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EFFECT OF TEMPERATURE FIELDS HETEROGENEITY IN THE TUNDISH ON PRIMARY STRUCTURE OF CONTINUOUSLY CAST INGOTS

WPŁYW NIEJEDNORODNOŚCI PÓL TEMPERATURY W KADZI POŚREDNIEJ NA STRUKTURĘ PIERWOTNĄ WLEWKÓW CIĄGŁYCH

The formation of the cast strands' primary structure is a very complex process in terms of the thermodynamics and physicochemical. It occurs during solidification and crystallization of the liquid steel in the crystallizer and in the secondary cooling zone of the CC device. On the basis of the experience gained in the industry and knowledge arising from theory of metals and alloys solidification it can be concluded, that substantial influence on the shape of cast strands primary structure have the temperature of overheating of the liquid steel above liquidus temperature and solidification velocity. A proper control of those casting parameters allows to obtain the cast strands with desired primary structure. In the one and two-way symmetric devices regulation like this is not problematic, in the multi-way devices – specially in the asymmetric – causes a series of problems. In those devices can occur a major temperature difference in each outlet zone of the tundish working space caused by i.e. the distance length diversity of liquid steel stream from the inlet to each outlet and by disadvantageous layout of liquid steel flow zones (turbulent flow zone, plug flow and dead zones) in working area of tundish. Particularly high values of those diversity can be expected in the asymmetric tundishes.

The article presents results of laboratory research – model and industrial regarding impact of the liquid steel overheating temperature, but also heterogeneity of the temperature fields in the tundish on primary structure of the cast strands.

Keywords: steel, steel continuous casting, physical modelling, primary structure

Tworzenie się struktury pierwotnej wlewków ciągłych jest bardzo złożonym, pod względem termodynamicznym i fizykochemicznym procesem. Zachodzi on w trakcie krzepnięcia i krystalizacji ciekłej stali w krystalizatorze i strefie wtórnego chłodzenia urządzenia COS. Na podstawie doświadczeń uzyskanych z praktyki przemysłowej oraz wiedzy wynikającej z teorii krzepnięcia metali i ich stopów można stwierdzić, że istotny wpływ na postać struktury pierwotnej wlewków ciągłych ma temperatura przegrzania ciekłej stali ponad temperaturę likwidus oraz prędkość krzepnięcia. Właściwa regulacja tych parametrów odlewania umożliwia uzyskiwanie wlewków o wymaganej strukturze pierwotnej. O ile w urządzeniach jednożyłowych i dwużyłowych symetrycznych taka regulacja nie stwarza większych problemów, to w urządzeniach wielożyłowych, a szczególnie niesymetrycznych nastręcza szereg problemów. W tego typu urządzeniach mogą wystąpić znaczne różnica temperatury w poszczególnych strefach wylewowych przestrzeni roboczej kadzi pośredniej, spowodowane np. zróżnicowaniem długości drogi dotarcia strumienia ciekłej stali z punktu wlewowego do poszczególnych wylewów i niekorzystnym układem stref przepływu ciekłej stali (strefy przepływu turbulentnego, tłokowego i stref martwych) w przestrzeni roboczej kadzi pośredniej. Szczególnie dużych wartości tych różnic można się spodziewać w kadziach niesymetrycznych.

W artykule przedstawiono wyniki badań laboratoryjnych – modelowych i przemysłowych dotyczących wpływu temperatury przegrzania ciekłej stali oraz niejednorodności pól temperaturowych w kadzi pośredniej na strukturę pierwotną wlewków stalowych.

1. Introduction

Metals and their alloys solidification defined as a change of state phenomenon (from liquid to solid) associated with emission of a certain amount of heat and the formation of the primary crystalline structure on the way of physically and chemically complicated crystallization process [1,2]. The primary structure formation process consists of two sub-processes running successively:

- nucleation of solid phase,
- growth of nucleus to crystals form.

