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著者	岡田　益男
journal or publication title	IEEE Transactions on Magnetics
volume	23
number	5
page range	3193-3195
year	1987
URL	http://hdl.handle.net/10097/46463

IMPROVEMENTS OF THE MAGNETIC PROPERTIES OF EQUIAXED Fe-Cr-Co-Mo HARD MAGNETS BY TWO-STEP THERMOMAGNETIC TREATMENT

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ABSTRACT

Present works describe the developments of the equiaxed Fe-Cr-Co permanent magnets with high coercivity and high energy products. The studied alloy compositions are Fe-(26-32)wt%Cr-15wt%Co-3wt%Mo. The magnetic properties of the alloys have been enhanced by the two-step thermomagnetic treatment (two-step TMT) and by prolonging all of the heat-treatment time. The energy products above 43 kJm^{-3} (5.4MGOe) are obtained for almost all of the studied compositional alloys. Fe-30%Cr-15%Co-3%Mo alloy gives good magnetic properties as iHc=76.8 kAm^{-1} (960 Oe), (BH)max≈49.6 kJm^{-3} (6.2 MGOe). The highest coercivity achieved with Fe-32%Cr-15%Co-3%Mo alloy is 80.8 kAm^{-1} (1010 Oe).

INTRODUCTION

Fe-Cr-Co alloys are potential permanent magnets because of their good ductilities and magnetic properties [1]-[10], so that the alloys have been utilized for high-performance small magnet circuits, which are difficult to make with Alnico or ferrite magnets [6][7]. In general Fe-Cr-Co alloys have the coercivity of 45-54 kAm^{-1} (570-650 Oe), which is lower than that of Alnico 6 or 8 magnets. In order to expand the applications of Fe-Cr-Co alloys, the enhancement of coercivity is strongly required.

The magnetic hardening of the alloys is associated with decomposition within the miscibility gap, producing modulated structures consisting of two phases, an FeCo rich phase (α_1) and a Cr rich phase (α_2) [11]-[13]. It is generally noted that the addition of Mo to the alloys enhances the anisotropic decomposition, namely decomposing along <100> directions, and increases the coercivity [1][14]. Recently, a columnar grain structure Fe-24wt%Cr-15wt%Co-3wt%Mo alloy has the magnetic properties up to (BH)max=76 kJm^{-3} (9.5 MGOe) [15] and a <100> ridge single crystal Fe-22wt%Cr-18.5wt%Co-3wt%Mo alloy achieves the maximum energy products of 91.2 kJm^{-3} (11.4 MGOe) which is highest among the reported values so far [10]. But it requires large outlays to develop a columnar grain structure and a single crystal. Thus the purpose of this work is to design the new heat-treatment of Mo added equiaxed Fe-Cr-Co permanent magnet alloys giving high coercivity and energy products.

APPROACH

The coercivity of Fe-Cr-Co alloys arises from the shape anisotropy of α_1 phase, so the coercivity is highly affected by the morphology of α_1 particles. The optimum microstructure is such that the FeCo rich phase (α_1) with a diameter of 30 nm and an aspect ratio of over 3 is embedded in non-magnetic Cr rich phase (α_2), aligning parallel to one direction.

To achieve the high coercive force, an Fe-Cr-Co-Mo system with higher Cr contents than the conventional ones was chosen in this investigation by following reasons; (1) The Mo added alloys are apt to decompose along <100> directions, since the elastic energy of Mo added Fe-Cr-Co alloys is higher than that of the ternary alloys without Mo. So the shape anisotropy of α_1 phase is higher than one in Fe-Cr-Co alloys without Mo. (2) The coercive force increases with increasing Cr content because the packing fraction of α_1 phase decreases with increasing Cr. Then the Fe-(26-32)% Cr-15%Co-3%Mo alloys were chosen in this investigation.

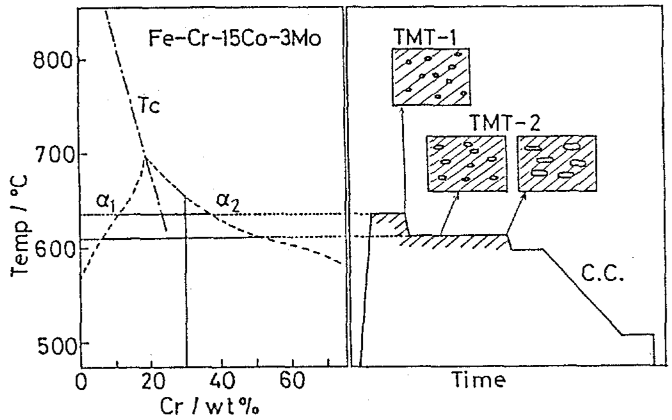

Fig. 1 Fe-Cr-15Co-3Mo phase diagram and expected two-phase structure.

