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► To cite this version:

A. Sakakura. The Development of Double-Oriented Silicon Steel with Cube Orientation. Journal de Physique IV Proceedings, 1995, 05 (C7), pp.C7-219-C7-224. 10.1051/jp4:1995724 . jpa-00254017

HAL Id: jpa-00254017

<https://hal.science/jpa-00254017>

Submitted on 1 Jan 1995

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The Development of Double-Oriented Silicon Steel with Cube Orientation

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Abstract. Silicon steels with cube orientation were extensively studied in the 1950s and 1960s, primarily for the purpose of using them as core materials for generators and large motors. In this paper, the research and development history of double-oriented silicon steel is outlined, as are the original attempts to subject hot bands containing AlN precipitates to cross-rolling treatment. It was found that the hot bands developed a (001) plane oriented secondary recrystallization structure after cross rolling and annealing, and that the percentage of grains with either (001)[100] or (001)[110]-orientations varied in accordance with the contents of carbon and AlN contained in hot band. Finally, some related fundamental research is discussed.

I. INTRODUCTION

This paper focuses on the process for producing silicon steel having a (001) plane in the rolling plane of the sheet. A grain-oriented silicon steel with (011)[100]-orientation is widely used as core material for transformers and turbo-generators, as shown in Fig.1(a). Of course, it would be preferable to use a double-oriented silicon steel with (001)[100] or (001)[110]-orientations in large-sized stator (Figs.1(a) &(b)). Moreover, though a non-oriented silicon steel has been used as core material for large-sized motors (Fig.1(c)), it would be more valuable to use a (001) plane oriented silicon steel in these motors. The object of this paper is to explain the process for producing a double-oriented and (001) plane oriented silicon steel, and to clarify the metallurgical mechanism by fundamental experiments using AlN containing 3%Si-Fe single crystals.

Double-oriented silicon steels with cube orientation were extensively studied in the 1950s and 1960s. J.L. Walter and co-workers [1~3] disclosed the multiple stage cold-rolling process of an oriented ingot for

producing a 3%Si-Fe with cube texture. F. Assmuss and co-workers [4~5] invented the original multi-stage cold-rolling process for treating a 3%Si-Fe. This process was characterized by the final annealing in purified atmosphere. The (001)[100] cube oriented secondary recrystallization proceeds with the surface energy differentials acting as a driving force. H.H. Mobius[6~7] showed the two stage cold-rolling process for the production of a pronounced cube-orientation in a 2%Si-steel which was characterized by subjecting the cold-rolled sheets to a predetermined ageing before final annealing. S. Taguchi and this author [7~11,13] disclosed a cross-rolling process for treating 3%Si-Fe containing a small amount of Al. The principle underlying this process is such that after the formation of a matrix by cross-rolling in which the cube grains are likely to grow, secondary recrystallization driven by grain boundary energy is initiated with impurity inhibition being effected by AlN. Furthermore, cube grains containing AlN(S) so obtained could reproduce the same cube orientation after cold-rolling and final annealing (Table 1).

Figure 1: Cores of large rotating machines

Table 1 Magnetic properties of product developed by NSC[10]

3%Si-Fe(Al)→Hot-roll(3.0-mm)→Cross Cold-roll(40×40%,1.1-mm)→Decarb.→Anneal(1150°C,N50)→Cube(AIN)
 →(S) 3CR(72%,0.30-mm)→Final anneal(1200°C,20h,N00)...Secondary recrystallization(SC)
 →(P) De-AIN →3CR(72%,0.30-mm)→Final anneal(1200°C,20h,N00)...Primary recrystallization(PC)

(S) Structure	Direction	B ₁₀ (Gauss)	W _{15/50} (W/kg)	(P) Structure	Direction	B ₁₀ (Gauss)	W _{15/50} (W/kg)	Note of magnetic properties
Secondary recrystn.	RD TD	19200 19100	1.01 1.02	Primary recrystn.	RD TD	16800 16300	1.50 1.58	B ₁₀ : Induction at 10 Oersted W _{15/50} : Core loss at 1.5T & 50Hz

2. EXPERIMENTAL RESULTS

2.1. Experimental procedures for production of (001)-oriented samples

Four different ingots 1, 2, 3 and 4 are processed by the methods as shown in Table 2.

