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Effect of skin pass rolling reduction rate on the texture evolution of a non-oriented electrical steel after inclined cold rolling

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ABSTRACT

In order to promote the magnetically favourable <001>//ND texture (θ-fibre) and minimize the unfavourable <111>//ND fibre (γ-fibre) in non-oriented electrical steel, an unconventional cold rolling scheme was employed in this study, in which the cold rolling was carried out at an angle (i.e. 30°, 45°, 60°, and 90°) to the hot rolling direction (HRD). After annealing, two steel sheets (i.e. those after cold rolling at 60° and 45° to the HRD) were found to have considerably different textures from other sheets, i.e. showing the strongest and the weakest θ-fibre textures, respectively. These two sheets were then subjected to skin pass rolling to various reduction rates from 5–20% to investigate the effect of rolling reduction on the evolution of texture. It was found that during skin pass rolling, the cube texture ({001}<100>) was gradually weakened and the rotated cube orientation ({001}<110>) was strengthened. With the increase of the reduction rate, the {112}<110> orientation on the α-fibre became a major component. Upon final annealing, the cube texture was slightly restored, but the volume fraction was considerably lower than that before skin pass rolling.

1. Introduction

Non-oriented electrical steels have been widely utilized as a core lamination material for electric motors, generators, alternators, etc. to amplify magnetic flux, and have thus found many applications in general appliances, wind mills, electric vehicles (EVs), etc. [1–5]. Superior magnetic properties are desired in traction motors in EV, since high torque is required when accelerating, which needs a high magnetic flux density for the winding core, while at regular driving speeds, core loss is desired to be minimum to reduce the energy loss, which requires the core material to have low iron loss [4]. It is well known that the magnetic properties of non-oriented electrical steels are influenced by a number of factors such as chemical composition, sheet thickness, grain size, residual stress, crystallographic texture, etc. [1–3,5]. In order to improve the magnetic permeability and reduce core loss, a <001>//ND texture (θ-fibre), which comprises the cube, rotated cube, and all orientations with the {001} planes parallel to the sheet plane, is desired since it contains the most number of the easy magnetization axes <001> in the sheet plane. The <111>//ND (γ-fibre) texture has the hard magnetization axes <111> in the sheet plane, and thus needs to be suppressed in the final steel sheets [6,7].

For electrical steel with a given chemical composition, the final texture of the sheet is highly dependent on the manufacturing processes that usually include casting, hot rolling, cold rolling and annealing. During crystallization (solidification), plastic deformation, phase transformation and recrystallization, the orientations of the crystals will be altered several times, and the final texture will be affected by all these processes [8–10]. Although numerous investigations have already been carried out to optimize the operational parameters (e.g. temperature, rolling reduction rate, annealing conditions, etc.), very limited improvement in the final texture has been achieved. This is mainly due to the fact that, in conventional rolling, the θ-fibre formed in hot rolling generally changes to the γ- and α-fibres after cold rolling and annealing. A number of unconventional processing techniques, e.g. cross rolling [6,11], two-stage cold rolling [12–15], columnar grain growth [16], phase transformation annealing [17,18], etc., have also been developed to optimize the texture of non-oriented electrical steels. However, these techniques are usually difficult to be implemented in industry for mass production.

In a recent study, He et al. [19,20] investigated the influence of initial texture on the final annealing texture of non-electrical steels, in which the cold rolling direction was intentionally inclined at an angle between 0° and 90° to the hot rolling direction (also known as *inclined rolling*). It was shown that inclined rolling was able to significantly

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enhance the cube texture in the final sheets when the inclination angle was 60°. Although the inclined rolling process was not feasible to be implemented in a continuous production line either, it was proven that by simply changing (rotating) the initial texture before cold rolling, the final annealing textures could be significantly altered. An advantage of inclined rolling was that the chemistry, microstructure and processing history can all be kept the same, while only the initial texture was changed. In this way, it was able to investigate the effect of initial texture on the deformation and annealing textures without the influence of other parameters such as microstructure, chemistry and processing history. In inclined rolling, by simply cutting the sample at an angle to the hot rolling direction and rolling the material conventionally, the initial texture can be altered in a wide range, and this makes it possible to examine how different initial textures affect the deformation and final annealing textures. Inclined cold rolling does not require special heat treatments after deformation, while the proposed alternatives in the literature such as phase transformation annealing, columnar grain growth, etc., usually need long holding times at high temperatures to achieve the optimal texture, which is both energy and time consuming.

Since in non-oriented electrical steel processing the annealed thin sheets are usually subjected to final skin pass rolling in order to flatten and straighten the sheets, it is of interest to investigate the effect of skin pass rolling on the texture of the annealed steel. Also, skin-pass-rolled sheets need to be final annealed to release the stress introduced during the final rolling pass, thus it is also interesting to examine if the skin pass rolling has an effect on the final annealing texture. In this paper, a non-oriented electrical steel was first incline rolled to a thickness of 0.5 mm (with ~78% reduction) and annealed. It was then skin pass rolled (without applying tension) to various reduction rates up to 20%. The textures before skin pass rolling, after skin pass rolling, and after final annealing were evaluated by electron backscatter diffraction (EBSD) techniques. The effect of the rolling reduction rate on the deformation and final annealing textures was examined.