The characteristic quantity of the solid phase nucleation process is the amount of the crystallization nuclei created in specific conditions in the unit of volume of liquid and during unit of time. On the other hand, the crystal growth of nuclei is characterized by the crystallization speed or linear speed of crystal growth.

Because of the complexity of the solidification and crystallization process during steel casting in CC device the primary structure of continuous ingots may consist of differential character areas (frozen crystals, columnar crystal, equiaxed

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crystals). From the point of view of ingots quality the aim is to obtain a homogeneous primary structure with the smallest equiaxed grains throughout the volume of the ingot. Such a structure provides the optimal course of further processing. To obtain required quality of ingots primary structure it is needed to identify process parameters that decides about the range of each crystallization zone on the surface of ingots cross-section. Identification of those parameters allows to efficiently control the CC process from the point of view of discussed issue.

2. Theory of solidification and crystallization

The change of physical state of metals and alloys, but also crystallographic form are classified as phase transition of the first type from the thermodynamic point of view. In contrast to the chemical transformation, during phase transformations the substance can change its form and physical properties, however, it remains the same substance in the chemical sense. Characteristic feature of all phase transitions is equality of Gibbs free energy in points of transitions. If the phase transition point is temperature then at constant pressure in the transition point Gibbs free energy of emerging solid phase is equal to Gibbs free energy of liquid phase. Phase's equilibrium state illustrates Fig. 1.

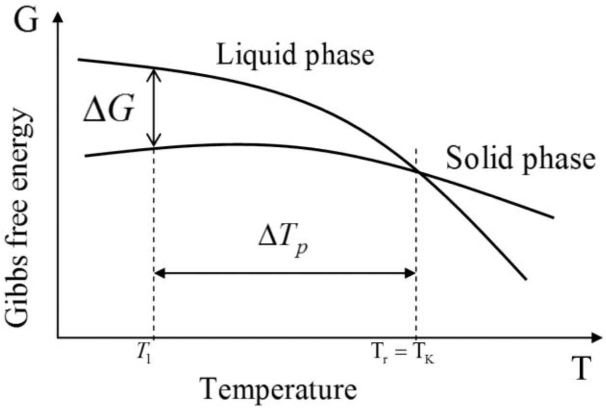

Fig. 1. Diagram of equilibrium phase during metals' solidification

Under the conditions different from equilibrium state the permanent phase is characterized by the one with less free energy. Lowering the temperature of system below the equilibrium temperature $T_r\,(T_r = T_K)$ leads to the formation of solid phase as a result of development of solidification and crystallization processes of liquid phase and reduction of system's Gibbs free energy by the ΔG amount (ΔG amount has a minus sign). This means that for the course of solidification and crystallization process is required determined overcooling state of the system – the temperature of the system has to be lower than the equilibrium temperature T_r, which is equal to solidification temperature T_K.

With the increase of overcooling occurs greater negative volume change of the Gibbs free energy, and thus the process of solidification and crystallization progress easier. In other words, the overcooling is the "driving force" of solidification and crystallization process of metals and their alloys.

$$(-)\Delta G = Q_K \frac{\Delta T_P}{T_K} \tag{1}$$

where:

ΔG – change of Gibbs free energy, $J \cdot kg^{-1}$,

Q_K – solidification heat, $J \cdot kg^{-1}$,

ΔT_p – overcooling, K,

T_K – solidification temperature, K.

3. Primary structure of a continuously cast ingots

Continuous ingots' primary structure of killed steel is formed under very complex in terms of thermal, chemical and physical processes of solidification and crystallization in CC device technological line. From the thermodynamic point of view important impact on primary structure formation of ingot have steel cooling intensity and it's degree of thermal overcooling, which are conditioning solidification rate. The final physical, chemical, macrostructural form of the ingot, and its mechanical properties depend on many phenomena that accompany solidification of killed steel, which as the most important are the following: division of the steel components in the range of temperature solidification, diffusion of components in the liquid phase, oxidation of steel components the on the solidification front, concentrational overcooling of the liquid phase, contraction.

