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

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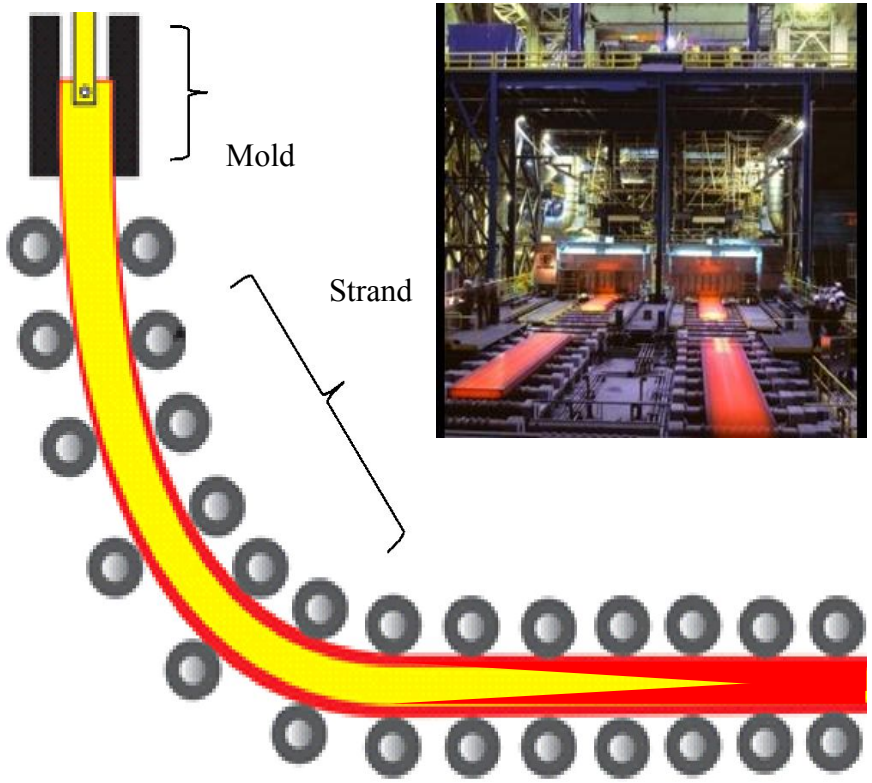
1. Introduction

- The higher strength and the thicker steel products are necessary

1. Introduction

■ Continuous casting process

Continuous caster



Casting slab

Longitudinal crack

Transverse crack

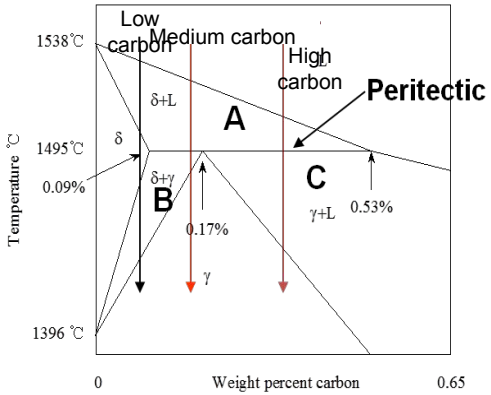
- Behavior of solid shell unevenness is an important factor to understand for cracking mechanism.

