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ABSTRACT

Magnetic torque measurements have been made for a single crystal of Co of hcp structure in a very low field region where the torque intensity was not saturated. In this region it had been considered to be impossible to determine the magnetocrystalline anisotropy constants from observed torque curves. Recently, a new method of analyzing the torque curves was proposed by the present author with the help of a least mean square routine instead of the usual Fourier analysis. By using this method the first magnetocrystalline anisotropy constant K_{u1} was, for the first time, determined at 77 K. It was found that the K_{u1} determined in the low field range between 0.3 and 0.5 T coincides with the value determined at a high field region where the torque curve was saturated enough. Below 0.2 T the value of K_{u1} decreased with decreasing the field. This region was found to correspond to the domain wall formation.

INTRODUCTION

It has been considered to be very difficult to determine the magnetocrystalline anisotropy constants from a magnetic torque curve measurement in an external field far below the anisotropy field, H_a, which is equal to $2K_{eff}/M_s$. This situation is often encountered when we wish to study the anisotropy energy in highly anisotropic crystals such as the recently developed high-energy product permanent magnet materials based on $R_2Fe_{14}B$ intermetallic compounds. In such situation, magnetization measurements along various crystallographic axes are generally made, at first, and then analyzed to obtain the anisotropy constants. The accuracy in determining the anisotropy constants, however, by using this method is, in general less than the torque curve measurements. Therefore, a method is strongly needed with which it is made possible to determine the anisotropy constants from unsaturated torque curves.

In the case of hcp Co, the situation mentioned above has often been encountered[1], because the anisotropy field is of comparable order to the maximum field generated by a usual electromagnet. It has been pointed out by the present author[1-3] that the method using the least mean square routine is superior to the Fourier analysis, which has widely been used.

According to the recent study of magnetocrystalline anisotropy constants in hcp Co made by Paige et al. [4], the value determined by using the least mean square routine has been confirmed. This method has extensively applied in the case of unsaturated torque curves in $Nd_2Fe_{14}B$ intermetallic compound[5,6] of which the magnetocrystalline anisotropy constants are one order of magnitude larger than in hcp Co. To check the applicability of the new method, measurements and analysis have been made for hcp Co in a very low magnetic field range.

The magnetic field dependence of the magnetocrystalline anisotropy constants was pointed out to involve an information about the electronic band structure[7-10]. Therefore the low field data of the magnetocrystalline anisotropy constants in ferromagnetic transition metals which have not been obtained yet, are needed.

In the present paper, an extensive application of the new method to the case of hcp Co in low temperature and in low external field is described.

TORQUE CURVE MEASUREMENTS

Measurements of torque curves were made for a thin single crystal disc of pure Co of which the disc plane was parallel to the (1010) plane. The diameter and the thickness of the disc were 6 and 0.1 mm, respectively. The measurements were made at 77 K and at room temperature in a wide magnetic field range between 0.1 and 1.69 T.

Observed torque curves at room temperature are shown in Fig.1. In this figure it is seen that torque

