Effect of Manganese Segregation on Fine-grained Ferrite Structure in Low-carbon Steel Slabs

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(Received on March 18, 2003; accepted in final form on June 22, 2003)

Using a 100 mm thick continuously cast slab with a chemical composition of 0.10C–0.16Si–0.58Mn–0.01P–0.003S (mass%), we have clarified the effect of the manganese segregation on the transformed ferrite structure when the slab was reheated to make austenite grains equi-axed and smaller and followed by the Grain Refinement Process (GRP) of heavy compression and subsequent controlled cooling. Samples from which the Mn segregation was eliminated were also prepared for comparison. The resultant microstructure was examined for compressive strains between 0.7 and 2.1.

When the austenite grain size is 160 or 120 μm prior to GRP, the ferrite grain size of the samples with the Mn segregation is smaller at the given strain than that of the samples from which the Mn segregation was eliminated. The Mn band formed by the heavy compression is thought to act as a barrier in the form of a relatively stable austenite against the ferrite growth.

Moreover, we found a unique equation to predict the transformed ferrite grain size in the samples with the Mn segregation. Namely, the ferrite grain size can be accounted for according to a parameter, ES (effective spacing): a mean spacing that considers both the pancake austenite grain boundary and the Mn band. We also suggest that the smaller Mn band spacing may make the ferrite structure finer even when the austenite grain size is large.

KEY WORDS: cast slab; low carbon steel; heavy deformation; TMCP; HDR; HCR; phase transformation; grain boundary; ferrite grain; austenite grain; grain size; Mn segregation.

1. Introduction

Ultra-fine grained ferrite structure has been pursued to improve strength and toughness simultaneously. Large plastic deformation in the so-called “unrecrystallized” austenitic regime and subsequent controlled cooling (hereafter mentioned as Grain Refinement Process: GRP) will generate ferrite grains that are smaller than 5 μm .

In the last decade, the rolling process that is directly-connected with continuous casting called the Hot Direct Rolling (HDR) process or the Hot Charge Rolling (HCR) process has advanced as an energy-saving manufacturing process of hot rolled steel products as shown in Fig. 1.^{1–4)} Although some have reported mechanical properties with sheets produced by the HDR or HCR process^{5,6)} extensively, only a few have investigated the relationship between the process conditions and the ferrite grain structure.

In particular, the microstructure prior to GRP may have a significant influence on the evolution of the ferrite grain structure. In other words, it is very important to understand the kind of microstructure that is the most effective as the initial microstructure prior to GRP in the HDR or HCR process.

The microstructure prior to GRP depends on the precedent treatments and can be classified into four categories according to the austenite grain structure and the degree of

micro-segregation as summarized in Table 1.

Type 1 is the as-cast or the as-solidified microstructure. The morphology of austenite grains is mostly columnar with a grain size of several millimeters. The solidified structure remains, and the micro-segregation is dominant.

Fig. 1. Schematic schedule for manufacturing of hot rolled steel plates.

Table 1. Four kinds of microstructures.

	Austenite grain size	Micro-segregation
Type 1	$\geq 1 \text{ mm}$	Not eliminated
Type 2	$\geq 1 \text{ mm}$	Eliminated
Type 3	20~300 μm	Not eliminated
Type 4	20~300 μm	Eliminated

Type 2 is the homogenized form of Type 1 without forging. The micro-segregation disappears by heating for several hours at an elevated temperature. The austenite grain size is large. This type is not always utilized practically but is important from a scientific viewpoint.

For Types 1 and 2 microstructures, the recrystallization process has been developed and essentially combined with GRP to obtain fine austenite grains. The addition of Nb and Ti has been adopted for this purpose especially for Type 1.⁷⁻¹¹⁾

Type 3 is the reheated form of Type 1 that is cooled once in the fully ferritic temperature regime. The micro-segregation remains but the austenite structure becomes equi-axed and smaller. The austenite grain size is between 20 and 300 μm .

Type 4 is somehow classical. First the solidified structure is destroyed by some deformation at an elevated temperature, then it is homogenized and normalized. **Figure 2** illustrates the difference between Types 3 and 4 microstructures prior to GRP. Micro-segregation does not exist, and the austenite grain size is mostly as small as that of Type 3. Torizuka *et al.* reported that the size of ferrite grains transformed from the heavily deformed austenite depends on the thickness of the compressed austenite grain for a Si-Mn steel with a Type 4 microstructure.^{12,13)}

For Types 3 and 4 microstructures, a fine austenite grain size can be easily obtained by austenitizing or reheating the steel for a relatively short period in a lower austenitic temperature. The micro-segregation is believed to decrease the toughness of the perpendicular direction of the rolled plate.¹⁴⁾ To eliminate the micro-segregation, forging and/or homogenization have been applied using Types 2 and 4. However, for practical cases, such treatment is not always adequate to eliminate the micro-segregation with Types 1 and 3.

