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THE INFLUENCE OF MOLYBDENUM ON THE TEXTURE AND MAGNETIC ANISOTROPY OF Fe–xMo–5Ni–0.05C ALLOYS

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Diagrams of remanent induction, B_r, versus saturation induction, B_s, for Fe–5Ni–xMo–0.05C alloys, where x is equal to 11%, 15% or 19%, were determined for samples 60%, 80%, 90% and 97% cold rolled and magnetically age-annealed at 610°C for 1 h. The texture evolution in those alloys was analysed as a function of rolling reduction, by means of the orientation distribution function (ODF). The results show that a sharp {100}⟨110⟩ texture component develops in the 11%-Mo alloy for rolling reductions in excess of 90%. This leads to the highest values of the remanent induction, B_r, and of the B_r/B_s ratio for this alloy as a result of ⟨100⟩ directions, the easy magnetization directions, lying at 45° to the rolling direction.

Keywords: Cold rolling; Magnetic aging; Texture

INTRODUCTION

Fe–Mo–Ni alloys are highly ductile materials with magnetic properties similar to those displayed by commercial Fe–50Co–(3–14)V. Their main advantage over the latter is the absence of the expensive element cobalt. These alloys have a bcc structure from room temperature to

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1200°C (Jim and Tiefel, 1981) which, together with their high ductility, makes them amenable to magnetic property improvement via thermomechanical treatments.

Magat *et al.* (1988) showed that severe cold deformation prior to magnetic aging improves the remanent induction B_r and coercive force H_c of Fe–20Mo–5Ni alloys. They showed that both the textural and magnetic anisotropies are a result of the cold deformation introduced in these alloys. Tavares *et al.* (1994) showed that the addition of 0.12% carbon improves B_r and H_c but the alloys become brittle, probably as a result of grain boundary carbide precipitation. Jim and Tiefel (1981), studying Fe–Mo–Ni alloys, found very low values of H_c for the compositions with low Mo content.

In a previous work in this same journal, Abreu *et al.* (1998) cold rolled Fe–20Mo–5Ni–*x*C, with *x* varying between 0.020% and 0.092% in weight, to different reductions up to 99%. They showed that in the samples cold rolled between 80% and 90% there was a decrease in the volume fraction of the $\{001\}\langle 100\rangle$ orientation while in those cold rolled 97% and 99% an increase was observed, after age-annealing. Their results also indicated that the increase in the $\{001\}\langle 100\rangle$ volume fraction depended strongly on alloy composition.

The goal of the present work is to determine the influence of the Mo content on the textural changes in Fe–Mo–5Ni–0.05C alloys and relate these changes to the observed variation in magnetic properties. This is part of a more comprehensive investigation on Fe–Mo–Ni–C alloys being carried out by the authors.

EXPERIMENTAL

Three Fe–Mo–5Ni–0.05C ingots were prepared by induction melting under vacuum. The composition of each ingot is shown in Table I. The ingots were soaked at 1250°C for 30 min and hot rolled to 60% reduction

TABLE I Chemical composition of the alloys in weight percent

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

in one pass. The strips were reheated to 1220°C and quenched in water. The hot-rolled strips were cold rolled to 60%, 80%, 90% and 97% whence samples were removed. Magnetic aging of these samples was carried out at 610°C for 1 h.

The magnetic properties and the hysteresis loops were measured in a vibrating sample magnetometer EGG-PAR model 4500.

The samples for texture measurement were 20 mm × 14 mm rectangles cut from the sheets with the smaller dimension parallel to the rolling direction. These were ground to a 600-mesh finishing and chemically polished in a solution of HF in H_2O_2.

The crystallographic textures were determined by calculating the orientation distribution function – ODF – using the Roe method (Roe, 1965). The ODFs were computed from experimental {110}, {200} and {211} incomplete pole figures using a series of spherical harmonics expanded to $l = 22$. The orientation density distributions were represented in $\varphi_2 = 45°$ sections in Bunge coordinates (Bunge, 1993).

