A study on the surface quality of carbon steel for continuous casting

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Abstract

The solid-shell unevenness which influence surface cracking during continuous casting was measured for various steel grades. Then the data were used to develop a model to predict the degree of solid-shell unevenness. The model to calculate an index of solid-shell unevenness was developed under the following conditions. Solid-shell unevenness is formed at the initial solidification under the constant cooling rate, which occurs only where solid fraction(fs) is from 0.9 to 1.0. In addition, solid-shell unevenness is proportional to the amount of phase transformation and inversely proportional to the temperature range of ΔT_{PT}; between the temperature of fs = 0.9 and the solidus temperature. This model could explain about 80% of the variation in the experimental results of this study.

Key words: Continuous casting, Surface crack, Solid shell unevenness

1. Introduction

When a shell solidifies non-uniformly, tensile strain concentrates on thin regions, and can easily cause longitudinal cracking. In addition, if the solid shell is uneven, heat transfer is interrupted by air gaps which is formed between solidified shell and mold wall; this interruption extends the time for which the initial solidification layer is exposed to high temperature, and thereby promotes coarsening of grains on the surface of the cast steel. These coarse grains cause concentration of segregation and stress at grain boundaries, so surface cracking is facilitated.[1] During continuous casting, peritectic steels in which the shell is severely unevenly solidified also have relatively large mold level fluctuations, which degrade the quality of the cast surface.[2, 3] So one way to minimize the surface defects on cast steel produced by continuous casting is to design chemical compositions that yield an evenly solidified shell. And casting conditions such as mold flux, mold oscillation, tundish superheat etc., carefully should be decided based on degree of shell unevenness.[4]

The composition of the steel affects its initial solidification behavior and heat flux of mold. The low value of heat flux in the specific carbon region is due to the air gap by δ / γ transformation.[5] However, the shell unevenness may not exactly coincide with heat flux of mold,[6] because the both phenomena are also affected by other factors including casting speed,[6, 7] tundish superheat,[8] mold lubricant,[5, 9, 10] oscillation conditions and mold-level fluctuation.[6] Some attempts have been made to quantify the unevenness of the solidified shell by measuring the solidification profile of steel according to the carbon concentration ([C]). Most studies showed that degree of shell unevenness was high around [C] 0.1 wt%.[11-15] Some studies showed high shell unevenness even in the ultra-low carbon region.[16, 17] However, current understanding is not sufficient to guide development of a model that can predict the unevenness of shell solidification by considering the steel composition.

During solidification, peritectic steel grades undergo relatively large volume shrinkage.[18-20] As a result, the shell unevenness can be severe during continuous casting, so longitudinal cracking can easily occur. Longitudinal cracking depends on upon the extent of peritectic transformation, so the tendency of steels to form delta-ferrite (δ)

during solidification is an important factor. The tendency can be expressed as a ferrite potential. Studies of ferrite potential have attempted to predict the severity of longitudinal cracking by calculating the degree of separation of steel composition from the peritectic point,[21-23] or by defining the thermal strain caused by density change as a consequence of phase transformation during solidification. However, various casting conditions also contribute to longitudinal cracking of cast steel. Therefore, previous research has not adequately predicted the degree of uneven solidification of the shell.

The purpose of this study was to develop a model that can predict how surface unevenness in cast steel is affected by its steel composition.

2. Experiments

Thirteen carbon steels (Table I) that liquid fraction at the start of peritectic reaction from 0.0 to 1.0 were examined to determine the solid shell unevenness. To accurately measure the degree of shell unevenness according to the only steel compositions, process factors (e.g., mold flux, mold oscillation, tundish superheat) that could affect the shell unevenness were excluded during the experiment. All samples were machined as cylindrical (diameter 43 mm) for easy charging into an alumina crucible and weighed ~ 950 g. A vacuum/pressure casting machine (VTC 200V, Indutherm) was used; it consisted of a melting chamber and a casting chamber(Fig. 1). The melting chamber fully melts the specimen, then rotates and pours the molten steel into the copper (Cu) mold of the casting chamber. The melting chamber has an induction coil that can heat the specimen in alumina crucible; a pyrometer is installed to measure temperature of the molten steel in the crucible. During melting and casting processes, the chambers were purged with Ar gas after vacuuming $\leq 10^{-3}$ Torr to prevent oxidation of the specimen. The super heat of the molten steel was set to 50 °C. Inside the Cu mold in the casting chamber, cooling water is supplied to the lower part and passes through the water channel to the upper part. The cooling water is designed to maintain a constant temperature and flow rate. Solidified specimens that had contacted the copper mold were observed under a microscope to get the surface 3D-profile, which was then converted to seven 2D profiles by vertically cutting the measured 3D-profile at 2.5-mm intervals. Maximum depths of 2D profiles were measured(Fig.1) and the profile depth was the average of the maximum depths. The measured profile depth was used as the degree of solid-shell unevenness.

