Control of Recrystallization during High-Temperature Hot-Rolling of Grain-Oriented Silicon Steel

M. Muraki, T. Obara, M. Satoh, and T. Kan

Recrystallization kinetics of 3% Si steel after hot rolling in the temperatures between 1373 and 1573 K, which is quite important to obtain uniform magnetic properties, was studied. Recrystallization rate after hot rolling was relatively slow because of low dislocation density, which resulted from rapid recovery, and its behavior was strongly influenced by the initial grain size and coexistence of the γ phase. Based on these findings, controlling technology of recrystallization during hot rolling of grain-oriented Si steels is discussed.

Keywords

hot rolling, recrystallization, silicon steels

1. Introduction

GRAIN-ORIENTED 3% silicon steels have been widely used for electrical products; hence, improving their properties is strongly desired to save electricity. It is well known that both uniform texture and finely precipitated inhibitors are important factors to achieve uniform secondary recrystallization and magnetic properties of grain-oriented silicon steels (Ref 1, 2). So that inhibitors are dissolved prior to precipitation, the silicon steel slabs undergo prolonged heat treatment of extremely high temperature before hot rolling, which results in coarsened grains as large as 20 mm. Because some of them, such as (100)[011] oriented grains, often fail to recrystallize even after cold rolling and annealing (Ref 3, 4), control of recrystallization during the hot rolling process is of great importance to reduce undesirable inhomogeneity in texture.

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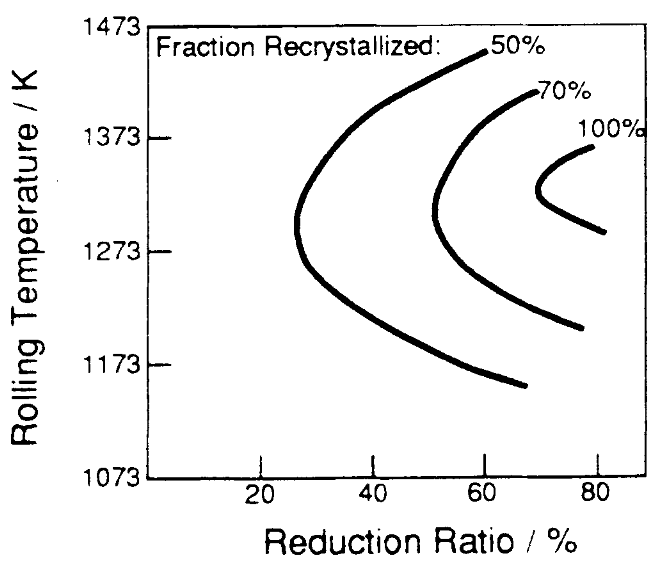


Fig. 1 Recrystallization behavior of 3% Si steel by hot rolling (Ref 5)

From this point of view, Harase et al. (Ref 5) and other researchers (Ref 6, 7) investigated the effect of a second phase and reported that the addition of C and the resulting coexistence of a γ phase in silicon steels promote dynamic recrystallization during hot rolling. This effect, however, was limited only around 1300 K (Fig. 1). Since this process is not able to fully recrystallize the huge grains mentioned above, the undesirable nonuniformity was not overcome completely.

In the higher temperatures, it was generally accepted that recovery dominates the restoration process of bcc silicon steel, and little attention was paid to the recrystallization behavior above 1473 K.

Manabe and some of the present authors (Ref 8) previously reported that an α single-phase silicon steel may statically recrystallize in temperatures of 1473 to 1673 K under suitable conditions. The effect of this recrystallization on inhibitor precipitation and new findings affecting the recrystallization process mentioned above are discussed in the present paper.

2. Materials and Experimental Procedures

Vacuum melted silicon-iron steels containing 3.0 to 3.6 mass% Si, 0.001 to 0.07 mass% C, and 0.06 to 0.07 mass% Mn were cast into 50 or 100 kg ingots and hot rolled to a 30 to 50 mm thickness at 1400 to 1500 K. Specimens were machined to a 10 to 30 mm thickness, first heat treated at 1573 or 1623 K for 360 to 3600 s to control initial grain diameters, and hot rolled in a single pass at 1373 to 1573 K with or without precipitation treatment of the γ phase at the same temperature before and after the deformation, followed by water quenching. Rolling reduction was 50%, and strain rates applied are approximately 10 per s. The thermomechanical treatment is shown in Fig. 2. Metallographic observations were carried out on cross sections perpendicular to either the normal or transverse direction of rolling.

