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GRADIENT MICROSTRUCTURE IN $FeCr_{30}Co_8$ HARD MAGNETIC ALLOY SUBJECTED TO TENSION COMBINED WITH TORSION

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Abstract. The article presents the results of microstructure evolution studies of the $FeCr_{30}Co_8$ hard magnetic alloy, subjected to deformation by tension and torsion at 700 and 720 °C. The observations in the longitudinal section of the samples in the scanning electron microscope (SEM) showed a formation of gradient microstructure with the maximum grain refinement in the surface layer of the material. The EBSD examination confirmed the refinement of structure in the surface layer and the presence of sub-grained structure of the material. A little larger refinement of α phase grains was observed at temperature of deformation 700 °C than at 720 °C. However, the deformation was inhomogeneous along the whole longitudinal section of the sample. The highest deformation degree resulted from the torsion.

1. INTRODUCTION

The development of new generation of high-speed electrical machines in recent times requires high strength characteristics from the magnetic materials used. Most magnetic materials of today possess high magnetic characteristics but are brittle and have low ultimate rupture strength. The highest level of mechanical properties in magnetically hard materials is realized in commercial alloys of the Fe – Cr – Co system. Fe – Cr – Co based alloys belong to the deformable magnetic materials of the precipitation-hardening class [1]. Due to their good ductility in the certain structural states, excellent magnetic properties and low cost, they are used for the production of permanent magnets of various sizes and shapes, such as wire, tube, bar, strip magnets, *etc*. A high-coercive state is obtained by a magnetic treatment and multistage tempering. This leads to the decomposition of the solid α solution into the isomorphous α_1 and α_2 phases, containing ordered and coherent precipitates [1,2]. The formation of such structures, in which each precipitate of the α_1 phase is a single magnetic domain, provides superior magnetic properties. However, internal stress fields, which originate from the formation of coherent boundaries between the precipitates of the α_1 and α_2 phases, cause a reduction in plasticity and strength.

It is known that the structure of material and its mechanical properties can be changed using severe deformation techniques [3,4]. Complex loading by compression, stretching, and torsion at an elevated temperature is rather new method of severe plastic deformation [5]. It ensures a substantially refined structure without changing the shape of the specimen. Depending on the mode of the deformation chosen, this method makes it possible

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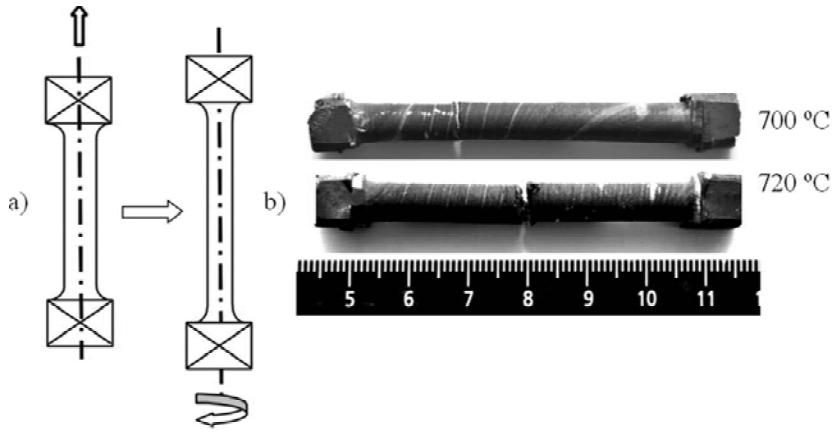

Fig. 1. Scheme of deformation of the $FeCr_{30}Co_8$ alloy by tension applied to the upper part of sample and then torsion applied to the bottom part of sample (a). The samples of the $FeCr_{30}Co_8$ alloy after deformation by tension and torsion at 700 and 720 °C (b).

to localize strain in specific regions of the perform and ensures formation of a gradient structure with different combinations of magnetic and mechanical properties in different regions [6].

The aim of the present work consisted in studying the evolution of the structure and microhardness of Fe-30Cr-8Co hard magnetic alloy during complex two-stage tension–torsion under isothermal conditions at different temperatures.

2. EXPERIMENTAL

In order to obtain a solid α solution the FeCr30Co8 alloy after casting and rolling was subjected to homogenization and water-quenched from 1200 °C. The chemical composition of the examined alloy is 27.6 wt.% Cr, 7.9 wt.% Co, 1.8 wt.% Si, 1.1 wt.% Ti, 0.2 wt.% V, balance Fe.

