STUDY OF CC NARROW-FACE TAPER DESIGN – INFLUENCE OF THE CASTING SPEED AND STEEL COMPOSITION

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ABSTRACT

The objectives in this work were to develop, calibrate, and apply a model to predict ideal taper profiles down the narrow faces of the SIDERAR slab casting mold for several different casting speeds, steel grades, flux powder compositions, and widths.

A significant amount of original research was undertaken for this challenging problem. A finite difference model of transient 1-D heat conduction and solidification in the slab casting mold and shell was developed: CON1D. The model has been enhanced to make shell shrinkage and ideal taper predictions in slab molds, including narrow-face distortion and wide-face expansion.

The CON1D model was calibrated to match the heat extraction rates for the wide face of the SIDERAR slab-casting mold under several casting conditions. These results were validated through comparison with published results for the same caster.

A 2-D elastic-viscoplastic thermal-stress finite-element model, CON2D, was applied to perform computations of shell shrinkage during slab casting, and compared with the 1-D model shrinkage predictions for the same thermal conditions. The calibrated models were used to predict ideal taper profiles down the narrow face for several casting conditions at SIDERAR, where mold temperature measurements were available. The effects of several different types of mold distortion were taken into account, in addition to variable flux layer thickness profiles.

Parametric studies were performed to investigate the effects of steel grade, casting speed, and mold powder on ideal taper (over 20 cases in all).

Key words: slab casting, mold design, taper, modelling

MODEL DEVELOPMENT

The CON1D model was developed and validated to predict heat transfer in the continuous slab-casting mold, including the solidifying steel shell, the interfacial gap containing the mold flux, and in the mold.

Significant effort was made to extend this model to predict ideal taper, based on a finite difference calculation of shrinkage. This model was found to make reasonable predictions of shrinkage for high carbon steels (which have low creep rates). However, comparisons made with a more accurate finite-element model, CON2D, which includes elasticity and creep plasticity, in addition to thermal strain, revealed that creep effects are very important for low carbon steels, containing delta-ferrite. This causes the CON1D model (and all similar models) to over predict taper for low carbon steels. Thus, the better CON2D model was used for the optimal taper calculations for this study and the simple CON1D model was used for heat transfer only. Further details are provided elsewhere on the CON1D model [1] and CON2D model [2].

Next, a study was undertaken with the fully 2-D transient CON2D model to determine the best way to optimize taper, based on avoiding cracking defects. Too much taper causes transverse corner cracks (or longitudinal off-corner sub mold cracks), and too little taper causes narrow face thinning, longitudinal cracks, and even breakouts. The results revealed that the optimal taper should not completely eliminate the gap near the corners, or else this region will get too cold.

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Simulation Conditions

Taper was predicted for a range of casting conditions for the Siderar slab caster, including variations in casting speed, mold powder composition, and steel grade. For all cases, the Standard Conditions given in Table I, were assumed. These also were chosen to match typical Siderar conditions. Other conditions include: 0.1 x 0.1 mm mesh size (6-node triangular elements), application of the ferrostatic pressure began at 0.3s, and time step increases from 0.001s (meniscus) to 0.5s (mold exit).

Mold with x thickness	206 mm x 45 mm
Strand with	1000 mm
Mold length	900 mm
Meniscus distance below mold top	100 mm
Working mold length	800 mm
Copper Thickness (top of mold)	40 mm
Slot depth	15 mm
Water slot thickness	5 mm
Slot spacing (typical central slot)	20 mm (center to center)
Machine radius	10.185 (IR) 10.385 (OR)
Water slot heat transfer coefficient	Sliecher & Reuse Eq. (~0.045 MW/(m^2 ºK)
Copper thermal conductivity	350 W/(m-K) (0.1%Ag – Cu alloy)
Water temperature	30º C (inlet)

Table I. Conditions assumed for simulation in all cases.

