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Effect of lanthanum on recrystallization behavior of non-oriented silicon steel

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Abstract: Non-oriented silicon steels containing different mass fractions of lanthanum were prepared using a high-frequency suspended furnace. Microstructures were observed by a metallographic microscope and micro-orientations were analyzed by a scanning electron microscope (SEM). The results showed that at the annealing temperature of 870 ºC, recrystallization started at 90 s and completed at 120 s during annealing. Without lanthanum, no matter Cube or {111}<110> grains, recrystallized grains nucleated mainly in deformed {111}<110> and {113}<031> grains. With lanthanum, however, they nucleated in the deformed {110} and {112}<132> grains. This indicated that addition of lanthanum changed the micro-orientation relationship between new grains and the matrix.

Keywords: non-oriented silicon steel; lanthanum; recrystallization; rare earths

As an important metal soft magnetic material, the non-oriented silicon steel has been widely used as the laminated cores of motors and generators in electrical, electronic and military industries. Enhancing magnetic induction and reducing core loss effectively improve its magnetic properties. Generally, the magnetic induction is mainly dependent on the texture, while the core loss, the sum of hysteresis loss and eddy current loss, are minimized at an optimum grain size. Consequently, it is clear that the recrystallization behavior in annealing process can affect the magnetic properties significantly in the non-oriented silicon steel. Thus, studies on the recrystallization microstructure and texture of the non-oriented silicon steel have been conducted by many researchers. On the one hand, recrystallization grain size optimizing was achieved by controlling chemical compositions and optimizing processing variables at each processing step[1–5]. On the other hand, attentions have been paid to the evolution of texture in order to control the formation of recrystallization texture[6–9]. Li et al.[8] reported the evolution of microstructures and textures of {100} initial texture in an electrical steel. Liu et al.[7] investigated the formation of {001} <510> recrystallization texture and magnetic property in strip casting non-oriented electrical steel. They concluded that the formation of {001} <510> recrystallization texture can be attributed to the preferred nucleation and grain growth by the strain-induced grain boundary migration (SIBM) mechanism. Park et al.[9] investigated the mechanism of recrystallization texture in non-oriented electrical steels. The formation of recrystallization texture is explained by oriented nucleation.

In recent years, the applications of rare earth have provoked great interest for their fascinating properties[10–12]. Effects of rare earth (RE) on the textures, inclusions and microstructures of the non-oriented silicon steel were studied[13–16]. Takashima et al.[16] found that addition of both 0.003 wt.% cerium and aluminum into the non-oriented electrical steel could reduce core loss by coarsening grain size in a range of 45–70 μm after stress relief annealing. Hou et al.[13] studied the effect of cerium content on the magnetic properties of non-oriented silicon steels. They showed that the element cerium affected the texture and the final grain size through coarsening inclusion size. Wan et al.[15] investigated the effect of lanthanum content on the inclusion size distribution, microstructure, texture and magnetic properties of the non-oriented electrical steel. They found that the magnetic properties were improved through influencing the formation of large size inclusions by adding lanthanum. Zhang et al.[14] discussed the formation and change of inclusions of final steel sheets after RE treatment. They concluded that after the suitable RE treatment, the formation of AlN and MnS irregular inclusions were restrained.

In brief, previous studies indicate that moderate rare earth element addition can improve the magnetic properties and influence the formation of the inclusions in non-oriented silicon steels. However, less attention has been paid to effect of rare earth on the evolution of recrystallization texture and microstructure, which are of great necessities to the optimization of magnetic properties.

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In this study, the effects of lanthanum on the recrystallization behavior were studied. The microstructure was observed by an optical microscope and the formation of recrystallization texture was analyzed by a SEM.

1 Experimental

Three non-oriented electrical steels with different lanthanum weight fractions were melted in a high frequency suspended furnace on basis of the steel with C: 0.003 wt.%–0.006 wt.%, Si: 0.89 wt.%~0.93 wt.%, Mn: 0.24 wt.%, P: 0.065 wt.%–0.099 wt.%, S: <0.002 wt.%, Al: 0.257 wt.%. The basic materials were divided into three groups and added 0, 0.0015 wt.%, 0.0040 wt.% lanthanum, respectively, by smelting rare earth alloys. The rare earth alloy and basic steel were melted in a high frequency suspended furnace for 5 times to make sure the raw materials melt and mixed completely. The ingots were heated to 1200 ºC, held for 20 min and followed by hot-rolling. The hot-rolling finishing temperature was conducted at 850 ºC and then the samples were cooled to 350 ºC with a rate 21 ºC per hour in a furnace. The thickness of steel ingots after hot rolling was 3 mm. Then, the hot-rolled bands were uniformly milled to 2.3 mm by a milling machine from both sides to remove scales on the surfaces. The hot rolled specimens were cold rolled to the thickness reduction of 78% at room temperature and the final thickness is 0.5 mm. Then, the cold-rolled specimens were cut into 20 mm×15 mm coupons both in longitudinal and transverse directions with respect to the rolling direction. Finally, the specimens were annealed in a continuous annealing furnace set at 870 ºC for 80, 90, 100, 110, 120 and 210 s with an atmosphere of 25% H_2 and 75%N_2. All the specimens were cooled in the air.

