

# Effect of Mold Oscillation on Powder Consumption and Hook Formation in Ultralow-carbon Steel Slabs

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

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,<sup>8</sup> while others show a better correlation with positive strip time.<sup>9</sup> Another concept is the negative strip area ratio, which was found to increase with increasing powder consumption in a study involving nonsinusoidal mold oscillation.<sup>10</sup> 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 this 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),<sup>11-17</sup> which often become sites for transverse crack formation on the wide and narrow faces.<sup>17-18</sup> Shallower oscillation marks are reported for shorter negative strip times,<sup>1,6,8,14</sup> shorter stroke<sup>5,12,16</sup> and higher frequency.<sup>16,19</sup> To reduce oscillation mark depth, it is standard practice to lower the negative strip time by using higher oscillation frequency and shorter oscillation stroke.<sup>8,14,17,19</sup> Specifically, typical commercial practice over the past several decades has increased frequency from ~60 to ~180 cycles/minute and decreased stroke from ~10 to ~5 mm. The cost of these measures has been an 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

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**This article investigates the effect of mold oscillation conditions on slab surface quality, including an examination of subsurface hook characteristics. The effects of casting conditions on mold flux consumption and hook formation are quantified.**

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minimize breakout occurrence<sup>1-2</sup> and to minimize surface quality problems. One important quality problem is the formation of deep oscillation marks and subsurface hooks, especially in ultralow-carbon steels. These can cause defects such as slivers and pencil-pipe blisters in the final rolled sheet product,<sup>3</sup> even after expensive surface grinding to remove them.

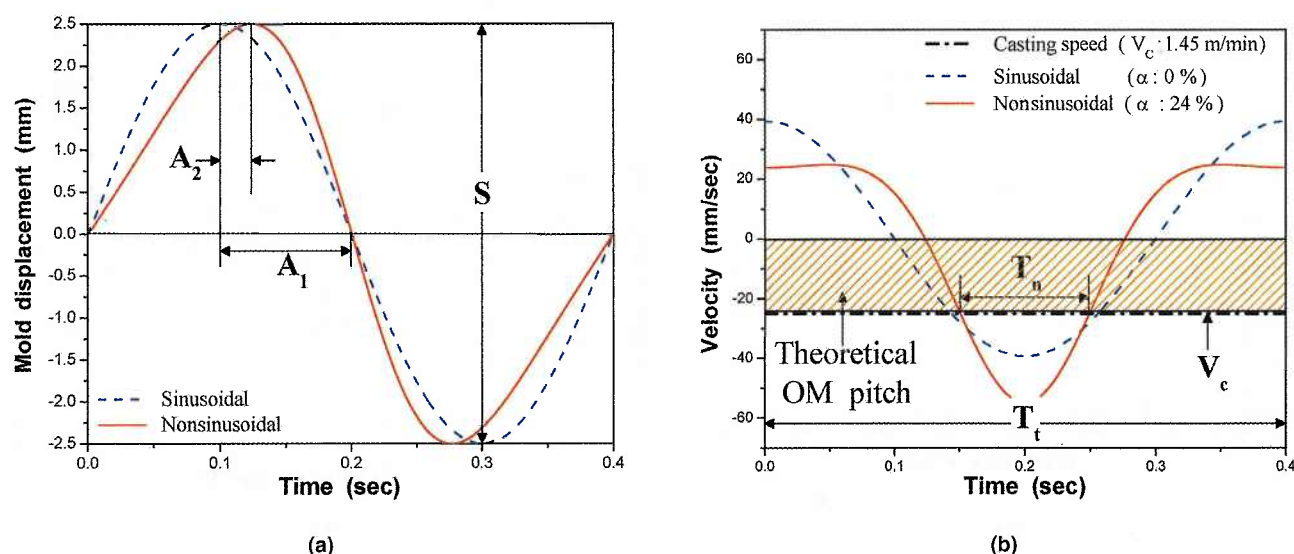
For consistent and uniform lubrication, different theories have been proposed for the infiltration of liquid mold flux into the interfacial gap between the solidifying steel shell and the mold at the meniscus. Most investigators found that increasing casting speed and increasing liquid flux viscosity at 1,300°C tends to lower the consumption rate of mold powder.<sup>4-6</sup> In order to predict consumption rate, several different concepts have been developed and applied, with varying success.<sup>7</sup> These



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**Figure 1**



Schematic diagram of (a) mold displacement and (b) velocity in the case of sinusoidal and nonsinusoidal oscillation mode.

their easy entrapment of mold flux and inclusion-laden gas bubbles.<sup>15,20</sup> Since their discovery by Emi,<sup>12</sup> 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,<sup>21–22</sup> submeniscus<sup>23–24</sup> and/or solidification<sup>25–27</sup> of the meniscus shell. Both oscillation marks and hooks are affected by oscillation conditions,<sup>21</sup> 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, South Korea, for several different oscillation conditions. Oscillation stroke, frequency and the effect of nonsinusoidal 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

Nonsinusoidal mold oscillation provides an additional degree of flexibility in choosing oscillation conditions, relative to a traditional sinusoidal oscillator. As shown in Figure 1, nonsinusoidal 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),<sup>28</sup> allowing longer positive strip times

for the same stroke and frequency conditions,<sup>1</sup> and improving lubrication uniformity.

Table 1 shows the three 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 1a. Stroke is also twice the amplitude. Frequency is the number of cycles per unit time, as given by  $F$  (cpm). The modification ratio ( $\alpha$ ) characterizes the extent of asymmetry of the nonsinusoidal 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 1. It varies from zero (sinusoidal) to 24 percent in this work.