The heat flux measured based on cooling water temperature measurements was calculated from data provided by the caster Level II system. In addition, analysis of the plant data showed that:

1) Heat flux was slightly higher on the loose side (than the fixed), and on the right narrow face (than the left). This suggests possible asymmetries in strand support or mold water flow.
2) There was very little variability in the heat flux levels (although the low speeds, 0.8 m/min have the highest variability).
3) Higher heat flux was found with higher casting speed (as expected).
4) The middle carbon and peritectic grades have slightly lower heat flux. These results were found to match reasonably with the empirical equation published by Cicutti et al. [3]

$$Q_G = 4.63\cdot 10^6 \, \mu^{-0.09} \; T_{flow}^{-1.19} \; V_C^{0.47} \left\{ 1 - 0.152 \exp\left[-\left(\frac{0.107 - \%C}{0.027} \right)^2 \right] \right\} \qquad (1)$$

Where:

Q_G is the mean heat flux (MW/m^2),
μ is the powder viscosity at 1300º C, (Pa-s),
Tflow is the melting temperature of the mold flux (ºC),
Vc is the casting speed (m/min),
%C is the carbon content.

Thus, the CON1D model was calibrated for each run in the parametric studies by adjusting its parameters – (specifically the solid flux velocity ratio and gap resistances) until it matched the empirical equation (1) within 1%. For low carbon steels, the instantaneous heat flux profile is shown in figures 1a, 2a and 3a.

Ideal Taper Calculation

For this study, taper is defined as % / mold as follows.

$$\% \; taper(\% / mold) = 2 \frac{\Delta W}{W} * 100\% \qquad (2)$$

Results are presented as mm of deflection per side, based on a 1000 mm wide slab. Thus, a value of 5mm of deflection (at mold exit) represents an ideal taper (at mold exit) of 1% / mold, (or 1.25% / m based on an 800 mm working mold length).

The ideal change in strand width, (relative to the mold wall position at ambient temperature) .W, was found by summing the contributions from several different components:

$$W\,(mm) = W_{shell} - W_{NF\text{-}D} - W_{WF\text{-}E} - W_{WF\text{-}D} - W_{FLUX} \qquad (3)$$

W_{shell} is the decrease in wide face width due to shrinkage of the shell (mm), calculated with CON2D.
$W_{NF\text{-}D}$ is the narrow face distortion down the mold minus the distortion in the meniscus,
$W_{WF\text{-}E}$ is the wide face expansion at the meniscus minus the wide face expansion down the mold,
$W_{WF\text{-}D}$ is the wide face distortion,
W_{FLUX} is the flux layer thickness down the mold minus that at the meniscus.

Casting Speed Study:

The model was run for different steel grades simulating several different casting speeds, using the powder type appropriate for each grade. The following figures present detailed results for the effect of casting speed on temperature, shell thickness, heat flux, shrinkage, and taper, all for a typical low carbon steel (0.07%C) using powder E (see table IV).

Higher casting speed produces less dwell time in the mold, a slightly higher surface temperature, (figure 1a), a thinner shell (figure 1b) and higher average mold heat flux (figure 1c). This is because heat flux through a thinner shell is higher and the flux layer is thinner at higher casting speeds. Thus, the resistance to heat flux is lower.

At higher casting speeds, the shell shrinkage and the ideal taper would be less, due to the thinner shell. The decrease in shrinkage is not as much as might be expected, however, because the higher average mold heat flux (1a) lowers the shell surface temperature (for a given time). The net effect of casting speed on shrinkage and taper is relatively small, as shown in figures 1d and 1e.

More important are the effects of mold distortion and flux layer changes. Increasing casting speed increases narrow face distortion, which tends to lessen ideal taper. Changes in flux layer thickness and wide face expansion, if present, would greatly lessen ideal taper, as seen by comparing Figs. 1e and 1f. Thus, in choosing ideal taper, it is important to understand the details of flux layer behavior and interaction between the wide and narrow faces (through clamping and screw adjustments). Without knowing details of these two subjects, it might be safer to assume the larger ideal taper based on the assumption in Fig. 1f, that mold flux layer does not change down the mold, and that wide face distortion is not a factor.

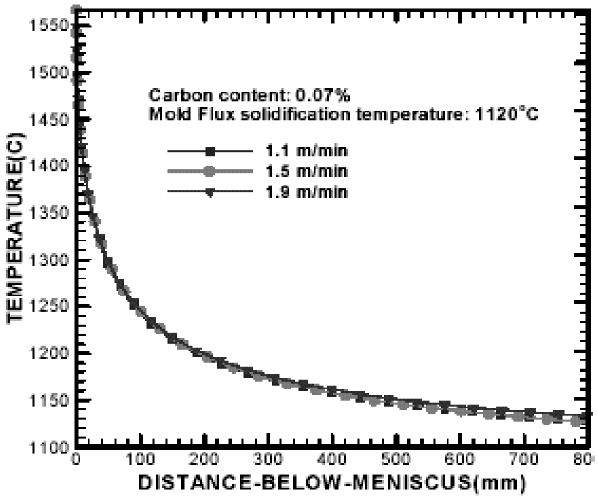

Figure 1a). Shell surface temperature for FK08F, Powder E.

