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Magnetic Anisotropy in Mo-Permalloy Crystals Induced by Plane-Strain Compression

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Magnetic properties of molybdenum Permalloy single crystals have been studied in terms of the Chikazumi–Suzuki–Iwata (CSI) theory of slip-induced directional order. The crystals were deformed in a plane-strain-compression apparatus which restricts lateral spreading of the specimen. This type of deformation is similar to that of ordinary rolling. However, the operating slip systems required for analysis are more readily determined in plane-strain compression, which permits slip line observations as well as analysis of specimen shape change. In this work, 4-79 Mo-Permalloy crystals were compressed on the (110) plane and constrained to elongate in the $[\bar{1}12]$ direction. This orientation is particularly suitable for study in that slip occurs on only two systems $\{(111)[10\bar{1}]$ and $(11\bar{1})[011]\}$ and that the orientation remains stable with deformation, hence avoiding possible complications due to lattice rotation. A simple analysis based on the CSI theory predicts for this orientation a slip-induced uniaxial anisotropy with the easy axis lying between $[\bar{1}11]$ and $[\bar{1}10]$ directions on the (110) compression plane, depending on the type of ordering in the alloy. Magnetic torque measurements on disks cut from the deformed crystals indicate the presence of both long- and short-range order. The induced anisotropy energy K_u was found to increase with thickness reduction to a value of 120×10^3 erg/cm^3 after 50.5% reduction. Similar results were obtained with crystals deformed by rolling.

INTRODUCTION

IN order to test some calculations[1] based on the Chikazumi–Suzuki–Iwata (CSI) theory of slip-induced directional order,[2] we have studied the magnetic anisotropy of molybdenum Permalloy crystals subjected to plane-strain compression. For an ordered face-centered cubic alloy such as Ni_3Fe which deforms by slip on {111} planes and in ⟨110⟩ directions, the CSI theory predicts two types of behavior: (1) Provided that long-range order (only) is present, if the accumulated slip displacement on a slip plane is small compared with the size of the ordered domains, an excess of like-atom pairs (Fe–Fe and Ni–Ni) is induced along the ⟨110⟩ direction perpendicular to the slip direction; (2) if only short-range order is present, or if the slip displacement is comparable to the size of ordered domains, excess like-atom pairs are induced in all three ⟨110⟩ directions connecting neighboring slip planes, causing the slip plane normal to become the effective like-atom pair direction. These two types of behavior are designated as L.F. (long-range order and fine slip) and S.C. (short-range order and coarse slip), respectively, in the CSI theory. They can be analyzed very simply for a crystal compressed on the (110) plane and constrained to elongate only in the $[\bar{1}12]$ direction. As shown by the dashed lines of Fig. 1, the active slip systems during plane-strain compression are $(11\bar{1})[011]$ and $(111)[10\bar{1}]$, as is confirmed later. Now, it may be seen from Fig. 1 that based on the L.F. analysis, the directions of induced like-atom pairs, which have been verified as "hard" directions of magnetization in Fe–Ni alloys,[2] are aligned with $[01\bar{1}]$ and [101]. (These are the ⟨110⟩ directions perpendicular to the slip directions [011] and $[10\bar{1}]$, respectively.) Consequently, the $[\bar{1}11]$ direction, which is normal to both $[01\bar{1}]$ and [101] hard axes, becomes the induced easy direction on the (110) plane. For S.C.-type deformation, on the other hand, $[11\bar{1}]$ and [111] (slip-plane normals) become the effective like-atom-pair directions, resulting in $[\bar{1}10]$ being the easy axis on the (110) plane. Thus, depending on the contribution from each type of deformation, the predicted slip-induced easy axis on the (110) plane should be between $[\bar{1}11]$ and $[\bar{1}10]$. For quantitative calculations on this orientation, see Ref. 1.

Besides the simplicity of analysis, the $(110)[\bar{1}12]$ orientation remains stable to large degrees of deformation[3]; hence, the induced anisotropy is not complicated by lattice rotations.