2. Material and experimental procedures

The material investigated was a low silicon (0.88 wt%) non-oriented electrical steel, and its chemical composition is given in Table 1. The steel was melted in a vacuum furnace and cast into 200×200×300 mm^3 (width×thickness×length) ingots. The steel was then heated up to a nominal temperature of 1311 K (1038 °C) and hot rolled to a thickness of 25 mm (from 200 mm) with ~90% reduction. After removing the oxides from the surfaces, a second hot rolling (at the same reheat temperature of 1038 °C) was carried out in order to further reduce the thickness to 2.5 mm (also with ~90% reduction). The steel was then pickled at 355 K (82 °C) using a hydrochloric acid solution. The material was subsequently annealed at 1113 K (840 °C) for 60 h in a dry 100% hydrogen atmosphere.

The annealed steel was then cut into small rectangular pieces (200×50 mm^2) at various angles (0°, 30°, 45°, 60°, 90°) to the hot rolling direction (HRD), which were cold rolled to a final thickness of 0.5 mm (Fig. 1). The cold-rolled steel sheets were subsequently annealed at 1023 K (750 °C) for 5 min in argon protected atmosphere and furnace cooled. The texture after annealing was characterized by electron backscatter diffraction (EBSD). Two samples, i.e. those incline rolled at 45° and 60° to the HRD, were selected to undergo further skin pass rolling with various reduction rates (5, 10, 15 and 20%). The skin-pass-rolled samples were annealed again (final annealing) at 750 °C for 5 min, and the textures were characterized.

Table 1
Chemical composition of the investigated steel (wt%).

C	Mn	P	S	Si	Al	Fe
0.002	0.31	0.01	0.001	0.88	0.46	balance

The microstructures of the steel after cold rolling, annealing and skin pass rolling were characterized by optical microscopy. The samples were prepared using conventional metallographic procedures and etched with a 2% nital solution for 30 s. The grain size was measured according to ASTM standard (ASTM E112-96) [21]. For EBSD characterization, a final polishing step using a 0.05 μm colloidal silica solution was applied after the conventional metallographic preparation steps. EBSD scans were performed on the RD-ND cross-sections in a field emission gun scanning electron microscope (FEG-SEM) (Nova NanoSEM, FEI) equipped with an EDAX Orientation Imaging Microscopy system (OIM 6.2). The scanned areas (approximately 0.5×2.2 mm^2) usually covered almost the entire thickness of the steel sheets. Orientation distribution functions (ODFs) were then calculated using a harmonic series expansion method, in which the series rank and the Gaussian half-width were set to 22 and 5°, respectively [22]. Typical texture components were plotted on the φ_2=45° section of the Euler space (Bunge notation) [23,24]. The volume fractions of ideal textures and fibres were calculated from the ODFs within a 15° tolerance from the exact orientation. Taylor factors were calculated for the major texture components using a family of slip systems for bcc metals, i.e. {110} < 111 > , {211} < 111 > and {321} < 111 > .

3. Results

3.1. Microstructure

After inclined cold rolling at various angles (0°, 30°, 45°, 60° and 90°) to the HRD, the microstructures were characterized and shown in Fig. 2. Three differently etched regions can be noticed in the optical micrographs of the deformed sheets: i) lightly etched regions (L) that essentially contain no shear/deformation bands, indicating relatively homogeneous plastic deformation, ii) moderately etched regions (M) with visible shear bands in some areas within the grains, iii) heavily etched (dark) regions (H) with dense dislocations, implying highly inhomogeneous plastic deformation and high stored energy. These three regions are present in all the samples regardless of the rolling direction to the HRD. However, it is noted that rolling at 30°, 45° and 60° to the HRD produced more inhomogeneous regions (M and H) than those rolled at 0° and 90° angles.

The microstructures of the samples after annealing at 1023 K (750 °C) for 5 min are shown in Fig. 3. Although the cold rolling direction is at different angles to the HRD, the average grain sizes of all the samples after annealing are very close with each other, i.e. from ~28 μm to ~34 μm (Table 2). Rolling at 60° to the HRD produces the smallest average grain size (27.9 μm), while cross rolling (90°) results in the largest average grain size (33.9 μm). The microstructure is inhomogeneous at all the rolling angles, i.e. in each case, the grain diameters vary from a few microns to more than 100 μm.

The EBSD inverse pole figure (IPF) maps of the samples after cold rolling and annealing are illustrated in Fig. 4. In all the maps, the dominant colors are red, orange and pink, indicating that most of the crystals have orientations close to < 001 > //ND. There is essentially no blue color, implying that there is almost no < 111 > //ND (γ-fibre) texture. Some purple grains are apparently shown in all the samples (especially in the sample rolled at 0° to the HRD), which indicates that a < 112 > //ND texture is present. Crystals in green color (< 011 > //ND) are also noticed in all the samples. In each case, the grain structure is inhomogeneous, i.e. grain sizes vary considerably from a few microns to more than 100 μm, which is similar to those observed in optical micrographs (Fig. 3). The small grains are usually distributed in bands parallel to the rolling direction. After conventional rolling (0°) and annealing, the grains near the sheet surfaces are generally smaller than those in the middle thickness. When the angle is 30°, the small grains are distributed near the middle thickness plane, but there are