



Research articles

Assessment of Co-Ga alloys magnetostriction



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ABSTRACT

The magnetostriction of Co-Ga alloys: Co-14Ga, Co-24Ga and Co-33Ga (atomic), is studied at room temperature for the first time. All three alloys are ferromagnetic. Co-14Ga microstructure is biphasic, a mixture of ϵ (hcp) and α (fcc) phases. Co-24Ga presents three phases ϵ , α and β (ordered bcc) and Co-33Ga is single β phase alloy. It was found that all three alloys present negative saturation magnetostriction λ_s . The most interesting material for applications would be the alloy Co-33Ga since the magnetostriction saturates for a small field.

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1. Introduction

The magnetostriction λ is the deformation of a ferromagnetic material submitted to a magnetic field at constant temperature. The magnetic field exerts a pressure over the magnetic moments that tend to align in the direction of the field and causing a change in the material magnetization. This change of the specimen magnetization can cause the material expansion or contraction in a given direction. The type of deformation depends on the direction of the field as well as the magnetic anisotropy of the material. The application of mechanical stresses to the material can also change the magnetization and consequently its magnetostriction and this is a consequence of the coupling between the crystal lattice and the magnetization called magnetomechanical coupling. On the other hand, the intensity of the magnetomechanical coupling depends on the intensity of the spin-orbit coupling and also on the crystal field. Therefore, magnetostrictive materials with high magnetomechanical coupling can be used to construct, for example, force sensors and/or actuators and they are normally described as piezomagnetic materials. A typical curve of magnetostriction as a function of magnetic field, λ vs H , shows an almost linear change as the field is increased up to a field H_s , the saturation field. Beyond H_s , the curve saturates reaching a constant value as the field continues to be increased. The saturation corresponds to the point where all magnetic moments are aligned in the direction of the field. For

application as sensor or actuator, the value of $d = d\lambda/dH$, called sensibility, should be as high as possible. This can be achieved by having high values of saturated magnetostriction and as low as possible values of H_s . Desirable values of d are greater than 1 nm/A or 1 ppm/(kA/m) [1]. The low values of H_s are also necessary to warrant small sizes of the sensor or actuator, such that only small coils are necessary to produce the magnetic field to magnetize the material. Materials with low magnetic anisotropy have small values of H_s . In general, materials with cubic structures have lower magnetic anisotropy than with uniaxial structures.

The addition of gallium to iron and nickel results in materials with interesting magnetic properties, especially magnetostriction, but Co-Ga alloys magnetostriction was not studied so far. Gallium added to iron, in particular the alloy $\text{Fe}_{81.6}\text{Ga}_{18.4}$ (at.%), presents high saturation magnetostriction (λ_s) values in low fields and also good mechanical properties. The magnetostriction of a single crystal in the crystallographic direction [100] is about 400 ppm [2], while for a polycrystalline sample is about 90 ppm [3]. For comparison, pure iron single crystal shows $\lambda_s = 20$ ppm. The alloy $\text{Fe}_{81.6}\text{Ga}_{18.4}$ microstructure is formed of bcc phases: $\text{Fe}(\text{Ga})$ - α with A2 disordered structure plus Fe_3Ga and/or FeGa with ordered structures D03 and B2 respectively [4]. All the cubic phases are ferromagnetic and present appreciable magnetostriction at lower fields [5]. On the other hand, Ni-Ga Heusler alloys are famous to exhibit Magnetic Shape Memory property, especially with the substitution of gallium by manganese. However the deformation under magnetic field of this material is due to martensitic twinned phase movement instead of an intrinsic magnetostrictive phenomenon [6].

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Reviewing some properties of pure cobalt, the Curie temperature is 1125 °C. The hexagonal crystal structure (hcp, ϵ Co phase) is stable below ~ 417 °C and above an structural change to fcc α Co phase occurs [7]. The ϵ Co phase quasi saturated magnetic polarization value of 1.48 T is obtained for a magnetic field of 775 kA/m (0.97 T) at room temperature and the maximum longitudinal magnetostriction of a polycrystalline sample of Co was measured to be -45 ppm near this field. The dependence of the magnetostriction on field is just about linear and unsaturated for this field strength [8,9]. This non saturate state is a signature of high magnetic anisotropy, typical of materials with uniaxial anisotropy. Moreover, fcc metastable α Co phase at room temperature was also studied and a quasi saturated magnetization of 1.65 T was obtained at a field 1.5 T [10]. Both phases have a high magnetic anisotropy.

With respect to Co-Ga alloys, a few data was found in the literature. Studies on the substitution of cobalt by gallium show that up to 45 at.% of gallium, the alloy is ferromagnetic at room temperature. From the equilibrium phase diagram showed in Fig. 1. Co-Ga alloys with gallium concentrations lower than 14% presents the same phases of pure cobalt, hcp ϵ Co(Ga) phase with structure A3 below 422 °C and above the phase fcc, α Co(Ga) with structure A1. In the range of $33 < \text{at.\% Ga} < 57$ (43–67% of Co) exists only the single bcc ordered phase β with structure B2. In the intermediate range $13 < \text{at.\% Ga} < 33$ there is the coexistence of phases of low Ga content ϵ Co(Ga) and/or α Co(Ga) and the cubic phase β of higher Ga content [7]. The alloys with pure cubic phase β are interesting because they should have lower anisotropy compared to α Co and ϵ Co phases, therefore should saturate for lower fields and are more suitable for applications. In addition, the Curie temperature is sufficiently high for application. The Curie temperature T_C of Co-Ga alloys with 60 at.% Co is ~ 228 K [11] and with the increasing of cobalt content is estimated to be ~ 540 °C for 66% of Co (34% Ga). In the range of existence of the B2 phase, studies using experimental diffuse neutron scattering associated to magnetic properties revealed the presence of superparamagnetism at Co concentrations lower than $\sim 56\%$ Co in rapidly cooled samples. For $x^{\text{Co}} > 56\%$ there is coexistence of ferromagnetic and superparamagnetic phases [8,9]. Following

