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J. Mater. Sci. Technol., 2012, 28(10), 889–894.
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Effects of Processing Parameters on Microstructure and Properties of Ultra High Strength Linepipe Steel

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[Manuscript received December 16, 2011, in revised form March 16, 2012]

To examine the effect of processing parameters on microstructural evolution and to obtain the excellent combination of strength and toughness, simulation of thermo-mechanical processing was conducted using the Gleeble machine. Trial production was then conducted under the conditions obtained by Gleeble tests. Based on the results of microstructure analysis and mechanical property evaluation, the relationship between microstructural features and mechanical properties was elucidated. The result shows that the volume fraction of constituted phases can be controlled through adjusting the cooling rate and finish cooling temperature in order to get different strength levels. As cooling rate increases, the volume fraction of upper bainite increases, which leads to the increase of strength. The upper shelf energy (USE) increases with increasing volume fraction of acicular ferrite in bainite base because of the small effective acicular ferrite grain size. Ductile-brittle transition temperature (DBTT) decreases with increasing acicular ferrite volume fraction. High reduction in the rough stage has great influence on grain refinement.

KEY WORDS: Linepipe steel; Microstructure; Gleeble test; TMCP (thermomechanical control process)

1. Introduction

Linepipe steel is used to transport natural gas and oil from remotely located sources. Until now a primary interest has been in obtaining higher strength in order to improve the transportation efficiency. However, as the application of linepipe steel expanded to frontier reserve areas such as arctic regions or the deep sea, improvement of toughness without decreasing strength became more important. The ultra high strength linepipe steel consists mostly of bainite or martensite, which has poor toughness. Some researchers have proposed that lower bainite might be helpful to improve the toughness of high strength linepipe steels. However, it is very difficult to obtain such microstructure in practical rolling processes because of the extremely limited phase field in the continuous cooling transformation (CCT) diagram. In current study, improvement in toughness by the formation of acicular ferrite within bainitic structure is considered. To examine the effect of processing parameters on microstructural evolution and to obtain adequate rolling conditions for the optimum microstructure with the excellent combination of strength and toughness, simulation of thermomechanical processing was conducted using a Gleeble machine. Thermomechanical treatment (*i.e.*, rolling) was also conducted in pilot plant scale under the conditions obtained by Gleeble tests. Based on the results of microstructure analysis and property evaluation, the relationship between microstructural features and mechanical properties was elucidated in the present study.

2. Experimental

The chemical composition of the designed steel is shown in Table 1. The chemical composition was based on the idea of low-carbon, high-manganese, Ni–Cu–Mo–V–Nb microalloying, and Ti–B bearing.

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Table 1 Chemical composition of the designed steel (wt%)

C	Si	Mn	Ni	Cu	Mo	V	Nb	Ti	B	Al	P_{cm}	C_{eq}
0.06	0.25	1.8	0.3	0.3	0.308	0.04	0.04	0.014	0.001	0.018	0.207	0.428

Notes: P_{cm} is cold crack susceptibility. P_{cm}=C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B; C_{eq} is carbon equivalent. C_{eq}=C+(Mn/6)+{(Cu+Ni)/15+(Cr+Mo+V)/5}

