Journal of University of Science and Technology Beijing
Volume 10, Number 4, August 2003, Page 1

Review

Aspects of microstructure in low carbon steels produced by the CSP process

Delu Liu, Xiangdong Huo, Yuanli Wang, and Xianwen Sun

Materials Science and Engineering School, University of Science and Technology Beijing, Beijing 100083, China
(Received 2003-05-20)

Abstract: The solidification structure, microstructure evolution during rolling and precipitates with nanometers in dimension of the low carbon steels produced by CSP process with thin slabs have been studied in recent years. Important differences in microstructure and mechanical properties between the CSP products and the conventional one were observed. These differences may arise from the much rapider solidification rate and cooling rate after casting of the thin slabs. Some aspects of the microstructure for the low carbon steels of the CSP thin slabs are summarized and compared with the conventional one.

Key words: low carbon steel; CSP hot strip; microstructure evolution; grain refinement

[*Supported by the State foundation for key project: New Generation of Steels (No: G1998061500)*]

1 Introduction

Since the first CSP (compact strip production) steel plant was commissioned at Nucor in 1989, 36 production mills with total 54 streams have been established in the world. The total capacity has reached to 55 Mt annually including the processes of CSP, ISP, DSP, QSP, FTSR and ConROLL [1]. In 1999 the first CSP production line in China started up successfully in Zhujiang Steel Ltd Co. [2, 3]. It is expected that more than 160 million tons of hot strip products will be produced with these thin slab casting and rolling processes in mini mills worldwide by the year 2013 [4-6]. The rapid development of these compact flat product mills has taken place in the last decade owing to their obvious advantages such as low specific investment, low energy consumption and high productivity *etc.* A typical CSP line is illustrated in **figure 1**.

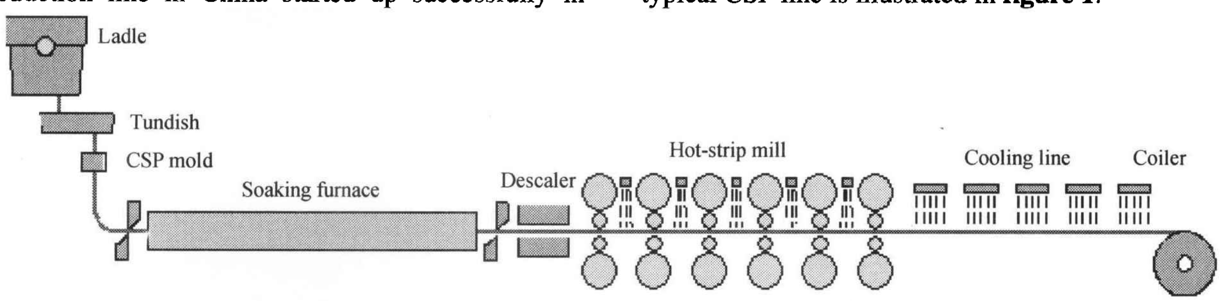

Figure 1 Schematic illustration of a typical CSP process.

Mechanical properties of the hot strips produced by CSP process are usually good. Compared with plain low carbon steels such as Q195, the EAF-CSP products have much higher strength and good ductility. Above 380 MPa yield strength with elongation 35%-40% is obtainable for the plain low carbon steel strips produced by EAF-CSP process. Composition of these steels is similar to that of Q195 (or SS-330), namely C ≤0.06%, Si≤0.10%, Mn≤0.50%, S≤0.035%, P ≤0.025%, Cu≤0.20% and Al 0.025%-0.040% (mass frcation). The mechanical properties are almost no difference between the transverse and rolling direction of the strips [7]. Systematic investigations on the microstructure evolution of CSP steels have been carried out and reported [8-11].

