An analysis of the high-temperature initial susceptibility of single-crystal cobalt

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Abstract. The ac initial susceptibility of a cobalt single crystal with [0001] orientation has been measured in the temperature range 300 to 820 K. A theoretical treatment of the susceptibility in the range 300 to 700 K has been given in terms of the contributions of domain wall displacements and magnetization vector rotations in the appropriate temperature intervals; this theoretical treatment is found to be in good agreement with the experimentally observed variation. Measurements in the range 700 to 820 K include the martensitic phase transformation at 710 K, which has a pronounced influence on the susceptibility. Magnetic relaxation measurements have also been made over the whole temperature range (300 to 820 K) and are found to be fully consistent with the interpretation of the susceptibility data. An important feature of the relaxation spectrum is a null region (584 to 710 K) which corresponds to that temperature range where contributions to the susceptibility occur due solely to magnetization rotations.

1. Introduction

The initial susceptibility of single-crystal cobalt shows an interesting temperature dependence in the region above 300 K. This is because, in this temperature range, the anisotropy constants which determine the magnetic behaviour are strongly temperature dependent [1, 2]. The resulting variation of the susceptibility is thus an elegant illustration of how, within different temperature ranges, magnetization processes can be observed which may be attributed solely to domain wall displacements in the absence of magnetization rotations and, conversely, solely to magnetization rotations in the absence of domain wall displacements, and also to a combination of these two processes. In the case of cobalt, all of these processes occur within a relatively narrow and accessible temperature range and there is also the additional feature of a martensitic phase change at 710 K, thus conveniently enabling us to monitor the magnetic properties through a structural phase transformation [3].

The temperature dependences of the magnetic properties of single-crystal cobalt were first investigated in detail, both theoretically and experimentally, by Kronmüller and co-workers almost three decades ago [4]. These workers considered the case of a long single crystal with its axis making an angle of 51° to the basal plane and with an applied field directed in the basal plane. Predictions were made for various magnetic parameters, the theoretical model being compared successfully with experimental results; the influence of dislocations on these parameters was also discussed.

In the present paper, we consider a more specific problem: namely that of the temperature dependence of the initial susceptibility of a cylindrical single crystal with [0001]

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orientation and with the further simplification of the measuring field being applied along the *c*-axis. In common with earlier workers, we divide up the temperature range from 300 to 700 K into three regions (I, II, III). In two of these regions (I and III), our results agree with earlier conclusions in that, in region I, we find that the susceptibility is due only to domain wall displacements and, in region III, only to magnetization rotations. However, in the intermediate temperature range (II), we find that magnetization processes occur due to rotational effects together with a contribution from domain wall displacements. This is in contrast to earlier work, where there was no contribution from magnetization rotations.

We also report the corresponding experimental results for a single crystal with this particular orientation and observe good agreement between the present theory and experiment. In addition, we have extended the measurements of susceptibility up to 820 K, i.e. through the temperature range of the martensitic phase transformation and into the cubic phase.

The present susceptibility measurements are complemented, over the whole of the temperature range, by measurements of the magnetic after-effect, i.e. the disaccommodation of the initial susceptibility. This relaxation behaviour, and its temperature dependence, correlates well with our interpretation of the mechanism for the initial susceptibility. An especially interesting feature of the results is the complete absence of any relaxation in the temperature range 584 to 712 K. This we attribute to the fact that, in this region, magnetization processes occur only via rotation of the magnetization vector rather than by domain wall displacement. Such processes are much less sensitive to the reorientation of lattice defects than are domain wall displacements.

2. Experimental details

The Co sample used for the measurements had the dimensions $1.0 \times 1.0 \times 18$ mm^3 and was spark-eroded from a larger, high-purity single crystal grown at the Institute for Nuclear Research, Warsaw. It was cut such that its length lay along the *c*-axis and thus had an [0001] orientation. Further details of sample preparation have been given in an earlier paper [5] and will not be repeated here.

The initial susceptibility measurements were performed using a fully automated, ac technique described elsewhere [6]; the measuring frequency was 5 kHz. This technique enabled both real and imaginary components of the complex susceptibility, together with their time dependences, to be determined simultaneously, although here we present results only for the real component. In principle, it is possible to convert the present ac measurements into corresponding dc values, although to do so with any accuracy and over a wide temperature range requires, amongst other things, a knowledge of the temperature dependence of the electrical resistivity of the particular sample being investigated. The presence of after-effects in the sample also adds to the difficulty; this problem is discussed in some detail by Kronmüller [7].

