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Model of Mold Powder Consumption during CC of ULC steel

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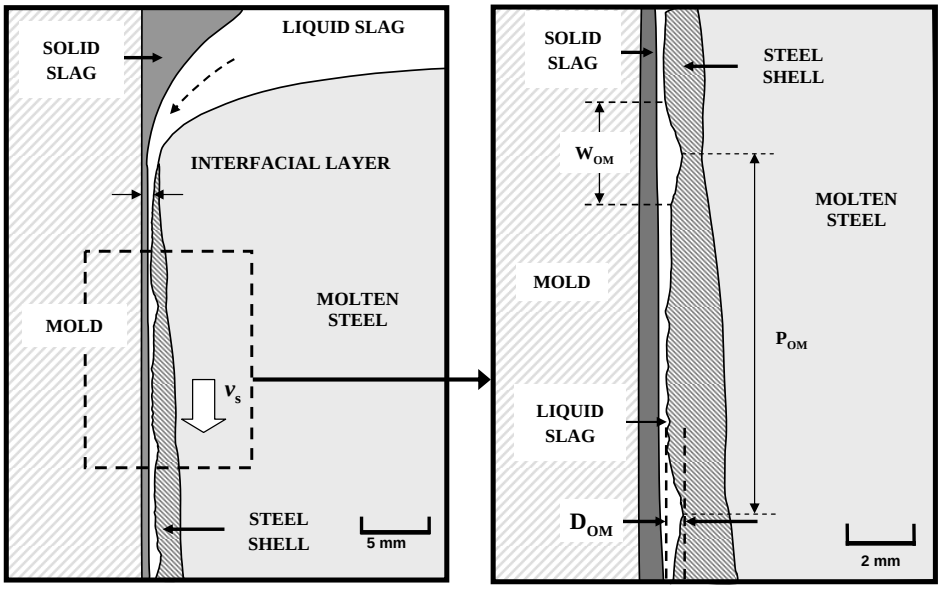
Acknowledgements

- Continuous Casting Consortium at UIUC
- Postech: Gogi Lee and SH Kim.
- Posco (measurements): JM. Park
- Joydeep Sengupta

- Submitted to ISIJ International, May, 2006

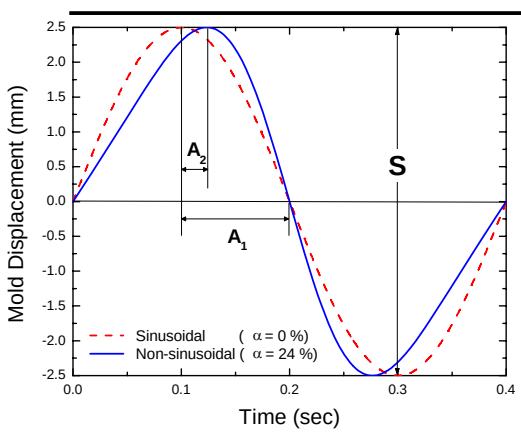
Interfacial gap between the mold and solidifying shell

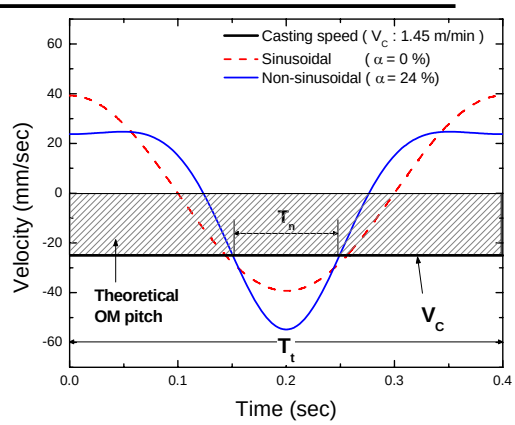


Mold flux consumption occurs as 1) lubrication and 2) in oscillation marks

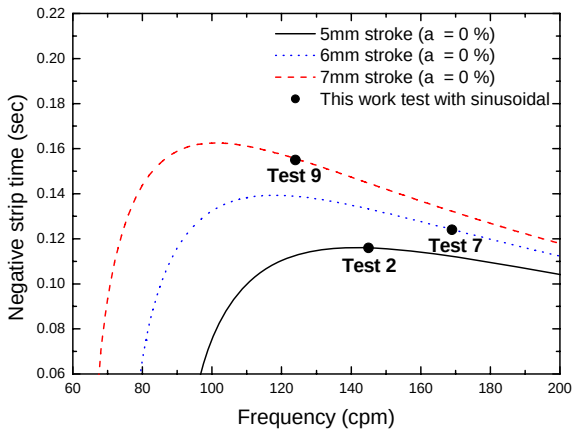
Mold Oscillation Parameters

S : Stroke (mm)
F : Frequency (cycles / minute)
α : Modification ratio for non-sinusoidal mode (%) = (A_2 / A_1) × 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/πF×arc cos (1000×V_C /πSF), Equation for α = 0
T_P: Positive strip time (sec) = T_t - T_n
Theoretical oscillation mark pitch (mm) = 1000×Vc / F