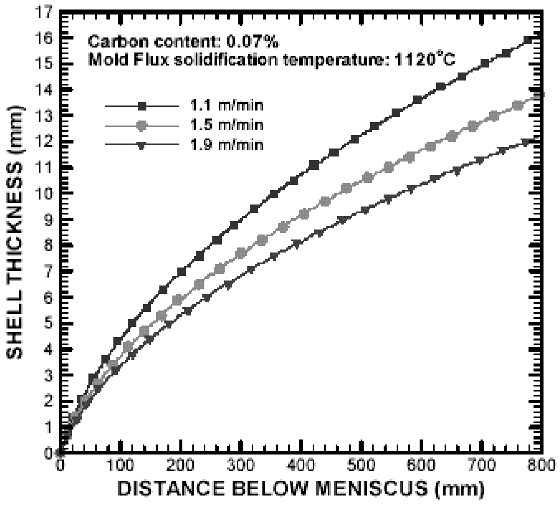

Figure 1b). Steel shell thickness for FK08F, Powder E.

Previous Home Table of Contents Author Index Exit Next

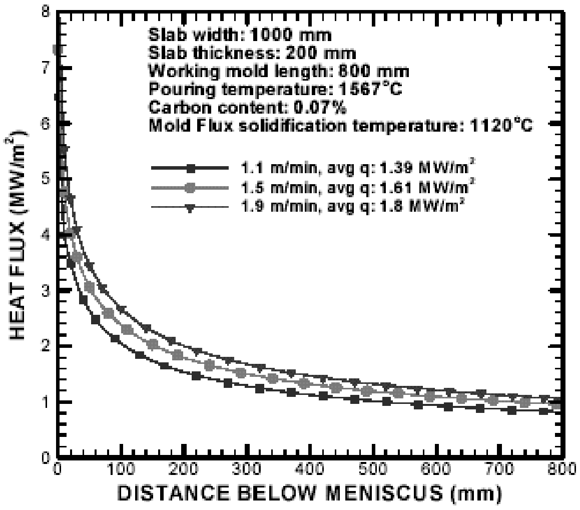

Figure 1c). Heat Flux profiles for FK08F, Powder E.

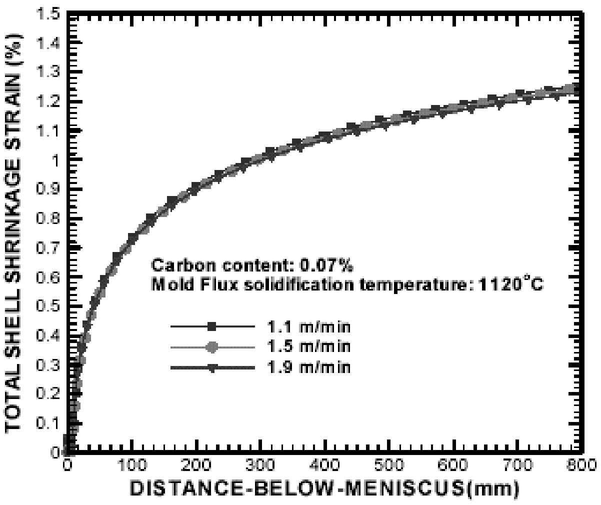

Figure 1d). Total shell shrinkage for FK08F, Powder E.

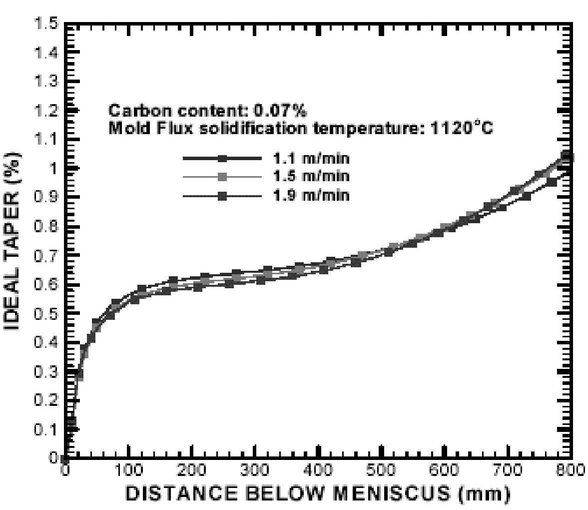

Figure 1e). Ideal taper (including wideface expansion and mold flux layer thickness effect) for FK08F, Powder E.