The microstructures of the cross section parallel to the rolling direction of the partially recrystallized specimens were observed using an optical microscope. A 4% natal solution was used as an etchant. The recrystallized microstructures were also observed by the optical microscope. Micro-orientation measurement was carried out on the partially recrystallized specimens by Zeiss Suppra55 SEM Laboratories.

2 Results and discussion

2.1 Microstructure evolution during recrystallization

The microstructures of the samples annealed at 870 ºC and held for different time are shown in Figs. 1–4. It is clear from Fig. 1 that deformed grains remain recovered without any nucleation. Recrystallization takes place after holding for 90 s at the annealing temperature of 870 ºC, shown as Fig. 2, and the number and the size of the recrystallized grains increase with time extension. It is observed that the deformed grains are completely replaced by new grains after holding for 120 s, shown as Fig. 4.

It can be seen from Figs. 2 and 3 that the new grains prefer to nucleate on the specific substrate and the size of the new grains vary significantly depending on which deformed grain they nucleate from. This is related to stored energy. Hatherly et al.[17] used X-ray to find out

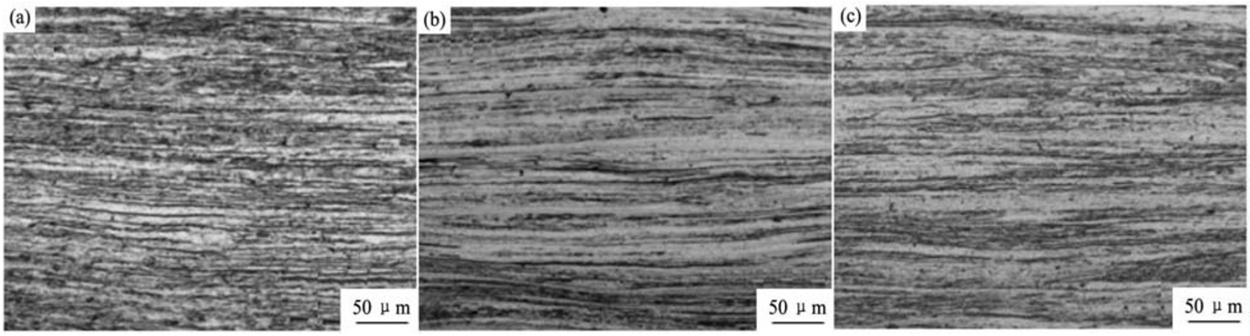

Fig. 1 Microstructure of the samples after recrystallization annealing for 80 s with different lanthanum contents
(a) 0 wt.%; (b) 0.0015 wt.%; (c) 0.0040 wt.%

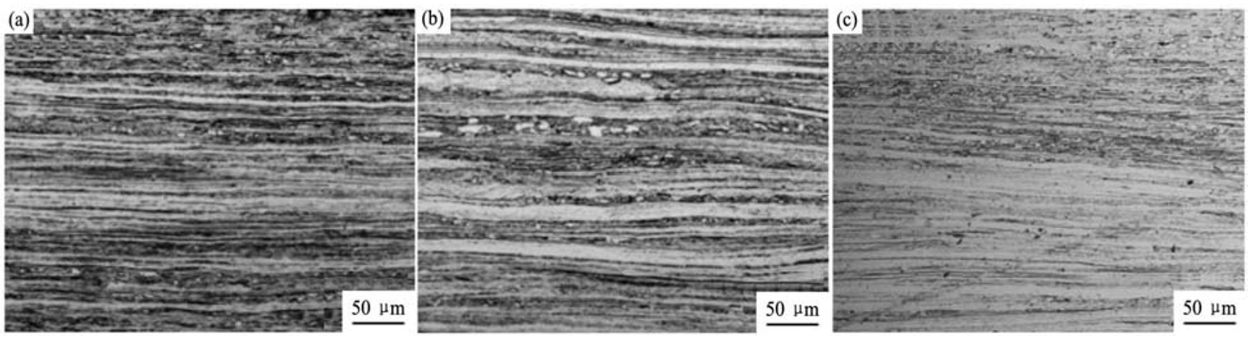

Fig. 2 Microstructure of the samples after recrystallization annealing for 90 s with different lanthanum contents
(a) 0 wt.%; (b) 0.0015 wt.%; (c) 0.0040 wt.%

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