It is easier to obtain fine austenite grains with Type 3 than with Type 1. Type 3 does not need the previous reduction of continuous casting slab (CC-slab) thickness, and it has more room for heavy reduction in the TMCP with a given slab thickness. Hence, in a practical meaning, the finer ferrite structure may be obtained more easily in Type 3 than in Type 1.

Therefore, in the present study, we have clarified how the fine ferrite structure can be produced for the Type 3 microstructure in the same way as that for Type 4 by comparing it to the Type 4 case for the low carbon Si-Mn steel.

The ferrite grain refinement through the γ - α transformation is discussed by the following three factors:

- (1) Density of nucleation sites
- (2) Nucleation rate
- (3) Grain growth rate

The major difference between Types 3 and 4 is the existence of the micro-segregation. Thus, intensive attention should be given to how the micro-segregation influences these three controlling factors.

At a constant cooling rate, the density of the nucleation site is the main factor for determining the ferrite grain size as reported by Torizuka *et al.*, since the austenite grain boundary acts as the preferential nucleation site in the heavy deformation condition. So far, there has not yet been any clarification on how the micro-segregation affects this

Fig. 2. Comparison of austenite grain structures for Types 3 and 4.

Table 2. Chemical compositions of the investigated steel (mass%).

C	Si	Mn	P	S
0.11	0.16	0.58	0.01	0.003

factor.

The nucleation rate is also related to the degree of under-cooling. The beginning temperature for phase transformation ($=A_{r3}$ point) may change by the concentration distribution of the micro-segregation. Ouchi *et al.* introduced the following equation concerning the A_{r3} point of the steel rolled by a 50% reduction or more in the unrecrystallized austenite region¹⁵⁾:

$$A_{r3}(^{\circ}\text{C}) = 910 - 310\text{C} - 80\text{Mn} + 0.35(t - 8) \dots \dots \dots (1)$$

t : thickness of plate (mm)

Thus, a highly segregated area has a large degree of under-cooling. Furthermore, the height or the profile of the Mn segregation may also affect the grain growth rate.

In the present study, the effect of heavy deformation of austenite on the grain size of the transformed ferrite has been clarified using a 100 mm thick CC-slab of the low carbon Si-Mn steel with special attention on the Type 3 microstructure with the Mn micro-segregation.

2. Experimental Procedures

2.1. Sample Preparation

The chemical compositions of the investigated steel are listed in **Table 2**. The steel is a SS400 grade. A continuous cast slab made in a laboratory-scale was prepared for the present study. The details of the casting are reported in the literature by Yoshida *et al.*¹⁶⁾ and also mentioned in **Table 3** with other preparations for GRP samples. The average spacing of the primary dendrite arms was 318 μm and the average spacing of the secondary dendrite arms was 137 μm .¹⁶⁾

Using this slab, each specimen with or without the elimination of micro-segregation was prepared. The former was cut directly from a quarter thickness of the slab for the Type 3 microstructure, and the latter was rolled to a plate by 70% in nominal reduction ratio and reheated for 86.4 ks at 1 623 K to eliminate the Mn micro-segregation for the Type

Table 3. Conditions of the pre-treatment and the Grain Refinement Process.

	Pre-treatment Process			Grain Refinement Process
	Continuous Casting	Homogenization	Austenitization	Compression/Controlled Cooling
Type 3	Melt: 2.5 ton Casting Velocity: 0.8-1.0 m/min Slab Size: 100 mmT 800 mmW 3000 mmL	1)Rolling Heating: 1273 K, 40 min Start: 1273 K Finish: 1093 K Reduction rate: 70% 2)Reheating 1623 K, 86.4 ks	Heating Rate: 5 K/s Reheating Temperature: 1)1473 K, and 2)1223 K Holding Time: 60 s	Cooling Rate: 10 K/s Compression: Temperature: 1093 K Reduction Rate: 30%,50%,75% Strain rate: 10 /s Controlled Cooling: 10 K/s
Type 4

Fig. 3. Schematics of the hot compression test.

4 microstructure.