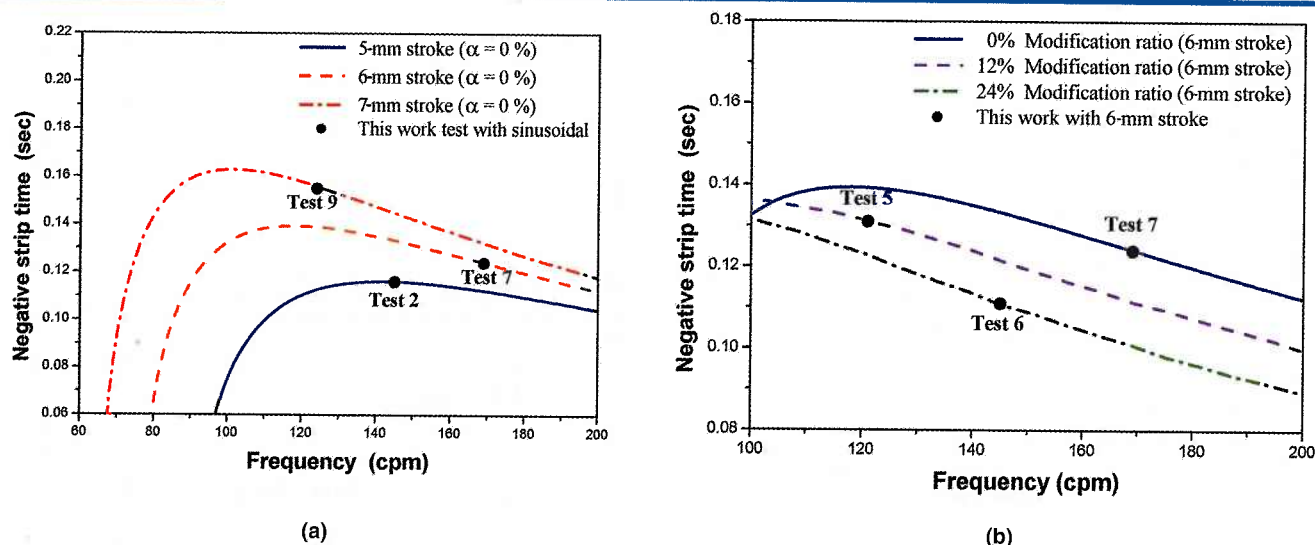
The important concepts of negative and positive strip times depend on the oscillation parameters and the casting speed ( $V_c$ ). The negative strip time, sometimes called “heal

**Table 1**

### Definition of Oscillation Parameters

$S$	Stroke (mm)
$F$	Frequency (cycles/minute)
$\alpha$	Modification ratio for nonsinusoidal mode (%) = $(A_2/A_1) \times 100$
$V_c$	Casting speed (m/minute)
$T_t$	Total period of oscillation cycle (seconds/cycle) = $60/F$
$T_n$	Negative strip time (seconds) = $60/\pi F \times \arccos(1,000 \times V_c/\pi S F)$ , equation for $\alpha = 0$
$T_p$	Positive strip time (seconds) = $T_t - T_n$
Theoretical oscillation mark pitch (mm) = $1,000 \times V_c/F$	

**Figure 2**



Influence of (a) sinusoidal and (b) nonsinusoidal oscillation conditions on negative strip time.

time,” is the time when the mold is moving downward faster than the casting speed, as shown in Figure 1b. 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.<sup>1,29</sup> Table 1 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 1b from the area of casting speed times the total cycle period of oscillation.

### Plant Trials

Plant trials were performed with different mold oscillation conditions on a conventional parallel-mold continuous slab caster at POSCO Gwangyang Works No. 2-1 caster from February to September 2002. The mold is equipped with a hydraulic mold oscillator, which allows a variety of nonsinusoidal oscillation modes in addition to changing stroke and frequency. Stroke, frequency and modification ratio were changed systematically according to the 10 tests shown in Table 2. Each test lasted for most of one sequence (4–6 heats). For all tests, the section size was 230 x 1,300

**Table 2**

#### Mold Oscillation Conditions

	Stroke (mm)	Frequency (cpm)	Nonsinusoidal mold oscillation ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Consumption rate of mold flux (kg/m <sup>2</sup> )
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 3****Steel Composition of Ultralow-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

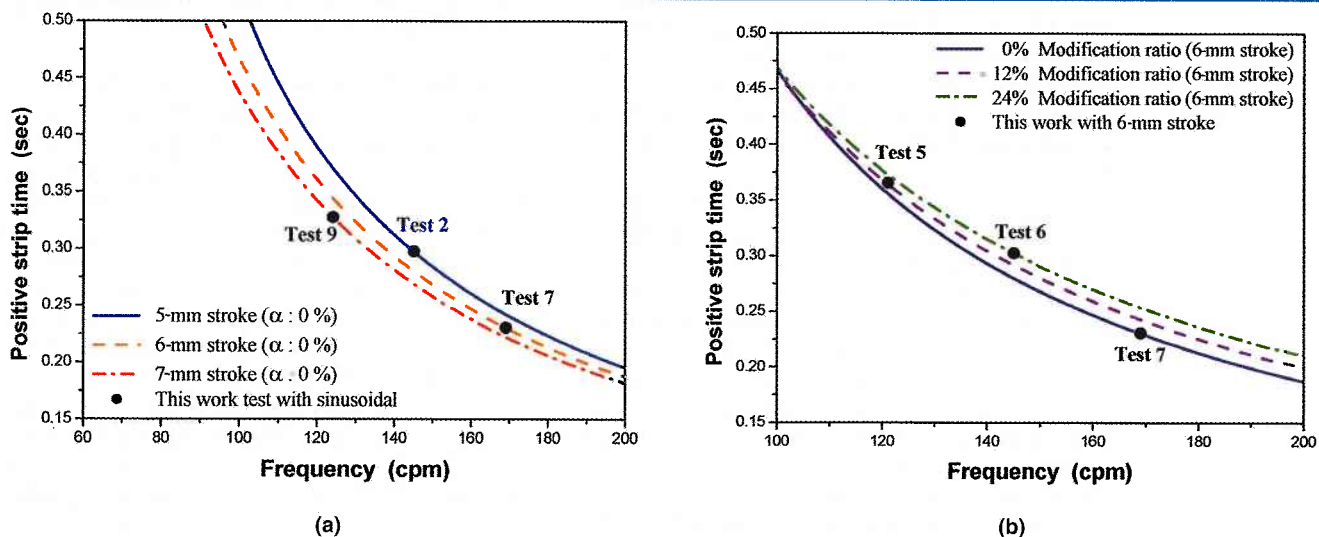
**Table 4****Mold Powder Composition and Properties**

Chemical composition													
Basicity	SiO <sub>2</sub>	CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	F	B <sub>2</sub> O <sub>3</sub>	Li <sub>2</sub> O
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													
Solidification temperature (°C)			Softening temperature (°C)			Melting temperature (°C)			Viscosity at 1,300 °C (poise)				
1,149			1,170			1,180			3.21				

mm and the casting speed was kept relatively constant at 1.45 m/minute, even during ladle exchanges. For all tests, the composition of the ultralow-carbon steel grade cast is given in Table 3, and the composition and properties of the mold powder are given in Table 4. The mold powder consumption rate in Table 2 was calculated from the weight of the bags consumed during each entire sequence, which includes more than 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

