FORMATION OF HIGH-COERCIVITY STATE IN PLASTICALLY-DEFORMED KH33K16D2B ALLOY

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Abstract

The deformation-aging process developed by us for the alloy (wt.%) 16 Co - 33 Cr - 2 Cu - 0.5 Nb - Fe (balance) includes the (1) quenching from 1100 °C to form the single-phase α-solid solution, (2) aging resulting in the formation of spherical α_1-phase precipitates during cooling in a temperature range of 650 - 625 °C at a rate of 40 °C/h; (3) monoaxial plastic deformation with the ε = 79 % reduction of area in order to give the shape anisotropy of α_1-phase precipitates and to produce the mechanical texture, and (4) final controlled cooling from 605 °C to 540 °C at a rate of 8 °C /h, in the course of which the more complete compositional separation of strongly magnetic α_1-phase and weakly magnetic α_2-matrix precipitates is reached. The developed heat treatment allowed us to obtain the following magnetic characteristics of the Kh33K16D2B alloy: H_c = 64-64.5 kA/m, B_r = 1.02-1.1 T and $(BH)_{max}$ = 41.4 - 42.2 kJ/m^3.

Keywords: Kh33K16D2B alloy, heat treatment, plastic deformation, shape anisotropy, magnetic properties.

1. INTRODUCTION

The plastically deformed Kh33K16D2B alloy is among high-coercivity Fe-Co-Cr system alloys whose high magnetic properties are reached by deformation aging rather than the thermal magnetic treatment. This fact allows one to obtain high both H_c and $(BH)_{max}$ magnitudes [1-3]. Among dispersion-hardened alloys, compositions with relatively low Co content, in particular, Fe - (30-33) % Cr - (7-12) % Co are widely used for production of permanent magnets. The alloys demonstrate adequate manufacturing properties, whereas alloys with the higher Co content are less manufacturable and almost understood. The aim of the present study is to investigate the formation of high-coercive state in the Fe - 33 % Cr - 16 % Co, which, to improve the manufacturing properties, were alloyed with 2 % Cu and 0.5 % Nb.

2. EXPERIMENTAL PROCEDURE

The alloys were melted in an open induction furnace equipped with a neutral crucible using K0 cobalt, Kh00 chromium, electrolytic copper, niobium bars, and carbonyl iron. The weight of melt was 20 kg. The melted ingots were subjected to hot forging and rolling at 1200 - 1000 °C into rods 10×9,5 mm in section, which subsequently were used for dispersion-hardening experiments. During heat treatment, the temperature was measured and controlled with an accuracy of ± 1.5 °C. The magnetic properties were measured using a UIFI hysteresisgraph. The error of magnetic measurements did not exceed ± 3 %. The microstructure of alloys was studied with magnification of to x500 using an MMP-4 optical microscope. An electrolyte consisting of 880 ml H_3PO_4 and 120 g CrO_3 was used for the etching of sections and preparation of foils. Electron-microscopic studies were performed using a TESLA BS-540 microscope and an accelerating voltage of 120 kV.

3. RESULTS AND DISCUSSION

Studies of the microstructure of Fe - 33 % Cr - 16 % Co - 2 % Cu - 0.5 % Nb alloy, which was subjected to homogenizing annealing at 1200 - 1000 °C and subsequent water quenching, showed that, after annealing at $T_{ann} \geq 1100$ °C, the structure of the alloy consists of single-phase α-solid solution; at $T_{ann} \geq 1150$ °C, the active

grain growth starts. Taking into account the obtained data, we determined the following heat-treatment conditions of the alloy before deformation aging: annealing at 1100 °C for 10 min and subsequent water quenching. Electron-microscopic studies of the structure of Fe - 33 % Cr - 16 % Co -2 % Cu - 0.5 % Nb alloy, which was preliminarily quenched from 1100 °C and subsequently tempered at 700 - 600 °C, showed that the decomposition of the solid solution $\alpha \rightarrow \alpha_1 + \alpha_2$ starts at tempering temperatures below 670 °C. As the tempering temperature decreases, the decomposition $\alpha \rightarrow \alpha_1 + \alpha_2$ becomes more intense; the amount of the α_1-phase in the structure of alloy increases. **Fig. 1a** shows micrographs of the structure of the Fe - 33 % Cr - 16 % Co -2 % Cu - 0.5 % Nb alloy subjected to aging under different conditions.

