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Effect of Mold Oscillation on Powder Consumption and Hook Formation in Ultra Low Carbon Steel Slabs

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INTRODUCTION

Mold oscillation in continuous casting affects several important phenomena, including mold powder lubrication and cast slab surface quality. Recently, attention has focused on improving mold powders and optimizing mold oscillation and other casting conditions for high speed casting, in order to minimize break-out occurrence [1-2], and to minimize surface quality problems. One important quality problem is the formation of deep oscillation marks and subsurface hooks, especially in ultra-low carbon steels. These can cause defects such as slivers and pencil-pipe blisters in the final rolled sheet product [3], even after expensive surface grinding to remove them.

For consistent and uniform lubrication, different theories have been proposed for the infiltration of liquid mold flux into the interfacial gap between the solidifying steel shell and the mold at the meniscus. Most investigators found that increasing casting speed and decreasing liquid flux viscosity at 1300 ℃ tends to lower the consumption rate of mold powder [4-6]. In order to predict consumption rate, several different concepts have been developed and applied, with varying success [7]. These include the negative strip time and the positive strip time, which are defined as the periods when the mold is moving downward or upward relative to the strand. Some results show that mold powder consumption rate increases with negative strip time [8] while others show a better correlation with positive strip time [9]. Another concept is the negative strip area ratio, which was found to increase with increasing powder consumption in a study involving non-sinusoidal mold oscillation [10]. It is difficult to predict and optimize mold oscillation for lubrication because it is not clear what the mechanisms of mold flux lubrication are. In spite of these difficulties, the first aim of the present work is to investigate mold powder consumption rate for various oscillation conditions.

Many previous studies of surface quality have focused on the influence of oscillation conditions on oscillation marks (OM) [11-17], which often become sites for transverse crack formation on the wide and narrow faces [17, 18]. Shallower oscillation marks are reported for shorter negative strip times [1, 6, 8, 14], shorter stroke [5, 12, 16] and higher frequency [16, 19]. To reduce oscillation mark depth, it is standard practice to lower the negative strip time by using higher oscillation frequency and shorter oscillation stroke [8, 14, 17, 19]. Specifically, typical commercial practice over the past several decades has increased frequency from ~60 to ~180 cycles/min and decreased stroke from ~10 to ~5mm. The cost of these measures has been increased rate of sticker breakouts and the need for breakout detection systems.

Subsurface hook formation at the meniscus during continuous casting of steel slabs is an important cause of surface defects, owing to their easy entrapment of mold flux and inclusion-laden gas bubbles [15, 20]. Since their discovery by Emi [12], hooks have been the subject of several studies, which often find them associated with deep oscillation marks. Many different mechanisms of oscillation mark and hook formation have been proposed. These involve bending [21, 22], sub-meniscus [23, 24], and / or solidification [25-27] of the meniscus shell. Both oscillation marks and hooks are affected by oscillation conditions [21], which is the second aim of this work to investigate.

In this study, slab samples and operation data were collected during casting trials conducted at POSCO in Gwangyang, S. Korea for several different oscillation conditions. Oscillation stroke, frequency and the effect of non-sinusoidal wave were varied systematically, although unintentional changes in other casting conditions were also monitored. Hook characteristics and oscillation mark depth and pitch were measured from sectioned slab samples and correlated with operating conditions. This study is the first step of a larger project to understand the formation of oscillation marks and hooks, and to find ways to minimize their detrimental effects in practice.

MOLD OSCILLATION PARAMETERS

Non-sinusoidal mold oscillation provides an additional degree of flexibility in choosing oscillation conditions, relative to a traditional sinusoidal oscillator. As shown in Figure 1, non-sinusoidal operation allows sharpening of the velocity changes during the period of negative strip. This mode is reported to have the advantages of allowing shorter negative strip times for the same powder consumption (with accompanying shallower oscillation mark depth) [28], allowing longer positive strip times for the same stroke and frequency conditions [1], and improving lubrication uniformity.

Table I shows the 3 independent mold oscillation parameters used in this work. Stroke is the distance between the highest and lowest displacements of the oscillation cycle, as given by S in Figure 1 (a). Stroke is also twice the amplitude. Frequency is the number of cycles per unit time, as given by F (cpm). Modification ratio (α) characterizes the extent of asymmetry of the non-sinusoidal mode. Modification ratio is defined as the time shift of the highest (or lowest) peak from the corresponding sinusoidal peak, compared to one quarter of the total period of the oscillation cycle, T_t, as shown in Figure 1 and defined in Table I. It varies from zero (sinusoidal) to 24% in this work.

The important concepts of negative and positive strip times depend on the oscillation parameters and the casting speed (V_C). The negative strip time, sometimes calls 'heal time', is the time when the mold is moving downward faster than the casting speed, as shown in Figure 1 (b). During this time, the frictional force in the mold changes from tensile to compressive, so that any steel that is sticking to the mold will be squeezed onto the existing shell and "stripped" from the mold wall. Without negative strip, stickers are so common that continuous casting is infeasible. Positive strip time is the rest of the oscillation cycle. The equations defining negative and positive strip time are discussed elsewhere [1, 29]. Table I includes the strip time equations for sinusoidal operation. Negative strip ratio is defined as the mean mold velocity during negative strip time compared to the casting speed. Theoretical oscillation mark pitch is the distance between oscillation marks, which can be found graphically in Figure 1 b) from the area of casting speed times the total cycle period of oscillation.

Table I Definition of oscillation parameters

S :	Stroke (mm)
F :	Frequency (cycles / minute)
α :	Modification ratio for non-sinusoidal mode (%) = $(A_2 / A_1) \times 100$
V_C :	Casting speed (m/minute)
T_t:	Total period of oscillation cycle (second / cycle) = 60 / F
T_n:	Negative strip time (sec) = $60/\pi F \times \arccos(1000 \times V_C / \pi SF)$, Equation for α = 0
T_P:	Positive strip time (sec) = $T_t - T_n$
	Theoretical oscillation mark pitch (mm) = $1000 \times Vc / F$

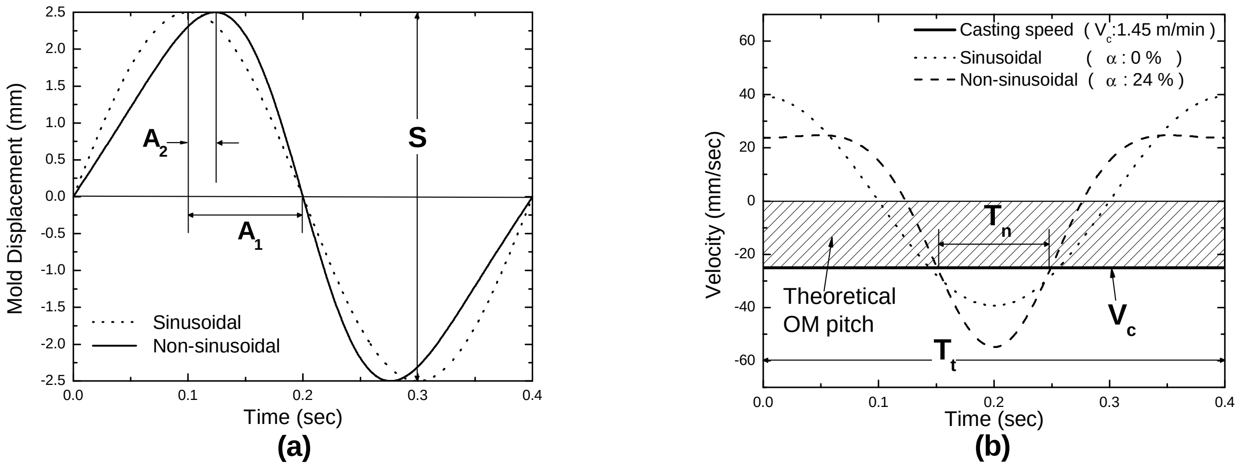

Figure 1 Schematic diagram (a) mold displacement and (b) velocity in case of sinusoidal and non-sinusoidal oscillation mode

PLANT TRIALS

Plant trials were performed with different mold oscillation conditions on a conventional parallel-mold continuous slab-caster at POSCO Gwangyang Works #2 -1 caster during February to September, 2002. The mold is equipped with a hydraulic mold oscillator which allows a variety of non-sinusoidal oscillation modes in addition to changing stroke and frequency. Stroke, frequency and modification ratio were changed systematically according to the ten tests shown in Table II. Each test lasted for most of one sequence (4-6 heats). For all tests, the section size was 230 x 1300 mm and the casting speed was kept relatively constant at 1.45 m/min, even during ladle exchanges. For all tests, the composition of the ultra-low carbon steel grade cast is given in Table III, and the composition and properties of the mold powder is given in Table IV. The mold powder consumption rate in Table II was calculated from the weight of the bags consumed during each entire sequence, which includes over 20,000 oscillation marks. A 100-mm long portion of the slab length was collected sometime during the second or third heat of each test when conditions were stable. Hook and oscillation mark characteristics were measured on the narrow face of each slab sample. Oscillation mark pitch and depth were measured with a laser-based surface profilometer along 21 different lines down the narrow face. Hook shape down the narrow faces was then measured from etched cross-sections taken at 5 different distances between the wide faces.

