Investigation of Oscillation Marks and Hook Formation in ULC Steels using Metallurgical Analysis and Models

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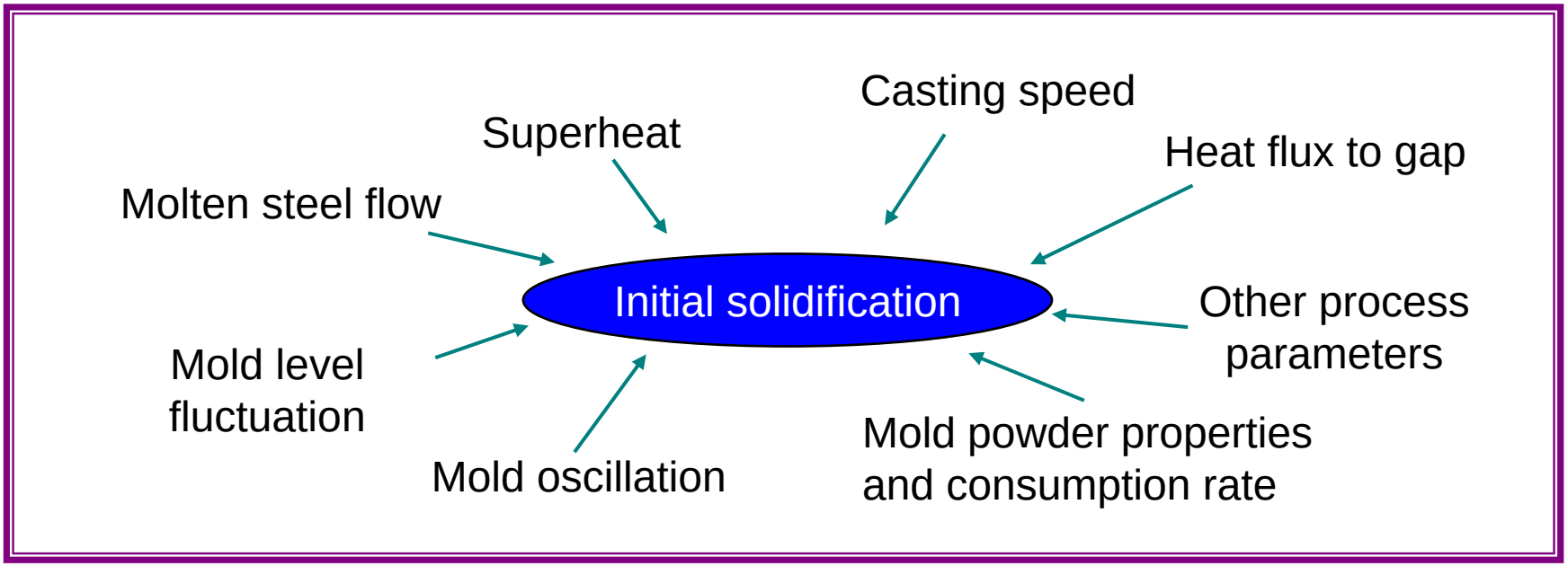
May 10, 2004

Acknowledgement

- Professor Brian G. Thomas
- Professor Seon-Hyo Kim
- Dr. Ya Meng
- Mr. Go-Gi Lee, POSTECH
- Continuous Casting Consortium
- POSCO

Introduction

- Initial solidification during continuous casting of steel slabs greatly affects surface quality of slabs



Most operation parameters have strong interdependencies

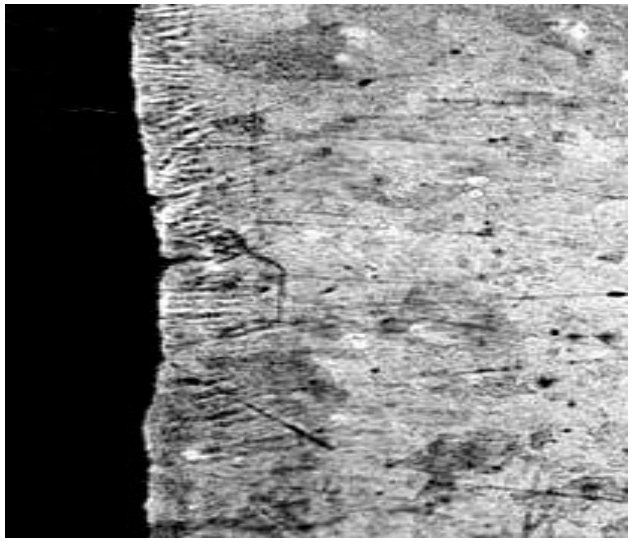
➡ This makes prediction and interpretation of initial solidification phenomena difficult

Importance of Initial Solidification

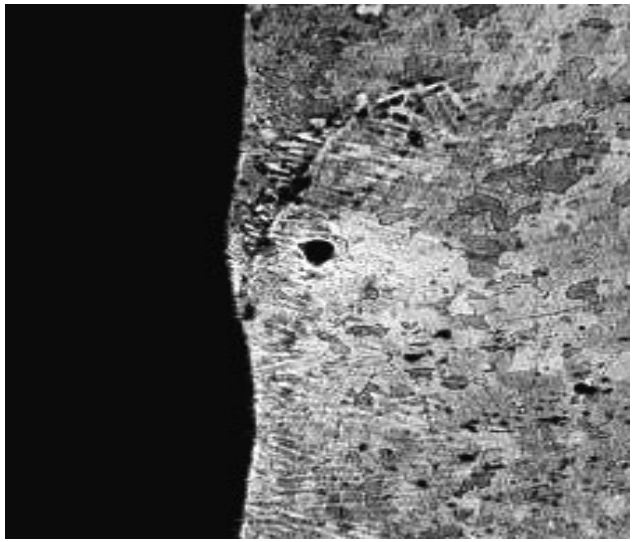
- Initial solidification behavior affects the formation of oscillation marks (OM) and subsurface hooks
- Initial solidification features related to surface quality problems

  - Deep oscillation mark : Transverse crack formation

  - Deep hook : Easy Entrapment of mold flux and inclusion-laden gas bubbles

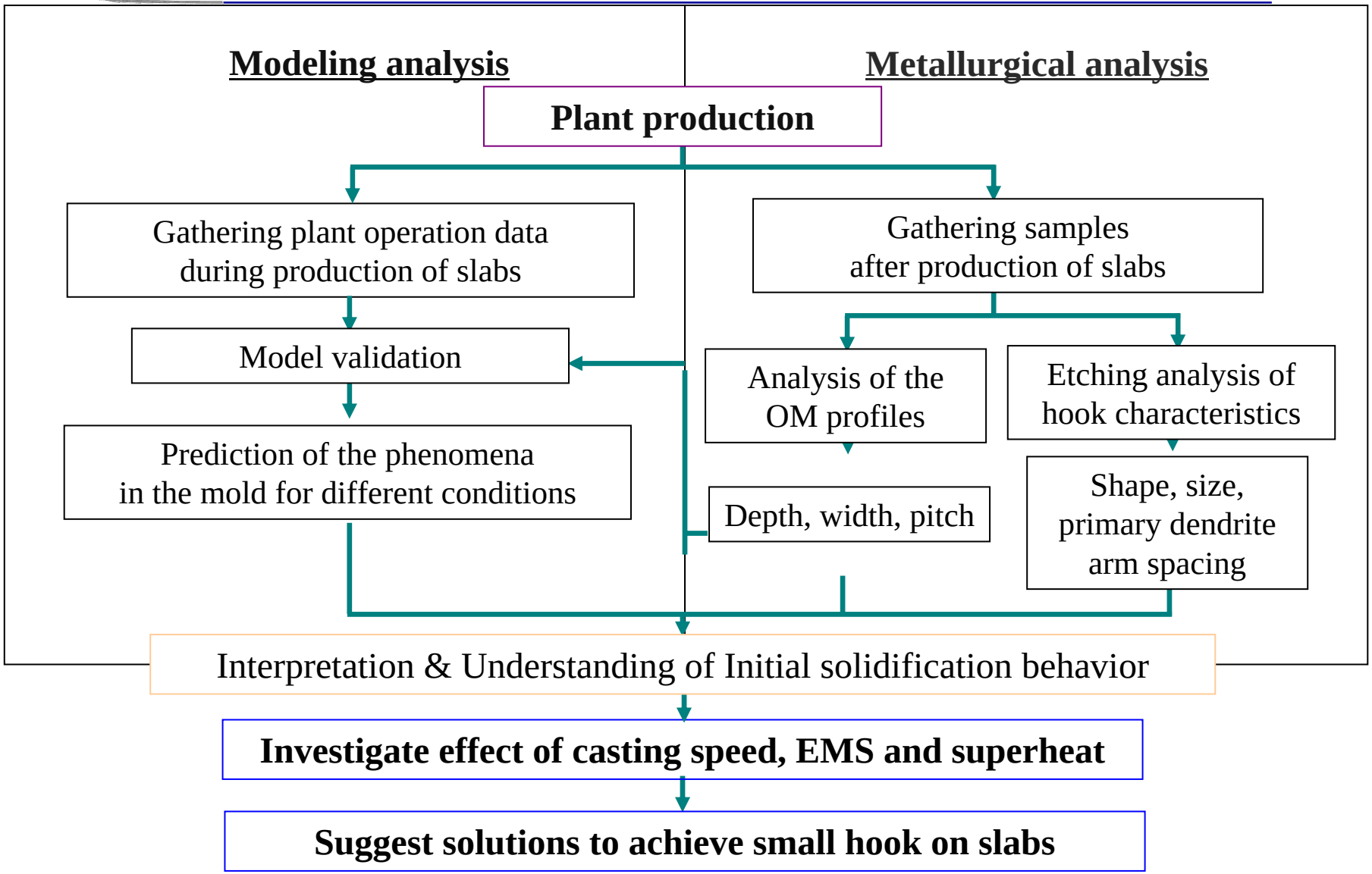


< Transverse Crack at valley of OM>



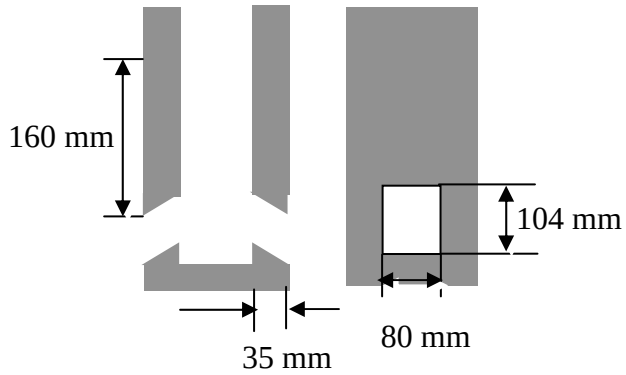
< Bubble captured by hook >

Objectives


Modeling analysis
Metallurgical analysis
Plant production
Gathering plant operation data during production of slabs
Model validation
Prediction of the phenomena in the mold for different conditions
Gathering samples after production of slabs
Analysis of the OM profiles
Etching analysis of hook characteristics
Depth, width, pitch
Shape, size, primary dendrite arm spacing
Interpretation & Understanding of Initial solidification behavior
Investigate effect of casting speed, EMS and superheat
Suggest solutions to achieve small hook on slabs

Test Conditions (2003)

- Steel grade : Ultra low carbon steel (C ≤ 0.005%)
- Slab thickness : 230 mm
- Nozzle submergence depth : ~ 160 mm
- Oscillation asymmetry : 59 %



	Test 1	Test 2	Test 3	Test 4	Test 5
Casting speed (m/min)	1.75	1.42	1.22	1.47	1.47
Pour Temperature (℃)	1560	1564	1564	1571	1571
Electromagnetic current (A)	313	234	0	277	0
Slab width (mm)	1300			1570	
Working mold length (mm)	775	796	790	782	774
Oscillation stroke (mm)	7.5	6.83	6.43	6.93	6.94
Oscillation frequency (mm)	187	155	135	159	160

Mold Powder Properties

Melting Characteristics	Softening, Melting, Flowing point (℃)					
	1,145					
Physical Properties	Density (g/㎖)	Viscosity (poise)				Solid Temp (℃)
	2.7	1400 ℃	1300 ℃	1200 ℃	1100 ℃	1,101
		1.28	2.62	5.85	~ 1000	
	Crystal Temp. (℃)	Crystal Ratio (%)		SF-Tension (d/cm)		Shape
		6.80		48.72		Granule

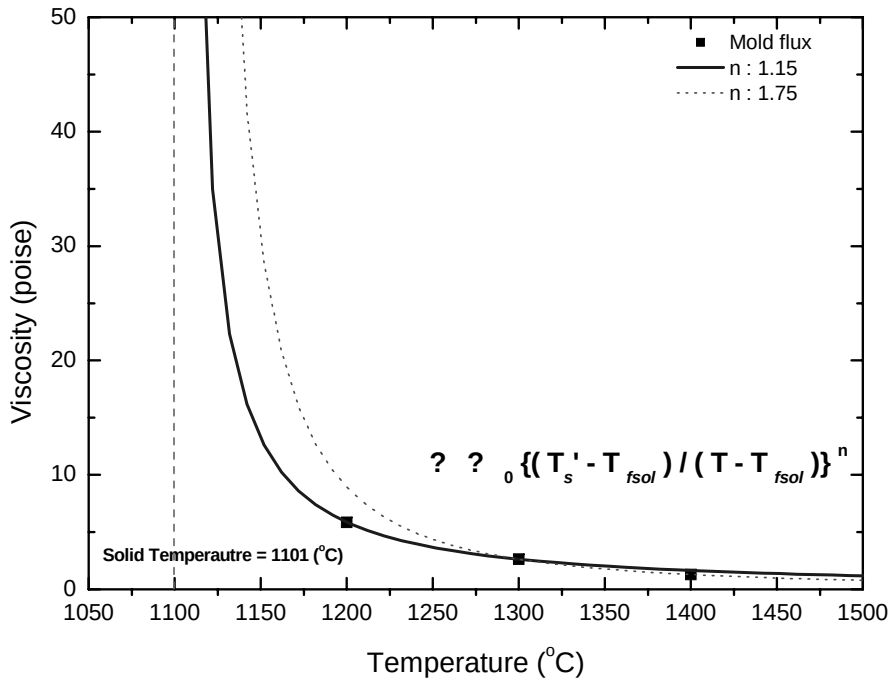
$$\mu = \mu_s \left(\frac{T_S^{'} - T_{fsol}}{T - T_{fsol}} \right)^n$$