The optimum heat-treatments to achive the high coercive force in Fe-Cr-15Co-3Mo polycrystalline alloys must be considered in referring to the Fig. 1. Figure 1 shows the section of the phase diagram of Fe-Cr-15%Co-3%Mo alloys and the heat-treatment diagram with expected two-phase microstructure. First of all, the new heat-tratment must be such one as α_1 particles precipitate uniformly for obtaining the optimum number and sizes, and as α_1 particles elongate along the applied field direction with suppressing the decomposition along the <100> directions. Secondly, Figure 1 gives two facts for concerning the new heat-treatment for this high Cr content alloys; (1) the temperature of miscibility gap shifts to lower one with increasing the Cr content, and (2) the difference in the composition between the α_1 phase and the α_2 phase increases at lower temperature in the same Cr content alloy. So new heat-treatment for this high Cr content Fe-Cr-Co-Mo alloys must be such one which has enough diffusion time to grow α_1 particls and to reach the equilibrium volume fraction of α_1 particles.

Then we separate the thermomagnetic treatment (TMT) into two steps and prolong its time, as shown in Fig. 1 (two-step thermomagnetic treatment: two-step TMT). At the first step (TMT-1), α_1 particles suppose to precipitate spherical and uniformly in order to controll the number of α_1 particles in final microstructure, because the temperature is relative high and the elastic energy is still low at the temperature. It is reported that the number of α_1 particles during following aging is kept almost constant [9]. At the second step (TMT-2), the temperature of which is lower than that of TMT-1, α_1 particles are made to grow and to elongate along the applied field direction with suppressing the decomposition along <100> directions. The conditions of the controlled cooling after the two-step TMT are also altered.

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The effects of two-step TMT and the controlled cooling on the magnetic properties and microstructure of Fe-30%Cr-15%Co-3%Mo alloy are studied in detail hereafter.

EXPERIMENTAL PROCEDURE

The Fe-(26-32)wt%Cr-15wt%Co-3wt%Mo alloys were chosen for this investigation. The alloys were induction melted from 99.9% electrolytic iron, 99.9% electrolytic chromium, 99.5% cobalt and 61.7% ferromolybdenum with 0.3% titanium as the carbon excluding element in argon atomosphere and cast into a cylindrical mold with an inside diameter of 25 mm. The alloys are then prepared to the diameter of 5 mm by cold-forging and swaging.

The alloys at first were solution-treated at 1200°C for 0.5h. After the solution treatment, the alloys were aged at 630-645°C for 15-25min (TMT-1) and were aged at 610-625°C for 1-6h (TMT-1) in a magnetic field of 160kAm^{-1} (2kOe). The alloys were then held at 600 or 610°C for 2h, followed by the controlled cooling at a rate of 2-8°C/h and held at 500°C for 10h.

The magnetic properties were measured with automatic flux-meter. The microstructure was observed by transmission electron microscopy (TEM).

RESULTS AND DISCUSSIONS

A. Thermomagnetic Treatment

The optimum TMT-1 conditions such as temperature and time for Fe-30%Cr-15%Co-3%Mo alloys were determined as 635°C and 20min, respectively, from the variation in the magnetic properties versus the TMT-1 conditions. If the TMT-1 temperature or time deviates 5°C or 10min from the proper condition, the magnetic properties are reduced abruptly. This is due to the fact that initial diameter of α_1 particle does affect the final microstructure and the magnetic properties.

Figure 2 shows the variation of magnetic properties of Fe-30%Cr-15%Co-3%Mo alloys versus TMT-2 conditions. The magnetic properties are not so sensitive to TMT-2 temperature as to TMT-1 temperature. So iHc is nearly constant in the range of 610°C to 620°C, but (BH)max exhibits a peak at 615°C. As the TMT-2 time is prolonged, iHc and (BH)max increase and exhibit a peak at 4h. The optimum TMT-2 conditions are decided to 615°C for 4h and the obtained magnetic properties are iHc=76.4 kAm^{-1} (955 Oe), (BH)max=43.2 kJm^{-3} (5.4 MGOe).