RESULTS AND DISCUSSION

Figure 1(a)–(c) shows the ODF $\varphi_2 = 45°$ sections for alloys B, H and M cold rolled 80%, 90% and 97% and magnetically aged at 610°C for 1 h. It can be seen that the fibres that characterize the bcc texture become sharper for reductions above 80%. The increase in sharpness with rolling reduction is better observed in Fig. 1(a), for alloy B (11% Mo); the sharpness decreases with increasing Mo content. The texture development is similar to that observed in rimming steels, but it is retarded with respect to the latter when the textures for the same rolling reduction are compared. The texture seems to be the result of a normal cold rolling and recrystallization behaviour when the latter is hindered by the presence of fine precipitates (not confirmed in this work). The main components are $\{001\}\langle 1\bar{1}0\rangle$, $\{111\}\langle 0\bar{1}1\rangle$ and $\{111\}\langle 1\bar{2}1\rangle$.

Figure 2 shows the variation of the $\{001\}\langle 110\rangle$ ODF intensity with cold rolling reduction for the three alloys. One can observe that the maximum intensity, 22 times random, is attained by alloy B, containing 11% Mo, and for the 97% cold reduction condition. The curve for alloy B also shows that the development of this orientation is accelerated for reductions above about 90%. This is an important result since it leads

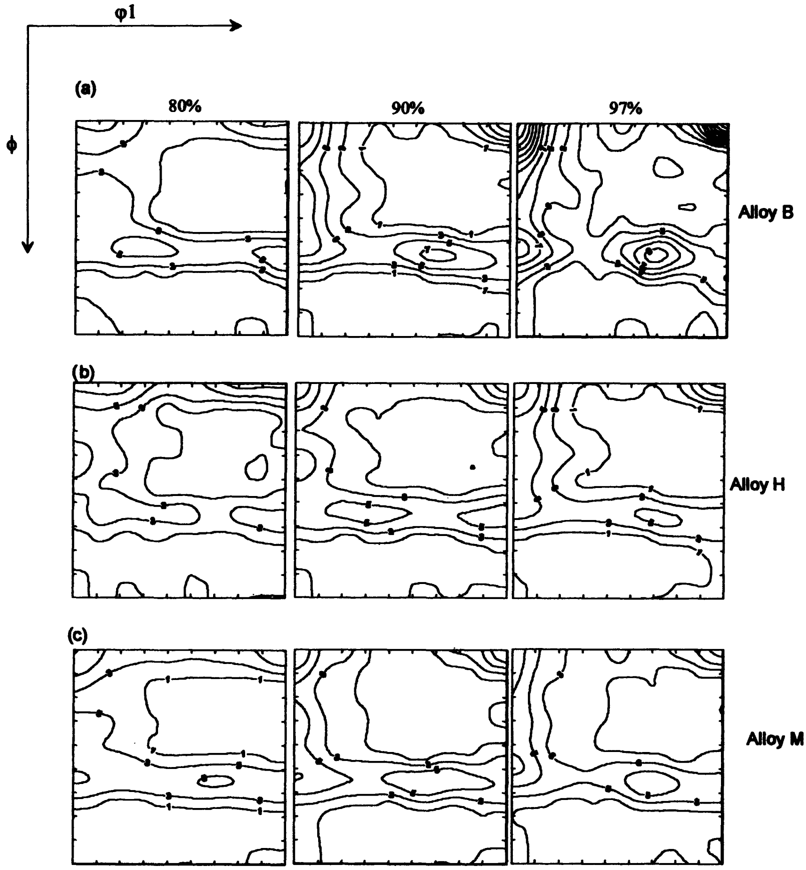

FIGURE 1 ODF $\varphi_2 = 45°$ sections for alloys B, H and M (contours at $1, 3, 5, \ldots$).

to an increase in the magnetic anisotropy on account of the ⟨100⟩ directions, the direction of easy magnetization, lying in the sheet plane at 45° to the rolling direction.