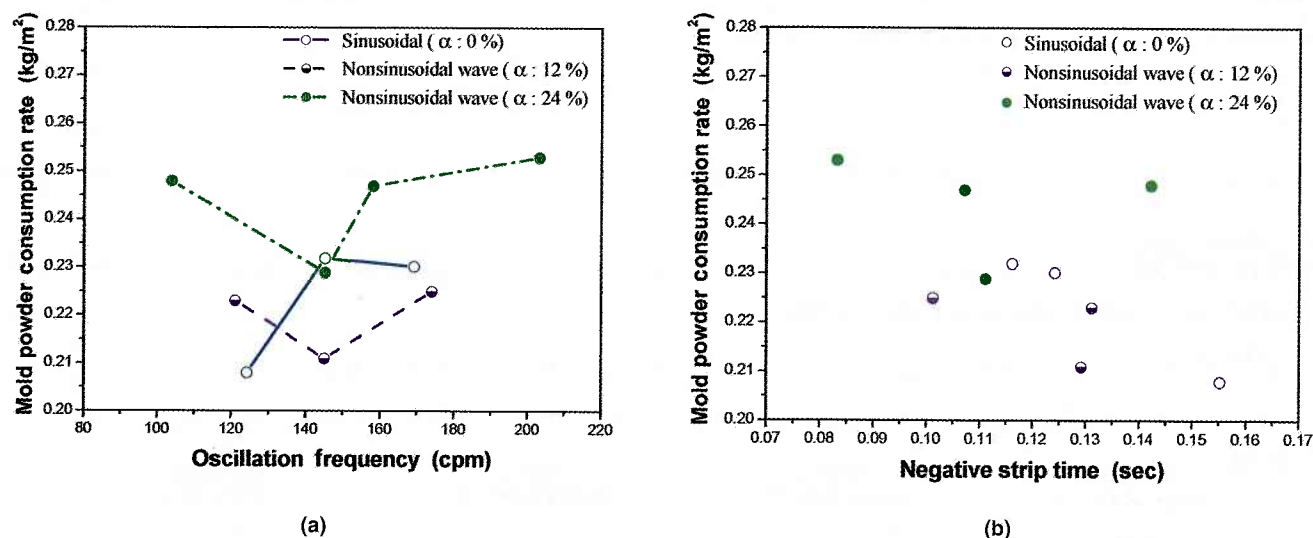
narrow face. Hook shape down the narrow faces was then measured from etched cross-sections taken at five different distances between the wide faces.

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 (2, 7, 9) 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 2b shows that increasing the asymmetry of the nonsinusoidal oscillation (increasing  $\alpha$ ) also decreases the negative strip time, although the effect is not as important as stroke.

**Figure 3**

Influence of (a) sinusoidal and (b) nonsinusoidal oscillation conditions on positive strip time.

Figure 4



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

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.

### 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.<sup>30</sup> First, 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. Second, 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 it has been termed the "lubrication consumption."<sup>30</sup> Third, 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.

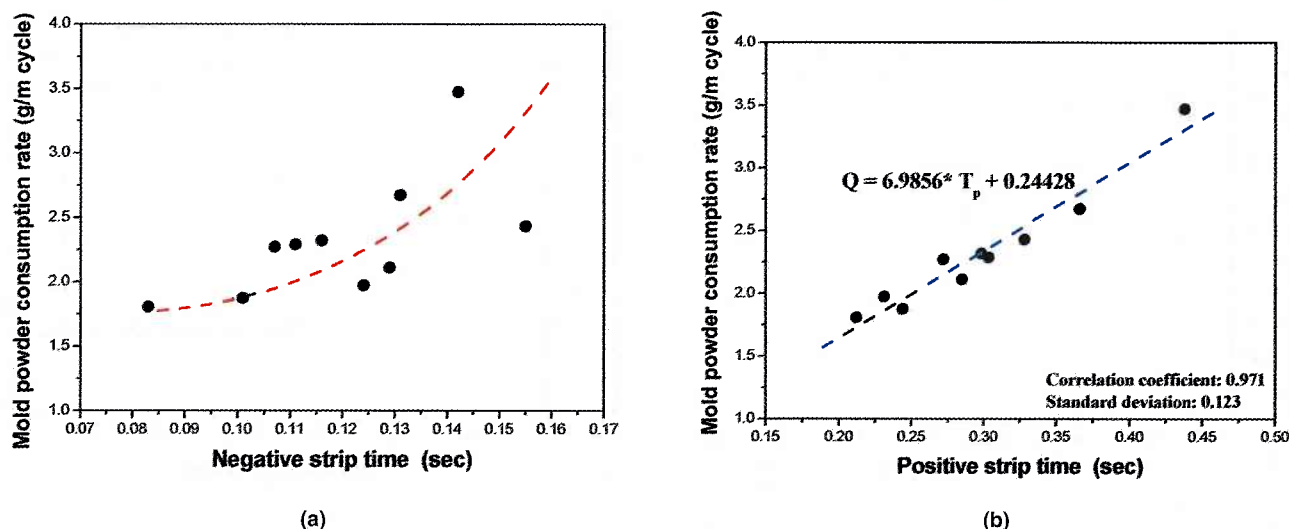
The total consumption rate of mold powder for each test condition is given in Table 2. Consumption starts when liquid flux is pumped into the gap between the steel shell and the mold wall at the meniscus during oscillation. Thus, oscillation parameters naturally have an important effect on consumption. Because the mold powder consumption rate also depends greatly on the casting speed<sup>4-5</sup> and mold flux properties,<sup>6</sup> for every test in this study the casting speed was fixed (1.45 m/minute) and the same mold powder was used. This allows investigation of the subtle effects of the three 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 4a shows the influence of oscillation frequency on the measured powder consumption rate, expressed as mass per unit area of strand surface. For sinusoidal operation ( $\alpha = 0$  percent), there is a slight trend of increasing consumption rate with increasing frequency. 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.<sup>10</sup> However, with nonsinusoidal 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<sup>8</sup> or increasing positive strip time.<sup>9-10,31</sup> These indicators are considered to be more fundamental than frequency because they also include the effects of stroke and casting speed. Figure 4b shows the influence of negative strip time on mold powder consumption rate per unit area. There is no clear relation when nonsinusoidal 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