Table I. Chemical Composition of Test Steel (Balance Fe).

	wt.%									
	C	Si	Mn	P	S	Ni	Cu	Ti	Nb	liquid fraction at the start of peritectic reaction
Steel 1	0.03	-	0.02	0.006	0.008	0.01	0.02	-	-	< 0.00
Steel 2	0.09	0.21	0.35	0.015	0.015	0.05	0.16	-	-	0.01
Steel 3	0.09	0.22	0.37	0.015	0.016	0.06	0.17	-	-	0.02
Steel 4	0.06	0.26	1.44	0.006	0.001	0.45	0.14	0.01	0.01	0.04
Steel 5	0.05	0.01	1.90	0.007	0.002	0.90	0.28	0.01	0.01	0.05
Steel 6	0.06	0.28	1.92	0.006	0.002	0.50	0.18	0.01	0.03	0.08
Steel 7	0.14	0.60	0.55	-	-	0.20	0.10	-	-	0.15
Steel 8	0.15	0.28	1.31	0.011	0.004	0.01	0.01	-	0.02	0.23
Steel 9	0.19	0.25	0.50	-	-	-	-	-	-	0.26
Steel 10	0.28	0.22	0.36	0.015	0.012	0.06	0.18	-	-	0.48
Steel 11	0.37	0.21	0.35	0.014	0.011	0.01	0.02	-	-	0.70
Steel 12	0.44	0.23	0.60	0.010	0.002	0.01	0.01	-	-	0.95
Steel 13	0.56	0.24	0.67	0.013	0.011	0.01	0.02	-	-	> 1.00

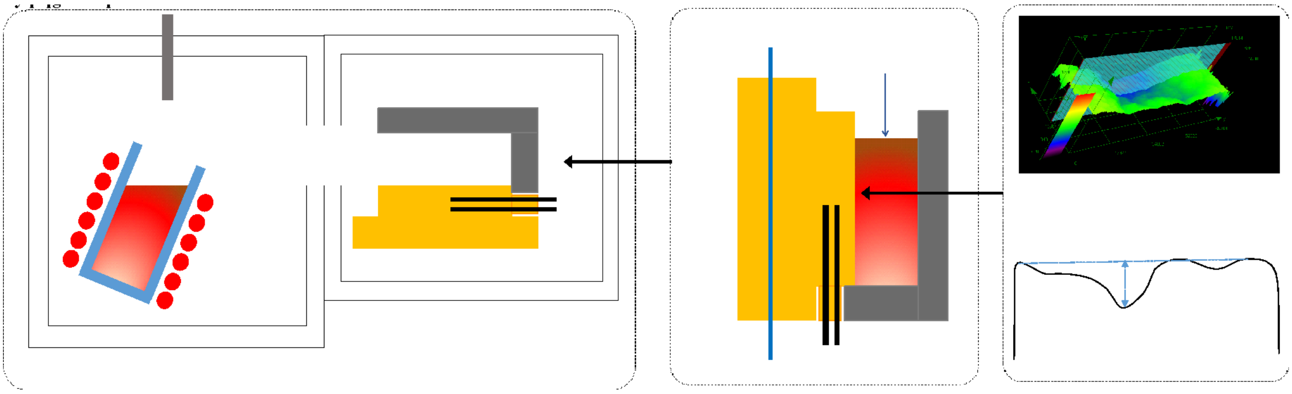

Fig. 1. Schematic diagram of experimental equipment

3. Results and Discussion

3.1 Surface profile of test specimens

Each surface roughness of specimen was shown as 3D profile(Fig. 2a) and profile depth(Fig. 2b). At the initial liquid fraction at the start of the peritectic(f_{lsp}) was 8% or less, the profile depth increased with increase of f_{lsp}, but at f_{lsp} was > 8%(steel 7~13), the profile depth decreased with increase of f_{lsp}. The largest profile depth was 1125 μm; it occurred in the specimen that had f_{lsp} = 8%(steel 6). At f_{lsp} > 50%(steel 11~13), the profile depth became very small.