Table II Mold oscillation conditions

	Stroke (mm)	Frequency (cpm)	Non-sinusoidal mold oscillation ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Consumption rate of mold flux (kg/m^2)
Test 1	6.4	158	24	0.107	0.273	0.247
Test 2	5.0	145	0	0.116	0.298	0.232
Test 3	5.0	174	12	0.101	0.244	0.225
Test 4	5.0	203	24	0.083	0.212	0.253
Test 5	6.0	121	12	0.131	0.366	0.223
Test 6	6.0	145	24	0.111	0.303	0.229
Test 7	6.0	169	0	0.124	0.231	0.230
Test 8	7.0	104	24	0.142	0.437	0.248
Test 9	7.0	124	0	0.155	0.328	0.208
Test 10	7.0	145	12	0.129	0.285	0.211

Table III Steel composition of ultra-low carbon steel (wt. %)

C	Mn	Si	P	S	Cr	Ni	Cu	Ti	Al
0.002 ~ 0.005	0.08	≤ 0.005	~ 0.015	~ 0.01	0.01	0.01	0.01 ~ 0.02	0.05	~ 0.04

Table IV Mold powder composition and properties

Chemical composition	Basicity	SiO_2	CaO	MgO	Al_2O_3	TiO_2	Fe_2O_3	MnO_2	P_2O_5	Na_2O	K_2O	F	B2O3	Li_2O
	1.10	38.60	42.28	0.89	6.34	0.19	0.36	0.03	0.03	3.64	0.12	7.14	0	0.37

Properties	Solidif. Temperature (°C)	Softening Temperature (°C)	Melting Temperature (°C)	Viscosity at 1300 °C (Poise)
	1149	1170	1180	3.21

The negative strip times associated with these trials are plotted in Figure 2 as a function of frequency. All test conditions have frequencies safely above the critical condition where negative strip time becomes extremely sensitive to frequency variations. Three tests (1,6,8) have sinusoidal oscillation. Figure 2a) shows how negative strip time for these tests decreases with both decreasing stroke and increasing frequency, with both being important. Figure 2 b) shows that increasing the asymmetry of the non-sinusoidal oscillation (increasing α) also decreases the negative strip time, although the effect is not as important as stroke.

The positive strip times are shown in Figure 3. Positive strip time depends mainly on frequency, and is affected only slightly by stroke and asymmetry.

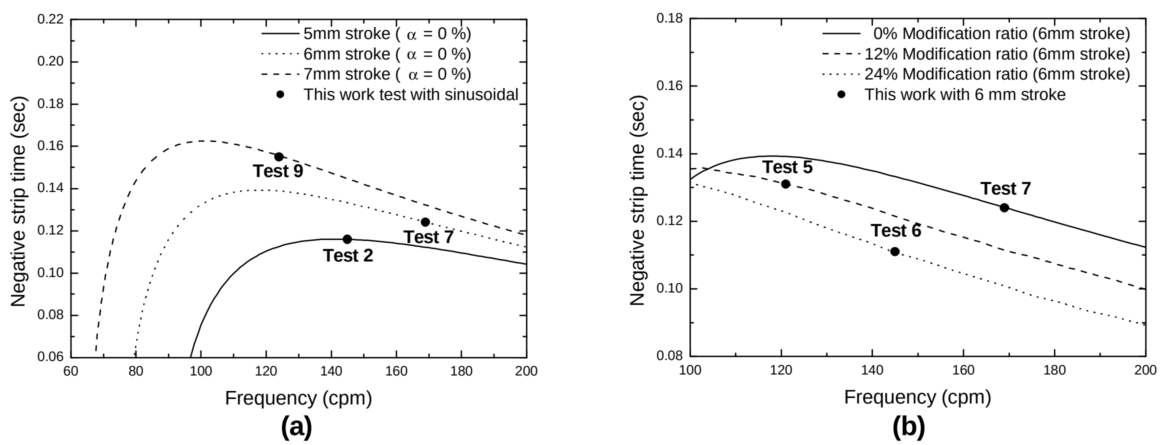

Figure 2 Influence of (a) sinusoidal and (b) non-sinusoidal oscillation conditions on **negative** strip time

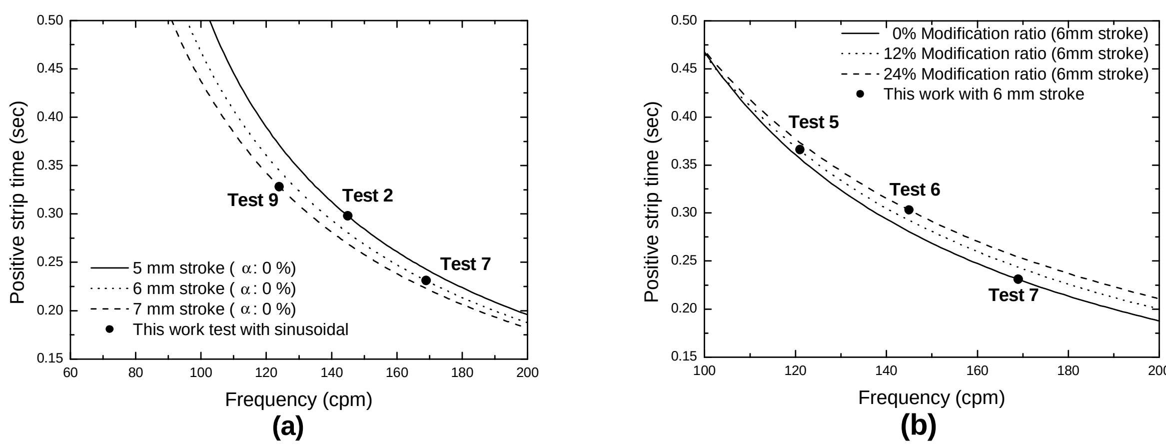

Figure 3 Influence of (a) sinusoidal and (b) non-sinusoidal oscillation conditions on **positive** strip time

MOLD POWDER CONSUMPTION RESULTS

The prediction of mold powder consumption is of practical importance, because it correlates with mold lubrication and quality. In addition, it is easily measured, and has an easily-quantified cost per ton. Mold powder consumption can be divided into three components [30]. Firstly, the thick solid layer that resolidifies from the liquid flux onto the mold wall can move intermittently downward if it detaches from the mold wall. Secondly, the thin layer of continuous liquid flux that separates the shell from the solid layer moves down at a speed between the casting speed and the solid layer speed. This is the only component that truly provides lubrication, so has been termed the “lubrication consumption” [30]. Thirdly, flux inside the oscillation marks is carried down at the casting speed, which accounts for the majority of flux consumption at lower speed when the oscillation marks are large.

The total consumption rate of mold powder for each test condition is given in Table IV. Consumption starts when liquid flux is pumped into the gap between the steel shell and the mold wall at the meniscus during oscillation. Thus, oscillation parameters naturally have an important effect on consumption. Because the mold powder consumption rate also depends greatly on the casting speed [4, 5] and mold flux properties [6], for every test in this study, the casting speed was fixed (1.45 m/min) and the same mold powder was used. This allows investigation of the subtle effects of the 3 oscillation parameters.