μ_s : viscosity at 1300 ℃

$T_S^{'}$: 1300℃

n : Exponent for temperature dependency of viscosity

***n* = 1.15 was chosen for this modeling**



Mold Calibration (Heat Flux Profile)

Differences of cooling water temperature and mean heat flux

	Measured ΔT (℃)	Measured mean heat flux (kw/m^2)	Calculated ΔT (℃)	Calculated mean heat flux (kw/m^2)
Test 1	6.75	1665.9	6.75	1709.4
Test 2	5.78	1428.5	5.78	1422.8
Test 3	5.72	1413.1	5.71	1417.2
Test 4	7.08	1429.8	7.08	1450.6
Test 5	7.49	1515.9	7.46	1544.8

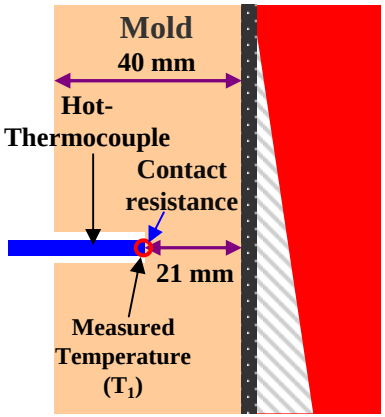
Distance of thermocouple location below meniscus

	Test 1	Test 2	Test 3	Test 4	Test 5
1st (mm)	173.8	160.1	149.3	162.6	159.7
2nd (mm)	126.2	128.9	113.8	133.2	129.0
3rd (mm)	115.7	109.7	102.6	113.3	112.0

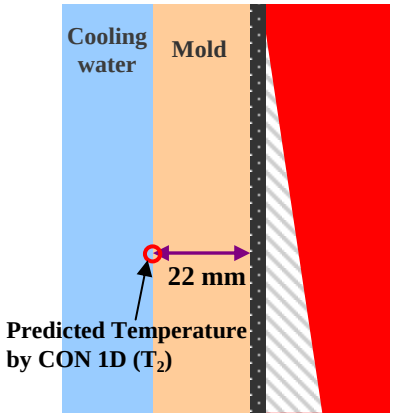
Mean temperature from hot thermocouple

	Test 1	Test 2	Test 3	Test 4	Test 5
1st (℃)	173.8	160.1	149.3	162.6	159.7
2nd (℃)	126.2	128.9	113.8	133.2	129.0
3rd (℃)	115.7	109.7	102.6	113.3	112.0

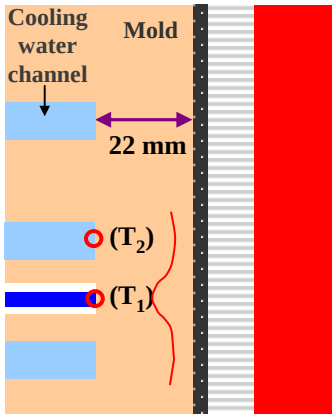
Calibration with measured temperatures of thermocouples



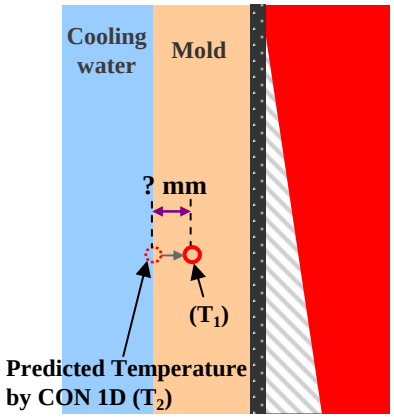
< Fig 1. Thermocouple location>



< Fig 2. Predicted temperature by CON 1D >

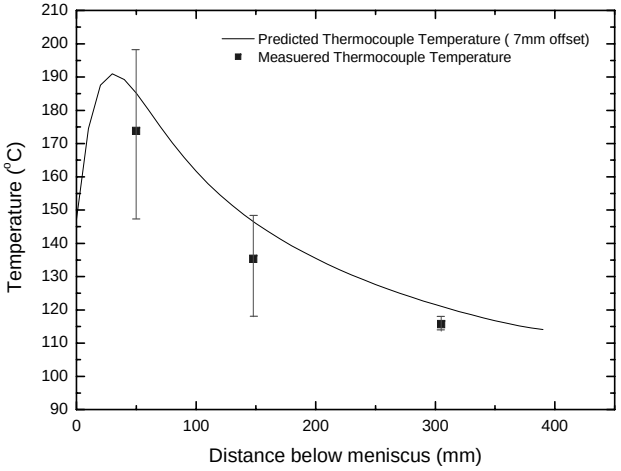


< Fig 3. Temperature gradient between water channel and thermocouple >

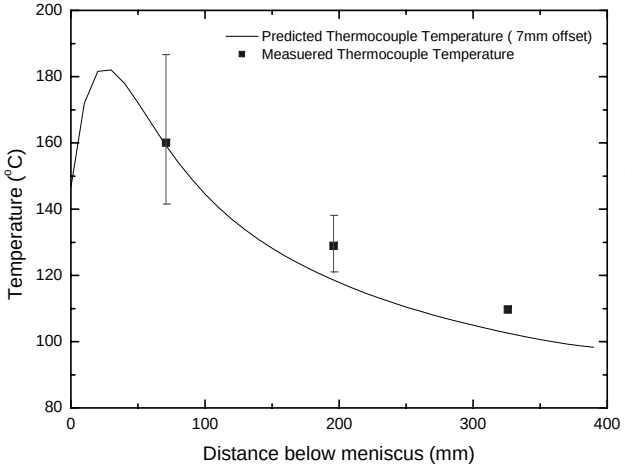


< Fig 4. Concept of Offset>

Matching model with mold temperature



< Test 1 >



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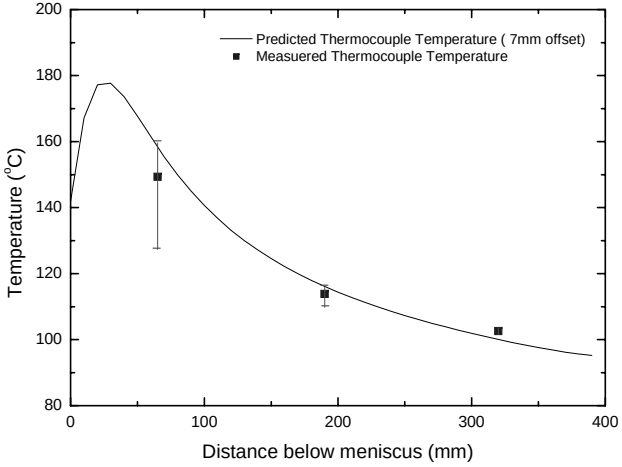

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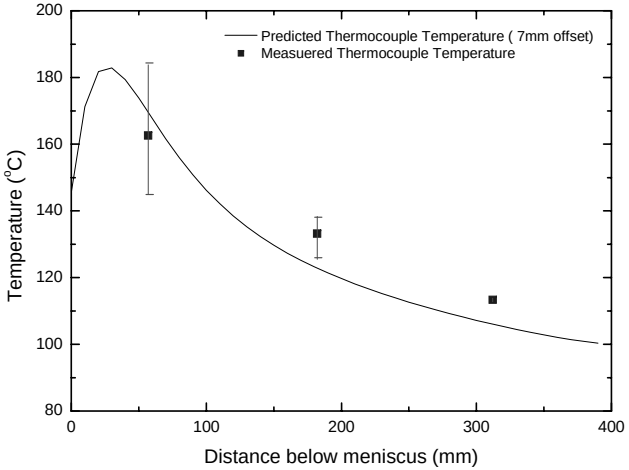

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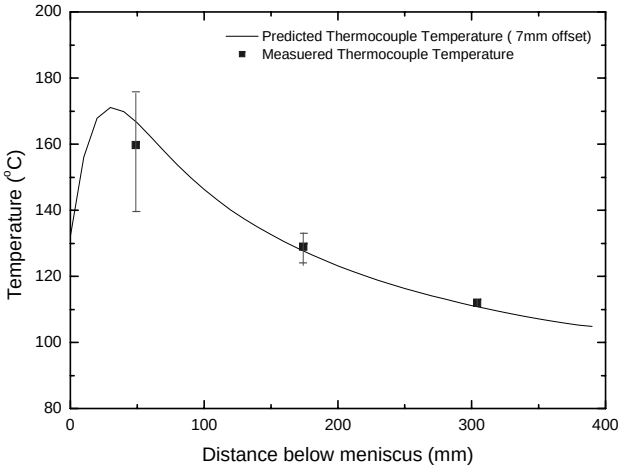
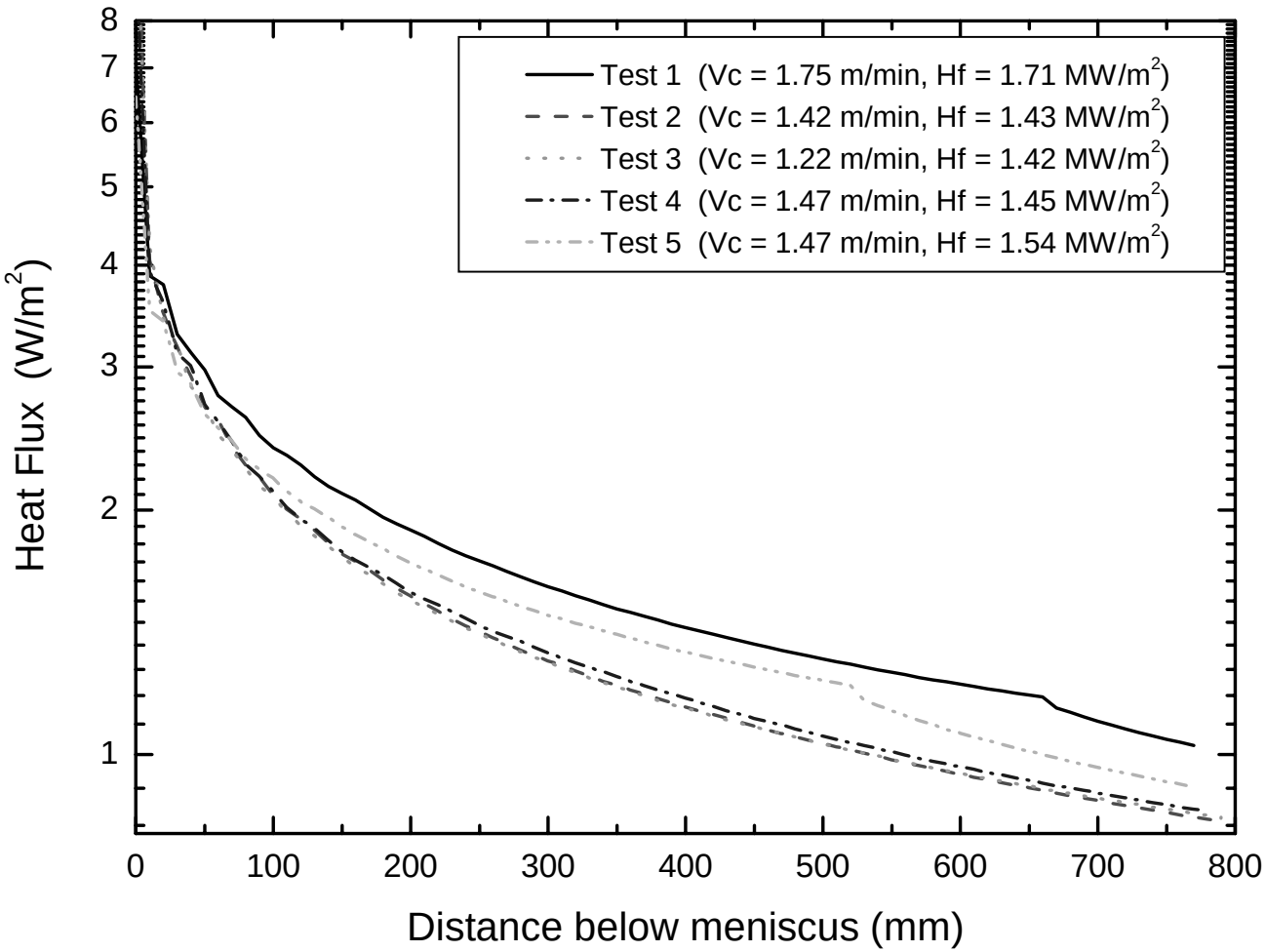
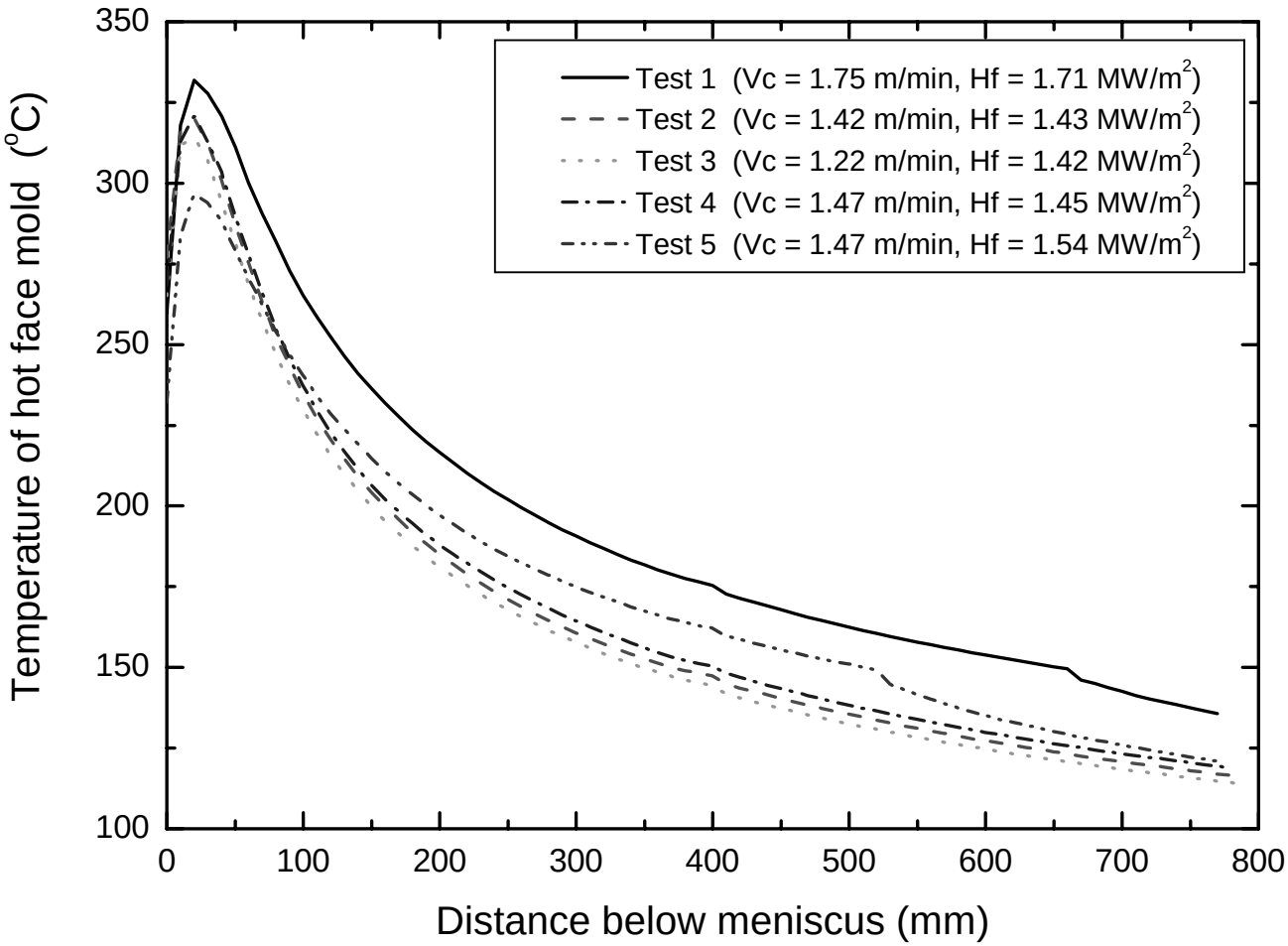


