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Raj Master

Manfred Wuttig
Missouri University of Science and Technology

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MAGNETOSTRICTIVE AFTEREFFECT IN A DILUTE 50Fe-50Ni-C ALLOY*†

Raj Master and M. Wuttig
Department of Metallurgical Engineering
University of Missouri-Rolla
Rolla, Missouri 65401

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Introduction

The specific free energy of a homogeneous strained ferromagnetic crystal at constant temperature containing a point defect is given in the harmonic approximation by (1,2)

$$F = F_o + \tfrac{1}{2} C_{ijk\ell} e_{ij} e_{k\ell} + B_{ijk\ell} e_{ij} \alpha_k \alpha_\ell + K_{ijk\ell} \alpha_i \alpha_j \alpha_k \alpha_\ell + \sigma^{(m)}_{ij} e_{ij} c^{(m)} + H^{(m)}_{ij} \alpha_i \alpha_j c^{(m)} + \tfrac{1}{2} n_M kT \, c^{(m)} c^{(m)} \quad (1)$$

if defect reactions are neglected. In Eq. (1), standard notation has been used. The first four terms represent the free energy of the unstrained crystal and the strain, magnetoelastic and magnetocrystalline energies of the defect free crystal, respectively. The remaining terms contain the contribution of the defects. The quantities $c^{(m)}$ denote the excess defect concentrations in the crystallographically equivalent m-sites of which n_M are energetically different. The defect property tensors σ and H represent the stress and anisotropy fields per defect. The magnitude of their components can be obtained from anelastic studies(3) which yield $|\sigma|$ or through investigations of the induced magnetic anistropy(2) yielding $|H|$. A rough estimation of $|H|$ is also possible through stabilization field or disaccommodation measurements(4). Neither of these studies, however, yields the sign of the defect property tensor components. The sign can be obtained from indirect evidence such as the structure of ordered defect phases or, if the components of one property tensor are known, the sign of the components of the other property tensor can be obtained from a study of the magnetostrictive aftereffects(5). Such a study has been performed on bcc Fe-C and Fe-N alloys. In

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these alloys the magnetostrictive aftereffect due to the reorientation of interstitials is negative. An analysis shows that the sign of H is negative and $|H|>|\sigma|$ signifying that the interstitials prefer smaller sites(6). It is the purpose of this paper to present the results of a study on the magnetostrictive aftereffect due to the redistribution of carbon interstitials in one Fe-Ni-C alloy. It will be seen that the sign of the aftereffect is positive in this case.

Experimental Details and Results

The investigation consisted of the preparation of pseudo single crystalline Fe-Ni-C alloys and the measurement of their dimensional changes upon changing the direction of the spontaneous magnetization in the temperature range around 130°C.

Disk shaped samples of Fe-Ni-C, 0.25 inches in diameter and 0.006 inches thick, were prepared from cold rolled 50Fe-50Ni stock* (unannealed Isoperm). These samples were carburized by packing in graphite at about 200 microns of air and annealing at 1000°C sufficiently long to insure a homogeneous carbon distribution. The carbon content was found by weighing to be 0.23 wt% which agrees sstisfactorily with the Fe-Ni-C equilibrium diagram(7). During carburization, a pronounced (001)[100] recrystallization texture developed as evidenced by subsequent x-ray analysis. Before being used for aftereffect measurements, the samples were annealed for 15 hours at 215°C to obtain a specific point defect configuration as will be discussed below.

A differential strain gauge technique was applied to measure the magnetostrictive aftereffect directly(6). In this technique four matched strain gauges are attached to the sample pairwise parallel and perpendicular to each other and in the desired "crystallographic directions". The gauges form a Wheatstone bridge and are interconnected such that homogeneous sample deformations do not unbalance the bridge. The temperature coefficient of the gauges was about the same as the coefficient of thermal expansion of the base Isoperm. The average sample temperature was controlled to within 0.1 degrees. All these provisions insured that the long time stability of the overall system measured in terms of strain was better than 10^{-8}.