To simultaneously account for the many factors that influence mold flux consumption, several different indicators have been proposed, including the oscillation frequency, the negative strip time and the positive strip time. The results of this study are first applied to evaluate these indicators.

Frequency indicator

Figure 4 a) shows the influence of oscillation frequency on measured powder consumption rate, expressed as mass per unit area of strand surface. For sinusoidal operation (α = 0 %), there is a slight trend of increasing consumption rate with increasing frequency (Fig. 4a). This is expected because the number of oscillation marks increases, and oscillation marks consume most of the mold flux. Increasing asymmetry also increases the powder consumption, which agrees with previous research [10]. However, with non-sinusoidal oscillation, no clear relation with frequency is observed.

Strip time indicators

The two most popular indicators of increasing consumption rate are increasing negative strip time [8] or increasing positive strip time [9, 10, 31]. These indicators are considered to be more fundamental than frequency because they also include the effects of stroke and casting speed. Figure 4 b) shows the influence of negative strip time on mold powder consumption rate per unit area. There is no clear relation when non-sinusoidal oscillation is present. For sinusoidal oscillation, consumption rate drops with increasing negative strip time. This is expected because increasing negative strip time indicates increasing frequency, if the casting speed is constant and the effect of stroke is small. However, this result is contrary to expectations that increasing negative strip time should increase consumption, which were made with varying casting speed. Thus, with the effect of casting speed removed, negative strip time is a poor indicator of flux consumption. The correlation with positive strip time is not much better.

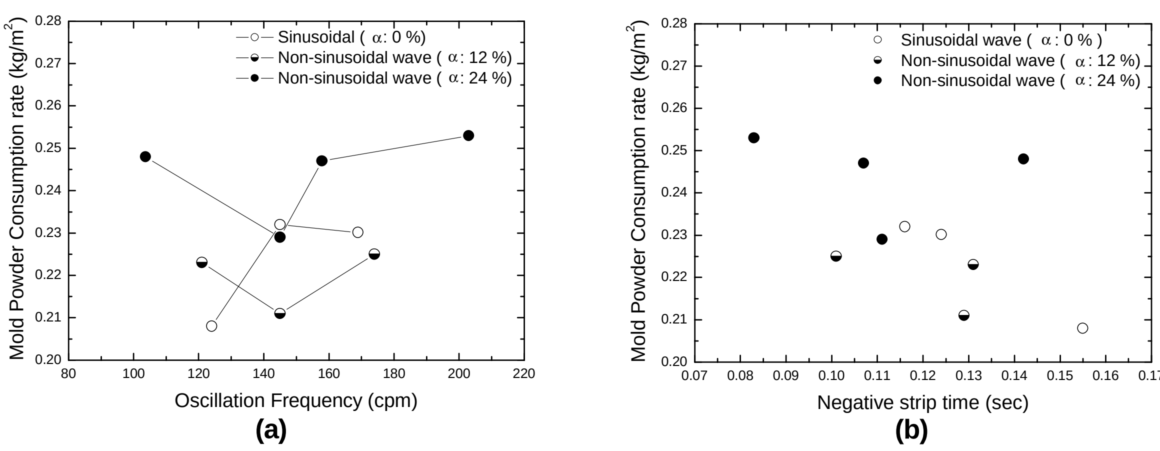

Figure 4 Influence of (a) oscillation frequency and (b) negative strip time on mold powder consumption rate

Strip time per cycle indicators

To better quantify the effect of mold oscillation conditions, powder consumption rate per unit area was converted to per unit length in a cycle of mold oscillation by multiplying by the theoretical pitch. The converted consumption rates are compared with negative and positive strip times in Figure 5. The correlation with positive strip time is much better and nearly linear. This is because the consumption per cycle at constant casting speed depends mainly on frequency, which also correlates most closely with positive strip time (see Fig. 3). This result agrees with the correlation of mold powder consumption rate with positive strip time per cycle found by Kawakami *et al* [9, 31]. Therefore the empirical equation expressing the linear relation with this form of consumption rate with positive strip time was explored further.

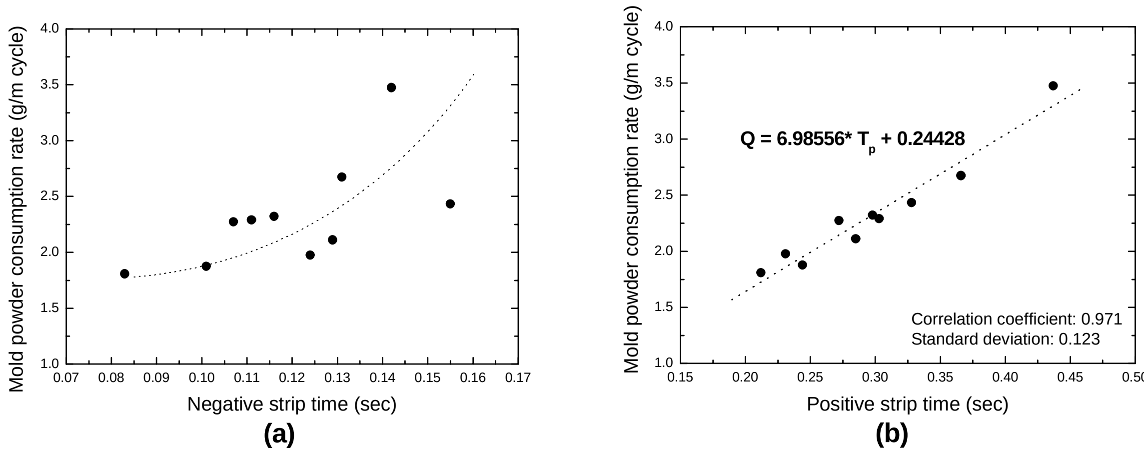

Figure 5 Relationship between mold powder consumption rate in one cycle and (a) negative and (b) positive strip time

First, this equation is shown to reproduce the known trends with casting speed. Two cases are studied: 1) frequency and stroke fixed independent of speed and 2) frequency increasing with increase of casting speed at fixed stroke, which is used in many plants. Figure 6 (a) shows that predicted consumption rate drops with increasing casting speed for both cases, which matches the trend measured in many plants [30]. Figure 6 b) shows that predicted consumption rate increases with increasing negative strip time for both cases, again as expected. The better trend of this figure relative to Fig. 4 b) is due to including the important effect of casting speed.

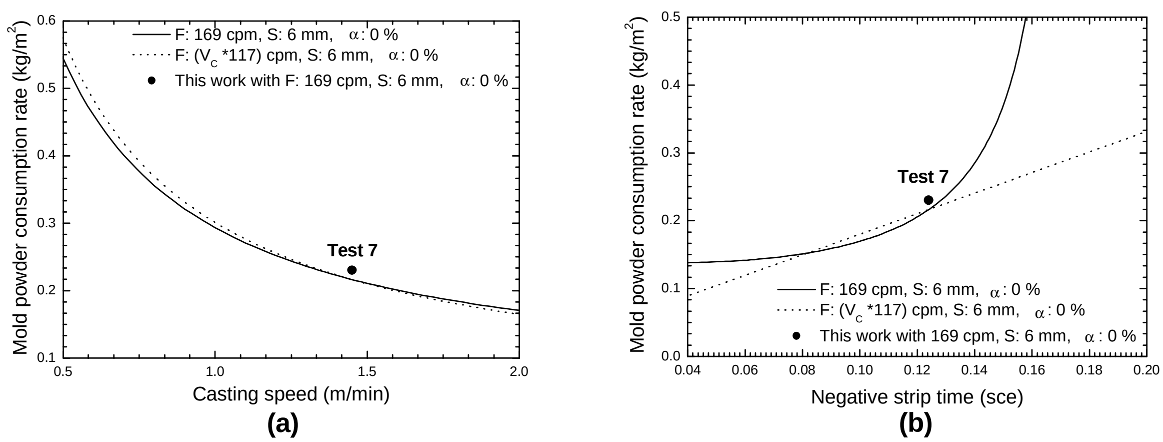

Figure 6 Influence of (a) casting speed and (b) negative strip time on predicted mold powder consumption rate

The consumption rate will increase with either an increase in lubrication consumption or an increase in the total oscillation mark volume (depth, width, or number). For sinusoidal oscillation with the same stroke, both positive and negative strip times decrease with increasing oscillation frequency, so both indicators predict the decrease in consumption with increasing casting speed observed with simultaneous increase in frequency. These findings suggest that increasing casting speed at constant frequency and stroke may increase consumption per cycle, owing to the increased positive strip time, even though consumption per unit area drops, owing to the smaller number of oscillation cycles. Negative strip time also decreases, so the same trend of decreased consumption is predicted. This explains previous observations that powder consumption is correlated with negative strip time [8].

