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The methods of calculating the solidifying strand shell thickness in a continuous casting machine

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ABSTRACT

Purpose: The steel solidifying process during continuous casting starts in the mould, where between 15 and 30% of total heat is abstracted. The strand withdrawn from the mould should have a solidified shell to ensure a failure free operation of the continuous caster. For a steel continuous casting process, it is necessary to obtain the correct shell thickness of the strand forming in the mould. If the shell thickness is insufficient, it will break out and the liquid core will leak, causing pouring of one or more segments of the machine. The presented paper shows the results of calculations of the shell thickness of the strand withdrawn, made with various mathematical models and the ProCAST software.

Design/methodology/approach: Three mathematical models with various degree of complexity with a complex numerical model were compared. Similar values of the strand shell thickness were have been received, and small differences result from the degree of complexity of the applied calculation models.

Findings: Similar findings related to the shell thickness were obtained. However, the use of more complex models is more likely to give correct and more accurate results.

Practical implications: For a failure-free steel continuous casting process, it is necessary to obtain the correct shell thickness of the strand forming in the continuous caster mould.

Originality/value: The presented paper compares the values of strand shell thickness obtained on the basis of mathematical models with various degree of complexity with a complex numerical model of the continuous casting process. Similar findings were obtained.

Keywords: Continuous casting process; Mould; Shell thickness

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The mould is one of the most important structural components of a continuous caster, and the success of the whole process depends on its correct operation. The mould is made of copper and has two wide walls (a fixed and a movable one) and two narrow walls, which are intensively water-cooled via a water channel system. The mould is the place of the first cooling stage of continuously cast steel, also known as the steel primary cooling stage. During cooling a solidified layer called shell forms, and its strength and thickness are the basic parameters of the continuous casting process.

The cooling of steel in the mould carries away between 15 to 30% of the total heat from the steel cast. The mould has the following basic tasks: to give the slab a pre-set shape and its lateral dimensions, to abstract heat from the solidifying steel, to provide a sufficiently thick and strong shell layer.

The mould length should ensure that a sufficiently thick solidified layer of strand forms, resistant to deformations and breakouts after leaving the primary cooling zone. If it is too long, it increases stress in the solidified layer, so its length has a decisive influence on the further properties of steel.

The amount of heat carried away from the mould walls is controlled by either changing the water flow rate through the mould or the cooling water temperature. However, there is no universal method for determining the optimum amount of heat abstracted in the mould, which is confirmed by the common occurrence of leakages caused by a breakout of the strand shell that was of insufficient thickness.

The annual number of breakouts largely depends on the applied method of heat transfer, and increases when cooling is insufficient. Therefore research is carried out around the world in order to determine the thickness of the shell of the strand forming in the mould. Most often, the shell thickness is determined immediately under the mould. [1-4]

2. Strand solidification and methods for determining the shell thickness in the mould

Steel solidification is a process of its transformation from liquid state to solid state. This process is accompanied by a decrease in the liquid volume and an increase in the solid phase volume. During the steel solidification, a crystalline structure is formed, and the growth of formed crystals occurs. The crystals precipitating from the liquid steel are called primary crystals, and the formed structure is known as the primary structure. The formed primary structure influences the further behaviour of steel during plastic working and, to some degree, the finished product properties.

Crystallization starts at a temperature in which the solid state has lower free energy than the liquid. At a certain temperature the free energy of the liquid substance is equal to the free energy of the solid, and at the same time the substance exists both in a liquid state and in a solid state. This temperature is called the equilibrium state temperature, or the theoretical crystallization temperature T_S and such a state is called the state of equilibrium. Above the equilibrium state temperature, a substance in its liquid state has lower free energy, and below this temperature the same substance has lower free energy in its solid state. Thus crystallization may only start when the free energy of the cooled liquid is lower than the free energy in the state of equilibrium. It is necessary to cool down the liquid below the theoretical crystallization temperature T_S, which is called liquid supercooling, and the magnitude of supercooling is called the degree of supercooling. However, the temperature at which the crystallization process commences is called actual crystallization temperature. Liquid steel is a multicomponent solution, and the above considerations only concern pure substances, and therefore the constitutional supercooling effect should also be considered.

The first stage of crystallization is the formation of crystallization nuclei, and the formation of the new nucleus-liquid interface, after which the formed nuclei may grow and increase their sizes. At a lower degree of supercooling, the difference between the free energy of liquid and the free energy of the forming nuclei is minimal, and therefore a small number of nuclei forms. A coarse-grained structure then develops because the nucleation rate is lower than the nucleus growth rate.