The time dependence of the initial susceptibility, $\chi(t, T)$, was measured isothermally at temperature, T, in the interval $t_1 < t < t_2$ following a demagnetization of the sample. This was achieved as follows. Firstly, the sample temperature was stabilized, this was ascertained by monitoring its temperature over a period of six minutes. The sample was then demagnetized and its susceptibility monitored for three minutes; this gave an effective rate of temperature rise of 0.3 K min^{-1}. After attaining the maximum temperature required, the sample temperature was then reduced at the same rate.

From a theoretical point of view, it is more appropriate to consider the reciprocal of the susceptibility, the reluctivity, $r(t, T) = 1/\chi(t, T)$. From measurements of $r(t, T)$ made at

various temperatures, we can construct isochronal relaxation curves via the expression

$$\frac{\Delta r(t_1, t_2, T)}{r(t_1, T)} \ (\%) = \frac{r(t_2, T) - r(t_1, T)}{r(t_1, T)} \times 100. \tag{1}$$

In our measurements, a field of amplitude 3 mOe (0.24 A m^{-1}) was applied along the c-axis of the sample and the measuring times were chosen such that $t_1 = 1$ and $t_2 = 2, 4, 8, 16, 32, 64, 100, 128$ and 180 s. For our initial susceptibility we have chosen the value measured 1 s after demagnetization.

3. Magnetic anisotropy

The magnetic anisotropy of Co has previously been investigated and discussed [1, 2, 3]. In this paper, therefore, we shall confine ourselves to a relatively brief account. The hcp (α-) phase in Co is stable up to 710 K, at which temperature there is a martensitic phase transformation to the fcc (β-) phase.

3.1. The hexagonal phase (T < 710 K)

For the hexagonal phase, the anisotropy energy, ϕ_K, can be written as

$$\phi_K = K_0 + K_1 \sin^2 \theta + K_2 \sin^4 \theta \tag{2}$$

where θ is the angle between the magnetization and the c-axis, and K_0, K_1 and K_2 are the anisotropy constants.

We divide the discussion of our results in this region into three temperature intervals, as described below.

(I) $T < 518$ K ($K_1 > 0$, $K_2 > 0$). Within this region, Co is magnetically uniaxial (the c-axis is the preferred magnetic axis). Therefore, only 180° Bloch walls exist, lying perpendicular to the basal plane.

(II) $518 < T$ (K) < 613 ($-2K_2 < K_1 < 0$, $K_2 > 0$). In this temperature interval, the easy direction of magnetization moves out of the c-axis towards the basal plane, lying along a cone whose semi-angle with the c-axis, θ_L, opens continuously with increasing temperature. The angle of canting of the magnetization is given by

$$\theta_L = \arcsin \sqrt{-K_1/2K_2}.$$

(III) $613 < T$ (K) < 710 ($K_1 < -2K_2$). Within this temperature range, the direction of easy magnetization lies in the basal plane.

Notice that in the present approximation the anisotropy energy has cylindrical symmetry. Therefore, in region II, all the directions of the cone which make an angle θ_L with the c-axis, and in region III all the directions lying in the basal plane, are equally probable.

3.2. The cubic phase (T > 710 K)

For the fcc phase, the anisotropy energy is written as

$$\phi_K = K_1(\alpha_1^2 \alpha_2^2 + \alpha_1^2 \alpha_3^2 + \alpha_2^2 \alpha_3^2) + K_2 \alpha_1^2 \alpha_2^2 \alpha_3^2 \tag{3}$$

where $(\alpha_1, \alpha_2, \alpha_3)$ are the direction cosines of the magnetization.

In this temperature interval, $K_1 < 0$ and $K_2 < 0$; therefore the easy directions of magnetization are the $\langle 111 \rangle$ directions.

4. Magnetic susceptibility

An excellent treatment of the magnetic susceptibility of a Co single crystal has previously been given by Kronmüller *et al* [4]. However, due to the fact that the particular single-crystal orientation used in the present experiment simplifies the calculations, and also results in the appearance of several new features which were not discussed in the original paper [4], we present the calculation in some detail.

