Mathematical modeling of the steel ingot teeming and the solidification process

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Abstract. The paper presents computer simulation-based findings on the teeming speed effect on the formation of the ingot structure and inner defects. It is reported that for a top-poured ingot, the average teeming speed (1.4-2.0 m/sec) proves to be the best choice as it is accompanied with a decreased number of surface defects and an increased metal yield resulting from a decreased shrinkage cavity.

1. Introduction

In spite of the fact that over the last years there has been a pronounced tendency in the growth of the amount of metal poured with continuous casters, up to 20% of metal is still top poured in ingots in electric furnace shops. Ingot quality is determined by such principal process parameters as teeming speed and melt temperature. The control of metal pouring temperature is more common compared with teeming speed control because there has not been much systematic research of the teeming speed yet.

It is a well-known fact that the amount of surface defects in top-poured ingots depends upon the nature of the stream effluence; the latter, in its turn, is determined by the pouring nozzle shape and metal teeming speed [1-4]. The major effect of the steel teeming process on the metal quality is noted in the works [5-9], which demonstrate a noticeable impact of the teeming rate on ingot macrostructure formation as well as the location, distribution and size of shrinkage defects in the ingot. Somehow, nowadays it is not common to use teeming speed to control the formation of the ingot structure and ingot internal defects.

Computer simulation is now widely commercially used not only to improve product quality, but also to cut down material costs and reduce new product development time [10, 11].

The paper is aimed at the analysis of the effect of steel teeming speed on steel ingot quality using a computer simulation of steel teeming and solidification processes.

2. Materials and methods

A method based on two software applications was developed for the research:

1) The LVMFlow application is designed to study metal convection flows and shrinkage defect location; a controlled volume method. The application makes it possible to visualize the process of mold filling with melt. The application was provided by the MKM Research and Development Shareholders Company Limited (the city of Izhevsk), Version No. 4.4r6 Time, License No. T0027.

2) The 'Crystal' computer simulation application developed to study the metal crystallization process with the finite difference method [12-15].

3. Results and Discussion

The metal teeming speed corresponded to the commercial rates of the metal level rise in the ingot and ranged from 0.7 to 2.5 meters per minute. While performing computer simulation with the LVMFlow application, the speed was altered by varying pouring nozzle diameters from 15 to 65 mm: the low teeming speed (0.7÷1.3 m/min) corresponded to the diameters from 15 to 30 mm; the average speed (1.4÷2.0 m/min) corresponded to the diameters from 30 to 54 mm, and the high speed (2.1÷2.5 m/min) corresponded to 45 up to 65 mm pouring nozzle diameters. In doing so, within each speed range, the effect of speed was studied at 0.1 m/minute intervals.

When analyzing the effect of the teeming speed on the alteration of model ingot crystal zone dimensions and the degree of shrinkage defects in them, the method of finite differences and the 3D modeling option in the LVMFlow application were used.

Since the main criterion for the top-poured ingot quality is the surface condition, it deemed of interest to evaluate the effect of the teeming speed on the spray process. When top pouring an ingot, spraying is the most intensive when liquid steel flow hits the ingot bottom. Consequently, the intensity of spray formation was assessed by the maximum elevation at which liquid metal drops rose from the ingot bottom at the beginning of teeming.

While modeling the teeming process, the following parameters were analyzed: circulation flow distribution throughout the ingot mass and solid phase build-up time when the mold was 50% full and 100% full.

The effect of the teeming speed on the solid phase build-up rate was assessed both with the LVMFlow application and a mathematical calculation:

$$Solid\ phase\ quantity = 100\ \% - X\ \%,$$

where 100% is the quantity of both liquid and solid phases; $X\ \%$ is the liquid phase quantity.

A comparative analysis of the effect of the teeming rate on the metal spray intensity at the beginning of pouring demonstrated that teeming at a low and a high speed intensifies the metal spray when a liquid steel flow hits the mold bottom; somehow, this phenomenon was not observed when pouring at an average speed. Figure 1 presents simulation results of spray types at the moment when the flow hits the mold bottom at various pouring speeds.

