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THE RELATIONSHIP BETWEEN MICROSTRUCTURE AND MAGNETIC
PROPERTIES IN HIGH-ENERGY PERMANENT MAGNETS CHARACTERIZED BY
POLYTWINNED STRUCTURES

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I. INTRODUCTION

This research program was initially conceived to investigate the structure-property relationships in a unique family of permanent magnet alloys which exhibit a polysynthetically twinned microstructure and high magnetocrystalline anisotropies [1]. The polytwinned structures derive from the A1 (cubic) \rightarrow L1₀ (tetragonal) atomic ordering wherein the strain energy attendant to the transformation is relaxed by the formation of twin-related lamellae through mutual arrangement of crystallographic variants of the c-axis [2]. This behavior is characteristic of the Co-Pt, Fe-Pt and Fe-Pd alloy systems in the vicinity of the equiatomic composition which exhibit a high, uniaxial crystal anisotropy ($K_1 \sim 10^7$ - 10^8 ergs/cm³) with an "easy" c-axis. The twinned microstructure results in a magnetically modulated state since the easy axis of magnetization varies quasi-periodically on a scale ≈ 10 to 100 nm. The transformation twins are conjugated along the {110} planes of the fcc parent phase. A similar polytwinned state emerges in the MnAl-base permanent magnet materials; however, in these L1₀ alloys, the ferromagnetic τ -phase is metastable deriving from a hexagonal parent phase and the transformation twins lie along the {111} planes of the L1₀ unit cell [3]. In this research program, the microstructural and magnetic studies have focused on the FePd polytwinned ferromagnets. In the latter stages of the program, the work on the L1₀ FePd alloys was extended to investigation of the relationship between the structure and properties of nanostructured FePd ferromagnets, as well as preliminary studies of the deformation behavior of the L1₀ FePd intermetallic phase.

II. RESULTS

A. Magnetic Domains and Coercivity

The mechanism of formation of the polytwinned microstructure characteristic of FePd(L1₀) ferromagnets was elucidated through the definitive transmission electron microscopy work of Zhang, Lelovic, and Soffa [4] and Zhang and Soffa [5] accomplished in this research program. The stress-affected nucleation, growth, and coarsening processes giving rise to the twin-related lamellae containing a high density of APBs revealed in the electron microscopy studies are in remarkable agreement with the simulation work of L.-Q. Chen, Wang, and Khachaturyan [6]. Lorentz microscopy studies of the magnetic domains revealed for the first time the magnetic structure of these magnetically modulated twin assemblies. A modified APB pinning model was formulated to account for the levels of coercivity, including the temperature dependence of the polytwinned structure [5]. Importantly, this analysis suggested that enhanced coercivities might be achieved by markedly changing the microstructural development in these high anisotropy ferromagnets. In the work of Klemmer and Soffa [7], a combined reaction involving concomitant recrystallization and ordering was used to increase the coercivity of the FePd alloys by a factor of 2-4. The combined reaction suppresses the formation of the polytwinned structures producing a more heterogeneous array of obstacles to wall motion, which substantially changes the magnetic hysteresis behavior of these materials. Okumura, Soffa, Klemmer, and Barnard [8] have recently extended the work to studies of the relationship between structure and magnetic properties in

nanostructured FePd ferromagnets produced by high-energy ball milling and vacuum sputtering. This new work produced definitive evidence of the role of so-called "interaction domains" in magnetization reversal in fine-particle aggregates and thin films.

B. Deformation Behavior of the $L1_0$ Ordered FePd Alloy

The thermomechanical processing and studies of the combined solid state transformation developed to manipulate the structure-property relationship in the FePd ferromagnets motivated the investigation of the deformation behavior of this $L1_0$ intermetallic phase characterized by a polytwinned microstructure. This new direction also was catalyzed in part by the resurgence of interest in the development of intermetallics for high-temperature structural applications, in particular, by the attention being focused on the γ -TiAl ($L1_0$) intermetallic phase. The TiAl-base alloys depending on composition and heat treatment can develop a polysynthetically twinned microstructure similar to the FePd system; however, a different transformation mechanism gives rise to twin-related plates conjugated along the $\{111\}$ planes separated by a thin layer of the α_2 - Ti_3Al phase [9]. These microlaminated structures emerging from the FePd and TiAl intermetallics introduce a novel constraint in plastic flow and are expected to have a major influence on the plasticity and fracture behavior. Indeed, the transfer of shear across the twin interfaces through successive twin lamellae is a challenging problem from both a continuum and mechanistic point of view [10]. In this work, Rao and Soffa [11] reported the first systematic studies of plastic flow and dislocation behavior in the FePd ($L1_0$) intermetallic phase exhibiting a polytwinned microstructure.

III. SUMMARY

This research program aimed at studying the structure-property relationships in the FePd polytwinned ferromagnets has pointed to new directions for enhancing the properties of these materials in the bulk and in fine-particle and thin film applications. Lorentz microscopy revealed for the first time the magnetic domain structure which develops in conjunction with these novel microstructures, including evidence for interaction domains in ultra-fine grained materials. Preliminary studies of the deformation behavior of the L1₀ FePd intermetallic phase suggest that further studies of these alloys might contribute significantly to elucidating the flow and fracture behavior of other L1₀ systems, such as the well-known TiAl-base alloys. This research program supported four (4) Ph.D. students and one (1) Master of Science student in the Department of Materials Science and Engineering at the University of Pittsburgh.

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APPENDIX

List of major publications resulting from the support of DOE award DE-FG02-89ER45390:

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