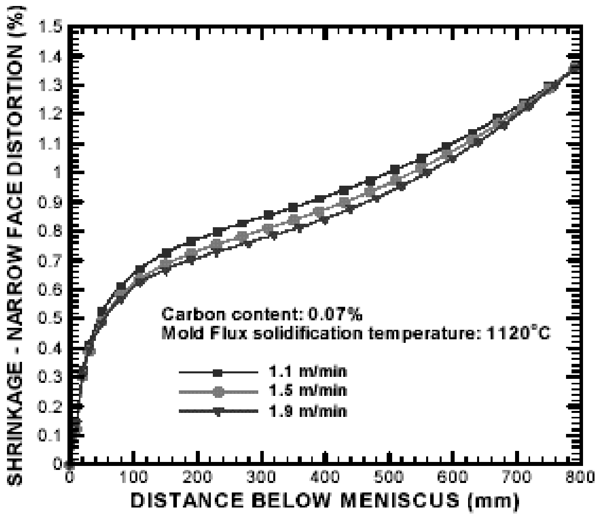

Figure 1f). Shell shrinkage – narrowface distortion for FK08F, Powder E.

Mold Powder Study:

The model was next run for each casting powder of interest, using the same steel grade (FK08F) and casting speed (1.5 m/min), with other conditions given in Table I. The powders studied are listed below (Table II). Viscosities (in Pa-s at 1300° C) were calculated using the IRSID model.

Table III and Fig. 2a)-e) present detailed results for the effect of mold powder composition on heat flux, temperature, shrinkage, and taper.

Powder	SiO_2	MnO	P_2O_5	MgO	CaO	Al_2O_3	TiO_2	Fe_2O_3	Na_2O	K_2O	Basicity	Viscosity
A	30.9	0.05	0.07	1.1	33.7	6.7	0.02	1.0	6.1	0.12	1.09	0.225
C	31.2	3.1	0.07	1.2	39.0	7.1		0.8	3.2		1.25	0.192
D	33.1			6.6	28.5	5.6	0.2	1.3	12.1	0.3	0.86	0.115
E	31.4	0.06	0.1	1.8	26.7	4.4	0.2	1.4	11.0	0.62	0.85	0.083

Table II. Mold powder compositions.

Steel: low carbon – FK 08 F				
Powder type	D	E	A	C
Viscosity (Pa-s)	0.115	0.083	0.225	0.192
Flux solidification temperature (C)	1040	1120	1160	1215
Flux consumption rate (kg/t)	0.25	0.25	0.25	0.25
Solid flux velocity ratio (V/Vc)	0.011	0.020	0.008	0.015
Oscillation mark depth (mm)	0.24	0.24	0.24	0.24
Casting speed	1.5	1.5	1.5	1.5
Tundish temperature (C)	1567	1567	1567	1567
Heat flux (MW/m^2): Q (Eq. 3)	1.71	1.61	1.41	1.36
CON 1D average	1.71	1.61	1.41	1.36
Surface temp exit	1090	1127	1202	1220
Shrinkage exit (mm) CON 1D	10.36	9.40	7.72	7.24
Shrinkage 50 mm CON 2D	3.08	2.73	2.12	1.88
Flux layer relative to meniscus (mm)	1.12	1.25	1.59	1.73
NF distortion relative to meniscus (mm)	-0.70	-0.66	-0.58	-0.58
WF expansion relative to meniscus	0.43	0.42	0.33	0.35
Ideal taper exit (mm)	5.97	5.20	3.64	3.12
Ideal taper exit (%)	1.19	1.04	0.73	0.62
Shell shrinkage – NF distortion (mm), exit	7.52	6.87	5.56	5.20
Shell shrinkage – NF distortion (%/mold), exit	1.50	1.37	1.11	1.04
Thermocouple 170º (C)	142	135	123	119
Thermocouple 370º (C)	110	105	96	94

Table III. Mold powder composition study.