Table 2 Experimental procedure for preparation of samples

Ingot→Slab-roll (Heat Temp.-°C, RD-LD, T-mm)→Hot-roll (Heat temp.-°C, RD-TD+LD or LD, T-mm)→
 Anneal (Temp.-°C, min., N₂%)→Cold-roll (Red.-%,T-mm)→Decarb.anneal (Temp.-°C, min., N₂%, wet)→
 OCA (Temp.-°C, hr, N₂%, wet)→Final anneal (Temp.-°C, hr, N₂%, dry)→Measurement

No	Melt & Ingot	Slab-roll	Hot-roll	Hot band annealing	Cold-roll	Decarb. annealing	OCA	Final annealing			
1-1	EF	1200,LD,90	1280,TD,27	1000, 5,N75	65,LD,1.0 ★2	800,15,N25w ★3	730,4,N25w	1200,20,N50d ★4			
1-2	500kg		→LD,3, ★1		60,LD→ 60,TD,0.45	as above	as above	1200,20,N00d ★5			
2	OHF 7-ton	1300,LD,100	1250,LD,3 ★6	1000,60,N75	65,LD,1.0 ★7	800,15,N25w ★8	730,4,N25w	1200,20,N50d ★9			
3	EF 500kg	1200,LD,100	1280,TD,25 →LD,1.6	950, 5,N75 ★10	70,LD,0.45	none	750,5,N00w	1200,20,N00d			
4	EF 1-ton	1200,LD,100	1300,TD,30 →LD,3	950, 5,N75 ★11	71,LD→ 60,TD,0.35	800,10,N00w	none	1200,20,N00d			
No	Chemical analysis (mass %)							Step	Texture & structure		
	C	Si	Mn	P	S	Al	N as AlN				
1	0.065	2.93	0.10	0.006	0.027	0.028	0.0054	★ 1	Fig.2(a) (★1,2,3), Fig.2(b) (★4), Fig. 3(★5) Fig.2(c) (★6,7,8), Fig.2(d) (★9)		
2	0.063	2.99	0.10	0.013	0.027	0.022	0.0058	★ 6			
3	0.075	2.94	-	-	-	0.026	0.0048	★10			
4	0.075	3.14	-	-	-	0.035	0.0058	★11			
No	Magnetic Induction (B ₂₅ , gauss)					Watt loss		(W _{10/50} , W/kg)		Thickness	Note of magnetic properties
	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	
1-2	16450	16570	16590	16410	16380	1.14	1.10	1.09	1.18	1.23	B ₂₅ : Induction at 25 Oersted
4	16520	16500	16530	16510	16520	0.79	0.80	0.78	0.80	0.79	W _{10/50} : Loss at 1.0Tesla & 50Hz

Note: RD-TD+LD (Rolling direction:Transverse direction+Longitudinal direction of ingot); T-mm(Thickness-mm)

EF (Electric furnace); OHF (Open hearth furnace); OCA (Open coil annealing); Decarb.:Decarburizing annealing

N25w (N₂,25%+H₂,75%,wet atmosphere); Magnetic properties (0, 22.5, 45, 67.5 and 90° to rolling direction)

2.2 Experimental results and discussion

As shown in Figs.2(a),(b),(c) and (d), (001)[100]-oriented secondaries are produced in the case of cross hot-rolling, while (011)[100]-oriented secondaries are produced in normal hot-rolling. Furthermore, in this cross hot-rolling process, the interesting fact has been found that even in carrying out the same cold-rolling and annealing processes, when more than 0.050%C is contained in an ingot, (001)[110]-oriented secondaries such as C7 and C8 in sample 1-1 come to be mixed after final annealing in response to the carbon content of the ingot (Fig.2(b)). Furthermore in the case of sample 1-2 (cross cold-rolling, 0.45-mm), (001) plane oriented silicon steel consisting of 45% of (001)[100]-oriented grains and 55% of (001)[110]-oriented grains respectively, is obtained (Fig.3). At any rate, the practical importance of this process for obtaining the (001) plane oriented silicon steel resides in the combination of cross hot-rolling of

Figure 3: Macrostructure showing secondaries of final annealed hot cross-rolled sample 1-2.