< Test 5 >

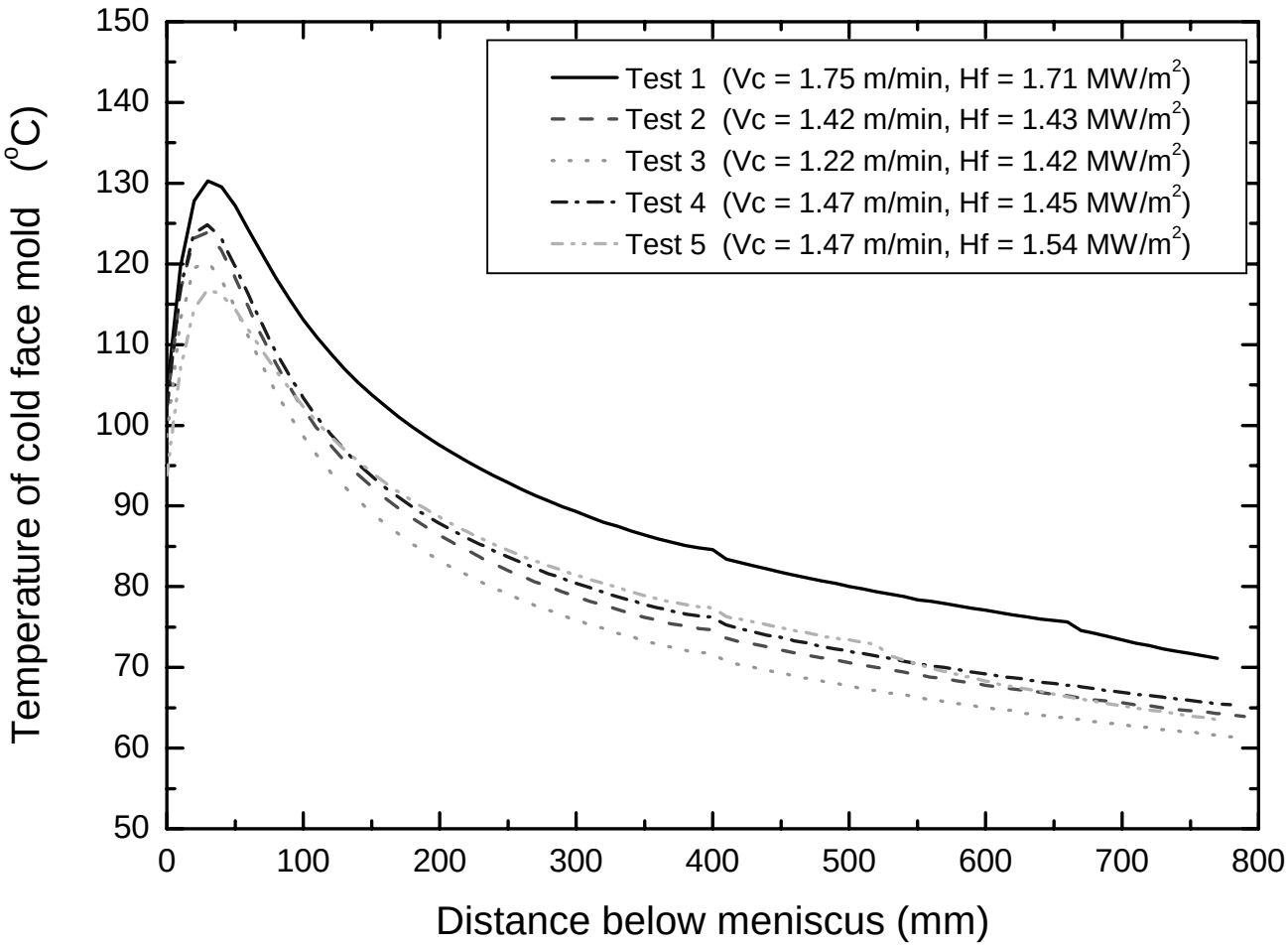
Heat Flux Comparison



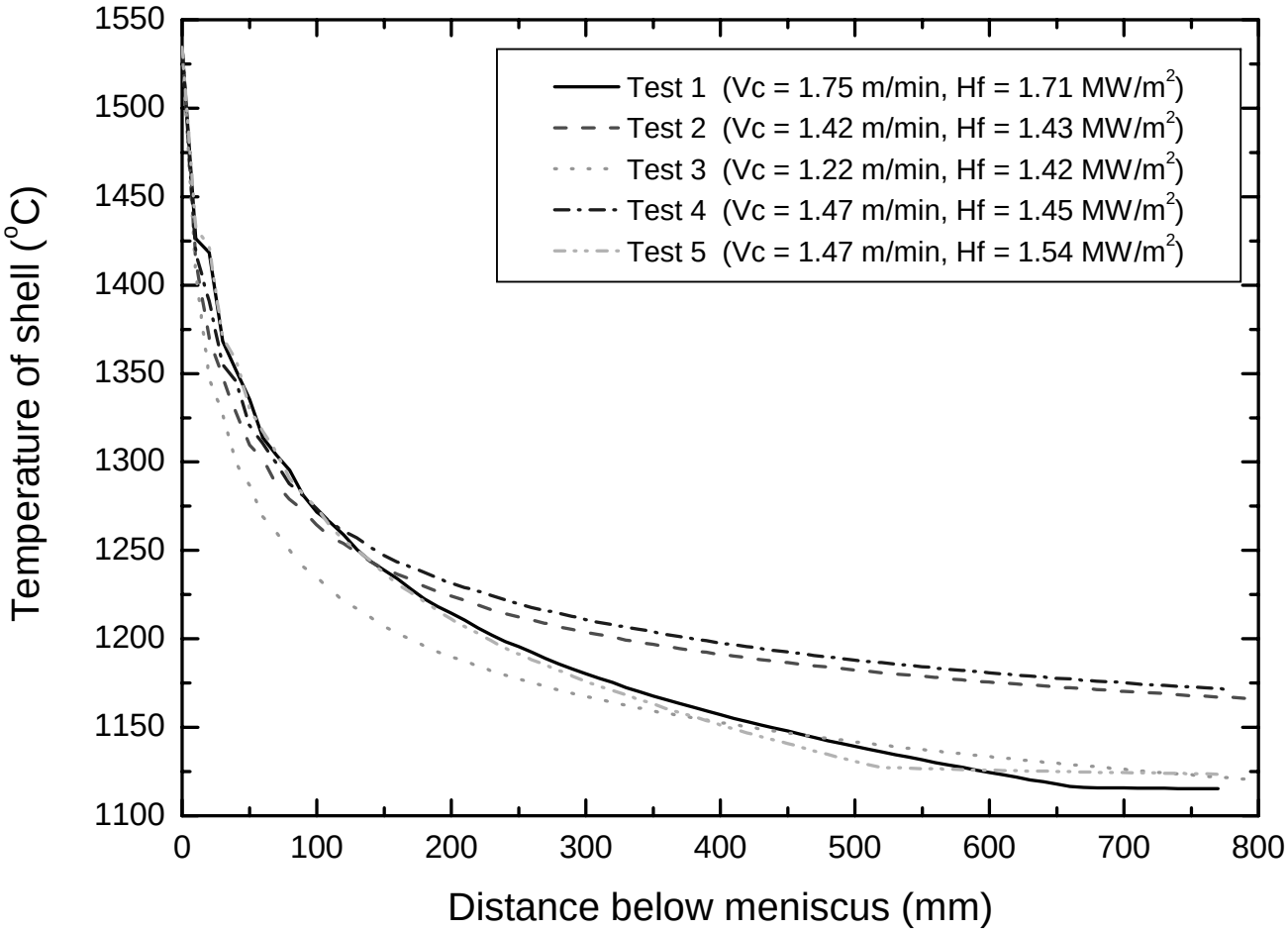
Mold Temperature Comparison



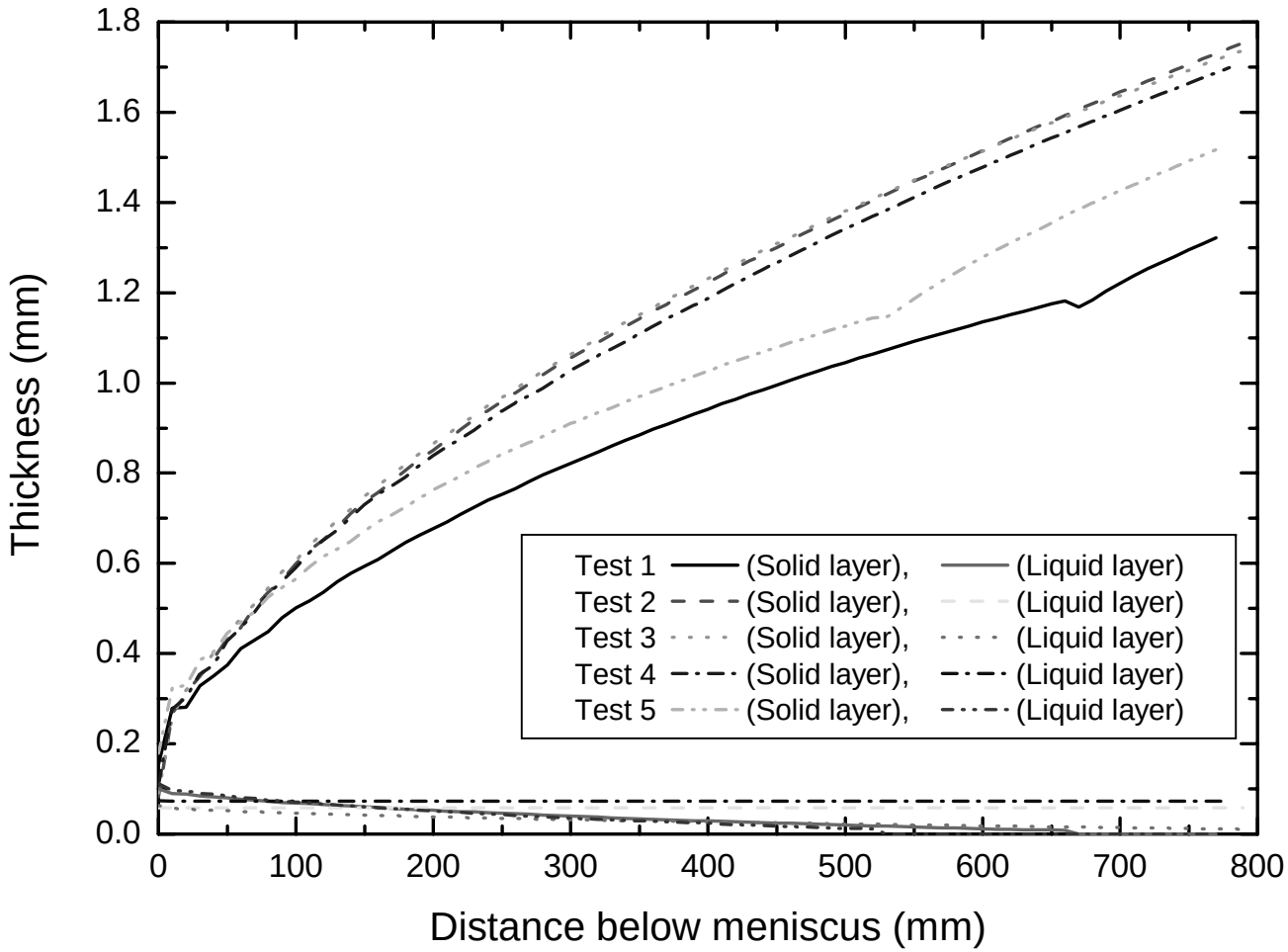
Mold Temperature Comparison



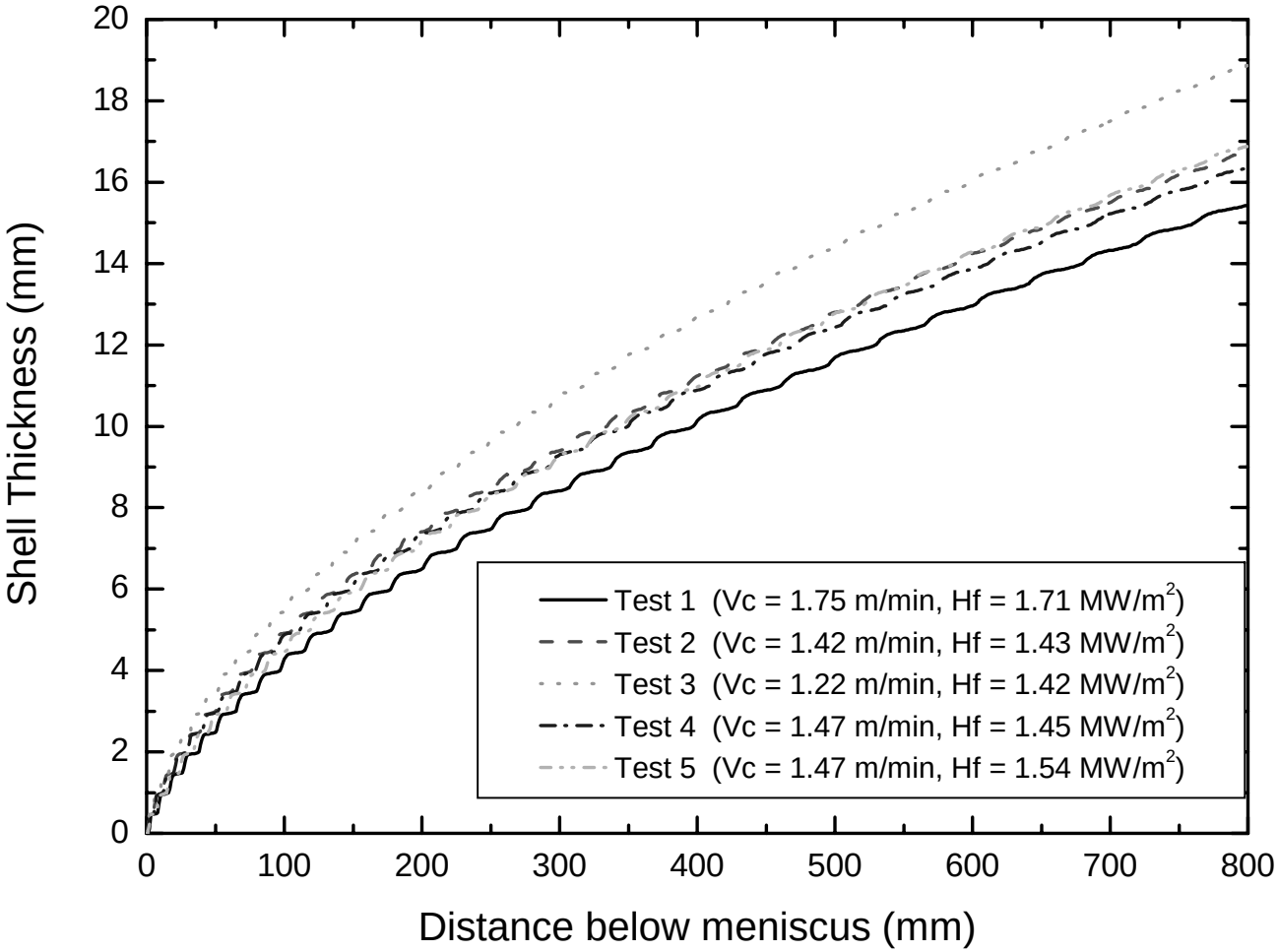
Shell Temperature Comparison



Mold Powder Layer Thickness in Gap

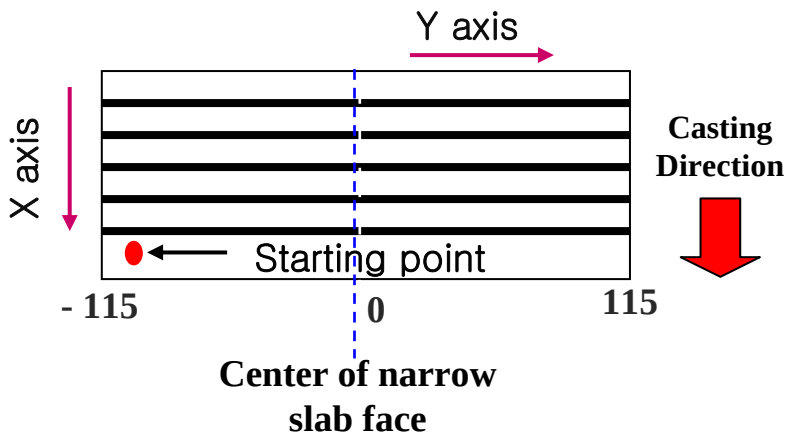


Shell Thickness Comparison



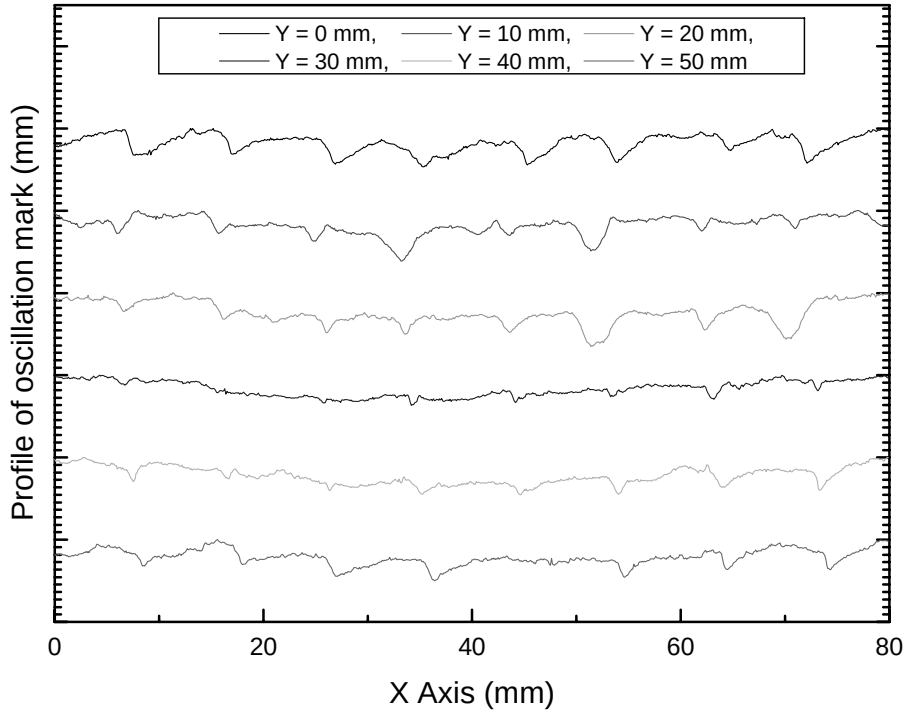
Measurement of OM Profile

Method



X axis : 0 ~ 80 mm

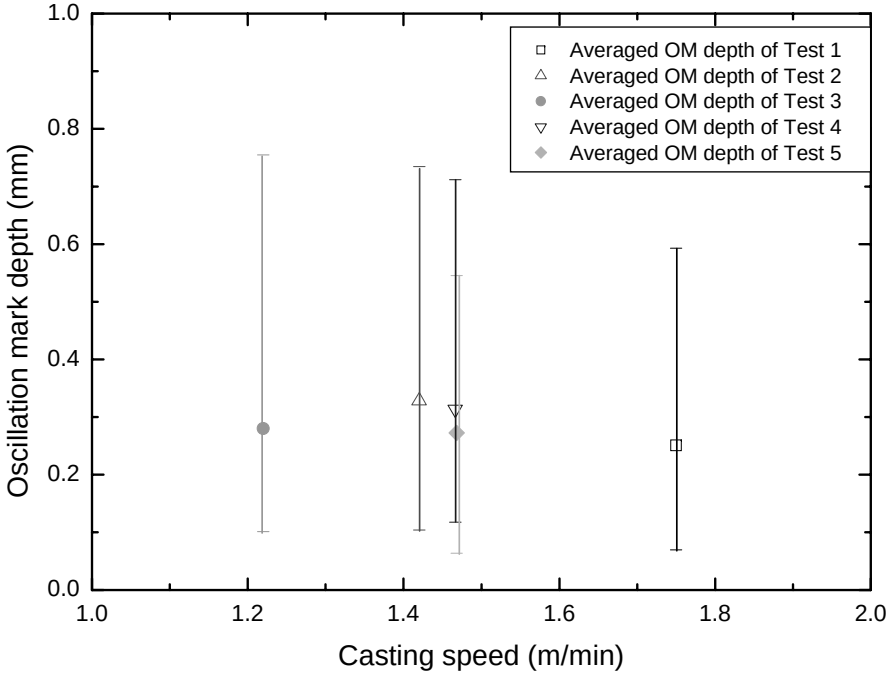
Y axis : 0 ~ 200 mm (10 mm Interval)



< Example of Oscillation Mark Profiles >

