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Improved cold rolling workability of warm rolled Fe–6.5wt%Si electrical steel with columnar grains by annealing

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Abstract: The effects of annealing temperature (with the annealing time being constant at 1 h) on the microstructure, ordering, residual stress, mechanical properties, and subsequent cold rolling workability of Fe–6.5wt%Si electrical steel with columnar grains were investigated, where the steel was warm rolled at 500°C with a reduction of 95%. The results show that recrystallization began to occur in the sample annealed at 575°C and that full recrystallization occurred in the sample annealed at 625°C. When the annealing temperature was 500°C or greater, the extent of reordering in the sample was high, which reduced the room-temperature plasticity. However, annealing at temperatures below 300°C did not significantly reduce the residual tensile stress on the edge of the warm rolled samples. Considering the comprehensive effects of annealing temperature on the recrystallization, reordering, residual stress, and mechanical properties of the warm rolled Fe–6.5wt%Si electrical steel with columnar grains, the appropriate annealing temperature range is 300°C–400°C. Unlike the serious edge cracks that appeared in the sample after direct cold rolling, the annealed samples could be cold rolled to a total reduction of more than 71.4% without the formation of obvious edge cracks, and bright-surface Fe–6.5wt%Si electrical steel strips with a thickness less than 0.1 mm could be fabricated by cold rolling.

Keywords: electrical steel; cold rolling; annealing; mechanical properties; workability

1. Introduction

Fe–6.5wt%Si electrical steel (high-silicon electrical steel) is an ideal material for the iron cores of generators, motors, and transformers because of its excellent soft magnetic properties, such as its high magnetic permeability, low magnetic loss, and near-zero magnetostriction coefficient [1–2]. However, unlike common electrical steel (< 4wt%Si), high-silicon electrical steel strips with a thickness of 0.1–0.5 mm for engineering applications are difficult to fabricate by the conventional rolling process because the ductility of conventional as-cast high-silicon electrical steel is almost zero.

Previous researches have made great progress in improving the cold rolling workability of high-silicon electrical steel through control of the rolling process and the degree of order. For instance, Shin *et al.* [3] reported that hot rolled high-silicon electrical steel sheets could be cold rolled with a reduction of 11% without severe edge cracks after the degree of order was reduced by heat treatment. Ros-Yáñez *et al.* [4] demonstrated that cold rolled high-silicon electrical steel strips with a thickness of 0.4–0.5 mm can be fabricated through comprehensive control of the rolling process and degree of order.

Our previous study indicated that the plasticity of high-silicon electrical steel samples with columnar grains fabricated by directional solidification is much higher than that of the samples with equiaxed grains [5]. Moreover, the ductility of the high-silicon electrical steel samples with columnar grains at intermediate and low temperatures can be further improved by pre-deformation [6], microalloying [7], and heat treatment [8]. After these plasticizing treatments, high-silicon electrical steel strips with a bright surface and a thickness of 0.15 mm can be fabricated by warm rolling (rolling at 400°C) followed by cold rolling (rolling at room temperature) directly, without any intermediate annealing [9]. These related studies provide a possible technological approach for short-process and high-efficiency fabrication

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of high-silicon electrical steel strips via large rolling deformation. However, edge cracks have been observed to still exist in the cold rolled high-silicon electrical steel strips, which substantially reduce the cold rolling yield.

Edge cracks appear in high-silicon electrical steel strips during cold rolling because of the high intrinsic brittleness of the alloy (the presence of B2 and $D0_3$ ordered phases) [10–11]. However, the residual tensile stress on the edge of the warm-rolled sheet, which is produced during the large warm rolling deformation, may also be an important factor leading to the formation of edge cracks during the subsequent cold rolling. Annealing is an effective method of relieving the residual stress in the sheet. However, the high-silicon electrical steel exhibits a reordering phenomenon at high temperatures [12]. The warm rolled sample with a low degree of order, which is disordered by large warm rolling deformation, will be reordered during annealing at high temperatures. This reordering leads to the high degree of order in the annealed sample and results in the reduction of cold rolling workability. Therefore, determining the appropriate annealing condition that can not only effectively reduce the residual tensile stress on the edge of the sheet but also avoid the reordering in the sample disordered by warm rolling as much as possible is the key to solving the problem of edge-crack formation during subsequent cold rolling.

Therefore, in this study, the effects of annealing on the microstructure, ordering, residual stress, mechanical properties, and subsequent cold rolling workability of the warm rolled high-silicon electrical steel sheets with columnar grains were investigated, and the appropriate annealing conditions were determined. The results can be effectively used to prevent the edge-crack formation in the high-silicon electrical steel during cold rolling.

2. Experimental

Referring to our previously reported method [13], the columnar-grained high-silicon electrical steel slab with a size of 100 mm × 55 mm × 7 mm (length × width × thickness) was fabricated by a directional solidification method using a Bridgman zone-melting equipment developed in our laboratory. The composition of the high-silicon electrical steel was 6.5wt% Si, 0.02wt% B, and balance Fe.

According to our previous study [12], the slab was warm rolled at 500°C along the growth direction of the columnar grain after the oxide skin was pickled. The reduction of each rolling pass was controlled in the range of 15%–20%, and the total reduction was 95%. The slab was first warm rolled on a two-high mill (with a roll diameter of 320 mm), which reduced the thickness from 7 mm to 1 mm, it was then rolled to a thickness of 0.35 mm using a four-high mill with a work-roll diameter of 120 mm. After the oxide skin was pickled, both the warm rolled sample and the samples after isochronal annealing were cold rolled on another four-high mill (with a work-roll diameter of 60 mm).

The isochronal annealing of the warm rolled samples was performed in a box-type resistance furnace at 200–700°C for 1 h, and then followed by furnace cooling to room temperature.

To analyze the effects of annealing temperature on the microhardness of the warm rolled high-silicon electrical steel samples, Vickers microhardness measurements were carried out using a HXD−1000T Vickers hardness tester with a load of 9.8 N and a holding time of 15 s.

