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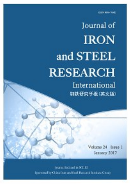

# Microstructure and texture evolution during recrystallization of low-carbon steel sheets

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ABSTRACT

Aluminum killed low-carbon steel sheets were cold rolled at different reduction ratios and annealed using different temperatures and holding time. The Vickers hardness was examined. The results show that when cold rolling reduction ratios increase from 40% to 81%, recrystallization temperatures decrease from 602 °C to 572 °C during 4 h isochronal annealing, as well recrystallization holding time decreases from 117 min to 5 min during isothermal annealing at 610 °C. All recrystallization temperatures and holding time can be calculated using the annealing experiment results. Microstructure was examined through electron backscattered diffraction (EBSD). The results show that as rolling direction preferentially grows, equiaxed grains grow into cake-type during recrystallization. Cake-type grains are more beneficial to obtaining ideal <111>//ND (normal direcrtion) orientation texture. {111} orientation grains nucleate and grow up preferentially. Deformation grains of {111}<110> orientations grow into new recrystallization grains of {111}<123> and {111}<112> during recrystallization. Texture formation can be explained by directional nucleation.

## 1. Introduction

Aluminum killed low-carbon steel sheets are deoxidized by adding aluminum, which produces high quality structural carbon steel sheets. They are widely used in the automotive, building and packaging industries because of their good formability and low strength[1-3]. A plastic strain ratio ($r$), a strain hardening exponent ($n$) and a total elongation ($e$) are predominantly indexes of deep drawability. High $r$, $n$ and $e$ values represent good deep drawability, and the steel sheets are easily manufactured into complicated parts. However, $r$ value is determined by grain orientation (textures) and is the most important parameter to deep drawability. Traditional production process generally includes continuous casting, hot rolling, acid pickling, cold rolling and annealing. Textures are formed in cold rolling and annealing and have an important effect on deep drawability. Thus, studies on evolution of microstructure and texture in cold rolling and annealing have important directive significance to improve deep drawability of the steel sheets[4-9].

However, most scholars have paid their attentions to recrystallization behavior of continuously cold rolled steel sheets and their annealing processing parameters, but few concern with influences of cold rolling reduction ratios on the recrystallization behavior of reversely cold rolled steel sheets and their annealing processing parameters. With the development of modern industry, demands for steel sheets with different thicknesses become increasingly pronounced. Optimizing production parameters for different thickness steel sheets can reduce energy-consumption and costs. Hence, it is an interesting subject in current research field. The deformation energy increases with increasing cold rolling reduction ratios, and is the main energy to recrystallization. Thus, evolutions of microstructure and textures vary with different reduction ratios during recrystallization[10,11]. To study the effects of cold rolling reduction ratios on microstructure and textures of steel sheets is an urgent need[12,13]. In this article, recrystallization and texture evolution were re-

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searched for different cold rolling reduction ratios of the steel sheets during annealing recrystallization.

## 2. Experimental Procedure

The composition of aluminum killed low-carbon steel sheets is shown in Table 1. The steel sheets were industrially produced and cold rolled to six different final thicknesses (i. e., 1.81, 1.43, 1.22, 1.07, 0.84 and 0.56 mm) with reduction ratios of 40%, 52%, 59%, 64%, 72% and 81%, respectively. The steel sheets were cut into dimensions of 40 mm×50 mm and then annealed. During annealing, the samples were heated from 400 °C to 760 °C at a rate of 30 °C/s and then held from 10 s to 4 h. Finally, the samples were air cooled to room temperature.