Average Results of OM Profiles

	OM Pitch (mm)		OM Depth (mm)	OM Width (mm)	Oscillation stroke (mm)	Oscillation frequency (cycle / minute)
	Calculated	Measured				
Test 1	9.35	9.44	0.251	6.12	7.50	187
Test 2	9.16	9.10	0.328	6.76	6.84	155
Test 3	9.00	8.91	0.280	6.66	6.42	135
Test 4	9.20	9.36	0.314	6.29	6.95	160
Test 5	9.19	9.09	0.272	6.57	6.92	159



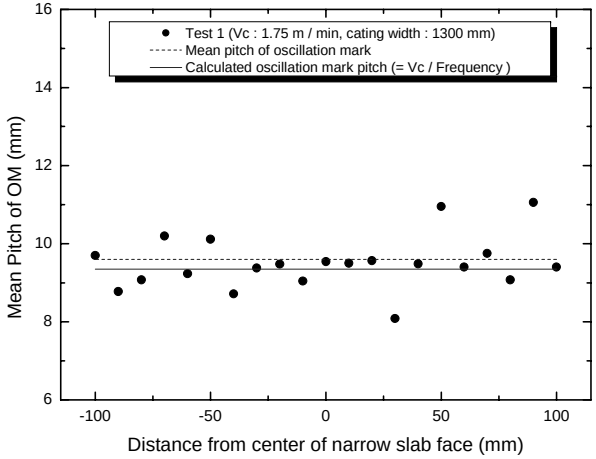
Stoke Set Point = $A_S + B_S \times V_C$

Frequency Set Point = $A_F + B_F \times V_C$

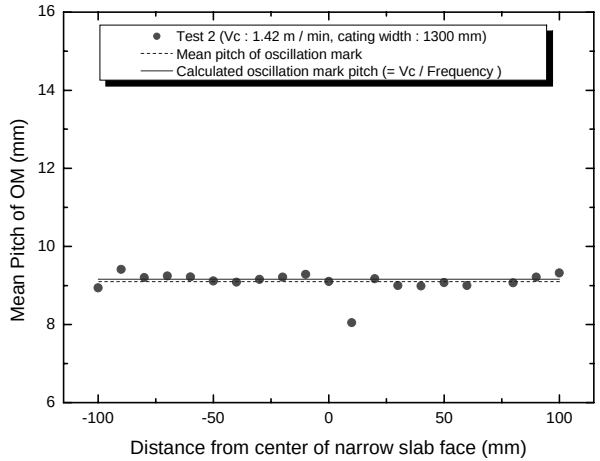
A_F, B_F, A_S, B_S : Coefficients,
F: Frequency, S: Stroke,
V_C : Casting speed