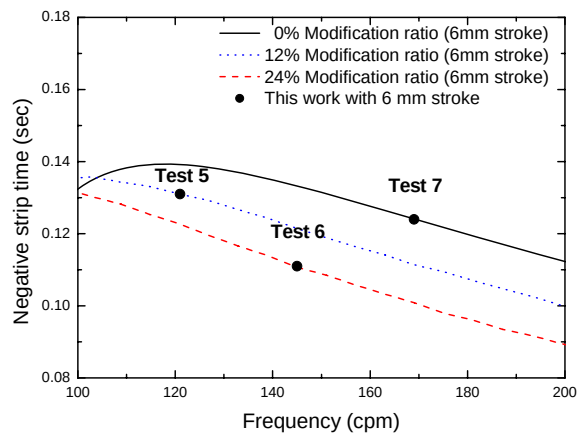




Influence of oscillation conditions on **negative** strip time

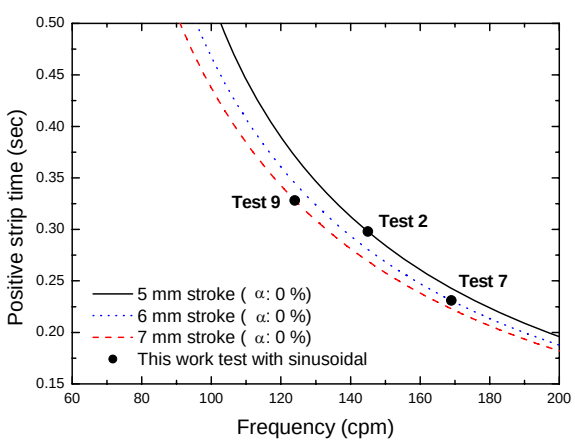


< Sinusoidal oscillation conditions >

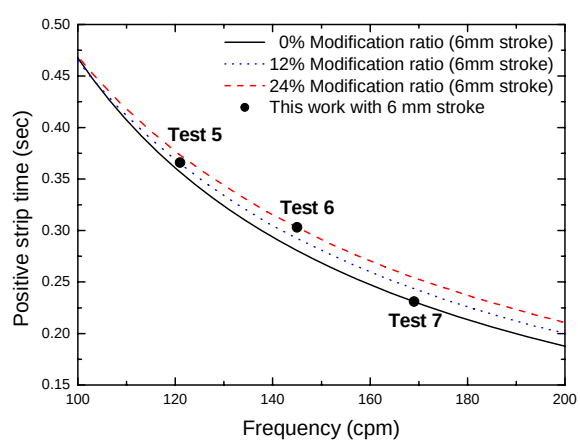


< Non-sinusoidal oscillation conditions >

Influence of oscillation conditions on **positive** strip time



< Sinusoidal oscillation conditions >



< Non-sinusoidal oscillation conditions >

Controlled Casting Trials

ULC steel
230 mm thick slab

Constant conditions for several heats per trial case

I. Steel:	
C (0.002~0.005%) – **Mn** (0.07~0.15%) – **Si** (≤ 0.005%) – **P** (0.01%) – **S** (0.01~0.012%) – **Cr** (0.01%) – **Ni** (≤0.01%) – **Cu** (≤0.01%) – **Ti** (0.025~0.05%) – **Al_{tot}** (0.035%)	
Density of liquid steel (kg m^{-3})	7127
Surface tension at 1550 °C (N m^{-1})	1.6
Liquidus temperature (°C)	1534
Solidus temperature (°C)	1519
*II. Mold Powder (**Trial A** and **B**):*	
CaO (39.8%) – **SiO_2** (36.3%) – **Al_2O_3** (3.4%) – **MgO** (0.8%) – **Li_2O** (0.4%) – **Na_2O** (3.4%) – **K_2O** (0.1%) – **Fe_2O_3** (0.3%) – **MnO_2** (0.03%) – **TiO_2** (0.2%) – **F** (6.0%) – **CO_2** (3.5%) – **C_{total}** (3.0%)	
Density of liquid slag (kg m^{-3})	2680
Viscosity at 1300 °C (Pa s)	0.321
Surface tension (N m^{-1})	0.431
Solidification temperature (°C)	1145
Melting temperature (°C)	1180
*III. Mold Powder (**Trial C**):*	
CaO (37.9%) – **SiO_2** (37.8%) – **Al_2O_3** (5.0%) – **MgO** (2.0%) – **Li_2O** (0.9%) – **Na_2O** (3.8%) – **K_2O** (0.1%) – **Fe_2O_3** (0.3%) – **MnO_2** (0.04%) – **TiO_2** (0.3%) – **F** (7.2%) – **CO_2** (3.2%) – **C_{total}** (2.6%)	
Density of liquid slag (kg m^{-3})	2660
Viscosity at 1300 °C (Pa s)	0.262
Surface tension (N m^{-1})	0.419
Solidification temperature (°C)	1101
Melting temperature (°C)	1145