4.1. General theory of the magnetic susceptibility

In this section we summarize the general theory of magnetic susceptibility adopting the approach and nomenclature employed by Kronmüller [8] and by Träuble [9].

Generally, magnetization changes occur simultaneously via both Bloch wall displacements and magnetization rotations. Where these two processes are reversible, the state of magnetization of a crystal may be calculated for any given external field from the variational principle, $\delta\Phi_G = 0$, where Φ_G is the total free enthalpy of the crystal.

We shall describe the state of a sample subdivided into domains by assigning all domains with the same magnetization directions, $\gamma_j^{(i)}$, $j = 1, 2, 3$, to a common phase, i, with a volume fraction v_i.

We consider that Φ_G is composed of the following terms:

$$\Phi_G = \Phi_K + \Phi_D + \Phi_H + \Phi_{El}. \tag{4}$$

In this equation, Φ_K is the magnetocrystalline anisotropy (equations (2) and (3)), and Φ_D is the demagnetizing-field energy:

$$\Phi_D = \frac{1}{2}N_\parallel M_\parallel^2 + \frac{1}{2}N_\perp M_\perp^2 \tag{5}$$

where $M_\parallel$, $M_\perp$ are the magnetizations and $N_\parallel$, $N_\perp$ the demagnetizing factors parallel and perpendicular to the field direction respectively.

Φ_H is the potential energy in the external field, H, and is given by

$$\Phi_H = -M_\parallel H \tag{6}$$

and Φ_{El} is the magnetoelastic coupling energy which, in turn, may be written as

$$\Phi_{El} = \Phi_{El,W} + \Phi_{El,R}. \tag{7}$$

Here, the first term represents the interaction of domain walls with long-range stresses and the second term represents the interaction between the magnetization inside a domain with long-range stresses. In these expressions, we have used the particular crystal orientation and applied-field direction as in our measurements, i.e. the field direction is perpendicular to the basal plane of our sample.

Following Kronmüller *et al* [4, 7] we assume that $\Phi_{El,W}$ may be written as

$$\Phi_{El,W} = \frac{1}{2}\sum_i R_i(\Delta v_i)^2 \tag{8}$$

where the sum over i is a sum over all the phases, Δv_i represents the change in phase volume and R_i is an interaction constant.

Finally, we assume that the effect of $\Phi_{El,R}$ is to change the anisotropy constants to effective values (see below).

The reversible magnetization processes are described by the two extremal equations:

$$\frac{\partial \Phi_G}{\partial v_i} = 0 \tag{9}$$

$$\frac{\partial \Phi_G}{\partial \gamma_j^{(i)}} = 0 \tag{10}$$

together with the conditions

$$\sum_i v_i = 1 \tag{11}$$

$$\sum_j (\gamma_j^{(i)})^2 = 1. \tag{12}$$

4.2. Application to cobalt

In general, the total susceptibility, χ_{tot}, is the sum of a contribution due to domain wall displacements, χ_{dw}, and a contribution from magnetization rotations, χ_{rot}. Thus we may write

$$\chi_{tot} = \chi_{dw} + \chi_{rot}. \tag{13}$$
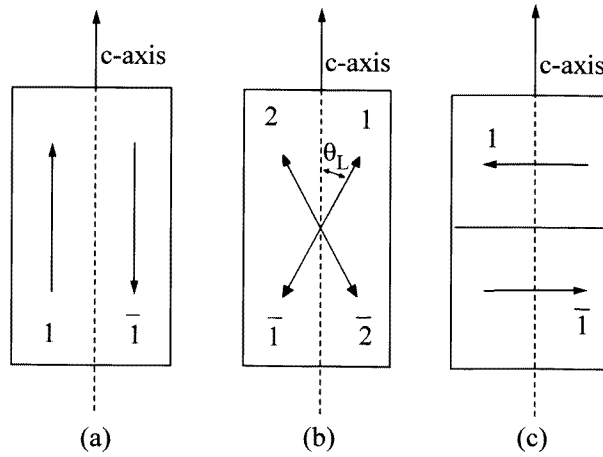

Figure 1. Directions of magnetizations assumed in the calculation of the initial susceptibility: (a) $T < 518$ K, (b) $518 < T$ (K) < 613 and (c) $T > 613$ K.

