Anomalous evolution of torque curves with the applied magnetic field in amorphous ribbons due to surface roughness

M. Tejedor, J. A. García, J. Carrizo, and L. Elbaile
Departamento de Física, Universidad de Oviedo, Calvo Sotelo s/n, 33007 Oviedo, Spain

J. Mira and J. Rivas
Departamento de Física Aplicada, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Spain

(Received 10 February 1998; accepted for publication 15 July 1998)

The behavior of torque curves of amorphous ribbons, in which their amplitude decreases with the applied magnetic field has been obtained in some samples of Vitrovac 6150. An explanation is given for this behavior based on the analysis of the superposition of orthogonal uniaxial magnetic anisotropies caused by the oriented surface roughness of the amorphous ribbons. Based on this explanation, important information on the magnetic anisotropies of amorphous magnetic ribbons is obtained and the values of the involved anisotropy constants are calculated. © *1998 American Institute of Physics.* [S0021-8979(98)04520-4]

I. INTRODUCTION

The most direct method for measuring the in-plane magnetic anisotropy in magnetic amorphous ribbons is torque magnetometry. This technique also produces additional information about the different origins of the in-plane magnetic anisotropy.[1] In general, when torque curves of amorphous ribbons are measured, their amplitude increases as the strength of the applied magnetic field increases, until the torque reaches its saturation value. This torque per unit volume is the in-plane magnetic anisotropy constant (Fig. 1). The resulting behavior is due to the increase of magnetization with the applied magnetic field until the saturation magnetization is reached. However, in general, as has been observed previously,[2] the amplitude of the torque curves increases with the applied magnetic field, until the samples have almost reached the magnetic saturation. This fact has been attributed to the contribution to the torque by unsaturated imperfections, located at the surface of the sample (roughness, surface residual stresses, surface crystallization, etc.) or inside the sample (microholes, crystalline precipitates, composition fluctuations, overstrained zones, etc.), that occupy a small volume and contribute negligibly to the total magnetization of the sample. These imperfections exhibit a high magnetic anisotropy, substantially affecting the magnetic torque exerted on the material in the presence of an external magnetic field.

Kraus *et al.*[3] reported the case of the amorphous alloy $Co_{69}Fe_{4.5}Cr_2B_{22}Si_{2.5}$, in which the amplitude of the measured torque decreased with the applied magnetic field, instead of the usual increase which has been explained above. Decreasing torque amplitudes have also been found in polycrystalline materials such as Fe_3NiAl,[4] Alnico,[5] cobalt ferrites[6] (in these materials a reversal in the sign of the torque with increasing magnetic field has been observed), and nickel after plastic deformation.[7,8] In all these latter cases, the explanation for the decreasing torque amplitudes was based on the existence of two perpendicular anisotropies, affecting different volumes in the sample with different rates of magnetic saturation. When the sample is not yet magnetically saturated, the superposition of these perpendicular anisotropies causes the decreasing torque amplitudes.

In this article we present another amorphous alloy, Vitrovac 6150, which exhibits decreasing torque amplitudes similar to those obtained by Kraus *et al.*[3] We can explain the unusual behavior of the torque amplitude as a consequence of the superposition of two mutually perpendicular magnetic anisotropies, as in the same way described before for polycrystalline materials.

We believe that this explanation can be extended to other materials which exhibit decreasing torque amplitudes, and must be taken into account in the interpretation of torque curves obtained in amorphous materials.

II. EXPERIMENTAL PROCEDURE

The torque curves were obtained in a commercial magnetometer (''DMS-1660'' from Digital Measurement Systems), with sufficient sensitivity to measure the torques that appear in this kind of materials.

The samples were measured at different increasing values of the applied magnetic field, in order to study the dependence of the maximum torque on the magnetic field. We have used circular samples with negligible eccentricity to avoid any shape effect in the torque curve. The samples were obtained from different ribbons of the very low magnetostrictive amorphous magnetic ribbon Vitrovac 6150 supplied by the German Company Vacuumschmelze. The method used to obtain the circular samples has been described elsewhere.[9] All the samples have an initial thickness of 25 μm and an average diameter of 10 mm, large enough to perform reliable torque measurements. Random mechanical polishing was performed with 0.1 μm grain size alumina. The surface profiles of the as-quenched and mechanical polished samples were obtained by means of a commercial profilograph with a maximum sensitivity of 0.1 μm. The thick-