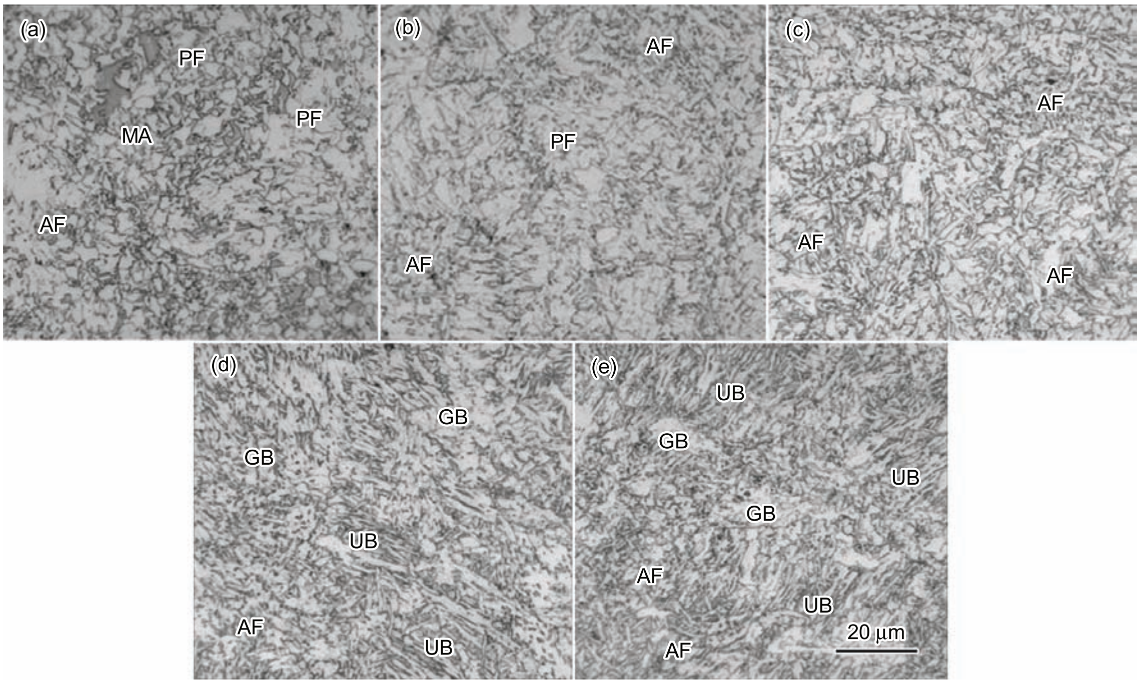

Fig. 1 Microstructure of Gleeble test samples at different cooling rates: (a) 1 °C/s, (b) 5 °C/s, (c) 10 °C/s, (d) 20 °C/s, (e) 30 °C/s (PF: polygonal ferrite, AF: acicular ferrite, GB: granular bainite, UB: upper bainite, MA: martensite and retained austenite)

Melting and casting were performed in the POSCO (Pohang Iron and Steel Company) research Lab, Korea. The Gleeble test was then conducted prior to the pilot plant rolling, which was also conducted in the POSCO research Lab. Finally, the tensile test, the Charpy V-notch impact test and microstructure observation (optical microscopy (OM) and scanning electron microscopy (SEM)) were carried out.

The microstructure of Gleeble test samples is shown in Figs. 1 and 2. According to the microstructure of Gleeble test samples, rolling parameters such as cooling rate and finish cooling temperature were determined. The rolling parameters are shown in Table 2. The values in parenthesis are designed values, and there is variation between the designed value and the actually measured value.

3. Results and Discussion

3.1 Effect of cooling rate

Fig. 1 shows the microstructure formed at various accelerated cooling rates after the Gleeble test. As shown in the figure, with increasing cooling rate, the volume fraction of polygonal ferrite (PF) decreases, while acicular ferrite (AF), granular bainite (GB) and upper bainite (UB) increase. There are substantial amounts of polygonal ferrite at the slow cooling rate (1 and 5 °C/s), while acicular ferrite dominates at the cooling rate of 10 °C/s. When the cooling rate is 20–30 °C/s, the volume fraction of acicular ferrite is about 20%–40% in bainitic base. This is similar to the designed volume fraction of acicular ferrite, which is 20%–30%. Therefore, cooling rates of 20 and 30 °C/s were selected in the pilot plant rolling schedule, which is shown in Table 2. Fig. 3 is the CCT diagram calculated using JMatPro software. The microstructure change with cooling rate can be seen in this figure.

3.2 Effect of finish cooling temperature (FCT) on microstructure

Fig. 2 shows the microstructure of samples by Gleeble test with different finish cooling temperatures. As shown in the figure, the volume fractions of acicular ferrite and granular bainite increase with increasing finish cooling temperature. In the CCT diagram, acicular ferrite and granular bainite transformation temperature ranges are above upper bainite. When finish cooling temperature is high, for example 500 °C, it is in the granular bainite transformation re-