Assuming the empirical relation between mold powder consumption rate per cycle and positive strip time is general allows predictions of the consumption rate with different oscillation conditions. Figure 7 shows the effect of frequency on powder consumption rate in sinusoidal mode. Lower frequency is observed to consume more flux, as expected. Fig. 7 b) also shows that increasing asymmetry consumes more flux, which matches observations. However, Fig. 7 a) also shows that a shorter stroke consumes more flux. This unexpected prediction indicates that further investigation is needed to understand mold consumption.

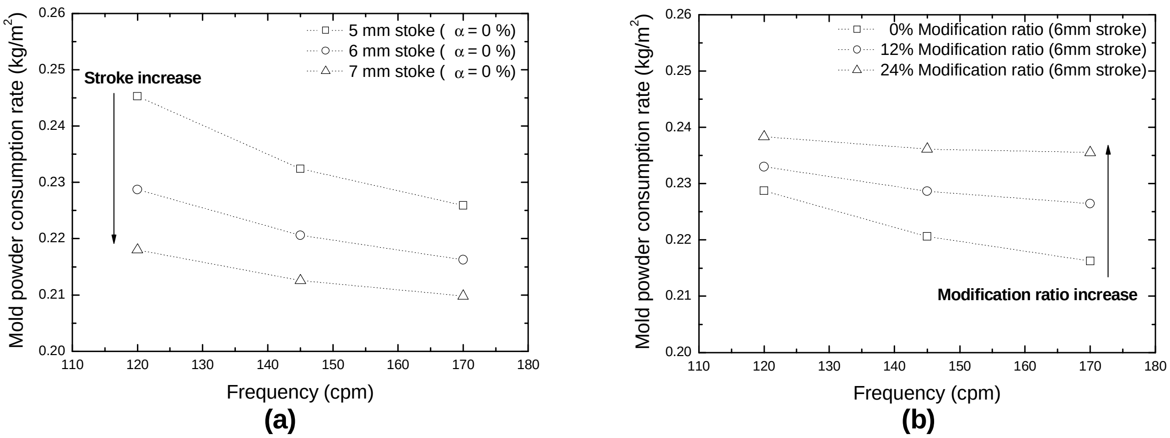

Figure 7 Influence of oscillation conditions on predicted powder consumption rate

HOOK AND OSCILLATION MARK CHARATERISTICS

Measurement Procedure

The narrow faces of each 100-mm long slab sample cast under the 10 different conditions given in Table II were sectioned for analysis of oscillation mark profiles and hook characteristics. Before measurement of the oscillation mark profile, each sample was sand-blasted to remove any scale from the surface. Oscillation mark depth and pitch were measured along an 80-mm length of the narrow face (6-11 oscillation marks) using a profilometer. Mean results were obtained by averaging across the slab thickness (230 mm) at 21 places (10 mm increments). After measuring the oscillation marks, sections through each narrow face sample were cut for hook analysis. After polishing to 0.25 μm, the sections were etched for ~45 minutes with a proprietary picric acid solution. Hook characteristics were then measured near each oscillation mark. Statistics were compiled by averaging the measurements obtained for the 10 ~27 hooks that were obtained for each test condition.

Previous work has proposed several different definitions of hook types [32-34] and characteristics [20, 32, 35], but there is no consistent way to define hook characteristics. The reason for this uncertainty is related to different understandings of the mechanism(s) of hook formation, which focus on different phenomena [21, 22, 24-27, 36]. The hook characteristics defined for this study were hook depth, hook length, hook angle and hook shell thickness, as illustrated in Figure 8.

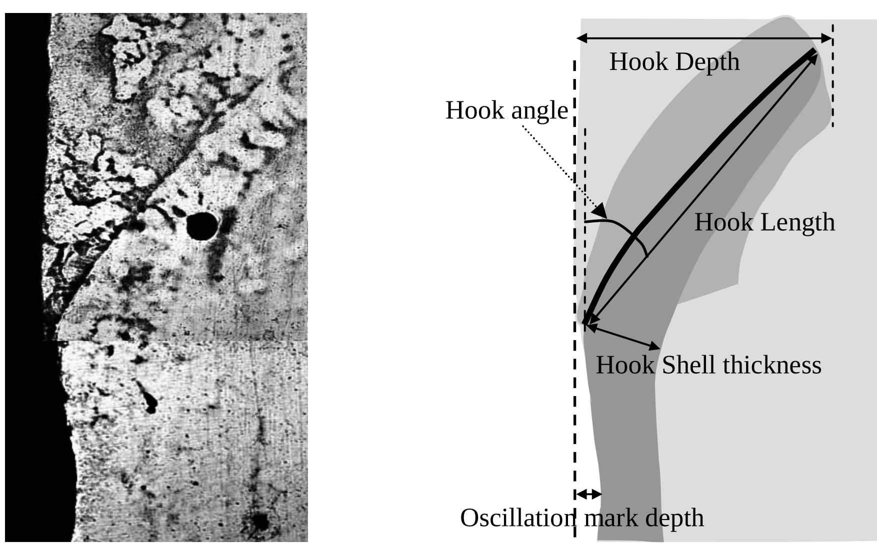

Figure 8 Example of oscillation mark and hook and definition of their characteristics

The hook definitions here are based on the hook starting as an initial solidifying shell at the meniscus region, which later curves away from the mold wall. As pictured in Fig. 8, each hook has an internal line, assumed to be the original surface. Cells of dendrites often grow in both directions from this line. Those growing toward the molten steel indicate the hook shell thickness while it was solidifying. Those growing towards the upper left likely occurred after the hook was overflowed with new liquid metal. Traces of entrapped mold powder or bubbles (Fig. 8) are often observed on the lower right side of the hook.

The hook depth is defined in this work as the perpendicular distance from the slab surface to furthest inner extent of the hook, as pictured in Fig. 8. This parameter is of practical importance, because it indicates the thickness of surface layer that should be removed during grinding to completely eliminate the hook and its associated inclusion. This definition differs from that of Kitano *et al.* [17], which considered only the perpendicular distance from the oscillation mark root to the end of the internal line of the hook.

Next, the hook length is defined as the linear distance from the starting point of the hook internal line near the oscillation mark to its end point, which matches the definition of Pütz *et al.* [35]. The hook angle is derived from the depth and length and indicates how much the hook bends away from the mold. Finally, the hook shell thickness is measured at the upper end of the oscillation mark where the hook starts, which generally represents the thickest part of the hook.

Results Summary

The average results of hook characteristics and oscillation mark depths are given in Table V.

Table V Mean value of oscillation mark and hook characteristics

	Tundish Temperature (°C)	Theoretical pitch of oscillation mark (mm)	Measured oscillation mark pitch (mm)	Measured oscillation mark depth (mm)	Measured hook depth (mm)	Measured hook length (mm)	Measured hook angle (degree)	Measured hook shell thickness (mm)
Test 1	1566	9.31	9.15	0.246	1.68	2.16	34.3	0.75
Test 2	1563	10.04	11.79	0.395	2.14	4.72	19.8	0.89
Test 3	1571	8.43	7.86	0.310	1.39	2.16	27.6	0.67
Test 4	1571	7.37	7.14	0.290	1.54	2.43	29.7	0.65
Test 5	1555	12.41	12.59	0.357	1.73	3.34	23.1	0.76
Test 6	1573	10.13	9.88	0.343	1.69	2.75	28.7	0.70
Test 7	1566	8.82	8.66	0.255	1.59	2.77	27.5	0.62
Test 8	1571	14.37	13.57	0.308	1.89	3.08	29.7	0.78
Test 9	1559	11.84	11.26	0.340	2.32	4.87	21.6	0.92
Test 10	1559	10.34	10.10	0.329	1.94	4.58	20.2	0.78

Effect of oscillation conditions on hook and oscillation mark depth

From a practical perspective, it is most important to examine how hook depth and oscillation mark depth decrease with changes in casting operations such as oscillation conditions and superheat. Figure 9 shows the effect of mold oscillation conditions on hook depth. Hook depth appears to decrease with increasing oscillation frequency and with increasing modification ratio, but it is difficult to find a trend with stroke. These results agree with Nakato et al [37]. Figure 10 shows the same trends for oscillation mark depth, although they are very rough.

