Large magnetocrystalline anisotropy energy of L10-type Co100-xPtx bulk single crystals prepared under compressive stress

Large magnetocrystalline anisotropy energy of $L1_0$-type $Co_{100-x}Pt_x$ bulk single crystals prepared under compressive stress

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$L1_0$-type $Co_{100-x}Pt_x$ single crystals in a single variant state were prepared by ordering under a compressive stress in order to determine accurately the uniaxial magnetocrystalline anisotropy constant K_U. Both the lattice constants a and c increase with increasing Pt concentration, whereas the axial ratio c/a becomes minimum at $x=50$. The value of K_U directly determined at 298 K exhibits a maximum value of 4.5×10^7 erg cm^{-3} for 50 at. % Pt. The second- and fourth-order anisotropy constants K_1 and K_2 determined by the Sucksmith–Thompson method become 4.1 and 0.6×10^7 erg cm^{-3}, respectively. The value of K_1+K_2 corresponding to the magnetocrystalline energy difference between the c and a axes becomes maximum at $x=50$. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861977]

$L1_0$-type $Co_{100-x}Pt_x$ alloys having large magnetocrystalline anisotropy energy (MAE) are potential candidates for ultrahigh dense magnetic recording medium. The uniaxial magnetocrystalline anisotropy constant K_U and the second- and fourth-order anisotropy constants K_1 and K_2 significantly affect the thermal stability and the magnetization reversal process in the medium.[1–4] Therefore, the precise evaluation of K_U, K_1, and K_2 is essential for the qualitative discussion on thermal stability and the magnetization reversal of $L1_0$-type $Co_{100-x}Pt_x$. When both the easy and hard axes of magnetization completely align along particular orientations, the value of K_U is directly obtained from the difference in the Helmholtz magnetic free energy given by

$$K_U = \int_0^{M_S} (H_{\text{eff}}^{a\ axis} - H_{\text{eff}}^{c\ axis})dM, \tag{1}$$

where $H_{\text{eff}}^{i\ \text{axis}}$ ($i=a$ and c) is the effective magnetic field defined as $H_{\text{ex}}-NM$ along the i-axis direction. Here, H_{ex} is the external magnetic field and N and M are the demagnetization factor and magnetization, respectively. The values of K_1 and K_2 can be evaluated by applying the Sucksmith–Thompson (ST) method to the magnetization curve along the a axis.[5] In the ST method, K_1 and K_2 can be, respectively, evaluated from the intercept and slope in the M^2 vs H_{eff}/M plot given as

$$\frac{H_{\text{eff}}}{M} = 2K_1\frac{1}{M_S^2} + 4K_2\frac{M^2}{M_S^4}. \tag{2}$$

Using Eqs. (1) and (2), K_U, K_1, and K_2 can accurately be determined. However, there are some difficulties to determine precisely the magnetocrystalline anisotropy constants for $L1_0$-type $Co_{100-x}Pt_x$. When a fcc-type single crystal transforms into an $L1_0$ phase, multivariant structures with conjugated c axis directions are induced. Since the c axis is the easy axis of magnetization, the magnetic properties of $L1_0$-type $Co_{100-x}Pt_x$ alloys are strongly influenced by microstructures.[6] In addition, almost all available experimental values of the magnetocrystalline anisotropy constants for $L1_0$-type $Co_{100-x}Pt_x$ were estimated from the magnetization process under magnetic fields less than the anisotropy field H_A evaluated to be above 100 kOe.[7–11] In the present letter, $L1_0$-type $Co_{100-x}Pt_x$ single crystals were prepared by ordering under compressive stress and a complete saturation along the hard axis of magnetization was achieved. Accordingly, K_U, K_1, and K_2 are determined from Eqs. (1) and (2), respectively, and then the Pt concentration and temperature dependences of those magnetocrystalline anisotropy constants are discussed.