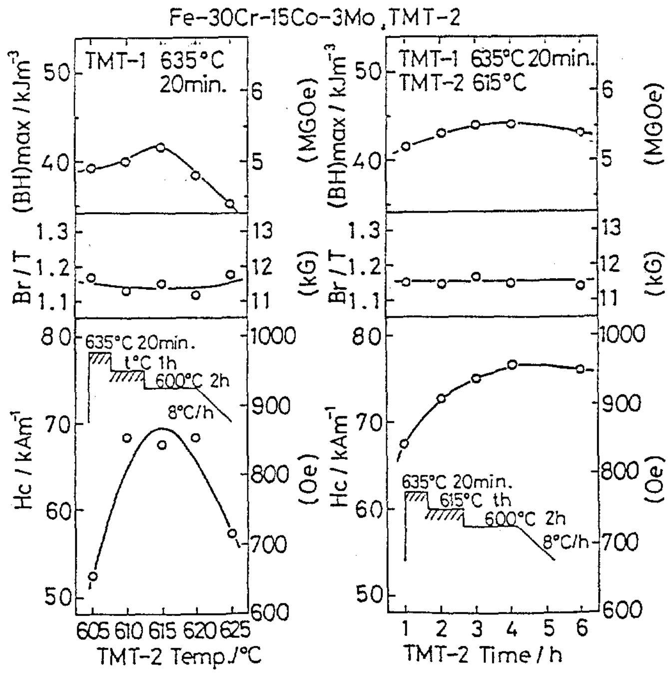

Fig. 2 The variation in magnetic properties versus TMT-2 conditions.

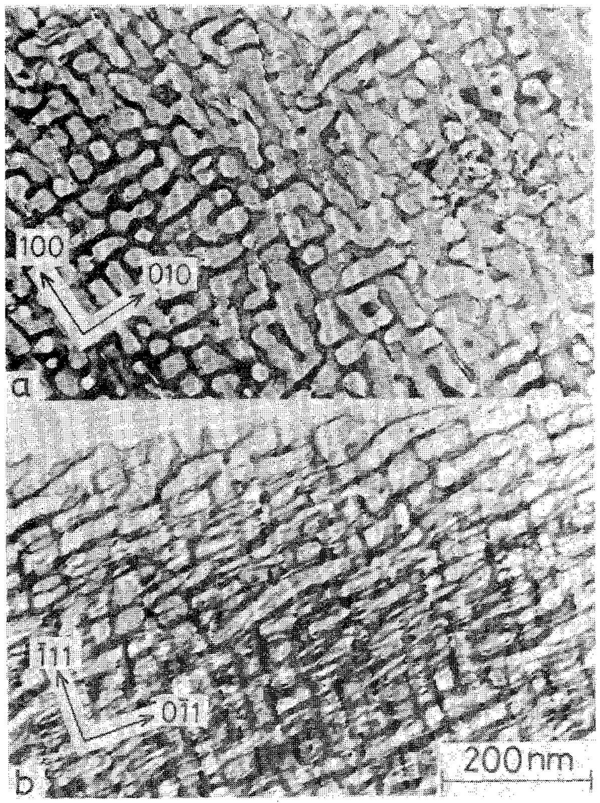

Fig. 3 The microstructures of Fe-30Cr-15Co-3Mo alloys undergone TMT-2 for (a) 1h and (b) 4h.

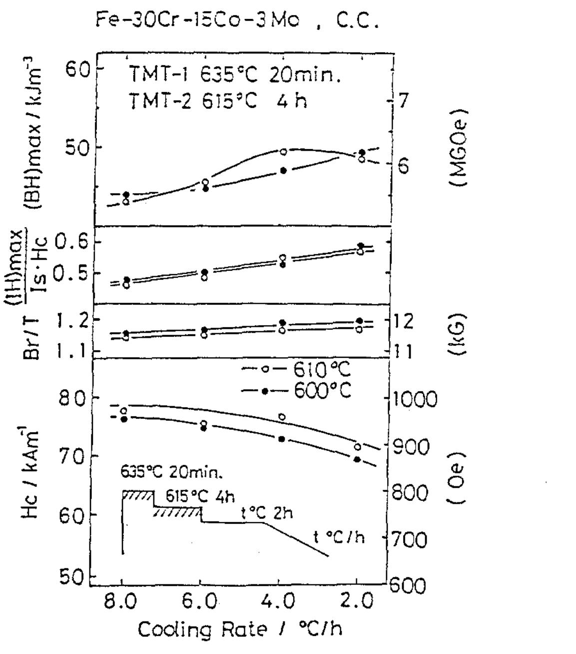

Fig. 4 The magnetic properties of Fe-30Cr-15Co-3Mo alloy versus controlled cooling rate with varying the begining temperature of controlled cooling.

The bright field micrographs of Fig. 3 show the microstructures taken from the alloy held for (a) 1h and (b) 4h at 615 ℃. The phase with bright contrast is FeCo rich phase (α_1), and the phase with dark contrast is Cr rich phase (α_2) [3][11]. The α_1 particles undergone TMT-2 for 4h are larger and longer than those undergone for 1h. It is generally noted that the coercivity mechanism of this alloys is based on the shape anisotropy, so the coercivity is closely related to molphology of the α_1 particles. It can be said that prolonging the TMT-2 time is effective in increasing the aspect ratio of α_1 particles along the applied field.