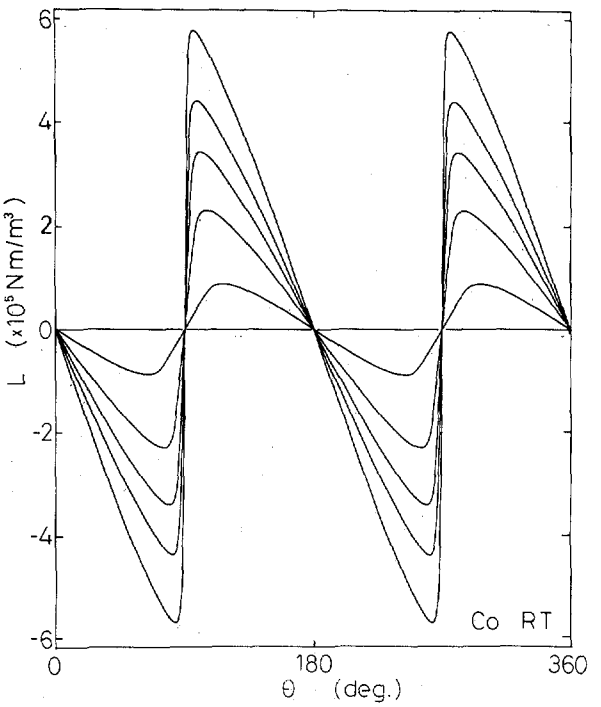

Fig.1 Observed torque curves at room temperature at the external fields of 0.1, 0.2, 0.3, 0.4 and 0.6 T.

curves are not saturated below 0.6 T (actually below 1 T), and the maximum intensity is proportional to the external field.

The torque curves observed at 77 K below 0.5 T are plotted in Fig.2. These torque curves are not saturated, and therefore, the usual method of Fourier analysis cannot be applied. The torque curves observed at 77 K above 0.6 T are shown in Fig.3. In this figure it is seen that the torque curve approaches to saturation at 1 T, which is exactly equal to the value of the anisotropy field, H_a.

ANALYSIS OF TORQUE CURVES

The torque of a hcp crystal in (1010) plane due to the magnetocrystalline anisotropy energy is expressed

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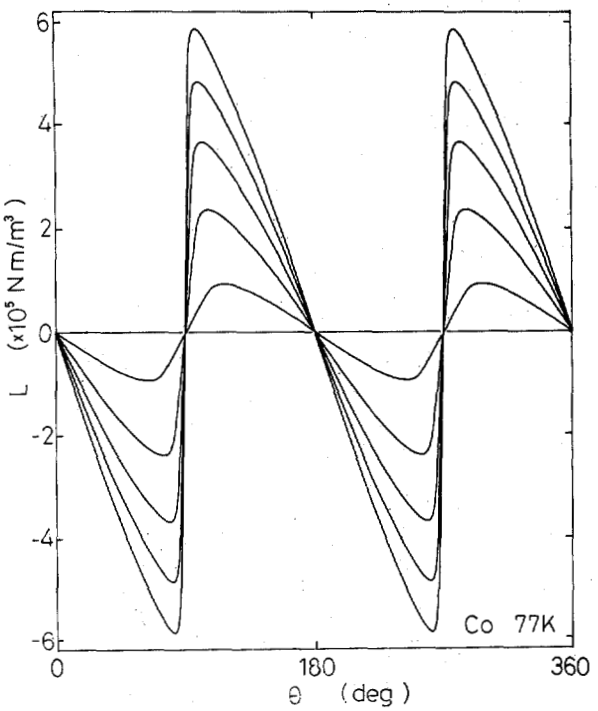

Fig.2 Torque curves observed at 77 K at external fields of 0.1, 0.2, 0.3, 0.4 and 0.5 T.

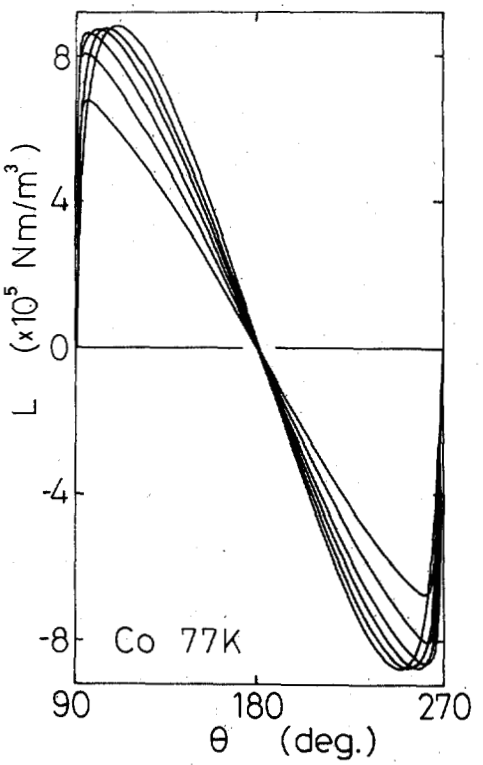

Fig.3 Torque curves at 77 K at 0.6, 0.8, 1.0, 1.2, 1.4 and 1.69 T.