3. Effect of Recrystallization on Inhibitor Precipitation

As mentioned above, the inhibitor is solution treated before the hot rolling process of grain-oriented silicon steels. MnS is one of the most popular compounds used as an inhibitor. Once precipitated, they only increase their mean diameter by Ost-

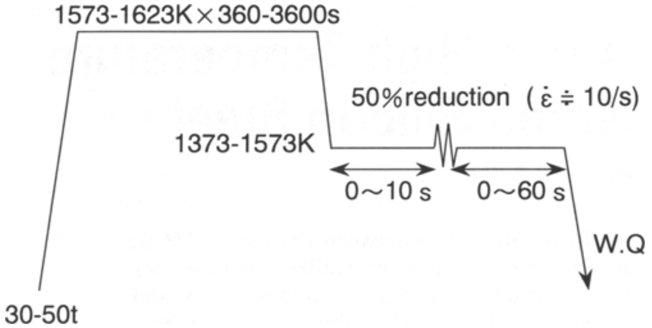


Fig. 2 Schematic representation of the thermomechanical treatment applied

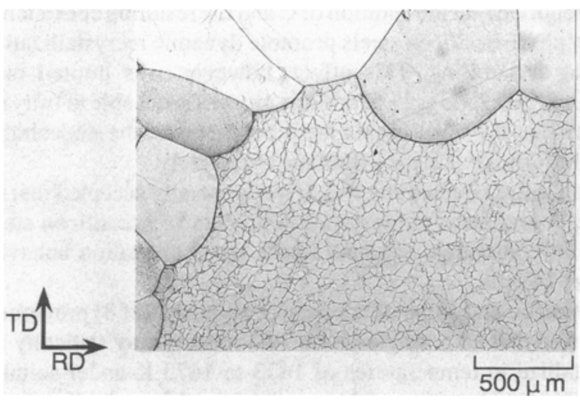


Fig. 3 Subgrain structure of 3% Si steel after hot deformation with newly recrystallized grains (0.02% C, rolled at 1523 K and water quenched within 3 s)

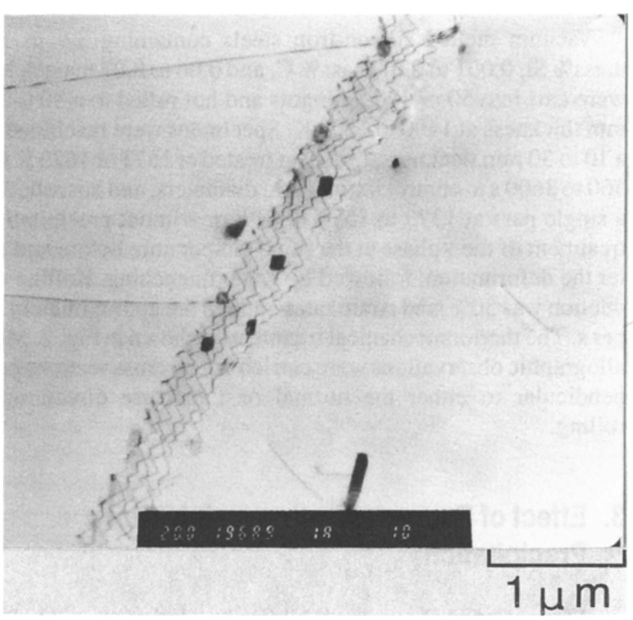


Fig. 4 TEM photograph of MnS inhibitors precipitated on the subgrain wall (Ref 9) (0.018% S, deformed and held for 60 s at 1173 K)