Same tendency with stroke and frequency of mold oscillation

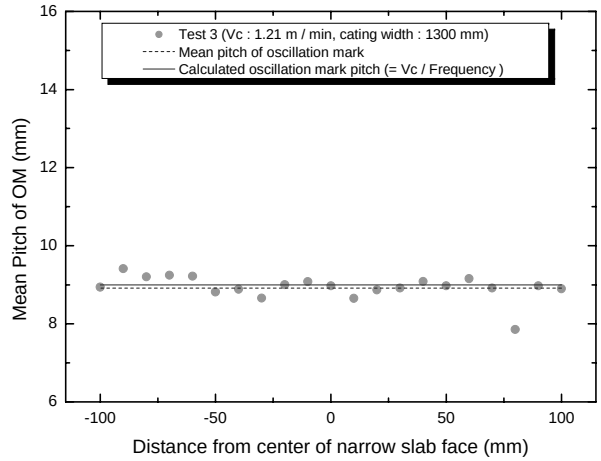
Results of Mean Pitch of OM around Strand Perimeter



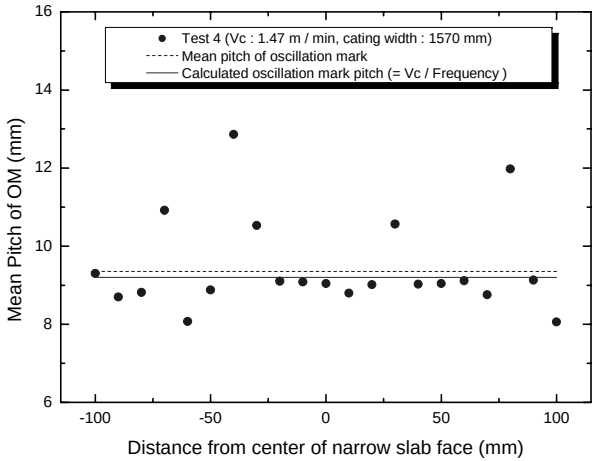
< Test 1 - EMS 313 A >



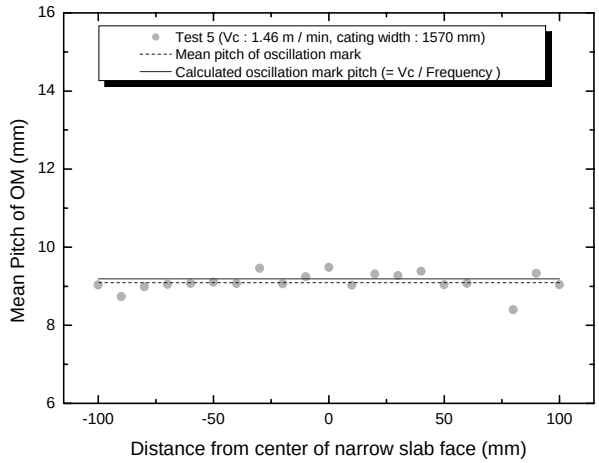
< Test 2 - EMS 234 A >



< Test 3 - EMS 0 A >



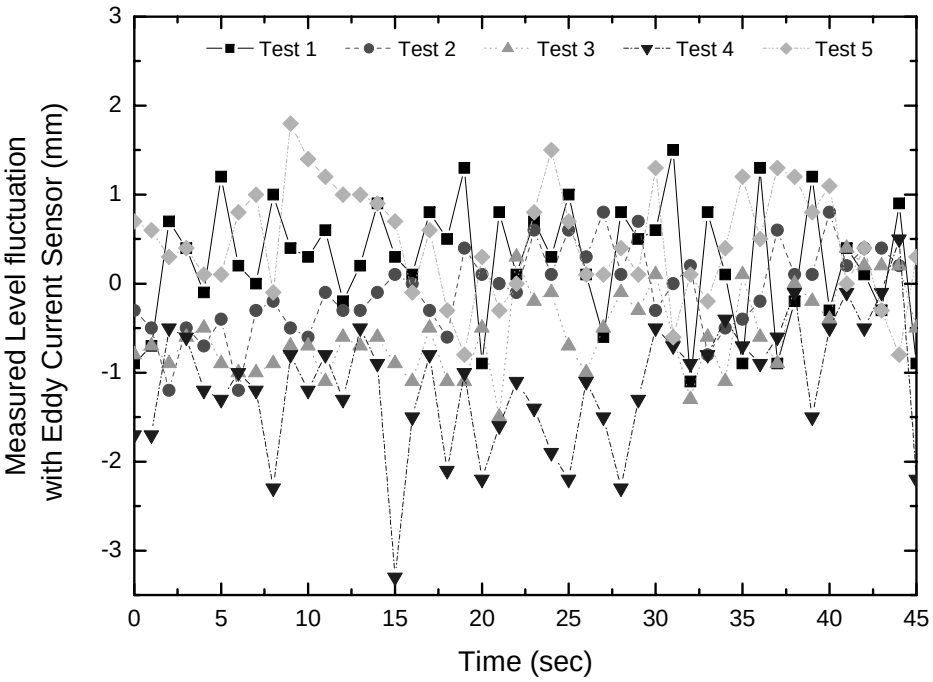
< Test 4 - EMS 277 A >

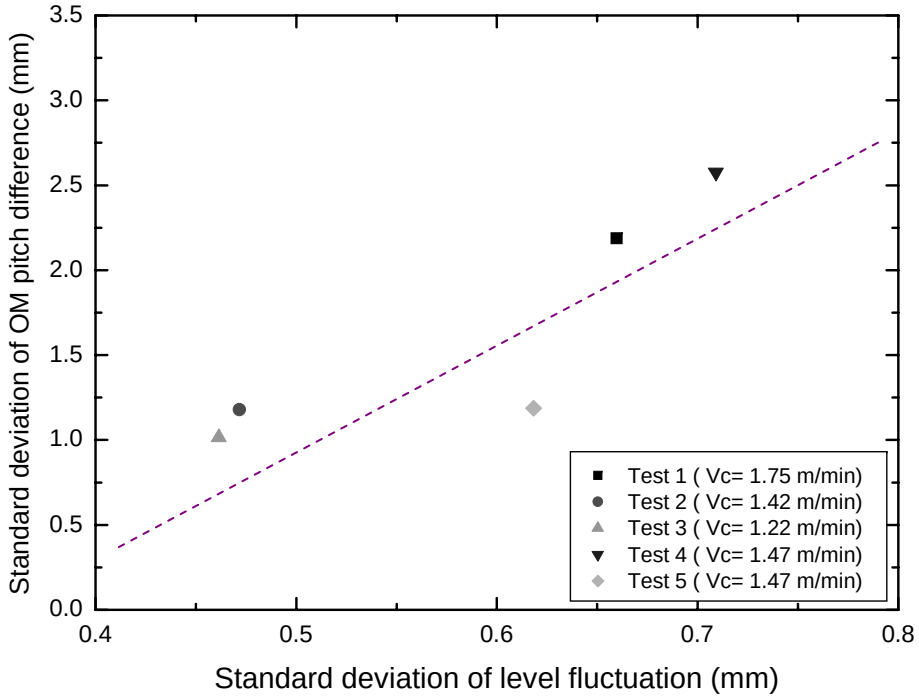


< Test 5 - EMS 0 A >

Higher EMS causes greater pitch variations

Relation between Level Fluctuation and OM Pitch

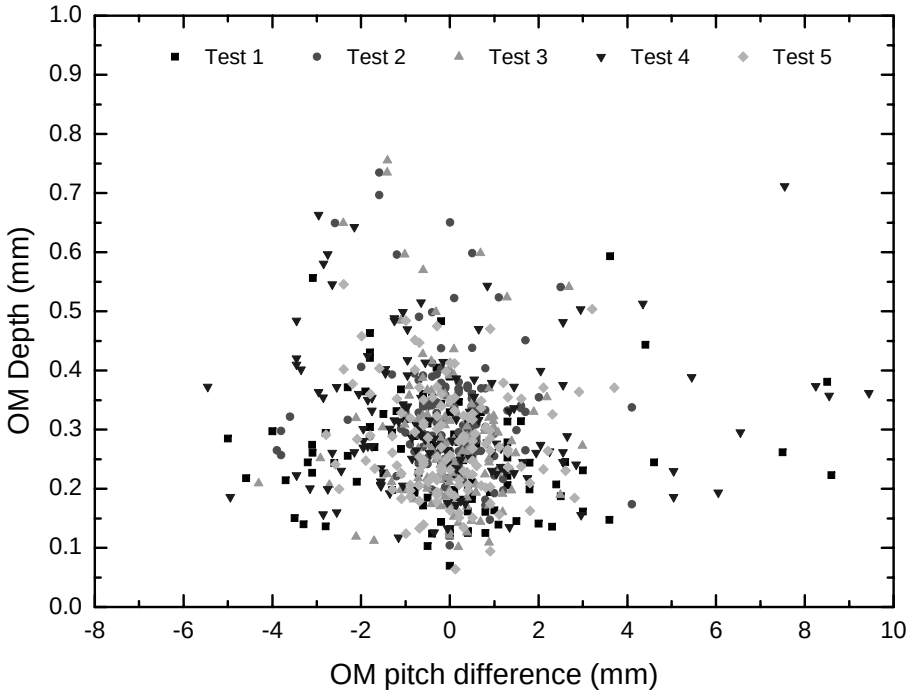


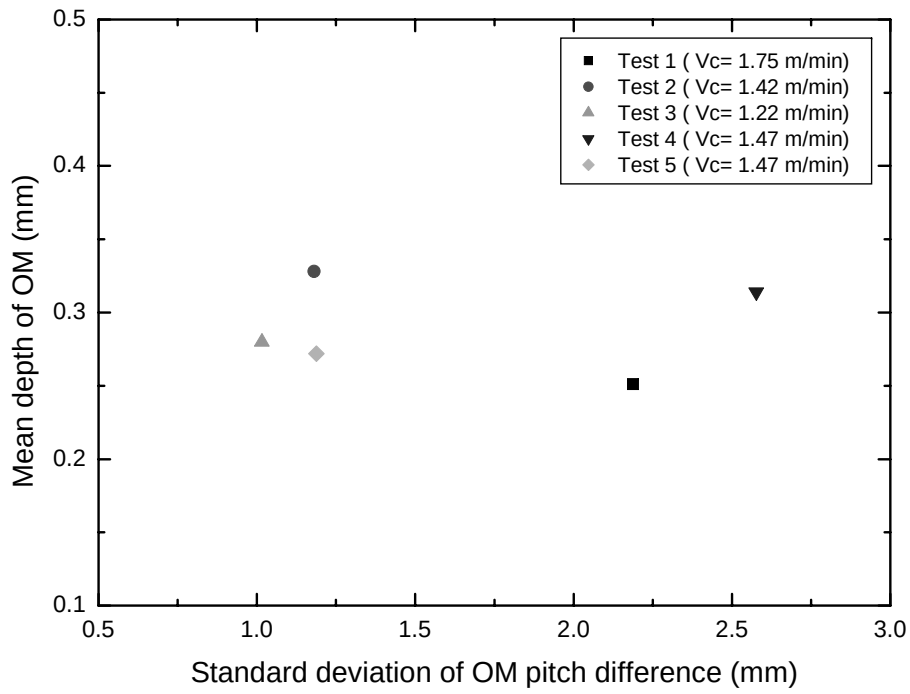


- Standard deviation of level fluctuation : average value during 45 seconds while the samples were produced

- OM pitch difference = (Measured OM Pitch) – (Calculated OM Pitch)
  * Calculated OM Pitch = casting speed / Oscillating frequency