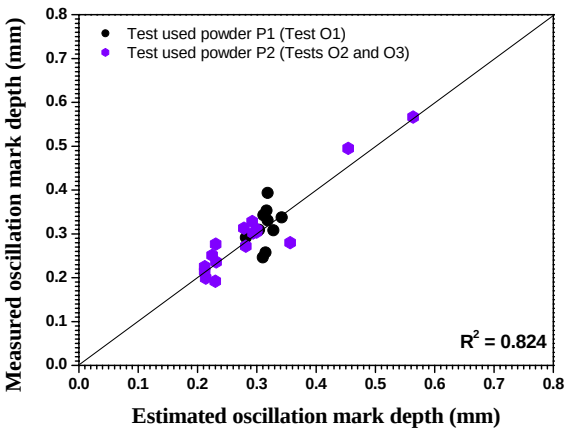
Trial measurements: OM depth

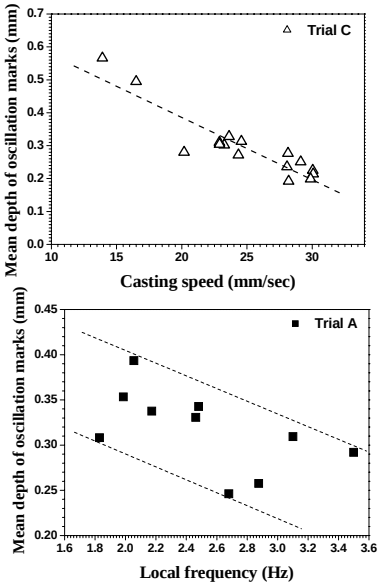
Test No.	Casting width (mm)	Casting speed (mm/s)	Solidification temperature of mold powder (°C)	Viscosity of mold powder at 1300 °C (Pa•s)	Negative strip time (s)	**Measured oscillation mark depth (mm)**
A-1	1300	24.4	1149	0.321	0.107	**0.246**
A-2	1300	24.3	1149	0.321	0.115	**0.393**
A-3	1300	24.5	1149	0.321	0.100	**0.309**
A-4	1300	24.9	1149	0.321	0.081	**0.292**
A-5	1300	25.0	1149	0.321	0.127	**0.353**
A-6	1300	24.5	1149	0.321	0.110	**0.343**
A-7	1300	24.8	1149	0.321	0.121	**0.258**
A-8	1300	24.8	1149	0.321	0.139	**0.308**
A-9	1300	24.4	1149	0.321	0.154	**0.338**
A-10	1300	24.9	1149	0.321	0.126	**0.331**
C-1	1300	29.1	1101	0.262	0.100	**0.251**
C-2	1300	23.6	1101	0.262	0.118	**0.328**
C-3	1300	20.2	1101	0.262	0.134	**0.280**
C-4	1570	24.6	1101	0.262	0.115	**0.313**
C-5	1570	24.3	1101	0.262	0.116	**0.272**
C-6	950	30.0	1101	0.262	0.092	**0.225**
C-7	950	30.1	1101	0.262	0.092	**0.214**
C-8	950	29.9	1101	0.262	0.092	**0.199**
C-9	1300	28.2	1101	0.262	0.097	**0.192**
C-10	1300	23.3	1101	0.262	0.114	**0.302**
C-11	1300	28.1	1101	0.262	0.097	**0.236**
C-12	1300	28.1	1101	0.262	0.097	**0.277**
C-13	1570	22.9	1101	0.262	0.115	**0.310**
C-14	1570	22.9	1101	0.262	0.115	**0.304**
C-15	1570	16.5	1101	0.262	0.152	**0.[illegible]**