**Figure 5**



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

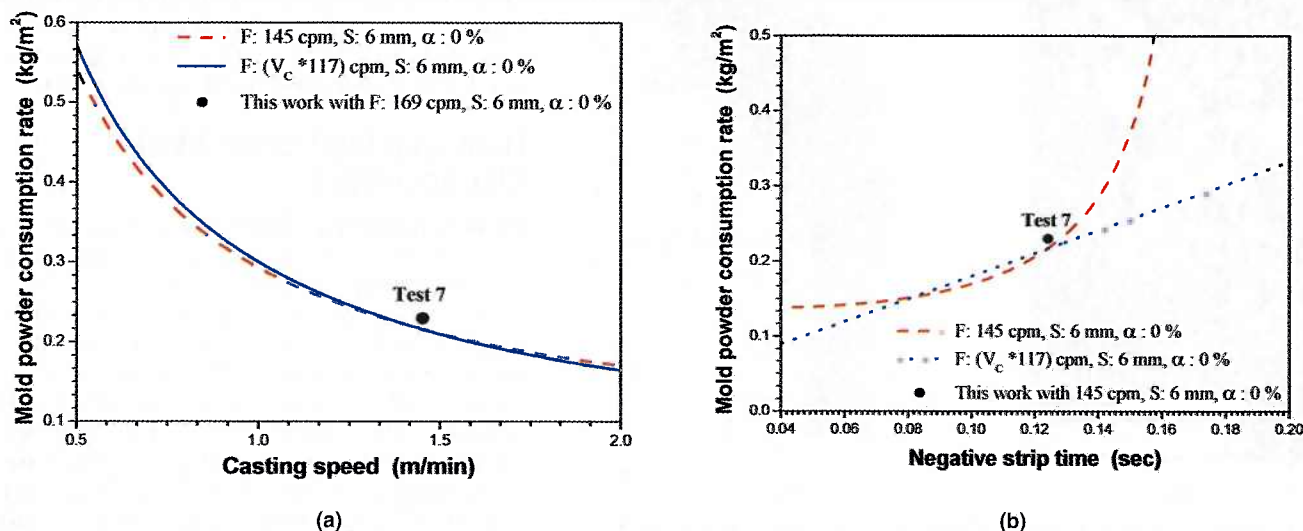
should increase consumption, which were made with varying casting speed. Thus, with the effect of casting speed removed, negative strip time is a poor indicator of flux consumption. The correlation with positive strip time is not much better.

**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 Figure 3). This result agrees with the correlation of mold powder consumption rate with positive strip time per cycle found by Kawakami et al.<sup>9,31</sup> Therefore, the empirical equation expressing the linear relation with this form of consumption rate with positive strip time was explored further.

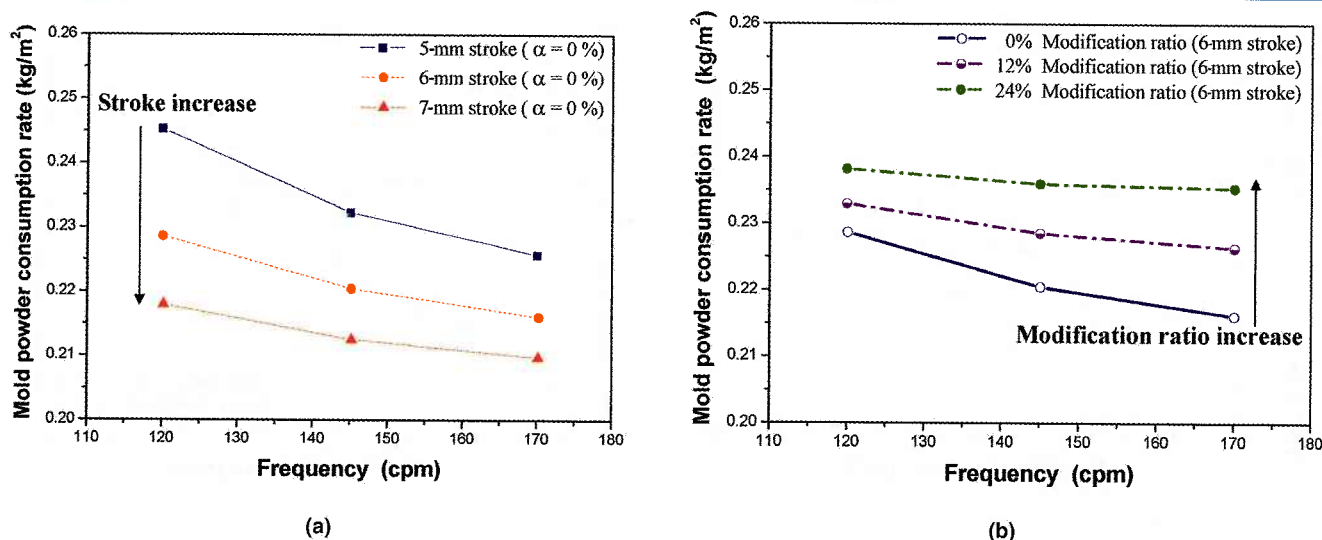
First, this equation is shown to reproduce the known trends with casting speed. Two cases are studied: (1) frequency and stroke fixed independent of speed and (2) frequency increasing with increase of casting speed at fixed stroke, which is used in many plants. Figure 6a shows that predicted consumption rate drops with increasing casting speed for both cases, which matches the trend measured in many plants.<sup>30</sup> Figure 6b shows that predicted consumption rate increases with

**Figure 6**



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



**Figure 7**

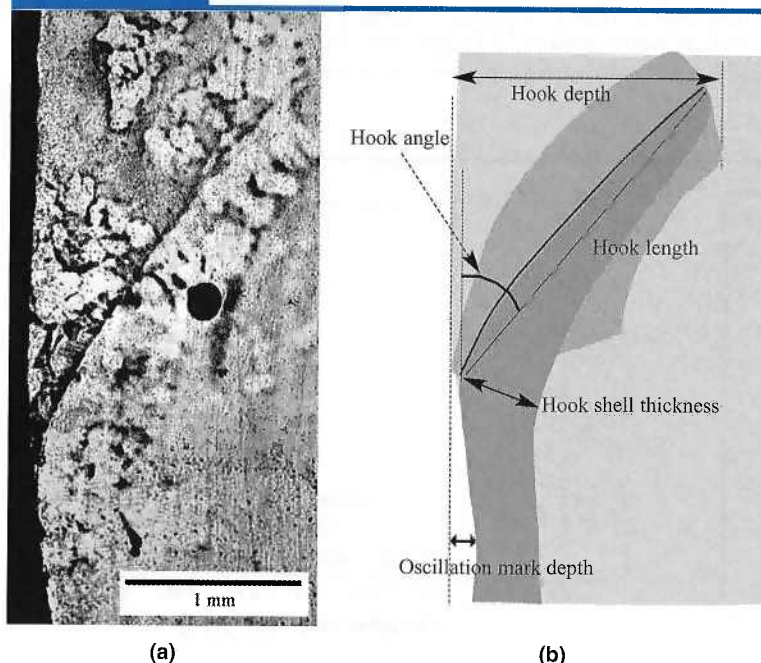
Influence of oscillation conditions on predicted powder consumption rate.

increasing negative strip time for both cases, again as expected. The better trend of this figure relative to Figure 4b is due to including the important effect of casting speed.

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.<sup>8</sup>

Assuming the empirical relation between mold powder consumption rate per cycle and positive strip time in 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. Figure 7b also shows that increasing asymmetry consumes more flux, which matches observations. However, Figure 7a shows that a shorter stroke consumes more flux. This unexpected prediction indicates that further investigation is needed to understand mold consumption.

