Ferrite Transformation during Deformation of Super-cooled Austenite

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The research results achieved by the Korean national project, HIPERS-21, on the ferrite transformation during the deformation of super-cooled low carbon austenite were summarized. Fine ferrite grains formed during the deformation of austenite, i.e. dynamically. The rate of ferrite nucleation was estimated to be accelerated several hundred times by the deformation of austenite. However, the grain refinement could not be explained by the accumulated strain alone. The application of stress during the ferrite transformation is known to effectively weaken the orientation relationship of the ferrite grains with austenite, making the coalescence of the grain difficult during the growth of ferrite and effectively increasing the nominal ferrite nucleation rate. The application of the dynamic ferrite transformation to industrial hot rolling or plate milling was also summarized. The multi-pass rolling technique was introduced to produce a fine ferrite grain structure and controlled cooling was adopted to produce a multi-phase structure in order to improve the work hardening rate of fine grained steels.

KEY WORDS: ultra-fine grained steel; dynamic transformation; multi-pass rolling; orientation relationship; stress effect.

1. Introduction

The Korean national project, HIPERS-21 (High Performance Structural Steels for the 21st Century), started in December 1997 with the goal of developing new technologies for high strength and high performance steels for the 21st century.1) In the first five year stage, basic studies on fine grained steels, weathering steels and high strength bolt steels resistant to hydrogen attack were carried out. The fundamental technologies related to the welding processes and HAZ performances of these steels were also studied. The second five year program was performed as a POSCO internal project and was geared toward the industrial application of the technologies developed in the first stage of the program. The major targets in the first and second stages are summarized in Table 1.

Among these topics, the major research results on the grain refinement through the heavy deformation of super-cooled austenite and the application of this concept to industrial steel mill technology are summarized in this review.

2. Ferrite Grains Formed by Heavy Deformation of Super-cooled Austenite

It is now well established that the heavy deformation of super-cooled austenite just above the Ar1 temperature results in the formation of a fine grained ferrite structure. A ferrite grain size of approximately 1–2 μm can be achieved using this technique.2–9) It is said that, in this case, the ferrite grains are formed dynamically, i.e. during deformation.2–9) Ferrite grain refinement by the deformation of

| Table 1. Main subjects of the HIPERS-21 project. |
|------------------------------------------------|
| First Stage (National Project) | Second Stage (POSCO Project) |
| Fundamental Technologies (1998-2002) | Commercial Developments (2003-2007) |
| Grain Refinement through Strain-induced Dynamic Transformation (SIDT) | Fine grained multi-phase hot strip for automotive application |
| Improvement of HAZ toughness with thermally stabilized TiN precipitates | Fine-grained line pipe steels for sour environment |
| Weathering steels for seaside environment | Fine-grained weathering steel plates |
| High strength bolt steels resistant to hydrogen attack | Thick gage plates for high heat-input welding |
| Construction design using fine-grained high strength steels | High strength bolt steels for construction application |
| | Manufacturing ferrite-cementite steels by SIDT and their applications |
Yada and his co-workers reported the formation of fine ferrite grains with a size of 2–3 μm by the heavy reduction of more than 50% of austenite near the Ar₃ temperature. They suggested massive transformation as the transformation mechanism of ferrite and excluded the possibility of carbon diffusion in this transformation. The difference in the strain energy between the deformed austenite and transformed ferrite was suggested as the driving force for the massive transformation. However, ferrite transformation induced by deformation was also observed at temperatures above the T₀ temperature and the grain morphology caused by the massive transformation was generally far from that of the fine ferrite grain structure observed in low carbon steels. Dynamic transformation was suggested by other authors. Figure 1 shows the fine ferrite grains formed by the 75% reduction of super-cooled austenite at 700°C. The chemical composition of the steel is 0.15C–1.4Mn–0.25Si–0.006B–0.03Ti–0.03Al. The size of these grains was evaluated to be about 2 μm and their orientations were more or less random. The transmission electron micrographs of these ferrite grains showed that they contain a high density of dislocations, probably due to either their lower transformation temperature or plastic deformation after ferrite transformation. Figure 1(b) shows the presence of martensite grains between the dynamically transformed ferrite grains. These martensite grains were formed during quenching after ferrite transformation. The TEM micrographs at a higher magnification showed that these martensites are twinned martensites, which implies that carbon redistribution occurred during the ferrite transformation. During deformation, ferrite grains nucleated firstly at the austenite grain boundaries and grew according to the carbon diffusion. When a heavier deformation was brought about, fine ferrite grains also formed at the intragranular shear bands of austenite and cementite particles formed at the ferrite boundaries.

