Journal of Materials Processing Technology 242 (2017) 182–195

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Skew rolling and its effect on the deformation textures of non-oriented electrical steels

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ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form
21 November 2016
Accepted 25 November 2016
Available online 27 November 2016

Keywords:
Non-oriented electrical steel
Texture
Rolling
Finite element analysis
Deformation

ABSTRACT

In order to effectively control the crystallographic textures of non-oriented electrical steels and optimize the magnetic properties of the final steel sheets, a new rolling scheme, i.e. skew rolling, was proposed and tested to process non-oriented electrical steels, aiming at altering the conventional rolling texture that normally contains magnetically unfavorable $\{111\}\perp$ND (normal direction) components which would retain or even strengthen after annealing. In the skew rolling process, the hot-rolled steel plates were fed into the cold mill rolls at an angle (0°–45°) from the conventional rolling direction. The in-plane rotation of the plate with respect to the rolls not only changes the starting texture obtained from conventional hot rolling and annealing, it also fundamentally alters the deformation features, i.e. from plane-strain compression to three-dimensional deformation, where not only the material is reduced in thickness and elongated, but it is also extended in the transverse direction (TD) and bent. These changes make the skew rolling process very effective in altering the deformation texture, thus it has the potential to optimize the final annealing texture. The skew rolling process was simulated by finite element methods to illustrate the deformation characteristics, and to reveal the stress/strain state of the material during deformation. Three non-oriented electrical steels with various silicon contents (0.9%, 1.8% and 2.8%, weight percentages) were cold rolled using this scheme. The textures after skew cold rolling were compared to those obtained by conventional rolling, and significantly different textures were observed.

1. Introduction

Non-oriented electrical steel sheets for motor core laminations are normally manufactured via a series of thermomechanical processing steps consisting of casting, hot rolling, cold rolling and annealing. The microstructure, crystallographic texture and magnetic properties of the final sheets are, to a large extent, determined by the rolling operations and the subsequent heat treatments. The ideal texture for non-oriented electrical steels is $\{001\}\perp$ND, since it has the most number of easy magnetization $\langle 100\rangle$ axes lying in the sheet plane and fulfills the requirement for rotating magnetization, while the $\{111\}\perp$ND texture should be avoided since it has the hard $\langle 111\rangle$ axes lying in the magnetization directions. Extensive research has already been carried out to vary the numerous operational parameters in the manufacturing processes, trying to optimize the final texture. Takashima et al. (1997) produced a $\{001\}\langle 210\rangle$ texture by using a two-stage cold rolling method on a 0.13% Si steel, but it was not clear if the cold rolling with intermediate annealing could produce similar textures in high silicon steels. Kawamata et al. (1997) investigated the effect of cold rolling parameters, i.e. roll radius and plate thickness, on the recrystallization texture, and found that the roll radius and plate thickness mainly had an effect on the surface texture of the rolled steel. Cheong et al. (2003) and Shimazu et al. (1994) reported the influence of temper rolling on the formation of the annealing texture, and observed that the temper mill extension and roll roughness had a significant effect on the magnetic properties, i.e. high temper mill extension and smooth work rolls resulted in a sharper texture and high anisotropy in peak permeability values between the rolling and transverse directions. Da Cunha and Paolinelli (2002) studied the effect of annealing temperature on the microstructure and magnetic properties of a 2% Si steel, and found that grain growth at high temperatures strengthened the unfavorable $\{111\}\perp$ND texture, but the adverse effect of this texture was overcome by the grain growth associated with the high temperatures. Although with these efforts and many other investigations, Kestens and Jacobs (2008) have pointed out that, “even the widest variation of the conventional processing parameters applied in the state-of-the-art steel manufacturing would only produce limited variations in the magnetic quality of the textures”.

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http://dx.doi.org/10.1016/j.jmatprotec.2016.11.033

It was very difficult to achieve the desired {001}⊥ND texture by using traditional rolling and annealing processes as metallurgical mechanisms that control the recrystallization of conventionally-cold-rolled sheets do not promote the formation of such a texture during annealing.

Rolling is a fundamental manufacturing technology used to transform preformed shapes into a form either suitable for further processing or as a finished product. The ingot or plate is passed through one or more pairs of rolls, and the material is compressed between the rolls while it is driven forward due to the friction between the rotating rolls and the metal surfaces. As a result, the material is reduced in thickness and elongated. The conventional sheet metal rolling is usually assumed to be a two-dimensional forming process in which deformation essentially occurs only in the normal and rolling directions (plane strain), and the material does not change in the width direction, i.e. lateral spread is negligible (Lenard, 2014). In addition, the sheet rolling process is symmetrical with respect to all the three axes, i.e. the normal, rolling and transverse directions (ND, RD, and TD).

Recent studies by Kestens and Jacobs (2008) and Hayakawa and Kurosawa (2002) have shown that by rotating the hot-rolled plate around the normal direction by 90° before cold rolling, i.e. switching the RD and TD (known as "cross rolling"), it was possible to produce very strong cube ({001}⟨100⟩) or rotated cube ({001}⟨110⟩) textures in the final sheets and thus achieve excellent magnetic quality. It is understood that the in-plane rotation of the plate before cold rolling actually changes the initial texture for cold deformation so that it can alter the paths of orientation flow during plastic deformation, and causes the formation of different textures (He et al., 2015; He and Hilinski, 2016; Kurosaki et al., 1999). These textures might have favored the formation of the cube components during the subsequent annealing process. However, rotating the hot-rolled plate by 90° before cold rolling is only possible in laboratory for research purposes. Implementing such a process in an industrial continuous production line is not feasible.