In analogy with the discussion of magnetic anisotropy, we subdivide our discussion of the initial susceptibility into the same temperature intervals (see below).

(I) $T < 518$ K. In this temperature range, the domain structure is composed of only two phases which we represent as 1 and $\bar{1}$; these are separated by 180° domain walls (figure 1(a)) and, for our sample orientation and applied-field direction, the only magnetization processes are domain wall displacements. The components of the magnetization parallel, $M_{\parallel}$, and perpendicular, $M_{\perp}$, to the Bloch wall are given by

$$M_{\parallel} = M_s (v_1 - v_{\bar{1}}) \tag{14}$$

$$M_{\perp} = 0 \tag{15}$$

where M_s is the saturation magnetization.

Using equations (10) to (13) we find that the susceptibility in the case of the absence of defects ($\Phi_{El} = 0$) is given by

$$\chi_{tot} = \chi_{dw} = \frac{1}{N_\parallel}. \tag{16}$$

Clearly, for an infinite cylinder, we have $N_\parallel = 0$ and $\chi \longrightarrow \infty$.

In the presence of defects we obtain

$$\chi_{tot} = \chi_{dw} = \frac{1}{N_\parallel + R/M_s^2} \tag{17}$$

where the interaction constant, R, is given by [9]

$$R = \frac{3.84L_3}{(F_B)^{1/2}} \lambda_{44} C_{44} b \sqrt{\frac{N\ell}{\pi \delta_B}}. \tag{18}$$

In this equation, L_3 represents the average domain size, F_B is the mean area of the domain wall that moves in each individual process, N is the dislocation density, b is the projection of the Burgers vector of dislocations onto the plane of the wall, ℓ is an effective dislocation-interaction length [4], C_{44} and λ_{44} are the components of the elastic and magnetostrictive tensors respectively and δ_B is the domain wall width, which, in this temperature interval, is given by [10]

$$\delta_B = \frac{\pi \sqrt{A}}{\sqrt{K_1 + K_2}}. \tag{19}$$

Here, A is the exchange interaction constant.

It should be noted that, due to the particular geometry considered in the present case, this calculation is valid for all values of K_1 and K_2 in this temperature range. In the more general case, for an arbitrary crystal orientation and direction of applied field, the calculation is more complicated and in the paper of Kronmüller *et al* [4] a solution is only found in the approximation $K_2 = 0$. Such an approximation is not valid for Co in the temperature range $400 < T$ (K) < 518.

(II) $518 < T$ (K) < 613.

(a) Susceptibility due to domain wall displacements. In this temperature range, the magnetization makes an angle θ_L with the c-axis. Following Kronmüller *et al* [4] we assume that the domain structure is composed of four phases which we represent as 1, $\bar{1}$, 2, and $\bar{2}$ (figure 1(b)). Furthermore, to avoid demagnetizing-field effects we assume $M_\perp = 0$. This last assumption implies

$$v_1 - v_{\bar{1}} = v_2 - v_{\bar{2}}. \tag{20}$$

A calculation along the lines of the preceding section gives us the following expression for the susceptibility:

$$\chi_{dw} = \frac{\cos^2 \theta_L}{N_\parallel \cos^2 \theta_L + R/2M_s^2}. \tag{21}$$

This equation is different to the corresponding equation given in [4].

In this temperature range, R is given [11] by equation (18) with

$$\delta_B = \frac{2\pi \sqrt{A K_2}}{2K_2 + K_1}. \tag{22}$$

In deriving this equation, a particular wall geometry was assumed; see, for example, [11].

If we assume that K_2 is approximately constant, which is a good approximation in this temperature interval [3, 4, 5], we have, according to equation (22), that χ_{dw} is a maximum for $K_1 = 0$ and decreases to zero for $K_1 = -2K_2$. It should also be noted that this result is 'physically correct', i.e. the susceptibility due to domain wall displacements is a maximum when the directions of magnetization and field coincide and is zero when the two directions are mutually perpendicular.