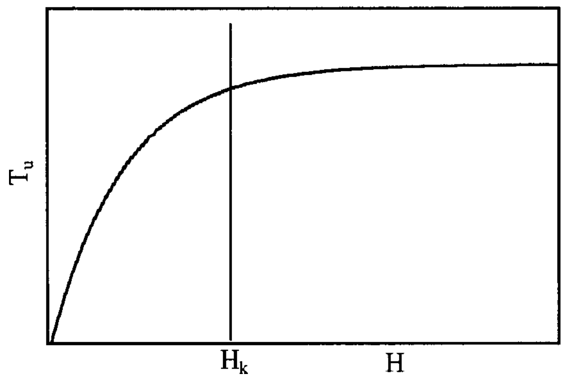

FIG. 1. General evolution of the amplitude of the torque curves, T_u, with the applied magnetic field, *H*, in amorphous magnetic materials.

ness of the samples was determined by weighing each sample, measuring its diameter, and using the density indicated in the catalog of the firm.

III. RESULTS AND DISCUSSION

The amplitude of the torque curves in the majority of the studied samples of Vitrovac 6150 shows the behavior indicated in Fig. 1, i.e., the torque amplitude increases to a saturation value. But there are some samples in which the evolution of the amplitude of the torque curves exhibits a different behavior. The amplitude of the torque curves T_u as a function of the applied magnetic field for these samples in the as-quenched state, is shown in Fig. 2 (curve a). Here T_u decreases until the applied magnetic field reaches 0.2 T, then T_u increases until the applied magnetic field reaches 0.6 T, and then remains constant.

The interpretation of this unusual effect is as follows: Usually the magnetic amorphous ribbons obtained by melt spinning exhibit a weak in-plane uniaxial magnetic anisotropy with the easy axis along the longitudinal direction of the ribbon. Using a torque magnetometer it is possible to measure the torque curve at a given applied magnetic field. From the Fourier analysis of the torque curve the uniaxial component of the torque T_u is obtained.

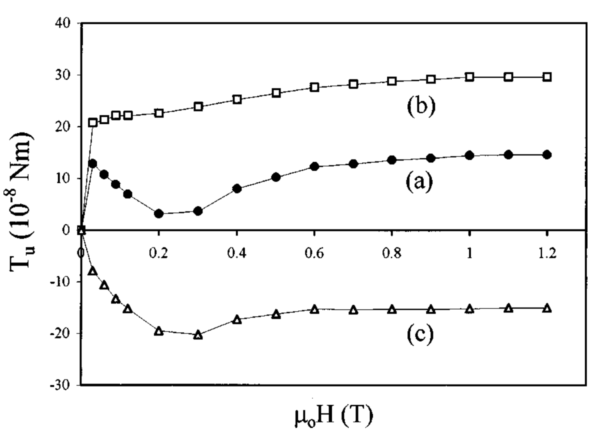

FIG. 2. Experimental evolution of the amplitude of the torque curves T_u of Vitrovac 6150 with the applied magnetic field $\mu_0 H$, in: (a) as-quenched samples, (b) after mechanical polishing, and (c) curve resulting from the subtraction of curves a and b.

If we measure T_u at different applied magnetic fields we will certainly obtain the results schematically shown in Fig. 1. There the value of T_u grows with the applied magnetic field H until the maximum value is reached at the field H_k. This value of H_k would be related to the anisotropy field of the sample. For higher applied magnetic fields the uniaxial torque T_u remains practically constant.

A different question arises when we consider the problem of the superposition of two uniaxial magnetic anisotropies affecting different volumes in a sample. In this case, if for simplicity, we assume that the two magnetic anisotropies were perpendicular, we can show that, depending on the relative strength of the anisotropies and the volume of material affected by them, their superposition gives a total uniaxial torque T_u that can vary with the applied magnetic field in different ways.

In a first attempt let us consider two zones I and II in the sample, which have volumes V_1 and V_2 and are affected by mutually perpendicular uniaxial magnetic anisotropies with constants K_1 and K_2, respectively. The zones contribute to the total uniaxial torque exerted on the whole sample with different amounts T_{u1} and T_{u2}. Their saturation values are related to the anisotropy constants and the volumes in the following way

$$T_{u1,\max}=K_1 V_1, \tag{1}$$

$$T_{u2,\max}=-K_2 V_2. \tag{2}$$

Then, the total uniaxial torque obtained at high fields when the saturation is reached would be

$$T_{u,\max}=K_1 V_1 - K_2 V_2. \tag{3}$$

Each contribution to the torque, T_{u1} and T_{u2}, reaches the saturation value at different values of the applied magnetic field H_{k1} and H_{k2}. If we suppose H_{k1} and H_{k2} to be of the order of the anisotropy fields then we can write

$$H_{k1}=\frac{2K_1}{\mu_0 M_s}, \tag{4}$$

$$H_{k2}=\frac{2K_2}{\mu_0 M_s}. \tag{5}$$

Here M_s denotes the saturation magnetization, which we assume to be the same in the two anisotropic regions.