**Figure 8**

Example of oscillation mark and hook (a) and definition of their characteristics (b).

## Hook and Oscillation Mark Characteristics

**Measurement Procedure** — The narrow faces of each 100-mm-long slab sample cast under the 10 different conditions given in Table 2 were sectioned for analysis of oscillation mark profiles and hook characteristics. Before measurement of the oscillation mark profile, each sample was sandblasted 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)

**Table 5****Mean Value of Oscillation Mark and Hook Characteristics**

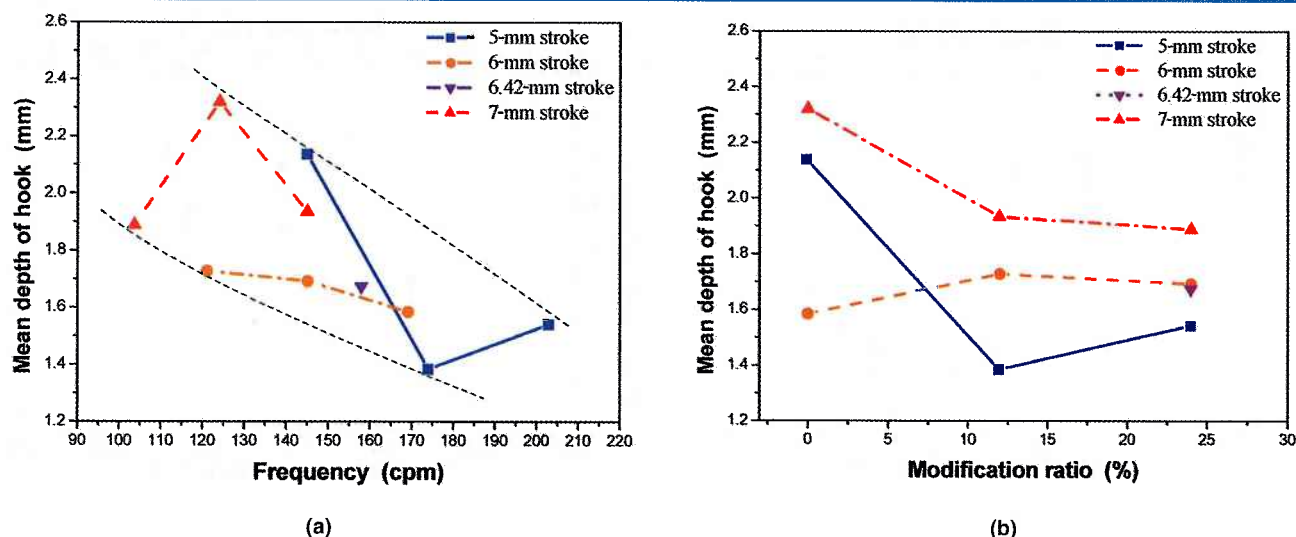
	Tundish temperature (°C)	Theoretical pitch of oscillation mark (mm)	Measured oscillation mark pitch (mm)	Measured oscillation mark depth (mm)	Measured hook depth (mm)	Measured hook length (mm)	Measured hook angle (degree)	Measured hook shell thickness (mm)
Test 1	1,566	9.31	9.15	0.246	1.68	2.16	34.3	0.75
Test 2	1,563	10.04	11.79	0.395	2.14	4.72	19.8	0.89
Test 3	1,571	8.43	7.86	0.310	1.39	2.16	27.6	0.67
Test 4	1,571	7.37	7.14	0.290	1.54	2.43	29.7	0.65
Test 5	1,555	12.41	12.59	0.357	1.73	3.34	23.1	0.76
Test 6	1,573	10.13	9.88	0.343	1.69	2.75	28.7	0.70
Test 7	1,566	8.82	8.66	0.255	1.59	2.77	27.5	0.62
Test 8	1,571	14.37	13.57	0.308	1.89	3.08	29.7	0.78
Test 9	1,559	11.84	11.26	0.340	2.32	4.87	21.6	0.92
Test 10	1,559	10.34	10.10	0.329	1.94	4.58	20.2	0.78

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  $\mu\text{m}$ , the sections were etched for approximately 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<sup>32–34</sup> and characteristics,<sup>20,32,35</sup> 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 for-

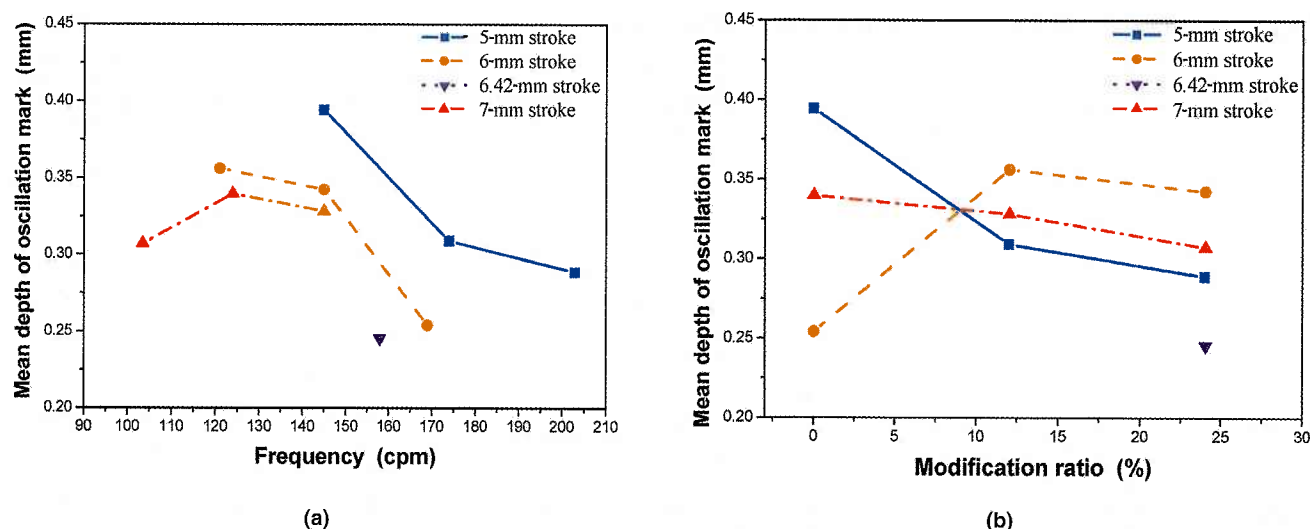
mation, which focus on different phenomena.<sup>21–22,24–27,36</sup> The hook characteristics defined for this study were hook depth, hook length, hook angle and hook shell thickness, as illustrated in Figure 8.