(b) Susceptibility due to magnetization rotations. Following [12] we assume that the local magnetic moments are distributed with equal probability in all the easy directions. In this case, the moments in all of the easy directions are equivalent and we thus have

$$\Phi_G = \Phi_K + \Phi_H = K_1 \sin^2 \theta + K_2 \sin^4 \theta - M_s H \cos \theta. \tag{23}$$

The equilibrium equation is

$$2K_1 \cos \theta + 4K_2 \sin^2 \theta \cos \theta + M_s H = 0 \tag{24}$$

from which we obtain

$$\chi_{rot} = M_s \frac{\partial \cos \theta}{\partial H}\bigg|_{\theta=\theta_L} = \frac{1}{4} \frac{M_s^2}{(K_1 + 2K_2)}. \tag{25}$$

Notice that $\chi_{rot} \longrightarrow \infty$ for $K_1 = -2K_2$.

(III) $613 < T$ (K) < 710. In this temperature range we have only magnetization rotations (figure 1(c)). A calculation similar to the preceding one gives

$$\chi_{rot} = M_s \frac{\partial \cos \theta}{\partial H}\bigg|_{\pi/2} = \frac{M_s^2}{2(K_1 + 2K_2)} \tag{26}$$

where we find again $\chi_{rot} \longrightarrow \infty$ for $K_1 = -2K_2$.
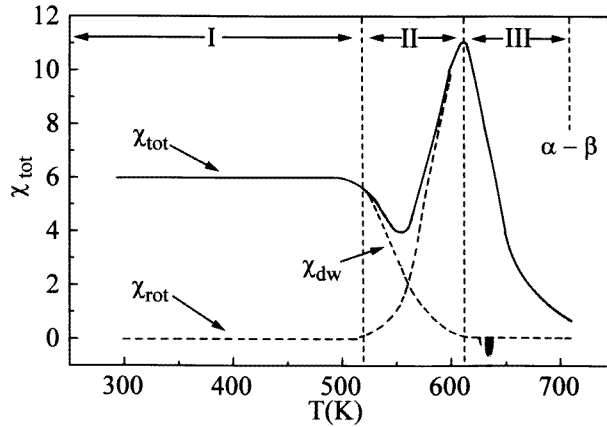

Figure 2. A schematic representation of the initial susceptibility as predicted by the present calculations for a single-crystal Co sample with orientation and applied field as given in the text. χ_{dw} is the susceptibility due to domain wall displacements, χ_{rot} is the susceptibility due to magnetization rotations and χ_{tot} is the resultant total susceptibility.

4.2.1. The temperature dependence of the initial susceptibility. A schematic representation of the temperature dependence of the total initial susceptibility, χ_{rot}, according to the above calculations is given in figure 2; this figure should be treated with some caution. We

do not intend it to represent the precise variation of the susceptibility, but only to give a general indication of the expected temperature dependence of results according to this simple theory. For example, in the representation of region I we have neglected the possibility of a temperature dependence of the susceptibility due to a temperature dependence of R and M_s. One can, however, argue that these temperature dependences are going to be very weak in this temperature interval. We thus expect the susceptibility in region I, which is due to domain wall displacements, to be approximately constant. The actual value depends on the value of the interaction constant, R, and this tends to zero continuously in region II for $K_1 \longrightarrow -2K_2$. We expect that the susceptibility due to magnetization rotations will be zero in region I and attain a sharp maximum for $K_1 \longrightarrow -2K_2$.
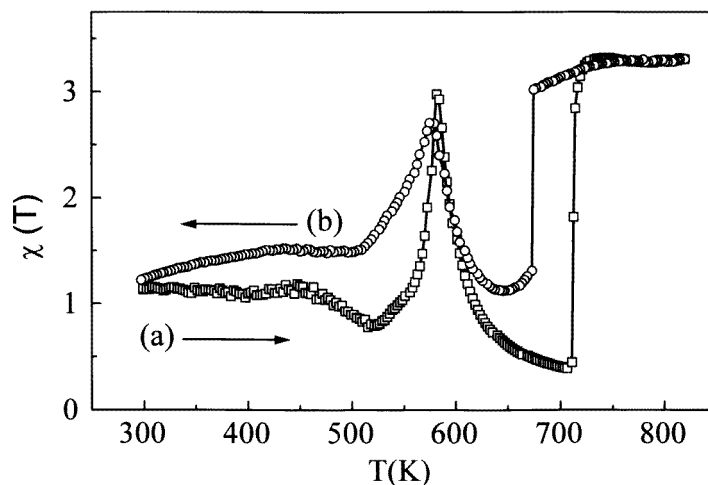

Figure 3. The temperature dependence of the real part of the initial susceptibility of a Co single crystal with [0001] orientation as measured for temperatures increasing from room temperature to 820 K (curve (a)) and immediately after, but for decreasing temperatures, curve (b).