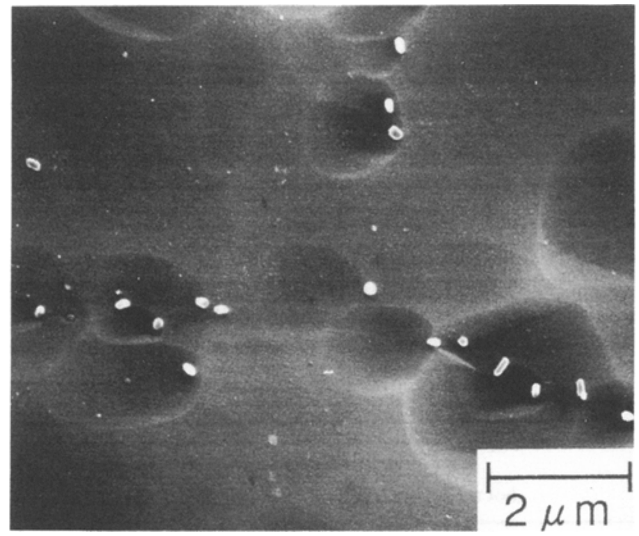


Fig. 5 Inhomogeneous precipitation of MnS on the recovered substructure (Ref 9) (0.018% S, deformed and held for 60 s at 1173 K)

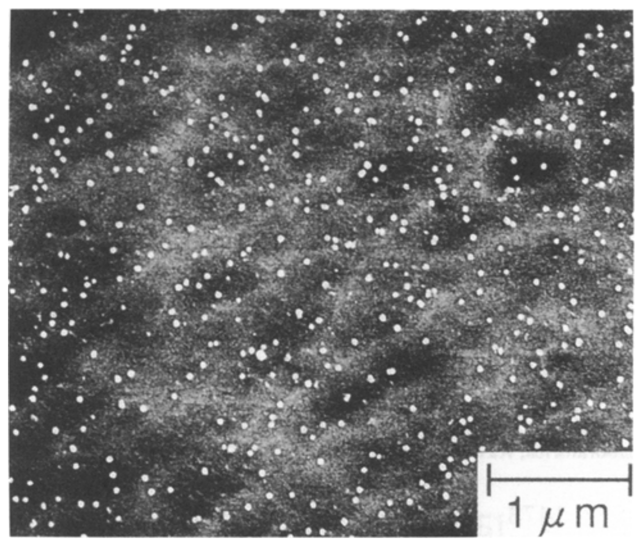


Fig. 6 Homogeneous precipitation of MnS on the deformed structure (Ref 9) (0.018% S, deformed and held for 60 s at 1073 K

wald ripening, decreasing pinning ability or Zener factor, until the initiation of secondary recrystallization. Therefore dispersion control of inhibitor that precipitates in the hot rolling process is highly important to obtain uniform magnetic properties of electrical steels.

Silicon steels, being bcc alloy with high stacking fault energy, tend to recover at high temperatures and exhibit subgrain structures when deformed (Fig. 3). Transmission electron microscopy (TEM) (Fig. 4) revealed that this subgrain wall provides nucleation sites for inhibitors (Ref 9), leading to undesirable inhomogeneous precipitation. See Fig. 5 (Ref 9). On the other hand, precipitation is retarded in the recrystallized grains that are substantially free from dislocations (Ref 9). It

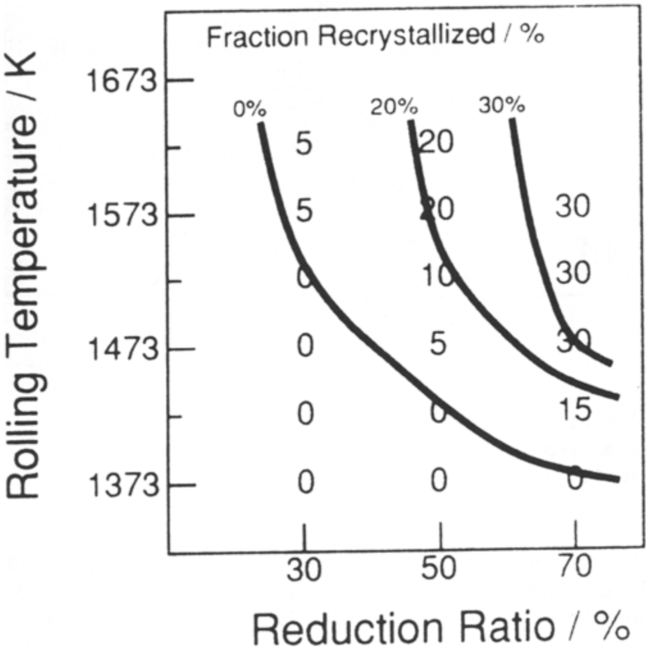


Fig. 7 Effect of rolling conditions on the fraction recrystallized (Ref 8)

