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Magnetic properties of Fe–Mo–5Ni–0.05C alloys with different contents of Mo

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Abstract

Magnetic properties such as coercive force H_c, remanent induction B_r, squareness B_r/B_s and maximum energy product BH_{max} for alloys with Fe–5Ni–0.05C and 11, 15 and 19 wt% of Mo were determined for samples cold rolled 60, 80%, 90 and 97% followed by magnetic aging at 610°C for 1 h. The results show that the addition of carbon to alloys with 11 and 15 wt% of Mo improves coercive force H_c and the amount of Mo has a significant role on remanent induction B_r and squareness B_r/B_s. After 97% of cold rolling and magnetic aging, an alloy with 11 wt% of Mo reaches $H_c = 290$ Oe, $B_r = 17\,800$ G, $B_r/B_s = 0.94$ and $BH_{max} = 3.4$ MGOe. Values obtained for H_c, B_r/B_s and BH_{max} are higher than those obtained by Jim et al. [J. Appl. Phys. 52 (3) (1981) 2503] in an alloy with 20% of Mo without carbon. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Fe–Mo–Ni alloys without carbon show high mechanical plasticity and magnetic properties similar to Vicalloy-I, also known as Koerzit T with composition 50 wt% Co, 3 wt% to 14 wt% V and Fe, whose main applications are small motor magnets and special purpose recording tapes. Their advantages include the absence of the expensive element cobalt and high mechanical ductility.

Jim et al. [1] investigated magnetic properties of Fe–Mo–5Ni with amounts of Mo from 11 to 20% (wt%) but without carbon. They concluded that the best magnetic properties are obtained in alloys with 20% Mo, solution annealed before magnetic aging. Alloys with 15 and 11 wt% of Mo showed very poor coercive force ($H_c \approx 90$ Oe) and high remanent induction ($B_r = 17\,800$ G). The presence of Mo causes precipitation of λ-Fe_2Mo that is responsible for magnetic hardening in these alloys [2].

The addition of 0.12 wt% of carbon was studied by Tavares et al. [3] in an alloy with 20 wt% of Mo. The main goal of this study was to produce a cheaper alloy melting steel instead of pure iron. They concluded that carbon improved magnetic

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properties H_c (coercive force) and B_r (remanence) but the alloy became brittle. The presence of carbon forms carbides M_6C where M can be Fe or Mo that behaves similar to λ-Fe_2Mo increasing magnetic hardening [4].

Magat et al. [5] and Lujinskaia et al. [6] showed that severe cold deformation prior to magnetic aging improved magnetic properties B_r and H_c in Fe–20Mo–5Ni (wt%) alloys probably due to the development of texture and magnetic anisotropy.

In a previous work, Abreu et al. [7] cold rolled Fe–20Mo–5Ni with carbon contents varying from 0.020 wt% to 0.092 wt% until 97% of reduction and showed that cold rolling in excess of 80% introduces magnetic anisotropy in these alloys. Their results showed that there is a sharp $\{1\,0\,0\}\langle 1\,1\,0\rangle$ texture component after magnetic hardening that increases with cold rolling reduction.

Table 1
Chemical composition of investigated alloys

Alloy	C	Ni	Mo	Co	Fe
B	0.052	5.0	11.0	< 0.01	bal.
H	0.050	4.7	14.5	< 0.01	bal.
M	0.057	5.0	19.3	< 0.01	bal.

This work analyzes how 0.05% of carbon influences the magnetic properties in alloys with 11 and 15 wt% Mo and how Mo influences magnetic properties and magnetic anisotropy of Fe–Mo–5Ni–0.05C wt% alloys after cold rolling and magnetic aging at 610°C for 1 h.

2. Materials and methods

Fe–Mo–Ni ingots were prepared by induction melting under vacuum. Composition of each ingot is in Table 1. Ingots were soaked at 1250°C for 30 min and then hot rolled with 60% of reduction in one pass. The strips were reheated to 1220°C and then were quenched in water. Hot-rolled strips were cold worked to get samples 60, 80, 90 and 97% reduced. Magnetic aging was performed at 610°C for 1 h.

Magnetic properties (hysteresis loops) were measured in a vibrating sample magnetometer EGG–PAR model 4500. Error for H_c and B_r measured by this equipment are better than 0.1%.

