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Increase of austenite grain coarsening temperature in banded ferrite/pearlite steel by cold deformation

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Abstract

The grain coarsening temperature (T_c) is quite low in the ferrite/pearlite (F/P) banded steel as compared with the non-banded steel. Here it is shown that the low T_c in the F/P banded steel can be increased significantly by applying cold deformation prior to austenitizing. The kinetics of abnormal grain coarsening above T_c is also largely retarded by the cold deformation. These should be attributed to the uniform distribution of fine AlN precipitates caused by the cold deformation.

Keywords: Austenite; Banded structure; Grain coarsening temperature; Cold deformation; Precipitate

Inhibition of austenite grain growth above the eutectoid temperature in steels is of great importance in the steel production processes. The presence of second phase particles substantially changes the grain growth behavior of austenite. Early attempts of grain refinement have centered on the formation of AlN precipitates by the addition of Al and N in steels.[1] The other additives such as Ni, V, Ti, and Nb have also been shown to lead to the grain refinement due to the formation of carbides or nitrides.[2-5] At lower temperatures, the precipitates are stable and the austenite grain boundaries can be effectively pinned and the grain growth is thus suppressed. At elevated temperatures, however, the second phase particles are unstable and they readily coarsen or dissolve.[6] Then, unpinning might occur and the grain growth becomes abnormal. During the abnormal grain growth (AGG) a few large grains grow discontinuously and consume the neighboring matrix of smaller grains, which results in the development of extraordinarily large grain.[7] There exists a critical temperature above which the grain growth kinetics changes from normal mode to abnormal mode. This temperature is defined as the grain coarsening temperature, T_c. Furthermore, when the temperature is much higher than T_c, normal grain growth (NGG) again takes place due to the nearly complete dissolution of pinning particles.[6]

AGG of austenite during manufacturing processes should be avoided because the mechanical properties of steels are degraded due to a bimodal grain size distribution of prior austenite caused by AGG.[8] T_c of steels is an important factor in determining the processing parameters so as to avoid the occurrence of AGG. Increasing T_c is an effective way to increase the stability of the steels against abnormal grain coarsening during thermal processing.[9]

There are numerous studies about the austenite grain growth behavior in many types of microalloyed steels. While AGG takes place in all the steels alloyed with Al, Ti, V, and Nb during the austenitizing treatment, T_c is quite different depending on the type and concentration of microalloying elements.[10] Ferrite/pearlite (F/P) banding is commonly observed in hot rolled low alloy steels.[11-17] Steels with the F/P banded structure, called F/P banded steel in this paper, are usually reheated prior to further processing such as carburization, nitridation and ausforming etc. In the authors' recent work[18] it was found that T_c of the F/P banded 0.2 mass% steel is about 1173 K (900 ^oC) which is quite lower than that of the non-banded steel (1323 K (1050 ^oC)). Namely, the F/P banded steel readily suffers from abnormal grain coarsening during reheating. It was found in our previous study that the low T_c in the F/P banded steel is due to the non-uniform pinning-effect of AlN precipitates between the former ferrite and pearlite regions.[18]

Furubayashi et al.[19] investigated the effect of cold deformation on the precipitation behavior of second phase particles. They concluded that the AlN precipitates are made very fine and distributed uniformly by cold deformation. Then one can expect that it may be possible to eliminate the non-uniformity of AlN in the F/P banded steel, thus increasing T_c by applying cold deformation prior to austenitizing. However, it was found in our recent work that the cold deformation lowers T_c of the non-banded steel.[20] Hence, it is unclear whether T_c is lowered or increased by the cold deformation in the F/P banded steel. The purpose of this study is to clarify the effect of cold deformation on T_c of the steel with F/P banded structure. In this paper, it is shown that T_c of the F/P banded steel can be increased significantly by applying cold deformation prior to austenitizing. Furthermore, the kinetics of abnormal grain coarsening above T_c is also made sluggish by the cold deformation.

A hot rolled bar of a hypoeutectoid steel (0.2C-0.2Si-0.8Mn-0.015P-0.005S-0.04Al-0.006N, mass %) was used in this study. To remove the residual stress in the as-received steel bar, the samples were normalized at 1173 K (900 ^oC) for 30 min in air and then furnace-cooled to room temperature. All specimens were taken from the same bar. Some of the samples were cold-rolled by 10 to 50% reductions before the austenitizing treatment. The samples were austenitized for 30 min in an argon atmosphere at temperatures between 1173-1473 K (900-1200 °C). The heating rate of the samples was approximately 5 K/s.

