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The role of molybdenum on evolution of deformation texture in the cold rolled Fe30Mn5Al1C-*x*Mo lightweight austenitic steels

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ABSTRACT

The effect of molybdenum addition on the evolution of deformation texture during cold rolling is studied in Fe30Mn5Al1C-*x*Mo (x = 0−3 wt%) light weight austenitic steels using EBSD. All the alloys have random texture prior to cold-rolling. After cold rolling, molybdenum promoted the formation of Brass-type texture. This texture can be attributed to dislocation based active deformation mechanisms because no deformation twins were found in the microstructure. The intensity of the major texture components: Brass and S increased up to 2 wt% Mo and then decreased. The increase in the molybdenum content did not affect mechanical properties significantly.

1. Introduction

Fe–Mn–Al–C-based lightweight austenitic steels (LWAS) are being explored as a candidate for structural applications due to their promising mechanical properties. The better mechanical property in terms of strength is attributed to solid solution strengthening, grain refinement, precipitation strengthening by intragranular κ-carbides, MicroBand Induced Plasticity (MBIP) etc. [1]. Among all the factors the formation of κ-carbides at the grain boundaries plays an important role in deciding the strength of the alloy. Hence, it is important to control the formation of κ-carbides at the grain boundaries by adopting suitable alloy design [2]. Recently, it was reported that the addition of molybdenum and chromium inhibited the kinetics of κ -carbide particles at the grain boundaries [3,4]. Though the addition of Mo and Cr inhibits the kinetics of formation of κ -carbide particles, the initial texture of the alloy plays an important role during thermo mechanical processing.

In general, the solute content could potentially influence the texture of the alloy. J. Hirsch et al. [5] had shown that the rolling texture changes from Copper to Brass type in Cu–Zn alloys with varying zinc content. J-Y.Kang et al. [6] investigated the role of aluminum (Al) and molybdenum (Mo) on texture in a dual phase steel. They reported that the presence of Al and Mo had led to reduced hot-band grain size, enhanced γ-fiber and led to a homogenous microstructure.

In the similar lines in LWAS, Haase et al. [7] studied the texture evolution in a high stacking fault energy (SFE) Fe-29.8Mn-7.65Al-1.11C (wt%) steel, with and without κ-carbides and reported that SFE is not responsible for the texture transition from Cu-type to Brass-type. Souza et al. [8] studied the effect of aluminum (2 and 8 wt%) on texture evolution during cold rolling in Fe-30.5Mn-1.2C (wt%) steel. It was reported that the transition of texture from Brass-type to Cu-type is due to increase in SFE from 2Al to 8Al. Ren et al. [9] studied the texture evolution in a cold rolled Fe–30Mn–11Al-1.2C (wt%) alloy. It was attributed that the transition from Cu-type to Brass-type texture is due to the transition in the deformation mode from dislocation glide to deformation twinning. These works suggest that there is a need to assess the conjoint effect of solute content and SFE on texture in LWAS.

Further, the evolution of deformation texture during manufacturing processes is dictated mainly by the deformation temperature, the strain imparted and the alloy content. Cold-rolling in combination with a suitable annealing treatment tailors the grain size, crystallographic texture and thereby the final mechanical properties.

Therefore in the present work the evolution of the crystallographic texture in the Fe–30Mn–5Al–1C- *x*Mo cold rolled alloys with varying molybdenum content (0–3) wt% is studied using EBSD. The uniaxial tensile properties at room temperature are evaluated to understand the mechanism of deformation and correlate with the deformation texture.

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2. Experimental details

Light weight austenitic steels with four different Mo concentrations: Fe30Mn5Al1C-xMo {x→0, 0.5, 2 and 3 wt%} were prepared using commercially pure iron, manganese, aluminum, molybdenum, and carbon through vacuum induction melting (VIM). The chemical compositions obtained by ICP-MS is reported in the earlier work [10]. The as cast alloys are solution treated at 1200 °C for 3 h and subsequently hot forged up to a strain of 0.6 and further hot-rolled (ϵ~0.56) at 1100 °C with a total strain imparted during hot deformation equal to 1.15. Alloys in hot rolled condition were homogenized at 1100 °C for 2hr followed by cold rolling up to 80% reduction in thickness. The microstructure is characterized by FESEM-EBSD and the crystal structure is identified by XRD. The samples for EBSD are prepared by grinding on SiC papers and final electropolishing in an electrolyte of perchloric acid in methanol (1:9) at 22V and 10s. The texture analysis is performed in TSL software. The room temperature uniaxial tensile tests at an initial strain rate of $10^{-3}s^{-1}$ are conducted for the cold-rolled alloys in an Instron 5967 universal testing machine equipped with digital image correlation (DIC) to measure the sample strain. Dog-bone shaped flat specimens were used for tensile testing with a gauge length of 6 mm and cross-sectional area of 2 mm^2.