Trial results: powder consumption

Test No.	Casting width (mm)	Casting speed (mm/s)	oscillation Stroke (mm)	oscillation frequency (Hz)	Modification ratio (%)	Negative strip time (s)	Positive strip time (s)	**Mold powder consumption (kg/m^2)**
A-1	1300	24.4	6.44	2.65	24	0.107	0.270	**0.247**
A-2	1300	24.3	5.00	2.43	0	0.115	0.296	**0.232**
A-3	1300	24.5	5.00	2.94	12	0.100	0.241	**0.225**
A-4	1300	24.9	5.00	3.49	24	0.081	0.205	**0.253**
A-5	1300	25.0	6.00	2.08	12	0.127	0.353	**0.223**
A-6	1300	24.5	6.00	2.45	24	0.110	0.299	**0.229**
A-7	1300	24.8	6.00	2.90	0	0.121	0.224	**0.230**
A-8	1300	24.8	7.00	1.77	24	0.139	0.426	**0.248**
A-9	1300	24.4	7.00	2.09	0	0.154	0.324	**0.208**
A-10	1300	24.9	7.00	2.49	12	0.126	0.276	**0.211**
B-1	1570	22.5	6.25	2.46	24	0.114	0.292	**0.271**
B-2	1570	23.0	6.30	2.52	24	0.112	0.285	**0.247**
B-3	1570	23.7	6.37	2.58	24	0.109	0.278	**0.256**
B-4	1300	24.7	6.47	2.69	24	0.106	0.267	**0.238**
B-5	1300	24.6	6.46	2.67	24	0.106	0.268	**0.237**
B-6	1300	25.3	6.53	2.74	24	0.104	0.261	**0.215**
B-7	1300	25.8	6.58	2.79	24	0.102	0.256	**0.212**
B-8	1050	27.5	6.75	2.96	24	0.097	0.241	**0.210**
B-9	1050	27.7	6.77	2.97	24	0.097	0.240	**0.194**
B-10	1300	24.4	6.44	2.66	24	0.107	0.270	**0.247**

Empirical equation for mean OM depth compared with trial results

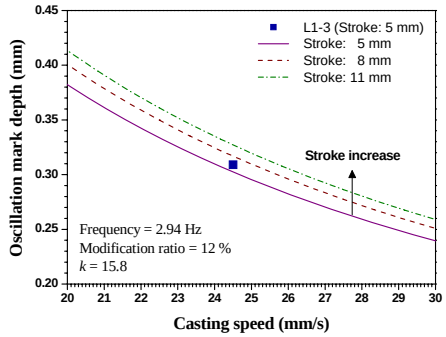


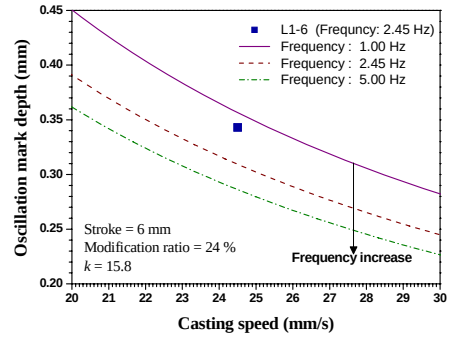


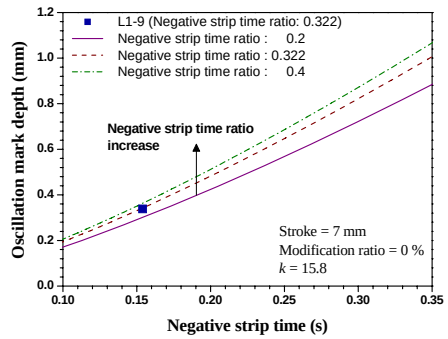
$$\underset{(mm)}{(D_{OM})_{estimated}} = k \times \underset{(s)}{t_n^{0.272}} \times \underset{(m/min)}{V_C^{-1.04}}$$

k is a coefficient depending on mold powder, k for P1 is 14.0 and for P2 is 15.8.

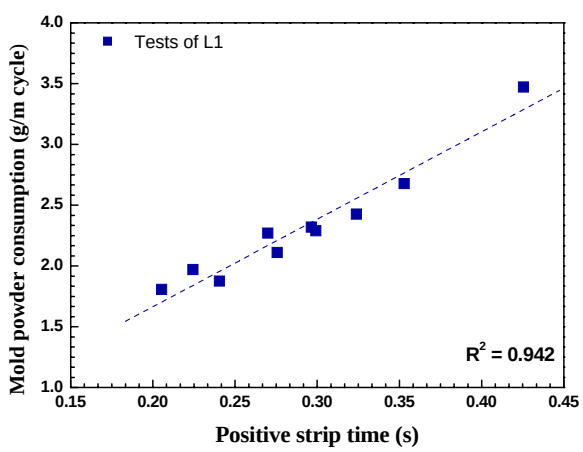
Influence of mold oscillation on OM depth