Solidification of pure metals occurs only with thermal overcooling and negative temperature gradient in the liquid phase. In contrast, the solidification of alloys – including steel – also takes place with positive temperature gradient in front solidification [3-6]. It is believed that the cause of alloys solidification (steel) with positive temperature gradient in the liquid phase is the concentrational overcooling phenomenon as a result of steel compositions division in the range of solidification temperature due to variable solubility of the component in the liquid phase and solid phase. In the case of a lower solubility of the component in the solid phase (which occurs during solidification of Fe-C type alloy) in front of solidification "front" border layer is formed (so-called diffusion zone) with higher concentration of component compared to the initial concentration [4,7]. Distribution of component concentration in the diffusion zone δ in the analytical form illustrates Tiller's equation [4, 7]:

$$C_L = C_0 \cdot \left[1 + \frac{1-k_0}{k_0} \cdot \exp\left(-\frac{v_K \cdot x}{D_i}\right)\right] \tag{2}$$

where:

k_0 – equilibrium coefficient of i component division,

D_i – diffusion coefficient of i component in the liquid phase, $m^2 \cdot s^{-1}$,

v_K – linear solidification velocity, $m \cdot s^{-1}$,

x – distance from the solidification front, m,

C_0 – initial concentration of component in the liquid phase, kg · m^{-3}.

As can be seen from the analysis of equation (2) the linear solidification velocity v_K is a key factor for the amount of component concentration in front of solidification front: when $v_K \to \infty$ then $C_L \to C_0$.

Accordingly to concentration of the component, the distribution of liquidus temperature in the diffusion zone is determined by the equation:

$$T_L = T_K - m \cdot C_L \tag{3}$$

where:

T_K – solidification temperature (smelting) of basic metal (e.g. iron), K,

m – slope of liquidus in equilibrium system of basic metal – i component, K/%.

If at any distance x from the solidification “front” actual temperature of the liquid phase T_{rz} is lower than the equilibrium liquidus temperature T_L, the liquid in front of solidification ”front” is in concentrational overcooling state. This means that the concentrational overcooling ΔT_S exists only under conditions when actual temperature gradient G_r in front of solidification front is lower than the equilibrium liquidus temperature gradient:

$$G_r < \left(\frac{dT_L}{dx}\right)_{x\to 0} \tag{4}$$

Assuming that the actual temperature distribution in the diffusion zone is determined by the equation:

$$T_{rz} = \left(T_K - \frac{m \cdot C_0}{k_0}\right) + G_r \cdot x \tag{5}$$

then concentrational overcooling value relative to the equilibrium liquidus temperature at a $x_1$distance from the solidification front is:

$$\Delta T_S = T_L - T_{rz} \tag{6}$$

where:

T_{rz} – actual temperature, K,

x_1 – distance from the solidification front, m.

After taking into account equations (2), (3) and (5) equation (6) will adopt expanded and precise dependence of concentrational overcooling on the chemical composition of the alloy, temperature and solidification velocity of the liquid phase. With the increase of ΔT_S the G_r gradient decreases, and the surface topography of phase division (solid phase and a liquid phase) varies from macroscopically planar through the cellular to dendritic creating the appropriate structural forms of the solid phase. The mechanism of the solidification process also changes: from the gradual solidification (directional) to the volumetric solidification. The condition for stability of planar boundary phase division (flat solidification front) and hence the gradual solidification process is to maintain inequality:

$$\frac{G_r}{v_K} \geqslant -\frac{m \cdot C_0}{D_i} \cdot \frac{(1-k_0)}{k_0} \tag{7}$$

gdzie:

G_r – gradient of temperature on solidification front, K,

m – slope of liquidus in equilibrium system of basic metal – i component, K/%,

With the reverse dependence the solidification conditions favor the formation of dendritic crystalline structure – a characteristic for steel ingots. Graphically illustrated in Fig. 2.