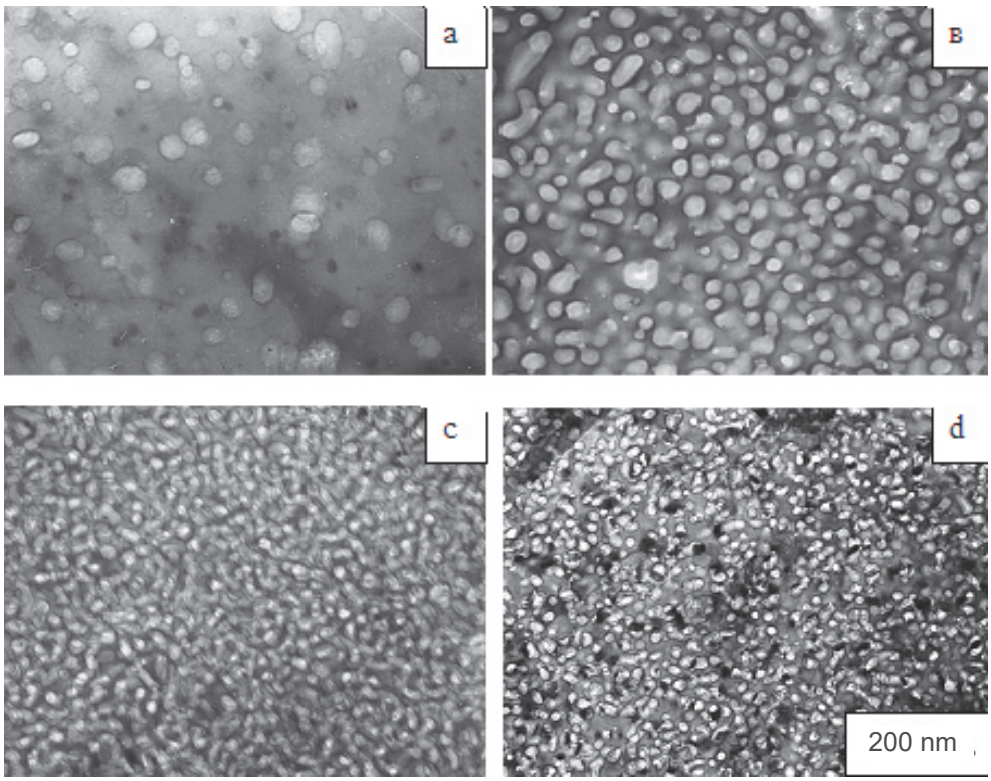

Fig. 1 Microstructure of the Fe - 33 % Cr - 16 % Co -2 % Cu - 0.5 % Nb alloy subjected to aging under different conditions: (a) tempering at 700 °C for 1 h; (b) cooling from 650 °C to 625 °C at a rate 40 °C/h; (c) cooling from 640 °C to 615 °C at a rate 20 °C/h; (d) cooling from 660 °C to 630 °C at a rate 50 °C/h

To decide the conditions of the heat treatment determining the formation of the optimum structure of products of the $\alpha \rightarrow \alpha_1 + \alpha_2$ decomposition before deformation, we compare structures obtained after isothermal heat treatment and controlled cooling in a temperature range of 660 - 615 °C. When performing the heat treatment, its both temperature and time were varied. During controlled cooling, the temperature of the onset and end of cooling and cooling rate were varied. To form the optimum $\alpha_1 + \alpha_2$ structure before deformation, the heat treatment under following conditions was used: controlled cooling from 650 °C to 625 °C at a rate of 40 °C/h. The microstructure of the alloy after such a treatment is shown in **Fig. 1b**. Almost equiaxed precipitates of the α_1 phase are observed; there are uniformly distributed over the foil field and separated from each other with the α_2 phase. As the temperature of the onset of cooling decreases and as the cooling rate decreases (**Fig. 1c**), the amount of the α_1 phase in the structure increases, the size of precipitates decreases, and the coalescence of α_1 phase precipitates and formation of elongated particles take place. On contrast, as the temperature of the onset of cooling increases and the cooling rate increases (**Fig. 1d**), the amount of the α_1 phase in the alloy structure decreases, distances between precipitates increase, and intergrown precipitates are observed. At the second stage of deformation aging, to give the shape anisotropy for equiaxed α_1 phase

precipitates and to create the texture of precipitates, samples of the alloy, which were heated to 650 °C and subsequently cooled to 625 °C at a rate 40 °C/h, were subjected to uniaxial deformation. Initially, the alloy samples were subjected to deformation in river rolls and subsequently to drawing with a total degree of reduction of area ε = 65 - 83 %. **Fig. 2a** shows the microstructure of the alloy after deformation at ε = 79 %.