The maximum spray (splashes formed at the height corresponding to ¼ of the mold height ≈ 400 mm) was observed at the speed of 2.5 m/min. When poured at average teeming speeds, the spray was of the order of 70 to 120 mm, while at low teeming speeds, the spray varied from 60 to 150 mm. It is noteworthy that the maximum height of splash from the mold bottom was registered for the teeming speed of 1.1 m/min.
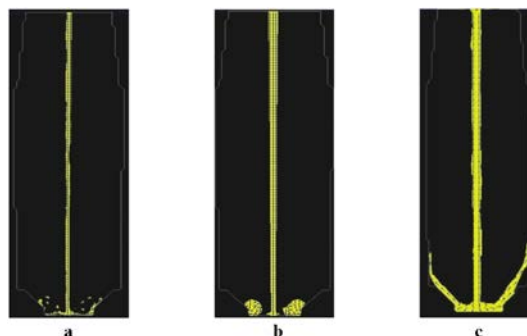

Figure 1. The schematic of spray formation at various teeming speeds: a) drop formation at a low speed; b) a uniform filling of the ingot with the melt poured at an average speed; c) the intense spray when teeming at a high speed.

When teeming at a low speed within the range of 0.7 to 1.0 m/min, a bad structure of the falling stream of metal was noted. The stream was characterized by loss of continuity and a distortion of the

flow structure. In addition, the low speed teeming results in heavy cooling of the melt: when the melt is poured into the mold, it loses part of it's overheat. It leads to an intensive oxidation which results in the increased quantity of oxides and increased porosity. Starting from the speed of 1.2 m/min up to 2.0 m/min, no intensive spray was observed due to the formation of a 'protective cushion' of the liquid metal in the mold bottom.

It was demonstrated that after the mold was approximately 50% full, steel flows emerged and started to circulate throughout the metal until the completion of teeming (Figure 2).
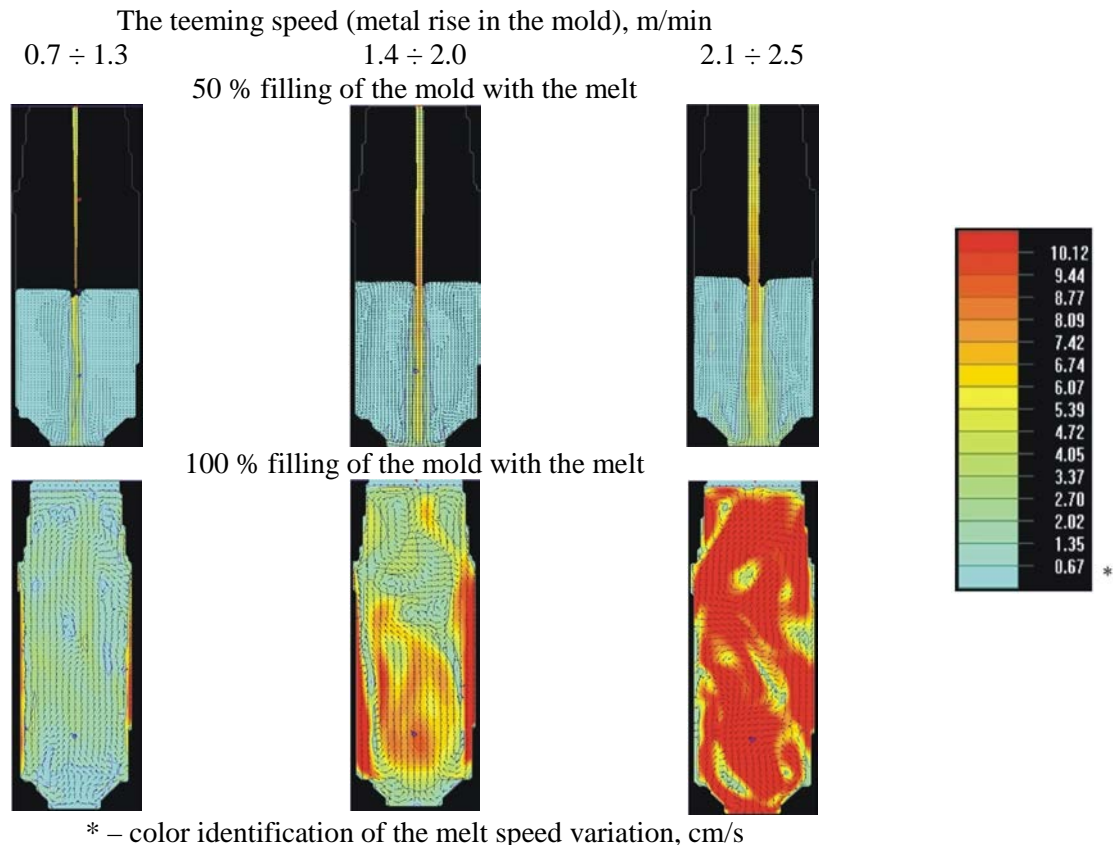
The teeming speed (metal rise in the mold), m/min

| 0.7 ÷ 1.3 | 1.4 ÷ 2.0 | 2.1 ÷ 2.5 |

50 % filling of the mold with the melt

100 % filling of the mold with the melt

* – color identification of the melt speed variation, cm/s

Figure 2. Liquid steel flow distribution while filling the mold with the melt.