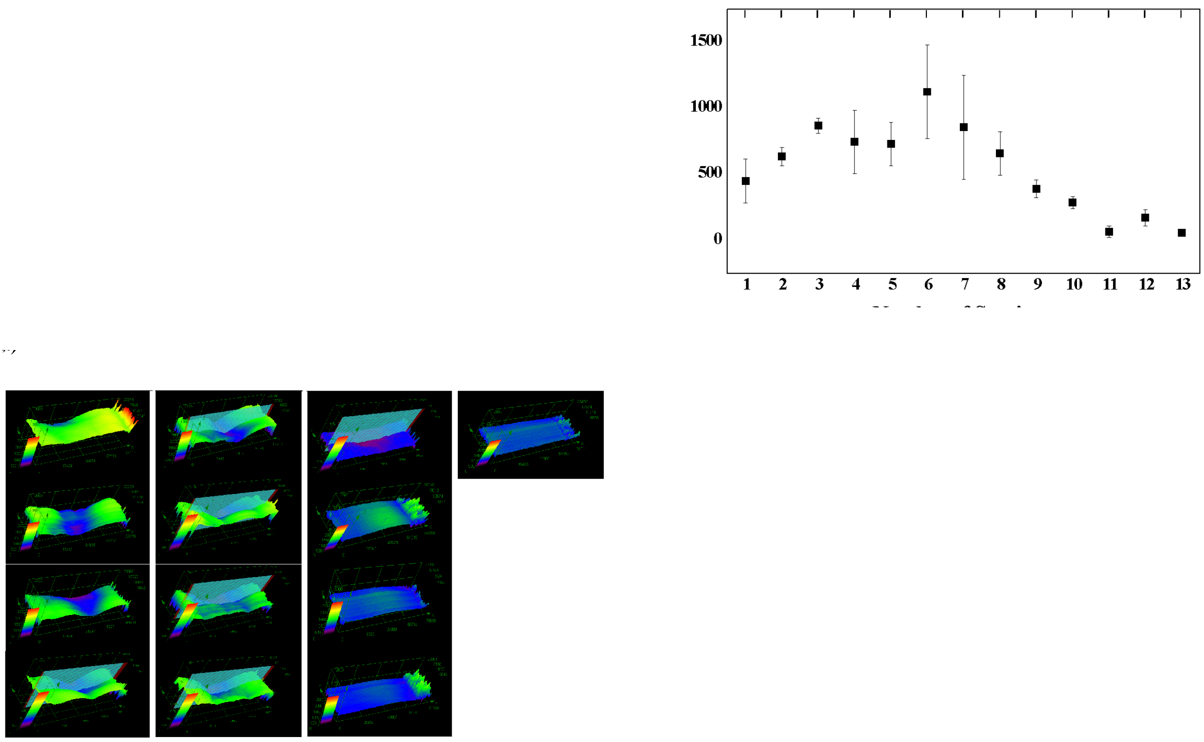

Fig. 2 Surface profile of test specimens; (a) Surface 3D profile, (b) Profile depth

3.2 Uneven Solidification Index

The main cause of solid-shell unevenness of cast steel is volume contraction due to the phase transformation occurring. And, the solid shell is very thin during the initial solidification period in which solid-shell unevenness occurs, so it can easily contact the mold. Thus, to study the effect of the steel composition on the solid-shell unevenness, it was regarded as the same mold cooling condition, that is, the same cooling rate.