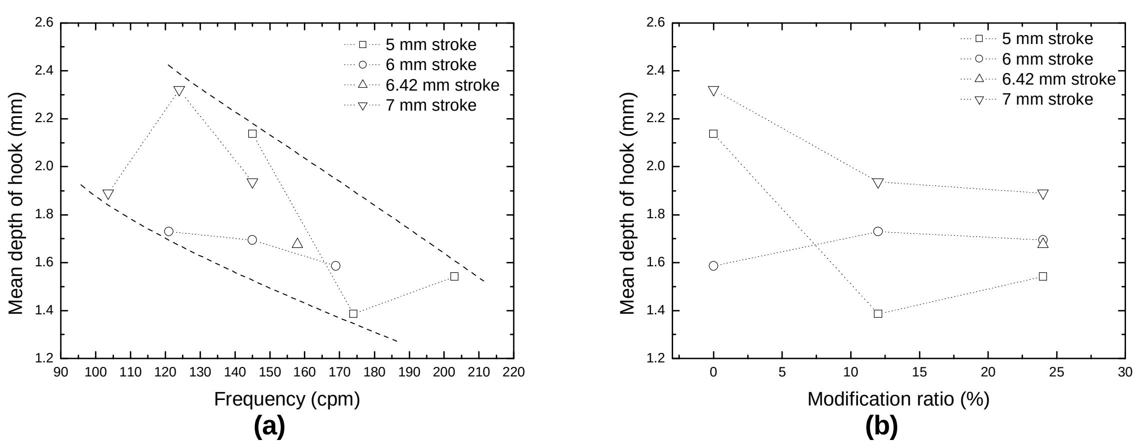

Figure 9 Influence of mold oscillation (a) frequency and (b) asymmetry ratio on **hook depth**

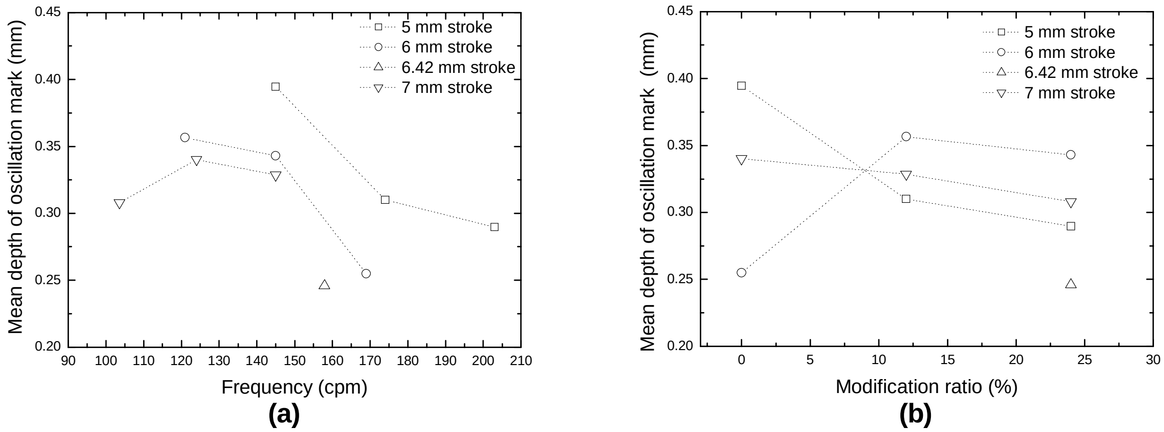

Figure 10 Influence of mold oscillation (a) frequency and (b) modification ratio on **oscillation mark depth**

Importance of Heat Transfer Conditions

In addition to oscillation conditions, meniscus phenomena such as hook formation depend greatly on other casting conditions, such as carbon content [29, 38], superheat in the mold, level fluctuations, and heat transfer conditions at the meniscus. Ultra-low carbon steels are particularly prone to hook formation, owing to their thin mushy zone [38]. High carbon steels experience fewer hooks, which is why steel composition was kept constant in this study. However, the results in Table V might be affected by other unintended changes in operation conditions, such as tundish temperature, which was measured every 8-13 minutes. Figure 11 a) shows that the measured hook length decreases dramatically for tundish temperatures above 1565^{o}C. The steel liquidus temperature varies from 1533 – 1534 ^{o}C, so this corresponds to superheats above ~32^{o}C. Hook angle is not quite as dependent on superheat, as shown in Figure 11 b).

The effects of oscillation frequency and stroke on hook length are shown in Fig. 12, divided into groups of high and low superheat. With high superheat, increasing frequency and deceasing stroke appears to decrease hook length slightly. No effect of modification ratio on hook length could be discerned. These results clearly show that the effects of superheat dominate over the relatively minor effects of oscillation practice, especially stroke. Higher superheat causes shorter hooks. This result is consistent with the mechanism of Bo *et al* [27].

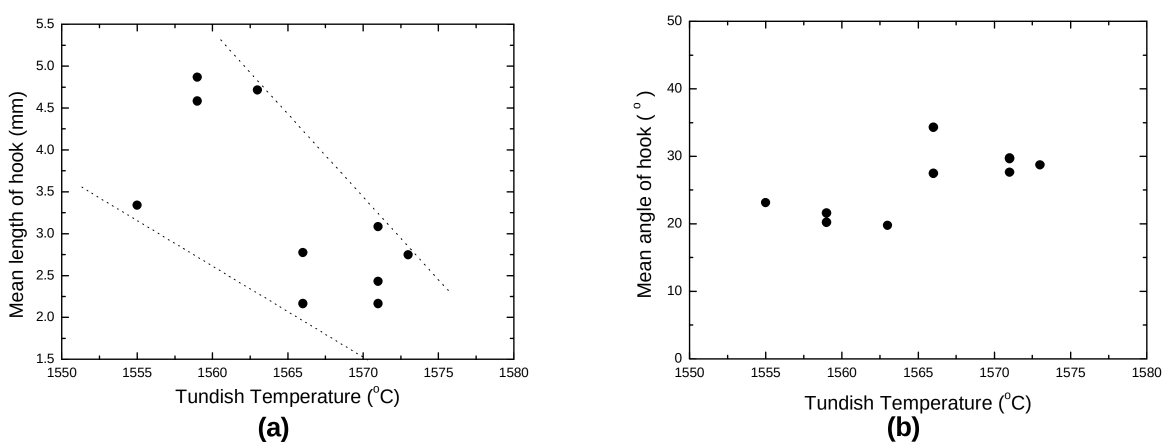

Figure 11 Influence of tundish temperature on hook shape: (a) length and (b) angle