$Co_{100-x}Pt_x$ ($x=45$, 50, and 55) single crystals were prepared by a floating zone method. The heat treatment for homogenization was carried out at 1473 K for 48 h. The alloy compositions were determined by the wavelength dispersion x-ray spectroscopy. The crystallographic orientations were determined by backreflection Laue and electron backscattering pattern methods. The specimens were cut into a cubic shape with six {001} planes. The $L1_0$-type $Co_{100-x}Pt_x$ in a single variant state was obtained by a heat treatment under uniaxial compressive stress. A compressive stress of 20–25 MPa was applied along one of the ⟨001⟩ directions in the fcc-type $Co_{100-x}Pt_x$. The lattice constants c and a, and the axial ratio c/a for $L1_0$-type $Co_{100-x}Pt_x$ single crystals were investigated using a four-axes x-ray diffractometer. The magnetization curves up to 140 kOe were measured with an Oxford MagLabVSM system in the temperature range from 10 to 298 K.

For the cubic shape specimens, the crystallographic misorientations are less than ±2°. In the x-ray diffraction patterns for $L1_0$-type $Co_{100-x}Pt_x$ with the scattering vector par-

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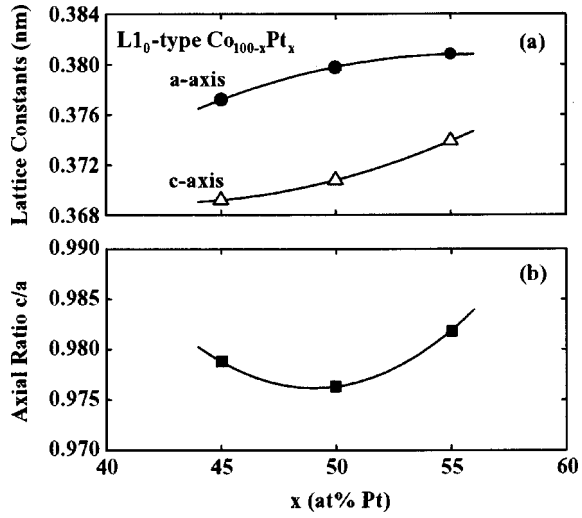

FIG. 1. Lattice constants c, a and the axial ratio c/a as a function of Pt concentration for $L1_0$-type $Co_{100-x}Pt_x$ single crystals.

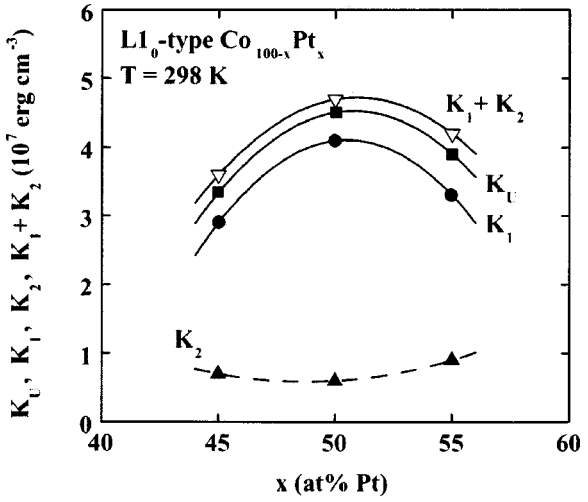

FIG. 3. Pt concentration dependence of the second and fourth anisotropy constants K_1 and K_2, together with the uniaxial magnetocrystalline anisotropy constant K_U.

allel to the c axis, the 001 and 003 superlattice diffractions as well as the 002 and 004 fundamental diffractions were observed, indicating that the c axis is uniaxially aligned. Since the integrated intensity ratio $I_{200}/I_{002} \approx 0$, the formation of the single variant state in $L1_0$-type $Co_{100-x}Pt_x$ is achieved. The lattice constants a and c, and the axial ratio c/a for the $L1_0$-type $Co_{100-x}Pt_x$ single crystals are plotted in Figs. 1(a) and 1(b), respectively. Both the a and c axes elongate with increasing Pt concentration, whereas the axial ratio c/a has a minimum value of 0.976 at $x=50$, resulting in the largest tetragonal distortion.