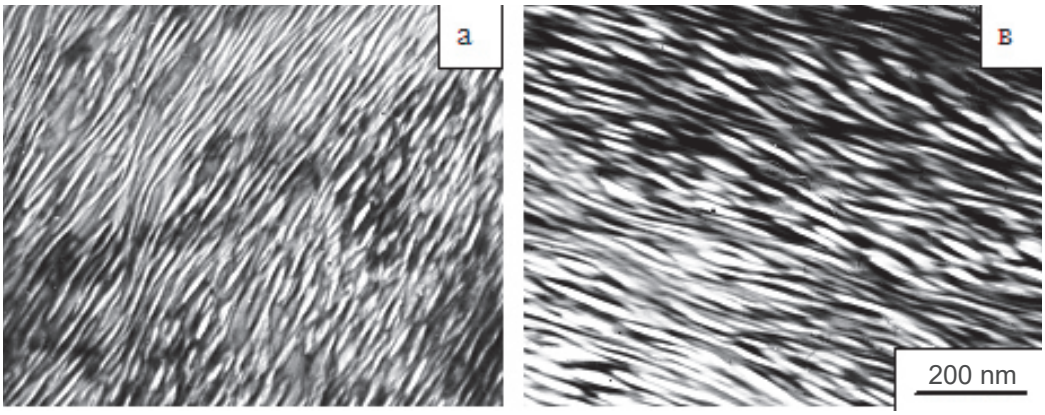

Fig. 2 Microstructure of the Fe - 33 % Cr - 16 % Co - 2 % Cu - 0.5 % Nb alloy after deformation aging: (a) cooling from 650 °C to 625 °C at a rate 40 °C/h + uniaxial deformation with ε = 79 %; (b) cooling from 650 °C to 625 °C at a rate 40 °C/h + uniaxial deformation with ε = 79 % + tempering at 605 °C for 1 h + cooling to 540 °C at a rate of 8 °C/h

As a result of realized deformation, α_1-phase precipitates become anisotropic in shape; their length-to-diameter ratio varies over wide ranges L/d = 3 - 35. Moreover, the structure of deformed alloy is characterized by slight misorientation of precipitates. The maximum coercive force of deformed alloy, which is H_c = 4 - 4.8 kA/m, was reached after deformation with ε = 75 - 79 %. The tempering of deformed samples, which includes the annealing at 605 °C for 1 h + cooling to 540 °C at a rate 8 °C/h, leads to a slight increase in the lateral size of precipitates (**Fig. 2b**) and increases the coercive force to H_c = 63.7 - 64.5 kA/m. In this case, the residual inductance is B_r = 1.02 - 1.1 T and the maximum energy production is $(BH)_{max}$ = 41.4 - 42.2 kJ/m^3. The maximum energy product that was reached for the Fe - 33 % Cr - 16 % Co - 2 % Cu - 0.5 % Nb after deformation aging exceed markedly the value $(BH)_{max}$ = 31.8 kJ/m^3 obtained for the Fe - 30 % Cr - 15 % Co - 3 % Mo - 0.5 % Ti alloy that was subjected to isothermal thermal magnetic treatment to form the high-coercivity state [4].

CONCLUSIONS

The deformation-aging process developed for the alloy (wt.%) 33 % Cr - 16 % Co - 2 % Cu - 0.5 % Nb - Fe (balance) includes the quenching from 1100 °C to form the single-phase α solid solution, aging resulting in the formation of spherical α_1-phase precipitates during cooling in a temperature range of 650 - 625 °C at a rate of 40 °C/h; monoaxial plastic deformation with the ε = 79 % reduction of area in order to give the shape anisotropy of α_1-phase precipitates and to produce the mechanical texture, and final controlled cooling from 605 °C to 540 °C at a rate of 8 °C/h, in the course of which the more complete compositional separation of strongly magnetic α_1-phase and weakly magnetic α_2-matrix precipitates is reached. The developed heat treatment allowed to obtain the following magnetic characteristics of the Kh33K16D2B alloy: H_c = 64-64.5 kA/m, B_r = 1.02-1.1 T and $(BH)_{max}$ = 41.4 - 42.2 kJ/m^3.

ACKNOWLEDGEMENTS

This study was supported by the Ministry of Educations and Science of the Russian Federation and is performed in accordance with the basic part of State Assignment no. 2014/113 for 2014.

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