Figure 3 shows the variation of the texture severity parameter – TSP – with cold rolling reduction for the three alloys. The TSP measures the depart of the texture from random and is equal to unity for the uniform distribution. It can be seen that the increase in TSP is larger for alloy B, in agreement with the trend observed in Fig. 1. The curves in Figs. 2 and 3 are similar in shape. The increase in TSP results mainly from the increase in the {001}⟨110⟩ volume fraction. From the data in both Figs. 2 and 3

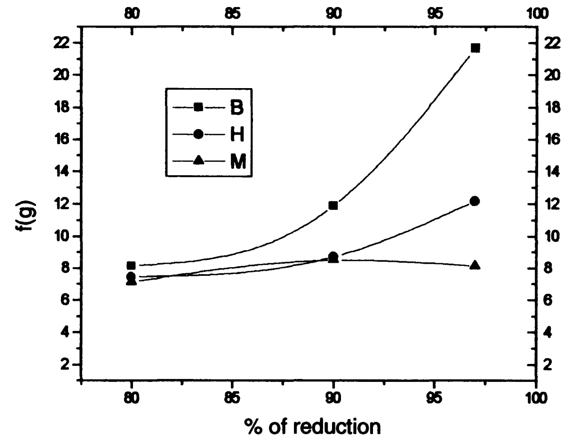

FIGURE 2 Variation of the ODF intensity of the {001}⟨110⟩ orientation with cold rolling reduction.

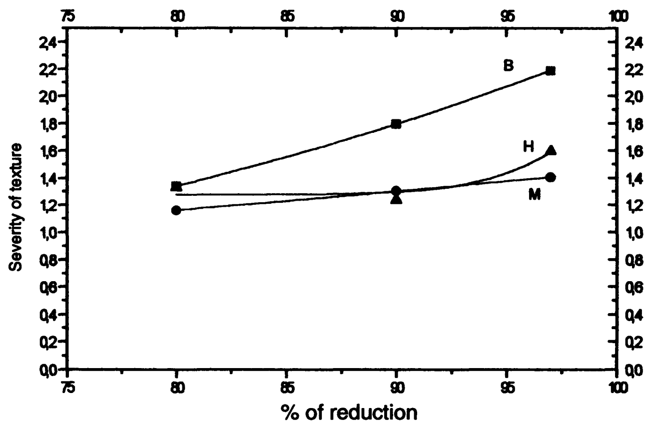

FIGURE 3 Variation of the texture severity parameter, TSP, with cold rolling reduction.

one can see that the development of the {001}⟨110⟩ component with rolling reduction is hindered by the increase in Mo content.

Figure 4 shows the variation of the ratio between remanent induction and saturation induction, B_r/B_s with cold reduction. It is generally accepted that this ratio, when larger than 0.8, is an indication of magnetic anisotropy. It can be seen that all three alloys show magnetic anisotropy for reductions equal to and higher than about 80%. In fact, both

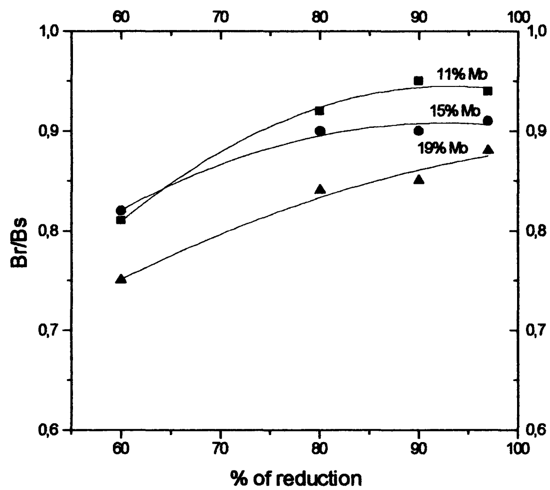

FIGURE 4 Variation of the B_r/B_s ratio with rolling reduction for alloys B, H and M.