As the temperature decreases, the liquid phase transforms into a solid phase, resulting in volume contraction. If the liquid phase moves to the area where the volume contraction occurs to compensate for the contraction, deformation of the solid phase is difficult to occur. Therefore, it is considered that only the volume contraction that occurs while the liquid phase is difficult to move can cause the deformation of the solid phase. Figure 6a[24] is a schematic diagram showing the correlation between the flow of the residual liquid phase and the solid fraction(fs). Liquid can penetrate between the solid phases only at a temperature higher than the limiting temperature (LIT). When volume contracts due to phase transformation, if the liquid fills those spaces, then solid shell deformation may not be easy, so the solid-shell unevenness can be assume to occur if temperature is between LIT and solidus temperature. This condition can be indicated in the phase diagram of carbon steel (Fig 3b; LIT = dotted line). It can be said that solid-shell unevenness occurs in a rangeΔT_{PT} from LIT to solidus temperature. The solid fraction f_{LIT} at LIT has been shown to be 0.9.[20,25]

The chemical composition of a steel affects its phase-transformation speed, and distortion occurs only when the phase transformation speed is fast.[26] In other words, as the transformation speed increases, the amount of deformation causing distortion increases. In addition, at a constant cooling rate, the phase transformation speed increases as the temperature range T_{PT} between the phase transformation start and its completion decreases (Figure 3b). After solidification is completed, the solid shell is sufficiently strong that it can be considered to be unaffected by any subsequent phase transformation.

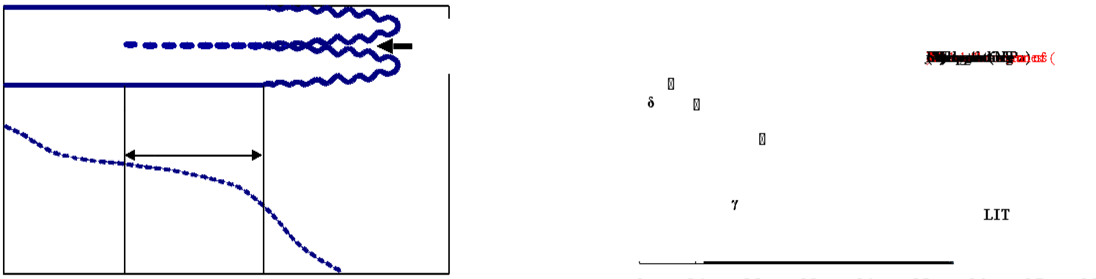

Fig. 3 Schem[illegible] drawing [illegible] erature range where solid shell unevenness forms; a) Relation between temperature range [illegible]venness formation and dendritic structure b) Calculation temperature range(T) for solid-shell unevenness according to carbon content, LIT ≤ T ≤ T $_{f\mathrm{s}=1.0}$,ⓐ is the L/δ transformation, ⓑ is the (δ+L)/γ transformation, ⓒ is the L/γ transformation.

A model to predict solid-shell unevenness was developed under the following conditions.

1) Solid-shell unevenness occurs when the solid shell begins to form, and the contact state between the solid shell and the mold during this period is very good. Therefore, the cooling rate is constant regardless of the chemical compositions of the steels.
2) The deformation that causes solid-shell unevenness occurs only at temperatures between LIT and the solidus temperature.
3) The amount of deformation increases as phase transformation speed increases. Therefore, the amount of deformation is proportional to amount of phase transformation, and inversely proportional to the range of ΔT_{PT} (Figure 3b).

The degree of deformation occurrence, that is, the degree of solid-shell unevenness, was defined as Uneven Solid shell Index (USI) (Eq. 1).

$$\text{Degree of solid-shell unevenness (USI)} \qquad (1)$$

$$\propto \text{Change of phase fraction} / \Delta T_{PT}$$

$$\propto \frac{\Delta L/\delta}{\Delta T_{L/\delta}} + \frac{\Delta(L+\delta)/\gamma}{\Delta T_{(L+\delta)/\gamma}} + \frac{\Delta L/\gamma}{\Delta T_{L/\gamma}}$$

where $\Delta L/\delta$ is the amount of phase transformation which liquid changes to delta ferrite (Figure 3b, region ⓐ), $\Delta(L+\delta)/\gamma$ term is the amount of phase transformation which liquid and delta ferrite change to austenite (Figure 3b, region ⓑ), $\Delta L/\gamma$ is the amount of phase transformation which liquid changes to austenite (Figure 3b, region ⓒ), and $\Delta T_{i/j}$ is the temperature range in which the phase changes from i to j.