1. Introduction

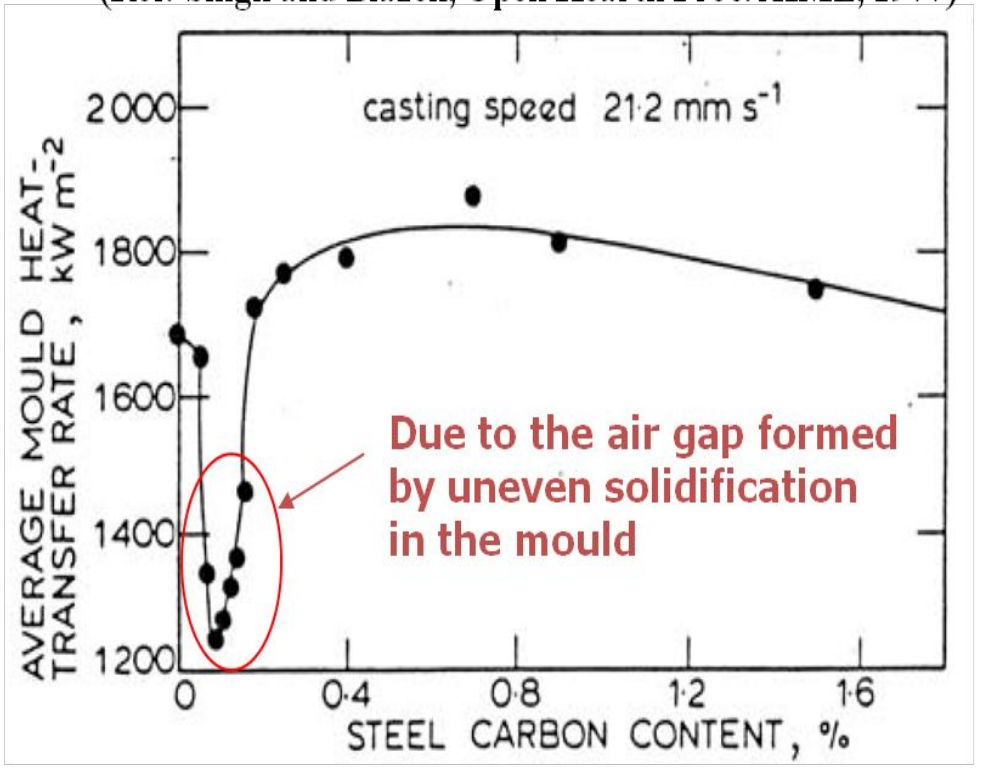
■ Solidification behavior

○ Each steel grade have different solidification

○ Uneven solidification □ Air gap □ Interruption of heat transfer



(Ref: Singh and Blazek, Open Hearth Proc. AIME, 1977)



1. Introduction

■ Crack mechanism in mold

Volume Change

- Shrinkage by cooling and phase transformation

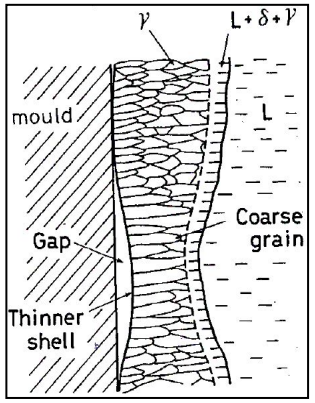
Solid Shell Unevenness → Longitudinal Crack

Air gap

- **tensile strain concentrate on thinner shell**

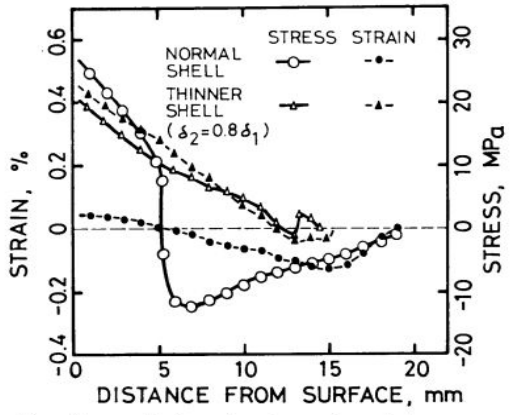
Heat transfer → Transverse Crack

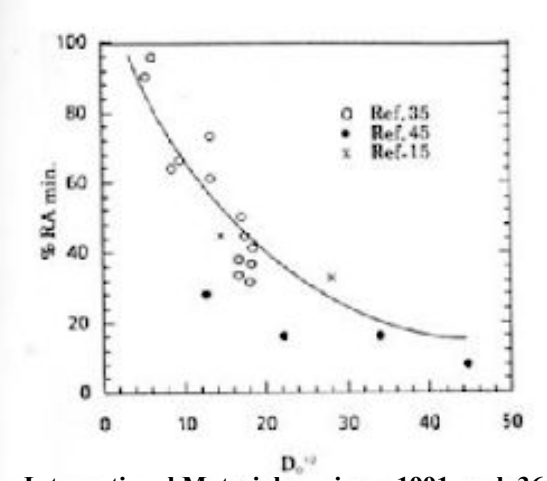
- **Increasing AGS**
- **Decreasing ductility**