alloys B and H satisfy that condition for the whole range above 60% reduction. For 97% cold reduction the B_r/B_s ratio is 0.94, 0.88 and 0.81, respectively, for alloys B, H and M. The deleterious effect of the Mo content can again be observed. The coercive force, H_c, practically did not vary with rolling reduction for any of the three alloys. The average values were about 280, 320 and 350 Oe, for alloys B, H and M, respectively.

Figure 5 shows the second quadrant of the hysteresis loop for alloys B (11% Mo) H (15% Mo) and M (19% Mo). Figure 5(a), for alloy B, shows an almost perfect square relation between B_r and B_s leading to high B_r/B_s ratios. Both these figures reflect again the influence of the Mo content and the corresponding increase in the $\{001\}\langle110\rangle$ volume fraction.

CONCLUSIONS

Three Fe–5Ni–xMo–0.05C alloys, where x is 11%, 15% or 19%, were cold rolled 60%, 80%, 90% and 97% and magnetically aged at 610°C for 1 h. The texture in these alloys shows the typical carbon steel-like development of the $\{hkl\}\langle110\rangle$ and $\{111\}\langle uvw\rangle$ partial fibres, these reaching the highest values for the 11% Mo alloy and decreasing with

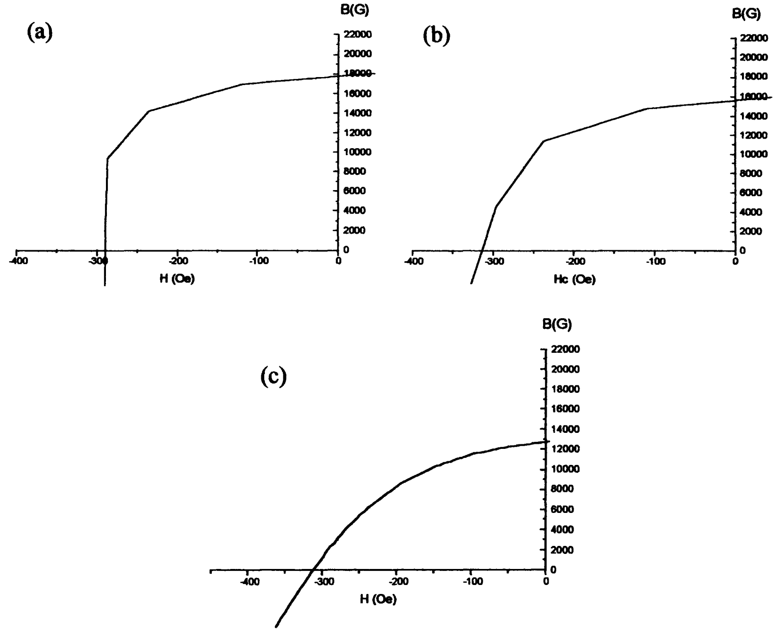

FIGURE 5 Second quadrant of the hysteresis loops for the 97% cold rolled and magnetically aged samples of the alloys with (a) 11% Mo, (b) 15% Mo, (c) 19% Mo.

increasing Mo content. The ODF intensity of the {001}⟨110⟩ component continuously increase with rolling reduction, for the 11% Mo alloy only, and reaches a maximum at 97% reduction. This increase is responsible for the high B_r/B_s ratios observed in this alloy. Taking into account the results obtained by Abreu *et al.* (1998) on the influence of the carbon content in Fe–Mo–Ni–C alloys, the alloy Fe–11Mo–5Ni–0.05C seems to be an optimized composition, displaying high magnetic properties and cold ductility and having the advantage of being less costly than Co-containing alloys.

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