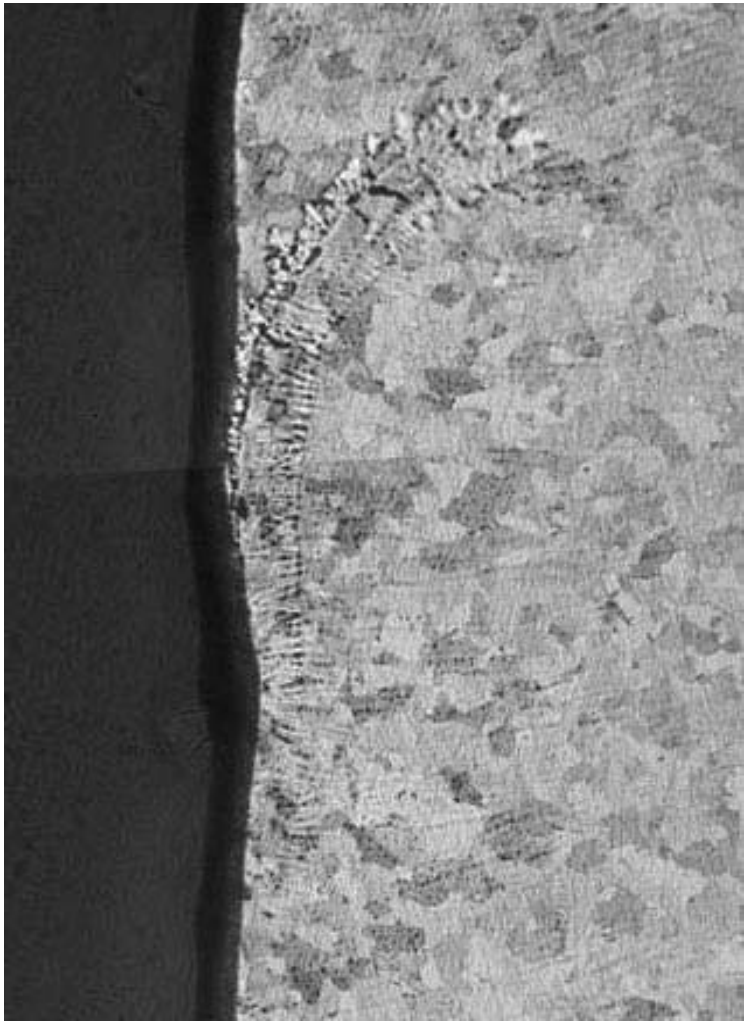
Relation OM Pitch and Depth

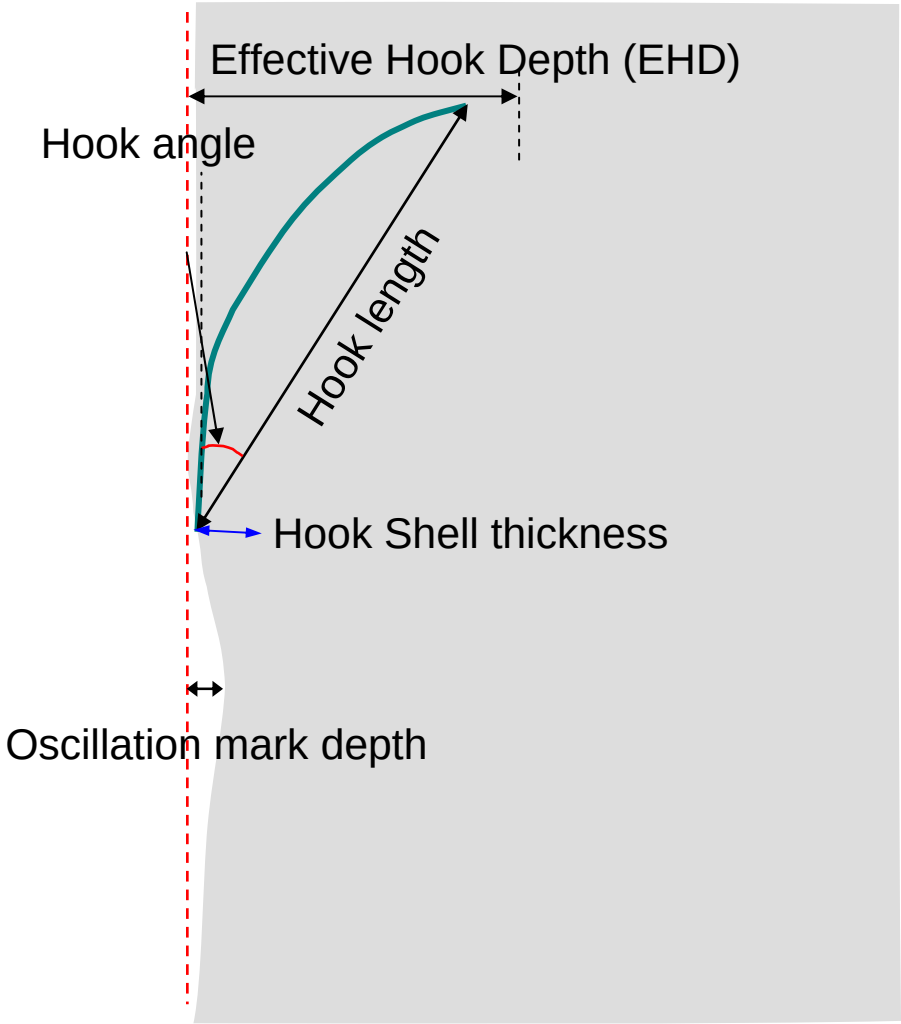




OM pitch difference = (Measured OM Pitch) – (Calculated OM Pitch)
* Calculated OM Pitch = casting speed / Oscillating frequency

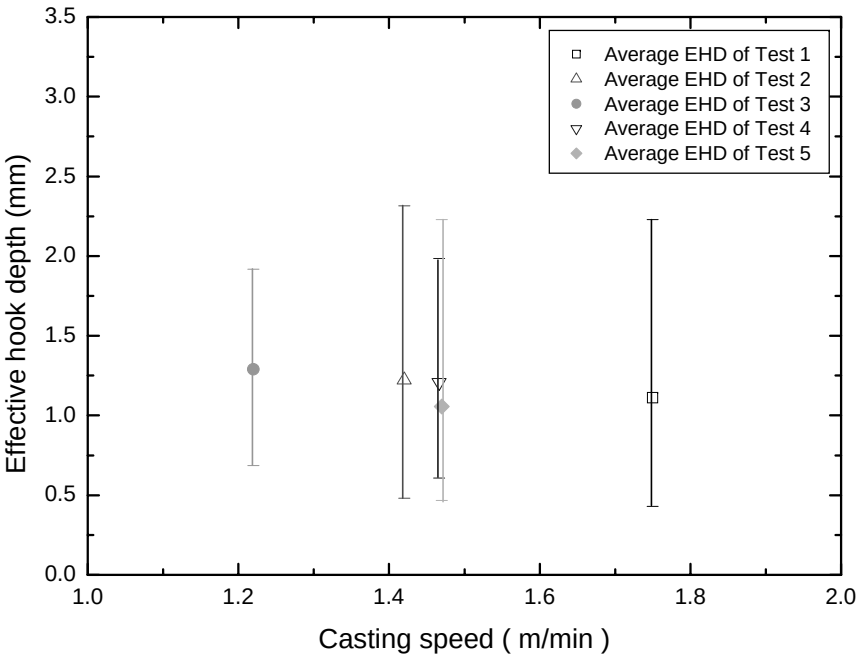
Definition of Hook Characteristics

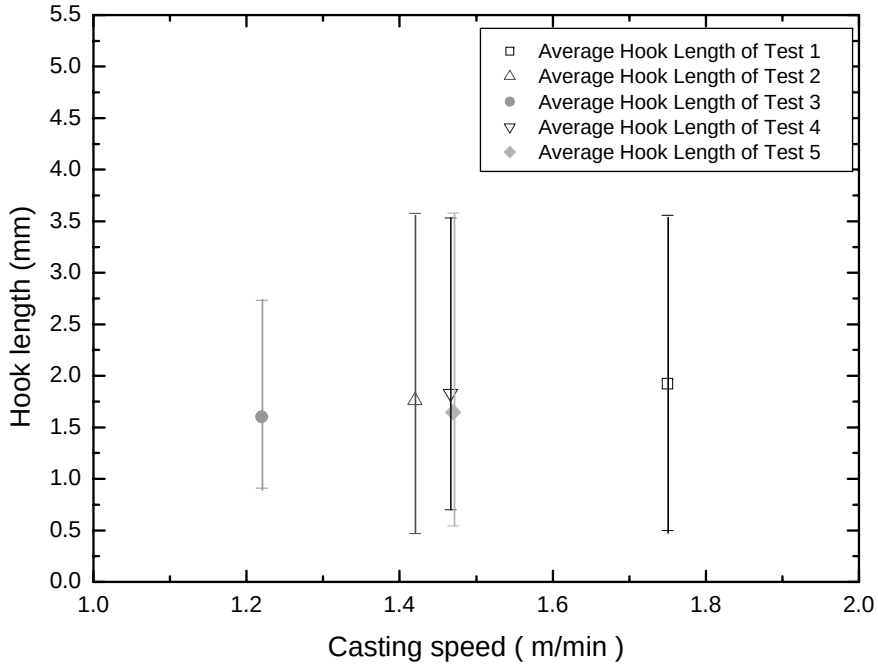




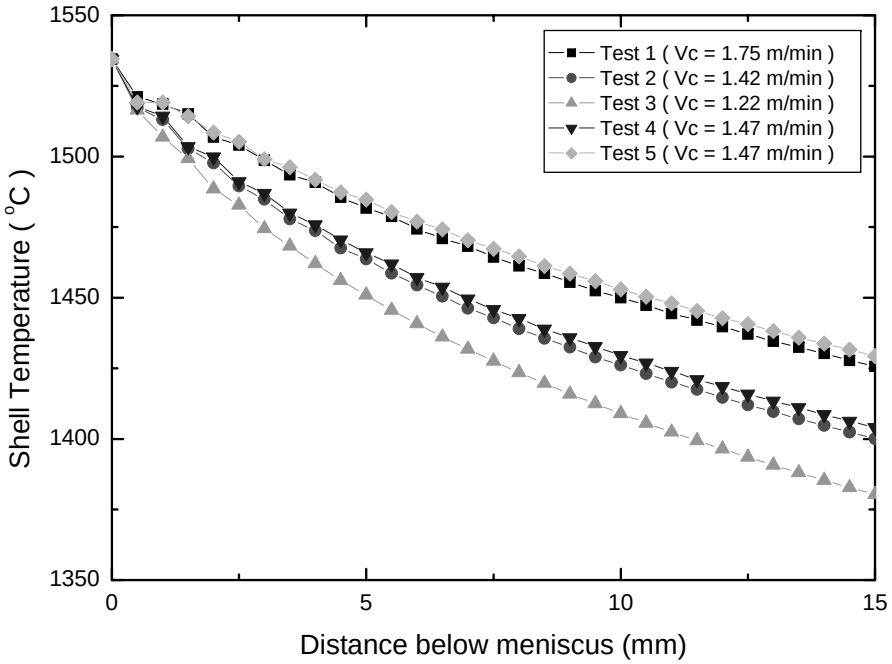
Measured Hook Characteristics

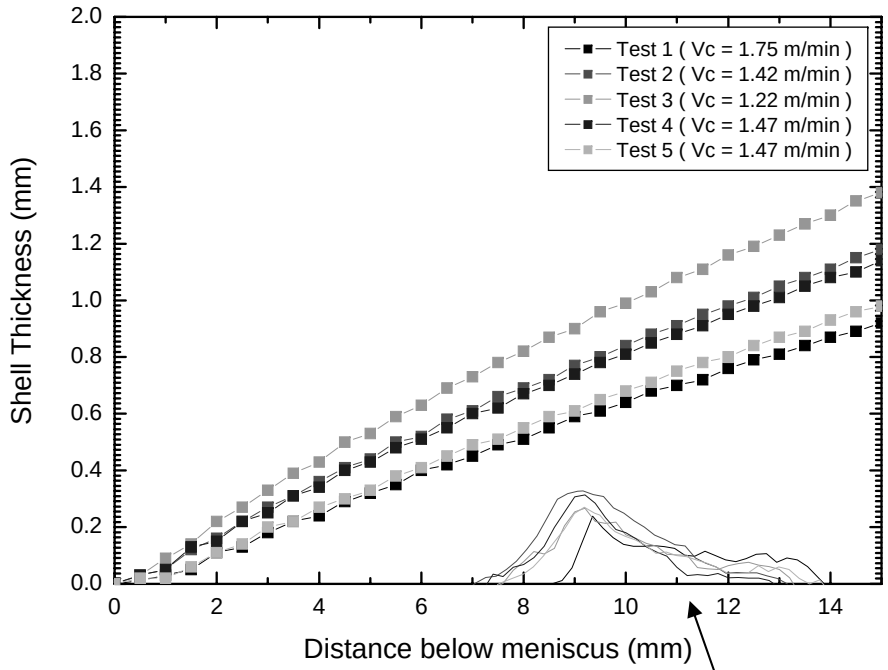
	Effective hook depth (mm)	Hook Length (mm)	Hook Angle (degree)	Hook Shell thickness (mm)	OM Depth (mm)
Test 1	1.11	1.92	27.0	0.462	0.282
Test 2	1.22	1.76	30.9	0.520	0.300
Test 3	1.29	1.60	34.6	0.723	0.268
Test 4	1.21	1.83	26.1	0.557	0.347
Test 5	1.06	1.65	28.0	0.463	0.236