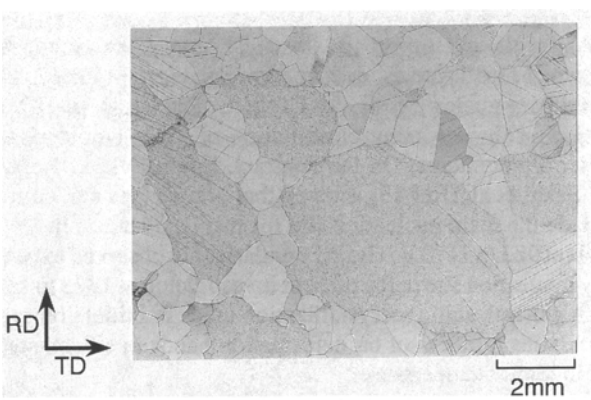
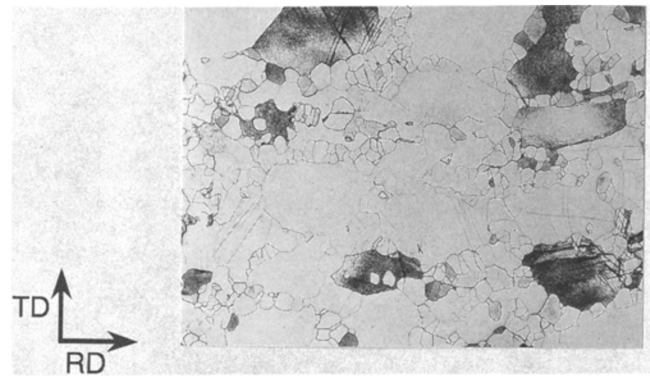
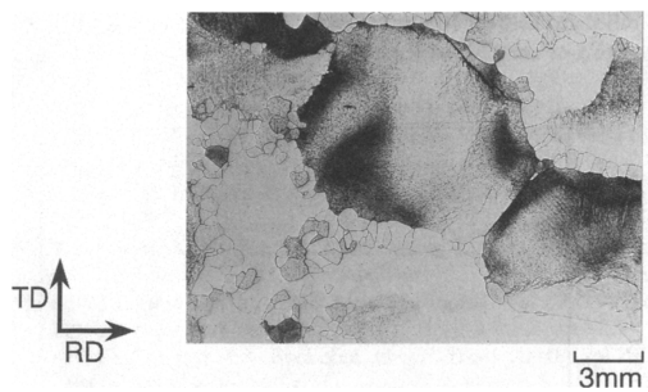


Fig. 8 Typical microstructure of partially recrystallized 3% Si steel in α single-phase region (0.02% C, rolled at 1523 K and water quenched within 3 s)

has been shown that deformation at lower temperature induces finely dispersed inhibitor precipitation. See Fig. 6 (Ref 9). It is therefore preferred that the large grains are thoroughly recrystallized first at high temperatures to suppress undesirable coarse precipitation of inhibitors and, afterwards, in the later stage of hot rolling process, rolled to give rise to fine precipitation by the introduction of dense dislocation substructures at relatively low temperature, in the production process for grain-oriented silicon steels.



(a)



(b)

Fig. 9 Effect of initial grain diameter on recrystallization (0.001% C, rolled and held at 1553 K for 6.5 s); (a) heat treated for 360 s at 1573 K before rolling; (b) heat treated for 3600 s at 1573 K before rolling

4. Statically Recrystallized Structure in α Single-Phase Region

Recrystallized fraction is reported to increase either by increasing temperature or by increasing rolling reduction in this temperature region. See Fig. 7 (Ref 8). A typical microstructure of the hot deformed sample is shown in Fig. 8. Newly recrystallized grains are predominantly located on preexisting grain boundaries and free from subgrains indicating recrystallization proceeded statically. Figure 9 shows the partially recrystallized structures with different initial grain diameters. Recrystallized fraction increases with decreasing original grain diameter because grain boundary is substantially the sole nucleation site for recrystallization in the α single-phase region.