5. Experimental results

5.1. Initial susceptibility

Figure 3 shows the temperature dependence of the real part of the initial susceptibility of the Co single crystal as measured, curve (a), for temperatures increasing from room temperature up to 820 K. After attaining this maximum temperature, the sample was immediately measured at decreasing temperatures, curve (b). Several important features can be clearly observed, as detailed below.

  (1) At low temperatures, $T < 500$ K, the initial susceptibility is almost temperature independent. However, the curve for increasing temperatures is clearly below that obtained for decreasing temperatures.
  (2) There is a pronounced maximum at 584 K, curve (a). This peak is shifted to lower temperatures by 10 K, curve (b), after measurement up to 820 K.
  (3) For measurements made with increasing temperature, there is an abrupt increase in the susceptibility at 710 K. The corresponding step for decreasing temperatures is shifted down by about 40 K to 670 K.

(4) Above 710 K the susceptibility is very large and almost constant in value.

(5) Over the whole of the temperature range, the susceptibility obtained for decreasing temperature is almost everywhere above that for increasing temperature.
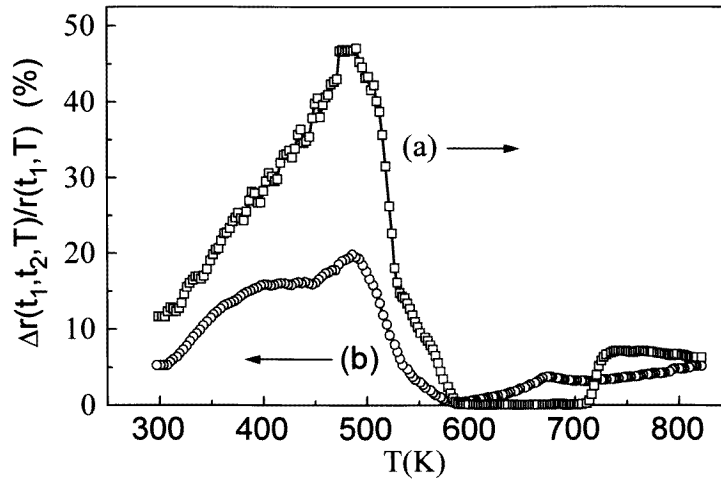

Figure 4. Magnetic relaxation spectra for the Co single crystal for which the measurements displayed in figure 3 were made. The measurements were for (curve (a)) increasing and (curve (b)) decreasing temperatures. The times chosen in this representation are $t_1 = 1$ s and $t_2 = 180$ s.

5.2. The magnetic after-effect

Figure 4 shows the magnetic relaxation spectra for the same Co single crystal as was used for the measurements shown in figure 3 and measured at the same time as the initial susceptibility, i.e. for temperatures increasing up to a maximum of 820 K, curve (a), and then decreasing from 820 K down to room temperature, curve (b).

The relaxation spectrum may be conveniently divided into three regions, as detailed below.

(a) T < 584 K. In this region, there is a strong, broad relaxation peak with a maximum at 480 K. The amplitude of the relaxation is much greater for increasing temperatures than when observed for decreasing temperature.

(b) 584 < T (K) < 710. On measuring to higher temperatures, we find that there is a total absence of any relaxation process in this temperature interval. The start of this temperature region is defined by the position of the peak in the susceptibility curve (584 K); the end of the region coincides with the abrupt increase in susceptibility observed for increasing temperature (710 K). In order to emphasize the correlation between susceptibility and after-effect, the two curves are plotted on the same axes (see figure 5).