In comparison with the conventional cold charge process, there exists a series of important differences for the CSP process. Firstly, much faster solidification and cooling rate are characteristics for the thin slabs, which lead to distinct in the solidification structure, interdendritic segregation and precipitation of second phases during solidification and cooling process. Some of the parameters for conventional slabs with 250 mm thick and thin slabs with 50 mm in thickness are summarized in **table 1** [12]. Secondly, the hot strips produced by CSP process had undergone different thermo-mechanical processes. No $\gamma \rightarrow \alpha$ and reverse transformations take place prior to rolling in the CSP process. After soaking at 1050 to1100℃ the thin slabs with solidified structure are rolled directly [13].

Corresponding author: Delu Liu, **E-mail:** dlliu@mater.ustb.edu.cn

This approach will bring remarkable effects on the microstructure transformations and precipitations and hence the final microstructure and mechanical properties. Thirdly, the capability of microstructure controlling by cooling rate in the run out table is a very important factor, which has been much improved in the impact production lines. Therefore, much attention has been attracted to this new research field [14-16]. Some aspects of microstructure in the hot strips produced by CSP process will be discussed in the following text.

Table 1 Comparison between the conventional and CSP processes

Process	Conventional slab (250mm)	Thin slab (50mm)	Ref.
Solidification period / min	10-15	1	[12]
Cooling rate (1560-1400℃) / $(K \cdot min^{-1})$	9	120	[12]
Transformation before rolling	Yes	No	[12]
Total deformation / %	99	95	[12]
Total strain / %	4.6	3.0	[12]
Maximum rolling speed /$(m \cdot s^{-1})$	20	10	[12]
Casting speed / $(m \cdot min^{-1})$	1.4-1.8	2.8-5.5	[1], [10]
Slab soaking temperature /℃	1150-1250	1050-1150	[3], [20]

2 Characteristics of solidified structure

Much faster solidification and cooling rate are the characteristics of the thin slabs. It is pointed out [12] by table 1 that the period of solidification for the thin slabs is about one tenth of that for the conventional slabs, and cooling rate for the thin slabs is about thirteen times faster than that for the conventional slab in temperature range from 1560 to 1400℃. The casting speed is also much faster [17, 18] but the soaking temperature is about 100-200 K lower than the reheating temperature of conventional slabs. Differences in these parameters will lead remarkable diversity in the microstructure of the slabs and hence the strips.

Figure 2 shows the macrostructure of a longitudinal section from a thin slab with 50 mm in thickness, which is a low carbon steel containing 0.18 C, 0.09 Si and 0.30 Mn (mass fraction in %, so as the follows). The optical micrographs showing the microstructure in as cast slab of the steel at room temperature are given in **figure 3**. Prior austenite grain boundaries can be distinguished in the pictures. Microstructure at its surface layer and central region (at half thickness position of the slab) of the slab is given in figure 3(a) and 3(b), respectively. Solidification structure of the thin slabs is characterized by the following features.

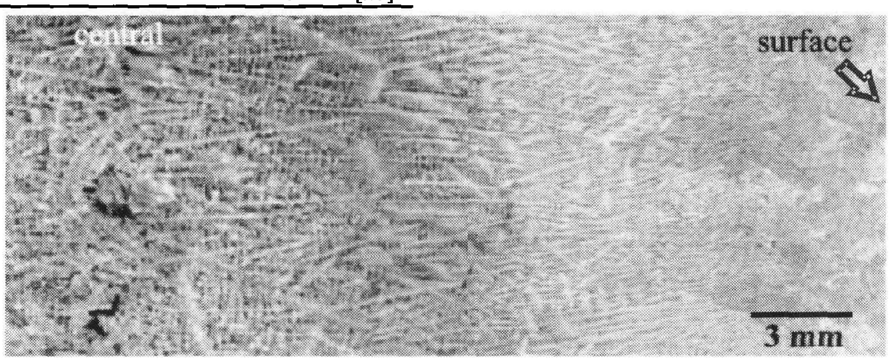

Figure 2 Macrostructure of a low carbon steel slab (50 mm thick) produced by CSP process.