The FeCr30Co8 alloy was deformed with the method of complex load which allows deformation of materials without their destruction at room and at higher temperatures [5,6]. In this work, cylindrical samples, 8 mm in diameter and 44 mm of length, were deformed to destruction in two separate stages: the tension applied to the upper part of sample and then the torsion applied to the bottom part of sample (Fig. 1). The samples were subjected to tension at the rate of $6 \cdot 10^{-4}\ s^{-1}$ to obtain the deformation of 30%. Then, the samples were deformed by torsion at the rate of $8.5 \cdot 10^{-4}\ s^{-1}$ for up to 7 and 16 rotations at 700 and 720 °C, respectively. The temperature 700 and 720 °C as well as deformation rates corresponded to the superplasticity conditions of the examined alloy.

The degree of tension was calculated based on the following formula (1):

$$\varepsilon = \ln\left(l_0 / l_i\right), \tag{1}$$

where l_0 [mm] is the sample length before deformation and l_i [mm] is the sample length after deformation.

The degree of torsion was calculated based on the formula (2):

$$\varepsilon = \ln\left(1 + \left(\varphi \cdot R_i / l_i\right)^2\right)^{1/2}, \tag{2}$$

where φ [rad] is the angle of torsion deformation and R_i [mm] is the radius of the deformed sample.

The degree of tension and torsion deformation at 700 °C reached 0.22 and 0.97, respectively and 0.22 and 1.77, respectively at 720 °C.

The microstructure was examined by means of scanning electron microscopy (SEM) XL 30, Philips. The maps of orientations were measured with EBSD method for the analysis of microstructure. The EBSD analysis was carried out in the middle and at the surface of material near the place, where the sample broke. The X-ray diffraction analysis was performed at the Philips PW1710 diffractometer using Co $K\alpha$ radiation.

3. RESULTS AND DISCUSSION

The example of initial microstructure and its X-ray diffraction are presented in Fig. 2a. The grain size of á phase was about 200 μm. The X-ray analysis of the initial state showed only reflections of α solid solution (Fig. 2b).

Before the deformation, a scratch was made along the length of every sample, which became a spiral during torsion. Basing on the observation of the distribution of the spiral trace (Fig. 1b) it was

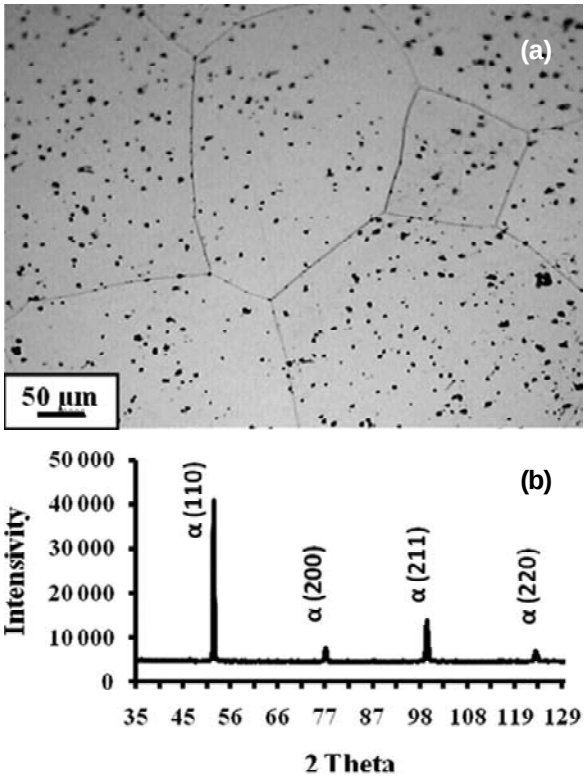

Fig. 2. Initial microstructure of the α-solid solution after homogenization at 1200 °C.

stated that at temperature 700 °C the deformation was inhomogeneous and the highest deformation occurred at the side of torsion. The elevation of the temperature by 20 °C enabled increasing the number of sample rotations up to its destruction from 7 to 16. In that case a similar spacing of the spiral thread along the sample was observed, which confirmed the homogenous deformation along the longitudinal axis of the sample.

Significant difference in plasticity detected during torsion at 700 and 720 °C may be caused with the fact that the temperature of spinodal decomposition for the composition of the alloy under study is close to 700 °C [7]. Thus partial immiscibility of solid solution at 700 °C can give rise to localization of deformation and decrease of plasticity.