Region I occupies a volume V_1 with an anisotropy constant K_1. This volume contributes with a magnetic torque T_{u1} to the total measured torque. We can assume for T_{u1} the behavior shown in Fig. 1, i.e., it will grow with increasing magnetic field. When the magnetic field reaches the corresponding anisotropy field H_{k1}, the torque reaches its saturation value $K_1 V_1$. At the same time region II, with a volume V_2 and an anisotropy constant K_2, contributes with a magnetic uniaxial torque $T_{u2} < 0$, opposite because it is dephased by $\pi/2$; T_{u2} increases its absolute value until the magnetic field reaches H_{k2}, when the value of the uniaxial torque is $T_{u2,\max}=-K_2 V_2$.

Figure 3 shows all the extreme possibilities that can arise when two mutually perpendicular anisotropies coexist in independent volumes of a sample. In each case the uniaxial

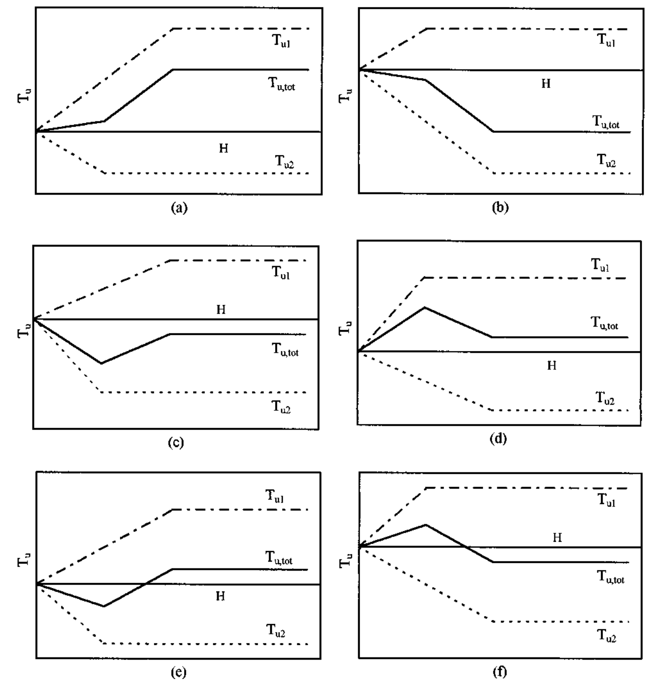

FIG. 3. Linear approximation of the evolution of the amplitude of the torque curves with the applied magnetic field in samples with two zones I and II affected by mutually perpendicular uniaxial magnetic anisotropies for different cases. T_{u1}, T_{u2}, and $T_{u,\mathrm{tot}}$ indicate the amplitude of the uniaxial component of the torque curves corresponding to zones I, II, and the whole sample, respectively.

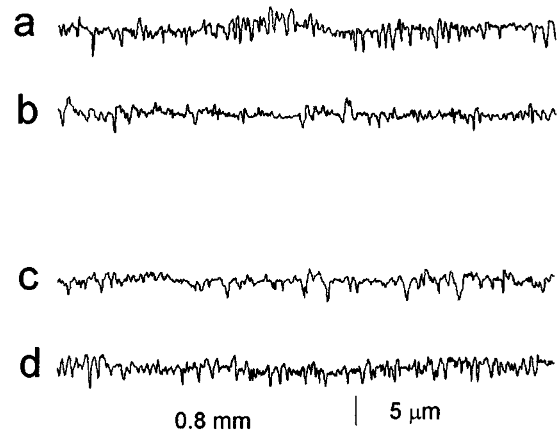

FIG. 4. Surface profiles of the wheel surface of samples of Vitrovac 6150: (a) and (b) profiles along the transversal and longitudinal direction in the majority of the ribbon, (c) and (d) the same as (a) and (b) but in the parts affected by the anomalous behavior of the torque measured.

torques T_{u1} and T_{u2} are plotted as well as their sum $T_{u,\mathrm{tot}}$ which would be measured by a torque magnetometer. In all cases a linear approximation has been made.

Observing Figs. 3(a)–3(f) we can distinguish the three main different behaviors, according to the above discussion, for the total uniaxial torque $T_{u,\mathrm{tot}}$.

(i) In the case of Figs. 3(a) and 3(b), the absolute value of the torque grows monotonically with the magnetic field.