Figure 4: The effects of C and Al on the development of (001)-oriented secondaries through the fundamental processes which are characterized by the normally hot-rolled and cross-rolled.

3. FUNDAMENTAL EXPERIMENTS

3.1 Experimental procedure

A study was made of the effects of AlN on recrystallization in cross-rolled and annealed (001)-oriented 3%Si-Fe single crystals to clarify the origination mechanism of (001)-oriented silicon steel. The single crystals used in this study were 3%Si-Fe with the (001) plane in the rolling plane (Table 3). These were prepared by the author's method[11]. In the final annealing of this process, the sheets were kept for 20hrs at 1200°C and cooled at the rate of 100°C/h in an N50 (N250%+H250%) atmosphere. These crystals were then subjected to preheat treatments in order to change the size and distribution of AlN, and then cold rolled crosswise in the direction of 0° and 45° from the [100] direction, and finally annealed at 1200°C. The processing conditions and the recrystallization structures and textures after final annealing are shown in Table 4.

3.2 Experimental results and discussions

Though the orientation of secondaries almost coincides with the initial crystal orientation (Fig.6), thereproducibility of the initial orientation is much more difficult in the case of (001)[110] (SR) than in the case of (001)[100] (SC)-orientation. These (001)-oriented secondaries develop in crystals P00 and P45 which contain small amounts of AlN, precipitated as needles of about 1μm or less in length (Fig.7(b)).

Of course, in crystals N00 and N45 containing little or no AlN, normal grain growth structures PC and PR (Table 4) are formed. On the other hand, in (001)[110]-oriented crystal Q45 containing very fine AlN of about 0.01~0.1μm in length (Fig.7(a)), QR structure appears. This structure seems to be secondaries having four sets of a doublet {1,3,10}<421>-orientation (Fig.6) corresponding to the minor

Figure 5: The relationship between the percentage of recrystallization grains in (001)[100] & (001)[110]-orientation and C & AlN contents in starting material.

Table 3 Chemical composition of starting crystals

Orientation of starting crystals	Methods of preparation	Chemical composition (mass%)							Thickness, Diameter (mm)	Name of sample
		Si	Mn	Al	C	S -N	TN as AlN			
(001)-plane	Ref.11	2.95	0.09	0.026	0.0040	0.0008	0.0150	0.0130	1.00, 100 φ	P, Q, N00; P, Q, N45

Table 4 Effects of AlN on the recrystallization textures in cold-rolled and annealed (001)-oriented crystals

No	Pre-heat treatment				N as AlN (ppm)	Reduction(%) & Thickness(mm)	Direction of rolling	Final anneal			Final structure & Orientation (PGG: Primary grain growth)
P00	-----	-----	-----	-----	130		[100]				SC: (001)[100]-Secondary
P45	-----	-----	-----	-----	"		[110]				SR: (001)[110]-Secondary
Q00	1350, 5,		N75,	WQ	13	Cross rolling 50x50, 0.25	[100]	1200	20	N00	PC: {113}<301>-PGG
Q45	as above				"		[110]				QR: {1,3,10}<421>-Secondary
N00	1200, 20,		N00,	Slow	4		[100]				PC: {113}<301>-PGG
N45	as above				"		[110]				PR: {113}<110>,{113}<332> + {1,3,10}<421>-PGG

