ANNUAL REPORT 2005

Meeting date: June 1, 2005

Mold Powder Consumption Rate, Oscillation Mark Profiles and Lubrication Prediction

Ho-Jung Shin
(Visiting Scholar from POSTECH)
Brian G. Thomas

Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

Acknowledgements

- Continuous Casting Consortium at UIUC
  (Nucor, Postech, LWB Refractories, Accumold, Algoma, Corus, Labein, Mittal Riverdale)
- POSCO
- Korea Science and Engineering Foundation
- Professor Brian G. Thomas
- Professor Seon-Hyo Kim
- Dr. Joydeep Sengupta, UIUC
- Mr. Claudio Ojeda, UIUC
- Mr. Go-Gi Lee, POSTECH

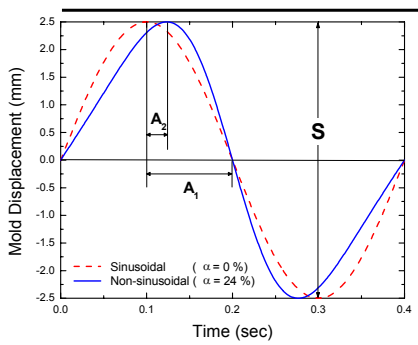
Requirements of mold powder

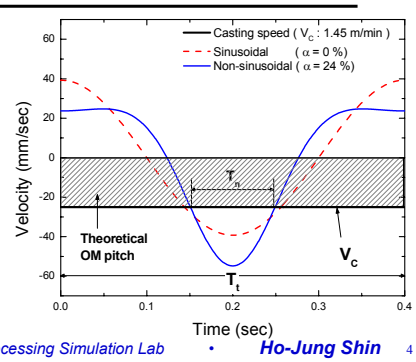
- Reducing the friction between the strand and the mold wall for **prevention of break-out**
- Controlling **the heat transfer** between the solidifying shell and the mold
- Promoting absorption of inclusions rising to the steel surface
- Providing thermal insulation for the top surface of the molten steel pool
- Protecting the molten steel against oxidation

Mold oscillation parameters

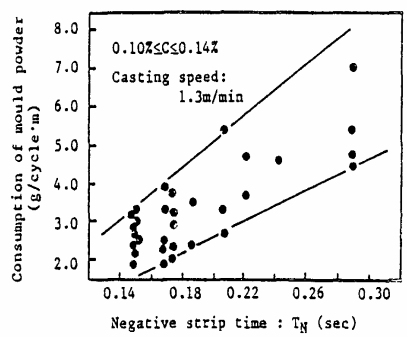
S : Stroke (mm)
F : Frequency (cycles / minute)
α : Modification ratio for non-sinusoidal mode (%) = (A_2 / A_1) × 100

V_C : Casting speed (m/minute)
T_t: Total period of oscillation cycle (second / cycle) = 60 / F
T_n: Negative strip time (sec) = $60/\pi F \times \arccos(1000 \times V_C / \pi SF)$, Equation for $\alpha = 0$
T_P: Positive strip time (sec) = $T_t - T_n$
Theoretical oscillation mark pitch (mm) = 1000×Vc / F