Figure 2 shows the magnetization curves at 298 K along the c and a axes for the $L1_0$-type $Co_{50}Pt_{50}$ single crystal. A marked difference between the magnetization curves along the c and a axes is observed. The magnetization curve along the c axis is immediately saturated under an effective magnetic field of less than 10^3 Oe. In contrast, a very high magnetic field is necessary for saturation along the a axis. The coercive force H_c observed in the magnetization curves along the c and a axes are, respectively, about 400 and 800 Oe, much smaller than that in the multivariant $L1_0$-type CoPt alloys.[15–17] These facts imply that less pinning sites for the domain wall displacement exist in the single variant, compared with multivariant samples. The magnetocrystalline

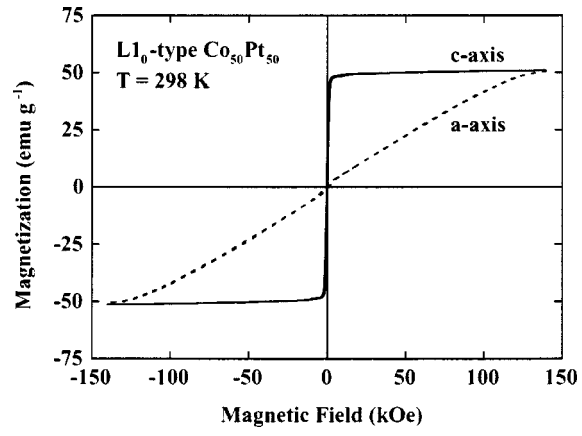

FIG. 2. Magnetization curves at 298 K for $L1_0$-type $Co_{50}Pt_{50}$ single crystal. The solid and dashed curves represent the values measured along c and a axes, respectively.

anisotropy within the c plane is weak; hardly any difference was observed between the magnetization curves along the a axis and the [110] directions.

The second- and fourth-order magnetocrystalline anisotropy constants K_1 and K_2, and the value of K_1+K_2 together with K_U for $L1_0$-type $Co_{100-x}Pt_x$ single crystals are plotted as a function of Pt concentration in Fig. 3. For determining those constants, the shape anisotropy energy is taken into account as the demagnetization energy. The uniaxial magnetocrystalline anisotropy constant K_U at 298 K exhibits the largest value of 4.5×10^7 erg cm^{-3} for $x=50$. The fourth-order magnetocrystalline anisotropy constant K_2 is much smaller than K_1, being 0.6×10^7 erg cm^{-3} at $x=50$. The value of K_1 has a maximum value of 4.1×10^7 erg cm^{-3} for $x=50$, giving $K_1+K_2=4.7\times10^7$ erg cm^{-3} for $x=50$ at 298 K. The slight difference between K_1+K_2 and K_U would be caused by the contribution from domain walls included in Eq. (1) under the low magnetic fields. In general, the magnetization process under low magnetic fields is dominated by magnetic domain wall displacements. Since the ST method is premised on the coherent magnetization rotation in the single magnetic domain state, the quantitative accuracy for the evaluated values of K_1 and K_2 decreases when domain walls exist under such low magnetic fields. In the present investigation, the linear relation between M^2 and H_{eff}/M in Eq. (2) was confirmed under the magnetic fields of more than 50 kOe. The reliability of the present data obtained from the ST method should be higher than that of the results reported previously because the magnetization along the a axis was measured up to much higher magnetic fields as shown in Fig. 2.