T. Emi et al., Mat. Sci. and Eng., 2005, pp 2

T MATSUMIYA, Tetsu-to-Hagané, 1982

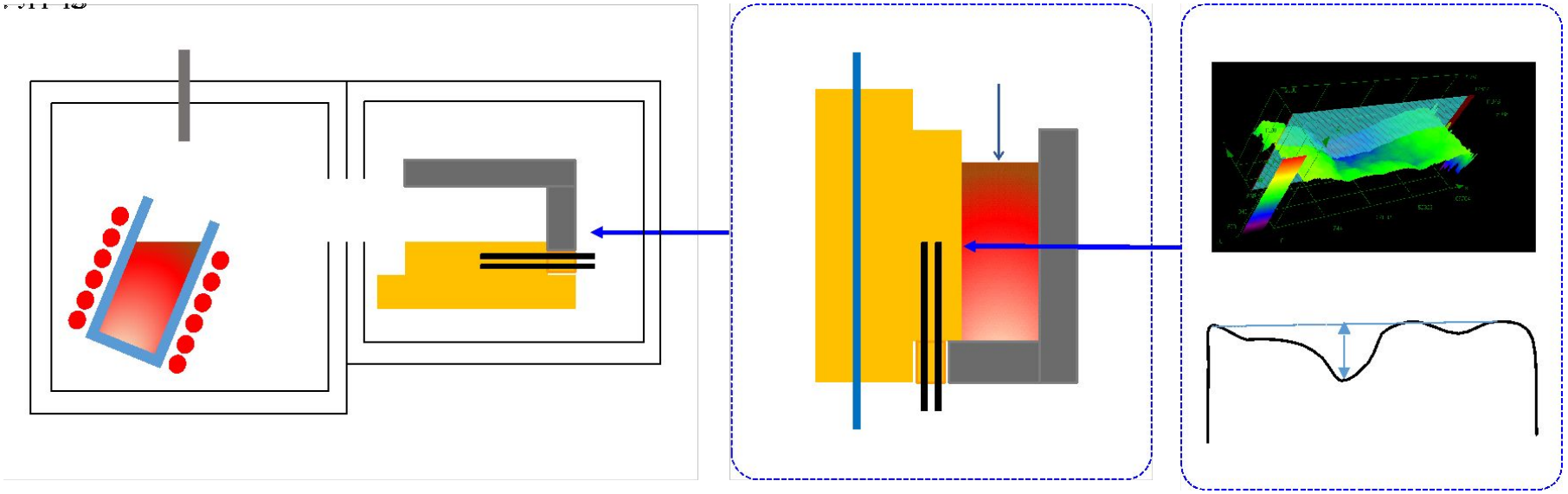




B.Mintz ,International Materials reviews, 1991 , vol. 36, pp187

2. Experiment procedure

■ Measurement of solid shell unevenness



○ Samples were machined to cylinders (~950g)

○ During melting and casting processes, the chambers were purged with Ar gas

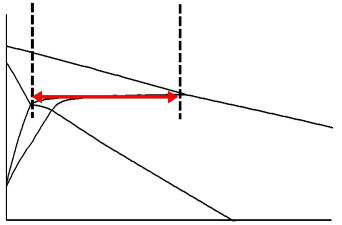
○ Solid shell unevenness : A specimen surface was observed using microscope(maximum depths were measured)