RESULTS AND DISCUSSION

To test the above theoretical prediction, $(110)[\bar{1}12]$ single-crystal slabs of molybdenum Permalloy (4% Mo–17% Fe–79% Ni) were cut from a large grain in a slowly solidified ingot. The crystals were compressed in a channel formed by hardened steel blocks.[4] Besides restricting lateral flow of the specimen during compression, the test setup permits highly accurate orientation alignment even for very small crystals. By electropolishing the samples prior to deformation and lubricating the surface with 0.005-in.-thick Teflon sheets during compression, slip lines could be observed. This evidence, together with a detailed analysis of the specimen shape change,[5] confirmed the equal and symmetric

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operation of the $(11\bar{1})[011]$ and $(111)[10\bar{1}]$ slip systems. Magnetic torque measurements were made of disks cut from samples deformed to different thickness reductions; the results are shown in Fig. 2. The crystalline anisotropy is negligible in these crystals. Figure 2 shows that the induced anisotropy is uniaxial, with the easy axis aligned between $[\bar{1}11]$ and $[\bar{1}10]$ directions, as predicted by theory. The anisotropy energy

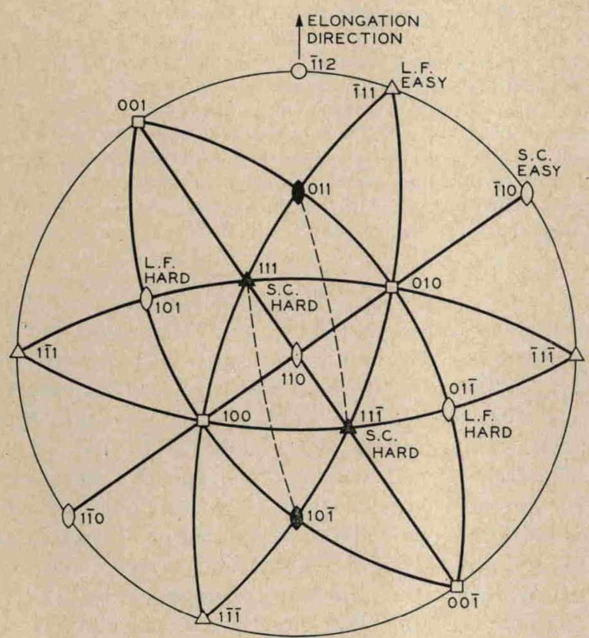

FIG. 1. (110) stereographic projection of a cubic crystal. During (110) $[\bar{1}12]$ plane-strain compression, (111) $[10\bar{1}]$ and $(11\bar{1})$ [011] slip systems become active. In L.F. deformation, $[01\bar{1}]$ and $[\bar{1}01]$, which are perpendicular to the slip directions [011] and $[10\bar{1}]$, respectively, become hard axes, resulting in $[\bar{1}11]$ being the easy axis. In S.C. deformation, the slip plane normals [111] and $[11\bar{1}]$ are hard axes, leading to $[\bar{1}10]$ as the easy axis.

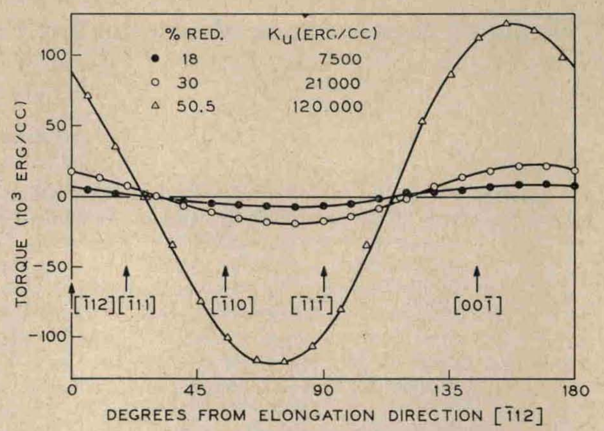

FIG. 2. Magnetic torque curves of molybdenum Permalloy crystals subjected to different reductions in plane-strain compression. Note easy direction lies between $[\bar{1}11]$ and $[\bar{1}10]$ as predicted by theory. Torque on (110) plane.

rises from a value of 7500 erg/cc after 18% reduction to a value of 120 000 erg/cc after 50.5% reduction. The fact that the easy axis lies between $[\bar{1}11]$ and $[\bar{1}10]$ rather than at either direction, implies the presence of long-range as well as short-range order in the crystals. It is hoped to alter this easy direction by deforming crystals with different degrees of long-range order initially.

Similar magnetic results were obtained by ordinary rolling instead of compression in the steel die. This is to be expected since rolling also approximates plane-strain conditions.

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