Using the method for estimating residual stresses by microhardness sharp indentation, the residual stress of the warm rolled and annealed samples were evaluated on the basis of the ratio of various indentation hardness areas [14–15]. The indentation area ratio C^2 is defined as

$$C^2 = A/A_{\text{nom}} \tag{1}$$

where A is the real area of the indentation, and A_{nom} is the nominal projected area (the quadrilateral area is obtained by connecting the diagonal vertex of the indentation). In this study, the indentations were formed at the location with a distance of 500 μm from the sheet edge, and 11 indentation tests were performed for each sample. Variable C_0^2 is defined as the indentation area ratio of the residual stress-free state. When C^2 is greater than C_0^2, the indentation area is in the compressive stress state, and greater values of C^2 indicate greater residual compressive stress. In contrast, when C^2 is smaller than C_0^2, the indentation area is in the tensile stress state and smaller values of C^2 indicate greater residual tensile stress. Zhang *et al.* [16] have reported that the indentation area ratio of the residual stress-free state in high-silicon electrical steel is 0.99.

The warm rolled and annealed samples were subjected to tensile tests with a strain rate of 1×10^{-4} s^{-1} along the rolling directions using a MTS810 testing machine. The tensile fracture morphologies were observed using a SU8020 scanning electron microscope.

The optical micrographs of the samples were observed by optical microscopy. A Tecnai G2 F30 transmission electron microscope (TEM) operated at 300 kV was used to detect the dislocation configuration and degree of order of the samples. After being mechanically thinned to about 50 μm, the samples for TEM were electropolished in a solution consisting of 5vol% perchloric acid and 95vol% ethanol at −30°C using a twin-jet polisher operated at a voltage of 50 V.

3. Results and discussion

3.1. Effect of annealing temperature on the microstructure of the warm rolled sheets

The longitudinal section microstructures of the high-silicon electrical steel samples under the states of directional solidification, warm rolling, and annealing at various temperatures are shown in Fig. 1. The local magnified microstructures were inset in the top-right corner of each image of the warm rolled and annealed samples. As shown in Fig. 1(a), grain boundaries (GBs) of the columnar grains were approximately parallel to the direction of crystal growth. After the warm rolling process, the grain boundaries of the columnar grains became fuzzy and a large number of deformation bands appeared inside the columnar grains (Fig. 1(b)).

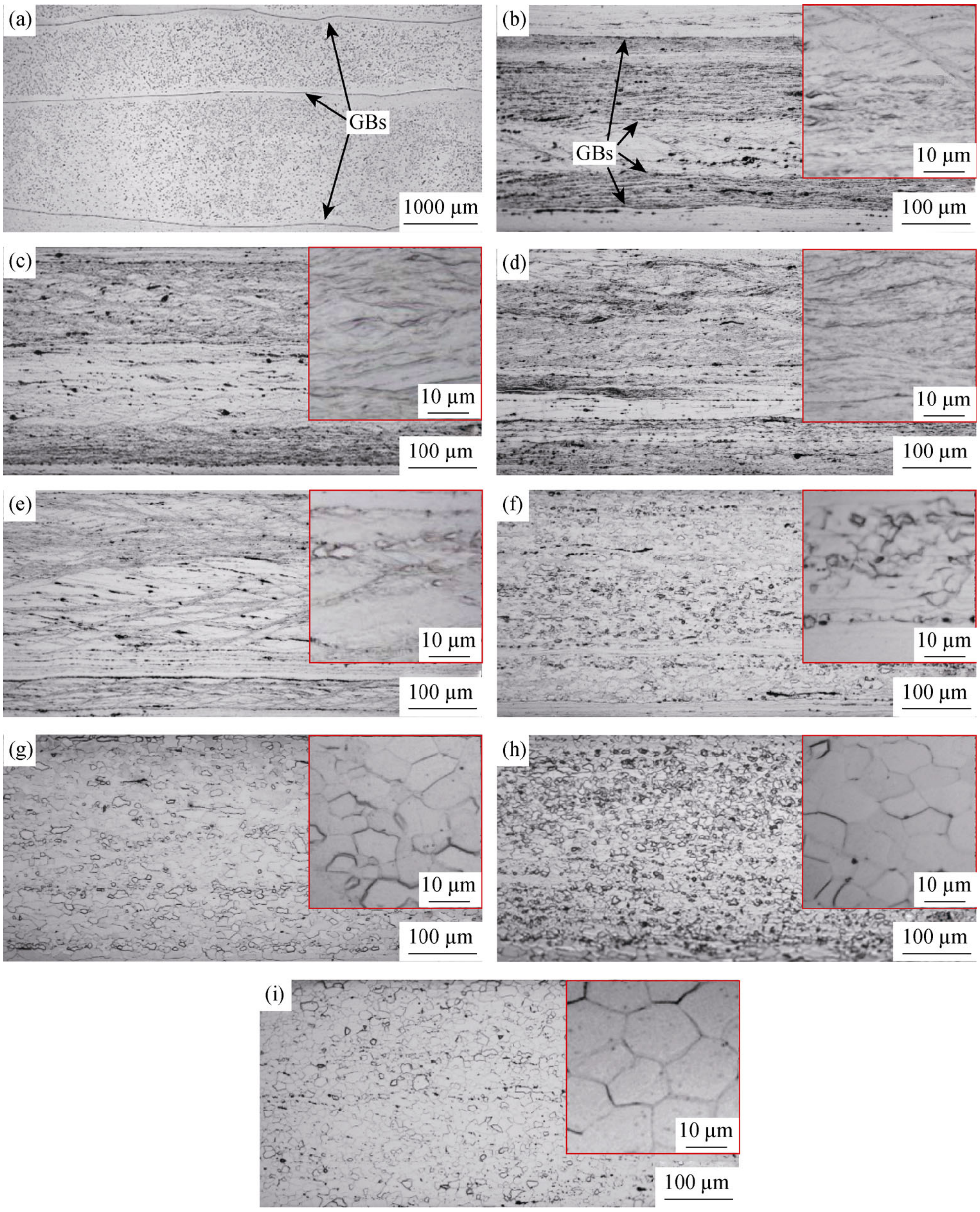

Fig. 1. Longitudinal section micrographs of the high-silicon electrical steel under various states: (a) directional solidification (the crystal growth direction is parallel to the horizontal direction), (b) warm rolled, (c) annealed at 500°C, (d) annealed at 550°C, (e) annealed at 575°C, (f) annealed at 600°C, (g) annealed at 625°C, (h) annealed at 650°C, and (i) annealed at 700°C.

The optical microstructures of the samples annealed at 500°C and 550°C were not significantly different from that of the warm rolled sample (Figs. 1(c) and 1(d)). When the annealing temperature was raised to 575°C, small equiaxed grains appeared in local deformation bands, which indicate that recrystallization began to take place in the sample (Fig.