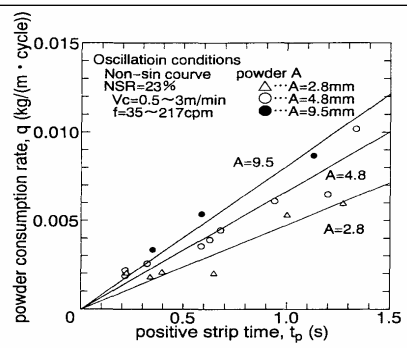


Mold powder consumption rate with mold oscillation conditions



< Relationship with negative strip time >

K. Hamagami *et al.*, Steelmaking conference proceedings, 1982



< Relationship with positive strip time >

K. Tsutsumi *et al.*, Testu-To-Hagane, 1998

(g / m · cycle): powder consumption rate for a cycle of mold oscillation

Powder consumption rate related with t_P

Authors	Experimental place	Oscillation conditions	Oscillation parameters related to powder penetration
K. Kawakami *et al.* (1981)	Conventional slab caster	Sinusoidal oscillation mode	$Q = (k_1 \cdot t_P \cdot f) / V_C$
M. Suzuki *et al.* (1991)	Conventional slab caster designed and constructed for hot direct rolling	Sinusoidal & Non-sinusoidal oscillation mode	$q_P = (k_2 \cdot t_P)$
O.-D. Kwon *et al.* (1991)	Conventional slab caster	Sinusoidal oscillation mode	$q_P = (k_3 \cdot t_P)$
K. Tsutsumi *et al.* (1998)	Laboratory scale experiment	Sinusoidal & Non-sinusoidal oscillation mode	$q_P = (k_4 \cdot t_P)$
T. Araki and M. Ikeda (2000)	Conventional slab caster and a pilot slab caster	Sinusoidal & Non-sinusoidal oscillation mode	$Q = 0.047 + 0.202 * (R_{NA}^{0.3} * t_P^{0.5})$

Q : Powder consumption rate per unit area (kg/m²), q_P: Powder consumption rate per one cycle (g/m · cyle), k, k_1, k_2, k_3, k_4 : constant (-), t_P : positive strip time (sec), f : oscillation frequency (cpm), V_C : casting speed (m/min)

Mold powder consumption rate correlates with positive strip time

Powder consumption rate related with t_n

Experiments related to the direct observation of initial stage solidification in continuous casting

Authors	Used materials	Oscillation conditions	Observations
K. Tsutsumi *et al.* (2000)	Metal: Sn-5% Pb alloy Quasi-powder : Stearic acid	Sinusoidal & Non-sinusoidal	- Most shapes of oscillation mark were observed as the overflow type - Mold powder flowed into the aperture between mold and solidified shell during t_p and t_n
Y. Itoh *et al.* (2000)	Metal: Cu alloy Powder : CaO-SiO_2-Na_2O-B_2O_3 system	Sinusoidal & Non-sinusoidal	- The molten slag inflow from the meniscus into the flux channel was clearly visualized and observed mainly during the period of the t_n

Negative strip time (t_n) also correlated with mold powder consumption rate

Current study: measure and predict powder consumption and OM profiles

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

Mold powder composition and properties

Chemical composition (wt. %)	Basicity	SiO_2	CaO	MgO	Al_2O_3	TiO_2	Fe_2O_3	MnO_2	P_2O_5	Na_2O	K_2O	F	B_2O_3	Li_2O
	1.10	38.6	42.3	0.9	6.3	0.19	0.36	0.03	0.03	3.6	0.1	7.1	0	0.4

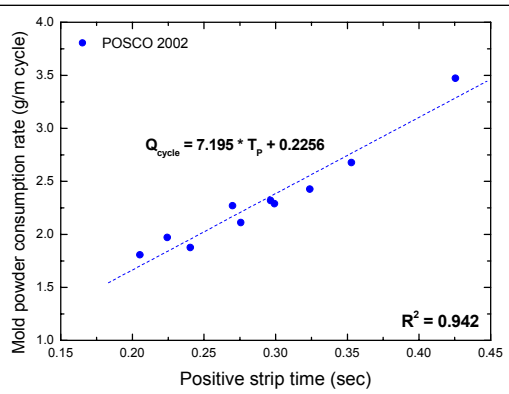
Properties	Solidif. Temperature (°C)	Softening Temperature (°C)	Melting Temperature (°C)	Viscosity at 1300 °C (Poise)
	1149	1170	1180	3.21

Test Conditions

- keep casting conditions constant for ~4-6 250-tonne heats (~4 hours) per test
- Slab thickness: 230 mm; Slab width: 1300 mm; Casting speed: 1.45 m/min

	Stroke (mm)	**Frequency (cpm)**	**Modification ratio for non-sinusoidal mode (%)**	Negative strip time (sec)	Positive strip time (sec)	Measured OM depth (mm)	Consumption rate of mold flux (kg/m^2)
Test 1	6.4	158	24	0.107	0.270	0.246	0.247
Test 2	5.0	145	0	0.115	0.296	0.393	0.232
Test 3	5.0	174	12	0.100	0.241	0.309	0.225
Test 4	5.0	203	24	0.081	0.205	0.292	0.253
Test 5	6.0	121	12	0.127	0.353	0.353	0.223
Test 6	6.0	145	24	0.110	0.299	0.343	0.229
Test 7	6.0	169	0	0.121	0.224	0.258	0.230
Test 8	7.0	104	24	0.139	0.426	0.308	0.248
Test 9	7.0	124	0	0.154	0.324	0.338	0.208
Test 10	7.0	145	12	0.126	0.276	0.331	0.211