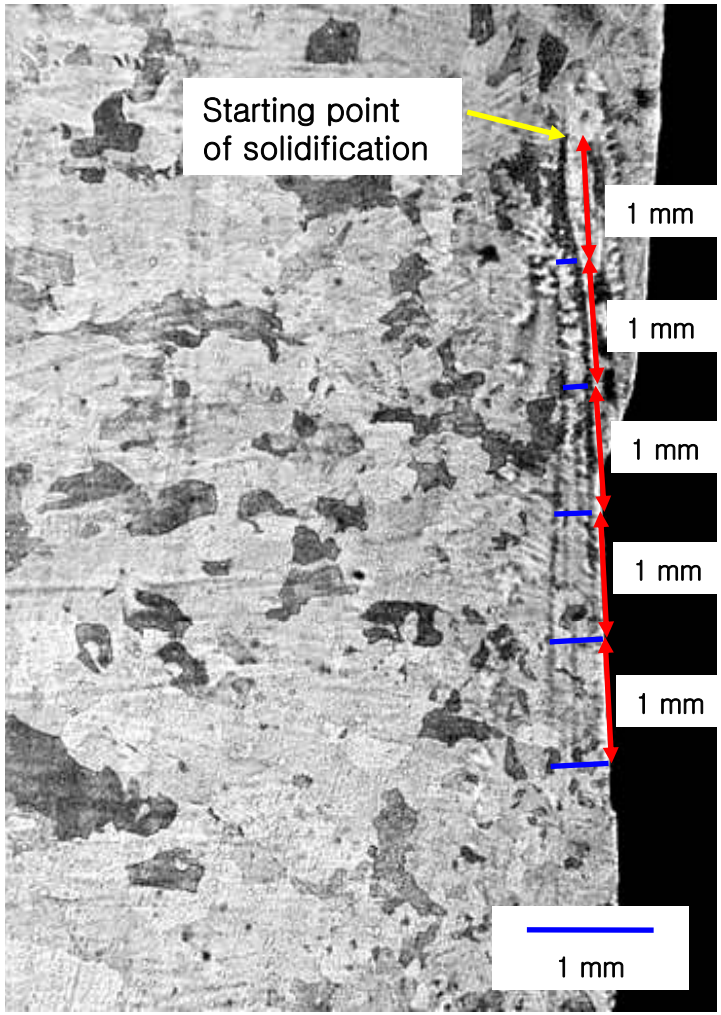
CON 1D Predictions at Meniscus Region



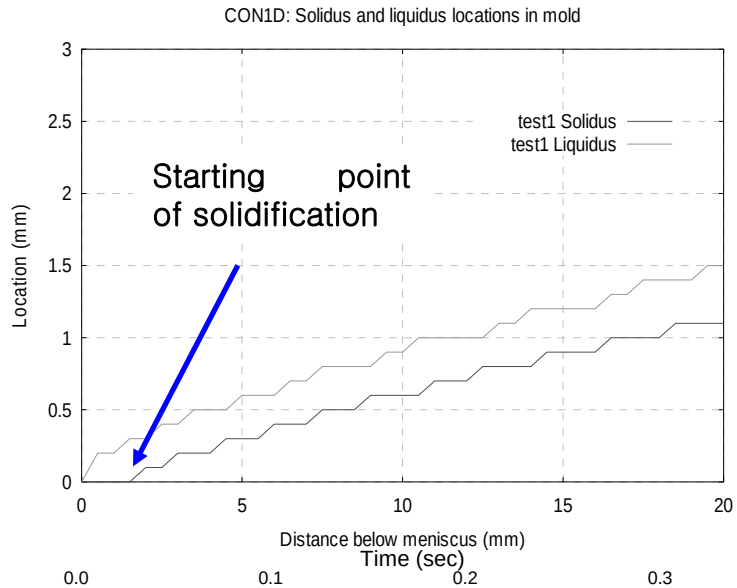


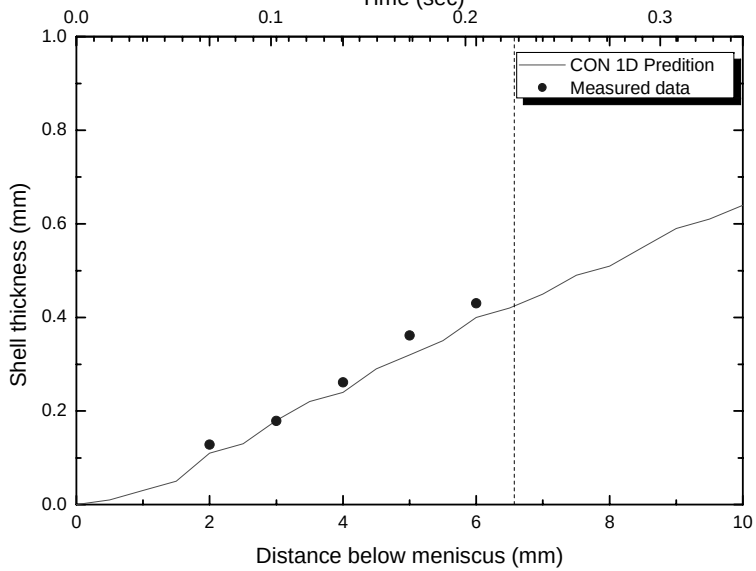
- Ignoring local effect of oscillation mark

Comparison hook shell thickness with modeling prediction

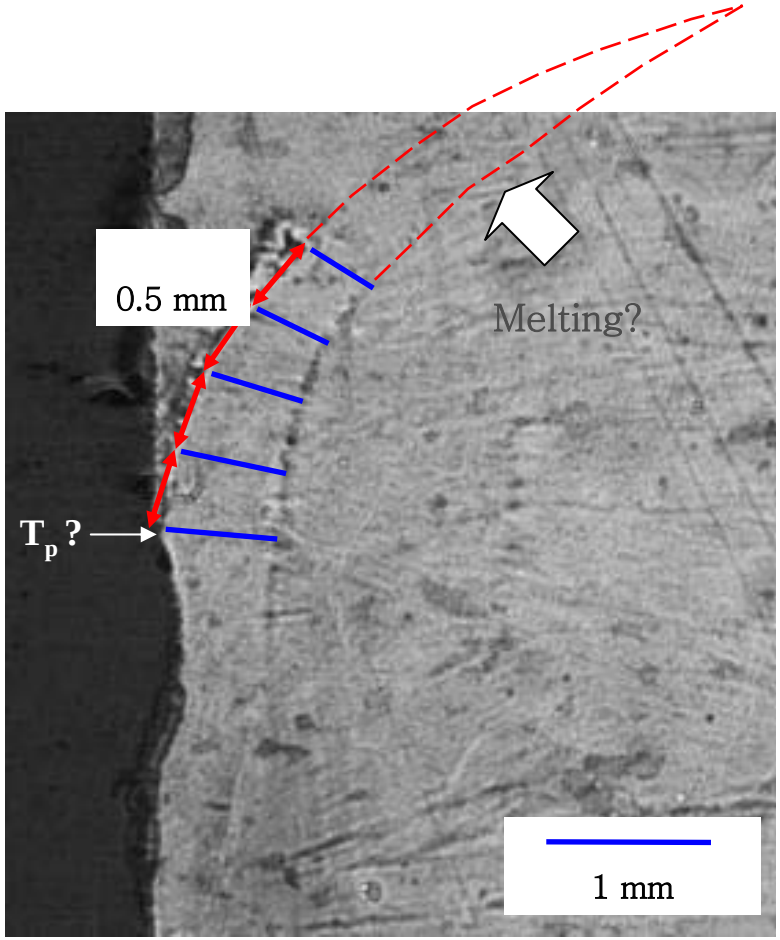


< Test 1 >





Typical Hook Shape Matching to Model Prediction



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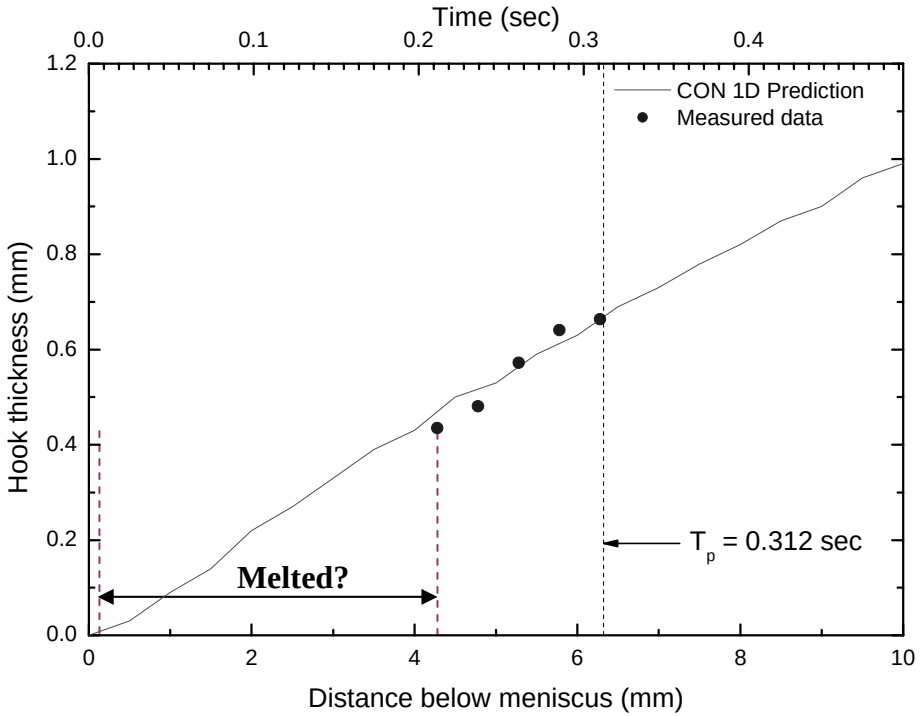
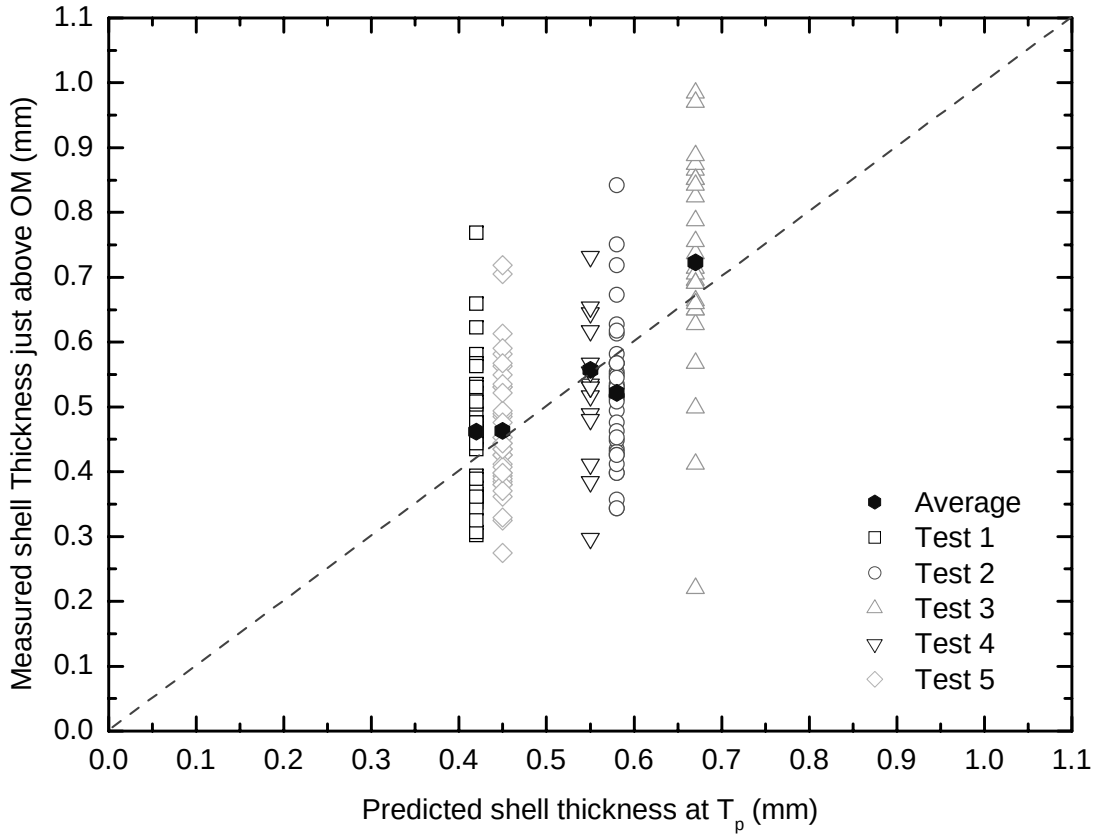
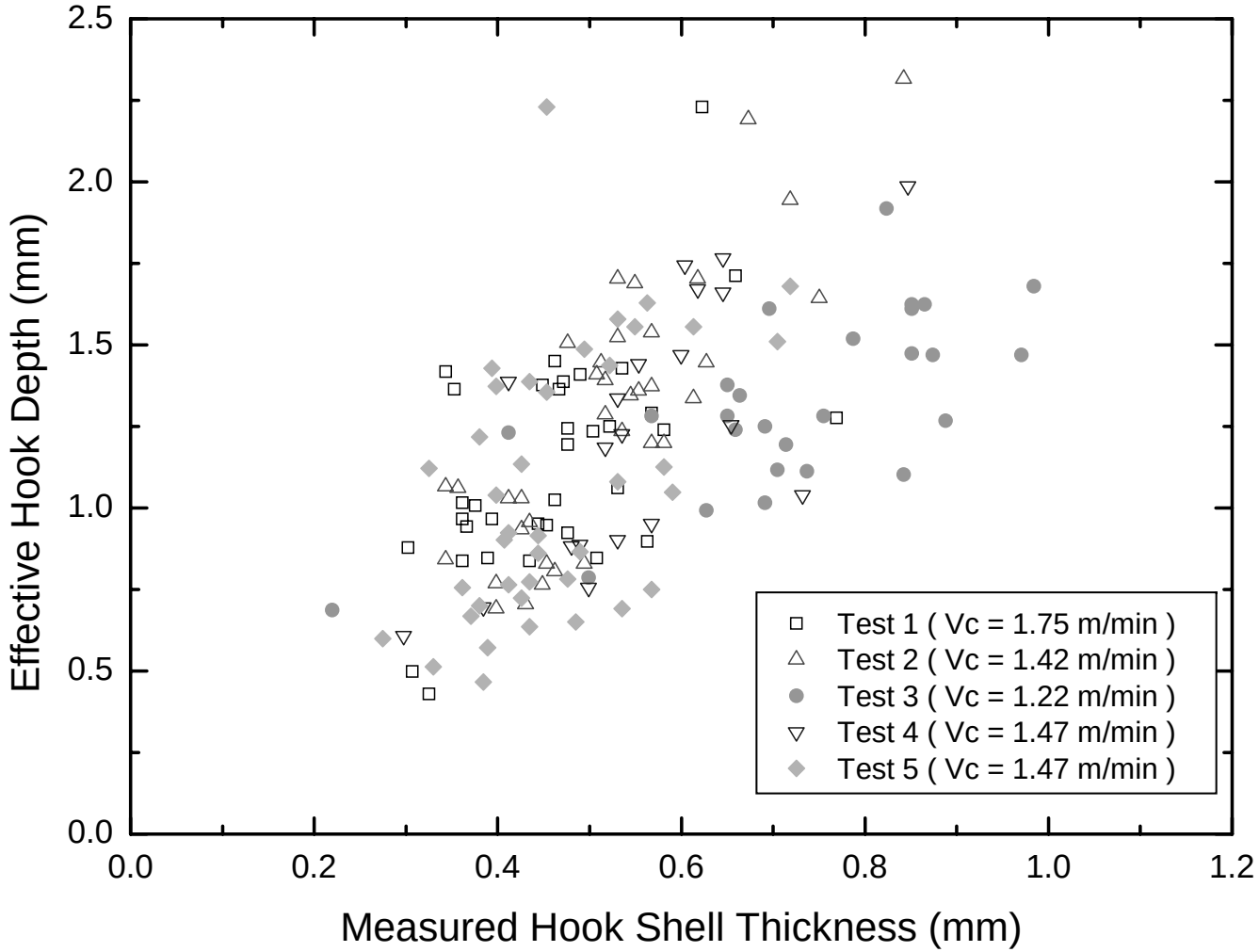