As the degree of supercooling grows, the difference between the free energy of liquid and the free energy of the forming solid nuclei increases, which causes an increase in the nucleation rate and the nucleus growth rate. In this case, the nucleation rate increase is higher than the increase in the nucleus growth rate. A large number of nuclei forms with a small growth tendency, and the structure of the solidified steel is fine-grained.

The knowledge of solidification laws is important for the operation of the steel continuous casting process, because:

- it allows the thickness of the solidified strand layer in the most hazardous places to be determined, for instance at the mould outlet,
- it enables the length of cast strand path to be determined,
- it enables the cast strand solidification rate, which influences its chemical inhomogeneity, to be determined.

The thickness of the solidified strand layer is often determined by a simplified method with the formula :

$$d = k \cdot \sqrt{t} \tag{1}$$

where:
d – thickness of the solidified layer, mm
t – time, min
k – solidification coefficient, also known as the solidification rate constant, $mm/min^{0.5}$

The solidification rate constant substantially depends on three factors: the dimensions of the cast strand cross-section, the temperature of steel superheating over the liquidus temperature, and the chemical composition of the steel cast and the cooling intensity.

The following may be rated among the methods for determining the cast strand solidification rate constant:

- the method of solidification temperature measurement with a set of thermocouples,
- the method of marking of the solidification front with radioactive isotopes or characteristic elements e.g. Pb, S,
- the method of pouring the non-solidified part of the cast strand.

With measurements of solidified layers of various cast strands, the solidification rate constant may be determined.

Examples of steel solidification coefficient values are presented in Table 1 [5].

An increase in the superheating of the steel cast reduces the value of the solidification rate coefficient. The dependency of the steel solidification coefficient k on steel superheating is presented in Table 2 [5]:

Table 1.
Average values of steel solidification rate coefficients

Melt number	Steel grade	Solidification coefficient, describe using method with radioactive isotopes, $mm/min^{0.5}$	Solidification coefficient, describe using method of pouring, $mm/min^{0.5}$
1	Carbon steel	22.4	-
2	34HN3M	30	23.4
3	St5	26	26
4	15G2S	26	-

Table 2.
The dependency of the steel solidification coefficient k on steel superheating above the liquidus temperature

Number	Superheating, K	Solidification coefficient, describe using method with radioactive isotopes, $mm/min^{0.5}$
1	10	26
2	45	20
3	60	16
4	80	13
5	100	10.5

A simple formula for calculation of the thickness of the shell of the forming strand is also given in the paper [6]. The formula is as follows:

$$d = 22.86\sqrt{t} - 3.05 \tag{2}$$

where:
d – shell thickness, mm
t – time, s

During the research conducted in the Department of Ferrous Metallurgy of the Faculty of Metals Engineering and Industrial Computer Science at the AGH University of Science and Technology, the following formula was used for the quick determination of the thickness of the forming strand shell:

$$d = \frac{\rho_w \cdot c_w \cdot G \cdot \Delta t}{\rho_s \cdot I_s \cdot l \cdot V + V \cdot a \cdot b \cdot \rho_s \cdot \Delta t \cdot c_s} \tag{3}$$

where:
d – shell thickness, m
ρ_w – water density, 1000 kg/m^3
c_w – water specific heat, 4200 J/kg K
G – flow rate of water cooling the mould, m^3/s
Δt – temperature difference of cooling water at the inlet and outlet of the mould, K
ρ_s – steel density, 7800 kg/m^3
I_s – steel enthalpy, 270000 J/kg
d – strand circumference, m
V – velocity of strand withdrawing, m/s
a – dimension of the first mould wall, m
b – dimension of the second mould wall, m
c_s – steel specific heat, 840 J/kg K

The obtained results were verified with the software package ProCAST 2010, in which the determination of the temperature field was possible by solving the generalized diffusion equation - the Fourier equation, which also describes heat transfer. In its general form the equation is written as follows [7]:

$$\nabla^T (\mathbf{K}\nabla T) + Q = c_p \rho \left(\frac{\partial T}{\partial t} + \mathbf{v}^T \nabla T \right) \tag{4}$$

where:
T – temperature, °C
K – matrix of thermal conductivity distribution function,
Q – heat generation rate, resulting from metal plastic deformation or phase transformations occurring in the material,
ρ – metal density at the temperature T, kg/m^3
c_p – specific heat at this temperature, m, J/kg K
v – velocity vector, m/s