5. Effect of Coexisting γ Phase

5.1 *γ Phase Precipitated before Deformation*

The effect of γ phase precipitation was studied for the specimen containing 0.04% C kept for 10 s at rolling temperature before rolling. Numerous recrystallized grains appeared not only

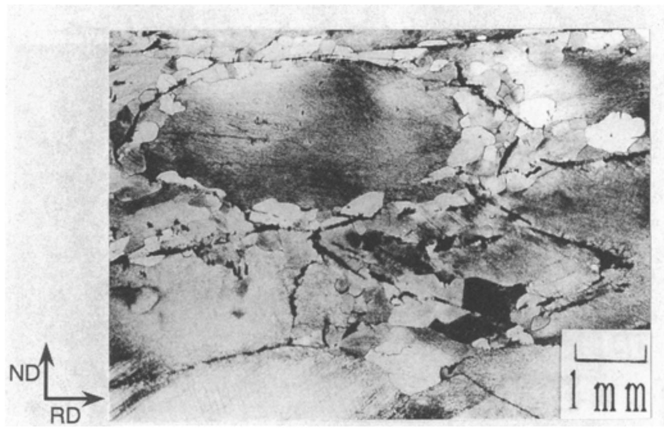


Fig. 10 Typical microstructure of hot deformed 3% Si steel with γ phase precipitated before the deformation (0.04% C, rolled and held for 10 s before and after rolling at 1423 K)

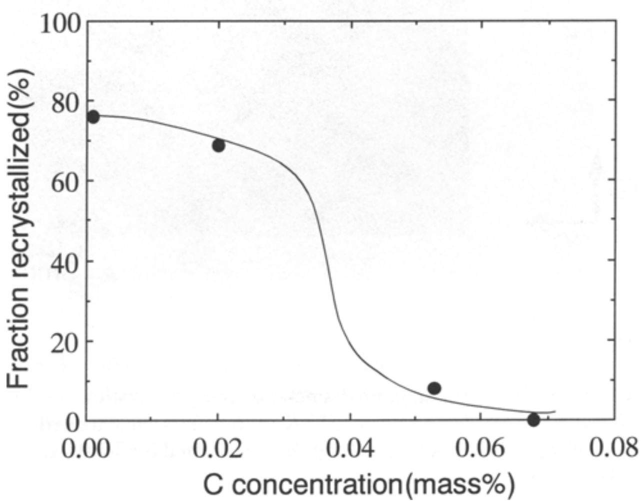


Fig. 11 Fraction recrystallized as a function of carbon concentration in 3% Si steel (rolled and held for 40 s at 1573 K)

on the preexisting grain boundaries but also inside the original grains. See Fig. 10. In contrast, no recrystallized grain was observed inside the original grains in the same specimen rolled immediately after the specimen reached the rolling temperature. Therefore, γ phase precipitated before rolling accelerated the static recrystallization of the α phase because of concentrated strain around the precipitated γ phase, which is harder than the α matrix. No recrystallization was observed inside the original grains even with a holding of 10 s prior to deformation in the specimen containing 0.001% C, which is insufficient to induce γ phase transformation in 3% Si steel.

5.2 *γ Phase Precipitated after Deformation*

Recrystallized fractions of specimens with varied C content, which were rolled without holding, before rolling, and with 40 s holding at 1573 K after rolling are shown in Fig. 11. The recrystallized fractions are more or less the same for 0.001% C and 0.02% C where no γ precipitation was observed, and the recrystallization proceeded when they were further heat treated.