The change in mold powder composition is taken into account by changing the powder viscosity (see table IV) and the solidification temperature. The most important effect is from the solidification temperature. Increasing solidification temperature tends to lower the heat flux, (Fig. 2a) owing to the thicker solid slag layer that forms. As a result, the steel shell temperatures are higher, (Fig. 2b) leading to less shell shrinkage (Fig. 2c) and consequently lower ideal taper (Figs. 2d and 2e).

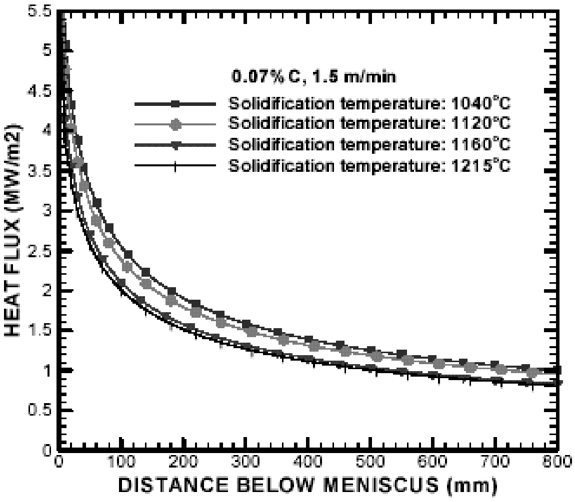

Figure 2a). Heat flux profiles for different powders for conditions in tables II and III.

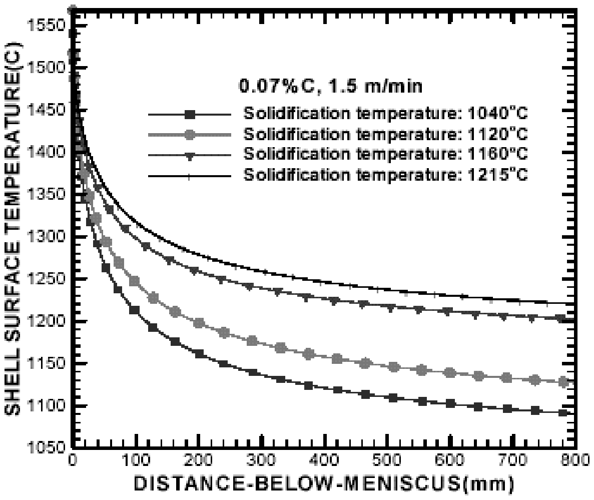

Figure 2b). Shell surface temperature for different powders for conditions in tables II and III.

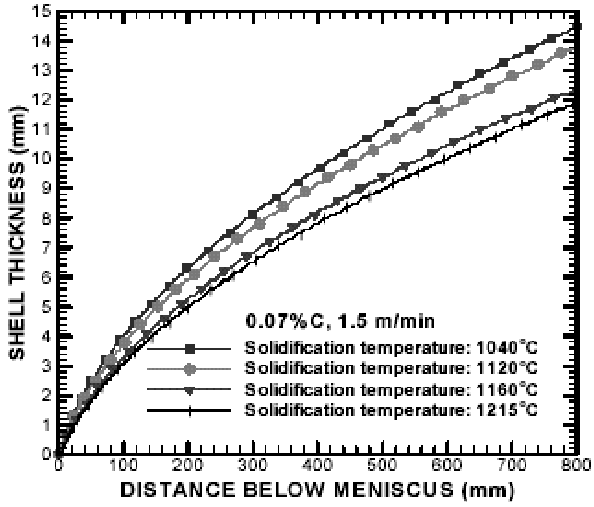

Figure 2c). Shell thickness for different powders for conditions in tables II and III.

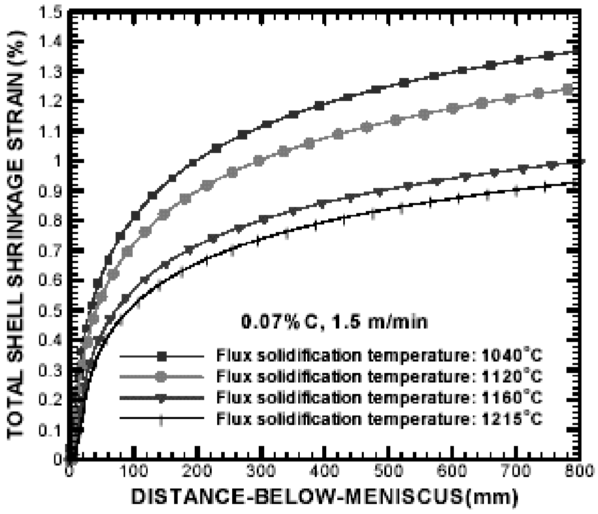

Figure 2d). Shell shrinkage for different powders for conditions in tables II and III.