Powder consumption rate per cycle
(reported in AISTech 2004)

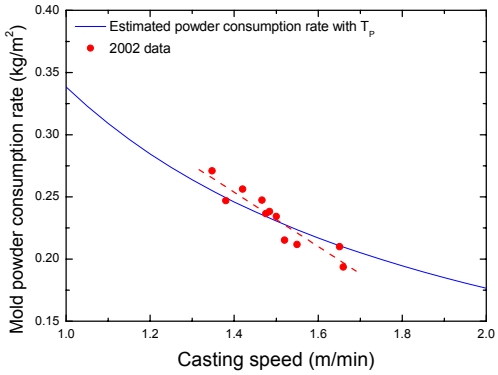


H.-J Shin & B. G. Thomas, AISTech 2004, Nashville

- Test period
  : Apr., 2002 ~ Nov., 2002
- Test conditions
  Casting speed : 1.46~ 1.52 m/min
  Oscillation conditions :
  independent from casting speed

Positive strip time ↑ → Mold powder consumption rate per a cycle ↑

Validation with measurements taken at different casting speeds



- Test conditions (2002 data)

Frequency (cpm) = A_F* Vc (m/min) + B_F
Stroke (mm) = A_S * Vc (m/min) + B_S
Modification ratio = 24 %

With changing casting speed, measured consumption rate is slightly tilted

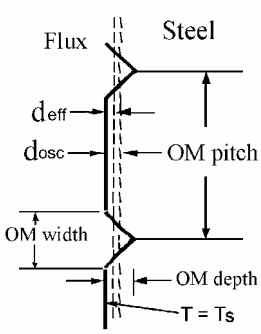
→ Other effects (t_n) may correlate with powder consumption

Model of powder inflow

Powder consumption has two components [Ref.]:

O) Consumption into the oscillation mark (Q_O)

L) "Lubrication consumption" molten flux layer between mold and cast strand (Q_L)



$$Q_T = Q_O + Q_L \text{ (kg/m}^2\text{)}$$

$$Q_O = (\rho \times d_{mark} \times L_{mark} \times f) / (2 \times V_C) \text{ (kg/m}^2\text{)}$$

(ρ : Density of molten flux (kg/m^3)

d_{mark} : Depth of oscillation mark (m)

L_{mark} : Length (width) of oscillation mark (m)

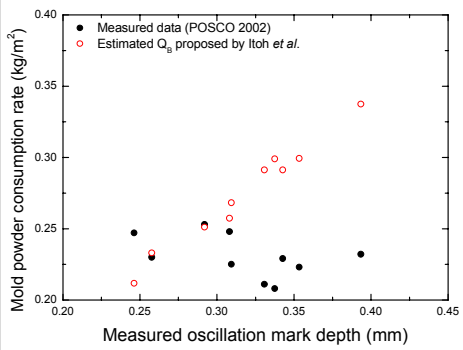
f: Frequency of mold oscillation (1/sec)

V_C : Casting speed (m/sec))

< Model treatment of oscillation marks>

Reference) B. Ho, MS Thesis, UIUC, 1992; Y. Meng & B. G. Thomas, Metall. & Materials Trans. B, 2003

Comparison with measured data of this work



Proposed OM area [ref]:

$d_{mark} = 2 \times t_n$

$L_{mark} = (t_n + t_p / 2) \times V_C$ (m)

If calculating with $(d_{mark})_{measured}$ and L_{mark} most cases: $Q_T < Q_O$

→ $Q_L < 0$

→ **Solidifying shell will adhere to mold**

Area of oscillation mark may be considered too large than actual value

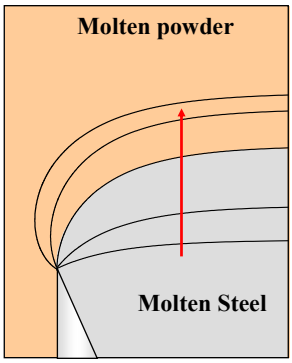
Need to estimate the area of oscillation mark with different way