2.2. Grain Refinement Process (GRP)

GRP samples with a thickness of 16 mm, a length of 16 mm, and a width of 15 mm were machined from the specimens mentioned above. Prior to GRP, two kinds of reheating were employed to change the austenite grain size: holding for 60 s at 1 223 and 1 473 K, respectively.

Figure 3 describes the hot compression test as a simulation of GRP. A sample sandwiched between a couple of anvils is heated directly by electric resistance heating and then compressed with a servo-hydraulic machine to a final thickness at a given temperature. The axis of compression is perpendicular to the direction of the secondary dendrite arms and parallel to the direction of the primary dendrite arms.

In the present study, compression with a nominal reduction ratio of 30, 50 and 75% at a strain rate of 10/s was applied at 1 093 K, followed by controlled cooling at 10 K/s. The A_{13} point of the Type 4 samples with a prior austenite grain size of 20 μm was determined to be 1 073 K at a cooling rate of 10 K/s from the thermal expansion test results. Hence the deformation temperature of 1 093 K was chosen as the temperature in the ‘unrecrystallized austenite regime’. The compressive strain ranges from zero at the surface of the sample to a maximum value of 4.6 at the center of the sample with a nominal reduction ratio of 75% (**Fig. 4**). The subsequent structure by a wide range of strains can be examined in a sample using this method. However, in the present study, the strain range up to 2.1, which corresponds to the maximum in the nominal reduction ratio of 50%, was adopted for the following analysis on the ferrite grain size since the useful effect of the practical strain or a strain that is not heavy should be explored

Fig. 4. Calculated compressive strain distribution in a sample.

first with high reliability.

2.3. Microstructural Characterization

2.3.1. Microstructure

Microstructural observation was carried out on a section cut through the center of the GRP sample parallel to the compression axis. Etchants for metallography were 3 vol% picric acid for observing the prior-austenite structure and 3 vol% nitric acid for the ferrite grains. The average ferrite grain size ($\bar{d}$) was determined by the equation of $\bar{d} = 1.128d$. The d corresponds to the average intercept length at each strain and was measured by Heyn's method.¹⁷⁾

2.3.2. Segregation

The analysis of the Mn segregation was carried out by EPMA (Electron Probe Micro Analysis). Each of the sample sections for analysis was identical to that in the microstructural observation. The EPMA was set at 15 kV–1 mA. The pixel size was 5 μm in square for the as-cast samples and 1 μm in square for the GRP samples. The number of pixel data was 250 000 per section.

3. Results

3.1. Microstructural Characteristics Prior to Grain Refinement Process

3.1.1. Austenite Grain Size

Figure 5 shows the prior-austenite grain structures after

Fig. 5. Comparison of austenite grain structures (3 vol% Picral etched).

Fig. 6. Comparison of the distribution of Mn segregation prior to the grain refinement process. (a): Type 3, (b): Type 4.

Fig. 7. Comparison of the distribution of Mn segregation in the compressed samples. (a): Type 3, (b): Type 4.

heating at 1223 and 1473 K. In the samples heated at 1223 K, the mean austenite grain size is 20 μm for both Types 3 and 4 microstructures. In the samples heated at 1473 K, the grain size is 160 μm for Type 3 and 120 μm for Type 4.

3.1.2. Mn Segregation

EPMA results demonstrates that Type 3 samples have the dendrite structure and the Mn segregation with a high concentration between the dendrite arms (Fig. 6(a)). The Mn concentration ranged from 0.4 to 0.8% with the lowest concentration in the dendrite arms and the highest concentration between the dendrite arms. On the other hand, the Mn segregation disappeared in Type 4 samples (Fig. 6(b)). In Type 4 samples, the Mn concentration disperses around the average of 0.58 mass% with a good distribution of Mn in the present condition.

3.1.3. Change of Mn Segregation Morphology by Compression

Figure 7 shows the Mn concentration maps by EPMA for Types 3 and 4 samples after the compression. It is clear that the Mn segregation in Type 3 samples does not disappear through the heating and compression. Here we define the term 'Mn band' as the elongated and Mn concentrated band. By observing the details, we can recognize that the Mn band spacing narrows with an increase in the compressive strain.

The change of the Mn band spacing for Type 3 samples in Fig. 4 is plotted against the compressive strain in Fig. 8. The error bars indicate the strain at both ends of the Mn band width. The Mn band was not detected in the highly compressed region with strains larger than 2.8, partly because the probe diameter of EPMA was of 1 μm order.