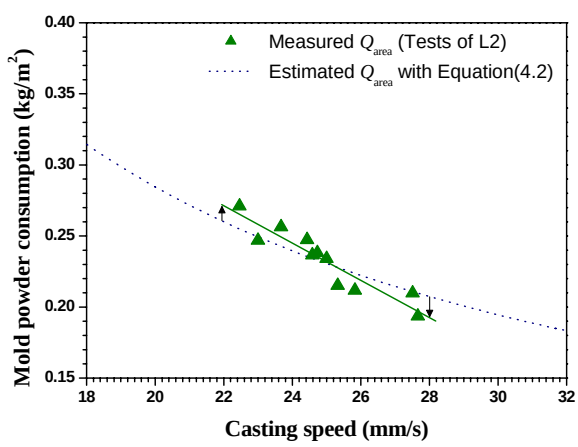






Relationship between mold powder consumption and positive strip time

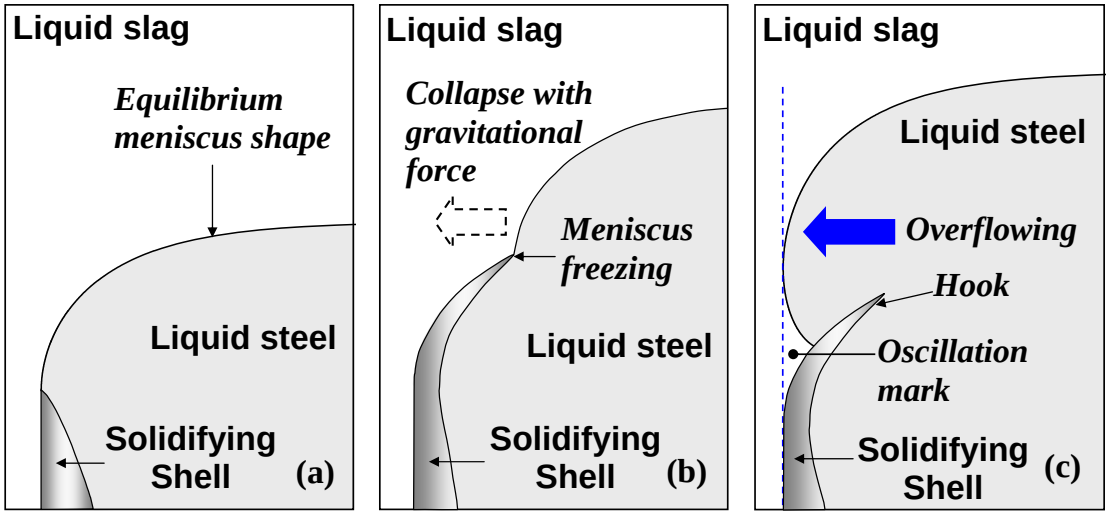




$$q_{\text{cycle}} = Q_{\text{area}} \times \left(P_{\text{OM}}\right)_{\text{theoretical}} = Q_{\text{area}} \times \frac{v_s}{f}$$

$$q_{\text{cycle}} = 7.195 \times t_{\text{p}} + 0.2256$$

Mechanism of OM formation in ULC steel



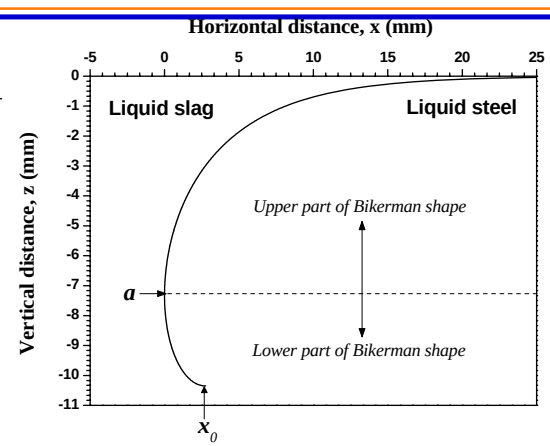
Steady state | **Meniscus freezing** | **Subsequent liquid steel overflowing**

Base meniscus shape on Bikerman Eq.

$$x - x_0 = -\sqrt{2a^2 - z^2} + \frac{a}{\sqrt{2}} \ln \frac{a\sqrt{2} + \sqrt{2a^2 - z^2}}{z}$$

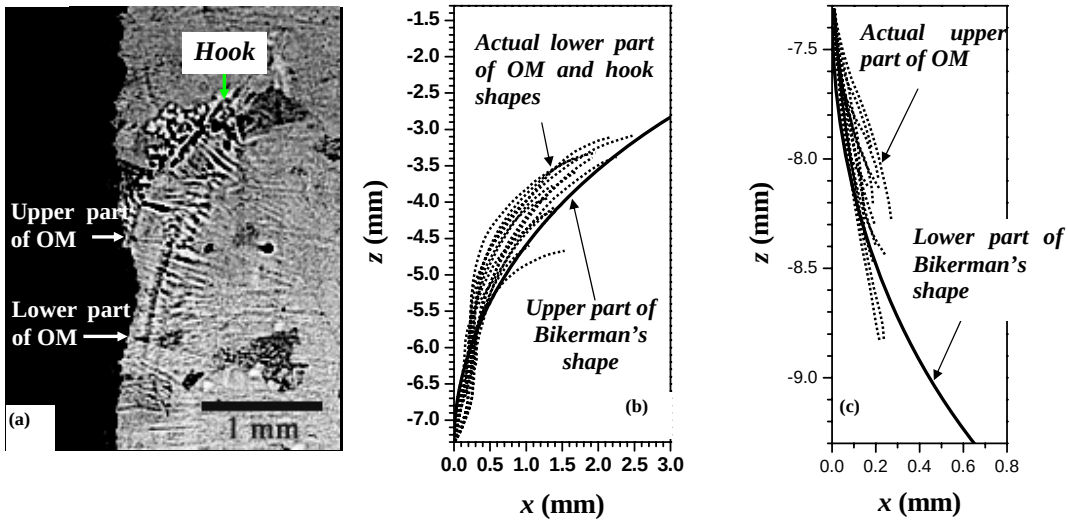
$$x_0 = a - \frac{a}{\sqrt{2}} \ln\left(\sqrt{2} + 1\right)$$