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 Figure 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 toward the upper left likely occurred after the hook was overflowed with new liquid metal. Traces of entrapped mold

**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.

powder or bubbles are often observed on the lower right side of the hook.

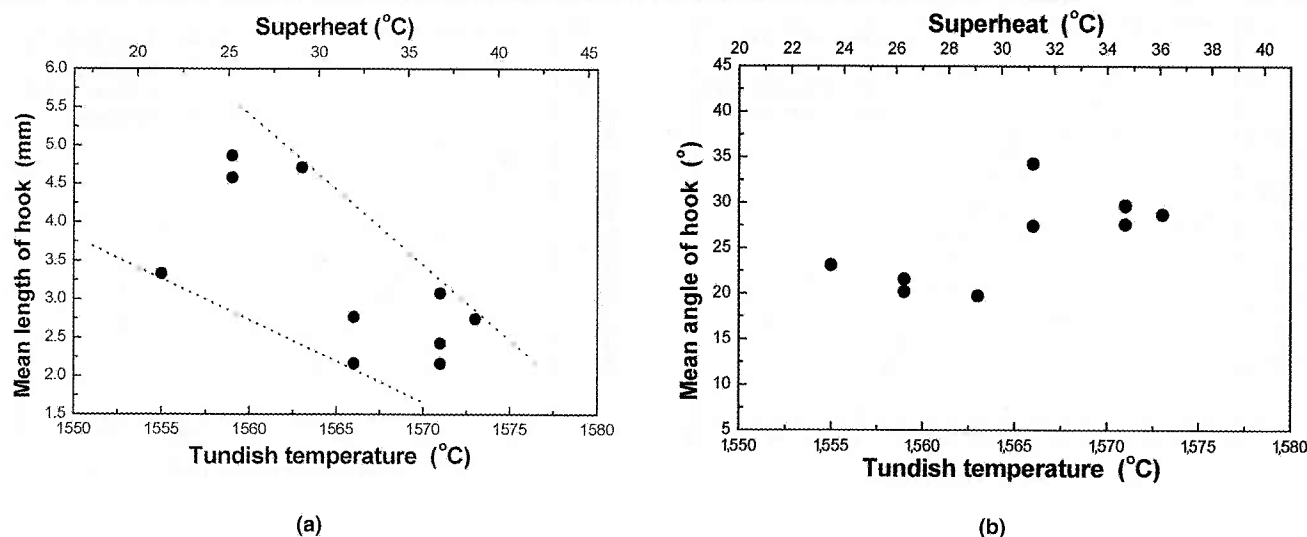
The hook depth is defined in this work as the perpendicular distance from the slab surface to the furthest inner extent of the hook, as pictured in Figure 8. This parameter is of practical importance, because it indicates the thickness of surface layer that should be removed during grinding to completely eliminate the hook and its associated inclusion. This definition differs from that of Kitano et al.,<sup>17</sup> 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

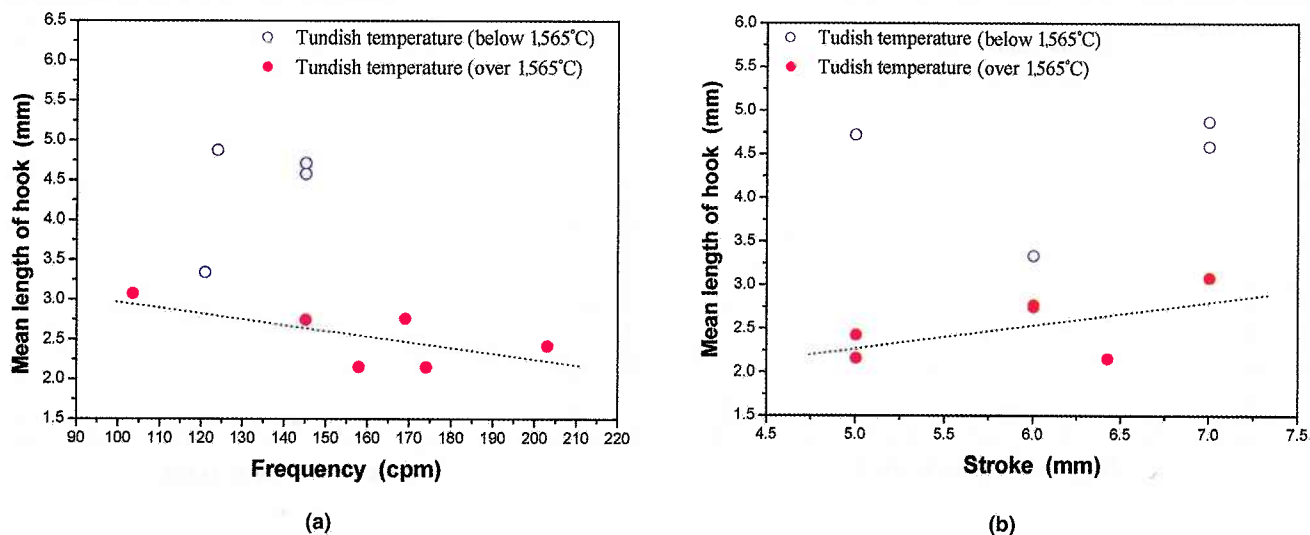
Pütz et al.<sup>35</sup> The hook angle is derived from the depth and length and indicates how much the hook bends away from the mold. Finally, the hook shell thickness is measured at the upper end of the oscillation mark where the hook starts, which generally represents the thickest part of the hook.