Changes of phase fraction ($\Delta L/\delta$, $\Delta(L+\delta)/\gamma$ and $\Delta L/\gamma$) and ΔT_{TP} ($\Delta T_{L/\delta}$, $\Delta T_{(L+\delta)/\gamma}$ and $\Delta T_{L/\gamma}$) (Fig. 4) were calculated using JMatPro (version 11). In steel 6, they were $\Delta L/\delta=2.4$, $\Delta(L+\delta)/\gamma=49.1$, $\Delta T_{L/\delta} = 2.72$ °C and $\Delta T_{(L+\delta)/\gamma} = 2.67$ °C, whereas steel 8 showed no L/δ transformation between $T_{fs=0.9}$ and $T_{fs=1.0}$; for the other transformations, the values were $\Delta(L+\delta)/\gamma=17.4$, $\Delta L/\gamma=7.2$, $\Delta T_{(L+\delta)/\gamma}= 0.76$ °C and $\Delta T_{L/\gamma} = 10.6$ °C. Because of these differences, in particular the differences in $\Delta(L+\delta)/\gamma$ and $\Delta T_{(L+\delta)/\gamma}$, the USI changes according to the steel composition.

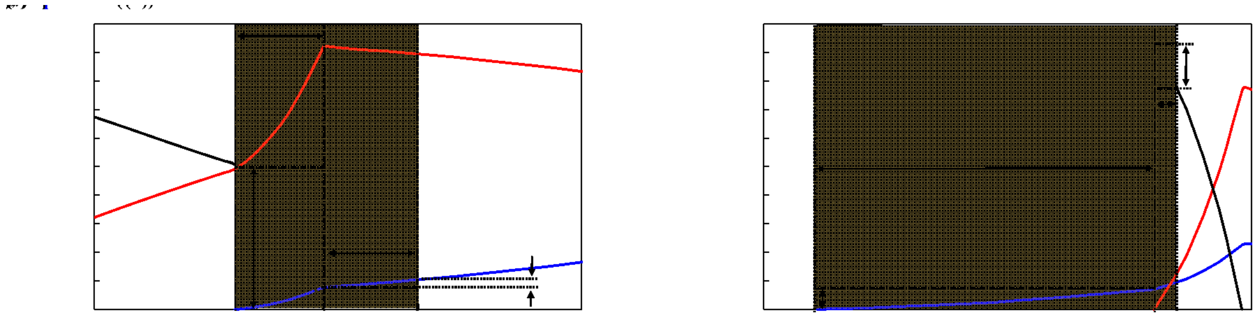

Fig. 4. Example of USI calculation for specimens a) steel 6, b) steel 8, the calculation temperature range is from $T_{fs=0.9}$ to $T_{fs=1.0}$ (Yellow box)

The consistency between the profile depth and the calculated USI value in Eq. (1) was investigated using the f_{LIT} and an exponent term $\Delta T_{PT}{}^{n}$ as variables. The consistency between the two factors was the best when $f_{LIT} = 0.9$ and $n = 0.3$. This result that $f_{LIT} = 0.9$, agrees well with previous results[21, 26)]. The results of USI calculation are positively correlated with the profile depth ($R^2 = 0.88$; Fig. 5a). Also, the USI varies nonlinearly according to f_{lsp} as the profile depth does, and can predict the range in which the profile depth is highest (Fig. 5b). This result confirms that the USI gives a good explanation of the solid-shell unevenness caused by phase transformation in the steel.