studies in [12], the authors concluded that T_C and saturation magnetization depends on the square of the excess of Co compared to the B2 structure stoichiometric compound. Magnetic properties with Ga concentrations less than 18% of Co-Ga alloys as well as magnetostriction data for any composition of Co-Ga alloys were not found in the literature. Therefore, in the present work we study the magnetostriction of Co-Ga alloys at room temperature with at.% $\text{Ga} \leq 33$. In the multiphase region a concentration of 24 at.% of Ga was select, which should result in an equal atomic fraction of phases ϵ and/or α plus β identified here as Co-24 Ga. In the extremes of the interval the chosen compositions of Ga is 14 at.% (ϵ Co or α Co) and 33 at.% (β) named as Co-14 Ga and Co-33 Ga, respectively. Besides the purpose of given a contribution by setting up data still missing in the literature on magnetic properties of Co-Ga alloys, the study of the magnetostriction of materials with the cubic β phase is of special interest due to the expected lower magnetic anisotropy and consequently lower saturation fields.

2. Methodology

The purity of cobalt and gallium used for sample preparation is minimum 99.99%. Samples of about 4 g were arc melted under argon atmosphere and cooled in a copper crucible.

The measurement of the phases present on Co-Ga alloys was made using X-ray powder diffraction (DRX) using Cu K- α radiation. The identification and quantitative determination of the phases present on the analyzed samples was made by using the phase's standard diffraction patterns [13] and Powder Cell – PCW program [14].

The microstructure was observed using scanning electron microscopy (SEM) in the mode of backscattered electrons, using a voltage of 20 kV. In addition, the chemical composition analysis was made using energy dispersive spectroscopy (EDS). For this purpose, the samples were prepared by using conventional metallographic preparation.

Magnetostriction measurements were made using a capacitive microdilatometer at room temperature and fields up to 1.1 T placed in a LakeShore Cryotonic® Electromagnet. The samples were cuboids having edges dimensions close to 2.5 mm. The magnetostriction was measured with the magnetic field applied along and perpendicular to the direction of the strain measurement, longitudinal λ_{long} and transverse λ_{trans} magnetostrictions, respectively. Magnetization measurements as a function of the applied field up to fields of 2.5 T were made using a PPMS-VSM Quantum Design Platform from Quantum Design.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the micrographs of the as cast Co-14Ga, Co-24Ga and Co-33Ga alloys. The EDS measurements confirmed the nominal compositions of the alloys with a relative deviation of less than 2%. The microstructures of the alloys Co-14Ga and Co-24Ga appear to present two phases while the alloy Co-33Ga is single phase. In the sample Co-24Ga the discontinuous phase is the phase β .

DRX results of Co-14Ga, Co-24Ga and Co-33Ga alloys powders are shown in Fig. 3. In the sample of the alloy Co-14Ga was identified the presence of phases α Co (A1) and ϵ Co (A3). However the sample with $x = 24$ presents phases α Co, ϵ Co and β and therefore has three and not two phases as give the impression from the microscopy analysis. From the equilibrium phase diagram, only the two phases were expected, but the samples are as cast sample, therefore out of equilibrium and a 3rd phase is observed. Finally, the alloy Co-33Ga has only the β phase (B2).

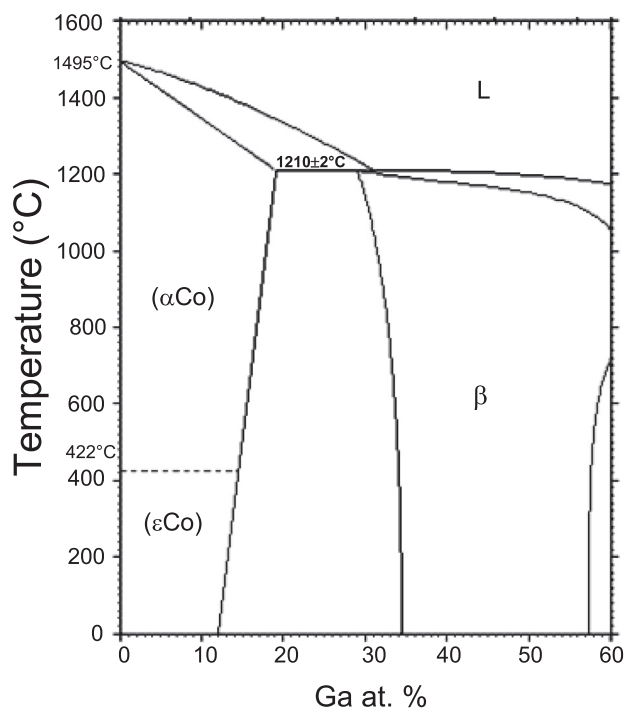


Fig. 1. Co-Ga phase diagram adapted from [1].

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