(c) T > 710 K. In this region, there is an increase in the magnetic relaxation to a plateau of almost constant amplitude, which is only weakly temperature dependent for temperature increasing or decreasing. The time dependence of the relaxation process in this temperature range has been investigated (see figure 6), and is found to be logarithmic.
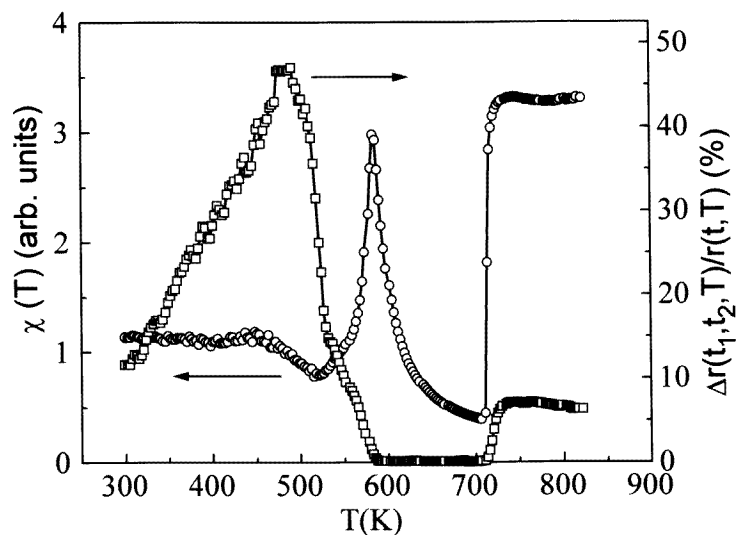
Figure 5. The correlation between the temperature dependence of the initial susceptibility and the magnetic relaxation spectrum for the Co single crystal as obtained for increasing temperatures.
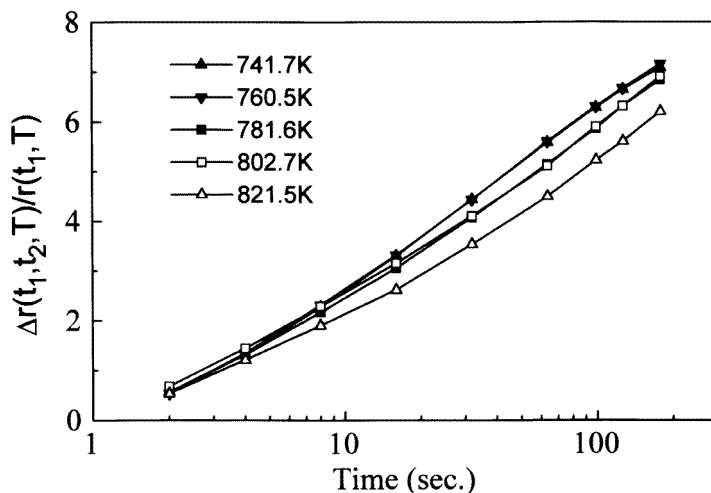

Figure 6. The time dependence of the disaccommodation of the initial susceptibility of a single crystal of Co in the temperature range $T > 720$ K.

6. Discussion

6.1. Preliminary remarks

It is important to emphasize both the similarities of and the differences between the present theoretical treatment and that of Kronmüller *et al* [4]:

(1) The expressions derived in the present work for the susceptibility in regions I and III are the same as those obtained in [4].

(2) In region II, Kronmüller *et al* calculated the susceptibility due to domain wall displacements only. These results differ from our equation (21). However, in our geometry, for this region an important contribution from rotational magnetization processes is also expected. A detailed calculation of this is given in the present treatment. In particular, we have found that the susceptibility peak which occurs at the temperature for which $K_1 = -2K_2$ is almost entirely due to rotational processes.

6.2. Initial susceptibility

Several important comments can be made about the experimental results:

(1) The magnetic susceptibility in region I is due only to domain wall displacements, whereas in region II it is due to a combined process of domain wall displacements and rotations of the magnetization vector, and in region III it is due only to rotations. It is a well-known fact [15] that domain wall displacements are impeded far more by lattice defects than are magnetization rotations. We therefore expect the susceptibility in regions I and II to be dependent upon annealing and sample purity/quality, whereas we expect the susceptibility in region III not to be. In particular, we note that, in our calculation, the peak in the susceptibility at 613 K is due almost entirely to rotations. Hence, we do not expect this peak to be very dependent on annealing. This is experimentally observed in figure 1, where the peak only shifts by 10 K; this effect is also observed in figure 2 of [5].