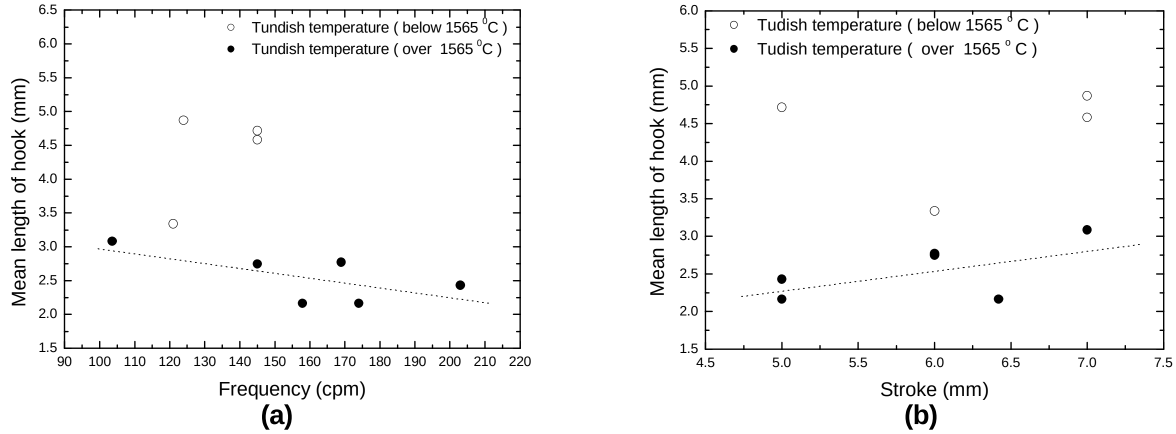

Figure 12 Influence of mold oscillation (a) frequency and (b) stroke on hook length

Effect of oscillation parameters and hook thickness on hook angle

Figure 13 shows the effects of frequency and asymmetry on hook angle, divided into groups of large and small hook shell thickness. Previous work [1, 5, 21] suggests that pressure due to mold oscillation causes the initial solidifying shell to deform, perhaps to a greater extent for a thin shell that is easier to bend. Thin hooks do not appear to correlate well with hook deflection angle, however. Perhaps this is because the hook length and shape depends more on superheat and other phenomena when the hook is thin. For thick hooks, however, decreasing frequency appears to increase the hook angle, as shown in Fig. 13 a). Fig. 13 b) shows that the angle of thick hooks also increases with increasing asymmetry. This trend is most severe with modification ratio over 12%. Perhaps the greater hook deflections arise because the higher frequencies and higher asymmetries generate higher pressures during the mold downstroke.

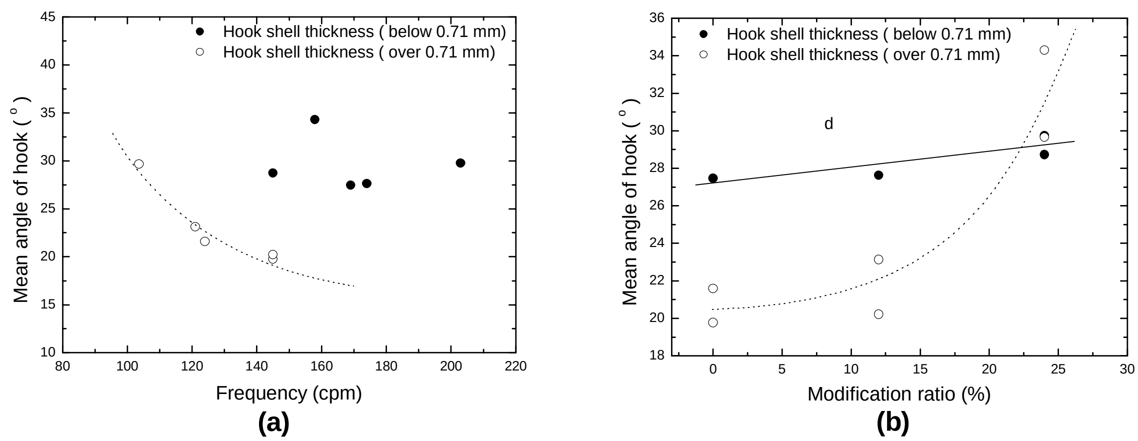

Figure 13 Influence of mold oscillation (a) frequency and (b) modification ratio on **hook angle**

Effect of strip time indicators on hook depth

Figure 14 shows the effect of negative and positive strip times on hook depth for different superheats. Hook depth appears to decrease with decreasing negative strip time or decreasing positive strip time, at least for higher superheats. Both indicators are equally good. Increasing superheat clearly decreases hook depth. The great importance of the superheat effect helps to explain the roughness in the trends observed with oscillation parameters.

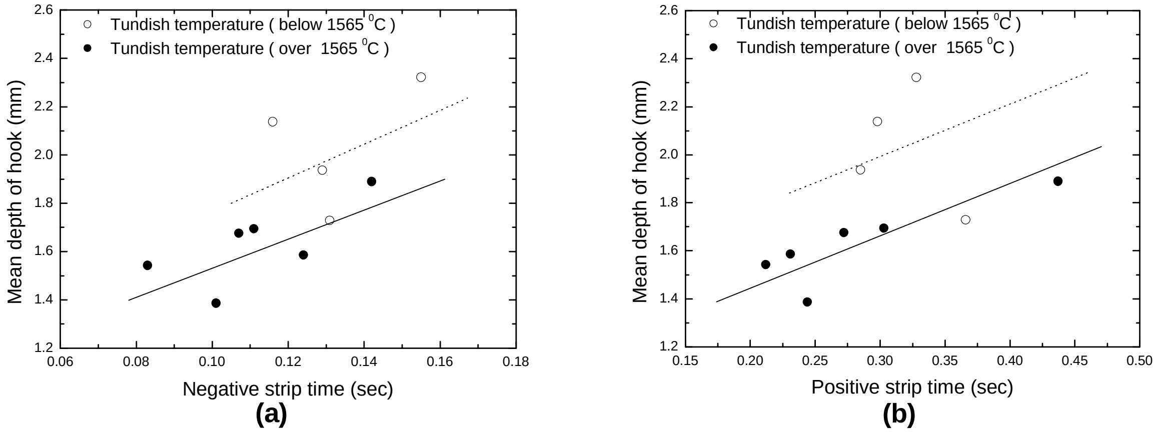

Figure 14 Influence of mold oscillation (a) negative strip time and (b) positive strip time on **hook depth**

Relation between mold powder consumption, oscillation mark depth and pitch

The oscillation mark depth decreases with increasing local frequency, as shown in Figure 15 a). The local frequency is calculated from the measured mean oscillation pitch, (Table V) to account for local variations in pitch caused by level fluctuations. This makes the trend slightly stronger than in Fig. 10 a). From the predicted equation relating mold powder consumption rate to positive strip time, (Fig. 5b) and the strong correlation between frequency and positive strip time, increasing frequency should lower consumption. Figure 15 b) shows that this expected trend is very strong. The flux consumed per cycle decreases with local frequency. This result also follows from the knowledge that oscillation marks are responsible for most of the flux consumption, as explained earlier. Each smaller-volume oscillation mark caused by the higher frequency (Fig. 15a) should carry less flux down the mold, as observed. None of the trends are as strong as they should be because the measured mold powder consumption are based on ~200m of cast length, while the oscillation mark depths are based on only ~0.1m of cast length. In addition, superheat has an important effect decreasing oscillation mark depth as previously discussed.

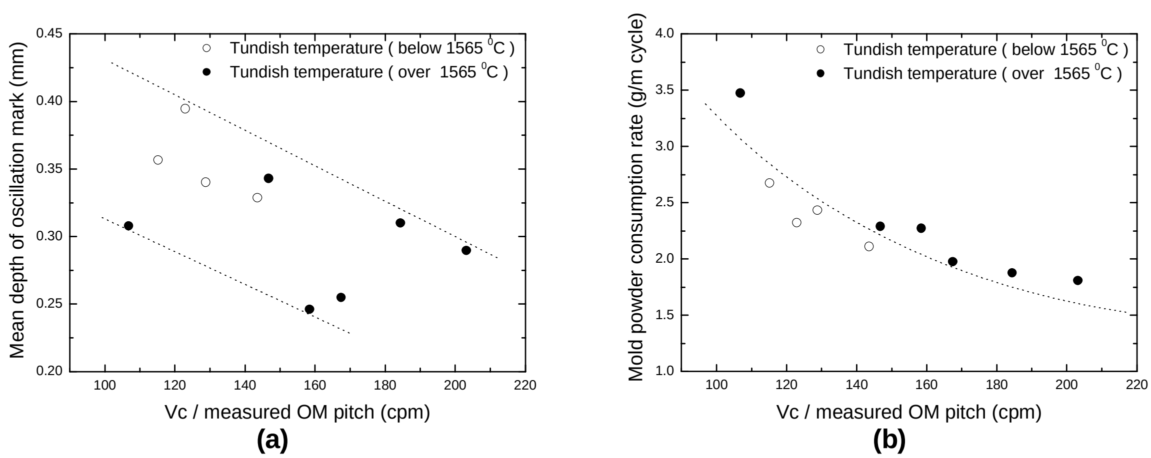

Figure 15 Influence of local frequency on (a) oscillation mark depth and (b) mold powder consumption rate

Effect of oscillation frequency on hook characteristics

A thinner hook shell is expected if the solidification time at the meniscus decreases or if the heat flux is lower due to a thicker flux layer. Increasing frequency causes the former effect, so produces thinner hooks, as shown in Fig. 16. Higher superheat tends to make thinner and shallower hooks, as shown in Figure 17. Figure 17 also shows that thinner hooks are strongly correlated with shallower hooks. These results help to explain how higher frequency makes shallower oscillation mark depth and hook depth, with better slab surface quality.