3. Results and discussion

Fig. 1 shows the variation of coercive force H_c with percentage of cold rolling reduction for the

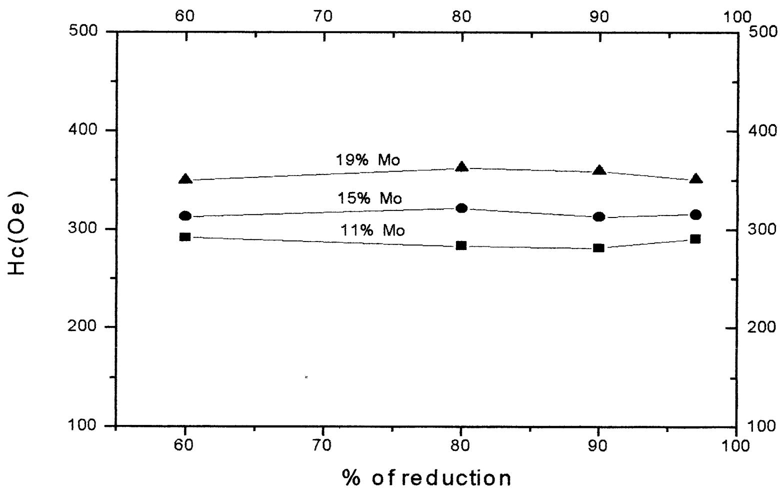

Fig. 1. Variation of H_c with % of reduction for alloys B, H and M.

three alloys analyzed. Coercive force H_c is higher for the alloy with more Mo and is not sensitive to cold rolling reduction. Molybdenum is used in both in quench hardening and precipitation hardening types of permanent magnets. Magnetic properties result from precipitation hardening. More Mo in alloy composition results in more precipitation. The influence of cold rolling and consequently crystallographic orientation on coercive force H_c is not very well defined for this family of alloys. Theory does actually suggest that the influence of orientation on coercive force may differ for various types of domain processes [8]. Some alloys increase H_c with crystallographic orientation like Alnico and others like some ferrites decrease H_c when they are well aligned. Comparing the values of H_c obtained for alloys with carbon in their composition with the values obtained by Jim et al. [1] for coercive force, it is possible to realize how carbon influences this property. For a Fe–11Mo–5Ni (wt%) wire drawn with 95–99% reduction in area and aged at 600–650°C for 2–5 h the highest value obtained for H_c by them was 87 Oe. From Fig. 1, H_c for samples cold rolled within 97% reduction in area and aged at 610°C for 1 h is 290 Oe. The highest value of H_c obtained by Jim et al. [1] for an alloy with 20 wt% Mo after solution annealing and aging was 220 Oe. The alloy with 19.3 wt% of Mo and 0.057 wt% C cold rolled 90%, solution annealed and aged has coercive force $H_c = 408$ Oe (Table 2).

Table 2
Magnetic properties for sample solutions annealed before aging (S) and aged after cold rolling (D)

	H_c (Oe)	B_r (G)	B_r/B_s	BH_{max} (MGOe)
S	408	8600	0.66	1.52
D	359	12 000	0.85	2.48

Fig. 2 shows the variation of remanent induction B_r with cold rolling reduction for alloys B, H and M, after magnetic aging. Remanent induction B_r decreases with increasing Mo and increases with cold rolling reduction. The reason for this behavior is because remanent induction increases with crystallographic orientation. The increase of the wt% Mo decreases the severity of texture and consequently magnetic anisotropy [9]. For a Fe–11Mo–5Ni wire drawn with 95–99% reduction in area and aged at 600–650°C for 2–5 h, the highest value obtained for B_r by Jim et al. [1] was 17 800 G. For a sample cold rolled with 97% reduction in area and aged at 610°C for 1 h, B_r in Fig. 2 has the same value. For alloy solutions annealed before aging values obtained for samples with carbon are higher [9].

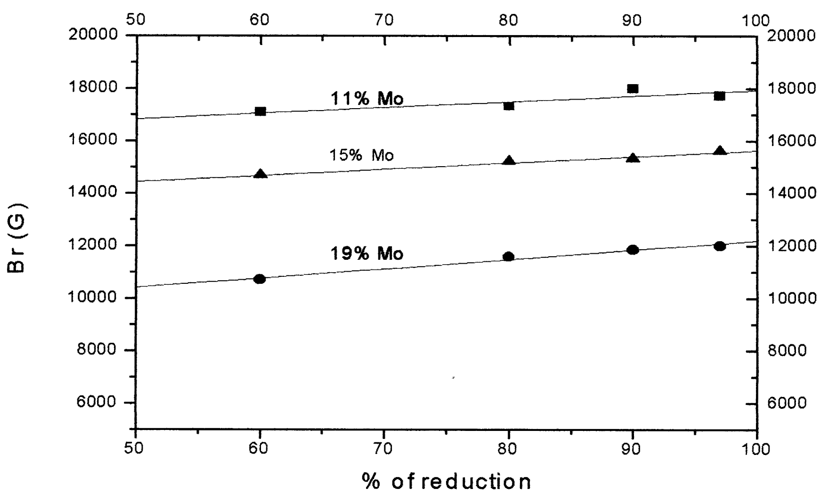

Fig. 2. Variation of B_r with % of reduction for alloys B, H and M.