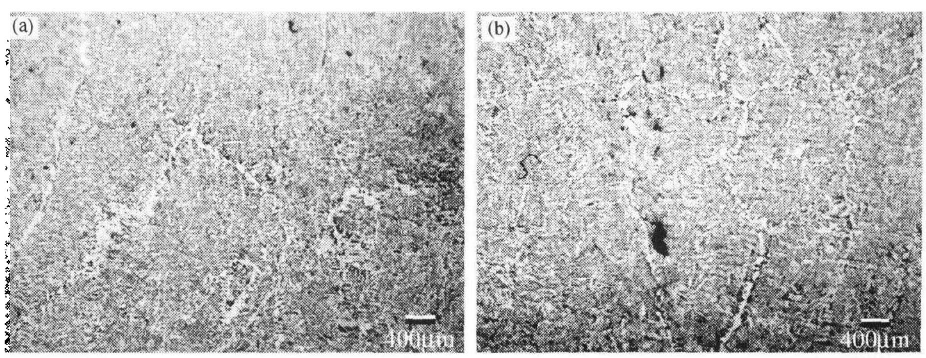

Figure 3 Micrographs showing austenite grains in as cast slab of a low carbon steel, (a) surface layer; (b) central region.

(1) Very thin equiaxed grain zone at the surface layer of the slabs. It can be seen in figure 2 that the thickness of this equiaxed grain zone is several millimeters. The austenite grain size is about 1-2 mm for the slab as shown in figure 3(a).

(2) The dominated structure of the thin slabs is co-

lumnar dentritic zone with much smaller dendrite arm spacing as can be seen in figure 2. The spacing of the first dendrite arms ranges from 0.25 to 1.83 mm. The mean secondary dendrite arm spacing varies from about 90 to 125 μm [19, 20]. In contrast with the thin slabs, the secondary dendrite arm spacing of the conventional slabs ranges between 200 and 500 μm [21, 22]. Therefore, the solidification structure of the thin slab is much finer than that of traditional continuous casting thick slabs.

(3) Due to rather rapid cooling after casting of the thin slabs redistribution of the solute elements such as Mn, Si *etc.* could be limited by insufficient diffusion time. The dendrite arm spacing is the distance over which atomic migration must occur during solidification. Thus the kinetics of homogenization in the thin slabs is obviously different from the conventional one [23]. Further study on both of theoretical and experimental aspects in detail is required for better understanding of the solidification and its effects on the succedent phenomena such as $\delta\rightarrow\gamma$ transformation, precipitation and segregation.

3 Grain refinement during rolling of thin slabs

Austenite grain size and microstructure is a very important factor for controlling the final microstructure of the strips. In the thin slabs of low carbon steels austenite forms from δ phase through $\delta\rightarrow\gamma$ transformation or peritectic reaction during cooling. The microstructure evolution of the thin slabs during rolling would be different from that of the slabs produced by conventional cold charge processes at least in the following aspects:

(1) Without $\gamma\rightarrow\alpha\rightarrow\gamma$ transformations before rolling thin slabs with as cast microstructure are directly deformed by finishing rolling. The austenite grain size, microstructure and segregation prior to the thermomechanical process of the thin slabs is quite different from that of the conventional one [24].

(2) In contrast with the conventional process the soaking of CSP thin slabs is at much lower temperature (see table 1) with shorter holding time (20-30 min). The grain growth of the austenite may be restricted by this condition.

(3) Various differences in precipitation of the nonmetallic compounds, segregation and the solidification structure resulted from rapider cooling rate would affect hereafter the transformations and final structure of the steels.

