy and the magnetostriction of nickel and iron remain often restricted to an interpretation of the temperature dependence of these phenomena. Relations have been deduced by Zener [1] and by Kittel and Van Vleck [2] in which the temperature dependence of the magnetic anisotropy and the magneto-elastic constants are related to that of the magnetization. These relations describe with reasonably good success the magnetic anisotropy energy of iron, see for instance the work of Klein and Kneller [3], and the magnetostriction of nickel, as has been pointed out by Lee and Birss [4]. For the magnetostriction of iron, where Tatsumoto and Okamoto [5] found a maximum in one of the magnetostriction constants not far from the Curie temperature, a different model has been proposed by Callen and Callen [6]. It presents arguments to understand this maximum in iron and the absence of such a maximum in nickel. In case of the magnetic anisotropy energy of nickel any simple model fails and one has to look for the basic interactions that are responsible for the magnetic anisotropy.

The spin-orbit interaction is generally assumed to be the origin of the magnetic anisotropy in nickel and iron. To get from this insight to an explicit value for the anisotropy and magnetostriction constants is not a very easy task. Several calculations on this subject have been reported in the literature. In the earlier work a localized spin model has been used. Van Vleck [7] has shown that there is for instance a pseudo dipolar coupling, due to the spin-orbit interaction, that may lead in second order perturbation calculation to an anisotropy in the energy with cubic symmetry. The higher order anisotropy constants follow in this theory from higher order perturbation calculations and have to converge rapidly, which is not in accordance with the experimental data for nickel. The temperature dependence of the magnetic anisotropy energy can be related also in this model to that of the magnetization. For nickel and iron it means that the first anisotropy constant K_1 has to change with a power of the magnetization in the order of ten [8], whereas the experimental value for this power varies for nickel between 50 and 100 in the low temperature region.

A theory for the magnetic anisotropy, based on the itinerant electron model, has been developed by Brooks [9] and it has been used by Brooks, Fletcher [10], Asdente and Delitala [11], Furey [12] and Mori [13] to calculate the anisotropy energy of nickel and iron. The spin-orbit interaction may be considered in this model as a small perturbation for the ferromagnetic band structure. The energy shifts of the bands, due to the spin-orbit interaction, can be calculated in general by perturbation theory. It turns out that these perturbation calculations have to be carried out to the fourth order before getting a non-vanishing contribution to the anisotropy in the energy for these metals. A perturbation calculation, in which contributions to the anisotropy energy arise from energy states over a large region of the Brillouin zone, can not yield the proper description of the experimental facts for nickel by nearly the same arguments as given before. Furey solved these problems by identifying the anisotropy energy of nickel with the energy shifts of a few bands in a small region of the zone. These bands are degenerate without the spin-orbit interaction and are situated close to the Fermi level. Higher order constants, obtained from contributions of these degenerate states, are not *a priori* small in comparison with the first anisotropy constant ; a series expansion of the anisotropy energy is even questionable in this model. Moreover large effects can be expected from a change in the location of the Fermi level.

The strong temperature dependence and the higher order contributions are not the only remarkable facts in the magnetic anisotropy of nickel. Looking for values for the anisotropy and magnetostriction constants of nickel in the literature one can find a large spread in the experimental data. Before going into the details of Furey's model we shall review the experimental situation around the magnetic anisotropy and try to bring some order in the experimental results.

II. **Phenomenological theory and experimental methods.** — The free energy F of a ferromagnetic single crystal is in general a function of the orientation α of the magnetization $\mathbf{M}$ and of the state of strain, denoted by the strain components e_{ij}. Follo-