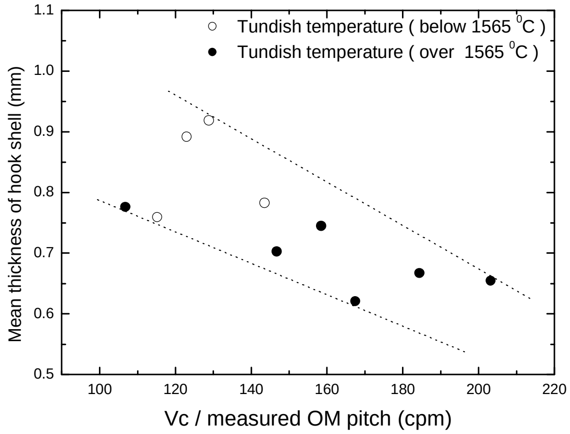

Figure 16 Influence of local frequency on hook shell thickness

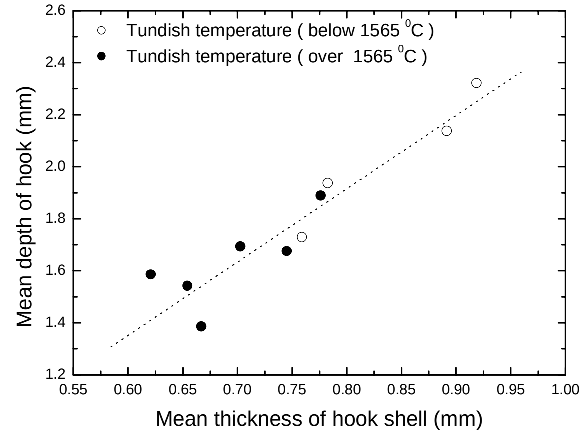

Figure 17 Influence of hook shell thickness on hook depth

Finally, Fig. 18 shows that increasing oscillation mark depth tends to accompany increasing hook depth and length, so are likely rooted in the same phenomena. This figure includes the results of other work conducted with different casting speeds. The trends are not strong, however, which suggests that oscillation marks and hooks also depend differently on the many casting conditions that affect meniscus phenomena. Much future work is needed to understand these mechanisms in order to identify the optimal casting conditions to minimize hooks and oscillation marks.

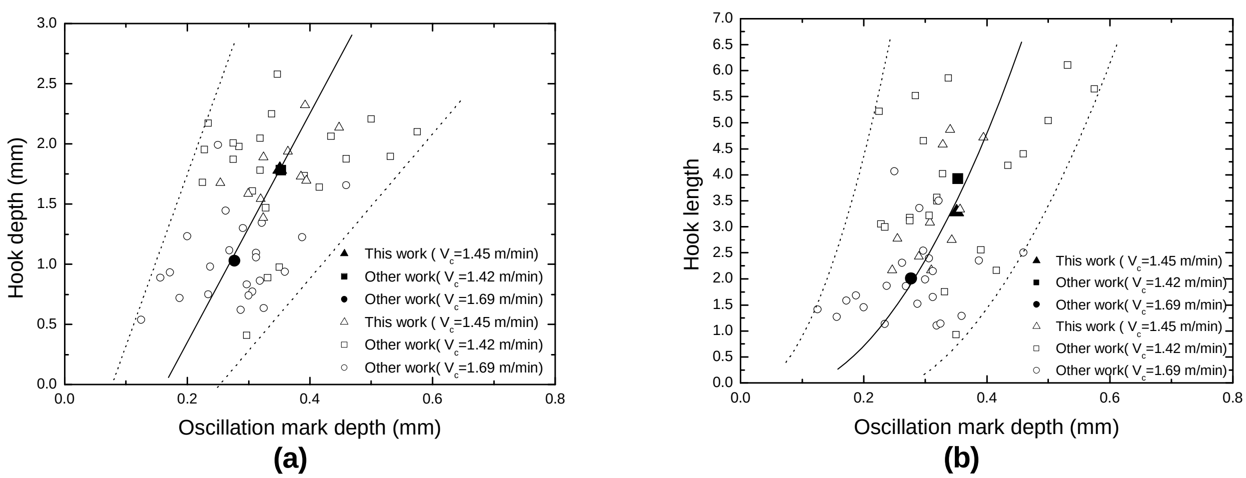

Figure 18 Influence of oscillation mark depth on hook shape: (a) depth and (b) length

SUMMARY

This study describes systematic measurements of continuous slab casting to quantify the effect of oscillation conditions and superheat on mold powder consumption rate, oscillation mark depth, and hook characteristics. Mold powder consumption rate per oscillation cycle depends strongly on positive strip time and also correlates with frequency and negative strip time. Increasing superheat has a strong effect on decreasing hook size, including both hook length and depth. Increasing oscillation frequency shortens solidification time, negative strip time, and positive strip time. This results in thinner, shallower hooks and shallower oscillation marks, which should improve surface quality. Higher frequency also shortens hook length and the angle of thick hooks. Increasing the asymmetry of non-sinusoidal oscillation tends to increase mold powder consumption, and increases the deflection angle of thick hooks. Hook depth is directly proportional to hook shell thickness. Shallower hooks also correlate slightly with shallower oscillation marks. Because mold consumption, oscillation mark, and hook formation all depend on so many inter-dependent process parameters that are difficult to control, much future work is needed to understand their mechanisms in order to accurately predict their behavior. This work is important in order to optimize the process conditions to improve surface quality.

