Comparison of alternative warm rolling and iron loss of 6.5wt% high silicon steel composite sheet

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Abstract. 6.5wt% high silicon steel is a pretty soft magnetic material applied in electrical devices. But it is hard to be fabricated in conventional rolling methods. In this work we report a laminar composite technique to obtain 6.5wt% high silicon steel composite plate and focus on alternative warm rolling and diffusion annealing to produce 0.3-0.5mm 6.5wt% high silicon sheets. Microstructure of samples at different states were observed by optical microscopy, and iron loss values of samples which are got diffusion annealing treatment at different frequencies were investigated and compared. Magnetic properties of transverse samples are better than the others. Laminar composite technique and conventional rolling is a referable way to produce 6.5wt% high silicon steel in large industrial potential.

Introduction

High silicon steels have been extensively used as transformers, motors and electrical devices in light of improving electrical characteristics. Especially 6.5wt% high silicon steel has a high permeability and near-zero magnetostriction at higher frequencies, low magnetocrystalline anisotropy, low hysteresis losses and eddy current losses[1]. However, this material becomes obviously brittle and hard at room temperature as silicon content increased. By vitrue of this reason many preparation approaches have been developed to prepare this alloy without rolling, such as chemical vapor deposition[2], direct powder rolling[3], hot dipping and diffusion annealing[4] and spray forming[5].

In this research, we focus on the subsequent deformation of 6.5wt% high silicon steel composite plate after hot rolling. A different method to produce 6.5wt% high silicon steel composite plate whose thickness is near 2mm by laminar composite technique has been reported[6]. Defects generated during warm rolling stage could be eliminated and it is ready for making 6.5wt% high silicon thin sheets by conventional rolling process for commercial products.

Experimental Methods

The experimental material in this research is about 2mm 6.5wt% high silicon steel composite plate after hot rolled, which detail of chemical composition of this three-layer composite plate is presented in Table 1. Deformation experiments were comprised of warm rolling process and diffusion annealing stage. The composite plate was heated up at 650℃ in 1h to get warm rolled to become a thin sheet. The samples are divided into two groups. The rolling direction of first group samples is same as the direction of hot rolling as shown in Fig. 1A. Another group is perpendicular to that of hot rolling which is rotated 90° as shown in Fig. 1B. The detail of pass reductions of warm rolling process is listed in Table 2. Samples were heated up 1200℃ for 1-1.5h during the diffusion annealing process. Optical microscope was used to investigate the samples which etched by a 6% solution of nitric acid in cold water. Magnetic properties like iron loss was examined and compared with each other.

Table 1 Chemical composition of 6.5wt% high silicon steel composite plate after hot rolled（wt%）

	C	S	P	Mn	O	Ca	Al	Si	Fe
outer layer	≤0.120	≤0.008	≤0.008	≤0.032	0.0055	-	≤0.007	≤0.070	balance
inner layer	≤0.008	≤0.009	≤0.01	≤0.031	0.0032	0.085	0.022	9.557	balance

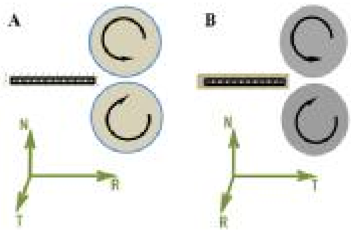

Fig. 1 Different direction of warm rolling with A) vertical direction; B transverse direction.