1(e)). When the annealing temperature was raised to 600°C, most of the original columnar grains were replaced by the equiaxed grains with a size of ~6 μm because of the increasing extent of recrystallization; in addition, the grain boundaries of the original columnar grains became fuzzier (Fig. 1(f)). After the sample was annealed at 625°C, the original columnar grains were fully replaced by equiaxed grains with a size of ~10 μm, which indicates that full recrystallization occurred (Fig. 1(g)). When the annealing temperature was further raised to 650°C and 700°C, the recrystallized grains grew to ~12 μm and ~15 μm, respectively (Figs. 1(h) and 1(i)).

The dislocation configurations of the warm rolled high-silicon electrical steel sample and the samples annealed at various temperatures are shown in Fig. 2. A high density

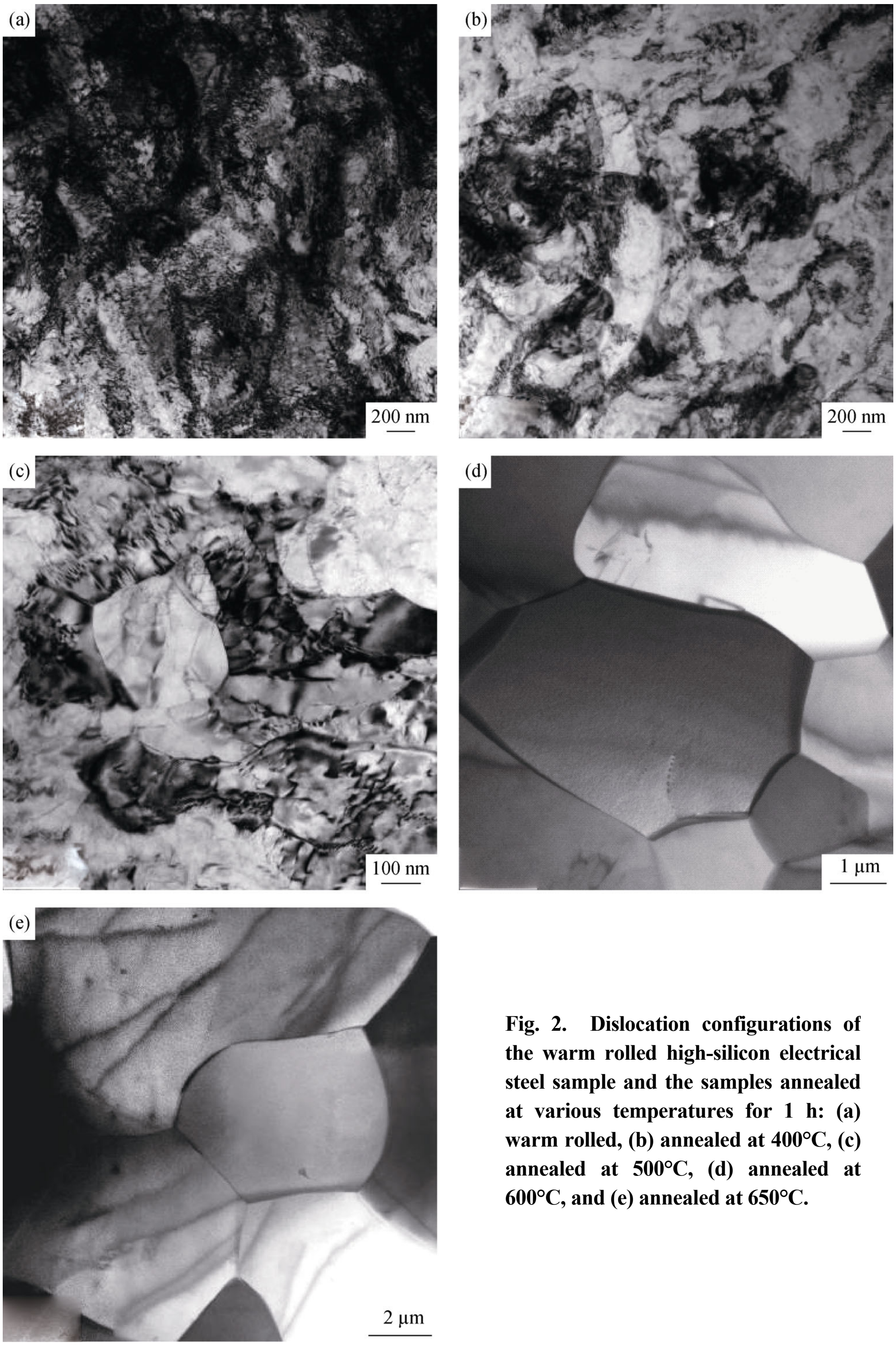

Fig. 2. Dislocation configurations of the warm rolled high-silicon electrical steel sample and the samples annealed at various temperatures for 1 h: (a) warm rolled, (b) annealed at 400°C, (c) annealed at 500°C, (d) annealed at 600°C, and (e) annealed at 650°C.

of dislocations and a high degree of dislocation tangles were observed in the warm rolled sample due to without dynamic recrystallization during warm rolling at 500°C with a reduction of 95%. Also, the dislocation clusters and fuzzy dislocation cells, which were formed from the dislocation tangles, were observed in the sample, as shown in Fig. 2(a). After being annealed at 400°C, the dislocation clusters and dislocation cells become clearer because of the motion and rearrangement of dislocations (Fig. 2(b)). When the annealing temperature was raised to 500°C, both the densities of dislocation and dislocation tangles were significantly reduced. The dislocation cells with shatter cell walls were still present in local areas of the sample. Meanwhile, a few subgrains were clearly observed in the sample (Fig. 2(c)). The equiaxed grains were observed in the recrystallization zone of the sample annealed at 600°C (Fig. 2(d)), and the growth of recrystallized grains occurred in the sample annealed at 650°C (Fig. 2(e)).

According to previous studies, the plasticity at intermediate and room temperature of the alloy with columnar grains is better than that of the alloy with equiaxed grains [5,17−19]. Thus, as the results of Figs. 1 and 2, to avoid the loss of plasticity due to the occurrence of recrystallization, 550°C or less is the most reasonable annealing temperature for the warm rolled high silicon electrical steel sheets with columnar grains.