Reference) Y. Itoh, et al. in Molten Slags and fluxes 2000, Stockholm, KTH

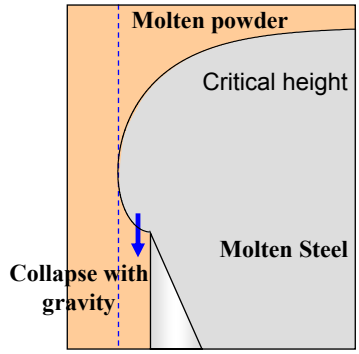
New approach to estimate powder consumption rate

1. Estimate oscillation mark area with Bikerman's equation
2. Validation of Bikerman's equation
   - Shape of hooks
   - Shape of oscillation mark
3. Estimate lubrication consumption rate with volume of oscillation mark
4. Validation of a new estimation of powder consumption rate with results measured under different casting speed

Concept of Bikerman's Eq. (with a solid shell as support)



< Upper part of Bikerman's Eq.>



< Whole part of Bikerman's Eq.>

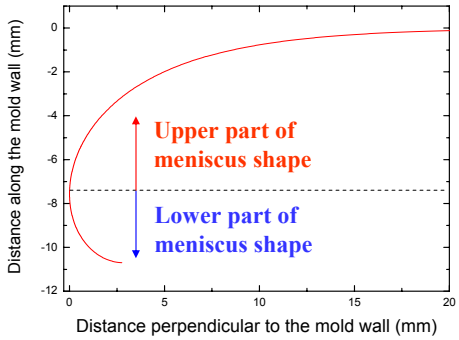
Bikerman's equation is still valid for some "overhang" of liquid

Overflow occurs when exceeding critical liquid level that surface tension can support

Meniscus shape using Bikerman's Eq.

Conditions of Bikerman Eq. for this work

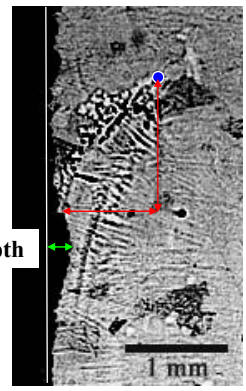
Steel density (kg/m^3)	7200
Molten powder density (kg/m3)	2680
Surface tension of steel (N/m)	1.7
Surface tension of molten powder (N/m)	0.432

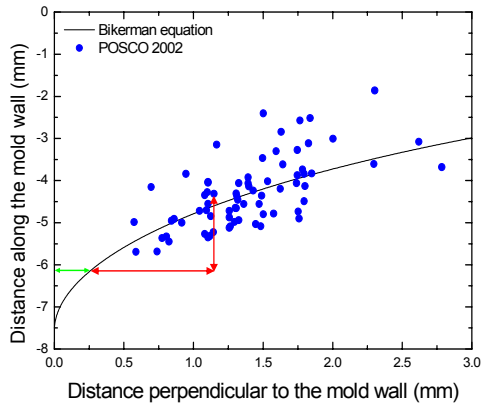


Upper part of meniscus shape : using for estimation of lower part of OM

Lower part of meniscus shape : using for estimation of upper part of OM

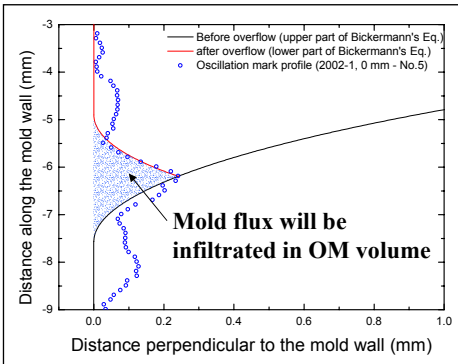
Comparison between hook shape and upper part of Bikerman' Eq.

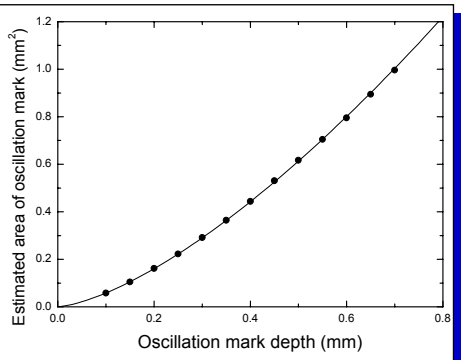




Hook shapes of this work match with upper shape of Bikerman' Eq.

Comparison between OM shape and lower part of Bikerman' Eq.