as,

$$L = -2K_{u1}\sin\theta\cos\theta - 4K_{u2}\sin^3\theta\cos\theta + \cdots, \quad (1)$$

where θ is the angle between the c-axis and the direction of the magnetization. When single domain, this angle can be known from the relation,

$$\theta = \theta' - \sin^{-1}(-L/M_sH), \quad (2)$$

where θ' is the angle between the c-axis and the direction of the external field.

By using the least mean square routine, eq.(1) is fitted to the experimental torque curves shown in Figs.1 and 2 after a transfer of the angle θ' to θ by using eq.(2). The first magnetocrystalline anisotropy constant determined in this calculation is plotted in Fig.4 as a function of the field. In this figure it

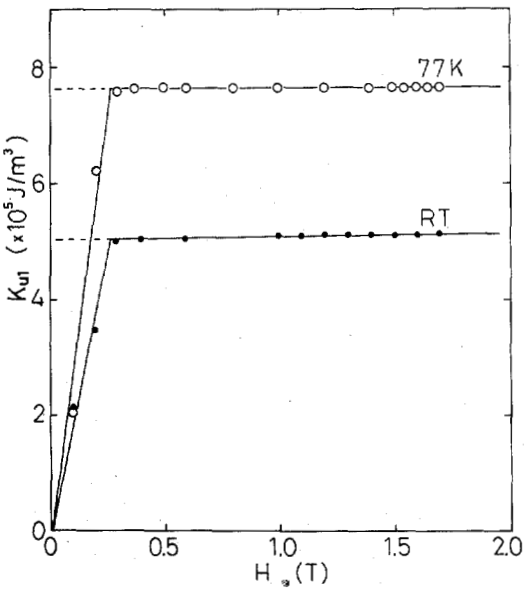

Fig.4 Magnetic field dependence of the first magnetocrystalline anisotropy constant K_{u1} at 77 K and at room temperature.

can be seen that the low field value of K_{u1} determined in the field range between 0.3 and 0.5 T agrees very well with the high field value determined in the range between 1.4 and 1.7 T. The difference between the low field and the high field values is within 0.5%, which is unexpectedly small, while the slope of the linear part above 0.3 T can be detected.

DISCUSSION

From the results of the torque curve analysis mentioned in the foregoing section, the new method proposed by the present author was found to be applicable for the case of hcp Co above 0.25 T. The errors for thus determined value of K_{u1} in the low field range between 0.3 and 0.5 T was found to be smaller than 0.5%, which is almost as low as the limit of the usual Fourier analysis in a high field region above the saturation. The origin of the high precision of the present method is due to the taking advantage of the least mean square routine.

The inclination of the K_{u1} vs. H curve shown in Fig.4 above 0.3 T is 1.8×10^3J/m³T, which is in good agreement with the value determined at a higher field region [2]. This value of dK_{u1}/dH is composed of two main terms, the Fermi level dependent term and the magnetization dependent contribution [9]. As was discussed in ref. [9], these two contributions are of the same magnitude. Thus, the band parameter $dK_{u1}/dE_{F\downarrow}$ determined in ref. [9] was also confirmed in the low field region. This value of the band parameter was determined from the results of the band theoretical calculation made by Mori et al.[11].

Apart from the perfect applicability of the present method above 0.3 T, as can be seen in Fig.4, our main interest, here, is to find out the reason why the value of K_{u1} deviates from a stright line below 0.25 T. It can be considered that this deviation is due to a nucleation of domain walls.