B. Controlled Cooling

Figure 4 shows the variations of magnetic properties of Fe-30%Cr-15%Co-3%Mo alloy undergone the proper two-step TMT versus the controlled cooling rate with varying the begining temperature of controlled cooling. As the controlled cooling becomes slower, the coercivity decreases and the remanence increases. The best magnetic properties obtained after cooling at a rate of 4 ℃/h from 610 ℃ are iHc=76.8 kAm^{-1} (960 Oe), (BH)max=49.6 kJm^{-3} (6.2 MGOe).

Figure 5 summarizes the magnetic properties of Fe-Cr-15%Co-3%Mo alloys versus Cr contents. The open circles exhibit the magnetic properties obtained by the conventional heat-treatment [15] and the solid circles exhibit those by two-step TMT and slow controlled cooling, respectively. The coercivity of alloys undergone two-step TMT increases monotoniously with increasing Cr contents. The highest coercivity obtained in these studies is 80.8 kAm^{-1} (1010 Oe) with Fe-32%Cr-15%Co-3%Mo alloy. The Fe-30%Cr-15%Co-3%Mo alloy gives good magnetic properties as iHc= 76.8 kAm^{-1} (960 Oe), (BH)max= 49.6kJm^{-3} (6.2 MGOe). The energy products above 43 kJm^{-3} (5.4 MGOe) are attained for almost all of studied compositions.

The demagnetization curves of Fe-30%Cr-15%Co-3%Mo alloy and Fe-32%Cr-15%Co-3%Mo alloy are shown in Fig. 6 in comparison with those of Alnico 8 and Alnico 6. The studied alloys have magnetic properties higher than Alnico 6. The coercivities of the studied alloys are smaller than those of Alnico 8 but the higher magnetic flux can be obtained above p=5 (p:permeance) with the advantage of cold formability. So it can be said that the Fe-30%Cr-15%Co-3%Mo alloy and Fe-32%Cr-15%Co-3%Mo alloy are potential magnets comparable to Alnico 8.

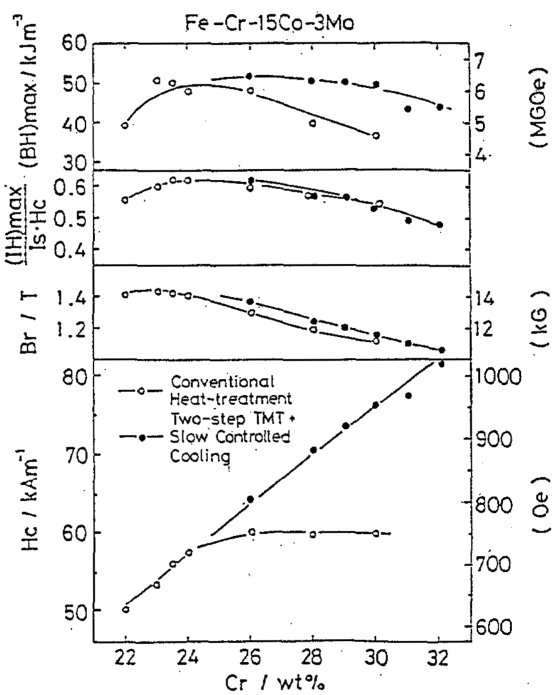

Fig. 5 The magnetic properties versus Cr contents of Fe-Cr-15Co-3Mo alloys.

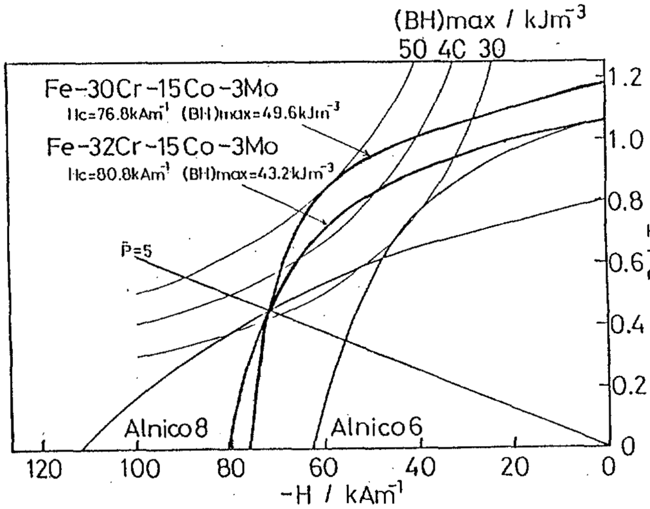

Fig. 6 The demagnetization curves of Fe-30Cr-15Co-3Mo and Fe-32Cr-15Co-3Mo alloys with those of Alnico 6 and Alnico 8.

ACKNOWLEDGMENT

The authors would like to thank T. Minowa for helpful discussions.

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