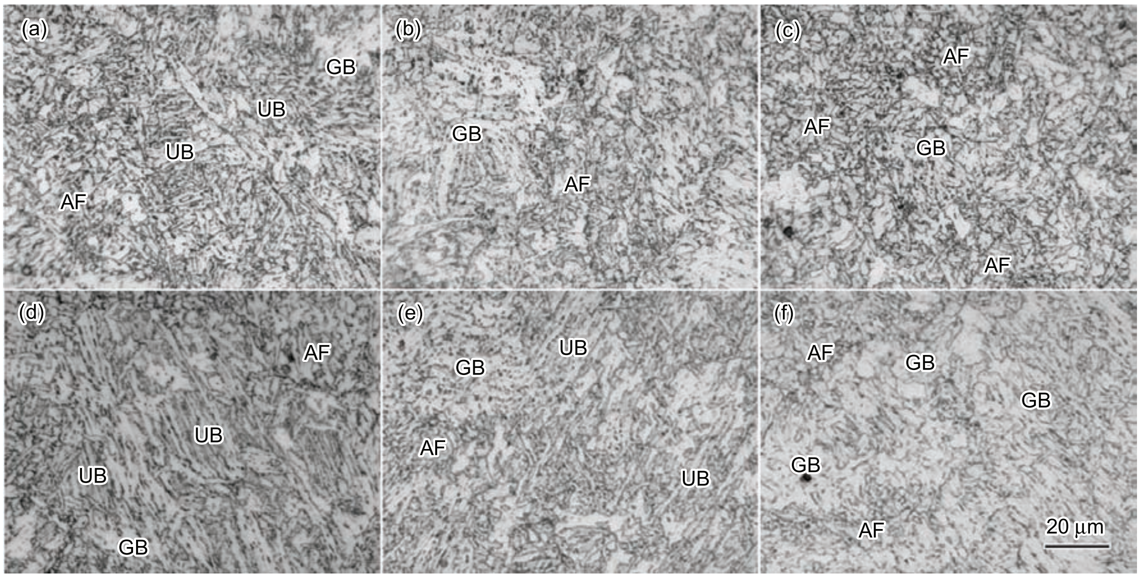

Fig. 2 Microstructure of Gleeble test samples with different finish cooling temperatures (FCT): (a) CR 20 °C/s and FCT 400 °C, (b) CR 20 °C/s and FCT 450 °C, (c) CR 20 °C/s and FCT 500 °C, (d) CR 30 °C/s and FCT 400 °C, (e) CR 30 °C /s and FCT 400 °C, (f) CR 30 °C/s and FCT 400 °C

Table 2 Rolling schedule

Samples	Reduction in austenite recrystallization region/%	Reduction in austenite non-recrystallization region/%	Start cooling temperature/°C	Cooling rate/(°C/s)	Finish cooling temperature/°C
A	35	70.3	780	38	380
B	52	60.2	780	22(20)	450
C	52	60.2	780	30	520(450)

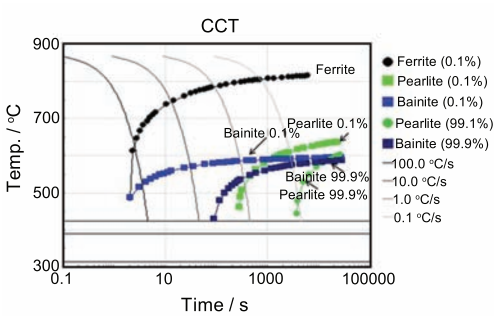

Fig. 3 CCT diagram calculated using JMatPro software

gion, which leads to a large volume fraction of GB in the microstructure. When finish cooling temperature is 400 °C, the transformation is mainly in the upper bainite transformation temperature range, so a large volume fraction of upper bainite is observed in the microstructure. Consequently, in the temperature range of this experiment, the volume fraction of upper bainite increases with decreasing finish cooling temperature.

3.3 Microstructure of hot rolled steel

Fig. 4 is the microstructure of samples after the pilot plant rolling. As shown in the figure, three samples have different microstructure as a result of different rolling parameters (the rolling parameters are shown in Table 2). Sample A contains about 80% upper bainite, 10% acicular ferrite and 10% granular bainite (80% UB+ 10% AF+10% GB); sample B contains about 60% upper bainite, 35% acicular ferrite and 5% granular bainite (60% UB +35% AF+5% GB); sample C contains 65% granular bainite, 25% acicular ferrite and 10% upper bainite (65% GB +25% AF +10% UB). Table 3 summarizes the volume fraction of constituent phases.