2. Experiment procedure

■ Test steel composition

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

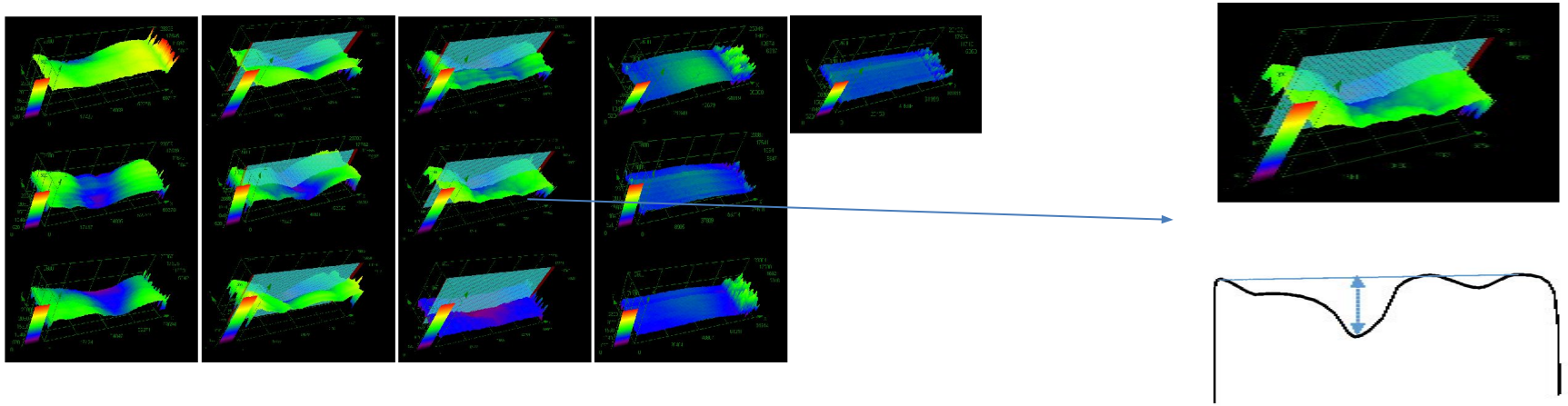
Liquid fraction at the start of peritectic reaction



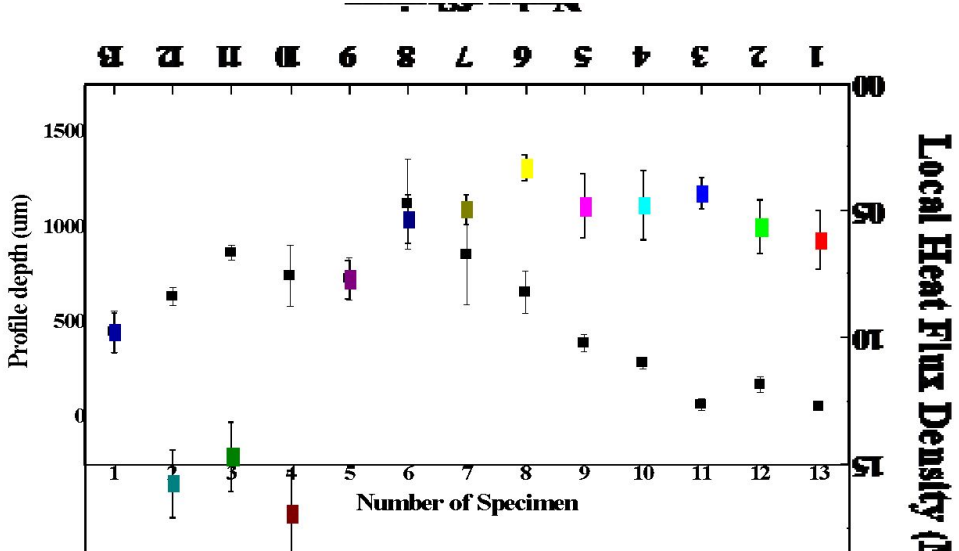
3. Experimental Results

■ Results of solid shell unevenness

○ 3D images for each specimen



○ The profile depth increase as [C] increased, and is the largest (1125 μm) in Steel 6.