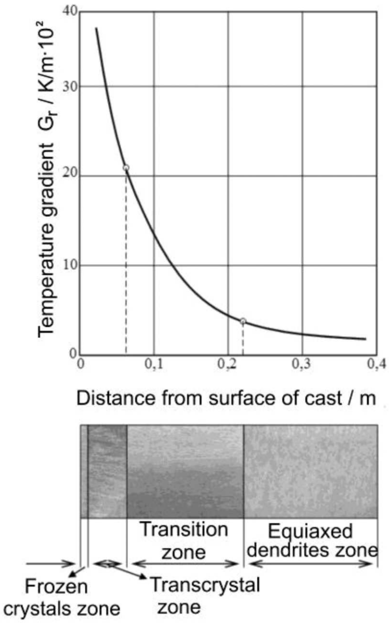

Fig. 2. Impact of the intensity of liquid steel cooling on ingot’s structural form

Ingot’s quality and macrostructure properties specifies the size of equiaxed crystals’ zone compared to steel cast’s cross-sectional area. The bigger area of equiaxed crystals’ zone is the better the quality of ingot’s macrostructure.

4. Model tests

Maintaining temperature homogeneity of the steel in the workspace of CC device’s tundish is a serious problem from the point of view of the quality of cast ingots. It has a significant impact on the character of forming primary structure in ingot. In the case of multi outlets tundishes, especially asymmetric [8], where the distances from the inlet point to each outlets are significantly varied due to the nature of flow, the distribution of temperature fields in a volume of liquid steel can be uneven. Research with the physical modeling nature of phenomena occurring in the temperature of the tundish is very difficult to achieve. Assuming that the distribution of the temperature fields in the working space of the tundish are related to nature of the liquid steel flow through it, by this method can be determined the trend of temperature distribution in the tundish. However, its objectification requires further verifying research in industrial conditions.

Model tests were conducted in the hydraulic physical model of the CC device, in which as the liquid steel modeling liquid water was used. Model has the character of segment model. In this type of models similarity rules are fulfilled by so-called main segment, and other segments serve as auxiliary elements. The main segment of the model is the construction element, in which relevant phenomena occur from the point of view of the expected results of the experiment. In the case of described model the main segment is a model of the tundish, and other structural elements (models of ladles, hydraulic system) serve as auxiliary segments. Fig. 3 presents the CC device’s physical model and the scheme of installed control and measurement apparatus.

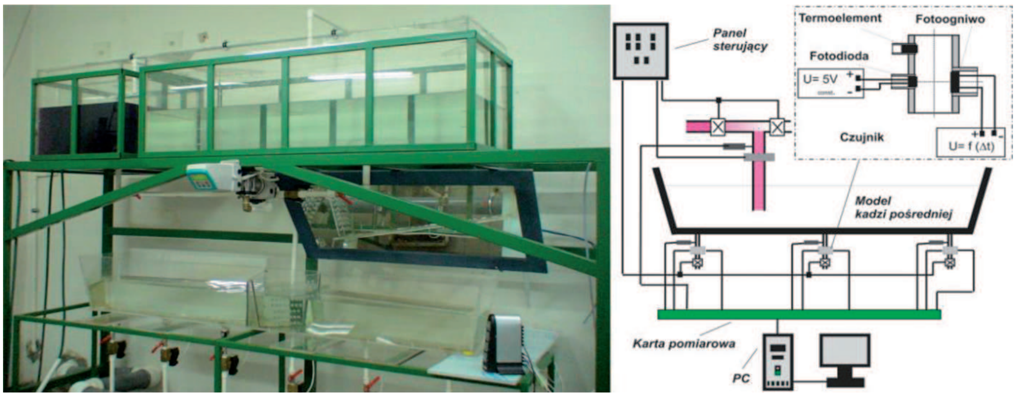

Fig. 3. The view of CC device's water model and scheme of control and measurement apparatus