After the austenization, the samples were immediately quenched by dropping into an iced-water bath. Longitudinal sections of the quenched samples were observed by optical microscope after grinding and polishing followed by chemical etching with supersaturated picric acid at 333 K (60 ^{o}C) for 40 s (to reveal the prior austenite grain boundaries). A linear intercept method was employed to obtain the average grain size. The grain size distributions were plotted in area-percent as a function of grain size range. The grain size distributions were investigated to evaluate the severity of AGG.

The microanalysis of AlN precipitates was conducted by using transmission electron microscopy (TEM) with carbon extraction replicas taken from the samples. The method for carbon extraction replica preparation was described elsewhere.[18] The observations and analyses were performed at an operating voltage of 200 kV in a JEOL JEM-2010 TEM equipped with an energy dispersive spectroscopy (EDS). The size of the particles were measured either on the screen at a suitable magnification or on enlarged micrographs. A minimum of 1000 particles were measured for each case to obtain the mean particle size.

The austenite grain sizes at each austenitizing temperature in the undeformed and 30%-deformed samples are shown in Figure 1. Both samples experienced several-staged grain growth mode under different austenitizing temperatures, which is similar with the previously reporting. [6, 10, 18, 21] Here it is important that at critical temperatures (1173 K (900 ^{o}C) for undeformed and 1323 K (1050 ^{o}C) for 30%-deformed samples) the grain size abruptly increases. These critical temperatures are the so called grain coarsening temperature, T_c. In Figure 1, two plots were used at T_c to signify the occurrence of AGG. These lower and higher plots indicate the grain sizes at early and late stages of austenitizing treatment. Hence, the T_c of undeformed and 30%-deformed samples corresponds to 1173 K (900 ^{o}C) and 1323 K (1050 ^{o}C), respectively. Thus, T_c of the 30%-deformed sample is higher than that of the undeformed sample.

Figure 2 shows the effect of the reduction ratio on T_c. It can be noticed that T_c increases with the increase in reduction ratio up to 30% and then it reaches a constant value of 1323 K (1050 ^{o}C) which equals that of the non-banded steel. This strongly indicates that the low T_c of the F/P banded steel can be significantly increased by the cold deformation.

Figure 3 shows the optical microstructures of the 30%-deformed and undeformed samples austenitized in the range of 1273-1373 K (1000-1100 ^{o}C) for 30 min. As is consistent with the previous finding,[18] the undeformed sample (Fig. 3(a)) displays extremely coarse grain structures at 1273 K (1000 ^{o}C) which results from AGG. On the other hand, the grains in the 30% deformed sample (Fig. 3(b)) are fine and uniform at 1273 K (1000 ^{o}C). This indicates that the AGG that occurs at lower temperatures in the F/P banded steel can be prevented by the cold-working prior to austenitizing.

At 1323 K (1050 ^{o}C), mixed grain structures are observed in both the samples, as shown in Figure 3(c) and (d). The extent of AGG in 30%-deformed sample seems not as severe as that in the undeformed sample, according to Figure 3(c) and (d). To compare the severity of AGG in the both samples quantitatively, the grain size distribution for both the samples held at 1323 K (1050 ^{o}C) were examined and the results are shown in Figure 4. Large size grains accounting for higher area fractions indicate the severer extent of AGG. From Fig. 4 it can be noticed that the grains with size larger than 100 μm account for 95% and 19% area fraction in the undeformed and 30%-deformed samples, respectively. Hence, the extent of abnormal grain coarsening in 30%-deformed sample is far less severe than that in the undeformed sample.

It should be mentioned that the austenite grain structures just after the completion of reverse transformation are fine and uniform in both the 30%-deformed and undeformed samples. Therefore, it can be said that the AGG kinetics at 1323 K (1050 ^{o}C) is made sluggish by the cold deformation. The same behavior was observed in the samples held at 1373 K (1100 ^{o}C) for 30 min (Figure 3 (e) and (f)).

Hence, T_c in the F/P banded steel (1173 K (900 ^{o}C)) is greatly increased to 1323 K (1050 ^{o}C) by the cold deformation. Furthermore, the AGG kinetics at the temperatures above T_c is also largely retarded by the cold deformation. These facts indicate that the AGG in the F/P banded steel can be well inhibited by applying cold deformation prior to austenitizing.