Table 2 pass reductions of 6.5wt% high silicon steel composite sheet warm rolled

Thickness/mm	Pass	Reduction/%
Heated up to 650℃ for 1h (first warm rolling)		
2.10	0	0
1.68	1	20
1.48	2	12
1.36	3	8
Reheated up to 650℃ for 45min (second warm rolling)		
1.12	4	18
0.98	5	12
0.91	6	7
Reheated up to 650℃ for 30min (third warm rolling)		
0.75	7	18
0.66	8	12
0.62	9	6
Reheated up to 650℃ for 20min (fourth warm rolling)		
0.51	10	18
0.45	11	12
0.41	12	7
Reheated up to 650℃ for 15min (fifth warm rolling)		
0.34	13	18
0.30	14	10

Results and Discussion

6.5wt% high silicon steel composite ingot was obtained by clad casting as shown in Fig 2. Thermo-mechanical processes were carried out on preparation of this composite plate. Due to silicon content of inner layer is high, its hardness and brittleness presented obviously. In order to decrease the cracks generated during hot rolling stage and eliminate residual stress, the composite plate after hot rolled cooled slowly to room temperature in furnace. The purpose of warm rolling is to inhibit transformation of ordered phases and reduce oxidation. That means accumulation of work hardening could prevent deformation developing continuously, but not produce cracks. Temperature range of warm forming is from 650℃ to 450℃ and the heating time of every step is different in terms of variation of thickness as shown in Table 2.

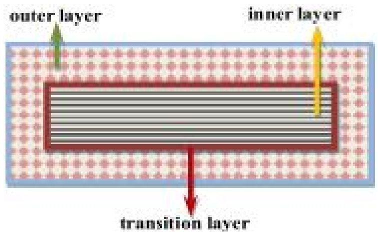

Fig. 2 Construction diagram of 6.5wt% high silicon steel composite ingot.

Morphology of this composite material before warm rolling is the state of annealing at 920℃ for 1h as shown in Fig.3a. Grains of outer layer are equiaxed at the end of annealing process, because temperature of annealing is higher than that of recrystallization. The middle layer of composite plate is core layer which silicon content is near 10wt%. It shows obviously brittle and hard at room temperature, however, defects would be generated during plastic deformation process as temperature reducing. There are some ordered phases transformation at low temperature conditions[7]. Mechanical properties of inner layer at high temperature are not bad than at low temperature, some ordered phases could be destroyed during the hot rolling stage. Rebuilding of these ordered phases were happening as recrystallization developing and grains growing up.

The direction of first group samples is as same as the direction of hot rolling which is along the length of composite plate. Direction of the second group of composite plates warm rolled is perpendicular to hot rolling. That is rotated 90° to the direction of the plate hot rolled. Microstructure of samples which got warm rolled along transverse direction is shown in Fig. 3b. Morphology of this composite plate is heated up 650℃ for 45min which thickness is near 1.2mm. Variation of transition is difficult to investigate comparison of Fig. 3a and 3b. Diffusion process could not develop in terms of low temperature. Micro-cracks are still in grain internal area or boundary which may be retained after hot rolling or generated in warm rolling stage. Grains boundary were elongated during warm rolling, but there were no defects. Recrystallization happened in the zone where some elongated large grains aggregated. Microstructure of samples got warm rolled along vertical direction is shown in Fig. 3c. That looks like morphology of samples transverse warm rolled. In order to improve protection of clad layer for inner layer, the rolling force should be enough and the rolling velocity should not be fast, however, inner layer could not get elongated. Defects of vertical sample look the same as that of transverse sample, such as little hole micro-crack. The recrystallization occurred where the area large elongated grains is aggregated. Comparison of the two diagram showings, obvious difference is the morphology of grains after warm forming. Grains boundary of transverse sample is straight likes the parallel lines. Its uniform forming is observed and less defects appeared during deformation stage. The vertical sample is reverse, especially the morphology of boundary of grains after forming with more curves intersecting. More defects generated and it is hard to maintain the integrity of this composite panel.

6.5wt% high silicon steel composite plate changed into thin sheet which thickness is near 0.3-0.5mm at the end of whole warm rolling process. According to the different thickness of sheets, heating times are determined, but the heat temperature is same as shown in Table 2. Two kinds of samples were taken to get diffusion annealing at 1200℃ for 1h, which vertical sample thickness is near 0.33mm and another one is near 0.35mm. Grains of transverse sample are bigger than that of vertical sample as shown in Fig. 3d and Fig. 3e. The former one is showing vertical sample after diffusion annealing process. That indicates more defects eliminated during the stage, but the size of grains grown up is limited. New grains boundary welded the cracks appeared in rolling stage. The latter one is about transverse sample after diffusion annealing stage. That shows size of grains is larger than the former one present, the limitation of grains grown up is decreased.