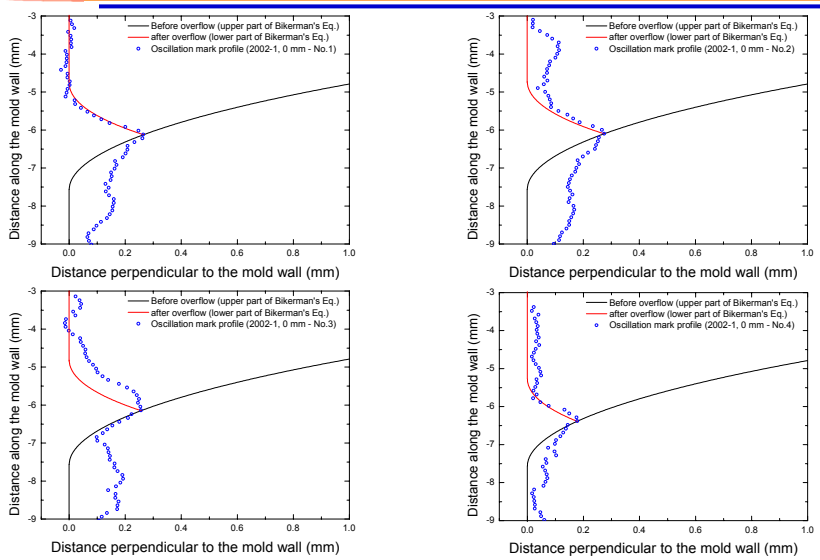




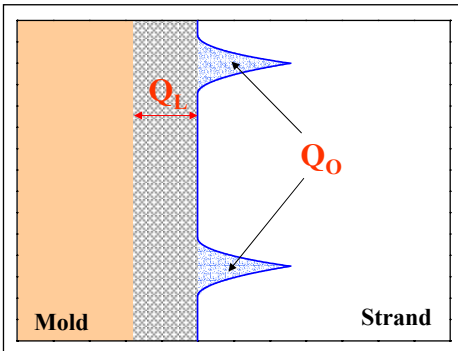
Estimated area of oscillation mark = 1.692 * (Oscillation mark depth)$^{1.465}$

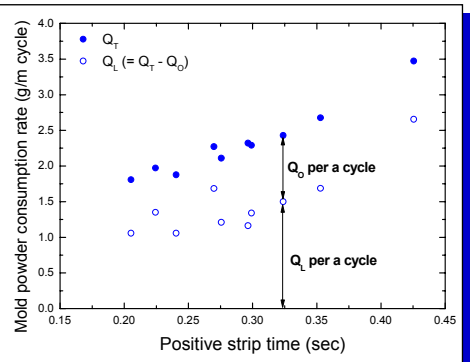
Oscillation mark shapes of this work match with Bikerman' Eq.

Examples of comparison between OM shape and Bikerman' Eq.



Concepts of powder consumption





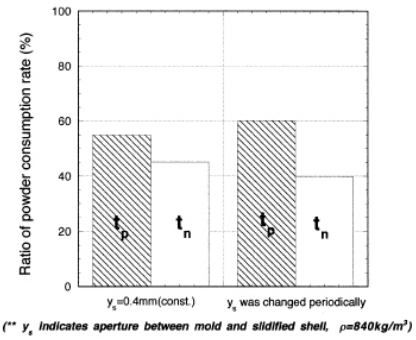
Q_T : Total amount of mold powder used in a cast

$Q_T = Q_L + Q_O$

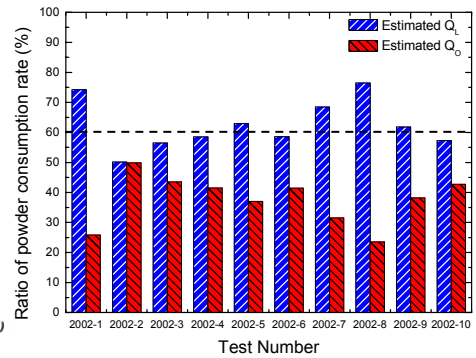
Q_L : Lubrication consumption rate between mold and solidifying shell