3.2. Effect of annealing temperature on the ordering of the warm rolled sheets

The degree of order of high-silicon electrical steel can be characterized by the intensity of superlattice spots in TEM diffraction patterns and by the size of the antiphase domain [20–22]. In this study, the intensity of superlattice spots in the selected area diffraction pattern (SADP) in the {100} zone axis and the size of the antiphase domain under TEM dark field images of {100} superlattice spots were used to evaluate the effects of annealing temperature on the degree of order of the warm rolled high-silicon electrical steel.

Fig. 3 shows the [001] SADPs of the warm rolled high-silicon electrical steel sample and the samples annealed at 400–650°C. As shown in Fig. 3(a), the intensity of the superlattice spots at 1/2{020} was too weak to be identified in the warm rolled sample. In the sample annealed at 400°C, the superlattice spots at 1/2{020} were observed fuzzily (Fig. 3(b)). In the case of the sample annealed at 500–650°C, the intensities of the superlattice spots increased and the spots became clearer (Figs. 3(c)–3(e)). Fig. 3 indicates that the degree of order of the warm rolled sample was low, and that the degree of order changed slightly in the case of the sample annealed at 400°C; however, in the case of the samples annealed at 500–650°C, the degree of order increased with increasing annealing temperature.

To further quantitative analyze the degree of order of high-silicon electrical steel samples under different conditions, the size of the antiphase domain under TEM dark field images of 1/2{020} superlattice spots was observed, as shown in Fig. 4. Specifically, the antiphase domain image of the warm rolled sample could not be obtained because the degree of order of the sample was so low that the superlattice spots at 1/2{020} could not be observed (Fig. 3(a)). Therefore, in this study, only the sizes of the antiphase domains in the samples annealed at various temperatures were analyzed.

From Fig. 4, the size of the antiphase domain in the sample annealed at 400°C was less than 10 nm, which indicates that the degree of order of the sample was low. Compared with the size of antiphase domain in the sample annealed at 400°C, that in the sample annealed at 500°C increased sharply to approximately 50–120 nm, which represents a greater than ten-fold increase. Further raising the annealing temperature to 600°C and 650°C resulted in an increase in the size of antiphase domains to approximately 100–400 nm and 500–1500 nm, respectively.

The ordered alloys exhibit the characteristics of disordering by deformation, also exhibit the characteristics of reordering resulting from the low order degree when annealing at high temperature [12,23–24]. Such a low degree of order in the warm rolled sample is due to the disordering by the large warm rolling deformation at 500°C with a reduction of 95%. The reordering of the warm rolled sample with low degree of order will occur during annealing, and the extent of reordering increases with increasing annealing temperature because of the high atomic activity. Therefore, the degree of order of the sample annealed at 400°C is low because of the little reordering during annealing at this temperature. When the annealing temperature were further increased to 500–650°C, the extent of reordering increased remarkably, which led to the high degree of order in the samples.

According to the results in Figs. 3 and 4, annealing at 400°C or below is beneficial to the subsequent cold rolling of warm rolled high-silicon electrical steel because of the little reordering during annealing.

3.3. Effect of annealing temperature on the residual stress of the warm rolled sheets

A high level of residual tensile stress on the edge of the warm rolled high-silicon electrical steel sheets, which results