In this study, a new rolling process (known as "skew rolling") was proposed and tested to intentionally alter the rolling textures of electrical steel sheets. This rolling scheme differs from "cross rolling" in that, instead of rotating the hot band by 90°, the plate is only rotated by an angle $\leq 45°$ from the hot rolling direction. In skew rolling, since the plate is still essentially driven forward along the longitudinal direction although lateral motion along the roll width direction also occurs, plates much *longer* than the roll width can be processed (not like in cross rolling where both the width and length of the plate are limited by the roll width). Nevertheless, the process may be interrupted when the plate hits one side of the roll stands, at which the plate needs to be moved back to the other end of the rolls to continue the process. Rolling experiments were conducted to test this new rolling scheme, and finite element analyses (FEA) were carried out to reveal the deformation characteristics of the skew rolling process. The deformation textures of three non-oriented electrical steels cold rolled at various skew angles were analyzed and compared.

2. Materials and experimental procedure

The materials used for this study were three non-oriented electrical steels containing 0.9%, 1.8% and 2.8% of silicon (wt%). The addition of silicon to the steel is to increase the electrical resistivity and thus reducing the eddy current loss. The chemical compositions and the resistivity of these steels are listed in Table 1. The materials were melted in a vacuum induction furnace and cast into 200 × 200 mm^2 (cross section) ingots (~227 kg each). The ingots were then reheated to a nominal temperature of ~1040 °C, and hot rolled from 200 mm to ~25 mm in 6 passes in a two-high reversing laboratory rolling mill. The oxides on the surfaces of the steels were machined in a lathe, and ~3.1 mm each side was removed. The plates were then applied with an anti-oxidation coating, cover plated with hot bands, and wrapped in stainless steel foil as a preventative measure against decarburization in the reheating operation at ~1040 °C. The plates were hot rolled again to a nominal band gauge of 2.2–2.6 mm in 4 passes. The hot bands were pickled in HCl acid and annealed in a 100% dry hydrogen atmosphere for ~60 h (with ~38 h of soaking at ~840 °C). The annealed hot bands were then cut to small rectangular plates (200 mm × 50 mm) with the longitudinal direction parallel to the hot rolling direction. These plates were then used for skew cold rolling tests.

Table 1
Chemical composition and electrical resistivity of the electrical steels (wt%).

Material	C	Mn	P	S	Si	Al	Fe	ρ (μΩ-cm)
Low-Si	0.0021	0.307	0.010	0.0011	0.875	0.461	Bal.	28.3
Mid-Si	0.0023	0.299	0.010	0.0011	1.826	0.515	Bal.	40.0
High-Si	0.0033	0.303	0.010	0.0011	2.767	0.516	Bal.	51.0

The schematic of the skew rolling process as well as the roll bite configuration are shown in Fig. 1, where the force in the nominal rolling direction is decomposed into two components along the hot-band transverse direction and the hot-band rolling direction, which causes the deformation and motion of the workpiece in these directions. As a result, skew rolling not only reduces the thickness, elongates the plate, but it also increases the width (lateral spread), and thus is a three-dimensional deformation process. Two different material feeding schemes were used (Fig. 1c): i) the skew feeding was kept in the same direction for all the rolling passes, *unidirectional feeding*; ii) the workpiece was flipped 180° about the nominal RD between alternative passes, *bidirectional feeding*. Theoretically, flipping the sheet between rolling passes does not change the deformation mode of the material. However, this will reverse the direction of the material motion along the roll axis. Flipping between alternative passes is equivalent to rotating the roll stands in opposite directions with respect to the sheet so that the distance travelled along the roll axis in the previous pass can be recovered in the next pass due to the motion in opposite direction. In this way, the workpiece can be kept within the range of the roll width and the rolling process may be continuous.

During skew cold rolling, the thickness and width of the sheet after every two passes (each pass with ~10% nominal thickness reduction) were measured and compared at different skew angles, which revealed the dimensional changes of the sheet after skew rolling. The textures of the cold-rolled sheets were measured by X-ray diffraction (XRD) at the mid-thickness plane of the sheet (the hot band RD, TD and ND were taken as the reference frame). The samples were prepared by first grinding to approximately half thickness, then polishing using 9 μm and 3 μm diamond pastes, and finally etching in a 7% HF solution in hydrogen peroxide (30% H_2O_2) for 10 s. Three incomplete pole figures (110), (211) and (200) were measured in a Bruker D8 Discover X-ray diffraction goniometer equipped with a Vantec 500 area detector using Co K-α X-ray operated at 35 kV and 45 mA (with oscillation of ±7 mm and ±5 mm in the HRD and HTD, respectively). The orientation density functions (ODFs) were then computed from the measured pole figures using the MTEX software (with the de la Vallée Poussin kernel, 5° halfwidth and resolution) (Hielscher and Schaeben, 2008). Bunge's Euler notation (Bunge, 1982) was used to represent the ODF sections.

3. Finite element simulation

The skew cold rolling process was simulated using commercial FEA software ABAQUS. An explicit dynamics approach was uti-