3. Acceleration of Ferrite Nucleation by Deformation of Austenite

According to the Pill-Box model proposed by Aaronson et al., the deformation of austenite can increase the ferrite nucleation either by increasing the free energy of austenite owing to the increased dislocation density, by increasing the carbon diffusivity in austenite due to the dislocation core diffusion, or by increasing the site density of ferrite nucleation. The dislocation density of hot deformed austenite in the temperature range of 700–1000°C was evaluated by Suh et al. and reported to reach 3.6×10¹¹/m² at 700°C and 7.9×10¹¹/m² at 1000°C. The dislocation density in deformed austenite saturated at a strain of about 0.2 due to dynamic recovery. Figure 2 shows the effect of strain on the ratio of the nucleation flux, J, of deformed austenite to that of non-deformed austenite. Figure 2 demonstrates that the deformation increases the ferrite nucleation due to all three factors described above, i.e. the nucleation site density, diffusivity and driving force terms. However, the increase of carbon diffusion and driving force saturate at a strain larger than 0.2. Figure 2 demonstrates that the deformation can increase the nucleation rate by several hundred times at a strain of 0.7, suggesting that there is a good possibility of the ferrite transformation occurring during deformation, i.e. dynamically. An example which shows the evidence of such a dynamic ferrite transformation is given in Figure 3, in which the dilatation curves during the ferrite transformation after austenite deformation at 700°C were compared. The solid line shows the dilatation curve when ferrite is transformed from the undeformed austenite.
Undeformed austenite and the dotted and dashed lines show the dilatation curves after the given deformation of austenite. The dilatation curves after deformation show that the ferrite transformation was accelerated by the deformation. The ferrite transformation was accelerated by the increase in the deformation, whereas the magnitude of the dilatations after austenite deformation was decreased. These results suggest that a part of the austenite was already transformed to ferrite during the deformation and that the volume fraction of austenite dynamically transformed to ferrite increases with increasing amount of deformation.

However, increasing the nucleation rate may not necessarily result in grain refinement. The grain growth rate may also increase with increasing deformation due to the increased carbon diffusion caused by dislocation core diffusion. Grain coalescence may also occur during growth. Figure 4 shows the ferrite grain structure formed in a 0.14C–1.2Mn–0.25Si–0.0033B–0.012Ti steel when the specimen was held at 700°C for 300 s after 50% deformation at 700°C, (b) after holding for 300 s after the same deformation.19) Two types of ferrite grains can be observed. Very fine ferrite grains formed near the prior austenite grain boundaries and coarse ferrite grains in the prior austenite grains. Very fine ferrite grains can also be observed when the specimens were quenched immediately after 50% deformation (Fig. 4(a)), which means that these fine grains formed dynamically, i.e., during deformation. Dynamically transformed fine ferrite grains are known to be resistant to grain growth, probably due to grain impingement by neighboring ferrite grains or by carbon enriched austenite grains.7) Coarse ferrite grains were only observed in the specimens held at 700°C for 300 s after 50% deformation.19) Two types of ferrite grains were also observed in the unstressed condition and their grain orientations were almost identical. On the other hand, a part of the austenite was already transformed to ferrite during the deformation, whereas, in the stressed condition, the deformation stress was maintained during the ferrite transformation. The stress relaxation during holding for the ferrite transformation was less than 30%. In the unstressed condition, the maximum distribution frequency was observed to be less than 5 degrees. However, in the stressed condition, the deviation angle of the maximum distribution frequency was increased to 5–10 degrees. Applied stress weakens the orientation relationships of the ferrite grains with the mother austenite. Figure 6 compares the orientation distribution of the ferrite grains nucleated at the prior austenite grain boundaries under the stressed and unstressed conditions in a 0.15C–1.4Mn–0.25Si–0.006B steel.21) Film-like ferrite grains were formed in the unstressed condition and their grain orientation is almost identical. On the other hand, a wide variation of the grain orientation was observed when ferrite was formed under the application of stress. Grain coalescence during growth is more difficult in this condition and the nominal nucleation rate will be larger in this case, even if the actual nucleation rate is identical to that in the unstressed condition. In this experiment, a deformation of

![Figure 4. Ferrite grain structure formed in a 0.14C–1.2Mn–0.25Si–0.0033B–0.012Ti steel. (a) Immediately after 50% deformation at 700°C, (b) after holding for 300 s after the same deformation.](image-url)

![Figure 5. Distribution of the deviation angle of ferrite orientation from the Kurdjumov–Sacks (K-S) orientation relationship with austenite.](image-url)