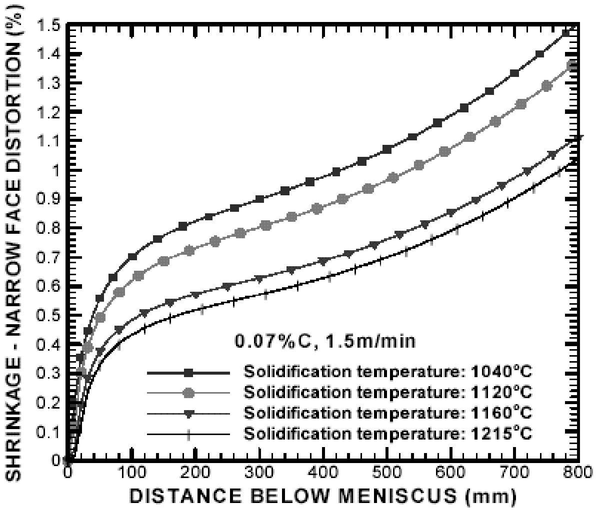

Figure 2e). Ideal taper (conservative estimate) based on Shell shrinkage – narrow face distortion for different powders for conditions in tables II and III.

Steel Grade Study:

The model was next run for each steel grade of interest, using the appropriate powder (C or E) and constant casting speed (1.5 m/min), with other conditions given in Table I. Details of the steel grades are given in Table IV below:

Steel Grade SIDERAR name	Low C FK 08 F	Peritectic FK 08 H	Medium C FK 12 MSA	Medium C FK 18 API	High C FK 45 MSA
C (%)	.07	.07 - .08	.12 - .14	.15 - .18	.44 - .49
Mn (%)	.25 - .35	.37 - .47	.50 - .65	.80 - .95	.65 - .85
Si (%)	0.03	0.02	.20 - .25	.12 - .16	.17 - .27
P (%) max	.02	.015	.015	.015	.025
S (%) max	.015	.015	.015	.010	.015
Al (%)	.025 - .050	.025 - .050	.024 - .048	.025 - .050	.029 - .049
Liquidus Tº (C)	1527	1527	1521	1517	1490
Tundish Tº (C)	1537 - 1567	1536 - 1566	1531 - 1561	1524 - 1557	1510 - 1525

Table IV Steel grades studied.

`Table V and Figs. 3a)-e) present further details for the conditions assumed and detailed results for the effect of steel grade on heat flux, temperature, shrinkage, and taper.`

Grade	Low C	Peritectic	Medium C	Medium C	High C
Grade number	FK 08F	FK08 H	FK 12 MSA	FK 18 API	FK 45 MSA
Powder type	E	E	C	C	E
Viscosity (Pa-s)	0,083	0,083	0,192	0,192	0,083
Flux solidification Temperature (C)	1120	1120	1215	1215	1120
Flux comsumption rate (kg/t)	0,245	0,245	0,245	0,245	0,05
Solid flux velocity ratio (V/Vc)	0,02	0,0185	0,0026	0,0091	0,009
Oscillation mark depth (mm)	0,24	0,24	0,34	0,34	0,05
Casting Speed (m/min)	1,5	1,5	1,5	1,5	1,5
Tundish temp (C)	1567	1567	1567	1567	1567
Heat Flux (MW/m2): Q (Eq.3)	1,61	1,59	1,29	1,38	1,65
CON1D average	1,61	1,59	1,29	1,37	1,64
Surf Temp exit (C)	1127	1134	1250	1218	1115
Shrinkage exit (mm) CON1D	9,40	5,96		6,52	4,96
Shrinkage 50mm CON2D	2,73	2,62	1,43	1,33	2,31
Shrinkage exit (mm) CON2D	6,21	6,04	3,72	3,74	4,61
Shrinkage exit (%/mold) CON2D	1,24	1,21	0,74	0,75	0,92
Flux layer relative to meniscus (mm)	1,25	1,31	1,98	1,97	1,51
NF distortion relative to meniscus (mm)	-0,66	-0,66	-0,53	-0,56	-0,68
WF expansion relative to meniscus (mm)	0,42	0,46	0,31	0,38	0,43
Ideal Taper exit (mm)	5,20	4,93	1,95	1,95	3,35
Ideal Taper exit (%)	1,04	0,99	0,39	0,39	0,67
Shell shrinkage - NF distortion (mm), exit	6,87	6,70	4,25	4,30	5,29
Shell shrinkage - NF distortion (%/mold), exit	1,37	1,34	0,85	0,86	1,06
Thermocouple 170 (C)	135	134	114	119	139
Thermocouple 370 (C)	105	105	89	92	104

Table V. Steel grade study.