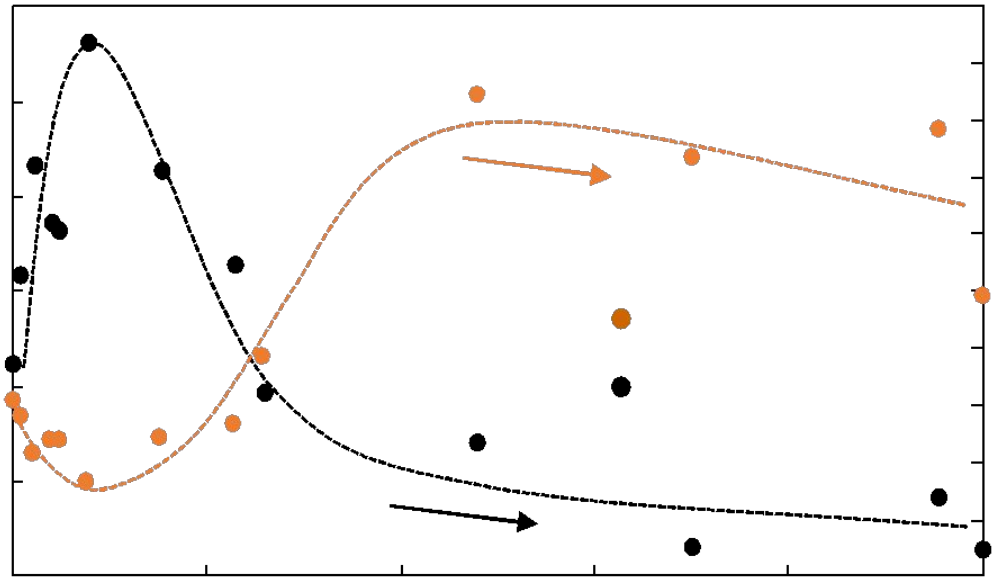
3. Experimental Results

■ The behavior of profile depth and heat flux

○ The liquid fraction < 0.4 : Profile depth and heat flux shows an inverse relation

○ The liquid fraction > 0.4 : The heat flux tends to decrease as profile depth decreases

- Profile depth < ~ 300 μm: heat transfer interruption due to the air gaps can be neglected
- The temperature of the molten steel has a relatively large influence on the heat flux



4. Uneven Solidification Index

■ Assumptions(A model to predict solid shell unevenness)

○ The cooling rate is constant regardless of the chemical compositions of the steels.

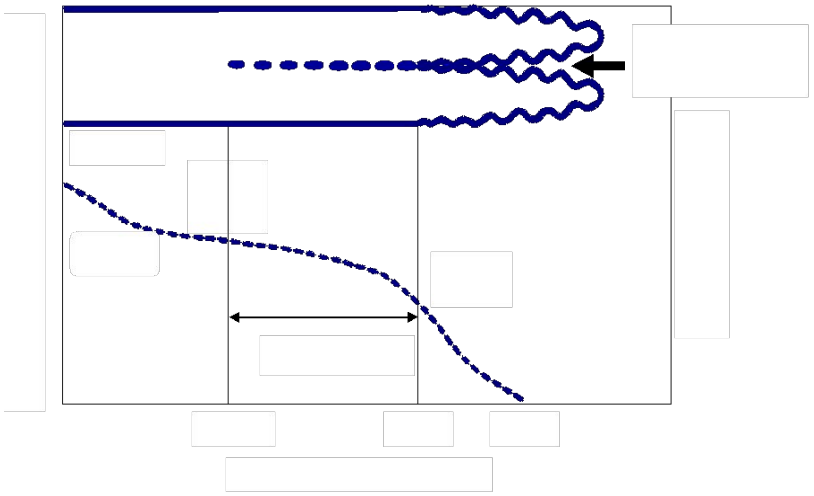
: Solid-shell unevenness occurs when the solid shell begins to form, and the contact state between the solid shell and the mold during this period is very good.

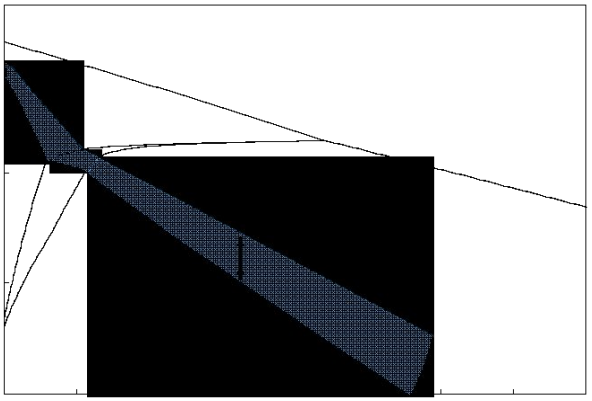
○ The deformation causing solid shell unevenness occurs only between the LIT and the solidus temperature

○ The amount of deformation is proportional to amount of phase transformation, and inversely proportional to the range of ΔT_{PT}

$$\text{Degree of solid shell unevenness(USI)} \propto \text{Change of phase fraction} / \Delta T_{PT}$$