From Table 2, it can be known that reduction in the roughing stage of samples B and C is 52%, and 35% in sample A. Even though the accumulated reduction in the finishing stage of sample A (70.3%) is more than that in samples B and C (60.2%), samples B and C have much finer microstructure than sample A, as shown in Fig. 4. Therefore, the heavy reduction in roughing stage has a greater impact on microstructure refinement than that in finishing stage.

3.4 Mechanical properties

3.4.1 Tensile strength

Table 4 shows the tensile properties of samples A, B and C. It is known that the strength of multiphase steel depends on the volume fraction and strength of constituent phases[1–7]. As shown in the table, sample A has higher tensile strength than samples B and

Table 3 Volume fraction of constituent phases

Samples	Upper bainite/%	Acicular ferrite/%	Granular bainite/%
A	80	10	10
B	60	35	5
C	10	25	65

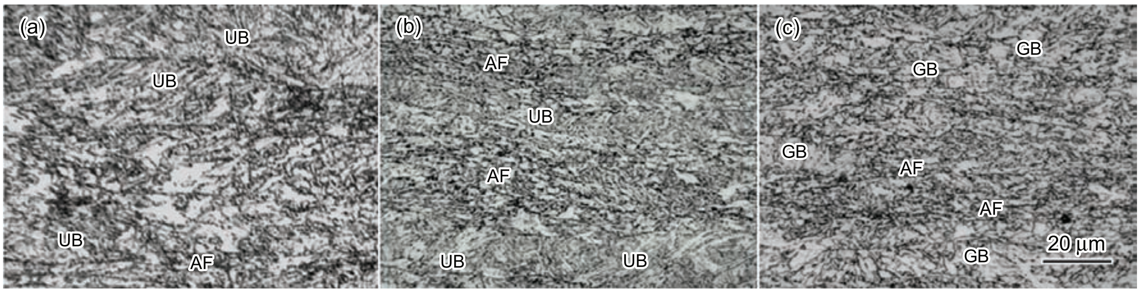

Fig. 4 Microstructure of samples after pilot plant rolling: (a) sample A, (b) sample B, (c) sample C

Table 4 Tensile properties of samples

Samples	YS/MPa	UTS/MPa	YR	EL/%
A	802	926	0.87	17
B	623	744	0.84	20.6
C	629	760	0.83	20.5

Notes: YS: yield strength, UTS: upper tensile strength, YR: yield ratio, EL: elongation

C. The tensile strength of samples B and C is similar. Sample A contains dominant upper bainite, so it has higher strength than samples B and C. Upper bainite consists of ferrite laths with carbon-enriched austenite and martensite islands between them. Bainite transformation is of shear mode, so it contains high dislocation density, which results in higher strength than granular bainite and acicular ferrite. Granular bainite has the same transformation mechanism as upper bainite, but the sheaves are coarser compared with upper bainite, so granular bainite shows a little lower strength than upper bainite.

It is known that yielding in multi-phase steels primarily takes place in ductile phases, and yield strength largely depends on the ductile phase[1]. Samples B and C contain similar amount of ductile phase-acicular ferrite, so they have similar yield strength even though the base microstructure of sample B is upper bainite and granular bainite of sample C. Sample B contains more acicular ferrite than sample C, so sample B shows a little lower yield strength than sample C.

3.4.2 Low temperature toughness

Table 5 shows the upper shelf energy (USE) and ductile-brittle transition temperature (DBTT) of the samples. As shown in Table 5, samples B and C have higher USE than sample A, and sample C has higher USE than sample B. This can be explained by the phase constitution of their microstructure. In general, USE obtained from the Charpy impact data is affected by the matrix structure, the kind, volume fraction and size of secondary phases[2–9]. According to currently available reports on the effect of microstructure on USE[3–8], polygonal ferrite shows the highest USE (300–500 J); however, acicular ferrite and bainite show the USE of 300–400 J and 150–300 J, respectively. This indicates that phases transformed at lower temperatures have lower USE than phases transformed at higher temperatures. Samples B and C contain about 20%–30% acicular ferrite, while sample A contains only 10% acicular ferrite; therefore, samples B and C have higher USE than sample A. Since granular bainite is softer than upper bainite, sample C has higher USE than sample B with 65% granular bainite in sample C and 60% upper bainite in sample B.