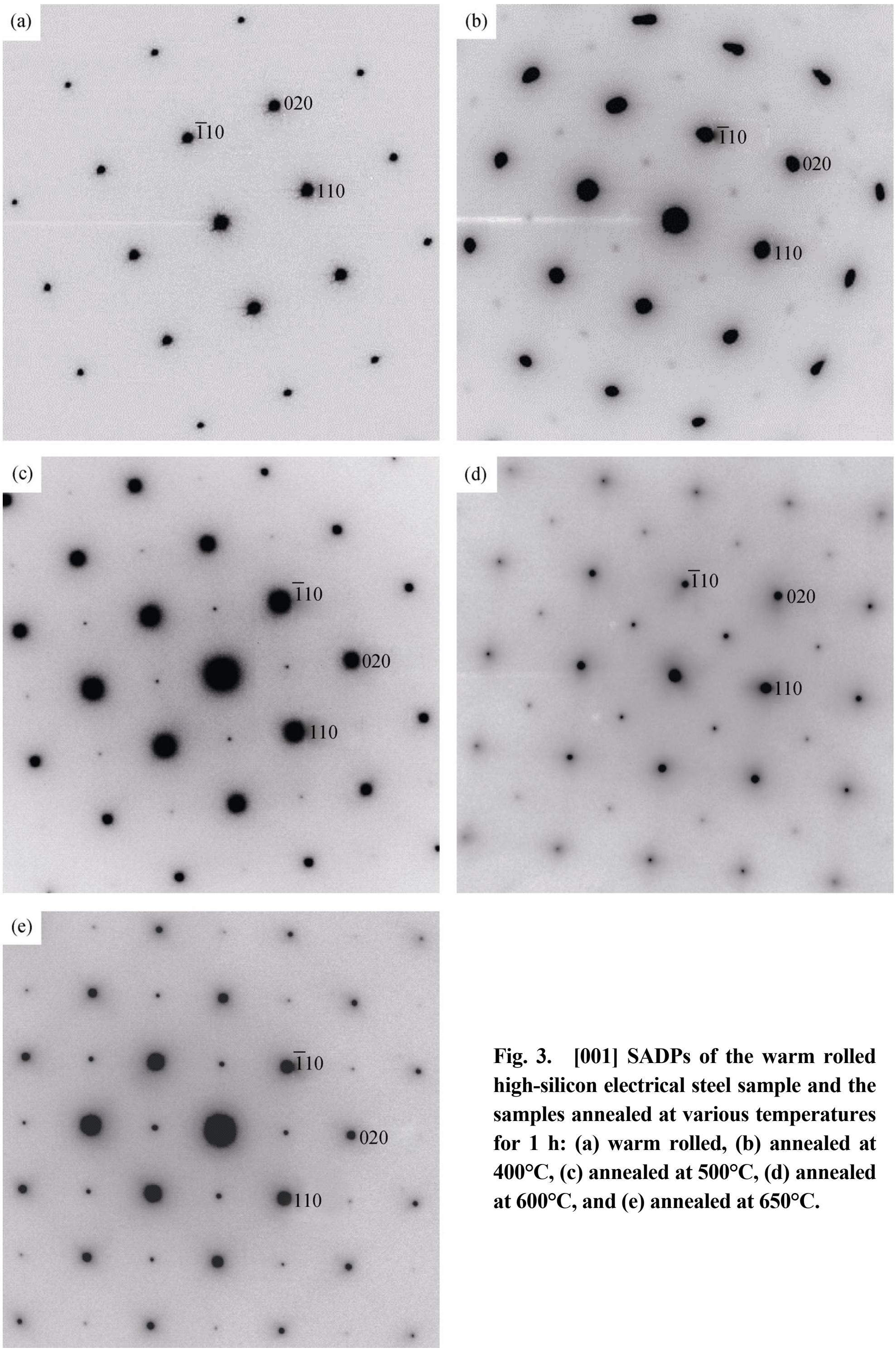

Fig. 3. [001] SADPs of the warm rolled high-silicon electrical steel sample and the samples annealed at various temperatures for 1 h: (a) warm rolled, (b) annealed at 400°C, (c) annealed at 500°C, (d) annealed at 600°C, and (e) annealed at 650°C.

from the greater deformation of the central part compared to the edge region along the rolling direction, may be an important factor leading to the formation of edge cracks during the subsequent cold rolling. Therefore, analysis of the residual tensile stress on the edge of the warm rolled sample annealed at various temperatures is necessary. The indentation area ratios of the warm rolled sample and the samples annealed at various temperatures are shown in Fig. 5. According to the work of Zhang *et al.* [16], the indentation area ratio of the residual stress-free state in high-silicon electrical steel is 0.99, as indicated by the dashed line in the figure. The indentation area ratio C^2 of the warm rolled high-silicon electrical steel was 0.88–0.98, which indicates that residual tensile stress exists on the edge of the sheet. After annealed at 200°C for 1 h, the indentation area ratios in the sample increased and their minimum value increased to 0.92, which implies that the level of residual tensile stress was partly reduced by this annealing. Raising the annealing temperature to 300°C, the indentation area ratios were further increased with a minimum value of 0.96, which indicates further reduction of the residual tensile stress. When the annealing temperature was further raised to 400–700°C, both the indentation area ratios and the minimum values changed little. The above results demonstrate that the residual tensile stress on the edge of the warm rolled sheet can be almost fully reduced when the annealing temperature is 300°C or greater.

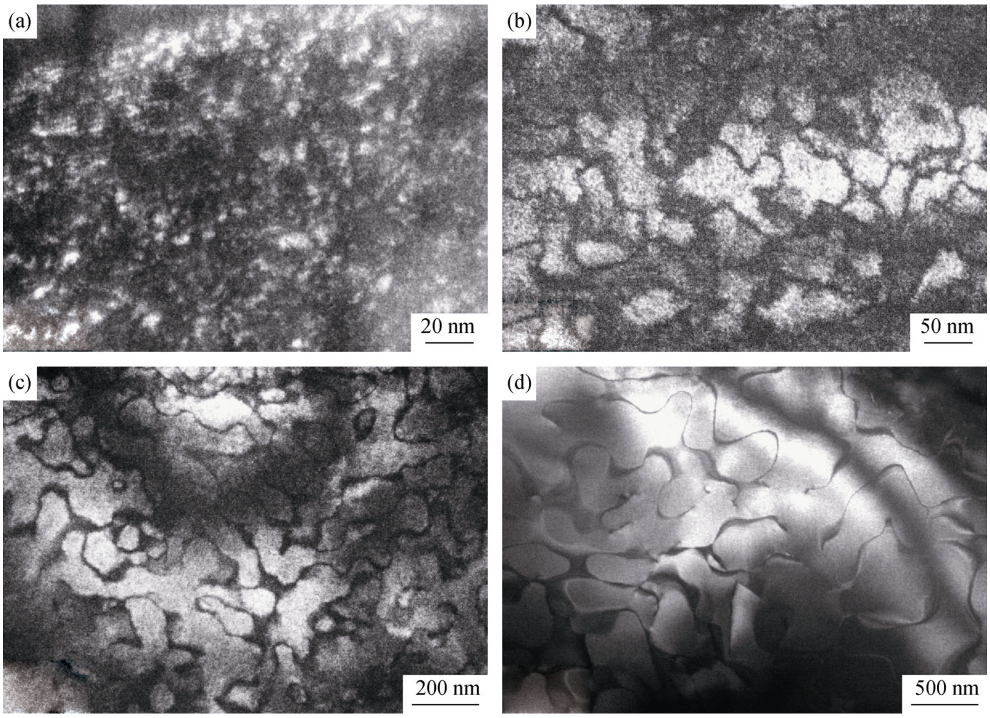

Fig. 4. Antiphase domains of the warm rolled high-silicon electrical steel samples annealed at various temperatures for 1 h: (a) annealed at 400°C, (b) annealed at 500°C, (c) annealed at 600°C, and (d) annealed at 650°C.

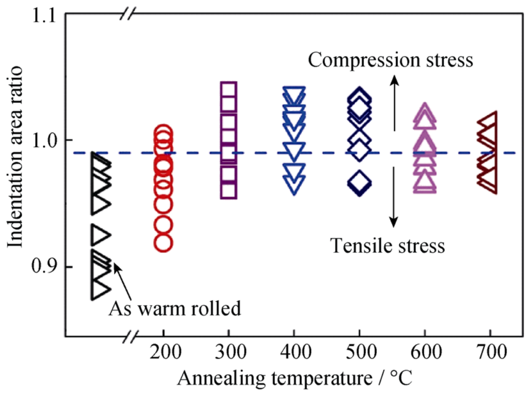

Fig. 5. Indentation area ratios of the warm rolled high-silicon electrical steel sample and the samples annealed at various temperatures (distance of 500 µm from the sheet edge).

When the residual tensile stress or the accumulated residual tensile stress on the sheet edge exceeds the ultimate strength of the material during rolling, edge cracks appear in the rolling sheet. Therefore, annealing plays an important role in reducing or eliminating edge cracks of the warm rolled high-silicon electrical steel sheet during subsequent cold rolling because it eliminates the residual stress.

3.4. Effect of annealing temperature on the mechanical properties of the warm rolled sheets

Fig. 6 shows the microhardness of the warm rolled high-silicon electrical steel sample and that of the samples annealed at 200–700°C. With increasing annealing temperature, the hardness of the samples tended to first decrease, then increase, and finally decrease rapidly.