Pearlite is a transformed structure from the austenite that remains after the ferrite transformation. When Mn as an austenite stabilizer is concentrated in the form of a band in Type 3 samples, such a region is believed to be the last one to remain in the austenite regime. Hence the pearlite band can be used as a trace of the Mn band in the largely compressed samples. As a matter of fact, the pearlite bands are observed in the largely compressed Type 3 samples and will be introduced later in Fig. 9. On the other hand, such a pearlite band is not seen for Type 4 samples where the Mn is distributed homogeneously. In Fig. 8, the pearlite band spacing is also plotted in a similar manner to the Mn band.

Assuming that the Mn band originally corresponds to the Mn concentrated area between the secondary dendrite arms as seen in Fig. 6, the Mn band spacing, L , is believed to reflect the compressed secondary dendrite arm spacing:

$$L = L_0 \cdot \exp(-\varepsilon) \dots \dots \dots (2)$$

L : Mn band spacing (in μm)

L_0 : Secondary dendrite arm spacing (=137 μm)

ε : Compressive strain

The straight line drawn in Fig. 8 is the one calculated by Eq. (2), and accounts for the relationship between the compressive strain and the Mn band spacing. Hence, we can notice that the secondary dendrite arms are compressed according to Eq. (2), and the spacing of the Mn and/or the pearlite band are also similar.

Fig. 8. Change of Mn band and pearlite band spacing by compressive strain.

3.2. Ferrite Grain Structure after GRP

3.2.1. Ferrite Structure

Figure 9 shows the ferrite grain structures by GRP. The compression direction is vertical and the elongating direction horizontal in each microphotograph.

When the austenite grain size is 20 μm (Fig. 9(a)), the ferrite grains for Type 4 samples are polygonal and uniformly fine. On the other hand, when the austenite grain sizes are 160 and 120 μm (Fig. 9(b)), the ferrite grain size clearly depends on the strain. The smaller size is given by the larger strain. A small volume fraction of pearlites are also observed. In Type 4 samples the pearlites are dispersed uniformly, but in Type 3 samples they form arrays when the strain is 2.1 as mentioned above. When the compressive strain is 0.8, the Mn band spacing is larger than 50 μm from Fig. 7. Hence the partitioning process may be active inside the austenite grain and bring about a uniform distribution of pearlites that can be seen in Fig. 9(b).

3.2.2. Ferrite Grain Size

Figure 10 shows the change of the mean ferrite grain size by the compressive strain. When the austenite grain size is 20 μm , the ferrite grain size for Type 4 samples does not depend much on the strain but decreases slightly with increasing compressive strain. A ferrite grain size of 5 μm can be obtained only by a heavy strain of at least 2.

When the austenite grain size is 160 or 120 μm , a larger ferrite grain size is derived than when the austenite grain size is 20 μm . Furthermore, the ferrite grain size of Type 3 samples with a larger austenite grain size is smaller than that of Type 4 samples at a given strain.

According to the analysis by Torizuka *et al.*, the ferrite grain sizes in Fig. 9 can be rearranged against the pancake austenite grain thickness (geometrical factor: TH_γ) in Fig. 11^{12,13}, where

$$\text{TH}_\gamma = d_0 \cdot \exp(-\varepsilon) \dots \dots \dots (3)$$

d_0 : Initial austenite grain thickness (μm)

ε : Compressive strain

The ferrite grain sizes with different initial austenite grain sizes are expressed well as a function of TH_γ for each of the Types 3 and 4 samples. TH_γ is a useful measure of

Fig. 9(a). Change of ferrite grain structures by compressive strain, in Type 4 samples with a prior-austenite grain size of $20\ \mu\text{m}$.

Fig. 9(b). Change of ferrite grain structures by compressive strain, in the samples with prior-austenite grain sizes of $160\ \mu\text{m}$ (Type 3) and $120\ \mu\text{m}$ (Type 4).

Fig. 10. Change of ferrite grain size by compressive strain.

Fig. 11. Relationship between ferrite grain size and pancake austenite grain thickness: TH_{γ} [μm].

Fig. 12. Calculated ferrite grain growth in holding at given temperatures. (a): Mn=0.4 mass%, (b): Mn=0.8 mass%.

the density of the nucleation site in the ferrite transformation from the heavily deformed austenite. Figure 11 confirms the significance of their approach. When TH_γ is larger than approximately $2\mu\text{m}$, the ferrite grain size becomes smaller with decreasing TH_γ .