**Results Summary** — The average results of hook characteristics and oscillation mark depths are given in Table 5.

**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 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.

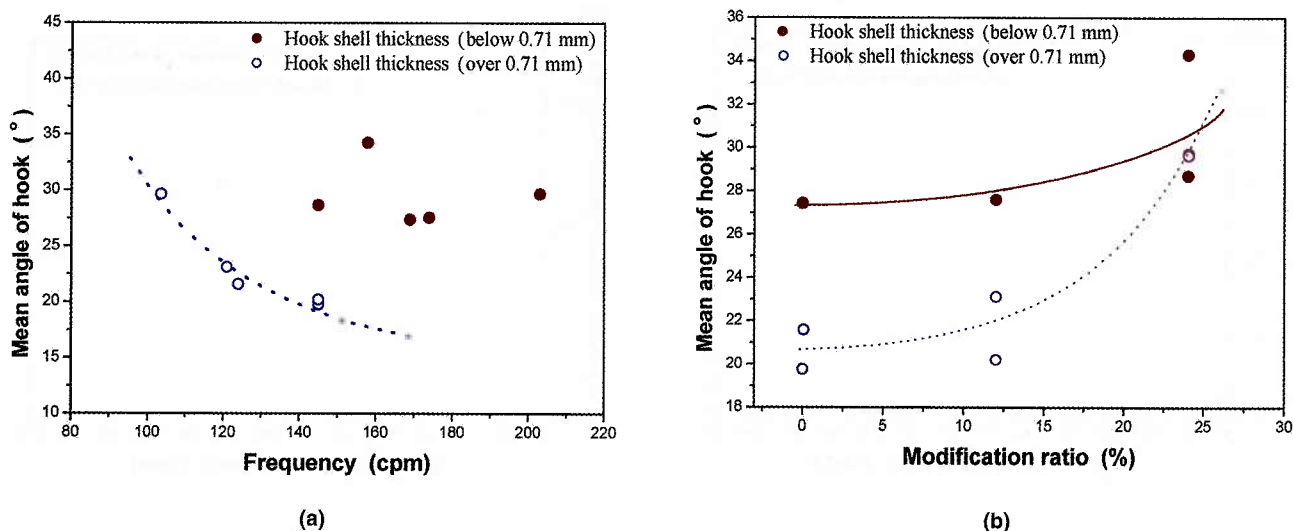
Figure 9 shows the effect of mold oscillation conditions on hook depth. Hook depth appears to decrease with increasing oscillation frequency and with increasing modification ratio, but it is difficult to find a trend with stroke. These results agree with Nakato et al.<sup>37</sup> Figure 10 shows the same trends for oscillation mark depth, although they are very rough.

#### Importance of Heat Transfer Conditions —

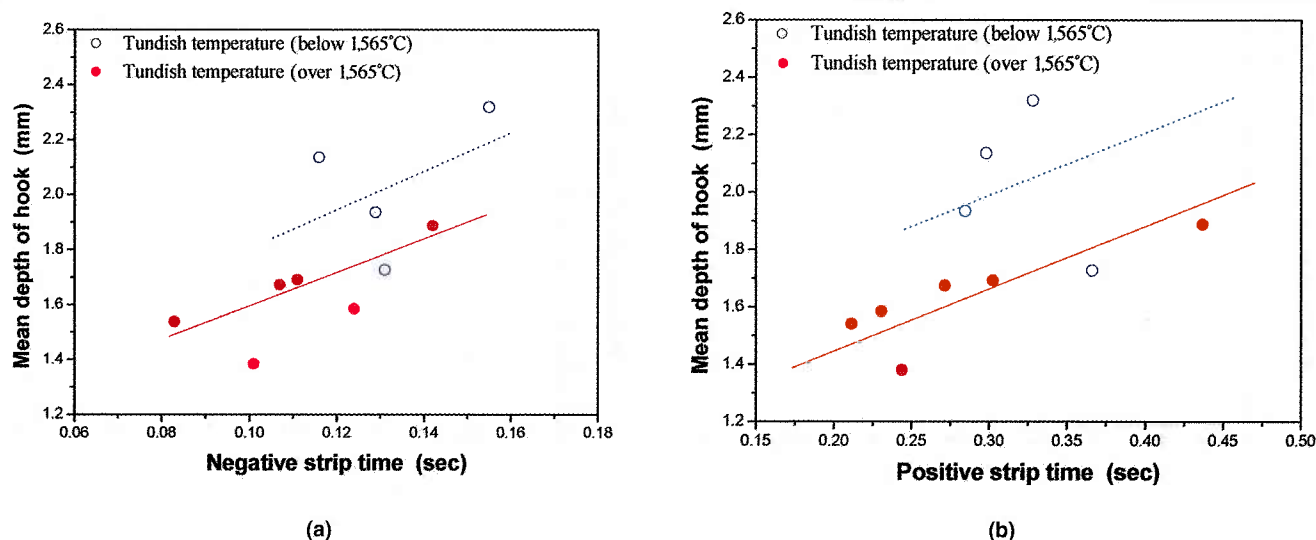
In addition to oscillation conditions, meniscus phenomena such as hook formation depend greatly on other casting conditions, such as carbon content,<sup>29,38</sup> superheat in the mold, level fluctuations, and heat transfer conditions at the meniscus. Ultralow-carbon steels are particularly prone to hook formation, owing to their thin mushy zone.<sup>38</sup> High-car-

bon steels experience fewer hooks, which is why steel composition was kept constant in this study. However, the results in Table 5 might be affected by other unintended changes in operation conditions, such as tundish temperature, which was measured every 8–13 minutes. Figure 11a shows that the measured hook length decreases dramatically for tundish temperatures above 1,565°C. The steel liquidus temperature varies from 1,533 to 1,534°C, so this corresponds to superheats above ~32°C. Hook angle is not quite as dependent on superheat, as shown in Figure 11b.

The effects of oscillation frequency and stroke on hook length are shown in Figure 12, divided into groups of high and low superheat. With high superheat, increasing frequency and decreasing stroke appears to

**Figure 13**

Influence of mold oscillation (a) frequency and (b) modification ratio on hook angle.

**Figure 14**

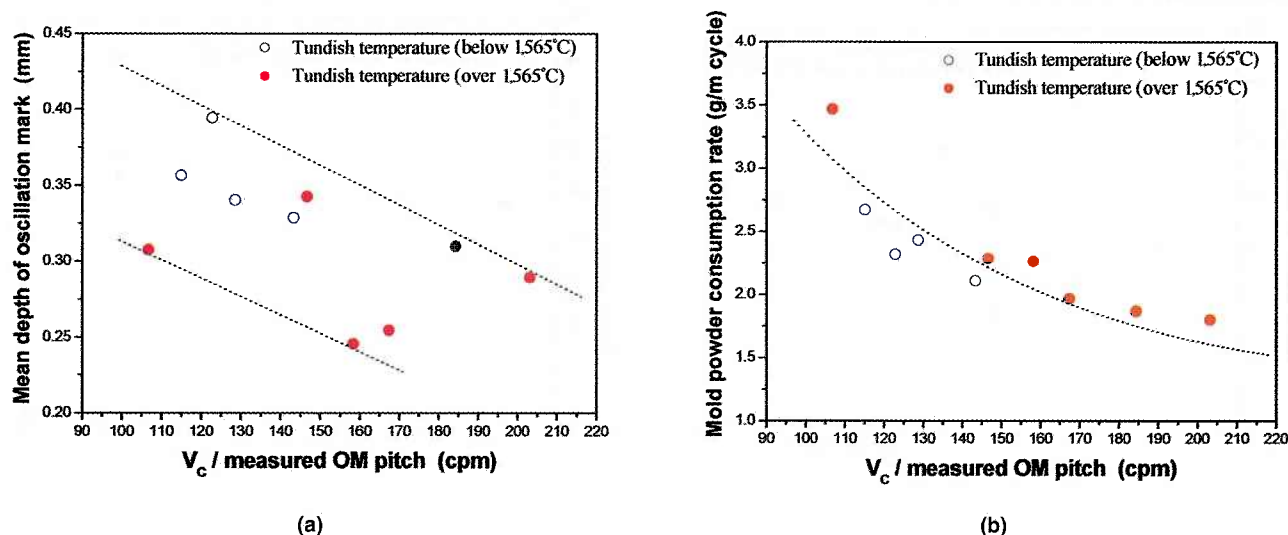
Influence of mold oscillation (a) negative strip time and (b) positive strip time on hook depth.