From Fig. 6, the hardness of the high-silicon electrical steel sample with columnar grains can approach to about 4.7 GPa after being warm rolled at 500°C with a reduction of 95%. Such behavior may be caused by work hardening during the larger warm rolling deformation, where a high density of dislocations and a high degree of dislocation tangles were produced in the sample without recrystallization (Figs. 1(b) and 2(a)).

When the warm rolled samples were annealed at temperature below 400°C, recovery occurred; the extent of the recovery increased with the increase of the annealing temperature. The increasing extent of the disappearance and rearrangement of defects (vacancies and dislocations), which leads to the more release of deformation stored energy, results in the decrease of the hardness (Fig. 2(b)).

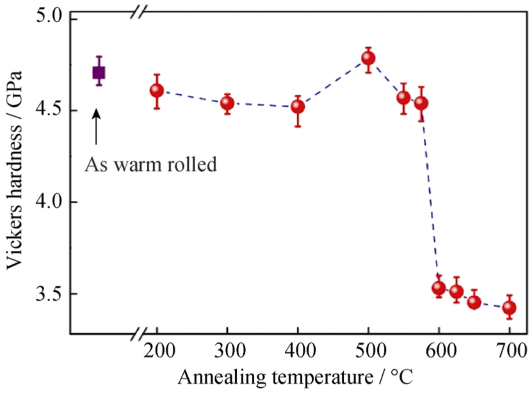

Fig. 6. Effect of annealing temperature on the microhardness of the warm rolled high-silicon electrical steel.

As shown in Fig. 6, the hardness of the sample annealed at 500°C increased abnormally. The hardness of the annealed sample should further decreased due to its further recovery (Fig. 2(c)). However, the degree of order in the sample annealed at 500°C was high because of its high reordering (Figs. 3 and 4(c)), which led to the increase of the hardness. The hardness of the sample increases when the increase of hardness induced by reordering is greater than the decrease of hardness induced by recovery. The result reflects that the reordering in the sample annealed at 500°C is high, which is unfavorable for the subsequent cold rolling workability.

The hardness obviously decreased when the annealing temperature was raised to 550°C or 575°C. When the annealing temperature was raised to 600°C, apparent recrystallization happened in the sample (Figs. 1(f) and 2(d)), which eliminated the work hardening and led to a decrease of the hardness. The reduction of hardness induced by recrystallization was greater than the increase of hardness induced by the reordering, which led to the sharp decrease of the hardness. Further raising the annealing temperature to 625–700°C, the hardness decreased slowly due to the full recrystallization.

Fig. 6 implies that the hardness of the warm rolled high-silicon electrical steel after annealing was affected synthetically by the microstructure and the ordering. When the high-silicon electrical steel was annealed at 400°C or below, its hardness was affected primarily by the recovery, which resulted in the hardness decreasing slowly with increasing annealing temperature. However, the increase of hardness was mainly due to a large amount of reordering when the sample was annealed at 500°C. In the case of annealing at 600°C or above, the hardness decreased to a low level because of the recrystallization.

To analyze the effects of annealing on the room-temperature mechanical properties of the warm rolled high-silicon electrical steel, the tensile properties of three groups of representative samples (i.e., warm-rolled samples, samples annealed at 400°C for 1 h (recovery and low degree of order), and samples annealed at 650°C for 1 h (full recrystallization and high degree of order)) were tested at room temperature. The engineering stress–strain curves and the elongation to failure are shown in Fig. 7.

From Fig. 7, the warm rolled high-silicon electrical steel sample exhibited a high tensile strength of about 1700 MPa, and the average elongation was about 0.73%. For the sample annealed at 400°C, the tensile strength decreased to about 1550 MPa and the average elongation increased to 1.19%, which indicates that the plasticity of the sample was significantly improved by this annealing. Further raising the annealing temperature to 650°C, the tensile strength of the sample further decreased to about 1050 MPa, whereas the average elongation decreased to 0.41%.

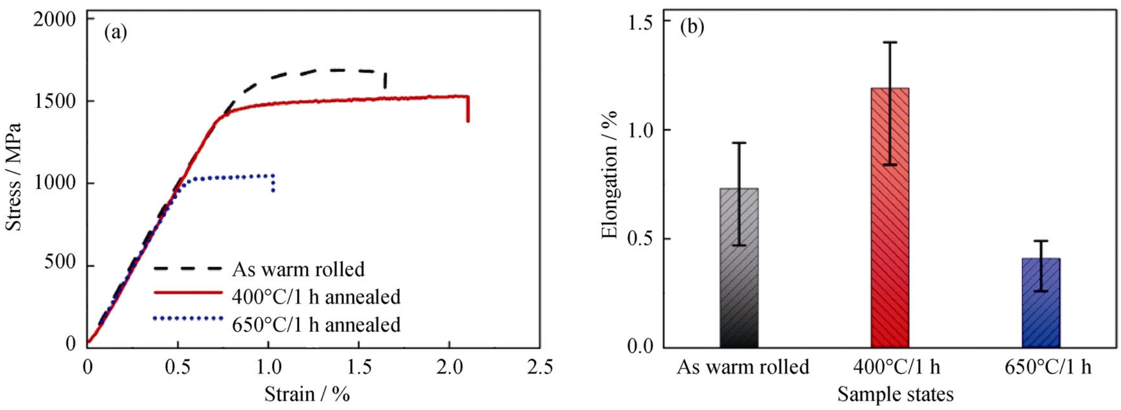

Fig. 7. Room-temperature tensile properties of the warm rolled high-silicon electrical steel sample and the samples annealed at 400°C and 650°C for 1 h: (a) engineering stress–strain curves and (b) elongations to failure.

Fig. 8 shows the tensile fracture morphologies of these three groups of samples. Figs. 8(a), 8(c), and 8(e) correspond to the fracture morphology of the warm rolled sample, the sample annealed at 400°C for 1 h, and the sample annealed at 650°C for 1 h. Figs. 8(b), 8(d), and 8(f) correspond to the local magnified images of Figs. 8(a), 8(c), and 8(e), respectively.