Note that the ferrite grain size of Type 3 samples is clearly smaller than that of Type 4 samples at a given TH_γ when TH_γ is larger than $15\mu\text{m}$. This indicates the possibility of a higher density of the nucleation site in Type 3 samples than in Type 4 samples. However, Type 3 samples have the distinct Mn segregation. The high concentration of Mn may affect the nucleation and the growth of ferrite. The mechanism that has the most influence on the difference in Fig. 11 will be discussed in the next chapter.

4. Discussion

4.1. Influence of Mn Segregation on Nucleation and Growth of Ferrite

In Fig. 6, the width of the Mn segregation band with no strain was about a tenth of the secondary dendrite arm spacing ($137\mu\text{m}$). The Mn concentration is 0.8% at the peak and 0.4% at the bottom. According to Eq. (1), the A_{r3} point is 30 K lower at the peak than at the bottom. Hence, by assuming the uniform nucleation of ferrite, the ferrite may become nucleated at the center of the bottom and start to grow. Due to the cooling rate of 10 K/s, the temperature at the Mn peaks reaches its A_{r3} point 3 s after the start of nucleation at the bottom.

Figure 12 shows the prediction of the growth rate of the interface between the austenite and ferrite in holding at given temperatures for the 0.4 and 0.8% Mn compositions.¹⁶⁾ The present prediction says that although the difference is not large, a lower growth rate is expected for the 0.8% Mn than for the 0.4% Mn. When we assume that the transformation starts after the compression below 1093 K and finishes above 973 K, the ferrite size may reach a value between 2 and $5\mu\text{m}$ in 3 s. The lower the transformation temperature range, the more the growth. Hence the 'free growth' of the ferrite is believed to be a minimum of $2\mu\text{m}$ and a maximum of $5\mu\text{m}$ at the bottom of the Mn concentration for the Type 3 samples.

Thus, other ferrites that are the same size as the initial one may be formed in the bottom area if their width is larg-

er than $5\mu\text{m}$, and finer ferrites may be formed in the Mn band if the band has enough width. However the mean size of ferrites grains will not be influenced much by the finer grains nucleated in the Mn band, since the effect has to be an order of 10% because the width of the Mn band is a tenth of the bottom width.

The Mn band may remain in the austenite regime due to the 'local equilibrium' at the end of the transformation in the bottom width. This suggests that in the heavily compressed condition, the Mn band in the austenite regime may act as a barrier against the ferrite growth and finally be transformed into pearlite. No additional ferrite influences the mean size of ferrites.

The under-cooling also affects the nucleation rate. The A_{r3} point at the bottom of the Mn segregation for Type 3 samples is estimated to be about 15 K higher than that of the bulk for Type 4 samples. However, this requires a lower nucleation rate for Type 3 samples than for Type 4 samples when they are subjected to a similar temperature history. Since finer ferrites were obtained for Type 3 samples, the possible difference in the nucleation rate due to the Mn segregation is also not plausible for the present result.

4.2. Barriers against Ferrite Growth

The grain boundary is the preferential nucleation site for ferrite in the heavily deformed austenite. We consider that each potential nucleation site is highly activated and that simultaneous nucleation is very much probable in the heavily deformed austenite. Furthermore, only the first nucleated grains survive by killing the neighboring potential sites under the condition that the growth rate is higher than $1\mu\text{m/s}$. Once transformed, the ferrites can act as barriers against the growth of each other, since the growth here means the transformation of austenite to ferrite.

Under such circumstances with highly dense nucleation sites and a rapid growth rate, we can discuss the possibility of a refinement effect by the growth barrier density or the suppression of 'free growth'. In Type 4 samples, the pancake austenite boundary acts as a growth barrier as well as a nucleation site. In Type 3 samples, the Mn band may also originally act as a growth barrier.

Figure 13 illustrates this idea, which implies the dividing effect of a pancake austenite by the Mn bands. Such division might initiate a delayed nucleation in the remaining

Fig. 13. Evolution of fine ferrite structure of Type 3 sample compared with Type 4 samples. (a): Type 3, (b): Type 4.

austenite regime that is blocked against the ferrite 'free growth' by the Mn band. In this sense, the Mn band can be regarded as an additional nucleation site. In other words, the ferrite is nucleated in the region between the Mn bands even if no austenite grain boundary exists within it.