The K matrix is defined as [7]:

$$\mathbf{K} = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \tag{5}$$

The solution of the heat problem being the T vector, representing temperature values in individual nodes of the finite element grid. The solution of the generalized diffusion equation - the Fourier equation - should meet the boundary conditions at the strand surface. The surfaces for which boundary conditions had been introduced were broken down into:

1. The primary cooling zone - the inner side of the mould - the solidifying strand surface
2. The secondary cooling zone
3. The surface of the liquid steel level
4. The water cooled mould insert outer side

For items 1, 2 and 4, the boundary condition was specified as the value of the heat transfer coefficient (a third-type condition). However for item 3, a first-type boundary condition (the Dirichlet condition) was applied.

In the ProCAST software, boundary conditions may be specified in three types. The equation below describes the second (the Neuman condition) and third types of boundary conditions [8]:

$$Q = Flux + h(T - T_a) + \sigma\varepsilon(T^4 - T_a^4) \tag{6}$$

The heat flux may be defined in the software directly as the Flux value (the Neuman condition), and with the convection (h - substitute heat-transfer coefficient) and radiation model (ε- emissivity) for heat transfer by radiation. The program allows calculations to be made with all three methods, but these calculations may also be conducted with only one method as chosen by the user.

In the model of heat transfer in the gap, two basic heat transfer mechanisms were assumed: by radiation and by conductivity. The radiation heat transfer coefficient [W/m^{2}K] was calculated from the radiation law between two flat surfaces slab - mold [9]:

$$h_r = \varepsilon_Z C_O \frac{T_P^4 - T_K^4}{T_P - T_K} \tag{7}$$

where:
ε_z – replacement emissivity coefficient
T_p – slab's surface temperature, K
T_k – mold's inner surface temperature, K

Heat transfer by radiation has been supplemented with the part defining the convectional heat transfer h_p derived from the empirical equation [9]:

$$h_P = (h_k - h_r)\exp^{\frac{T_P - T_{SO}}{200}} \tag{8}$$

where :
h_p – replacement coefficient of convectional heat transfer, W/m^{2}K
h_k – convectional heat transfer coefficient, W/m^{2}K
T_{SO} – solidus temperature, K

An outer side of a mold is cooled with water flowing through channels. Heat is transferred by the forced convection. Because of the way heat is absorbed by water flowing through the channel it is hard to determine the heat transfer coefficient for the mold's channels following available equations To find the Nusselt number, the equation has been chosen [10]:

$$Nu = 0.021 \mathrm{Re}^{0.8} \mathrm{Pr}_w^{0.43} \left(\frac{\mathrm{Pr}_W}{\mathrm{Pr}_K}\right)^{0.25} \tag{9}$$

where:
index w – for the mean water temperature in a channel
index k – for the strand's surface temperature

In order to compute the mean heat transfer coefficient h_{IV}, the following equation was used for the outer side of the mold [10]:

$$h_{IV} = \frac{Nu \lambda_W}{d_W} x_W \tag{10}$$

where:
x_W – the fraction of a surface cooled with water
d_W – the cooling channel diameter

3. Comparison of calculation results obtained with various methods

Using formulas 1-3 and software ProCAST, the strand shell thickness under the mould was calculated. Formula no. 1 is the most general, and the most elaborated calculation model was in the ProCAST software. Formulas 1-2 do not take into account the steel grade and the water flow rate in the mould channel and its dimensions. In formula no. 3, the shell thickness was determined by taking into account casting speed changes depending on the steel grade, mould dimensions and cooling water flow rate.

Examples of calculations obtained with formula no. 1 are presented in Tables 3a-d.

Examples of calculations obtained with formula no. 2 are presented in Table 4.

Examples of calculations obtained with formula no. 3 are presented in Table 5.

The changing shell thickness arises from fluctuations of the water flow rate in the mould.

Examples of calculations obtained with the ProCAST software are presented in Table 6.

The conducted calculations indicate that the strand shell thickness under the mould obtained with various calculation methods is similar.

The number of parameters considered in calculation models resulted in an increase in the accuracy of the results. In all calculations the strand shell thickness obtained ranged between 20 and 35 mm. The findings are similar to the assumptions used in industrial practice.