Optical micrographs given in **figure 4** showed the microstructure in the low carbon steel (with 0.18 C, 0.09 Si and 0.30 Mn) after 55% compression of rolling, which was taken from the same rolling piece as the slab of figure 3. Microstructure at surface layer and a central region (at half thickness position) in the rolling piece are shown in Figure 4(a) and 4(b), respectively. It can be seen by the comparison of figures 4 and 3 that the austenite grain size at the central region decreases from 1-2 mm in the slab to 100-200 μm after 55% compression. This is very close to the austenite grain size of the conventional slabs after reheatig and soaking at 1150-1250℃, which ranges from 50 to 250 μm for a C-Mn steel with a base composition of about 0.12 C, 0.30 Si and 1.40 Mn (yield strength level Grade 355 $MN\cdot m^{-2}$) [19]. But at the surface layer the prior austenite grains are elongated as a "pancake" shape. This can be explained by the strain distributions in the low carbon steel during rolling [25]. The finite element simulation results show that the deformation is not homogeneously distributed along the thickness of a rolling piece during rolling. The maximum shear strain, which is 0.13, mainly distributes at the superficial layer of the rolling piece, while the compressive strain is in the central area. It was reported that the existence of shear strain may refine the grain size more effectively [26].

Mathematical models have been used to estimate the recrystallisation behavior of the austenite during continuous rolling for a low carbon steel (with 0.07 C, 0.325 Mn, 0.03 Si, 0.14 Cu) produced by CSP process [26, 27]. Without roughing the thin slab with 50 mm in thickness was rolled through six finishing stands into 1.9 mm strip. The results showed that the dynamic recrystallisation of the austenite took place in the first pass of rolling, from the second to the fifth pass static recrystallisation of the austenite occurred. In the sixth pass the austenite is non-recrystallized. In general, the grain refinement of the austenite is significant from the first to the third rolling pass owing to the high deformation temperature and heavier deformation ($\varepsilon \geq 50\%$ for the first and the second pass).

These results have been confirmed by a series of experimental observations [10, 11]. Samples of the steels include those taken from the same piece of the slab but undergone different rolling passes. The specimens were cut from a rolling piece, which was obtained by suddenly stopping the rolling operation during continuous rolling. **Figures 5**(a)-5(f) are a series of micrographs showing the microstructure of the specimens at room temperature from this rolling piece. They were taken from the specimen central areas of the rolling piece after each pass. The average ferrite grain size for the samples from the first to the sixth pass is 41.6, 25.2, 21.4, 20.2, 13.1, 6.7 μm, respectively. Difference in the microstructure between the first and the second pass is obvious.

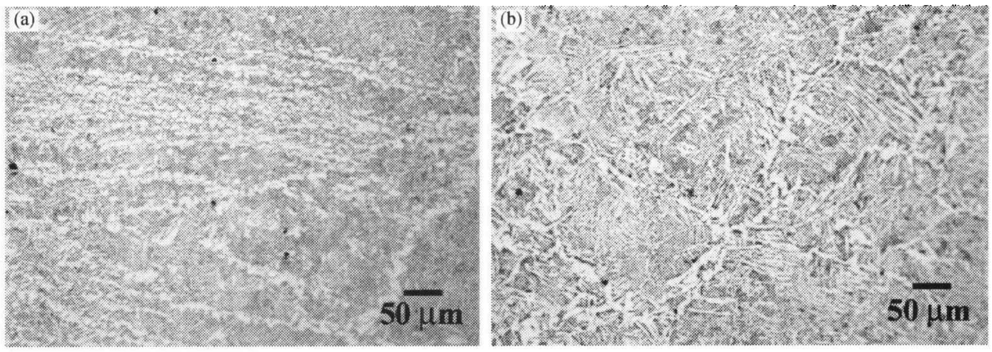

Figure 4 Microstructure in the low carbon steel after 55% compression of rolling, (a) surface layer; (b) central region in the rolling piece.