3. Results and discussion

Fig. 1(a–d) shows the back scattered secondary electron (BSE) micrographs of 0-Mo, 0.5-Mo, 2-Mo and 3-Mo alloys homogenized at 1100 °C for 2hr and the corresponding representative inverse pole figure (IPF) maps are shown in Fig. 1(e–h). The microstructures of all alloys consists of completely annealed, single phase equiaxed grains with mean linear intercept length in the range of 100 ± 20 μm and twin fraction in the range of 21–31%. Fig. 1 (i) shows XRD patterns of the corresponding alloys that are indexed with FCC crystal structure and austenitic phase (ICSD- Fe-00-052-0513). The orientation distribution function (ODF) maps of the homogenized alloys at $\varphi_2 = 45°$ shown in Fig. 1j-m indicate that all the alloys are dominated by random texture components. This suggests that there is no significant difference in the initial texture with addition of molybdenum in the homogenized condition at 1100 °C for 2hr. However, 3-Mo alloy has shown slightly higher intensity of brass component B {110} <112> that is observed at (φ_1, φ, φ_2) of (35°,45°,0°).

Fig. 2(a–d) shows the IPF maps of the 80% cold rolled alloys along with corresponding ODF maps in Fig. (e–h) depicting the deformation texture components and their fraction in Fig. 2i. The area fraction of (101) oriented grains increases with increase in the Mo concentration indicating that higher Mo content stabilizes the (101) orientation. For further understanding, the IPF and ODF maps are obtained for the deformed microstructure partitioned with grain orientation spread (GOS) > 1.5°. The possible texture components indicated in Table 1 are identified by comparing with the standard texture components for a deformed FCC crystal structure [11]. The IPF maps (Fig. 2a-d) indicate the evolution of newly oriented grains from the homogenized microstructure (shown in Fig. 1a-d). Further, it is observed that the area fraction of Brass(B) orientation (green color) increases with increase in Mo wt. % during cold rolling. The corresponding ODF sections at φ_2 = 0°, 45° and 65° indicated that the intensity of the Brass (B), S-component (S) and Goss(G) orientations increased with addition of molybdenum up to 2 wt% Mo followed by decrease at 3 wt%Mo. The difference in texture intensity of various components (shown in Fig. 2i) with concentration of Mo indicates that the operating deformation modes during cold rolling