**Table 1**

Chemical composition of experimental steel sheets (mass%)

| C | Si | Mn | P | S | $Al_s$ | Fe |
|---|---|---|---|---|---|---|
| 0.02 | 0.02 | 0.18 | 0.011 | 0.004 | 0.048 | Balance |

Vickers hardness tests were carried out on the vertical section of samples using a DHV-1000 microhardness tester. with test load of 0.98 N and holding time of 10 s, and each value was the average of five test points. Recrystallization textures in mid-thickness regions of samples were measured using a scanning electron microscope (SEM, Hitachi S-4800), coupled with an electron backscattered diffractometer (EBSD, facility manufactured by OXFORD Corporation in England along with Channel 5 HKL software). The value of working voltage was 20 kV, working distance was 15 mm, step size was 0.33—1.00 μm and the smallest scanning range is 242 μm×181 μm.

## 3. Result of Recrystallization Behavior

### *3.1. Evolution of Vickers hardness during isochronal annealing*

Vickers hardness values of cold rolled samples are 191, 216, 223, 225, 226 and 242 HV with reduction ratios of 40%, 52%, 59%, 64%, 72% and 81%, respectively. Fig. 1 shows values of Vickers hardness with different cold rolling reduction ratios after different isochronal annealing for 4 h. When annealing temperatures are equal to or lower than 550 °C, hardness values are insensitive to the temperatures. After isochronal annealing at 550 °C, hardness values change to 189, 200, 203, 209, 211 and 219 HV with above-mentioned reduction ratios, respectively. Hardness values of samples with 72% and 81% reduction ratios experience a distinct drop after isochronal annealing at 580 °C. However, hardness values of samples with 40%, 52%, 59% and 64% reduction ratios do not decrease by a noticeable percentage until isochronal annealing at 610 °C. When annealing temperatures are higher than 610 °C, hardness values are insensitive to cold rolling reduction ratios and decrease slightly with increasing annealing temperatures.

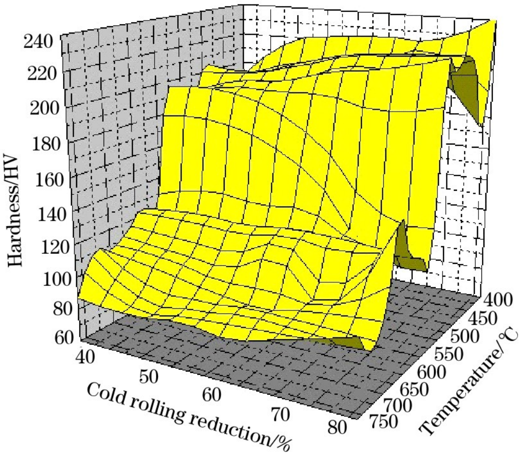

**Fig. 1.** Changes in hardness of samples with different reduction ratios after isochronal annealing at temperatures of 400—750 °C.

Previous researches showed that recrystallization temperatures correspond to halving work hardening effects[14,15]. Consistent with that, recrystallization temperatures are 602, 600, 596, 590, 576 and 572 °C, respectively, with reduction ratios of 40%, 52%, 59%, 64%, 72% and 81% by calculating according to Fig. 1. It shows that recrystallization temperatures obviously decrease with increasing reduction ratios, which indicates that cold rolling reduction ratios have remarkable effects on recrystallization. 80%—90% of energy stored in deformation grains in form of dislocations is the main driving force for recrystallization[16,17]. The dislocation density increases as cold rolling reduction ratios increase. Hence, samples undergone larger deformations have more stored energy, and then recrystallization occurs preferentially for them to offset work-hardening caused by cold deformation.

### *3.2. Evolution of Vickers hardness during isothermal annealing*

Fig. 2(a) shows the relationship between Vickers hardness and holding time for samples with different cold rolling reduction ratios during isothermal annealing at 610 °C. It shows that the trends of these curves vary with reduction ratios. After annealing for 10 min, hardness values of samples with 81% and 72% reduction ratios have significantly decreased to 150 and 159 HV, respectively, and it shows that recrystallization has occurred during the annealing. After annealing for 30 min, recrystallization occurred in the samples with 64% reduction ratios. However, recrystallization of samples with 40%