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.<sup>27</sup>

**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<sup>1,5,21</sup> 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 depend 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 Figure 13a. Figure 13b shows that the angle of thick hooks also increases with increasing asymmetry. This trend is most severe with a modification ratio over 12 percent. Perhaps the greater hook deflections arise because the higher frequencies and higher asymmetries generate higher pressures during the mold downstroke.

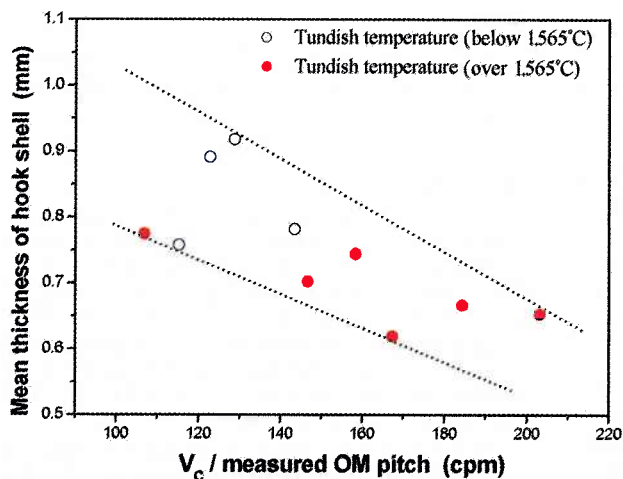
**Effect of Strip Time Indicators on Hook Depth** — Figure 14 shows the effect of negative and positive strip times on hook depth for

**Figure 15**

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

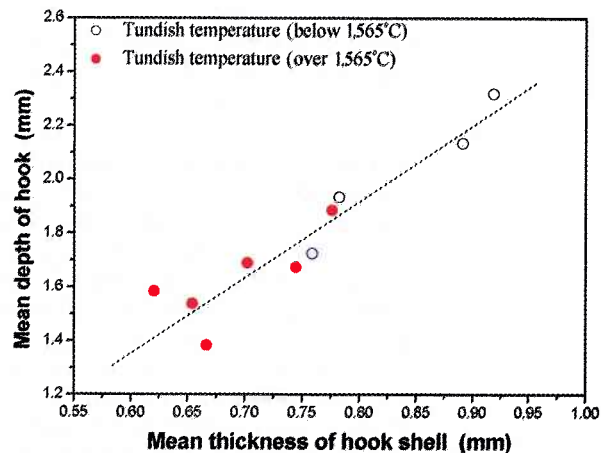


Figure 16



Influence of local frequency on hook shell thickness.

Figure 17



Influence of hook shell thickness on hook depth.

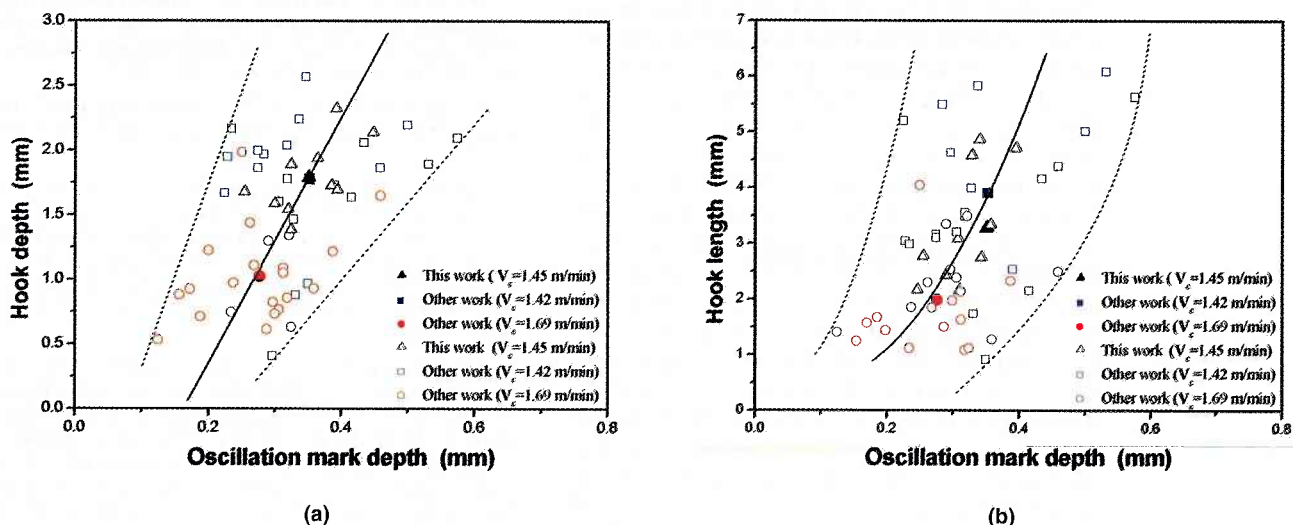
different superheats. Hook depth appears to decrease with decreasing negative strip time or decreasing positive strip time, at least for higher superheats. Both indicators are equally good. Increasing superheat clearly decreases hook depth. The great importance of the superheat effect helps to explain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

#### Relation Between Mold Powder Consumption, Oscillation Mark Depth and Pitch

— The oscillation mark depth decreases with increasing local frequency, as shown in Figure 15a. The local frequency is calculated from the measured mean oscillation pitch (Table 5) to account for local variations in pitch caused by level fluctuations. This makes the trend slightly stronger than in Figure 10a.

From the predicted equation relating mold powder consumption rate to positive strip time (Figure 5b), and the strong correlation between frequency and positive strip time, increasing frequency should lower consumption. Figure 15b 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 (Figure 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 rates are based on approximately 200 m of cast length, while the oscillation mark depths are based on only about 0.1

Figure 18



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

m of cast length. In addition, superheat has an important effect on decreasing oscillation mark depth, as previously discussed.

**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 and so produces thinner hooks, as shown in Figure 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.

Finally, Figure 18 shows that increasing oscillation mark depth tends to accompany increasing hook depth and length, so is 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 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.

## 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 nonsinusoidal 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 formation and hook formation all depend on so many interdependent 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.

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