Direct evidence for structural origin of stress-induced magnetic anisotropy in Fe–Si–B–Nb–Cu nanocrystalline alloys

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The structural origin of magnetic anisotropy in Fe–Si–B–Nb–Cu alloys annealed under a tensile stress of 200 MPa is studied by transmission x-ray diffraction. The diffraction peak of the (310) plane, whose normal vector is parallel to the tensile direction (ribbon direction), appears at a lower angle than the one perpendicular to it by about 0.1°. This indicates that the spacing of the (310) plane normal to the tensile direction is about 0.2% larger than the one parallel to it. This is direct evidence for the structural origin of the stress-induced magnetic anisotropy of nanocrystalline soft magnetic alloys. © 2003 American Institute of Physics. [DOI: 10.1063/1.1615672]
20 min under the tensile stress. The same annealing process without a tensile stress was applied to the same samples for comparison. The details of the sample preparation method are described in Refs. 10–12.

Figure 1 shows in-plane magnetization curves of Fe$_{73.5}$Si$_{15.5}$B$_7$Nb$_3$Cu$_1$ nanocrystalline alloys parallel to the ribbon direction with and without the tensile stress. The alloys annealed under the tensile stress show a large induced magnetic anisotropy field of 3000 A/m, while the alloy annealed without the tensile stress does not show any magnetic anisotropy. Small-angle x-ray scattering (SAXS) measurements and transmission electron microscope (TEM) observations, including selected area electron diffraction (SAED), were carried out on the sample annealed under the stress to check the shape of the anisotropy and its texture. As shown in Fig. 2, SAXS, TEM, and SAED show isotropic profiles (or shapes), indicating the absence of shape anisotropy and texture as described in the previous studies.7,9

In contrast, transmission XRD profiles of the alloy annealed under the tensile stress show a clear difference between the two directions. The measurements were performed using an instrument for conventional XRD with a Mo target, incident monochromator, and solid-state detector. By offsetting the sample stage 90° from the reflection mode, we can select a diffraction vector at a certain direction in the sample plane using the conventional $\theta$–$2\theta$ scan program. The samples were mounted on a glass substrate with a thickness of 0.5 mm to keep a high reproducibility of the sample position. Figure 3 shows XRD profiles of the alloys with and without the application of the tensile stress. To obtain a high accuracy and a reasonably high intensity, we chose the (310) peak for comparison in the two directions. The peak with a diffraction vector parallel to the tensile direction appears at a lower angle than the one with a diffraction vector perpendicular to the tensile direction in the alloy annealed under the
tensile stress. The difference of the peak top position between them is 0.1° in 2θ as shown in Fig. 3(a), corresponding to the ratio of the difference in the distance of the plane, \( \Delta d = \frac{d_{\text{parallel}}^{200 \text{MPa}} - d_{\text{perpend}}^{200 \text{MPa}}}{d_{\text{perpend}}^{200 \text{MPa}}} \) of about 0.2%. In contrast, the peak positions of these two directions in the alloy, annealed without the application of the tensile stress, match each other perfectly as shown in Fig. 3(b), indicating that there is no difference in the spacing of (310) between the two directions. Although there is a small difference in the perpendicular direction between the spacing of (310) in the alloy without the field, \( d_{\text{perpend}}^{0 \text{MPa}} \), and that of the alloy annealed under the stress, \( d_{\text{perpend}}^{200 \text{MPa}} \), a much larger change occurs in the direction parallel to the ribbon direction, i.e., the tensile stress direction as shown in Fig. 4. These results show that the lattice spacing of the (310) plane is elongated by annealing under the tensile stress. This causes the distance of the Fe atoms to elongate along the direction parallel to the tensile stress. Consequently, the magnetic anisotropy will appear and the domain wall will array perpendicular to this elongated direction as shown in the previous work.\(^7\)\(^8\)\(^9\)\(^10\) Because the measured peaks are from the bcc-Fe–Si phase, the structural origin of the anisotropy is mainly in the crystalline phase, not in the amorphous phase as previously suggested by Kraus et al.\(^7\) The obtained value of the elongation parallel to the tensile stress almost agrees with the expected values based on both magnetoelastic and pair ordering models as described in the previous studies.\(^8\)\(^9\)

In summary, we have detected a clear difference in the lattice spacing of the (310) planes between the two directions in the stress annealed Fe\(_{73.5}\)Si\(_{15.5}\)B\(_{7}\)Nb\(_{3}\)Cu\(_{1}\) nanocrystalline soft magnetic alloys. Although it is not clear whether or not the detected difference is attributed to the directional pair ordered array induced by distortion or distortion by internal stress, the lattice spacing along the tensile stress is elongated in the alloy annealed under the tensile stress. No such structural anisotropy has been observed in the alloy annealed without a tensile stress. This is direct evidence for the structural origin of stress-induced magnetic anisotropy of nanocrystalline alloys.

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