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Gradient submicrocrystalline structure in Fe–Cr–Co system hard magnetic alloys

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ABSTRACT

The evolution of the structure and microhardness of Fe–25Cr–15Co and Fe–30Cr–8Co (number indicate wt.%) hard magnetic alloys during complex two-stage upsetting-torsion under isothermal conditions at different temperatures is experimentally studied. It is revealed that the deformation leads to a strong refinement of the initial coarse-grained structure in both alloys. The generated structure is non-uniform through the body of the samples and has gradient character. In the active zone of deformation near to the mobile head, there is a microcrystalline layer with a grain size of about 5 μm in a single phase Fe–30Cr–8Co alloy and a micro duplex structure with a grain size of about 0.5 μm in a two-phase Fe–15Co–25Cr alloy. With removal from the active zone of deformation the grain size increases, and microhardness decreases.
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1. Introduction

Submicrocrystalline (SMC) materials have attracted the attention of investigators because of a number of specific physical and mechanical properties [1,2]. Severe plastic deformation (SPD) is one of the efficient ways of producing bulk SMC materials. In particular, torsion under quasi-hydrostatic pressure at room temperature [2] allows deformation without failure of both pure metals and brittle intermetallics. In this case, a structure with a grain size of 100–200 nm is formed in plastic and low-strengthened metals and alloys. The grain size of a structure formed upon plastic deformation in intermetallics, alloys with mutually insoluble elements, and metal–metalloid alloys is equal to 10–20 nm [2,3].

Fe–15Co–25Cr and Fe–30Cr–8Co alloys (number indicate wt.%) belong to hard magnetic materials of the Fe–Cr–Co system falling into the class of precipitation-hardening alloys [4]. Magnets based on these alloys are produced both by casting and forming techniques. The formation of a high coercivity state upon spinodal decomposition leads to an abrupt decrease in the strength parameters and plasticity because of the formation of a modulated structure consisting of ordered α_1-phase precipitates coherent with the α_2 matrix. Torsion deformation under pressure at room temperature of the Fe–25Cr–15Co alloy in the high-coercivity state allowed us to substantially increase the strength parameters and plasticity of the alloy [5]. The Bridgman anvil technique, however, has one disadvantage – the produced samples have small thickness (less than 1 mm). Thus, the aim of this ongoing work consists in analyzing the structure evolution of the hard magnetic Fe–15Co–25Cr and Fe–30Cr–8Co alloys with two-phase and single-phase structures at the temperature of hot working during more complex SPD, consisting of upsetting and torsion, which enables one to produce thick bulk samples.

2. Research material and methods

The composition of the investigated alloys studied was as follows (wt.%): Fe–25Cr–15Co–1Ti–1V–0.4Si–1Al–1Nb and Fe–30Cr–8Co–0.7Ti–0.5V–0.7Si. The initial coarse-grained structure was obtained by quenching after annealing at 1200 °C. This results in the formation of α-phase (bcc) solid solution with a grain size of about 100 μm.

Samples as cylinders 12 mm in diameter and 10 mm in height were deformed at temperatures of 700, 750, 800, and 850 °C that corresponded to the two-phase $\alpha+\gamma$ (γ – fcc) state of the alloy Fe–25Cr–15Co and single α phase state of Fe–30Cr–8Co alloy. The deformation was performed using a setup that allowed the combination of various loading schemes, such as tension–torsion and torsion–compression, with the simultaneous or step by step application of these components at various temperatures and rates of deformation.

In this work, samples were subjected to two-stage deformation under isothermal conditions. At the first stage, we used upsetting

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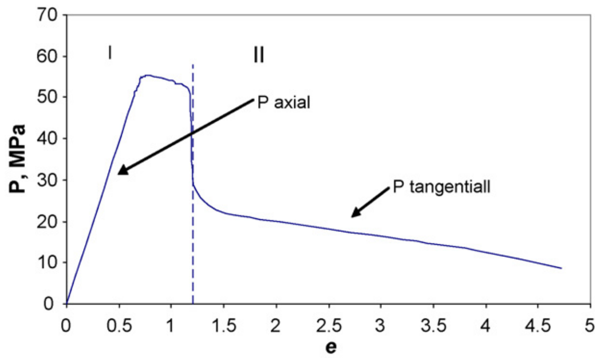

Fig. 1. Deformation curve of the Fe–30Cr–8Co alloy under complex loading at 750 °C (I – section of compression, II – torsion).

recording the axial load. At the second stage, samples were subjected to torsion deformation under constant axial pressure, while the tangential load was registered. The rate of upsetting and torsion deformation was $4 \times 10^{-3}\,s^{-1}$ and $4 \times 10^{-2}\,s^{-1}$, respectively. The total logarithmic degree of deformation was determined with allowance for the contributions of torsion e_1 and compressive deformation e_2 by Eq. (1) proposed by Degtyarev [6]

$$e = e_1 + e_2 = \ln\left(1 + \left(\frac{\varphi R}{h_{iR}}\right)^2\right)^{1/2} + \ln\left(\frac{h_o}{h_{iR}}\right) \quad (1)$$

where φ (rad) is the angle of rotation, R is the distance from the axis of rotation, h_o is the initial sample thickness, h_i is the thickness of the deformed sample at the distance R from the center. The degree of upsetting deformation is 1.2; the degree of torsion deformation determined at the distance $R/2$ from the center is 4.5.