The schematic shows that the intensity of liquid metal circulation flows notably increases with the rise in the teeming speed. When poured at a high teeming speed, the metal flow speed below the poured metal surface decreases approximately twofold when the stream reaches the mold bottom, and the stream diameter increases approximately by a factor of 1.5.

When teeming at an average speed, two classical circulation zones emerge inside the mold: those of rising and falling streams flowing at a speed of about 1.25 cm/s. The rising streams take up nearly 2/3 of the ingot cross-section and evenly rise from the bottom to the middle level. Starting from the middle level and up to the upper level, the flows chaotically mix up which might be caused by termination of teeming (stream effect) and the discard top effect.

The penetration depth of the metal stream while teeming at a low speed (0.7-1.3 m/min) is insignificant because the stream possesses low kinetic energy and cannot penetrate deeply into the melt. The characteristic speed of the circulation contour is the lowest and on the average equal to 0.7 cm/s. A low teeming speed results in a practically laminar flow of the melt, and in this case an upward and a downward flow circulation is observed. Based on speed color identifiers, the average value of the speed in this instance is 0.7 to 3.0 cm/s.
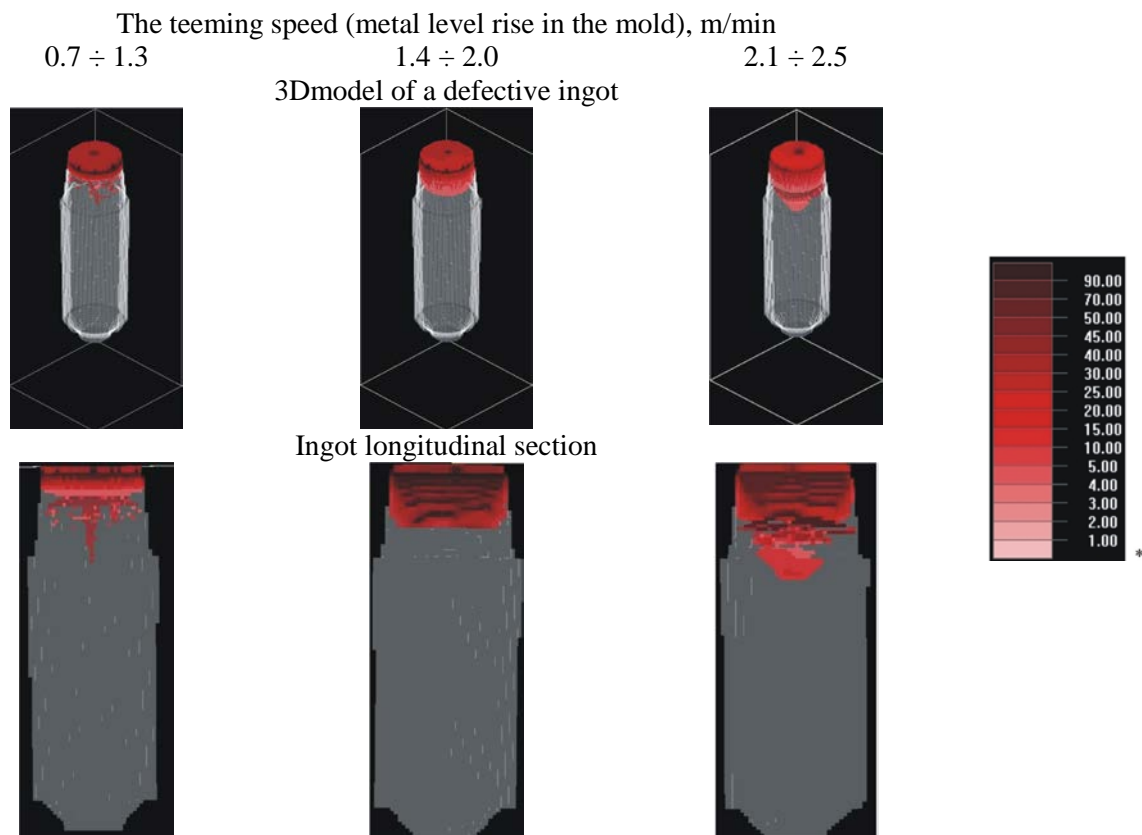
An increase of the teeming speed to 1.2 m/min leads to a more intensive flow circulation, and speed increases on the average to 6.0-8.0 cm/s (throughout the entire ingot). In doing so, the maximum speed is observed in the areas bordering on the mold walls (over 9.0 cm/s) and in the centre of the solidifying ingot within the lower and middle levels.