$$a = \sqrt{\frac{2 \cdot \Delta\gamma}{\Delta\rho \cdot g}}$$



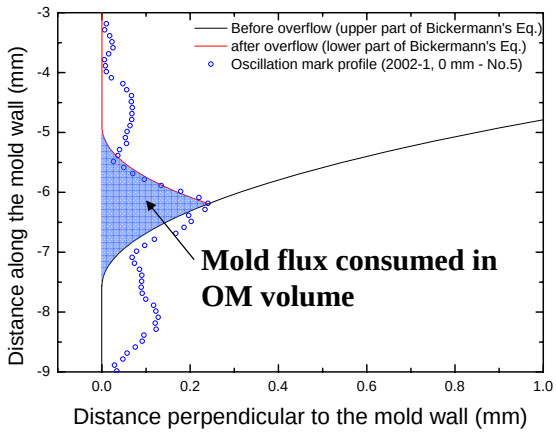
x = distance perpendicular to the mold wall in m
Z = distance along the mold wall in m
$\Delta\gamma$= surface tension between liquid steel and liquid flux) in N m^{-1}
$\Delta\rho$= density difference between liquid steel and liquid slag
g = gravitational acceleration = 9.81 m s^{-2}

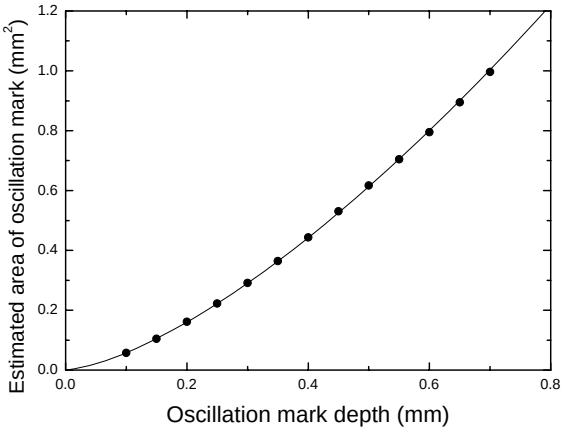
Comparison of equilibrium meniscus shapes with actual OM and hook shapes



Oscillation mark shape: use Bikerman Eq. separately to predict shape of lower and upper surfaces of OM

Model of OM shape from Bikerman Eq.





Estimated area of oscillation mark = 1.692 * (Oscillation mark depth)$^{1.465}$

$$Q_{OM} = \rho_{slag} \times A_{OM} \times \frac{f}{v_s} \times \frac{1}{1000}$$

New Model for Flux Consumption

$$Q_{\text{area}} = Q_{\text{OM}} + Q_{\text{lub}} + \underset{\text{ignore}}{\cancel{Q_{Solid\ flux\ moving}}} + \underset{\text{ignore}}{\cancel{Q_{gravity}}}$$

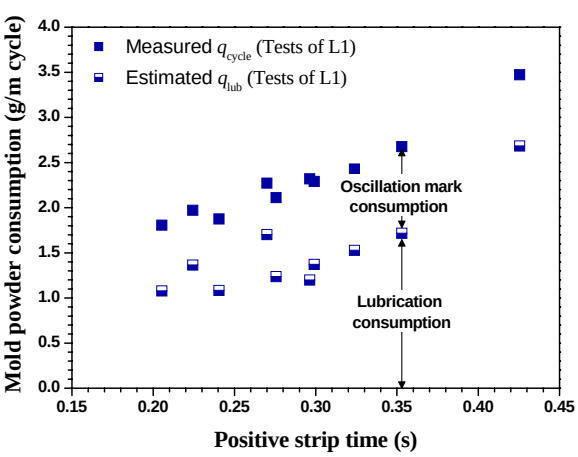
$$Q_{\text{area}} = \frac{Q_{cons}}{V_C \times (2W + 2N)}$$

