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The Additional Magnetic Anisotropy Induced by Magnetic Anneal in Ferromagnetic Face-Centered Cubic Solid Solutions

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A systematic experimental study has been made on the additional magnetic anisotropy induced by magnetic anneal in face-centered cubic Ni-Co and Ni-Fe alloys. The measured data on the dependence of the induced anisotropy on the temperatures of magnetic annealing and of torque measurement agree well with the theoretical results derived by Taniguchi and Yamamoto. However, some quantitative deviations from the theory have been found concerning the concentration and orientation dependence. These discrepancies may be due to the fact that the effects of atomic interaction and of the second and far neighbour atoms have not been properly taken into consideration in the current directional order theory.

Taniguchi and Yamamoto[1] and, independently, Néel[2] proposed previously the directional order theory to explain the uniaxial ferromagnetic anisotropy induced by magnetic anneal in ferromagnetic cubic solid solutions. The theory could interpret qualitatively the experimental results available at that time. In order to examine the theory in more detail, we have studied systematically, using a torque magnetometer specially designed for high temperature measurements, the character of the induced magnetic anisotropy in face-centered cubic solid solutions, as a function of the annealing temperature, measuring temperature, alloy composition, and orientation of magnetic field applied during annealing. Specimens used are polycrystalline discs of 10, 20, 30, 40, 50 and 60% Co-Ni alloys and (1$\bar{1}$0) disc single crystals of 12 and 20% Co-Ni alloys and of 17 and 56% Fe-Ni alloys.

The dependence of the induced magnetic anisotropy, K_u, on the temperature of magntic anneal, Θ, was studied with a 30% Co-Ni polycrystalline disc. It has been found that, as shown in Fig. 1, the measured data are expressed well by a relation derived by Taniguchi and Yamamoto[1]:

$$K_u = \text{const.} \times (I_\theta/I_0)^2/\Theta, \qquad (1)$$

where I_θ and I_0 are the values of the saturation magnetization at Θ (°K) and 0°K, respectively.

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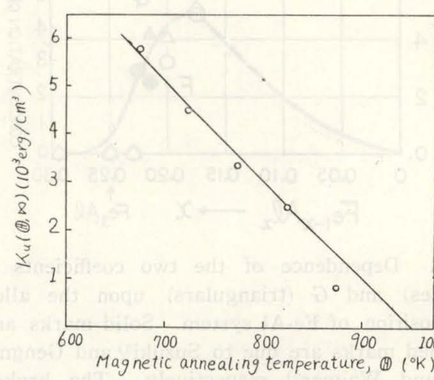

Fig. 1. Saturation value of the uniaxial anisotropy constant, $K_u(\Theta, \infty)$, as dependent on the temperature, Θ, of magnetic anneal in a polycrystalline disc of 30.84% Co-Ni alloy. Circles: measured value, solid line: calculated $(I_\theta/I_0)^2/\Theta$ vs. Θ curve.

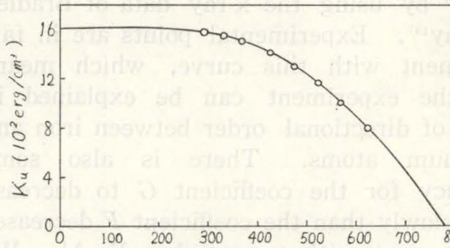

Fig. 2. Measuring temperature dependence of the uniaxial magnetic anisotropy induced by annealing in magnetic field of about 1700 Oe at 450°C for 5 hours in a (1$\bar{1}$0) disc of 12% Co-Ni single crystal. A solid line represents a calclated $(I_T/I_0)^2$ curve.

The dependence of K_u on the measuring temperature, T, was studied with (1$\bar{1}$0) disc of 12% Co-Ni single crystal. As seen from Fig. 2, the obtained result has been found to be expressed well by a relation derived also by Taniguchi and Yamamoto[1) :

$$K_u = \text{const.} \times (I_T/I_0)^2, \qquad (2)$$

where I_T is the saturation magnetization at T(°K).

The alloy composition dependence of K_u was studied with 10, 20, 30, 40, 50 and 60% Co-Ni polycrystalline discs. It has been found that K_u changes with increasing cobalt content, n, approximately as $n^2(1-n)^2$ and shows a peak value of 8.4×10^3 erg/cm^3 at about 50% Co after annealed magnetically at 400°C for 30 hours. In order to find a true composition dependence of the induced uniaxial anisotropy, the measured K_u values were corrected for the composition dependence of the Curie temperature and plotted as open circles in Fig. 3, where the corrected K_u values for 50% Co is chosen to be unity. The corrected K_u values show systematic deviations from a $n^2(1-n)^2$ curve predicted for ideal solid solution. According to the theoretical results obtained by Néel[2)], the upward deviation means that the ordering energy is negative and hence the alloys are of the precipitation type. But, the value of the ordering energy estimated using Néel's formula[2)] on the concentration dependence of K_u for non-ideal solid solution is, however, too large to explain the absence of any precipitation in Ni-Co alloys. For the sake of comparison, a similar analysis was made on the measured data with Ni-Fe alloys obtained by Ferguson[3)] (triangles in Fig. 3), and it has been found that thus estimated value of the ordering energy has a proper sign but is smaller than that estimated from the critical temperature of the superlattice Ni_3Fe by a factor of about 1/2. These quantitative discrepancies between theory and experiment may be due to the fact that the effect of atomic interaction is not properly taken into consideration in the current directional order theory.