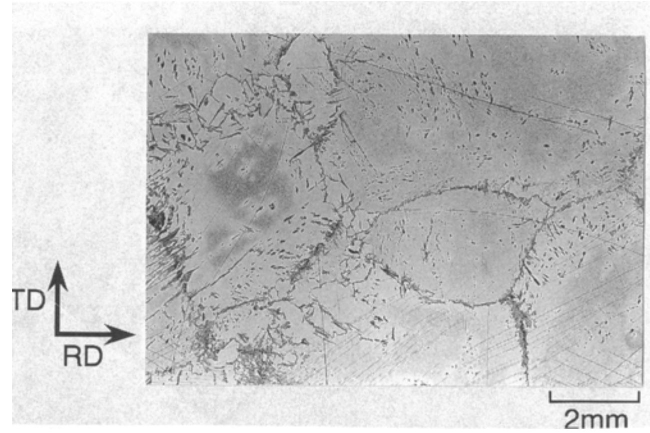


Fig. 12 Microstructure of hot deformed 3% Si steel with γ phase precipitated after deformation (0.053% C, rolled and held for 10 s at 1573 K)

On the contrary, there was little recrystallization observed in the specimens with 0.053% C or more, where dense precipitation of the γ phase was observed. The γ phase precipitated not only on the preexisting grain boundaries, but also inside the grains in this case. See Fig. 12.

6. Discussion

As for the nucleation site for static recrystallization in hot deformed ferritic steels, deformation bands are reported to be the primary nucleation site for Cr steels (Ref 10, 11) at 1073 to 1473 K with increasing contribution of grain boundaries at higher temperatures. On the contrary, English et al. (Ref 12) and Sakai et al. (Ref 13) showed that grain edges and corners provide the main nucleation site for recrystallization in 3% Si steels at 983 to 1173 K. Grain boundaries are observed to be the only nucleation site in the present investigation at 1373 to 1573 K. In general, static recrystallization tends to initiate on grain boundaries rather than on deformation bands in silicon steels and in higher temperatures.

The importance of initial grain size in controlling the recrystallization process of 3% silicon steel is shown in the present paper. Since recovered subgrain structure allows undesirable precipitation of inhibitor, they have to be fully recrystallized by one or a combination of more than one hot rolling before they reach the temperatures at which inhibitor precipitation takes place.

Recrystallization behavior was strongly affected by the coexistence of the γ phase, depending on the precipitation treatment before and after deformation, and also on C concentration. The γ phase may accelerate or suppress the static recrystallization of the α phase. It is accelerated if precipitation of the γ phase takes place before deformation. This is probably because strain is concentrated around the precipitated γ phase, which is harder than the α matrix. However, recrystallization is suppressed if precipitation of the γ phase takes place after deformation. This may be because concurrent precipitation of the γ phase on grain boundaries deprives the nucleation site for recrystallization, and the γ phase also shows pinning effect on migrating boundaries of the new grains.

Takeshita et al. (Ref 14) reported the similar effect of coexisting γ phase on static recrystallization in 17% Cr steel. Though they presumed the accelerating effect of the γ phase on recrystallization partly to be increased grain growth rate by purification of α matrix (mainly lowered C and N concentration in solution), changes in C from 0.001 to 0.02% did not show remarkable change in recrystallization rate in the present study, as shown in Fig. 11, as long as C remains in solution.

In conclusion, the kinetics of high-temperature recrystallization of 3% Si steel is affected not only by rolling conditions, but by temperature, initial grain size, C concentration, and γ precipitation that is controlled by thermal histories before and after each deformation step. These conditions are also related with inhibitor precipitation and must be controlled carefully in the production processes. By introducing high temperature deformation on 3% Si steels above 1473 K with appropriate cooling control, highly uniform texture and inhibitor precipitation is obtained, which consequently attains uniform magnetic properties of the product.

7. Summary

Single pass hot rolling experiments were conducted on 3% Si steel with various C content. Undesirable precipitation of inhibitor is liable to take place in the recovered silicon steel, and control of recrystallization is highly important. Recrystallized fraction increases with decreasing original grain diameter because grain boundaries facilitate nucleation of new grains. Coexisting γ phase may accelerate or depress the static recrystallization. It is accelerated when the γ phase precipitates prior to deformation because strain is concentrated around the precipitated γ phase, which is harder than the α matrix. Recrystallization is, however, suppressed when precipitation of the γ phase occurs after deformation because precipitation of γ prior to recrystallization on grain boundaries suppressed recrystallization that nucleates on the same site.

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