In order to understand the mechanism of the effect of cold deformation on

T_c of the F/P banded steel, the size and distribution of AlN precipitates in the pearlite and ferrite regions in the 30%-deformed sample held at 1008 K (735 ^{o}C) for 10 min (the same condition with the precious study[18]) were examined and the results are shown in Figure 5. The AlN particles are fine and uniformly distributed in both the ferrite and pearlite regions. The volume fraction of AlN precipitates can be calculated by the following equation:[22-23]

$$f = \left(\frac{1.4\pi}{6}\right)\left(\frac{ND^2}{S}\right) \qquad (1)$$

where N is the number of the precipitates, D is the mean diameter of the particles and S is the area of the matrix from which the precipitates were extracted.

The measured precipitates size (r) and volume fraction (f) of AlN in the ferrite and pearlite regions are summarized in Table.1. According to the Zener pinning theory,[24] the pinning force is proportional to f/r. In order to compare the pinning effect between ferrite and pearlite regions, f/r in each region is also displayed in Table 1. As for the undeformed sample, the pinning force of AlN precipitates is non-uniform between the ferrite and pearlite regions, which was proposed to be the reason for low T_c in the F/P banded steel.[18] As for the 30%-deformed sample, on the other hand, the values of f/r are almost the same in both regions viz., the pinning force is uniform throughout the sample. Hence, the AGG that occurs at low temperatures (below 1323 K (1050 ^{o}C)) in the F/P banded steel due to the non-uniform pinning effect can be prevented by the cold deformation. And T_c is increased up to the same value with that of the non-banded steel which should be determined by the stability of AlN precipitates at elevated temperatures.

The cold plastic deformation introduces high densities of dislocations into the steels. The dislocations may accelerate the diffusion rate of alloying elements during reheating making the Al distributed more uniformly. In addition, the dislocation loops introduced by the cold deformation which act as nucleation sites of the precipitation made the AlN precipitates very fine and distributed uniformly.[19] Hence, the low T_c of the F/P banded steel can be increased by the cold deformation.

As for the effect of cold deformation on the AGG of F/P banded steel above

T_c, some large grains might be formed due to non-uniform pinning force below 1323 K (1050 ^oC) during the continuous heating process in the undeformed sample. These large grains may grow preferentially during holding at 1323 K (1050 ^oC) because of their size advantage. In the deformed sample, however, some large grains triggering AGG might not be formed during the continuous heating process because the pinning force is uniform at low temperatures. Therefore, the AGG kinetics of the 30% deformed sample is retarded by the cold deformation, and, thus, the extent of AGG in the 30%-deformed sample is less severe. There may be also other possibilities of the effect of AlN particle size distribution on the AGG kinetics, which needs to be further confirmed. According to the above analysis, the cold deformation is effective in controlling the AGG in the F/P banded steel.

In summary, this study of effect of cold deformation on the grain coarsening temperature, T_c, in ferrite/pearlite (F/P) banded steel has shown that the T_c can be increased by the cold deformation. In other words, the abnormal grain growth that occurs in the F/P banded steel at lower temperatures can be prevented by applying the cold deformation. The kinetics of abnormal grain coarsening at temperatures above T_c is also largely retarded. These should be attributed to the fine and uniformly distributed AlN precipitates caused by the cold deformation.

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Figures:

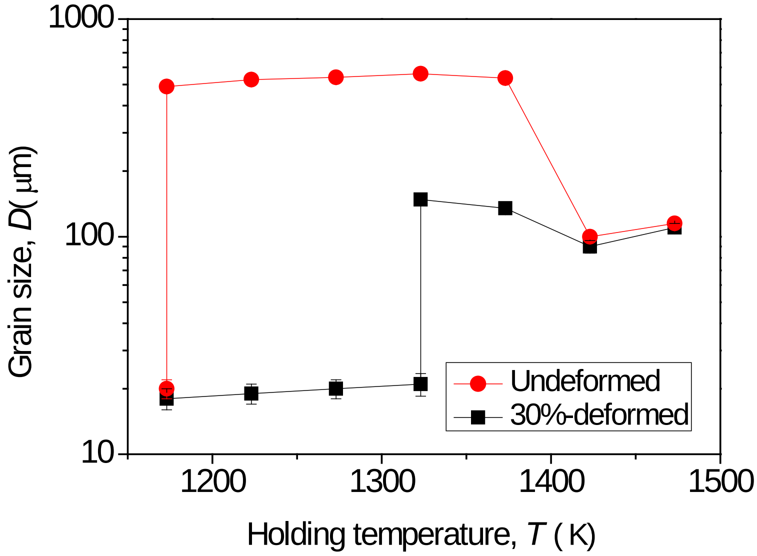

Fig. 1 Austenite grain size of the samples held at various austenitizing temperatures for 30 min.