The microstructure observation at the longitudinal sections of deformed samples showed the formation of microstructure of gradient type with the minimal grain size in the surface layer. According to the EBSD results, large elongated grains of α phase up to 45 μm long were observed in the middle part of the sample deformed at 700 °C, while at the surface, the grains were rounded with diameter of about 8 μm. The thickness of the surface layers with fine grains on both sample edges was about 2.5 μm compared to 7 μm of the thickness of the whole sample. The analogous situation occurred in the case of the sample deformed at 720 °C. The grain size at the surface was about 10 μm; it was about 60 μm in the centre, while the thickness of the fine-grain layer was about 2.4 μm.

The EBSD examinations revealed also the presence of sub-grain structure in the samples (Fig. 3).

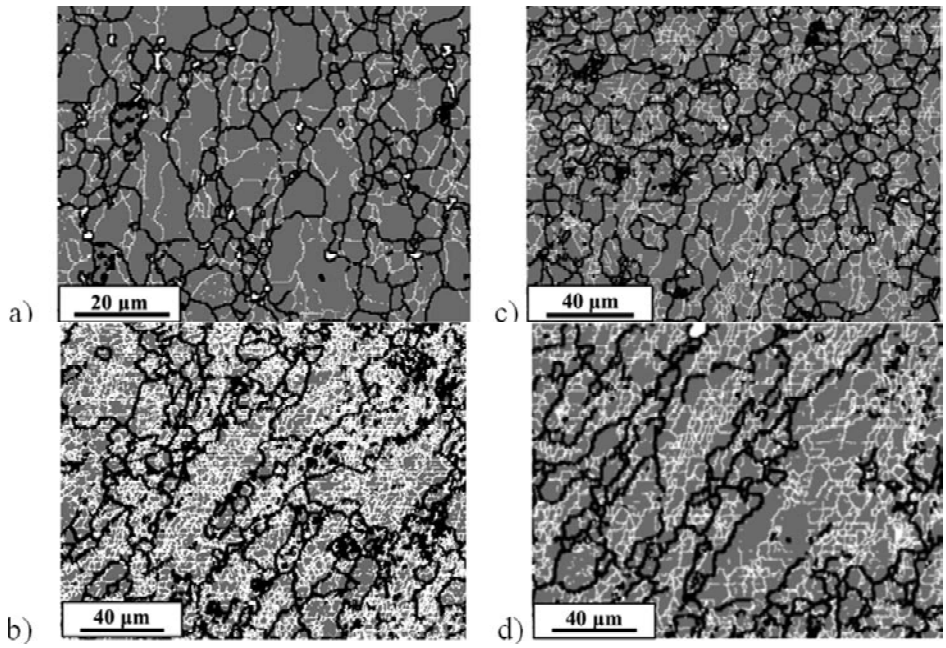

Fig. 3. Maps of phase distribution obtained at surface (a, c) and in the centre (b, d) of samples deformed at 700 (a, b) and 720 °C (c, d). The boundaries of high (disorientation angle >13.5) and low (from 1.5 to 13.5) angles are marked with thick black and thin light contours, respectively.
The α grains are colored in grey, σ phase grains in light.

The largest development of the sub-grain structure was observed in their central areas. For example, the fraction of the low-angle boundaries in the sample deformed at 700 °C was 87.6% and 65.2% in the middle and at the surface, respectively, while in that one deformed at 720 °C it was 79.1% and 70.1%.

A detailed analysis of the low angle boundaries showed, that in the sample deformed at 700 °C, the disorientation angles of subgrain boundaries were higher (up to 8 degrees) than at the edges (mostly up to 2-3 degrees), whereas during the deformation at 720 °C the disorientation angles at the edge and in the centre were similar and did not exceed 9 degrees.

It should be noticed that, together with the elongated grains of the α phase, small grains of the same phase of a round shape of 5 μm size were also observed, which could be the result of the occurrence of dynamic recrystallization. To check it, additional microstructure observations should be performed with the use of transmission electron microscopy technique.

The EBSD showed the presence of the intermetallic σ (Fe-Cr) phase in the amounts up to 3.1% and 1.5% at the surfaces of samples deformed at 700 and 720 °C, respectively.

4. SUMMARY

The deformation of $FeCr_{30}Co_8$ alloy through tension followed by torsion in the superplastic conditions resulted in the formation of gradient microstructure with refined grains in the surface layer of the material. During the deformation at 700 °C, the grain size in the surface layer became a little smaller than at 720 °C, but on the other hand the deformation of material was inhomogenous along the tension axis, which means that the most deformation originated from the torsion of the sample. The method of combined deformation may be used as a method of surface strengthening of material.

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