4.3. Effective Parameter to Determine Ferrite Grain Size

The Mn band spacing may also control the ferrite grain size for Type 3 samples. Hence we propose an effective spacing parameter, ES, by modifying the geometrical factor, TH_γ , defined by Eq. (3), in the following way:

$$A = \frac{1}{TH_\gamma} + \frac{1}{L} \dots \dots \dots (4)$$

A : Total number of austenite grains and Mn bands per unit length

L : Mn band spacing (in μm) defined by Eq. (2)

$$ES = \frac{1}{A} = \frac{L \cdot TH_\gamma}{L + TH_\gamma} = \frac{L_0 \cdot d_0}{L_0 + d_0} \exp(-\varepsilon) \dots \dots \dots (5)$$

ES: Effective spacing (in μm)

Figure 14 rearranges the data in Fig. 11 by replacing TH_γ by ES. The two bands in Fig. 11 meet into a single band successfully, which postulates the validity of our idea that the Mn band together with the austenite grain boundary acts as a growth barrier or a nucleation site in determining the ferrite grain size formed from the largely compressed austenite. We can eventually conclude that the Mn segregation is beneficial for obtaining a finer ferrite grain size through the GRP. In addition, we can design the ferrite grain size quantitatively by controlling the secondary dendrite arm spacing, the initial austenite grain size, the compressive strain, and the deformation temperature in the GRP in the present study for both Types 3 and 4 samples.

Figure 15 demonstrates the relationship between ES and L_0 , the secondary dendrite arm spacing taking d_0 , the initial austenite grain size, as a parameter when the compressive strain is 0. Even if d_0 is quite large, ES becomes very small with a small L_0 . On the other hand, when d_0 is as small as $20 \mu\text{m}$, ES is almost independent of L_0 . It has been said that the coarse austenite structure prevents the refinement of the ferrite grains in the HDR process or the HCR process. However, the present paper suggests that the smaller secondary dendrite arm spacing may make the ferrite structure

Fig. 14. Relationship between ferrite grain size and effective spacing.

Fig. 15. Relationship between effective spacing and secondary dendrite arm spacing with various initial austenite grain sizes.

even finer in the heavy compression even when the austenite grain size is quite large. The secondary dendrite arm spacing can be refined by a higher cooling rate in continuous casting.¹⁸⁾

5. Conclusions

Using a 100 mm thick continuously cast slab with a chemical composition of 0.10C–0.16Si–0.58Mn–0.01P–0.003S (mass%), we clarified the effect of the manganese micro-segregation that formed during solidification on the size of the ferrite grains that were transformed from the heavily deformed and unrecrystallized austenite. Specimens were cut from the cast slab and subjected to a compressive deformation perpendicular to the secondary dendrite arms with parallel alignment. The ferrite microstructure obtained was examined for compressive strains between 0.7 and 2.1.

Specimens that were rolled by 70% in nominal reduction ratio and reheated for 86.4 ks at 1 623 K to eliminate the Mn micro-segregation were also prepared for comparison.

(1) A high Mn concentration of 0.8 mass% existed between the secondary dendrite arms. The highest Mn concentration had an initial spacing (L_0) of 137 μm . The spacing narrowed with an increase in compressive strain (ϵ) following the eq. $L=L_0 \cdot \exp(-\epsilon)$, and the Mn concentration became a band-like form ("Mn band"). The pearlite bands were also observed in the largely compressed samples, and the pearlite band spacing was essentially the same as the Mn band spacing.

(2) The ferrite grain size decreased with an increase in compressive strain in the unrecrystallized austenitic regime. Interestingly, the ferrite grain size for the samples with the Mn segregation (the initial austenite grain size of 160 μm) was smaller than that for the samples in which the Mn segregation was eliminated (the initial austenite grain size of 120 μm).

(3) Supposing that the Mn band has the same effect as the austenite grain boundary, the ferrite grain size can be expressed in a single band relationship according to a parameter, ES (effective spacing) without considering the initial austenite grain size or the existence of the Mn segregation. $ES=L \cdot TH_\gamma / (L+TH_\gamma)$, where TH_γ is the austenite grain thickness, and L is the Mn band spacing.

(4) The Mn band formed by the heavy compression is thought to act as a barrier in the form of a relatively stable austenite against the ferrite growth and subsequently induces an increase in the ferrite nucleation.

Acknowledgments

The authors would like to thank Dr. T. Inoue and Mr. N. Yoshida at NIMS for the helpful discussions and Ms. T. Nozawa and Ms. E. Tsuchiya for their assistance in observing the microstructures of the samples.

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