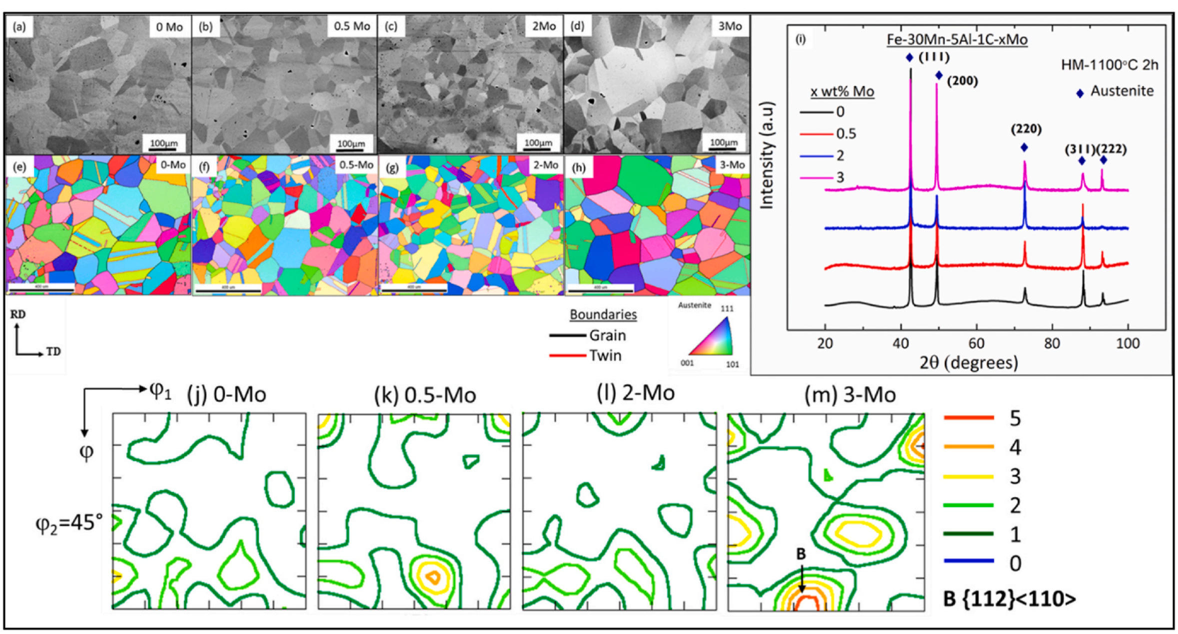

Fig. 1. (a–d) BSE micrographs, (e–h) IPF maps, (i) XRD patterns, (j–m) ODF (φ_2 = 45°) maps of the homogenized 0-Mo, 0.5-Mo, 2-Mo and 3-Mo alloys showing completely annealed microstructure with single phase, equiaxed grains consisting of random texture components and Brass component in 3-Mo.

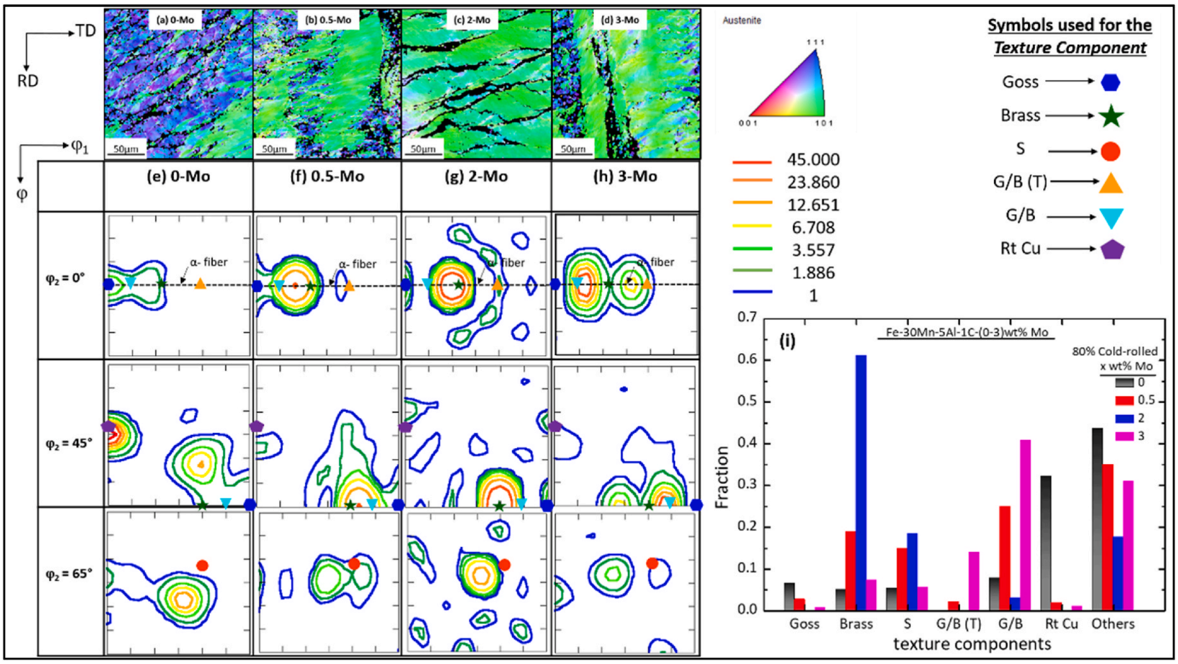

Fig. 2. (a–d) Inverse Pole Figure (IPF) maps of cold-rolled alloys, 0-Mo,0.5-Mo,2-Mo and 3-Mo alloy and (e–h) the corresponding cold rolled texture evolution shown in Orientation Distribution Function(ODF) sections at $\varphi_2 = 0°$, 45 and 65°, (i) the fraction of change in identified texture components with addition of molybdenum.