The study of the teeming speed effect on the intensity of the solid phase growth revealed that within each range of speeds the build-up of the solid phase remains practically the same: the quantity of the solid phase evenly grows within equal time intervals.

Somehow, the most intensive growth of the solid phase was observed in the low teeming speed group: for example, for the solidification time of 15 min, the solid phase quantity of 13 % corresponded to the speed of up to 1.3 m/min; for 8 % of the solid phase, the speed corresponded to the speed of up to 2.0 m/min; for 6 % of the solid phase quantity, the teeming speed was over 2.1 m/min. These figures can be explained by a noticeable cooling action of the mold walls on the relatively small quantity of the melt teemed from small diameter pouring nozzles. Somehow, as the crystallized layer is building up, heat conductivity decreases; it reduces the quantity of the solid phase formed. In this case, the teeming speed does not affect the solidification time because, according to the simulation, the ingots fully crystallize within two hours after the completion of teeming.

A 3D visualization of teeming and crystallization simulation using the LVM Flow application made it possible to locate and specify the typical dimensions of shrinkage defects in 4.5 ton ingots (see Figure 3).

The simulation with metal teeming speeds of up to 1.3 m/min showed the shrinkage cavity penetrated into the chill below the upper level. At average speeds, the shrinkage cavity, as a rule, is located mainly in the hot top metal. The maximum quantity of defects in the axial zone was observed at the teeming speed of above 2.3 m/min.

The teeming speed (metal level rise in the mold), m/min
0.7 ÷ 1.3   1.4 ÷ 2.0   2.1 ÷ 2.5
3Dmodel of a defective ingot

Ingot longitudinal section

* - color identification of the quantity of shrinkage defects in an ingot

Figure 3. A typical location of the shrinkage cavity inside the chill in a 3D model and in the model

axial section.

The metal teeming simulation results were used in the finite difference method to obtain data on the dimensions of typical structural zones for a 4.5 ton ingot; the data are presented in Table 1.

Table 1. The length of structural zones and physical non-heterogeneity zones of model ingots poured at various speeds (finite difference method)

Structural zone type	Zone extension (width) *					
	l, mm			% of the ingot height or diameter		
	teeming speed, m/min					
	0.7 ÷ 1.3	1.4 ÷ 2.0	2.1 ÷ 2.5	0.7 ÷ 1.3	1.4 ÷ 2.0	2.1 ÷ 2.5
Crust zone	14	11	9	2.2	1.74	1.42
Columnar dendrites	81	75	70	12.8	11.5	10.8
Equiaxial dendrites	135	141	137	21.6	22.38	21.3
Sedimentation cone**	593	605	688	29.8	30.5	34.6
Srinkage cavity**	339	309	358	15.1	11.0	18.1
Axial sponginess zone **	369	351	468	18.6	17.7	23.6

* structural zone extension was calculated as a mean value for the three levels
**over the chill height

The logging of the solid phase quantity data during solidification using the LVM Flow application and the measurement of solidified zone extension in solidified ingots using the 'Crystal' application showed that the crust thickness decreases by a factor of 1.5 with an increase in the teeming speed. The columnar crystal zone width decreases by a factor of 1.3 with the increase in the teeming speed, and the sedimentation cone height increases approximately by 1.6 %.

The depth of the shrinkage cavity penetration into the chill as well as the extension of the axial sponginess zone are the shortest at the average teeming speed. It is noteworthy that the volume of the axial sponginess zone reduces to 0.2 %. The computer simulation results showed that the teeming speed alteration effects both the location and dimensions of shrinkage defects.

4. Conclusion
Summing up, the control of the melt teeming speed is an important process parameter which can facilitate the production of ingots of the required structure with a convenient location of shrinkage defects and, thus, can improve the properties of the forgings produced. That is why, ingot quality control based on the properly chosen teeming speed is an important aspect of the ingot production process which does not require costly investment in the production process.

The use of various simulation models of steel teeming and crystallization combined with a metallographic study of the crystallized steel noticeably improves the predictive power of the models defect-wise; these defects can be eliminated in future by choosing optimal regimes of steel teeming.

Acknowledgments

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