Simulations were conducted to study the effect of steel grades containing 0.07, 0.13, 0.27, and 0.47 % C, assuming mold powder properties typically used for each grade. Changing steel grade affects taper in two main ways, which tend to offset each other somewhat. Firstly, it changes the steel thermal and mechanical properties, most notably the thermal expansion, which is larger for peritectic steels. Secondly, it affects the mold heat flux, which is 20% lower for peritectic steels (Equation 3, Table I, and Fig. 3a), due to deeper oscillation marks, and the higher solidification temperature of the mold flux used for these grades.

Note that mold powders with high solidification temperature and low viscosity (as proposed by Wolf) are adopted, to produce lower, but more uniform heat transfer rates to help avoid cracks in depression-sensitive grades, such as peritectic steels [4]. Slags with opposite properties are used for low and high carbon steels, to help avoid sticker problems. Thus, this study used the 1215º C solidification temperature slag for the 0.13 % C steel and 1120º C slag for the low and high carbon steels, which is typical of SIDERAR practice.

The effects of steel grade, and its associated heat flux, on shell temperature, shell thickness, shrinkage and ideal taper are shown in Figs. 3a-e). These figures show that the lower heat flux produces a hotter shell surface temperature (3b). This effect appears to outweigh the importance of the extra shrinkage of the peritectic steels. Thus, peritectic steels experience less shrinkage and require less taper than either low or high carbon steels.

The low carbon steels (< .16 %C) have extra plastic strain, owing to their microstructure being in the soft, rapidly creeping delta phase. This extra creep generated in the solid tends to lower the amount of shrinkage experienced by these grades. It was not accounted for in CON1D, which explains the big difference between CON1D and CON2D for these grades. The net effect is that low carbon steels experience both heat flux and shell shrinkage that is greater than for the other grades.

Comparing the results in Table V at mold exit and 50 mm below meniscus indicates that most of the shrinkage occurs very near to the meniscus, especially for the peritectic grade. This is likely the reason for the great sensitivity of the shrinkage to the heat flux high in the mold.

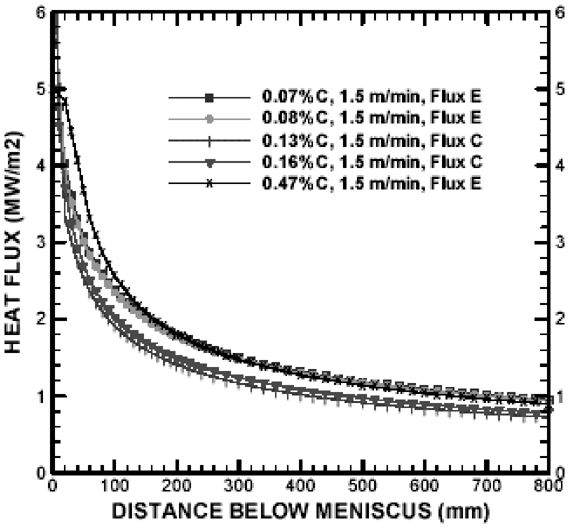

Figure 3a). Heat flux profiles for different steel grades for conditions in table V.

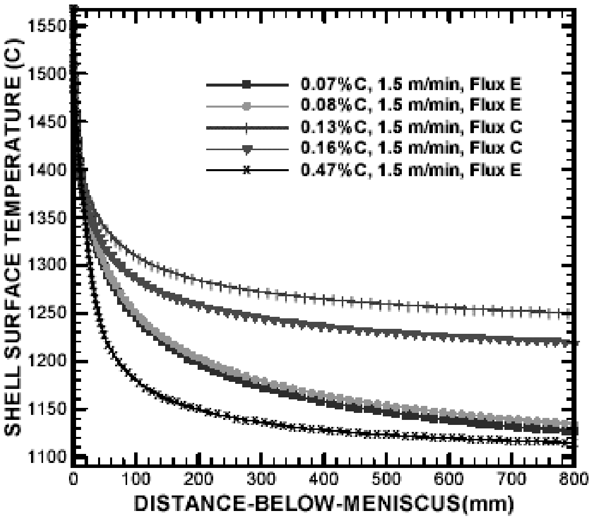

Figure 3b). Shell surface temperature for different steel grades for conditions in table V.