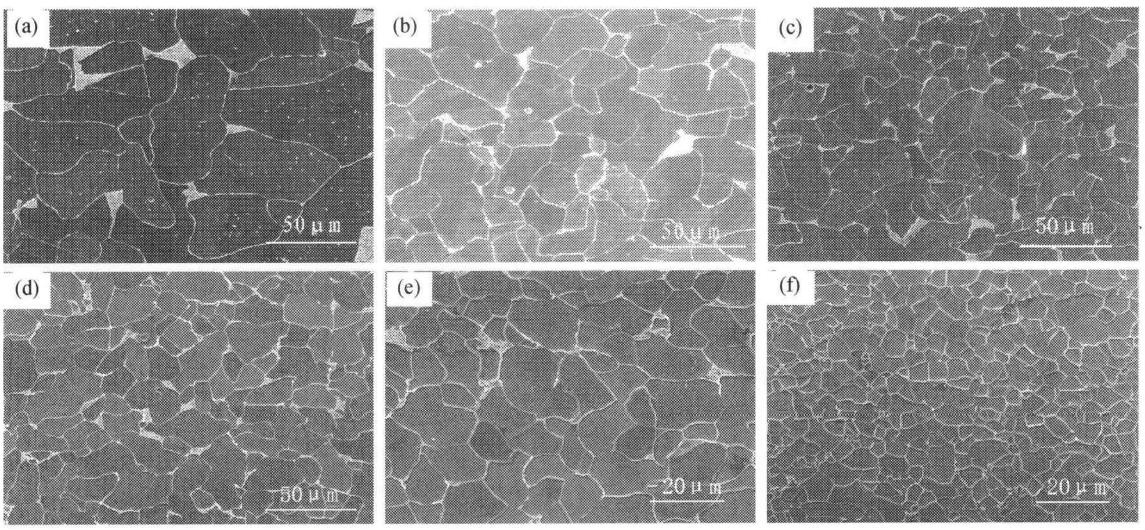

Figure 5 Microstructure of the specimens deformed through different rolling pass from the same slab, after the (a) first pass; (b) second pass; (c) third pass; (d) fourth pass; (e) fifth pass; (f) sixth pass rolling.

4 Accelerated cooling after rolling

Accelerated cooling after hot rolling is also an important factor for controlling the final microstructure [28]. The cooling rate can be controlled by the laminar cooling system in conjunction with water sprays for the CSP lines, which are computer controlled to ensure the designed cooling mode and uniformity of it in strips. It provides an additional grain refinement procedure for the products. The cooling start temperature or rolling finish temperature is usually above the Ar_3 and the coiling temperature or finish cooling temperature ranges from about 500 to 670℃ depending on the steel grades. Thus the parameters of cooling are very important as austenite decomposition reactions usually take place during the cooling process of the strips. Very fine ferrite grain size, for example about 4-5 μm, may be obtained by heavy deformation combined with appropriate cooling.

The cooling rate of the low carbon strips with thickness 2 and 4 mm in the CSP line at Zhujiang Steel Co. has been determined experimentally and summarized in **table 2**. **Figure 6** shows three micrographs of the 2 mm thick strips (low carbon steel ZJ330) obtained by different finishing rolling and coiling temperature but the same continued cooling mode. Their mechanical properties are given in **table 3**. It can be seen that increasing the cooling rate may suppress the pearlite reaction and result in a final structure of ferrite plus bainite (figure 6(b)). Lower finish rolling and coiling temperature leads to refinement of ferrite grains (figure 6(c)). The strength can be increased obviously by the refinement of the equivalent grain size.