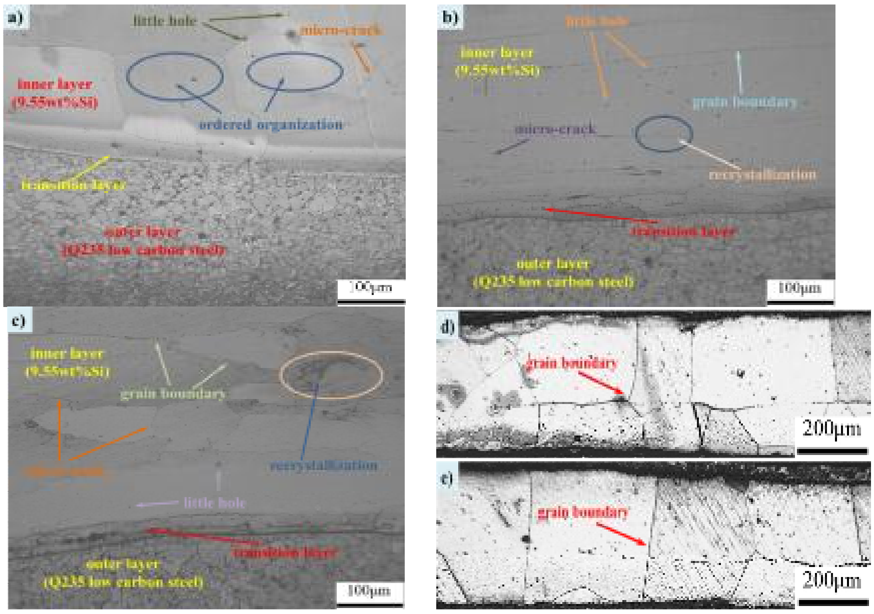

Fig. 3 Microstructure of 6.5wt% high silicon steel composite samples

a) 2mm sample after hot rolled and heat treated at 920℃ for 45min; b) 1.2mm sample after warm rolled along transverse direction and heat treated at 650℃ for 40min; c) 1.2mm sample after warm rolled along vertical direction and heat treated at 650℃ for 40min; d) 0.33mm sample after warm rolled along vertical direction and diffusion annealing treated at 1200℃ for 1h; e) 0.35mm sample after warm rolled along transverse direction and diffusion annealing treated at 1200℃ for 1h.

Table 3 Comparison of iron loss value of 6.5wt% high silicon steel composite sheet after warm rolled

Direction name	Thickness (mm)	Iron loss (W/kg)			
		W10/50	W10/400	W2/1000	W2/10000
vertical (R)	0.33	2.18	21.02	2.07	97
transverse (T)	0.35	2.03	20.35	1.86	81

Iron loss values of two kinds of thin sheet after diffusion annealing are investigated and the comparison result is shown in Table 3. Thickness of vertical sample is less than that of transverse sample, but the value of iron loss of the former is bigger than that of the latter. At low frequencies, value of iron loss of transverse sample is less than that of vertical samples, but superiority of the former one is not obvious. However, it is so clear that investigation of iron loss is at high frequencies. Deformation processes and heat treatment measurement method of samples are the same, but the magnetic properties are different.

Conclusions

1) Comparison with microstructure of vertical and transverse samples during warm rolling, few defects appeared in the inner layer as rolling direction along transverse direction and its grain size

is bigger. Investigation of iron loss values indicate that magnetic characteristics of transverse sample are better.

2) Coat casting and conventional thermo-mechanical processes, which contain hot forging, hot rolling, warm rolling and diffusion annealing, is a potential method to produce 6.5wt% high silicon sheet in commercial scale.

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