Table 5 Upper shelf energy (USE) and DBTT of steels

Samples	USE/J	DBTT/°C
A	90	−85
B	290	−97
C	310	−105

As for DBTT, samples A, B and C all have low DBTT. This is because samples A, B and C all contain a certain amount of acicular ferrite in bainite base. Acicular ferrite is known as the transformation product of a mixed shear and diffusion mode, which happens when the temperature range is slightly higher than bainite′s during hot rolling[10].

Some researchers claim that acicular ferrite is composed of an assemblage of interwoven ferrite grain with a fairly high dislocation density and dispersed precipitation carbonitride. There are ultra fine particles and carbon-enriched martensite/austenite (M/A) islands inside the lath or among the lath[11]. Others believe that an acicular ferrite grain consists of several

Fig. 5 Schematic illustration of acicular ferrite (AF) packet and bainite packet

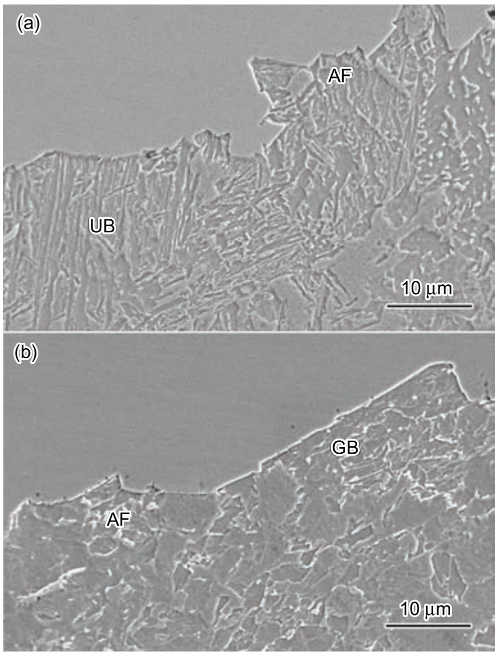

Fig. 6 SEM image of the cross-section area of fractured Charpy impact specimens of samples B (a) and C (b)

Fig. 7 Schematic illustration of the effect of acicular ferrite in bainite base on crack propagation

parallelogram-shaped sub-units, which have low dislocation density. The misorientation angle between sub-units is 1–2 deg. However, researchers agree that the small effective grain size of acicular ferrite contributes to toughness.

The set of adjacent acicular ferrite grains with crystallographic misorientation below 15 deg. makes up the so-called crystallographic packet. This crystallographic packet is also called effective grain, which acts as obstacle to cleavage crack propagation. The effective grain size is smaller than the morphological packet of bainite, which results in good toughness, especially low DBTT of the steel. Bainite packets consist of parallel laths with low-angled boundaries. The prior austenite grain size becomes effective grain size. Fig. 5 is the schematic illustration of acicular ferrite packet[11] and bainite packet.

Fig. 6 shows SEM images of the cross-section area of fractured Charpy impact specimens of samples B and C. As shown in the figure, the crack propagation path changes direction at grain boundaries of acicular ferrite, and thus inhibiting propagation of crack. Certain amount of acicular ferrite in bainite base can effectively improve the toughness of steel. The beneficial effect of acicular ferrite in bainite base on crack propagation is schematically shown in Fig. 7.

4. Conclusions

The designed steel was prepared and evaluated in the laboratory. Based on the experimental work, the following conclusions can be drawn:

(1) The volume fraction of each constituent phase (upper bainite, acicular ferrite and granular bainite) can be controlled by controlling cooling rate and finish cooling temperature. The volume fraction of upper bainite increases with increasing cooling rate, while volume fraction of acicular ferrite and granular bainite increases with increasing finish cooling temperature.

(2) The heavy reduction in the roughing stage plays a very important role in the refinement of microstructure.

(3) Sample A ,consisting mostly of upper bainite, has higher yield and tensile strength than samples B and C, which contain more than 25% of acicular ferrite in their microstructure.

(4) The upper shelf energy (USE) increases with the volume fraction of soft phase such as acicular ferrite. The presence of acicular ferrite in bainite base can significantly decrease DBTT and reduce effective grain size to inhibit crack propagation.

(5) The mechanical properties of pipeline steel with bainite base structures can be effectively im-

proved by the additional acicular ferrite.

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