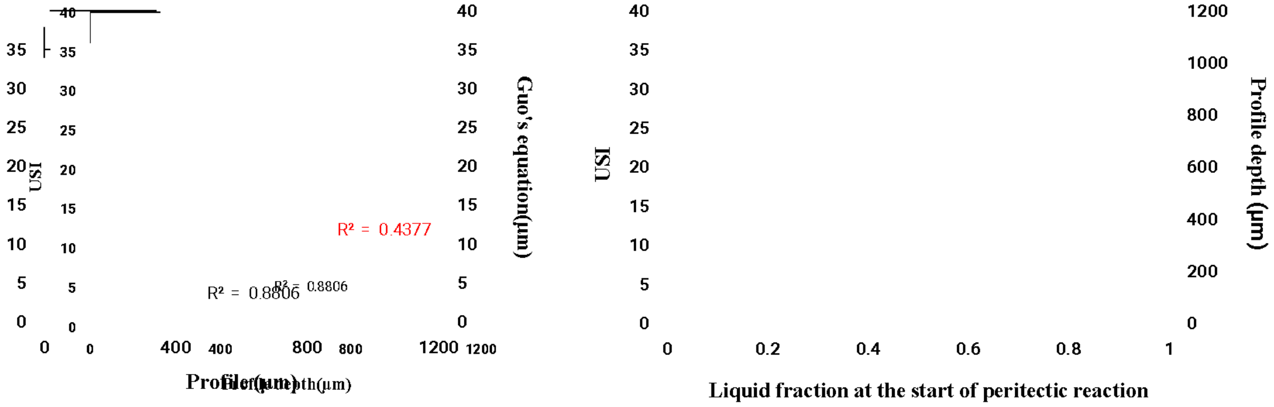

Fig. 5. Comparison of USI calculation result and profile depth a) Relation between USI and Profile depth b) Behavior of USI and profile depth according to liquid fraction at the start of peritectic reaction

The USI value calculated using the model developed in this study agree well with previous measurements of solid-shell unevenness (Figure 6). The developed USI are compared with reported unevenly solidified shells in steels with compositions of Si 0.2, Mn 0.5, P 0.02, S 0.02, Al 0.5 wt% (Fig. 6a)[12] and Si 0.3, Mn 0.3, P 0.01, S 0.01, Al 0.03 wt% (Fig. 6b).[11] The USI can explain all of the degrees of solid-shell unevenness that were measured in various experiments.

These results confirmed that the USI of this study can accurately predict the degree of solid-shell unevenness according to the steel composition. Therefore, USI may be useful to guide design of chemical compositions of new steel grades, or for optimization of casting operation to achieve stable surface quality of slabs.

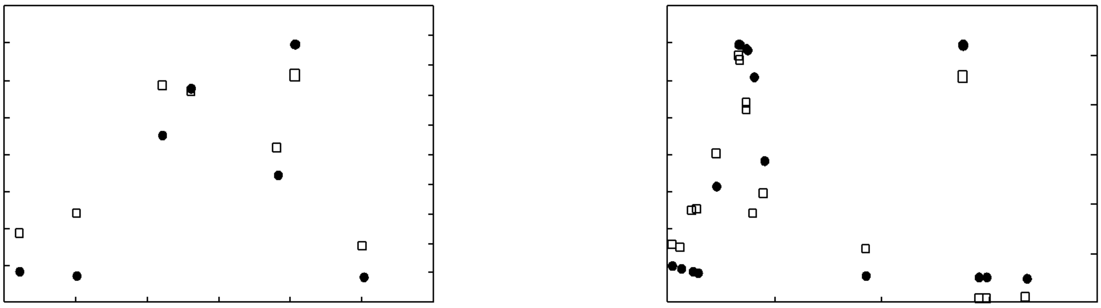

Fig. 6. Comparison of USI calculation result and profile depth a) Relation between USI and Profile depth b) Behavior of USI and profile depth according to liquid fraction at the start of peritectic reaction

3. Conclusion

To quantify the effect of the steel composition on solid-shell unevenness, the profile depth and Φ_q were measured for 13 steel grades. A model to predict the of degree of solid-shell unevenness was developed according to the steel composition. The main results are as follows.

1) An apparatus and method that uses a 950g ingot were developed to accurately measure solid-shell unevenness and heat flux according to the steel composition.
2) The model to predict uneven shell solidification was developed, under the following conditions:
   (a) Solid-shell unevenness is formed at the beginning of solidification and the cooling rate during this period is constant.

(b) Solid-shell unevenness occurs only at the stage of solidification with a liquid fraction ≤ 0.1.