Table 2 Cooling rate determined on a CSP line under different cooling mode

Strip thickness	Cooling mode	Cooling rate / (℃·s^{-1})
2 mm	Continued cooling	75-90
	Alternation cooling	~60
	Air cooling	~12
4 mm	Continued cooling	40-50
	Alternation cooling	~30
	Air cooling	~8

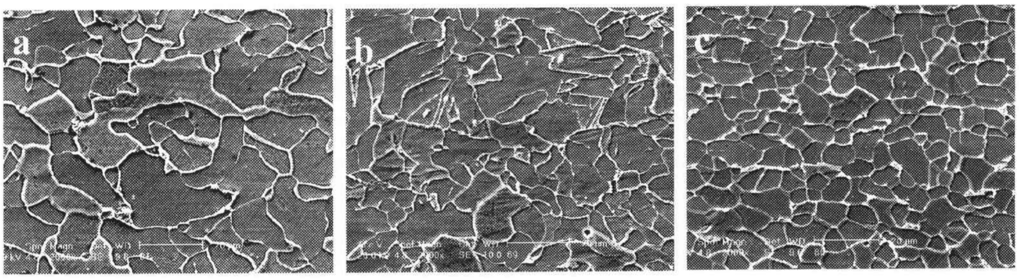

Figure 6 Strip (2 mm thick) microstructure corresponding to different finishing rolling and coiling temperatures, Finishing rolling (F.R) and coiling at (a) 880 and 660; (b) 880 and 550; (c) 800 and 550, respectively (continued cooling mode).

Table 3 Mechanical properties of the strips ZJ330 obtained by various cooling process

Thickness / mm	F.R /℃	Coiling /℃	Cooling mode	σ_s / MPa	σ_b / MPa	δ / %	σ_s / σ_b
4.0	880	600	continued	317	398	28	0.796
4.0	880	600	Alternation	302	384	30	0.786
2.0	880	600	continued	330	400	28	0.825
2.0	880	600	Alternation	329	394	30	0.835
2.0	880	550	continued	344	412	29	0.834
2.0	840	550	continued	357	410	25	0.870
2.0	800	550	continued	367	409	30	0.897
2.0	880	660	continued	334	386	28	0.865

5 Nanometer precipitates

The new results showed that oxides and sulfides may precipitate as dispersive particles in low carbon steels strips produced by EAF-CSP process. Large number of fine oxide and sulfide precipitates with nanometers in dimension in the steels have been observed by using transmission electron microscopy (TEM) and X-ray energy dispersive spectroscopy (XEDS) on both of extract replica and thin foil specimens. The particles may be divided into two groups according to their size. Dimension of the particles in the first group ranges from about 30 to 300 nm. They are mainly manganese and iron sulfides as well as iron oxides.

These precipitates exist in the thin slabs and all of the specimens in spite of the number of rolling pass. It can be deduced that most of them precipitated in the steels during soaking or even at higher temperature. This is also consistent with the calculation from the solubility product of MnS in the steels [29-30]. The sulfides include manganese sulfide, iron sulfide and copper sulfide [15, 31]. The XEDS analysis confirmed that the oxide particles are mainly Fe oxide, containing small amount of Si, Al or Cr. The structure of the oxide precipitates is consistent with the cubic system spinel structure with ($Fd\bar{3}m$) group as determined by electron diffraction. Their lattice parameter a is about 0.82 nm.

According to the Zener model migrating grain boundaries would be pinned by the sulfide and oxide particles [32]. Thus these particles can clog grain growth of the original and recrystallized austenite. This could be one of the important factors for the austenite grain refinement, which controls the final grain size of the steels.

The second group of the particles includes the dispersive precipitates with the size smaller than about 30 nm. These particles seem to settle out at lower temperature in the strips and far from the equilibrium conditions. The nature of these tiny precipitates are not very clear so far. It is very likely that deformation during rolling would have important effects on their precipitation. They may have significant influence on the grain refinement of ferrite and mechanical properties of the steels [33].

Besides the oxides and sulfides, small particles of carbide and nitride also exist in the hot strips. In certain condition carbides seem to nucleate at the surface of sulfide particles [34]. Some other precipitates could also appear. **Figure 7** shows the TEM micrographs of the particles in a thin foil specimen with a X-ray spectrum from one particle. The composition and structure of these particles are not those, which usually occur in conventional plain carbon steels.