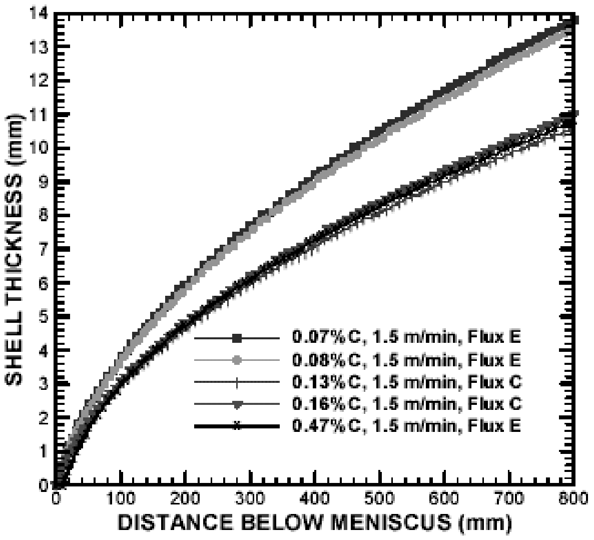

Figure 3c). Shell thickness for different steel grades for conditions in table V.

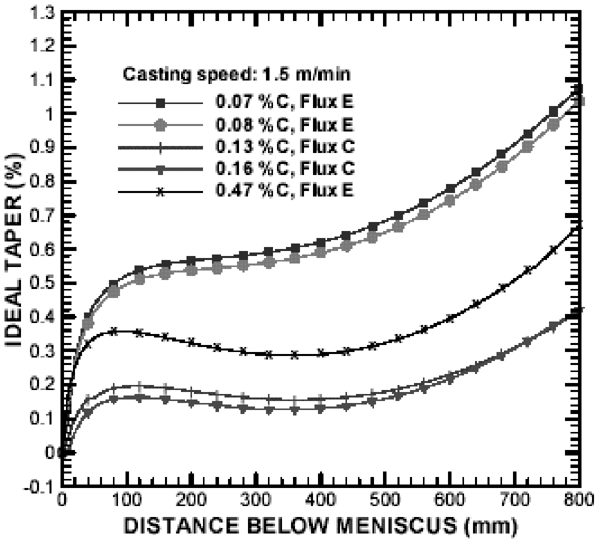

Figure 3d). Ideal taper for different steel grades for conditions in table V.

Results Interpretation

The optimal taper is difficult to predict, because the contribution from wide-face expansion and distortion depends on the state of clamping. If mold inclinometers are not available (and the taper is predicted based on the initial setup and relative position of the top and bottom screws holding the narrow faces), then the backlash in the screws is important. More than a few turns would allow wide face expansion to play a significant role, thereby requiring much less taper (making the "ideal taper" row – third to last row in Table II – the best prediction. This could be dangerous, however, if the screws were rigid, so that the narrow faces scraped a little against the wide faces, and didn't get extra taper due to the extra thermal expansion of the hot, upper wide faces.

We are more confident in the trends in figures 1-), than in the absolute values of the taper predictions.

Conclusions

1) More taper is needed for the higher heat flux, but less taper is needed at higher casting speed (due to less time in the mold and a hotter shell). These effects partly cancel, so the trend of increased taper with increased casting speed is not as great as expected.

2) More taper is needed near the top of the mold, such as achieved using parabolic taper.

3) Current practice shows slightly lower heat flux on the narrow faces of the FK12 and FK45 grades, suggesting that perhaps taper should be increased on those grades.

4) Mold width, mold thickness, and superheat (tundish temperature) are all expected to have only small effects on ideal mold taper.

5) Peritectic steels need less taper than either low or high carbon steels, owing to their lower heat flux, which is due in part to using a higher solidification temperature mold flux.

6) Mold distortion (especially wide face expansion) and behavior of the solid flux layers may significantly affect ideal taper and should be investigated further.

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