(2) Whereas there is a good qualitative agreement between theory and our experimental results, there is one important quantitative discrepancy: theory predicts a peak in the susceptibility at about 613 K (for $K_1 = -2K_2$), whereas the experimental peak is located at about 584 K. Various reasons, as detailed below, can be suggested to account for this discrepancy.

(a) Magnetocrystalline effects. Changes in the magnetocrystalline constants arise due to the presence of defects. Notice that the peak moves by approximately 10 K between the two consecutive measurements (figure 3). This suggests that the position of the peak is dependent upon internal stresses. For the order of magnitude of the magnetocrystalline energy in this region, $K \approx 10^6$ erg cm^{-3}, we can calculate the density of dislocations expected to give rise to an appreciable change in the magnetocrystalline constants. This corresponds to a dislocation density of the order of 10^{12} cm^{-2} [7]. This is a very high, but not unrealistic, value [5].

(b) Magnetostatic correction. In our calculation of the initial susceptibility due to magnetization rotations we have neglected the magnetostatic energy since, for a detailed calculation taking this effect into account, we need to know the domain structure of our samples in this temperature interval, and this is not a simple structure [14].

(3) The increase of the initial susceptibility after annealing at high temperatures, where curve (b) lies generally above curve (a) (figure 3), is a well-known consequence of the relief of internal stresses. The most important sources of internal stresses are dislocations. Thus, we attribute this increase of the susceptibility to a re-configuration and/or annihilation of dislocations in the sample. Similar behaviour is observed after thermal cycling to 800 K in figure 3 of [5].

(4) The step at 710/670 K is due to the allotropic transformation between the hcp and fcc phases. The onset of this transition is effectively the maximum temperature of region III. The shift in the position of the step results from the difference between the transformation temperature for the phase in the forward and reverse directions. This thermal hysteresis of approximately 40 K is a characteristic feature of the martensitic transition.

6.3. Magnetic after-effect measurements

Although a detailed study of the magnetic relaxation data is deferred to a later paper [13], we wish to mention here some important features of the magnetic relaxation spectra that corroborate the present interpretation of the magnetic susceptibility; these are listed below.

(1) The simultaneous decrease, after annealing, of the initial susceptibility and that of the relaxation process located in the temperature range $300 < T$ (K) < 584 is consistent with an interpretation of the relaxation process as being being due to defects (dislocations and foreign interstitials, C, N, H) in the sample [5]; these defects reduce the domain wall mobility and thus give rise to the observed after-effect.

(2) The complete absence of any magnetic relaxation process in the temperature range $584 < T$ (K) < 710, as observed in measurements made at increasing temperatures (figure 4), is a consequence of the fact that the domain walls are completely immobile in this temperature region. The lower temperature of this zero-relaxation region coincides with the temperature at which the contribution of domain wall displacements to the susceptibility vanishes and where the magnetization processes are due solely to magnetization rotation, i.e. the start of region II. The upper temperature of the region is the temperature at which the martensitic phase change occurs and is thus effectively the maximum temperature of region III.

It is relevant to remark here that it is both theoretically possible and desirable to observe magnetic relaxation phenomena where magnetization processes occur due to magnetization rotation only, since this can yield, under suitable experimental conditions, important information on the symmetry of the defect giving rise to the relaxation [7]. However, to the best of the authors' knowledge, such an effect has never been experimentally detected.

(3) The time dependence of the relaxation process in the temperature interval $T > 710$ K (figure 6) has been investigated and found to be logarithmic. This is interpreted as being a fluctuational after-effect associated with a first-order structural transition [16] and will be considered in more detail later [13].

7. Conclusions

We have studied both experimentally and theoretically, over the temperature range 300 to 820 K, the temperature dependence of the magnetic susceptibility of a Co single crystal with [0001] orientation and the measuring field applied along the *c*-axis. Good qualitative agreement between theory and experiment is obtained. We have also extended measurements up to 820 K, i.e. through the martensitic phase transition and into the cubic phase.

Results are also presented on the magnetic relaxation over the temperature range 300 to 820 K. The temperature dependence of these relaxation processes is fully consistent with the interpretation of the magnetic susceptibility data; there is a complete absence of any detectable relaxation in the range 584 to 710 K, which correlates with our interpretation of the magnetization process in this region as being due solely to rotation of the magnetization vector, rather than domain wall displacement. We believe this to be the first report of such a phenomenon.

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