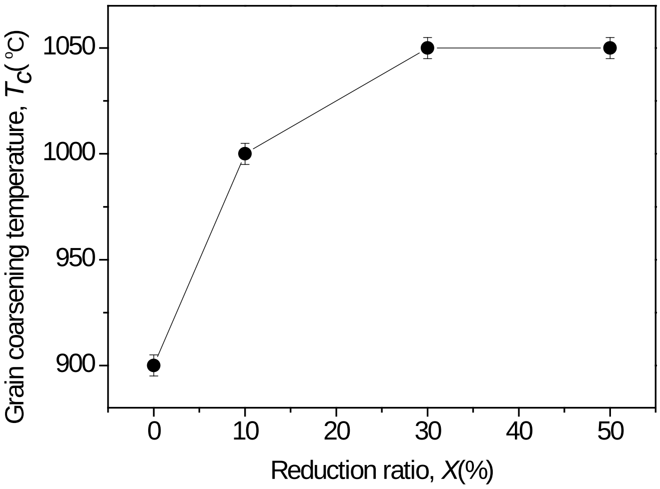

Fig. 2 Effect of reduction ratio on the austenite grain coarsening temperature

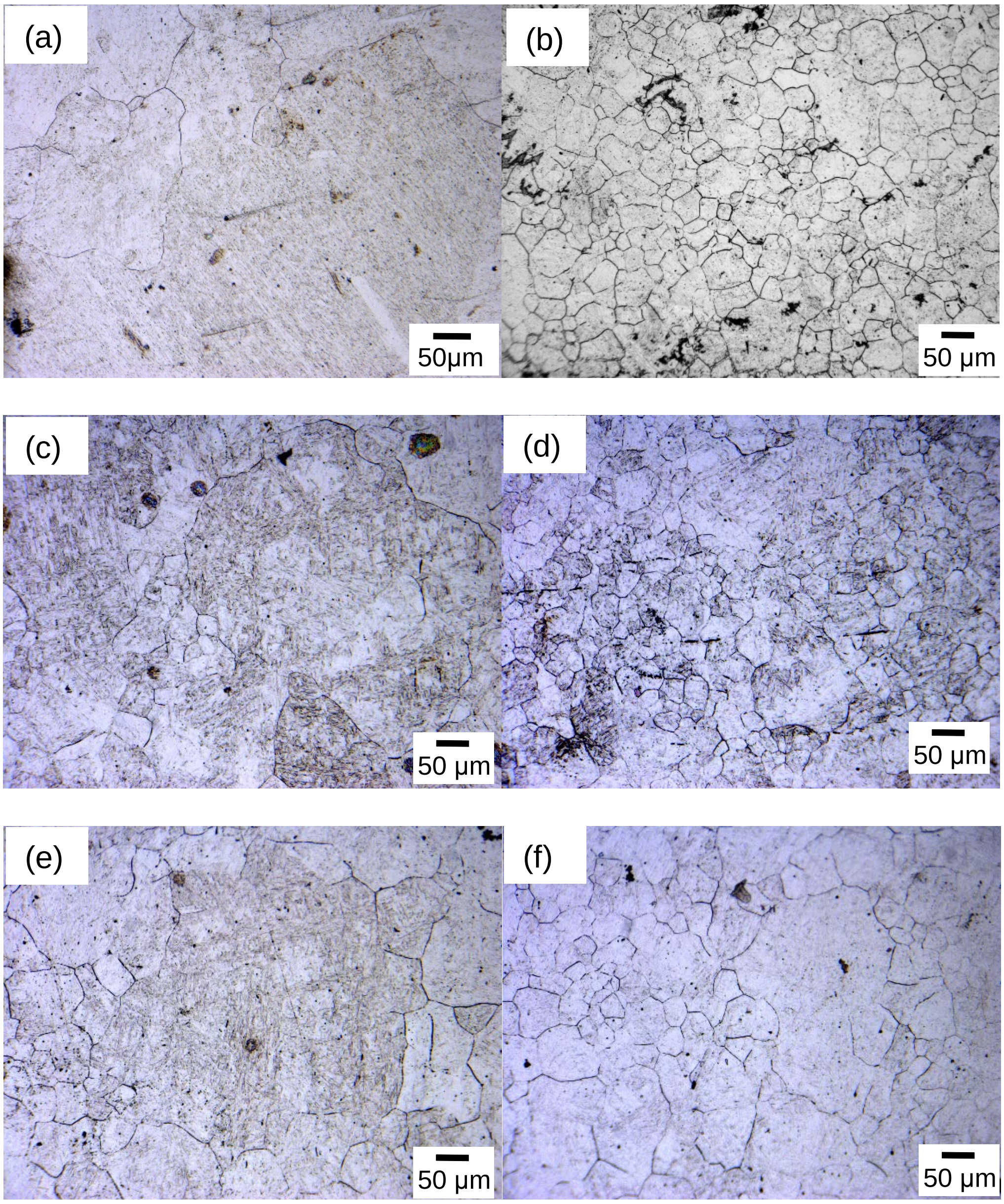

Fig. 3 Microstructures after austenitizing for 30 min at various temperatures in undeformed and 30%-deformed samples. (a) 1000 ^{o}C, undeformed, (b) 1000 ^{o}C, 30%-deformed, (c) 1050 ^{o}C, undeformed, (d) 1050 ^{o}C, 30%-deformed, (e) 1100 ^{o}C, undeformed, and (f) 1100 ^{o}C, 30%-deformed samples.

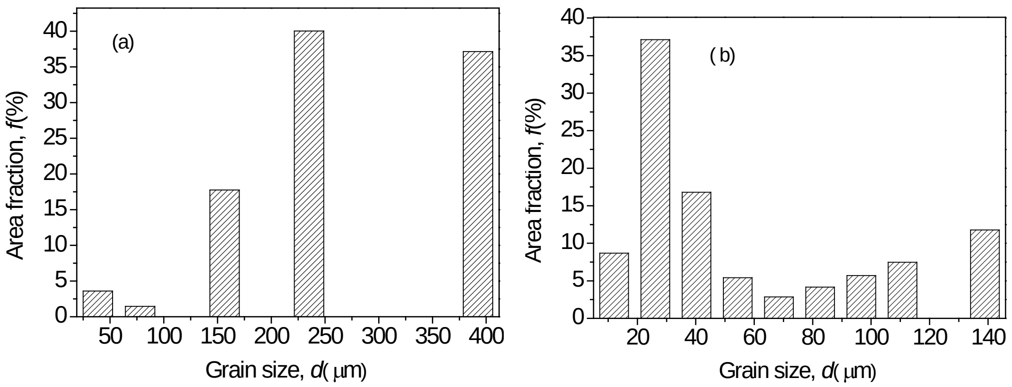