As shown in Figs. 8(a) and 8(c), the fracture morphologies of the warm rolled sample and the sample annealed at 400°C were basically similar, which were mainly featured as a mixture of cleavage fracture and dimple fracture. The local magnified images of dimple fracture in Figs. 8(a) and 8(c) are shown in Figs. 8(b) and 8(d), respectively, which indicates that local plastic deformation occurred in the samples. In the case of the sample annealed at 650°C, the fracture morphology of the sample mainly consisted of smooth intergranular fracture and cleavage fracture instead of dimple fracture (Figs. 8(e) and 8(f)).

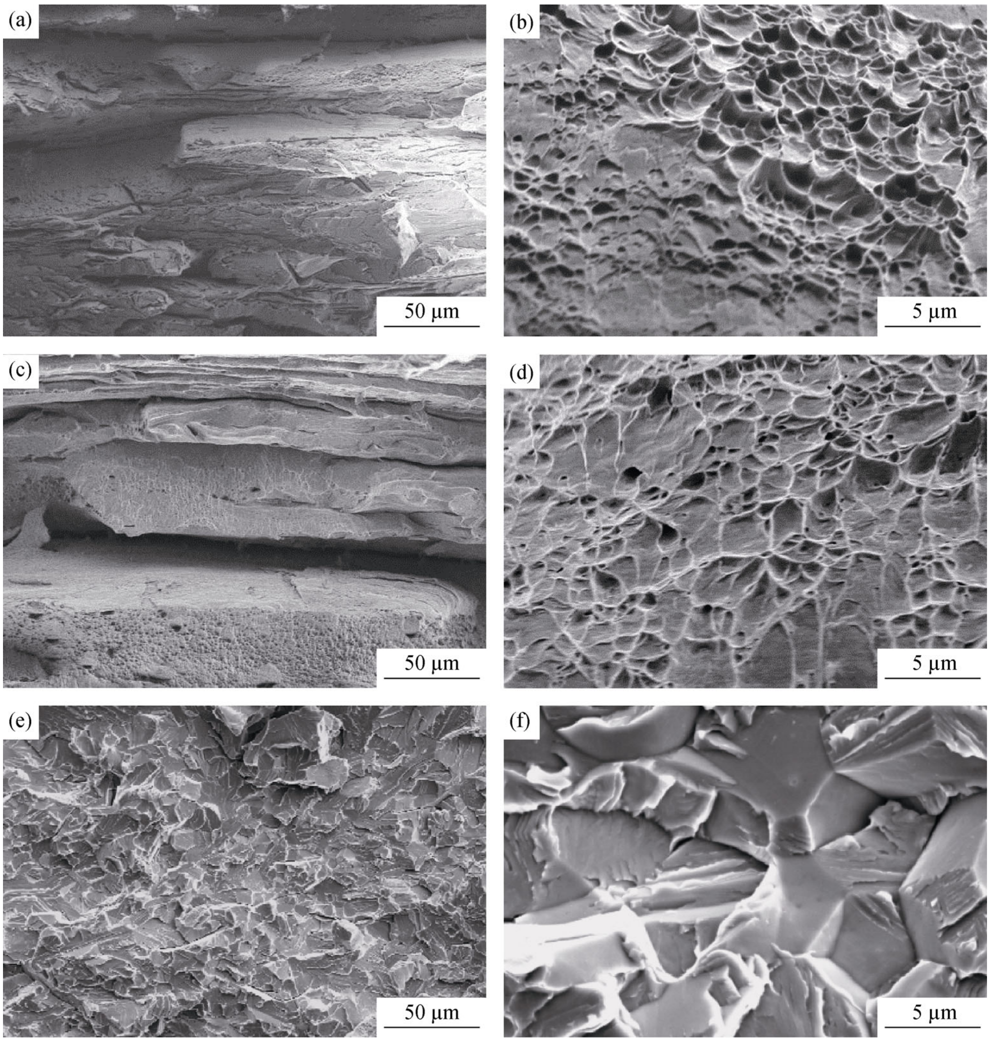

Fig. 8. Tensile fracture morphologies of the warm rolled high-silicon electrical steel sample and the samples after annealing: (a) warm rolled, (b) magnified image of (a), (c) annealed at 400°C for 1 h, (d) magnified image of (c), (e) annealed at 650°C for 1 h, and (f) magnified image of (e).

The results of the tensile properties can be analyzed as follows: the mechanical properties of the warm rolled high-silicon electrical steel samples could be improved by annealing at 400°C for 1 h because of the partial elimination of work hardening (Figs. 2(b) and 6) and the low degree of order in the annealed sample (Figs. 3(b) and 4(a)). Although the work hardening was eliminated by full recrystallization in the sample annealed at 650°C for 1 h (Figs. 1(h), 2(e) and 6), the room-temperature plasticity of this sample decreased because of its high degree of order (Figs. 3(e) and 4(d)).

3.5. Effect of annealing temperature on the cold rolling workability of the warm rolled sheets

After being pickled to remove their oxide skin, the warm rolled high-silicon electrical steel sheet sample and the samples annealed at 200–650°C were cold rolled under the same conditions (i.e., rolling by 3 passes, with a total reduction of 42.9% to a thickness of 0.2 mm), and photos of these cold rolled samples are shown in Fig. 9. After being cold rolled, the warm-rolled sample not subjected to annealing exhibited serious edge cracks. When the warm-rolled samples were annealed at 200–650°C, the degree of edge cracking in the samples first decreased and then increased with increasing annealing temperature.

As shown in Fig. 9(a), serious edge cracks appeared in the warm rolled sample after subjected to direct cold rolling. The high level of residual tensile stress on the sheet edge (Fig. 5), which is produced during the large warm rolling deformation, accumulates over the ultimate strength of the sheet during cold rolling, and results in the formation of serious edge cracks. After annealing at 200°C for 1 h, the degree of the edge cracking decreased because the residual tensile stress was reduced (Fig. 9(b)). The edge cracking of the sheet was effectively avoided after the samples annealed at 300°C or 400°C (Figs. 9(c) and 9(d)), which is mainly ascribed to the full elimination of the residual tensile stress on the sheet edge (Fig. 5). At the same time, the plasticity of the sample was further improved by annealing due to the partial elimination of work hardening (Fig. 7). After annealing at 500°C or above, the residual tensile stress was fully eliminated (Fig. 5); however, greater reordering occurred in the samples annealed at these higher temperatures, and the recrystallization led to the loss of the contribution of columnar grains to improving the room-temperature plasticity of the high-silicon electrical steel. Therefore, edge cracks occurred obviously when the annealing temperature exceeded 500°C (Figs. 9(e)–9(g)).