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

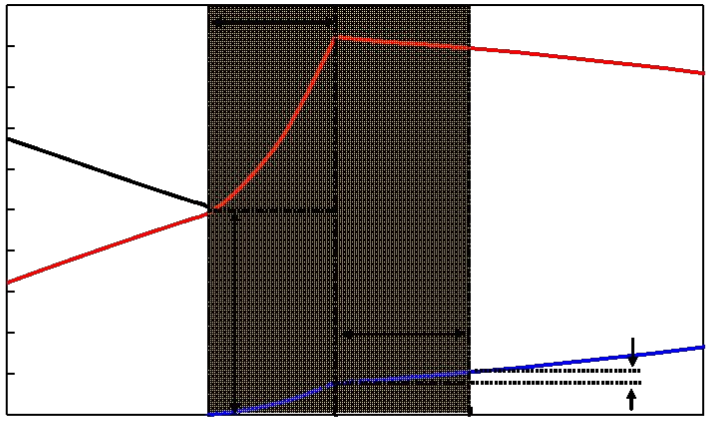


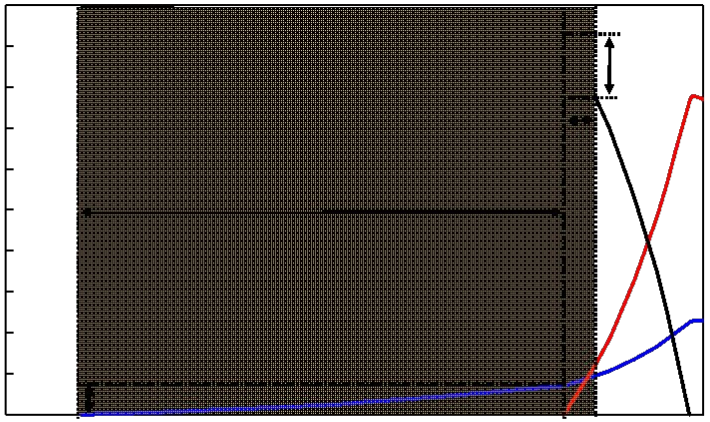


4. Uneven Solidification Index(USI)

■ Calculation examples for USI

- ○ A yellow box is a calculation range of USI which is LIT < T < Solidus Temp.
- ○ (a) Steel6: $\Delta L/\delta=2.4$, $\Delta(L+\delta/\gamma)=49.1$, $\Delta T_{L/\delta}=2.72$ and $\Delta T_{(L+\delta/\gamma)}=2.67$
- ○ (b) Steel8: $\Delta(L+\delta)/\gamma=17.4$, $\Delta L/\gamma=7.2$, $\Delta T_{(L+\delta)/\gamma}=0.76$ and $\Delta T_{L/\gamma}=10.6$





wt.%	C	Si	Mn	P	S	Ni	Cu	Ti	Nb	liquid fraction at the start of peritectic reaction
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Steel 8	0.15	0.28	1.31	0.011	0.004	0.01	0.01	-	0.02	0.23

4. Uneven Solidification Index

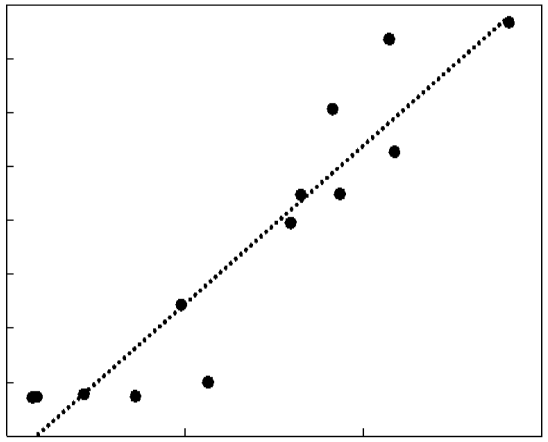
■ Calculation results

○ The profile depth can be predicted by the USI model with high accuracy (LIT fs=0.9, $\Delta T_{PT}^{0.3}$) with R^2=0.88