Comparison of Shell Thickness

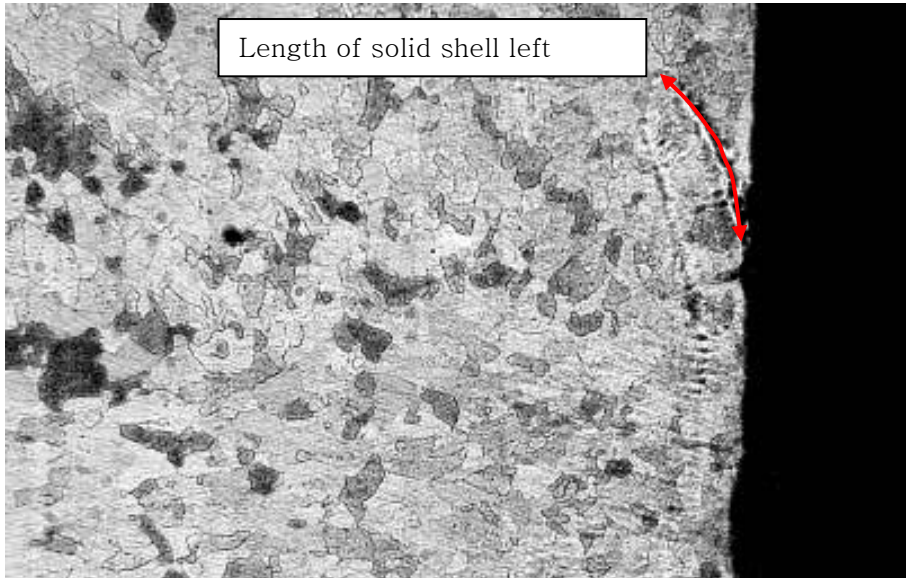


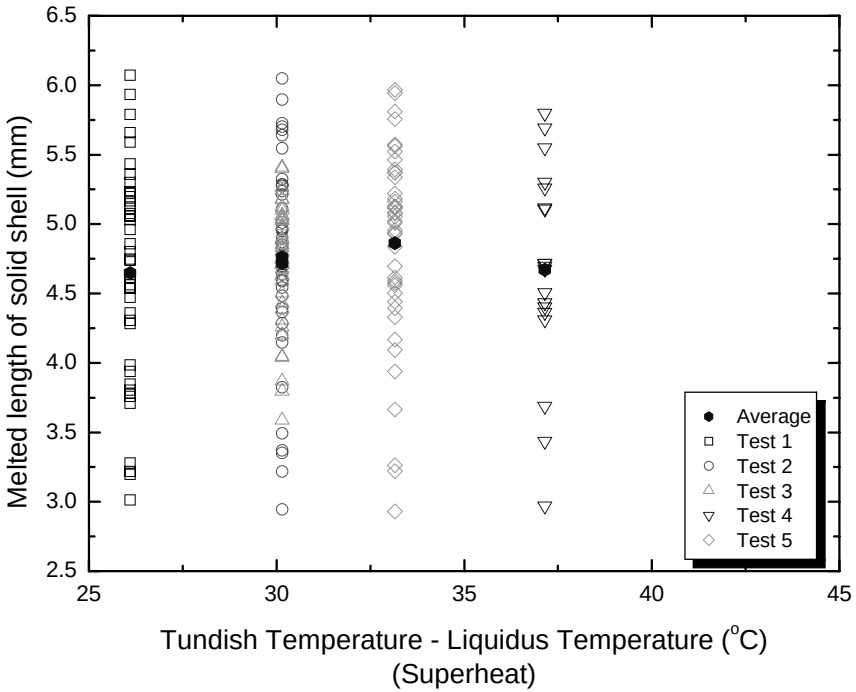
- Scatter due to local variations in undisturbed hook solidification time or level fluctuation

Relation between EHD and shell thickness



Relation between Hook and Superheat

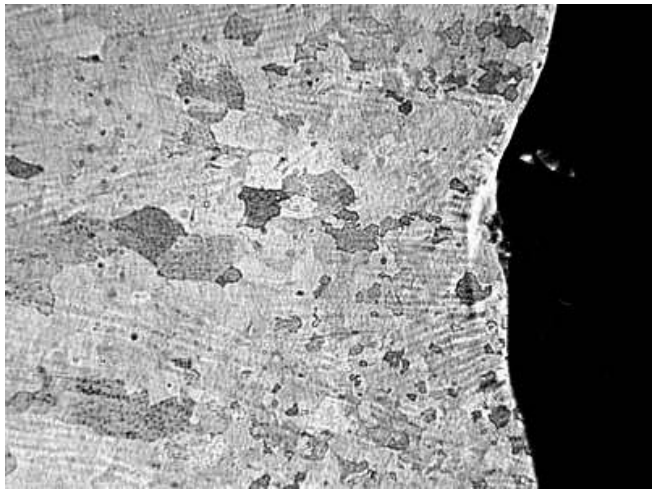


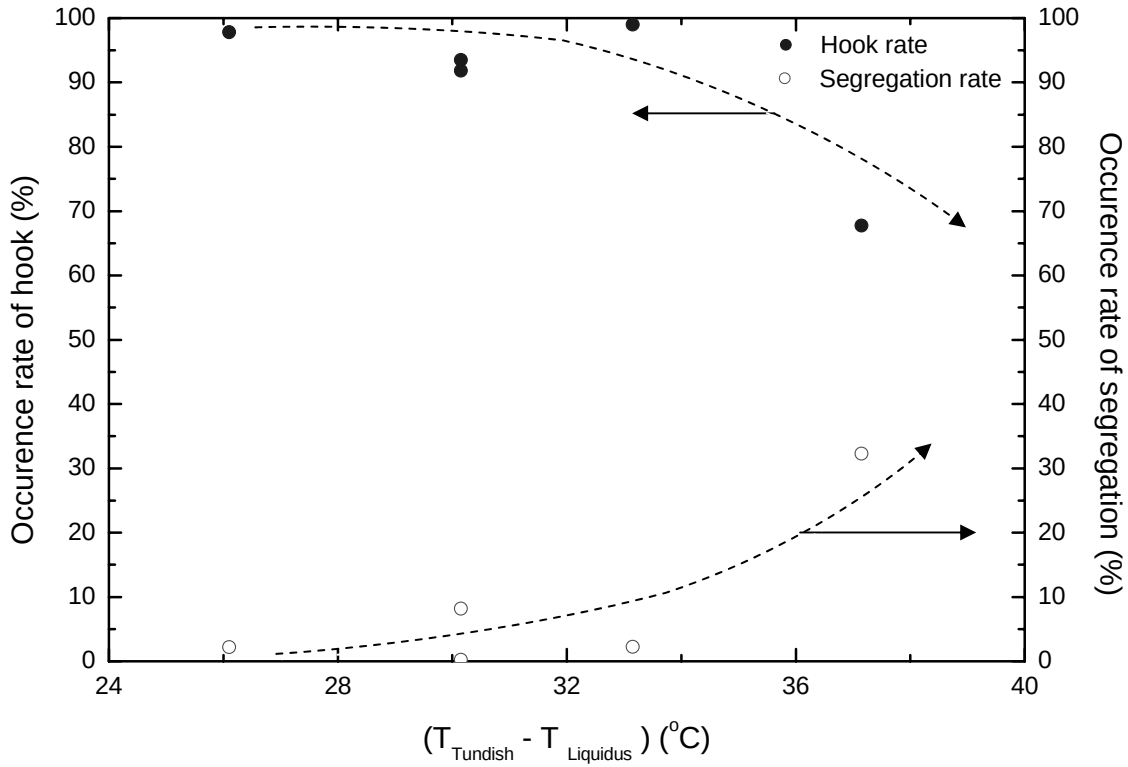


Superheat = Tundish Temperature – Liquidus Temperature

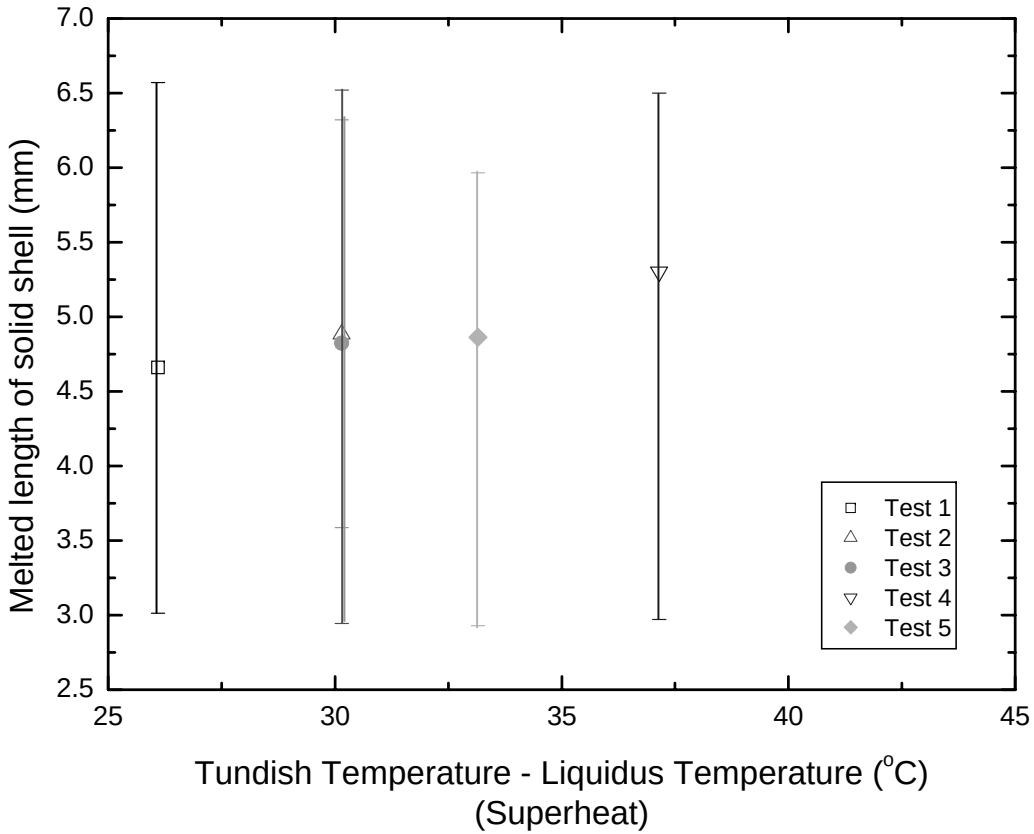
	Length of solid shell during T_p (mm)	Length of left solid shell (mm)	Remelted length of solid shell (mm)	Tundish temperature (℃)	Liquidus temperature (℃) - CON 1D	Occurrence hook rate (%)
Test 1	6.57	1.92	4.65	1560	1533.9	97.8
Test 2	6.52	1.76	4.76	1564	1533.9	91.8
Test 3	6.32	1.60	4.72	1564	1533.9	93.5
Test 4	6.50	1.83	4.67	1571	1533.9	67.7
Test 5	6.51	1.65	4.85	1567	1533.9	100

Occurrence rate of Hook with Superheat





Relation between Melted Shell and Superheat



- Assumption : no hook occurrence case and segregation hook type are all melted
- EMS off : little effect to melt shell
- EMS on : longer shell melted with increasing superheat

Conclusions

- Modeling analysis of shell formation focusing on initial hook formation was conducted with CON1D and parameters of real plant operation
- Measurement of OM depth, pitch and hook shape were made from samples of continuous casting slabs for different casting speeds, EMS power and superheat
- OM pitch is directly related to mold level fluctuations and deviations indicate the stability of level during production
- Increasing OM pitch deviation is correlated with deeper oscillation mark depth
- Hook shell thickness can be predicted using CON1D and the hook shell thickness at top of OM correlates with positive strip time
- Effective hook depths increase in proportion to hook shell thickness
- Hook length correlates with size and shape : longer hooks are deeper EHD
- Increasing superheat decreases hook length, likely due to melting.
- Increasing EMS correlates with more OM pitch deviation, level fluctuation and deeper hooks
- Increasing casting speed effect is complex because it increases both level fluctuation and superheat.