(ii) In Figs. 3(c) and 3(d), the absolute value of the total torque first grows, reaches a maximum, then decreases and finally stabilizes at its saturation value.

(iii) Finally, in Figs. 3(e) and 3(f), the behavior is similar to that shown in Figs. 3(c)–3(d), but in this case a change of the sign is observed in the total uniaxial torque (torque reversal).

In an amorphous ribbon the main sources that can give rise to magnetic anisotropy are residual stresses, directional order, and surface roughness. Taking into account that Vitrovac 6150 has a near-zero magnetostriction constant ($\lambda_s \leqslant 0.2\times10^{-6}$), we will not consider residual stresses in this case. The directional order gives rise to a magnetic anisotropy in the longitudinal direction of the ribbon.[1] Then the only possible source of an in-plane magnetic anisotropy in the transversal direction of the ribbon is the surface roughness.

In an amorphous ribbon the two surfaces show a different roughness. The wheel-side surfaces are marked with air pockets where the liquid metal did not wet the casting wheel surface. The air pockets are all elongated in the casting direction. The roughness of the air-side surfaces is much smaller and this surface has a negligible effect on the in-plane magnetic anisotropy of the sample.[10] Comparing the surface roughness in the longitudinal and transversal direction of the wheel side of the ribbon, measured with a profilometer, we can see that in general there is a greater surface roughness in the transversal direction of the sample than in the longitudinal direction [Figs. 4(a) and 4(b)]. But, in some parts of the ribbon these results are inverted, resulting in greater roughness for the longitudinal direction than for the transversal one [Figs. 4(c) and 4(d)]. Then, two perpendicular anisotropies originating from the surface roughness are present in these zones of the ribbon. It is in the samples obtained from these latter zones where the unusual evolution of the amplitude of the torque curves shown in Fig. 3(c) appear. Here the amplitude of the torque first decreases and then increases until the saturation value is reached.

In order to evaluate the contribution of the wheel-surface roughness of the ribbon to the total curve, we have performed a mechanical polishing of this surface to remove its roughness. The evolution of T_u vs H in the polished samples is shown in Fig. 2 (curve b). It can be seen that in this case T_u increases with H until it reaches a constant value which represents the expected general behavior of T_u.

The contribution of the wheel-surface roughness to the total torque is obtained by subtracting, in Fig. 2, curve b from curve a. The result is shown as curve c in the same figure. This curve is of the type represented in Fig. 3(c) and it can be considered as the sum of two mutually perpendicular anisotropies. Taking into account Fig. 3(c), the longitudinal anisotropy K_1 (positive torque) produces a lower torque than the transversal anisotropy K_2 (negative torque) but reaches its saturation at a higher magnetic field. The anisotropy field H_{k2} of the transversal anisotropy coincides with the field corresponding to the minimum of curve c (Fig. 2). Its value is 0.3 T and the corresponding anisotropy constant is 1.2×10^5 J m^{-3}.

The anisotropy field H_{k1} of the longitudinal anisotropy coincides with the field where curve c (Fig. 2) reaches a constant value. The value of H_{k1} is 0.6 T and the corresponding anisotropy constant is found to be 2.4×10^5 J m^{-3}.

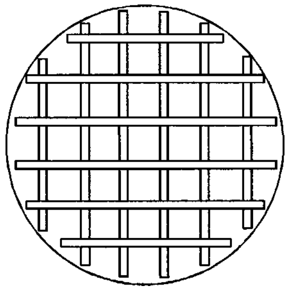

FIG. 5. Distribution between the strips (0.45 mm width and 23 μm thick) of $Co_{73.5}Ni_3Cu_1Si_{13.5}B_9$ in the sample simulating the surface roughness. Diameter of the sample 13 mm, spacing of the strips 1.5 mm.

Curve b in Fig. 2 shows the magnetic field dependence of the uniaxial torque of a sample without the wheel surface. As can be seen, the uniaxial torque at the lowest applied field strengths is near the saturation value (22×10^{-8} N m at 0.03 T and 28×10^{-8} N m when it is saturated). Then, the main contribution to the torque in this case is due to the directional order. The anisotropy constant would be 190 J m^{-3}, which is in good agreement with the results obtained in samples of Vitrovac 6150 without the anomalous behavior of the torque.[9]

These results confirm that the origin of the decreasing of T_u vs H in these kinds of samples in the as-received state is the surface roughness of those samples. The anomalous behavior of the torque is exhibited by those samples whose surface roughness in the longitudinal direction is greater than in the transversal direction. We believe that the results obtained by Kraus *et al.*[3] can be explained in the same way. Two mutually perpendicular anisotropies originate from the surface roughness which, with suitable amplitudes and saturation fields, lead to a behavior analogous to that represented in Fig. 3(c). Here, the amplitude of the torque first increases with the applied magnetic field, then decreases, and finally remains constant at the saturation value.