Table 1
Texture components in the present alloy system compared with standard FCC system [11].

Texture Component	Symbol	Miller Indices {hkl}<uvw>	Euler Angles $\varphi_1,\varphi,\varphi_2$
Goss		{110} <001>	0°,45°,0°
Brass		{110}<112>	35°,45°,0°
S		{123}<634>	59°,37°,63°
G/B (T)		{110}<111>	55°,45°,0°
G/B		{110}<115>	17°,45°,0°
Rt Cu		{112}<110>	0°,35°,45°

are different for different alloys. Further the stacking fault energy (SFE) of the material, which depends on alloy composition, activates different types of deformation modes during processing resulting in different texture evolution. It was reported that the concentration of solutes can alter the rolling texture and based on the solute content, there can be transition from brass-type to pure metal type or vice-versa [12]. Further, it was reported that twinning is not the dominant deformation mode for the alloy having stacking fault energy greater than 60 mJ/m^2 [13]. In the present alloy, hardly any deformation twins were observed after cold rolling (see Fig. 2 a-d) and hence the present texture evolution during cold rolling can be attributed to dislocation glide mechanism.

The uniaxial tensile behavior of the alloys (Fig. 3a) indicated that there is no significant difference in the yield strength (YS) and ultimate tensile strength (UTS) with addition of molybdenum. The YS and UTS lie in the range of 1612 ± 2 to 1632 ± 32 MPa and 1771 ± 14 to 1718 ± 12 MPa respectively. The fracture strain (FS) for all alloys lie in the range of 7.5 ± 0.8 to 9.6 ± 0.5. Further, the corresponding fractographs in Fig. 3b showed that all the alloys had transgranular ductile fracture with fine dimples. The evolution of texture showed that highest intensity of Brass texture (as shown in Fig. 3c) is observed for 2 wt% Mo after cold rolling compared to other alloys. However, increase in the Mo wt. % to more than 2 wt % leads to the decrease in intensity of Brass texture.

Fig. 4 shows the grain boundary fraction for both low angle grain boundaries (LAGBs ~ 2–15°) and high angle grain boundaries (HAGBs ~ 15–65°) in the cold rolled alloys with varying molybdenum content. It is observed that there is no significant difference in the grain boundary fractions lying in the range of 88–99% for LAGBs and 1–12% for HAGBs. However, the LAGBs slightly increased from ~90% in 0-Mo to 99% in 2-Mo and slightly decreased to 91% in 3-Mo. This suggests that for the strain imparted for 80% reduction in the alloys could not saturate the LAGBs for 3 wt % Mo which could be due to higher molybdenum content.

From above inferences it could be understood that, cold rolling texture had not significantly affected the room temperature mechanical properties with varying molybdenum. However, the effect of