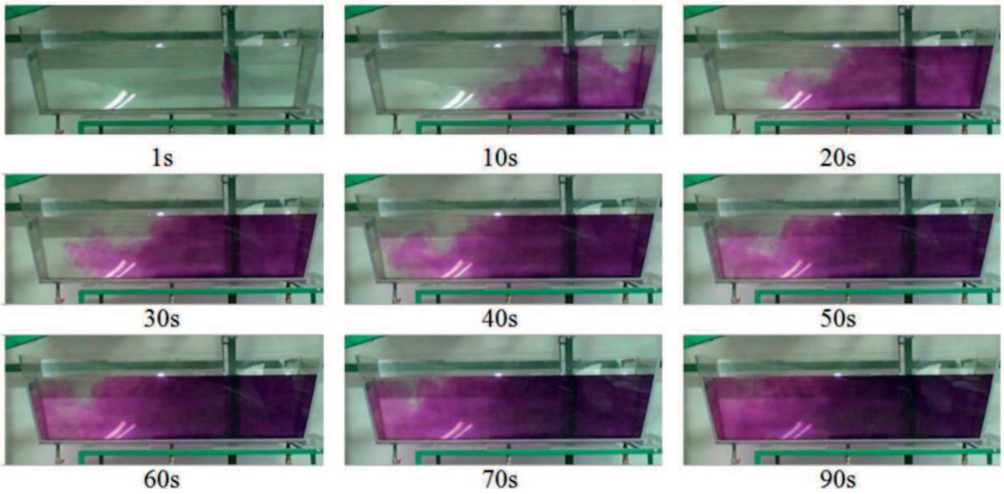
1s 10s 20s
30s 40s 50s
60s 70s 90s

Fig. 4. Example results of model tests with visualization character in the form of images for three-way tundish

The dominant similarity criterion of the model to industrial equipment is the Froude number (Fr). For the construction of physical model of industrial device as a linear scale reducing scale was adopted $S_L = 1 : 2 = 0{,}5$. The calculations of model flow velocity scales and flow time (S_Q i S_t) were made by assuming that in a real conditions cross-section of the cast ingot is 140 x 140 mm, with the casting speed $v_{odl} = 2\ \text{m}\cdot\text{min}^{-1} = 0{,}03\ \text{m}\cdot\text{s}^{-1}$. Physical model of steel CC device is designed for visualization character test and thanks to the installed measuring apparatus it enables the determination of residence curves – RTD [9-12].

Model tests with visualization character were conducted using as a marker aqueous solution of $KMnO_4$. Experiments were recorded by using a set of cameras. The results obtained in the form of film material were processed using specialized software. As the results images were obtained, which are presented in Fig.4.

As a result of research the insufficient mixing of model's liquid in the turbulent mixing zone was found. The turbulent flow is forced only by reflection of the liquid stream from the impact pad. This character of the turbulent flow zone does not provide the required steel's homogenization. The volume of this zone includes $2'^{nd}$ and $3'^{rd}$ outlets located within a short distance from the place of steel' stream entry into tundish. From the point of view of marker's retention time value in the working space of tundish's model outlets 2 and 3 are similar, but the nature of model's fluid flow in the area of the outlets varied. Stream created as the result of model's liquid rebound from the impact pad flowing around $3'^{rd}$ outlet bounces off of tundish model's side wall turning into the circulation flow. This is illustrated by a photo taken in $10'^{th}$ second of experiment. This area is essentially devoid of the piston flow. Piston flow zone is formed on the opposite side of the inlet area in the region of $2'^{nd}$ outlet ($20'^{th}$ second of the experiment) in the direction of $1'^{st}$ outlet. Piston flow front's moving speed is small, and model's liquid mixing in the region of 1'st outlet is very limited. This results in shaping of extensive dead zone in that region.