To find out the effect of the domain nucleation, the free energies of the two systems are to be compared. In the case of single domain structure, the free energy is expressed as,

$$F_{SD} = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta - M_S H\cos(\theta'-\theta) + \frac{1}{2} NM_S^2 , \quad (3)$$

where N is the demagnetization factor. On the contrary, for a multiple domain structure as shown in Fig.5, the free energy is written as,

$$F_{MD} = a[K_{u1}\sin^2\theta + K_{u2}\sin^4\theta - M_S H\cos(\theta'-\theta)]$$
$$+b[K_{u1}\sin^2\phi + K_{u2}\sin^4\phi - M_S H\cos(\theta'-\phi)] + \frac{1}{2}NM^2, \quad (4)$$

where a and b are the volume ratio of the majority and the minority domains, ϕ is the angle between the easy axis and the direction of the magnetization of the minority domain and θ' is between the easy axis and the external field.

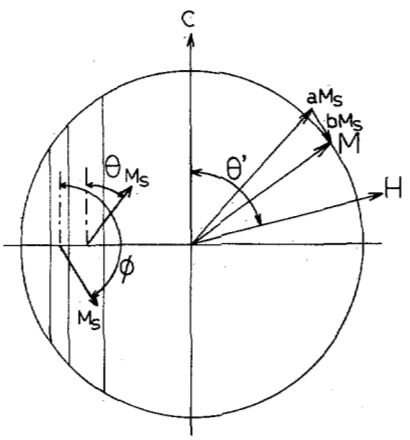

Fig.5 Multi domain configuration of hcp Co single crystal specimen in a (1010) plane.

The critical value of the field below which the multiple domain structure takes place can be estimated by putting,

$$F_{SD} = F_{MD} . \quad (5)$$

When the external field is applied along the direction perpendicular to the easy axis ($\theta'=90°$), above equation can easily be solved. By using the equilibrium condition,

$$\partial F/\partial\theta = 0, \quad (6)$$

for the expression (3) and for (4) with $\phi=\theta$, the equilibrium values of θ can be obtained as functions of H for both cases. Substituting these relations to eqs.(3) and (4), respectively, and then using eq.(5), a relation for H,

$$\left\{\frac{K_{u1}M_S^2}{(2K_{u1}+NM_S^2)^2} - \frac{M_S^2}{(2K_{u1}+NM_S^2)} + \frac{1}{2}\frac{NM_S^4}{(2K_{u1}+NM_S^2)^2} + \frac{M_S^2}{4K_{u1}}\right\} H^2 = \frac{1}{2} NM_S^2 , \quad (7)$$

is obtained. In deriving eq.(7), the higher order terms have been neglected. In the present case, the demagnetization factor is 0.48. By using this value the critical field is estimated to be 0.1 T, which is of the same order but smaller than the observed value of 0.25 T.

In the case of oblique angle, it is difficult to solve eq.(5) directly. Therefore, the same assumption as made by Pauthenet[12] is also adopted here for simplicity. Then, the critical field below which the multiple domain structure takes place is expressed as,

$$H_0 = NM\frac{\cos\theta}{\cos\theta'} . \quad (8)$$

A rogh estimation of H_0 is made for the case of H=0.2T at $\theta'=80°$. For this configuration H_0 is 0.29 T, which is higher than 0.2 T. Therefore the multiple domain structure takes place at this configuration. Thus, the deviation below 0.25 T can be explained by considering the multiple domain structure.

CONCLUSIONS

Torque measurements have been made for a single crystal specimen of pure hcp Co at 77 K and at room temperature. By using a new method proposed by the present author the magnetocrystalline anisotropy constant was determined, for the first time, in a very low field region between 0.3 and 0.5 T, where it had been considered to be almost impossible to determine the constant by using the conventional method of analysis. Thus estimated value agreed well with those determined at a higher field region where the torque curve was saturated enough. The unusual decrease of the anisotropy constant below 0.25 T was explained by considering a multiple domain structure.

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