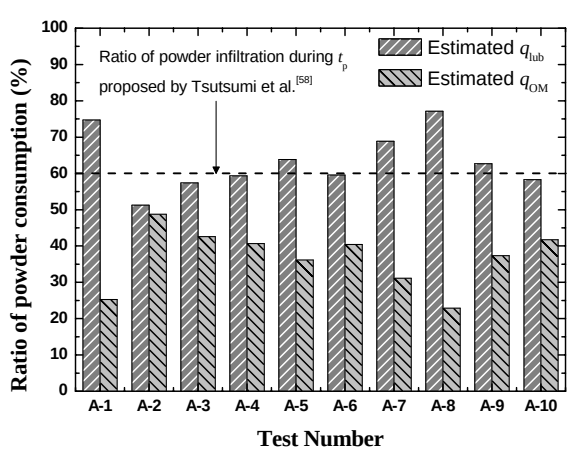
$$q_{\text{OM}} = 2.5 \times 10^{-2} \times \rho_{\text{slag}} \times k^{1.43} \times \left(\sqrt{\frac{2 \cdot \Delta\gamma}{\Delta\rho \cdot g}} \right)^{0.556} \times t_{\text{n}}^{\ 0.389} \times v_{\text{s}}^{\ -1.49}$$

$$q_{\text{lub}} = 5.07 \times e^{3.59 \times t_{\text{p}}}$$

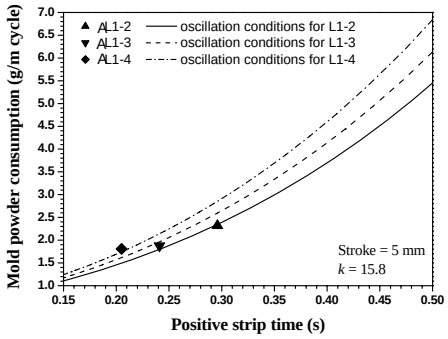
Q_{area}: Powder consumption per unit strand area (kg m^{-2})
Q_{cons}: Weight of the bags consumed per one minute (kg min^{-1})
q_{OM}: Oscillation mark consumption per unit length in one cycle of oscillation (g m^{-1} cycle^{-1})
q_{lub}: Lubrication consumption per unit length in one cycle of oscillation (g m^{-1} cycle^{-1})
t_{n}: Negative strip time (s)
t_{p}: Positive strip time (s)
v_{s}: Casting speed (mm s^{-1});
V_C: Casting speed (m min-1)
k : Coefficient for oscillation mark depth depending on mold powder (-)
N: Slab thickness (m)
W: Slab width (m)
$\Delta\gamma$: Difference of surface tension between liquid steel and liquid slag (N m^{-1})
ρ_{slag}: Density of liquid slag (kg m^{-3})
$\Delta\rho$: Difference of density between liquid steel and liquid slag (kg m^{-3})

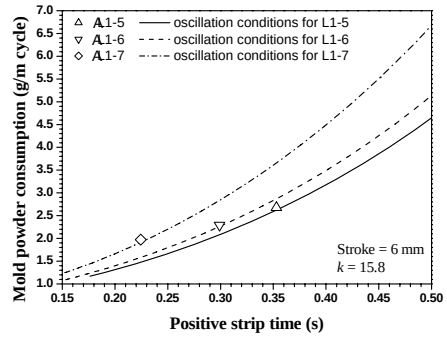
Comparison of consumption amount and ratio of lubrication and oscillation mark

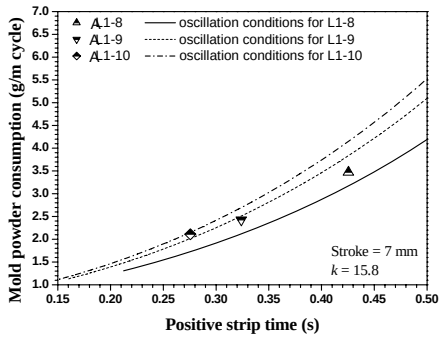




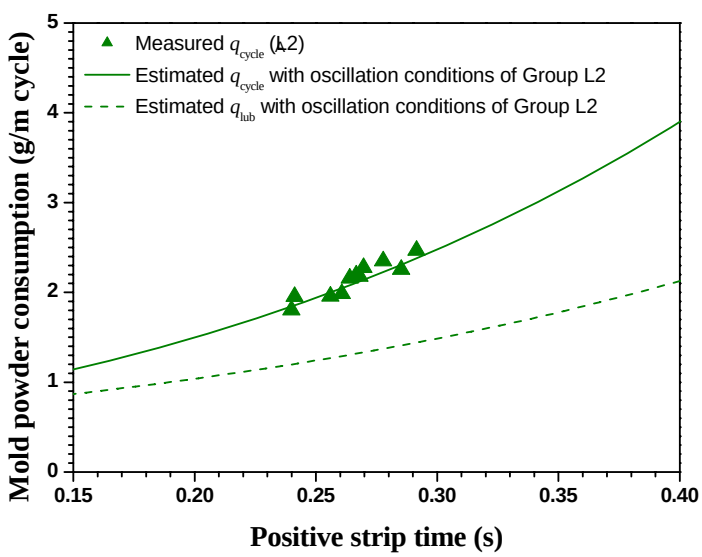
Validation of estimated powder consumption per cycle (L1 trials)