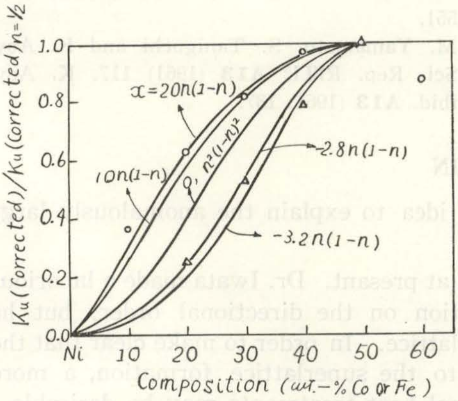

Fig. 3. Alloy composition dependence of the induced uniaxial magnetic anisotropy, corrected for the alloy composition dependence of the Curie temperature, as compared with the directional order theory. ○: the present measured data for Ni-Co alloys, and △: Ferguson[3)]'s measured data for Ni-Fe alloys.

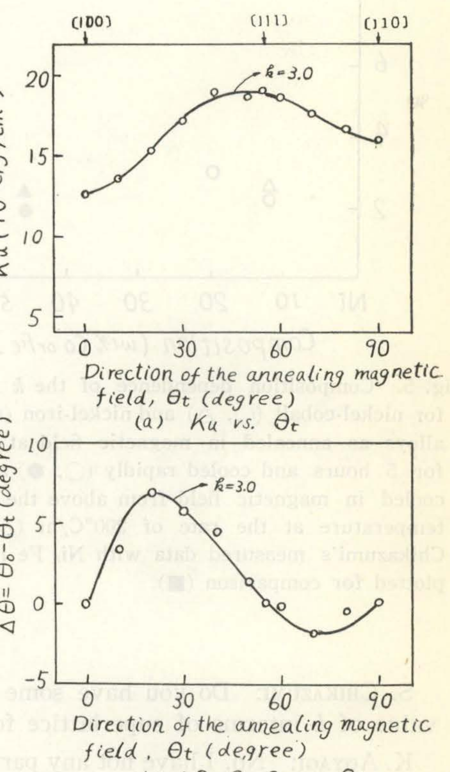

Fig. 4. The induced uniaxial magnetic anisotropy constant, K_u, and the deviation of the direction of easy magnetization, θ_0, from the direction of annealing magnetic field, θ_t. as dependent on θ_t in a (1$\bar{1}$0) disc of 20%Co-Ni single crystal annealed at 450°C for 5 hours and then cooled rapidly in magnetic field of 1700 Oe applied parallel to the plate surface. Solid curves in (a) and (b) are calculated from Eq. (3) using $k=3.0$.

The crystal orientation dependence of K_u was studied with $(1\bar{1}0)$ disc single crystals of 12 and 20% Co-Ni alloys and of 17 and 46% Fe-Ni alloys. It has been found that the measured K_u values and the deviations, $\Delta\theta$, of the direction of easy magnetization, θ_0, from the direction of the annealing field, θ_t, as dependent on θ_t are well described by a formula

$$K_u = -K(\Sigma_i \alpha_i^2 \beta_i^2 + k \Sigma_{j>i} \alpha_i \alpha_j \beta_i \beta_j)\,, \quad (3)$$

where K is a positive constant, k is a numerical factor, and α_i's and β_i's $(i=1, 2, 3)$ are the direction cosines of magnetization vector during torque measurement and during magnetic annealing, respectively. As an example, the results obtained for 20% Co-Ni alloy are shown in Figs. 4 (a) and (b). These figures show clearly that the experimental results agree completely with the formula (3) by taking the value of k as 3. The measured values of the k factor are plotted against the alloy composition in Fig. 5, from which it can be seen that the k factor is generally 2~3 for both of Ni-Co and Ni-Fe alloys but it is much larger only for Ni-Fe alloys nearby Ni_3Fe. These k values are either smaller or larger than 4 which is expected from the directional-order theory for face-centered cubic lattice. This difference may partly be due to the fact that the contribution from the second and far neighbour atoms is neglected in the theory. Rather large values for Ni-Fe alloys nearby Ni_3Fe may be due to the presence of superlattice.

More detailed reports of the present investigation were published quite recently.[5]

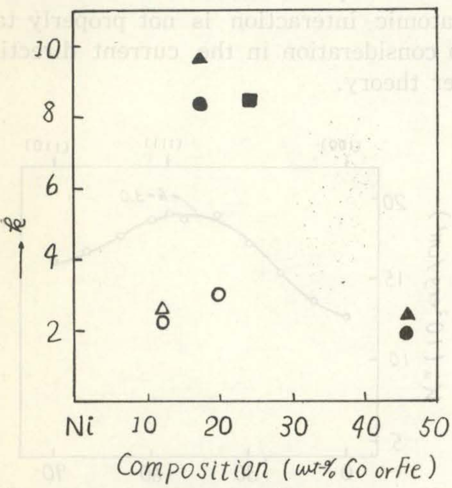

Fig. 5. Composition dependence of the k factor for nickel-cobalt (○, △) and nickel-iron (●, ▲) alloys as annealed in magnetic field at 450°C for 5 hours and cooled rapidly (○, ●) and as cooled in magnetic field from above the Curie temperature at the rate of 200°C/hr (△, ▲). Chikazumi's measured data with Ni_3Fe is also plotted for comparison (■).

References

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DISCUSSION

S. Chikazumi: Do you have some particular idea to explain the anomalously large value of k interms of superlattice formation?

K. Aoyagi: No. I have not any particular idea at presant. Dr. Iwata made a laborious calculation of an effect of superlattice formation on the directional order, but he could not find a lange value of k in A_3B superlattice. In order to make clear that the anomalously large value of k is really due to the superlattice formation, a more detailed study of k dependence on the isothermal heat treatments may be desirable.