Fig.4 Prior austenite grain size distributions of (a) undeformed and (b) 30%-deformed samples held at 1050 ^{o}C for 30 min.

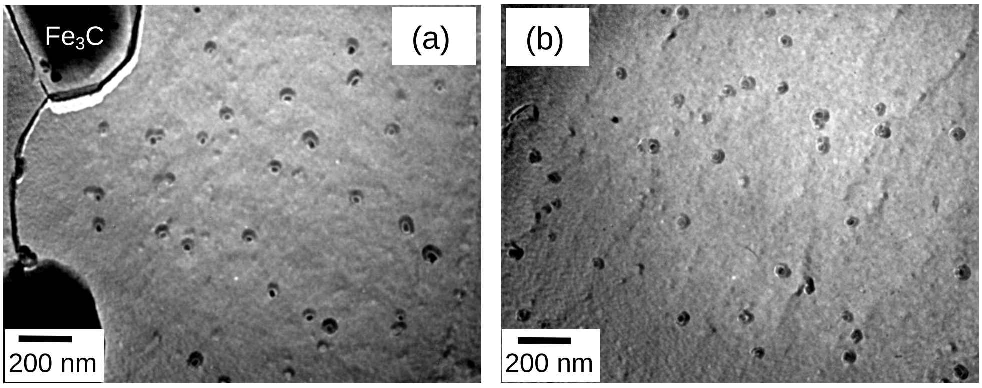

Fig.5 AlN particles in the 30%-deformed sample held at 735 ^{o}C for 10 min: (a) pearlitic ferrite (b) ferrite

Table:

Table 1 Precipitates sizes and volume fractions for the ferrite and pearlite regions

Sample	Average size, *r*(nm)		Volume faction, *f*($\times 10^{-4}$)		*f*/*r*($\times 10^{-4}$ nm^{-1})	
	Ferrite	Pearlite	Ferrite	Pearlite	Ferrite	Pearlite
Undeformed	15.0	10.0	5.79	7.37	0.39	0.74
30%-deformed	8.5	8.5	7.34	7.51	0.86	0.88