(c) The solid-shell unevenness are proportional to the amount of phase transformation and inversely proportional to the temperature range of the phase transformation.

The model(USI) is

$$\frac{\Delta L/\delta}{\Delta T_{L/\delta}^{\ 0.3}} + \frac{\Delta(L+\delta)/\gamma}{\Delta T_{(L+\delta)/\gamma}^{\ 0.3}} + \frac{\Delta L/\gamma}{\Delta T_{L/\gamma}^{\ 0.3}}$$

3) The prediction model developed in this study was about 88% correlated with the experimental results, and was consistent with the overall results of solid-shell unevenness measurement by other researchers. This prediction model may be used effectively to guide chemical composition design and mold operation optimization of new steel grades.

REFERENCES

[1] R. Dippenaar, S.C. Moon, E.S Szekeres: Iron and Steel Technology, (2007), 105

[2] Y. Li, X. Zhang, P. Lan and J. Zhang: International Journal of Minerals, Metallurgy and Materials, **20**(2013), 138

[3] Z. Jiang, Z. Su, C. Xu, J. Chen, J. He: Journal of Iron and Steel Research Int., (2019), https://doi.org/10.1007/s42243-019-00299-7

[4] T. Emi and H. Fredriksson: Met. Sci. Eng. A, **2**(2005), 413

[5] S. N. Singh and K. E. Blazek: Open Hearth Proc. AIME, **59**(1976), 264

[6] J. SUNI and H. HENEIN: Metall. Mater. Trans. B, **27**(1996), 1045

[7] T. Kanazawa, S. Hiraki, M. Kawamoto, K. Nakai, H. Hanazaki and T. Murekami: Tetsu-to-Hagane, **83**(1997), 701 (in Japanese)

[8] M. Suzuki and Y. Yamaoka: Mater. Trans, **44**(2003), 836

[9] V. A. Ulyanov, E. M. Kitaev, and A. A. Skvortsov: Steel in the USSR, Metals Society, London, **8**(1978), 617

[10] K. Saito and M. Tate: Open Hearth Proc. AIME, **56**(1973), 238

[11] Y. Sugitani and M. Nakamura: Tetsu-to-Hagane, **65**(1979), 1702–1711

[12] H. Murakami, M. Suzuki, T. Kitagawa and S. Miyahara: Tetsu-to-Hagane, **78**(1992), 105 (in Japanese)

[13] Y.M. Won, T. Yeo, D.J. Seol and K.H. Oh: Metall. Mater. Trans. B, **31**(2000), 779

[14] D. Pu, G. Wen, D. Fu, P. Tang and J. Guo: Metals, **8**(2018), 982

[15] J. Guo, G. Wen, D. Pu and P. Tang: Materials, **11**(2018), 571

[16] H. Shibata, M. Suzuki, and T. Emi: *Conf. Current Advances of Materials and Processes—ISIJ*, ISIJ, Tokyo, 1998, vol. 11, pp. 36–37.

[17] M. Suzuki, C.H. Yu, H. Sato, Y. Tsui, H. Shibata and T. Emi: ISIJ International, 1996 vol. 36, Supplement, pp. S171-S174

[18] S. Saleem, M. Vynnycky and H. Fresriksson: Metall. Mater. Trans. B, 2017, vol. 48, pp. 1625-1635

[19] H. Fredriksson: Met. Sci., 1976, vol. 10, pp77-86

[20] K.h. Kim, T.J. Yeo, K.H. Oh and D. N. Lee: ISIJ Int., **36**(1996), 284

[21] M.M. Wolf: Continuous casting, Iron & steel Socity, Warrendale, PA, **9**(1997), 63

[22] R. Sarkar, A. Sengupta, V. Kumar and S. K. Choudhary: ISIJ Int., **55**(2015), 781

[23] J. XU, S. HE, T. WU, X. LONG and Q. WANG: ISIJ Int., **52**(2012), 1856

[24] Y. Won, PH.D. Thesis, Seoul National University, (1999)

[25] T. W. Clyne, M. Wolf and W. Kurz: Metall Trans., **13**B(1982), 259

[26] S. Griesser, PH.D. Thesis, Wollongong University, Doctoral thesis, (2013)