The microstructure of samples was studied using a JXA 6400 for scanning electron microscopy (SEM) and a JEM 2000 EX for transmission electron microscopy. The microhardness was determined as a result of more than 15 measurements at a load of 1.96 N using PMT-3 tester. The measurement error determined for different samples at the same degree of deformation was less than 5%.

3. Results and discussion

Fig. 1 shows an example of dependence of the yield stress on the degree of deformation for the sample of Fe–30Cr–8Co alloy under complex loading at 750 °C. At the initial stage of loading one can see the stress growth caused by elastic deformation and then a change of the curve behavior associated with the onset of plastic yielding is observed. Torsion at stage II of loading sharply reduces working stresses, approximately by a factor of two at all temperatures of deformation. When the temperature of deformation increases from 750 up to 900 °C, there occurs a decrease in the yield stress from 55 MPa to 32 MPa. Similar deformation curves were obtained for Fe–25Cr–15Co alloy.

The deformation is found to cause the transformation of a coarse-grained structure to fine-grained structure that occurs over the sample volume. The formed structure is of gradient type in both alloys. Fig. 2 shows panoramic image and detailed images of the microstructure of the top, middle, and bottom parts of the two phase Fe–25Cr–15Co and the single phase Fe–30Cr–8Co alloys after deformation at 750 °C (the section is along the deformation axis). The deformation of Fe–25Cr–15Co was found to cause the transformation of a coarse lamellar to globular structure that occurs over the sample volume with a nanocrystalline structured layer formed in the active deformation zone near a mobile anvil.

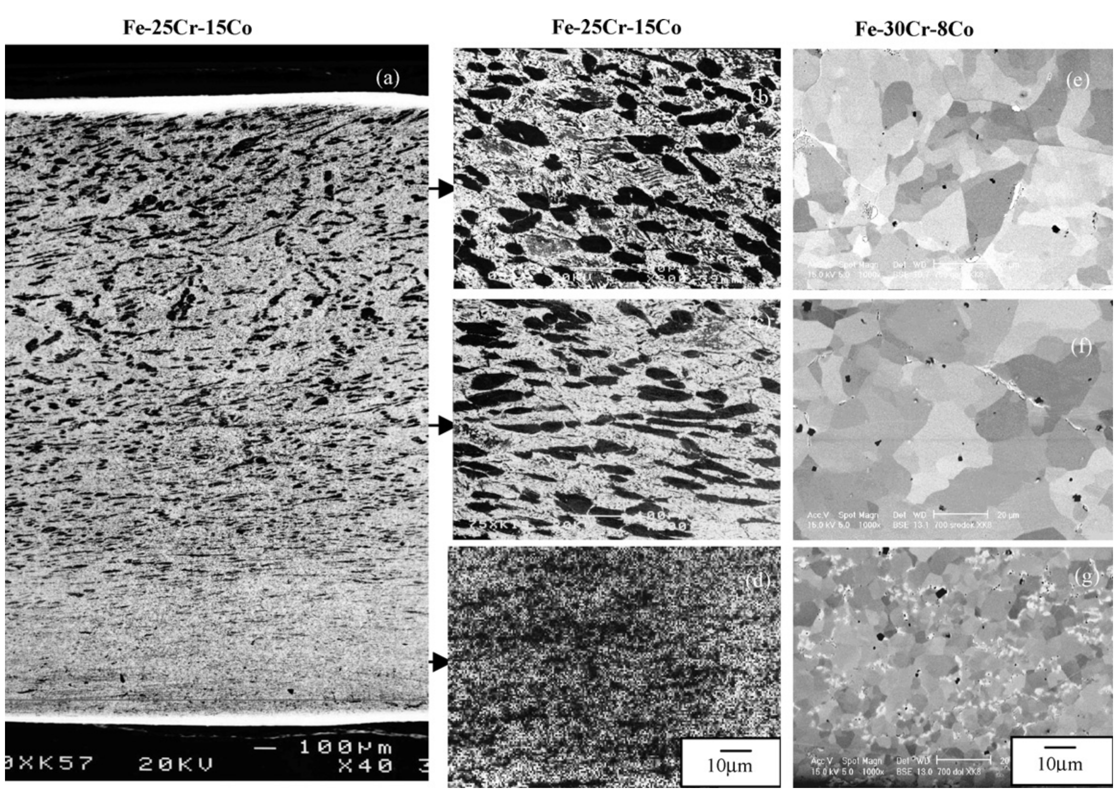

Fig. 2. (a) Panoramic SEM image of the cross-section after complex loading and optimal micrographs of (b and e) the top, (c and f) middle, and (d and g) bottom parts of (a–d) the Fe–25Cr–15Co and (e–g) Fe–30Cr–8Co samples after deformation at 750 °C.

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