The present data on the magnetocrystalline anisotropy constants are listed in Table I, together with available experimental and theoretical results. Some differences between the values reported previously and the present data are observed. Two kinds of values[6,8] evaluated by torque measurement and singular point detection (SPD) techniques are different from the present values of K_1+K_2 and K_1+2K_2, which are calculated to be 4.7 and 5.3×10^7 erg cm^{-3}, respectively. Both values[7,9] of second-order anisotropy constants are overestimated. The second-order magnetocrystalline anisotropy constant K_1 evaluated from the ST method for the $L1_0$-type $Co_{100-x}Pt_x$ single crystal[9] is also apparently overestimated

TABLE I. Uniaxial magnetocrystalline anisotropy constant K_U, the second- and fourth-order anisotropy constant K_1 and K_2 at 298 and 0 K for $L1_0$-type $Co_{50}Pt_{50}$ in a single variant state, together with available experimental (Refs. 6–10) and theoretical (Refs. 12–14) values of the magnetocrystalline anisotropy constants for $L1_0$-type CoPt alloys.

at. % Pt	Anisotropy constant (10^7 erg cm^{-3})		Temperature (K)	Remark	Reference
		4.5	298	Single variant state	
50	K_U	6.5	0	Integration up to 140 kOe	Present data
		4.1	298	Single variant state	
50	K_1	6.0	0	ST method up to 140 kOe	Present data
		0.6	298	Single variant state	
50	K_2	0.7	0	ST method up to 140 kOe	Present data
				Multivariant state	
49.5	K_1	4.9	RT	Torque curves under 27 kOe	7
				Multivariant state	
50	K_1+2K_2	4.3	298	SPD technique up to 15 kOe	8
				Multivariant state	
				Magnetization and torque	
50	K_1	5.08	RT	curves under 19.1 kOe	9
				Single variant state	
45	K_1	4.8	300	ST method up to 30 kOe	10
				Multivariant state	
				Magnetization and torque	
52	K_1+K_2	1.72	298	curves under 15 kOe	6
				Firstprinciples calculation	
50	K_U	9.0	0	LMTO-ASA	12
				First principles calculation	
50	K_U	9.0	0	LMTO-ASA	13
				First principles calculation	
50	K_1	6.9	0	LMTO-ASA	14

(see Pt concentration dependence of K_1 given in Fig. 3).

From the temperature dependencies of K_U and K_1, the values of K_U and K_1 at 0 K are extrapolated to be 6.5 and 6.0×10^7 erg cm^{-3}. The theoretical values of K_1 at 0 K obtained by the first principles calculations based on the linear-muffin-tin orbital method with the atomic-sphere-approximation are also listed in Table I. Compared with the present experimental values, the theoretical values in Refs. 12 and 13 are about twice as large. On the other hand, the theoretical value of K_1 (Ref. 14) is close to the present data, although the difference in the MAE between the *a* axis and the [110] direction is larger than that estimated from the present magnetization measurements. The calculated fourth-order anisotropy constant K_2 (Ref. 14) is one order of magnitude larger than the present experimental result. The disagreement among the calculated values could be caused by the difference in the radii of the atomic spheres, axial ratio, and numerical details in the calculations.

In conclusion, the lattice parameters and magnetocrystalline anisotropy constants are investigated for $L1_0$-type $Co_{100-x}Pt_x$ single crystals prepared under a compressive stress. The lattice constants along both the *a* and *c* axes increase with increasing *x*, whereas the axial ratio c/a becomes minimum at $x=50$. The magnetization along the *a* axis is completely saturated under the magnetic field of 140 kOe for $L1_0$-type $Co_{100-x}Pt_x$ single crystals. The uniaxial magnetocrystalline anisotropy constant K_U are directly obtained from the magnetization curve. The values of the second- and fourth-order magnetocrystalline anisotropy constants K_1 and K_2 determined by the Sucksmith–Thompson method at 298 K from the magnetization curve along *a* axis under 140 kOe for $x=50$ become 4.1 and 0.6×10^7 erg cm^{-3}, respectively. The extrapolated K_1 to 0 K is consistent with the theoretical value. The value of K_1+K_2 becomes maximum at $x=50$, associated with a high uniaxial symmetry.

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