Analysis of obtained by model tests RTD curves, that are the response to the jumping extortion allowed the estimation of characteristic time constants τ i T0. The interpretation of these constants is as follows: τ – time needed for marker arrival from inlet point to tundish model outlet, T0 – time of model's liquid mixing needed to reach the concentration of marker specified by k amplification.

Calculated values of time constants τ and T0 of model liquid's flow in individual outlet zones of tundish model are presented in Table 1.

After calculating the time constants on the real conditions results were obtained, which are presented in graphical form in Fig. 5.

TABLE 1
The values of calculated time constants τ and T0 for three-way model of tundish

Outlet number	Time constant τ, s	Time constant T0, s
1	47	767
2	10	409
3	8	373

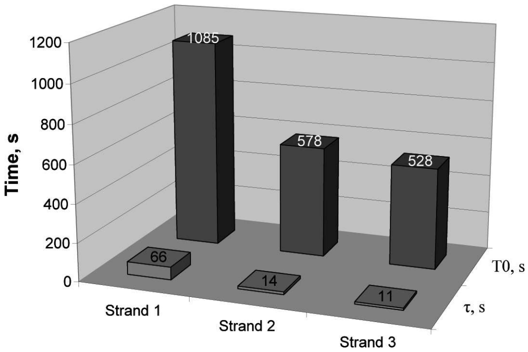

Fig. 5. Real values of time constants τ and T0 for three-way tundish of CC device

During the modeling of hydrodynamic processes occurring in asymmetric tundish was found a significant steel flow disturbance consists in a significant delay to the furthest outlet 1 in relation to outlets 2 and 3. The value of this delay on the basis of a time constant τ in real conditions determined on 52 s. Also, the mixing intensity of steel in the region of outlet 1 characterized by the time constant T0 is insufficient. These results of model tests were prerequisite to further studies on the thermal conditions prevailing in the researched tundish in industrial conditions. They should consist in measuring the temperature in the tundish and the mold. The results of these studies confirmed the expected effects of weak mixing of the steel in the region of outlet 1 on temperature decrease of the liquid steel in that area.

5. Industrial tests

Previously conducted model tests of hydrodynamic conditions in asymmetrical tundish, allowed to observe an adverse way of liquid steel flow through it. Based on that uneven temperature distribution of liquid steel in tundish working space it is possible, especially in the area of the furthest outlet. Therefore, the next stage of research was to conduct the temperature measurements of liquid steel in the tundish and molds under industrial conditions, then metallographic analysis of samples taken from ingots.

Before proceeding to temperature measurements of the liquid steel in the tundish and molds, a pilot studies were carried out to determine the technical conditions and possibilities of their realization, but also the methodology was developed of most advantageous from the point of view of minimizing their impact on the course of the technological process of continuous steel casting.

On the basis of pilot studies was found the necessity to expand the temperature measurement system in tundish that will be capable of obtaining results in three points, and use of continuous measurement system by using Contilance. It was also observed that for the temperature measuring of the steel in the molds optimum solution is to use Minilance with reusable sensors and without the steel cover, which limit the possible throw outs of liquid steel during their immersion in it. Because of the small size, which reduces the risk of impact on CC device's control system, which automatically reacts to the disturbances occuring in the mold by adjusting casting parameters e.g. changing the linear casting speed.

Pilot studies executed in such way under industrial conditions allowed to develop a precise program of research possible to achieve under movable conditions, determining the points of temperature measuring in the tundish and molds, the possibility of using steelworks' existing measuring apparatus and the ability to install and use of additional equipment needed for conduct the tests in a proper way. Scheme of temperature measurement system in tundish presents Fig. 6.