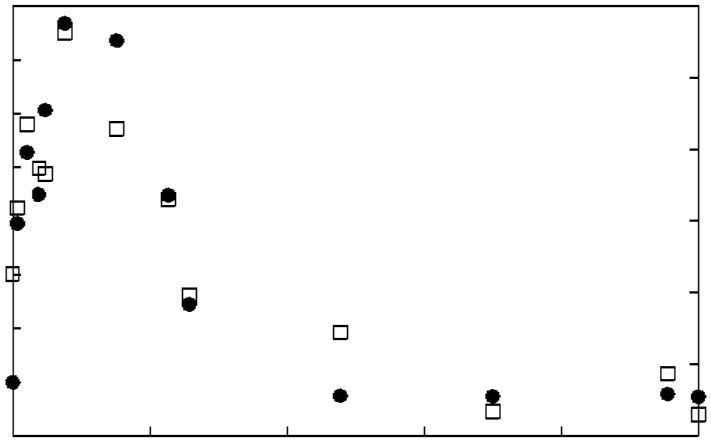
○ USI varies nonlinearly according to steel composition like the profile depth

$$\mathrm{USI} = \Delta L/\delta \Big/ \Delta T_{L/\delta}{}^{0.3} + \Delta(L+\delta)/\gamma \Big/ \Delta T_{(L+\delta)/\gamma}{}^{0.3} + \Delta L/\gamma \Big/ \Delta T_{L/\gamma}{}^{0.3}$$

(a)



(b)



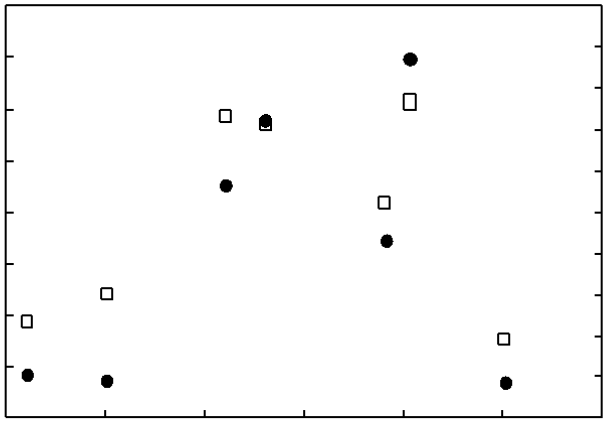
4. Uneven Solidification Index

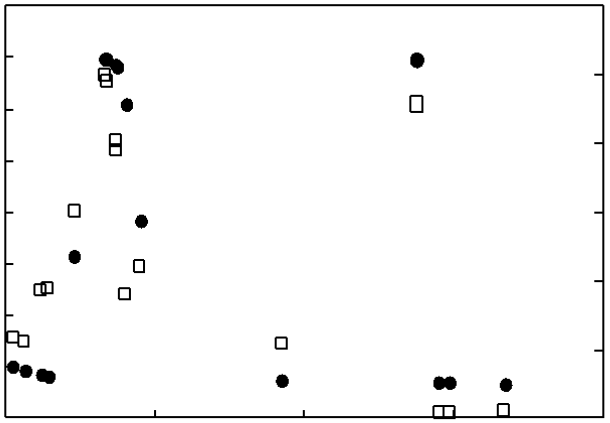
■ Relation between USI and previous studies of shell unevenness

○ The USI can explain all of the degree of solid shell unevenness which were measured by various experiments

H. Murakami, Tetsu-to-Hagane, 1992, vol 78, pp. 105-112

T. Emi . Met. Sci. Eng. A, 2005, vol. 2, pp.413-414





 The USI can be effectively used

: to guide design of chemical compositions of new steel grades

: for optimization of steel making operation

5. Conclusion

1. Apparatus and method have been developed to accurately measure solid shell unevenness according to the steel composition using 950g ingot and 3D optical microscope.

2. The model to predict uneven shell solidification was developed, under the following conditions:

- Solid shell unevenness is formed at the beginning of solidification and the cooling rate during this period is constant
- Solid shell unevenness occurs only at the stage of solidification with a liquid fraction of 0.1 or less
- The solid shell unevenness are proportional to amount of phase transformation and inversely proportional to the temperature range of the phase transformation.

$$USI = {}^{\Delta L/\delta}\Big/_{\Delta T_{L/\delta}{}^{0.3}} + {}^{\Delta(\mathrm{L}+\delta)/\gamma}\Big/_{\Delta T_{(\mathrm{L}+\delta)/\gamma}{}^{0.3}} + {}^{\Delta L/\gamma}\Big/_{\Delta T_{L/\gamma}{}^{0.3}}$$

3. The prediction model developed in this study was about 88% correlated with the experimental results