A permanent magnet supplying a reasonably homogeneous field at the position of the sample (10^3 $Acm^{-1}\pm5\%$) was used to fix the direction of the spontaneous magnetization parallel to the plane of the disk. Since the anisotropy field of Isoperm(8) is about 5 Acm^{-1} and the demagnetization factor of the sample in the field direction is approximately 10^{-2}, the strength of the magnetic field was sufficient for the present purposes.

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*kindly supplied by Carpenter Technology Corporation

The actual experiment consisted of equilibrating the sample at a given temperature and direction of magnetization and the subsequent observation of the magnetostrictive aftereffect after the direction of magnetization had changed. The result of a typical experiment carried out at 140°C is shown in Fig. 1. In this case, the gauges were mounted in [110] type directions. It can be seen that a sizeable aftereffect is observed, and that the sample expanded in the direction of the magnetization. The data in Fig. 1 are not corrected for the form effect as it is negligibly small for the present samples. A positive [100] aftereffect was also observed but its magnitude was much smaller than the [110] effect shown in Fig. 1. No magnetostrictive aftereffect was found in the temperature range of interest in uncarburized but recrystallized Isoperm.

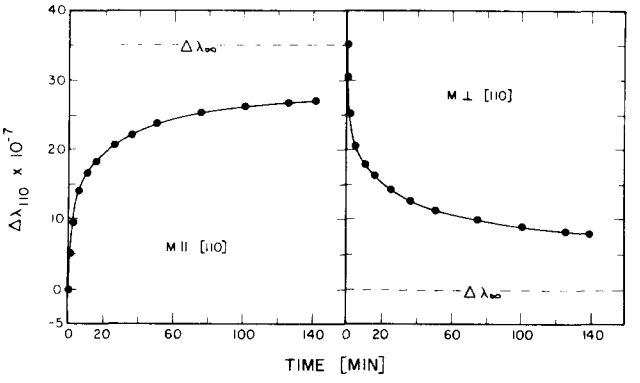

FIG. 1
Magnetostrictive aftereffect $\Delta\lambda_{110}$ of a 50Fe-50Ni-0.23C alloy, measured at 140°C

The kinetics of the aftereffect do not conform to simple exponentials. An analysis of the temperature dependence of the effective relaxation time yielded an activation energy of the process giving rise to the magnetostrictive aftereffect of 29 kcal $mole^{-1}$ confirming a previous observation(9).

Discussion

The present study was guided in such a way that the same defect configuration responsible for the disaccommodation and stabilization in dilute Isoperm carbon alloys gave rise to the magnetostrictive aftereffect. This configuration has been identified to be a mixture of [100] and [111] tetragonal and [100] and [110] orthorhomic Fe-Ni-C point defects(9). This defect mixture will give rise to magnetostrictive aftereffects in all crystallographic directions. The magnitude of the aftereffect in any specific direction will depend on the magnitude of the defect property tensors and the relative concentration of the various types of point defects. Both of these features are qualitatively inherent in a [110] type orthorhombic defect. Since this defect, shown in Fig. 2, also reflects the average iron-nickel concentration, this discussion will be couched in terms of its properties. Such a conceptual approximation is further justified by the fact

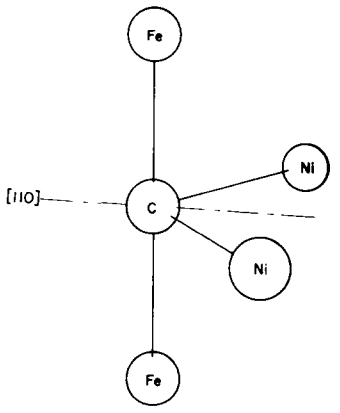

FIG. 2
[110] orthorhombic defect in a 50Fe-50Ni-C alloy

that only certain general features of the defect were to be extracted from the data of the experiment described above.