REFERENCES

1. M. Suzuki, H. Mizukami, T. Kitagawa, K. Kawakami, S. Uchida and Y. Komatsu, "Development of a New Mold Oscillation Mode for High-speed Continuous Casting of Steel Slabs," *ISIJ International*, Vol. 31, No. 3, 1991, pp. 254-261.
2. M. Kawamoto, K. Nakajima, T. Kanazawa and K. Nakai, "Design Principles of Mold Powder for High Speed Continuous Casting," *ISIJ International*, Vol. 34, No. 7, 1994, pp. 593-598.
3. K.-D. Schmidt, F. Friedel, K.-P. Imlau, W. Jäger and K. T. Müller, "Consequent Improvement of Surface Quality by Systematic Analysis of Slabs," Steel Research, Vol. 74, No. 11/12, 2003, pp. 659-666.
4. M. Inagaki, T. Hirose, C. Matsumura and J. Yamagami, "Improvement Technology of Surface Quality at Velocity Change," *CAMP-ISIJ*, Vol. 2, 1989, pp. 309.
5. S. Takeuchi, Y. Miki, S. Itoyama, K. Kobayashi, K. Sorimachi and T. Sakuraya, "Control of Oscillation Mark Formation during Continuous Casting," *Steelmaking Conference Proceedings*, 1991, pp. 37-41.
6. P. Andrzejewski, A. Drastik, K. U. Köhler and W. Pluschkell, "New Aspects of Oscillation Mode Operation and Results in Slab Castings," *9th PTD Conference Proceedings*, 1990, pp. 173-181.
7. M. Suzuki, M. Suzuki and M. Nakada, "Perspectives of Research on High-speed Conventional Slab Continuous Casting of Carbon Steels," ISIJ International, Vol. 41 No. 7, 2001, pp. 670-682.
8. K. Hamagami, K. Sorimachi and M. Kuga, "Study on Quality Improvements in Strand Cast Slabs at Chiba Works," *Steelmaking Conference Proceedings*, Vol. 52, 1982, pp. 358-364.
9. K. Kawakami, T. Kitagawa, H. Mizukami, H. Uchibori, S. Miyahara, M. Suzuki and Y. Shiratani, "Fundamental Study and its Application of Surface Defects of Powder Cast Strands," *Tetsu-to-Hagane*, Vol. 67, No. 8, 1981, pp. 1190-1199.
10. T. Araki and M. Ikeda, "Optimization of mold oscillation for high speed casting - new criteria for mold oscillation," *Canadian Metallurgical Quarterly*, v 38, n 5, Dec, 1999, p 295-300
11. M.M. Wolf, "Mold Oscillation Guidelines," *Mold Steelmaking Conference Proceedings*, Vol. 74, 1991, pp. 51-71.
12. T. Emi, H. Nakato, Y. Iida, K. Emoto, R. Tachibana, T. Imai and H. Bada, "Influence of Physical and Chemical Properties of Mold Powders on the Solidification and Occurrence of Surface Defects of Strand Cast Slabs," *Steelmaking Conference Proceedings*, ISS-AIME, Vol. 61, 1978, pp. 350-361.
13. R. V. Mahapatra, J. K. Brimacombe and I. V. Samarasekera, "Mold Behavior and Its Influence on Quality in the Continuous Casting of Steel Slabs: Part II. Mold Heat Transfer, Mold Flux Behavior, Formation of Oscillation Marks, Longitudinal Off-Corner Depressions, and Subsurface Cracks," *Metallurgical Transactions*, Vol. 22B, 1991, Dec., pp. 875-888.
14. A.W. Cramb and F.J. Mannion, "The Measurement of Meniscus Marks at Bethlehem Steel's Burns Harbor Slab Caster," *Steelmaking Conference Proceedings*, Vol. 68, 1985, pp 349-359
15. J.-P. Birat, M. Larrecq, J.-Y. Lamant and J. Petegnief, "The Continuous Casting Mold: A Basic Tool for Surface Quality and Strand Productivity," *Steelmaking Conference Proceedings*, ISS, 1991, pp. 39-50.
16. H. Takeuchi, S. Matsumura, R. Hidaka, Y. Nagano and Y. Suzuki, "Effect of Mould Oscillation Conditions on Oscillation marks of Stainless Steel Casts," *Tetsu-To-Hagane*, Vol. 69, No. 2, 1983, pp. 248-253.
17. S. Harada, S. Tanaka, H. Misumi, S. Mizoguchi and H. Horiguchi, "A Formation Mechanism of Transverse Cracks on Continuously Cast Slab Surface," *ISIJ International*, Vol. 30, No. 4, 1990, pp 310-316.
18. H. Yasunaka, K. Nakayama, K. Ebina, T. Saito, M. Kimura and H. Matuda, " Improvement of Transverse Corner Cracks in Continuously Cast Hypoperitectic Slabs," *Tetsu-to-Hagane*, Vol. 67, No. 8, 1981, pp. 1190-1199.
19. A. Howe and I. Stewart, "Reduction of Reciprocation Marks by High Frequency Vibration of the Continuous Casting Mold," *Steelmaking Conference Proceedings*, Vol. 70, 1987, pp. 417-425.
20. Y. Kitano, K. Kariya, R. Asaho, A. Yamauchi and S. Itoyama, "Improvement of Slab Surface Quality of Ultra Low Carbon Steel," *Tetsu-to-Hagane*, Vol. 80, 1994, pp. T165-168.
21. E. Takeuchi and J. K. Brimacombe, "The Formation of Oscillation Marks in the Continuous Casting of Steel Slabs," Metallurgical Transactions, Vol. 15B, Sept., 1984, pp. 493-509.
22. Y. Nakamori, Y. Fujikake, K. Tokiwa, T. Kataoka, S. Tsuneoka and H. Misumi, "Development of Measuring System for Friction in Continuous Casting Mold," *Tetsu-to-Hagane*, Vol. 70, No. 9, 1984, pp. 1262-1268.
23. J. Savage and W. H. Pritchard, "Problem of Rupture of Billet in Continuous Casting of Steel," *Iron and Steel Institute*, Vol. 178, No. Part 3, 1954, pp. 269-277.
24. E. S. Szekeres, "Overview of Mold Oscillation in Continuous Casting," *Iron and Steel Engineer*, Vol. 73, No. 7, 1996, pp. 29-37.
25. I. G. Saucedo, "Early Solidification during the Continuous Casting of Steel," *Steelmaking Conference Proceedings*, Vol. 74, 1991, ISS, 1991, pp. 79-89.
26. R. S. Laki, J. Beech and G. J. Davies, "Curved-Boundary Heat Transfer Model and its Application to Meniscus Zone during Casting," *Ironmaking and Steelmaking*, Vol. 11, 1984, pp. 283-291.
27. K. Bo, G. Cheng, J. Wu, P. Zhou and J. Wang, "Mechanism of Oscillation Mark Formation in Continuous Casting of Steel," Journal of University of Science and Technology Beijing, Vol. 7, No. 3, 2000, pp. 189-192.
28. A. Delhalle, J.-P. Birat, M. Larrecq, H. Tourscher, J. F. Marioton and J. Foussai, "Control of the First Formation during Continuous Casting of Steel," *Cahiers d'Informations Techniques - Revue de Metallurgie*, Vol. 86, No. 6, 1989, pp. 483-489.
29. H.-P. Liu, S.-T. Qui, Y. Gan, H. Zhang, and J.-Y. De, "Development of Mechanical Drive Type Non-Sinusoidal Oscillator for Continuous Casting of Steel," Ironmaking and Steelmaking, Vol. 29, No. 3, 2002, pp. 180-184.

30. Y. Meng and Brian G. Thoams, “Modeling Transient Slag-Layer Phenomena in the Shell/Mold Gap in Continuous Casting of Steel,” *Metallurgical and Materials Transactions*, Vol. 34, No. 5, 2003, pp. 707-725.
31. K. Kawakami, T. Kitagawa, M. Komatsu, H. Mizukami, A. Masui and T. Ishida, “Study on the Solidification Phenomena in Continuous Casting Mold,” *Nippon Kokan Technical Report Overseas*, No. 36, Dec., 1982, pp 17-25.
32. M. Suzuki et al., “Initial Solidification Behavior of Ultra Low Carbon Steel,” *CAMP-ISIJ*, Vol. 11, 1998, pp. 42-44.
33. A. Yamauchi, S. Itoyama, Y. Kishimoto, H. Tozawa and K. Sorimachi, “Cooling Behavior and Slab Surface Quality in Continuous Casting with Alloy 718 Mold,” *ISIJ International*, Vol. 42, No. 10, 2002, pp. 1094-1102.
34. M. Nadif, A. Solimine, P. Ominetti, P. Velluet, M. Blandel and M. Roscini, “Influence of Shell Solidification on Generation of Slab Defects-Use of Hydraulic Mold Oscillation at Sollac Florange,” *La Metllurgia Italiana*, Vol. 84, 1992, pp. 419-424.
35. O. Pütz, O. Vreitfeld and S. Rödl, “Investigations of Flow Conditions and Solidification in Continuous Casting Moulds by Advanced Simulation Techniques,” *Steel Research*, Vol. 74, No. 11/12, 2003, pp. 686-692.
36. B.G. Thomas and H. Zhu, “Thermal Distortion of Solidifying Shell in Continuous Casting of Steel,” *Proceedings of Internat. Symposia on Advanced Materials & Tech. for 21st Century*, TMS, 1996, pp. 197-208.
37. H.Nakato, T. Nozaki, Y. Habu, H. Oka, T. Ueda, Y. Kitano and T. Koshikawa, “Improvement of Surface Quality of Continuous Cast Slabs by High Frequency Mold Oscillation,” *Steelmaking Conference Proceedings*, ISS, 1985, pp. 361-365.
38. H. Yamamura, Y. Mizukami and K. Misawa, “Formation of a Solidified Hook-like Structure at the Subsurface in Ultra Low Caron Steel, ”, *ISIJ International*, Vol. 36, 1996, Supplement, pp. S223-226.