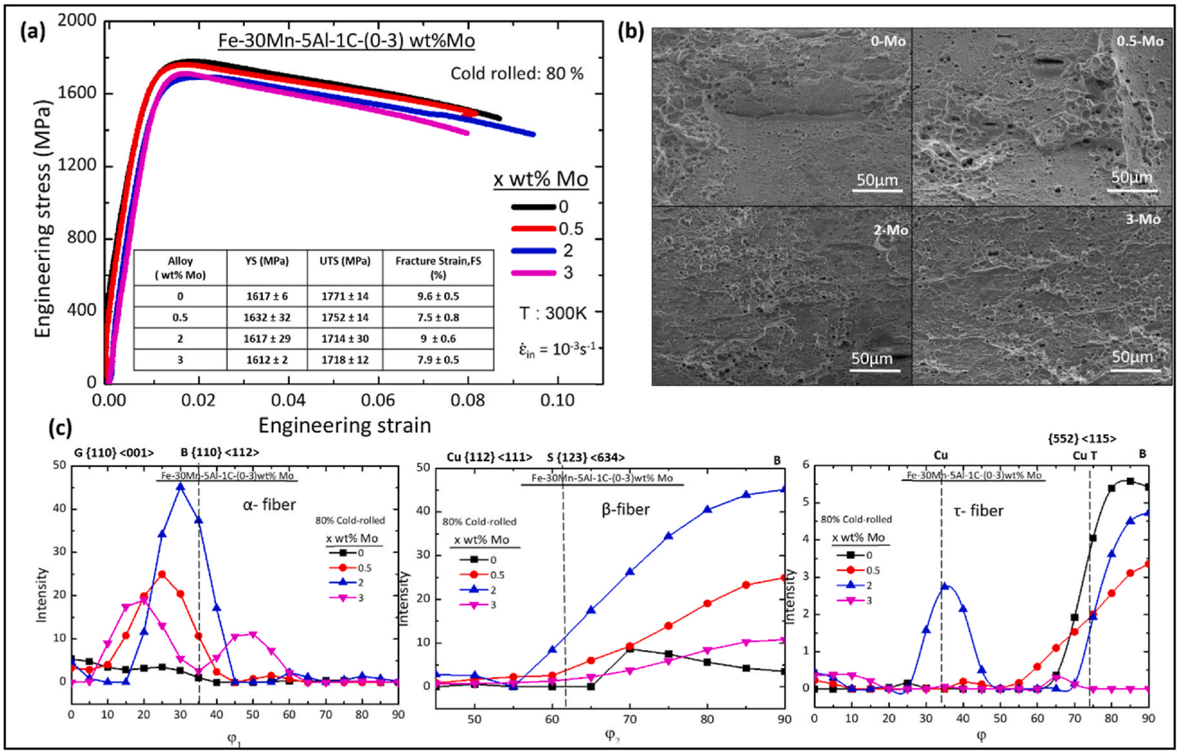

Fig. 3. (a) Engineering stress-strain curves for cold rolled alloys tested at 300K and corresponding, (b) fractographs, (c) α, β, τ-fiber intensities for the alloys.

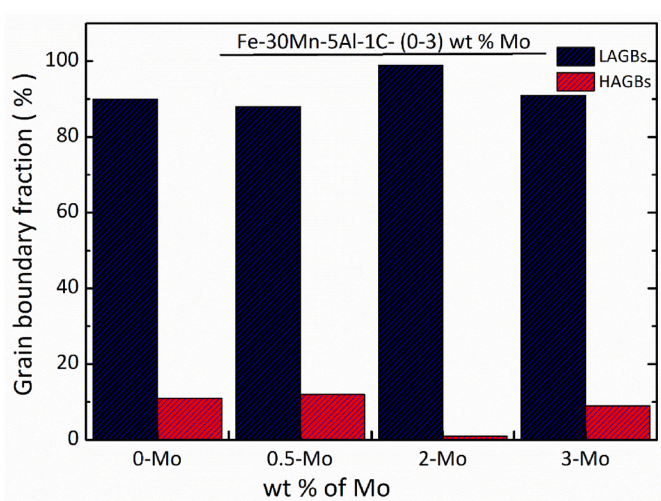

Fig. 4. Grain boundary fraction (Low angle grain boundaries (LAGBs) and High angle grain boundaries (HAGBs)) with varying molybdenum content.

molybdenum could be more understood with annealing texture which needs investigation.

4. Conclusions

The effect of molybdenum addition on the evolution of deformation texture and mechanical properties was studied in detail after cold rolling. The increase in molybdenum content up to 2 wt % promotes the formation of "Brass type" texture. The intensity of Brass component decreases for more than 2 wt % Mo. Although molybdenum has shown significant effect on the texture components, the room temperature strength is not affected significantly.

CRediT authorship contribution statement

Sairam Kotla: Methodology, Investigation, Formal analysis, Conceptualization. **R.K. Sabat:** Writing – review & editing, Investigation. **M.P. Phaniraj:** Writing – review & editing, Supervision, Project administration. **Rajesh Korla:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rajesh Korla reports financial support was provided by India Ministry of Science & Technology Department of Science and Technology. No conflicts of interest.

Data availability

Data will be made available on request.

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