4. Effect of Applied Stress on the Ferrite Grain Formation

As demonstrated in Fig. 4, the grain refinement of dynamically transformed ferrite cannot be explained simply by the accumulation of strain in austenite. The effect of the applied stress on the ferrite transformation should also be considered. Figure 5 shows the deviation of the ferrite orientation from the exact Kurdjumov–Sacks (K-S) orientation relationship with the mother austenite orientation.20) The chemical composition of the steel is 0.15C–1.4Mn–0.25Si–0.006B. Austenite was deformed by the application of 10% strain at 700°C in order to accelerate the ferrite transformation. Under the stress free condition, the deformation anvil was removed during the ferrite transformation after the deformation, whereas, in the stressed condition, the deformation stress was maintained during the ferrite transformation. The stress relaxation during holding for the ferrite transformation was less than 30%. In the unstressed condition, the maximum distribution frequency was observed to be less than 5 degrees. However, in the stressed condition, the deviation angle of the maximum distribution frequency was increased to 5–10 degrees. Applied stress weakens the orientation relationships of the ferrite grains with the mother austenite. Figure 6 compares the orientation distribution of the ferrite grains nucleated at the prior austenite grain boundaries under the stressed and unstressed conditions in a 0.15C–1.4Mn–0.25Si–0.006B steel.21) Film-like ferrite grains were formed in the unstressed condition and their grain orientation is almost identical. On the other hand, a wide variation of the grain orientation was observed when ferrite was formed under the application of stress. Grain coalescence during growth is more difficult in this condition and the nominal nucleation rate will be larger in this case, even if the actual nucleation rate is identical to that in the unstressed condition. In this experiment, a deformation of
10% was applied for the ferrite transformation. There is a good possibility that the orientation of the mother austenite near the grain boundary may deviate from that of the representative orientation of the grain, due to the pre-deformation. Deformation after ferrite nucleation was also reported to effectively aggravate the ferrite orientation relationship with the mother austenite. Recently, Han et al. reported the observation of permanent strain during the recrystallization of ferrite under an applied stress. If plastic strain occurs by interface boundary sliding during the transformation under the applied stress, as suggested by Han or Saotome, the rotation of the ferrite grain orientation during interface boundary sliding is to be expected during the course of the transformation.

5. Industrial Production and Application of Dynamically Transformed Ferrite Steels

5.1. Multi-pass Rolling for the Dynamic Transformation of Ferrite

As described in Sec. 2, we can obtain very fine (1–2 μm) ferrite grains by the dynamic transformation mechanism. The heavy deformation of super-cooled austenite can produce fine ferrite grains through this mechanism. The heavier the deformation, the larger the volume fraction of the dynamically transformed ferrite grains, and the lower the deformation temperature, the smaller the ferrite grain size. However, the rolling reduction that we can achieve per rolling pass in an industrial plate or hot rolling mill is limited by the mill’s capacity. It is almost impossible to achieve a reduction of more than 50% per pass in an industrial rolling mill and the reduction ratio may be further limited at lower temperatures. An alternative method would be multi-pass rolling. Even in multi-pass rolling, however, the rolling reduction should be larger than the critical strain required to form dynamic ferrite. The critical strain varies with the rolling temperature, strain rate, prior austenite grain size and alloy composition. Figure 8 shows an example of the multi-pass rolling of a low carbon steel at 780°C using a plate mill. The reduction per pass was 20% and
the inter-pass time was 10 s. After 4 passes of rolling, the ferrite volume fraction reached 0.78, the equilibrium fraction. Figure 9(b) shows the ferrite grains formed after 4 rolling passes in specimens that were immediately quenched after rolling. Fine ferrite grains with a size of about 2–3 μm were obtained.

### 5.2. Multi-phase Approach for Industrial Application of Fine Grained Ferrite Structure

It is well documented that the work hardening of fine grained ferrite steels is very poor and is not suitable for industrial applications. Figure 10 shows the tensile stress–strain curve of fine grained (2.1 μm) low carbon steel produced by asymmetric rolling (ASTM E8m subsize specimen was used in this experiment). Tensile deformation occurs mainly by Luders band propagation and practically no work hardening was observed until tensile fracture occurred. A method of improving the work hardening of fine grained steel is mandatory for industrial applications.

Figure 11 schematically shows the effect of the coiling temperature on the grain structure of dynamically transformed ferrite. By changing the coiling temperature after dynamic rolling, the precipitation of a second harder phase can be controlled. Figure 12 also shows a good example of the control of the work hardening rate of fine grained steels by the introduction of a second phase through the control of the cooling rate after dynamic rolling (WQ: water quenched, ACC: accelerated cooled, IC: accelerated cooled to 650°C and air cooled).
should not require too complicated thermo-mechanical processing which would hamper the productivity of the mill.

Dynamically transformed fine grained steels are now produced in industrial plate or hot rolling mills and have found a wide range of successful applications in steel structures, including bridge and building construction, line-pipe steels, and many automotive parts.

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