It is expected that the effective grain refinement resulted from these nano-scaled particles and grain boundary segregation of impurity elements would play very important role for greatly improving the mechanical properties of the low carbon steels.

In general, precipitation behavior especially the dynamics of the sulfides, some oxides, nitrides as well as carbides in a low carbon steel produced by thin slabs would have important differences from that in the conventional steels.

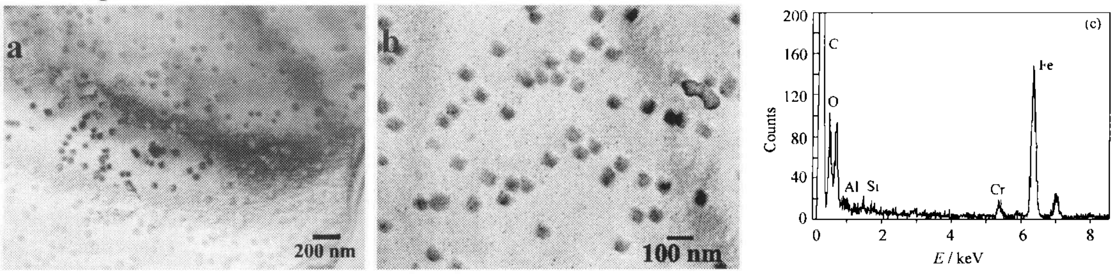

Figure 7 Precipitates in a low carbon steel strips produced by EAF-CSP process, (a) and (b) TEM micrographs of a thin foil specimen, (c) XEDS spectrum from one of the particles.

6 Summary

Rapider solidification and cooling rate of the thin slabs followed by the particular thermo-mechanical procedure in the CSP process would induce very important effects on the solidified structure, microstructure evolution during rolling and precipitations in low carbon steels. Nucleation, growth and coarsening of the precipitates as well as the transformations in the CSP steels would be quite different from that of the conventional steels. Study on these effects in detail is still undertaken. Clearer picture will be coming soon.

Acknowledgements

The authors are indebted to Prof. Jun Ke for his continued interest, encouragement and valuable discussions. Contributions of the colleagues in Zhujiang Steel Co. and University of Science and Technology Beijing are gratefully acknowledged.

References

[1] Z.Y. Zhong, [in] *Proc. of TSCR'2002* [C], Guangzhou: The Chinese Society for Metals, 2002, p.1.

[2] Z.B. Wang, *Iron Steel* [J] (in Chinese), 35(2000), No.12, p.16.

[3] Z.B. Wang, [in] *Proc. of CSM 2001 Annual Meeting* [C], 2001, p.411.

[4] Mott Rodney, Chase David, Hofmann Franz, *et al.*, *Metall. Plant Technol. Int.* [J], 7(1994), No.3, p.98.

[5] S.A. Fernandez Alfonso and Kueper Franz J., *Stahl und Eisen* [J], 116(1996), No.6, p.65.

[6] F.P. Pleschiutschnigg, G. Flemming, W. Hennig, *et al.*, [in] *Proc. of CSM 1999 Annual Meeting* [C], Beijing, China, 1999, p.19

[7] Z.B. Wang, L.J. Li, Y.L. Kang, D.L. Liu, and J. Fu, *Iron and Steel* [J] (in Chinese), 36(2001), No.10, p.33.

[8] H. Yu and Y.L. Kang, *J. Mater. Sci. Technol.* [J], 18(2002), No.6, p.501.

[9] H. Yu, and Y.L. Kang, *J. Univ. Sci. Technol. Beijing* [J], 9(2002), No.5, p.356.

[10] X.D. Huo, D.L. Liu, N.J. Chen, *et al.*, *Iron Steel* [J], 37(2002), No.7, p.45.

[11] D.L. Liu, X.D. Huo, Y.L. Wang, *et al.*, [in] *Proc. of TSCR' 2002* [C], Guangzhou, China, p.379.