Table 3a.
Shell thicknesses calculated with formula no. 1, k = 22.4

d, mm	k, mm/min$^{0.5}$	t, min
2.24	22.4	0.1
4.48	22.4	0.2
6.72	22.4	0.3
8.96	22.4	0.4
11.2	22.4	0.5
13.44	22.4	0.6
15.68	22.4	0.7
17.92	22.4	0.8

Table 3b.
Shell thicknesses calculated with formula no. 1, k= 23.4

d, mm	k, mm/min$^{0.5}$	t, min
2.34	23.4	0.1
4.68	23.4	0.2
7.02	23.4	0.3
9.36	23.4	0.4
11.7	23.4	0.5
14.04	23.4	0.6
16.38	23.4	0.7
18.72	23.4	0.8

Table 3c.
Shell thicknesses calculated with formula no. 1, k= 26

d, mm	k, $mm/min^{0.5}$	t, min
2.6	26	0.1
5.2	26	0.2
7.8	26	0.3
10.4	26	0.4
13	26	0.5
15.6	26	0.6
18.2	26	0.7
20.8	26	0.8

Table 3d.
Shell thicknesses calculated with formula no. 1, k= 30

d, mm	k, $mm/min^{0.5}$	t, min
3	30	0.1
6	30	0.2
9	30	0.3
12	30	0.4
15	30	0.5
18	30	0.6
21	30	0.7
24	30	0.8

Table 4.
Shell thicknesses calculated with formula no. 2

d, mm	t, s
4.18	6
7.17	12
9.47	18
11.41	24
13.11	30
14.66	36
16.08	42
17.40	48

Table 5.
Shell thicknesses calculated with formula no. 3

Steel grade	Dimension of the slab, mm	Casting speed, mm/min	Shell thickness, mm
B500 SP	160 x 160	2-2.5	30-35
ETZ	220 x 1100	0.6	30-35
S235	220 x 1100	0.8	25-30

Table 6.
Shell thicknesses calculated with the ProCAST software

Steel grade	Dimension of the slab, mm	Casting speed, mm/min	Shell thickness, mm
PS235	220 x 1100	0.6	26
S235	220 x 1100	0.8	24

4. Conclusions

For a failure-free steel continuous casting process, it is necessary to obtain the correct shell thickness of the strand forming in the continuous caster mould. If the shell thickness is insufficient, it will break out and the liquid core will leak, causing pouring of one or more segments of the machine. Therefore a number of calculation models are used for the calculations of the shell thickness of the strand withdrawn. Most often calculations of distribution of the solid fraction in the solidifying strand are conducted for the strand at the mould outlet. These calculations should take account of the continuous caster design.

The presented paper compares the values of strand shell thickness obtained on the basis of models with various degree of complexity. Similar findings were obtained. However, the use of more complex models is more likely to give correct results.

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References

[1] A. Röhring, D. Kohl, D. Spor, F. Kawa, High-performance devices for billets continuous casting of the quality steel, Proceedings of the Continuous Casting Conference, Katowice, 1989, 14 (in Polish).

[2] H.F Schrewe, Continuous Casting of Steel, Stahl und Essen, Düsseldorf, 1989.

[3] M. Dziarmagowski, W. Kubiński, Selection rules of construction for COS casting machines, Metallurgy - Metallurgical Engineering News LVIII/12 (1991) 395-399 (in Polish).

[4] The making, shaping and treating of steel, 11th Edition Casting Volume, The AISE Steel Foundation, Pittsburgh, 2008.

[5] Z. Kudliński, Casting technologies, Gliwice, 2006 (in Polish).

[6] J.K Brimacombe, I.V Samasakera, J.E Lait, Solidification during continuous casting of steel, Continuous Casting - Heat Flow, Solidification and Crack Formation 2 (1984) 171-183.

[7] ProCAST 2010 User Manual.

[8] B.G. Thomas, Modelling of the continuous casting of steel - past, present and future, Metallurgical Transactions B 33/12 (2002) 795-812.

[9] T. Telejko, Z. Malinowski, M. Rywotycki, Analysis of heat transfer and fluid flow in continuous steel casting, Archives of Metallurgy and Materials 54 (2009) 837-844.

[10] M. Rywotycki, K. Miłkowska-Piszczek, L. Trębacz, Identification of the boundary conditions in the continuous casting of steel, Archives of Metallurgy and Materials 57 (2012) 385-393.