Fig. 3 presents the variation of energy product BH_{max} with cold rolling reduction. The alloy with less Mo has the best BH_{max}. The value for BH_{max} = 3.4 MGOe obtained in this work for the alloy with Fe–11Mo–5Ni–0.057C wt% cold rolled with 97% induction and in area aged at 610°C for 1 h is almost four times higher than the 0.9 MGOe obtained in [1] for samples of Fe–11Mo–5Ni wire drawn with 95–99% reduction in area and aged at 600–650°C for 2–5 h.

Fig. 4 presents the variation of squareness, a relation between remanent induction and saturation induction B_r/B_s. This relation when higher than 0.8 is indicative of magnetic anisotropy. Alloys with less amount of Mo are more anisotropic and as a consequence develop a sharp {1 0 0}⟨1 1 0⟩ texture component after magnetic hardening [6].

Table 2 compares magnetic properties of an alloy *M* cold rolled 90% and solution treated at 1220°C before magnetic aging with another aged after 90%

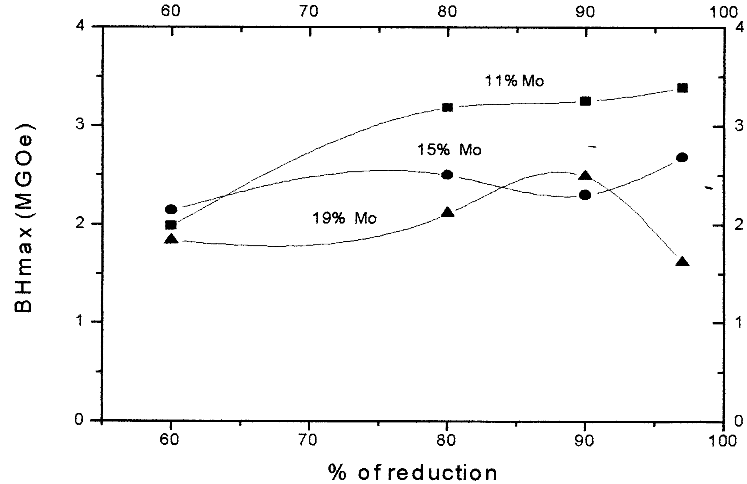

Fig. 3. Variation of BH_{max} with % of reduction for alloys B, H and M.

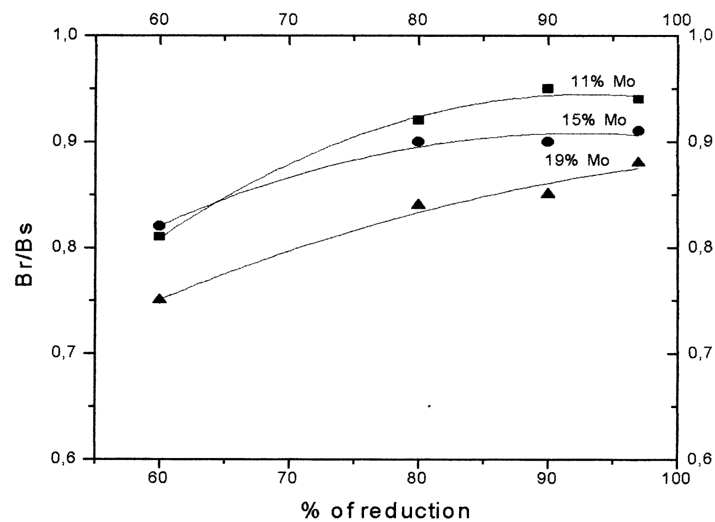

Fig. 4. Variation of B_r/B_s with % of reduction for alloys B, H and M.

cold rolling. Solution annealing before magnetic aging, as performed in most of samples analyzed in [1], increases coercive force H_c but decreases remanent induction B_r, squareness B_r/B_s and energy product BH_{max}.

4. Summary

The addition of carbon to Fe–Mo–5Ni alloys with 11 and 15 wt% of Mo improves coercive force without a reduction in remanent induction B_r. The increase in Mo amount improves coercive force but decreases remanent induction B_r. The influence of carbon on magnetic properties is sharper in alloys with less Mo. Samples with 11% of Mo are anisotropic and presented coercive force $H_c = 290$ Oe, remanent induction $B_r = 17\,800$ G, energy product $BH_{max} = 3.4$ MGOe and squareness $B_r/B_s = 0.94$. Solution annealing before magnetic aging improves coercive forces but the other properties including energy product BH_{max} are poorer than prior cold rolled samples.

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