To further corroborate our interpretation we have modeled the surface of a sample with longitudinal and transversal roughness fixing 12 thin strips (0.45 mm width and 23 μm thick), six in each direction, of the $Co_{73.5}Ni_3Cu_1Si_{13.5}B_9$ amorphous ribbons to a circular piece of plastic in the arrangement shown in Fig. 5. This way of modeling the surface roughness of amorphous ribbons has been used in a recent article.[11] The dependence of the uniaxial torque on the magnetic field in this sample is shown in Fig. 6. As can be seen, the magnetic field dependence of the torque is similar to that found in the samples of Vitrovac 6150 studied in this article.

IV. CONCLUSIONS

An evolution of torque curves with the applied magnetic field, in which the maximum first decreases, then increases, and finally remains constant, has been obtained in samples of Vitrovac 6150. An explanation for this behavior based on the existence of orthogonal magnetic anisotropies in different volumes has been presented. The anisotropy along the longitudinal direction of the ribbon originates with the oriented surface roughness and directional order, while the anisotropy along the transversal direction originates with surface roughness only. To further corroborate the above explanation a mechanical polishing of the samples has been performed. The amplitude of the torque curves in the polished samples increases when the applied magnetic field increases, until a constant value is reached, which is the expected general behavior. A sample simulating this kind of surface roughness has been made as well. It exhibits a magnetic field dependence of the torque similar to that obtained in the samples exhibiting this kind of surface roughness.

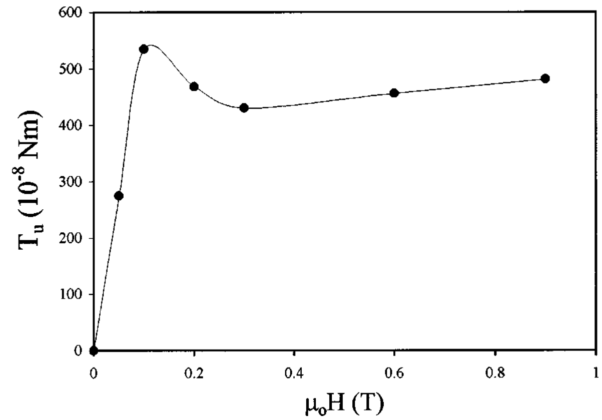

FIG. 6. Experimental evolution of the amplitude of the torque curves T_u of the sample of Fig. 5 with the applied magnetic field $\mu_0 H$.

From the results obtained in the as-quenched and polished samples the anisotropy constants for these anisotropies have been evaluated. We have obtained the values of 1.2 $\times10^5$ J m^{-3} for the transversal anisotropy, and 2.4×10^5 and 190 J m^{-3} for the longitudinal anisotropies, due to the surface roughness and directional order, respectively.

ACKNOWLEDGMENT

This work was supported in part by the CICYT under Grant No. MAT-96-0667 Madrid (Spain).

[1] M. Tejedor, J. A. García, and J. Carrizo, J. Magn. Magn. Mater. **131**, 329 (1994).
[2] M. Tejedor, J. A. García, and J. Carrizo, J. Magn. Magn. Mater. **118**, 333 (1993).
[3] L. Kraus, L. Tomás, E. Kratochvilová, B. Springmann, and E. Müller, Phys. Status Solidi A **100**, 289 (1987).
[4] E. A. Nesbitt, H. J. Williams, and R. M. Bozorth, J. Appl. Phys. **25**, 1014 (1954).
[5] E. A. Nesbitt and H. J. Williams, J. Appl. Phys. **26**, 1217 (1955).
[6] H. Williams, R. D. Heidenreich, and A. Nesbitt, J. Appl. Phys. **27**, 85 (1956).
[7] R. F. Krause and B. D. Cullity, J. Appl. Phys. **39**, 5532 (1968).
[8] M. Tejedor, J. Carrizo, B. Hernando, and A. Fernández, J. Appl. Phys. **61**, 427 (1987).
[9] M. Tejedor, J. A. García, and J. Carrizo, J. Magn. Magn. Mater. **117**, 141 (1992).
[10] S.-C. Huang and H. C. Fiedles, Metall. Trans. A **12**, 1107 (1981).
[11] M. Tejedor, J. A. García, J. Carrizo, and L. Elbaile, IEEE Trans. Magn. **34**, 278 (1998).