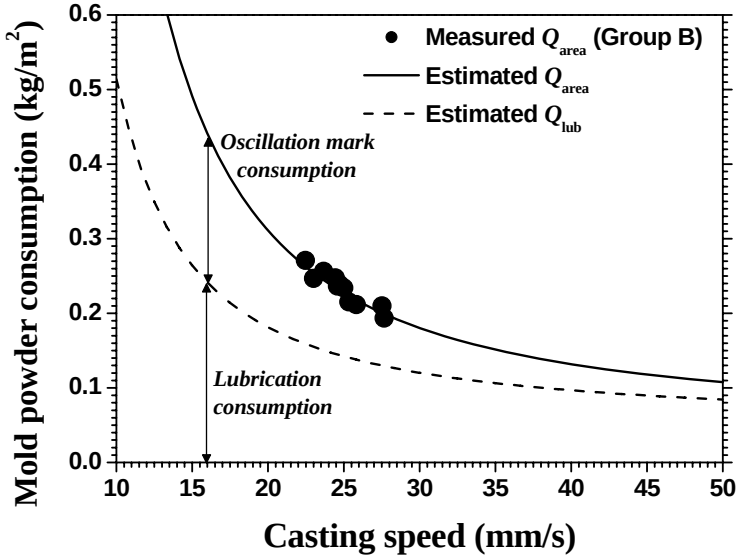




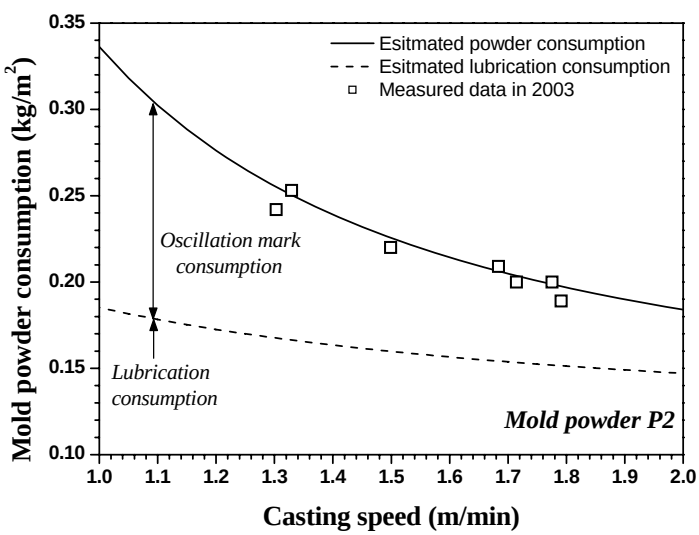
Validation of new powder consumption model with measurements (L2 trials)



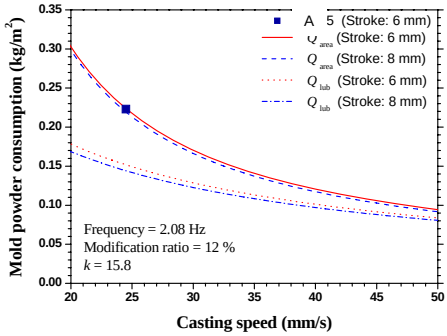
Estimated mold powder consumption (Q_{area}) and lubrication consumption (Q_{lub})

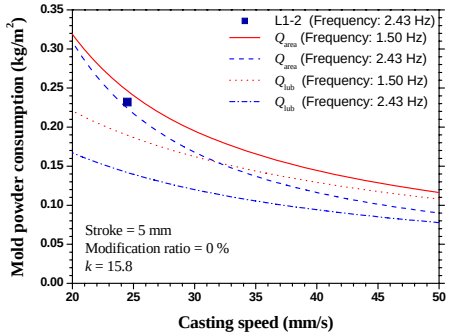


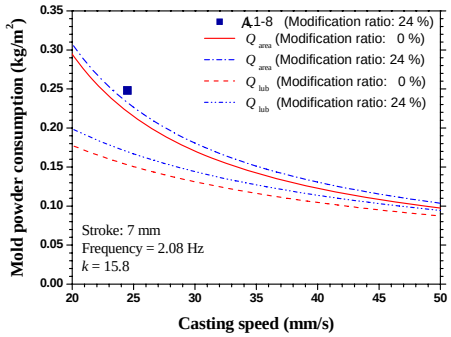
Powder consumption predictions (mold powder P2)



Influence of oscillation parameters on mold powder consumption







Conclusions

- Controlled mold trials and models used to develop:
  - New equation to predict mold powder consumption
  - New equation to predict OM depth (matches measurements and previous trends)
- Oscillation marks account for most of consumption at lower casting speed
- Model matches previous trends:
  Powder consumption increases with:
  - Lower casting speed
  - Decreasing oscillation frequency
  - Increasing negative or positive strip time
  - Increasing modification ratio
  - Stroke (negligible effect)