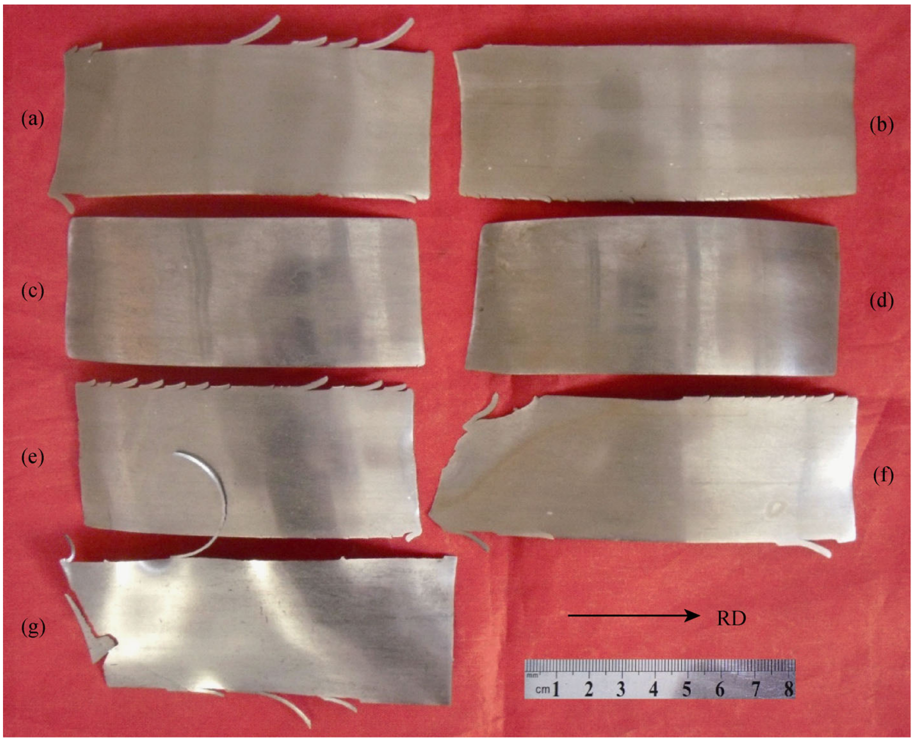

Fig. 9. Cold rolled sheets of the warm rolled high-silicon electrical steel sample and the samples annealed at various temperatures (rolling by 3 passes with a total reduction of 42.9%): (a) warm rolled sample directly cold rolled, (b) annealed at 200°C, (c) annealed at 300°C, (d) annealed at 400°C, (e) annealed at 500°C, (f) annealed at 600°C, and (g) annealed at 650°C (RD represents the rolling direction).

According to the effects of annealing temperature on the cold rolling workability of the warm rolled high-silicon electrical steel sheets with columnar grains, the cold rolling workability of the sheets was improved when they were annealed at 300–400°C for 1 h.

Fig. 10 shows a cold rolled strip of the high-silicon electrical steel with a thickness of 0.1 mm. The high-silicon electrical steel sheet with columnar grains was first warm rolled at 500°C with a total reduction of 95%, and was then annealed at 350°C for 1 h and finally multi-pass cold rolled to fabricate a strip with a thickness of 0.1 mm by an accumulative cold rolling reduction of 71.4%. The bright-surface strip, which is flexible enough to be coiled with diameter of less than 2.5 cm, does not exhibits obvious edge cracks and can still be cold rolled.

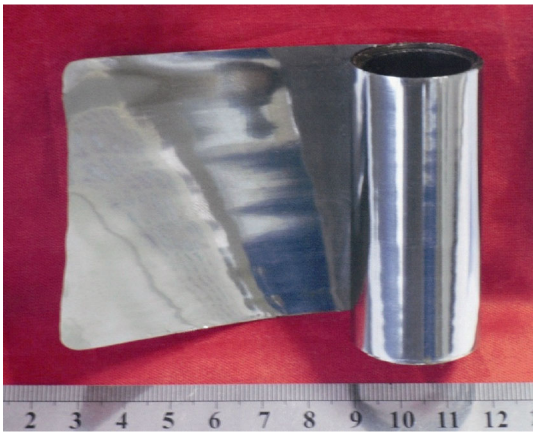

Fig. 10. Cold rolled strip of the high-silicon electrical steel with a thickness of 0.1 mm (annealed at 350°C for 1 h after being warm rolled, and then cold rolled with a cumulative reduction of 71.4%).

On the basis of above results and discussion, annealing under appropriate conditions can significantly improve the cold rolling workability of warm rolled high-silicon electrical steel sheets with columnar grains. This improvement is based on the ideas of controlling the columnar grains without recrystallization, avoiding a large reordering of the ordering in the sheet, and effectively reducing or eliminating the residual tensile stress on the sheet edge.

4. Conclusions

(1) After being warm rolled at 500°C with a total reduction of 95%, the high-silicon electrical steel samples with columnar grains were annealed at 200–700°C for 1 h. The columnar grains remained in the samples annealed at 550°C or below. Recrystallization began to occur in the sample annealed at 575°C and was complete in the sample annealed at 625°C. The reordering increased sharply in the sample annealed at 500°C or above, which adversely affected the room-temperature plasticity. The residual tensile stress on the edge of the sheet could not be effectively eliminated by annealing at temperature below 300°C.

(2) The room-temperature plasticity of the warm rolled high-silicon electrical steel samples was significantly improved by annealing at 400°C, i.e., the average elongation to failure increased from 0.73% to 1.19%. However, the average elongation to failure decreased to 0.41% in the case of the sample annealed at 650°C, and the fracture morphology transformed from a mixture of cleavage fracture and dimple fracture in the sample annealed at 400°C to a mixture of intergranular fracture and cleavage fracture in the sample annealed at 650°C.

(3) Considering the comprehensive effects of annealing on the recrystallization, reordering, residual stress, and mechanical properties of the warm rolled high-silicon electrical steel samples with columnar grains, the appropriate annealing condition is an annealing temperature of 300–400°C for 1 h. After being annealed under this condition, the warm rolled high-silicon electrical steel sheets could be cold rolled to a total reduction of more than 71.4% without obvious edge cracks, and the bright-surface strips with a thickness less than 0.1 mm could be fabricated by cold rolling.

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