The magnitude of the magnetostrictive aftereffect is obtained by minimizing the free energy given by Eq. (1) with respect to the strains and excess defect concentrations. The result for the effect in the [110] direction, $\Delta\lambda_{110}$, is

$$\Delta\lambda_{110} = \frac{1}{16kT}\left[\frac{3\sigma_1 H_1}{C_{11}-C_{12}} + \frac{8\sigma_2 H_2}{C_{44}}\right] \tag{2}$$

if the difference between the unrelaxed and relaxed elastic stiffness constants is neglected. In Eq. (2) the quantities σ_1 and H_1 represent the defect planar stress and anisotropy fields of the [110] orthorhombic defect and σ_2 and H_2 denote the shear component of the defect fields. For the purpose of this discussion, they denote the effective field components of the defect mixture.

From Eq. (2) it can be seen that the sign of the magnetostrictive aftereffect $\Delta\lambda_{110}$ can be both positive or negative depending on the signs and magnitudes of the two principle components of the two defect fields. The experimental results, sgn $(\Delta\lambda_{110})$ = sgn $(\Delta\lambda_{100})$ and $|\Delta\lambda_{110}|>|\Delta\lambda_{100}|$, thus indicate that the signs of the products $\sigma_1 H_1$ and $\sigma_2 H_2$ are positive as well. Deductions about the signs of the components σ_1, σ_2, H_1 and H_2 are only possible if assumptions are made about the nature of the defects comprising the mixture. For instance, it would appear reasonable to assume that some stress field components of individual defects are negative if they consist in part of vacancies(10). This assumption would result in corresponding negative anisotropy field components.

The magnitude of the magnetostrictive aftereffect $\Delta\lambda_{110}$ may be compared to the known magnetic anisotropy and internal friction in Fe-Ni-C alloys and their counterparts in Fe-C alloys. If details of the defect configuration are neglected for an order of magnitude estimation, it follows from Eq. (2) that

$$\Delta\lambda(\text{Fe-Ni-C}) \simeq \frac{\sigma(\text{Fe-Ni-C})}{\sigma(\text{Fe-C})} \cdot \frac{H(\text{Fe-Ni-C})}{H(\text{Fe-C})} \cdot \frac{C(\text{Fe-Ni-C})}{C(\text{Fe-C})}\,\Delta\lambda(\text{Fe-C}).$$

Using the values(3,9,11,12) $\sigma(\text{Fe-C}) \simeq 10^{11}\ \text{Jm}^{-3}$, $\sigma(\text{Fe-Ni-C}) \simeq 0.3\sigma(\text{Fe-C})$, $H(\text{Fe-C}) \simeq 6\text{x}10^{6}\text{Jm}^{-3}$, $H(\text{Fe-Ni-C}) \simeq 2\text{x}10^{6}\text{Jm}^{-3}$, $C(\text{Fe-C}) \simeq 0.008$ wt%, $\Delta\lambda(\text{Fe-C}) \simeq 10^{-6}$, $C(\text{Fe-Ni-C}) \simeq 0.2$ wt%, it is found that

$$\Delta\lambda(\text{Fe-Ni-C}) \simeq 2\text{x}10^{-6}$$

which agrees satisfactorily with the experimental value $\Delta\lambda(0)-\Delta\lambda(\infty) = 3.5\text{x}10^{-6}$ taken from Fig. 1.

The main result of the present study is the positive sign of the magnetostrictive aftereffect in dilute fcc Isoperm carbon alloys, just the opposite from the

bcc Fe-C,N cases. In the latter, the sign and magnitude of the magnetostrictive aftereffect could be used to determine directly the defect property tensor component equivalent to H_1 in Eq. (2). This is not so in Fe-Ni-C alloys with their more complicated defect structure. For their complete characterization, measure ments of the carbon induced anelasticity and magnetostrictive aftereffect in dilute Fe-Ni-C single crystals of various Ni contents would have to be made to fully complement the anisotropy data(9).

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