Q_O : Amount of mold powder infiltrated to the volume of oscillation mark

Comparison of lubrication and oscillation mark consumption rates



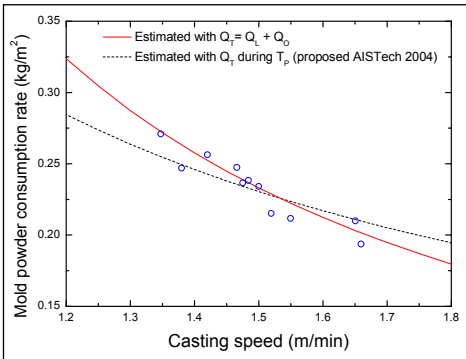
< Comparison of mold powder consumption rate in t_p and t_n periods >
K. Tsutsumi et al., ISIJ International, 2000

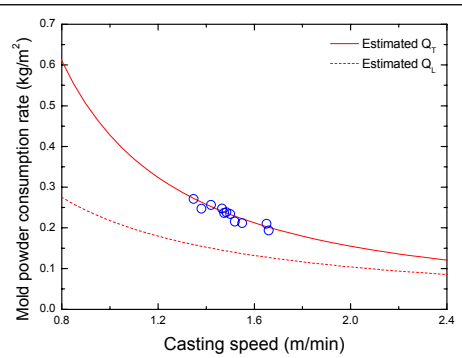


< Comparison of lubrication rate and oscillation mark consumption in this work >

Assuming the estimated Q_L in this work to penetrate during t_P

Estimated powder consumption rate





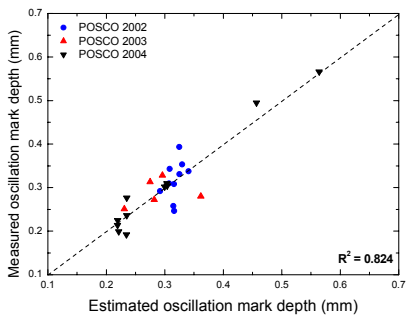
Newly proposed powder consumption rate shows;

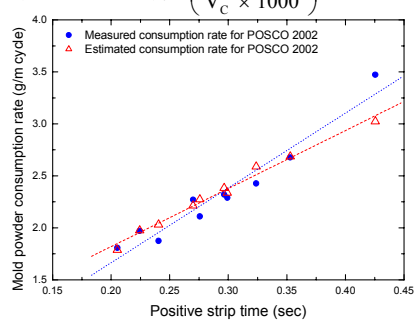
- Powder consumption rate decreases with increasing casting speed
- Flux inside the oscillation marks becomes the majority of flux consumption at lower speed

Equation of mold powder consumption rate

$$Q_T = Q_O + Q_L$$

$$= \left\{\left(1.692 \times \text{OM depth}^{1.465} \times \rho_{Flux}\right) + \left(5.183 \times t_p^{1.035}\right)\right\} \times \left(\frac{F}{V_C \times 1000}\right)$$





$$\text{Estimated OM Depth} = 0.4511 \times \mu_{1300^\circ C}^{0.6515} \times t_n^{0.1391} \times Vc^{-1.208} \times \text{Superheat}^{-0.09126}$$

< Plot with estimated powder consumption rate and oscillation mark depth for POSCO 2002 casting conditions>

ρ_{Flux} : density of liquid mold flux (g/cm^3), t_n : negative strip time (sec), t_p : positive strip time (sec), V_C : casting speed (m/min), F: Oscillation frequency (cpm), Superheat: $T_{Tundish} - T_{Liquidus}$ (°C)

Conclusions

- A new estimation of mold powder consumption rate is proposed with dividing two factor:
  - Consumed amount infiltrated in oscillation mark volume
  - Lubrication consumption rate between the solidifying shell and the mold
- Area of oscillation mark is estimated with Bikerman's Eq. and validated with shapes of hooks and oscillation marks, which are measured with metallurgical analysis
- Powder consumption infiltrated into the oscillation marks becomes major part of flux consumption in slower casting speed
- Proposed mold powder consumption rate for the flux used this work;

$$Q_T = Q_O + Q_L$$

$$= \left\{\left(1.118 \times \mu_{1300^\circ C}^{0.9544} \times t_n^{0.2038} \times V_C^{-1.770} \times (\text{Superheat})^{-0.1337} \times \rho_{Flux}\right) + \left(5.183 \times t_p^{1.035}\right)\right\} \times \left(\frac{F}{V_C \times 1000}\right)$$