Figure 6 Macrostructure of the annealed crystals and (100) pole figure showing the orientation of secondaries. **Figure 7:** Precipitated AlN, (a) very fine precipitates (0.01~0.1μm) being useful for reproduction of (011)[100][21], (b) fine precipitates formed as needles (1μm in length) being useful for reproduction of (001)[100].

components of normal grain growth structure (PR) observed in the same oriented crystal containing AlN needles of about 1μm in length. Furthermore, a doublet-{113}<110> and a doublet-{113}<332>-oriented main primaries disappeared. From these results, it seems that a doublet of {1,3,10}<421>-oriented secondaries develops at the expense of the above main primaries which are inhibited by very fine AlN of about 0.01~0.1μm in length.

It is important to note that (001)[100] and (001)[110]-oriented single crystals containing AlN needles of about 1μm in length reproduce the initial orientations by secondary recrystallization. This situation in the single crystal will be the same in hot band processing for formation of (001)-oriented silicon steel. Many (001)-oriented grains are observed in the centre layer of a hot band after hot cross-rolling. Some of them will behave just as a single crystal does, as described above, and grow into (001)[100] and (001)[110]-oriented secondaries at the expense of the matrix main primaries.

4. SUMMARY

Crosswise hot-rolled 3%Si steel hot band containing AlN originates (001)-oriented secondaries after cold-rolling and annealing. This phenomenon is possible when the ingot contains a small amount of C (0.03~0.08%) and Al (0.02~0.06%), and the ingot is subjected to slabbing, second-last hot-rolling at 1250~1000°C and then cross hot-rolled at 1000~800°C. The percentages of secondaries of (001)[100] and (001)[110]-orientations vary in accordance with the change in the contents of C and AlN in the hot-band.

When cross cold-rolled and annealed, the (001)[100] and (001)[110]-oriented single crystals containing AlN needles of about 1µm in length reproduce the initial orientations by secondary recrystallization. It is important to note that change in size and distribution of needle-like AlN could effect the development of not only these (001)-oriented secondaries but also a doublet of {1,3,10}<421>-oriented secondaries. The inhibition effect caused by the special orientation relationships between AlN and parent crystal seems to be a dominant factor.

In 1965, T-Electric, M-Electric company (Japan) and AEG (Germany) requested double-oriented silicon steel with excellent orientation at a cost not over 20% higher than that of commercial single oriented silicon steel for the core material of large turbo-generator (700~1000MVA). The goal was to decrease the local heat originating in the stator core. However, the quantity requested would be small, such as 100T/Y in Japan. After finishing the fundamental research, the development of our process in Yawata Iron & Steel Company took place over a period of six years from August 1961 to January 1967. The commercial hot strip was firstly annealed and cold-rolled at a reduction of 53%, and then the cold-rolled strip cut and welded by union-melt arc method, and then cold-rolled a second time in the transverse direction at a reduction of 50%. The factory tests were done eleven times, and we succeeded in getting a wide strip, 750-mmW×(0.7,1.0)-mmT×Coil. The discussions in the AEG about the application of this coil for large rotating machines carried on over two years, from April 1965 to April 1967. AEG's requests were as follows, (1) this coil would be used for the core material of very large rotating machines such as over 500MVA especially 1,200MVA in order to minimize the machine, (2) possible requested quantities were estimated to be 20,000T/Y in all EC, 6,000T/Y in Germany and 150T/Y for AEG at that time, (3) coil size could be 750-mmW×(0.7,1.0)-mmT×Coil with insulation film, and (4) the permissible price would be 10~15% higher, at highest 25%, than the price of commercial single oriented silicon steel. Generally, core steel prices at that time were 600~800DM (10DM=900¥) for non-oriented (dynamo core), 2,000DM for single oriented (transformer). Many tests and discussions with AEG concluded that commercial production of 500T/M would be possible using ZS sheet mill (investment 450M¥ at that time), but the production cost would be at least 30% higher. Finally, we had to give up this production program in August 1967.

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