[12] Ing. Rob F. Gadellaa., Dr. Ir. Piet J. Kreijger, *et al.*, [in] *METEC Congress 94* [C], Dusseldref, 1(1994), p.382.

[13] N.Y. Tian, *Thin Slab Continuous Casting and Rolling* [M] (in Chinese), Beijing: Metallurgical Industry Press, 1998, p.144.

[14] S.J. Cobo and C.M. Sellars, *Ironmaking Steelmaking* [J], 29(2001), No.3, p.230.

[15] D.L. Liu, J. Fu, Y.L. Kang, *et al.*, *J. Mater. Sci. Technol.* [J], 18(2002), No.1, p.7.

[16] D.L. Liu, X.D. Huo, Y.L. Wang, *et al.*, *J. Univ. Sci. Technol. Beijing* [J], 8(2001), No.4, p.314.

[17] Z.Q. Zheng, Z.Y. Li, F.M. Chen, *et al.*, *Iron Steel* [J], 30(1995), No.1, p.23.

[18] WB Morrison, *Ironmaking steelmaking* [J], 22(1995), p.453.

[19] D.G. Zhou, J. Fu, Z.B. Wang, *et al.*, [in] *Proc. of TSCR' 2002* [C], Guangzhou, 2002, p.355.

[20] Y.F. Wang, Z.B. Xu, Z.B. Zhang, and E. Tang, [in] *Proc. of TSCR' 2002* [C], Guangzhou, China, 2002, p.361.

[21] Z.Z. Liu, *Behavior of Non-metallic Inclusions and Second Phase Particles in Cold-rolled Silicon Steel* [D], University of Science and Technology Beijing, 2001.

[22] J.W. Martin, R.D. Doherty, and B.Cantor, *Stability of MiCrostructure in Metallic Systems* [M], Cambridge University Press, 1997, p.40.

[23] T.Yamashita, S.Torizuka, and K Nagai, [in] *Proc. of the 6th Workshop on Ultra-steel* [C], NIMS, Japan, 2002, p.40.

[24] Y.L. Kang, D.L. Liu, J. Fu, *et al.*, *Iron Steel* [J] (in Chinese), 36(2001), No.6, p.40.

[25] H. Yu, *Research on the microstructure refinement and strengthening mechanism of hot strip of low carbon steel produced by compact strip production* [D], University of Science and Technology Beijing, 2003.

[26] T. Inoue, S. Torizuka, and K Nagai, [in] *Proc. of the 6th Workshop on the Ultra-steel*[C], NIMS, Japan, 2002, p.44.

[27] Y.L. Kang, H. Yu, K.L. Wang, *et al.*, [in] Proc. of TSCR' 2002 [C], Guangzhou, China, 2002, p.313.

[28] Kojima A, *ISIJ Int.* [J], 36(1996), p.603.

[29] Y. Ueshima, Y. Sawada, S. Mizoguchi, and H. Kajioka, *Metall. Trans. A* [J], 20A(1989), p.1375.

[30] H.A. Wriedt and Hsun Hu, *Metall. Trans. A* [J], 7A(1976), p. 711.

[31] D.L. Liu, Y.L. Wang, X.D. Huo, *et al.*, *J. Chin. Electron Microsc. Soc.* [J], 21(2002), No.3, p.283.

[32] J.W. Martin, R.D. Doherty, and B. Cantor, *Stability of Microstructure in Metallic Systems* (Second edition) [M], Cambridge University press, 1997, p.326.

[33] D.L. Liu, Y.L. Wang, X.D. Huo, *et al.*, *Acta Metall. Sin.* [J] (in Chinese), 38(2002), No.6, p.647.

[34] D.L. Liu, N.J. Chen, X.D. Huo, *et al.*, [in] *Proc. of TSCR' 2002* [C], Guangzhou, China, p.323.