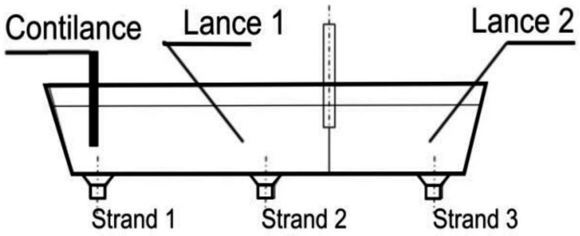

Fig. 6. Scheme of temperature measurement points in CC device's tundish

Measurements were made by using two lances with standard sensors immersed in the regions of outlets 2 and 3. In the region of outlet No. 1 Contilance installed on CC device for continuous measurement of temperature was used. For easy identification of each test cast, it was marked with WB symbol and numbered by consecutive digits from 1 to 5. The measurements were conducted in a series of three for each cast. 1'st measurement at the start of casting, 2'nd measurement in the middle, and 3'rd measurement at it's end. Temperature measurements in molds were conducted in parallel with measurements in tundish in such a way that they include the same batch of the cast steel.

A series of temperature measurement in tundish and molds were performed according to the methodology, during casting of 6 test casts of S480W steel marked with symbols WB1 ÷ WB5. The chemical composition of tested steel is shown in Table 2.

TABLE 2
Chemical composition of researched steel, %

	C	Mn	Si	P	S	Cr	Ni	Cu
min	-	-	-	-	-	0,25	-	0,25
max	0,25	1,70	0,50	0,035	0,035	0,45	0,30	0,45

Liquidus temperature of the cast steel was 1501°C and nominal casting temperature was 1535°C. The cross-section of ingots was 140×140 mm. Ingots were cast with use of feeding technique with lubrication of mold's walls using rapeseed oil. Feeder's channel diameter was 16.5 mm. Applied molds were Convex type with height of 801 mm and arc radius of 6000 mm.

Fig.7 graphically illustrates example results of temperature measurements in the tundish and molds for WB1 smelt.

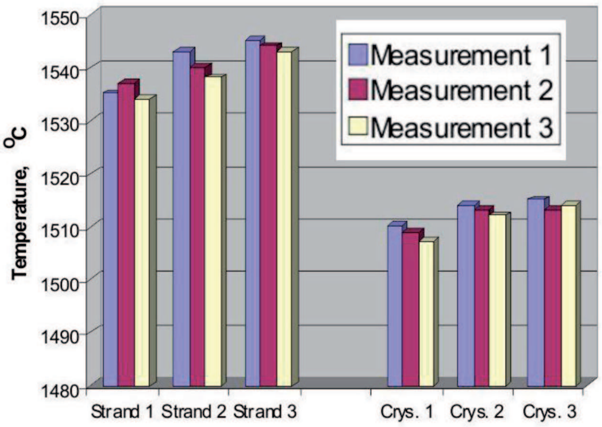

Fig. 7. Values of temperature measured in tundish and molds for WB1 smelt

Conducted temperature measurements of liquid steel indicate it’s diversity in different zones of tundish. In the region of outlets 2 and 3, it is minor and difference in liquid steel temperature varies near 5°C. However, in the region of outlet 1 a significant temperature decrease of liquid steel was noted in comparison to zone of outlet 3 reaching even 20°C. Steel in 1’st strand’s mold has a temperature significantly lower than the steel in the 2’nd and 3’rd molds’ strands.

Temperature results of conducted measurements confirm the expectations arising from model studies concerning the hydrodynamic phenomena in tundish.

6. Ingots primary macrostructure research

Ingot’s quality and macrostructure properties specifies the size of equiaxed crystals’ zone compared to steel ingot’s cross-sectional area. The bigger area of equiaxed crystals’ zone is the better the quality of ingot’s macrostructure.

The greatest impact on ingot’s primary structure have:

- ingot’s cross-sectional dimensions,
- steel’s chemical composition,
- liquid steel’s temperature,
- casting speed,
- ingot’s cooling intensity.

Taking into account that the parameters of the casting for all strands of CC device are identical, the main influence on the quality of the primary structure of the ingot has temperature of liquid steel in the tundish. Results of the measurements in researched tundish and molds showed differentiation between the strands of the device resulting from inappropriate hydrodynamic conditions prevailing in it. Therefore, differences can also be expected in size of the crystallization zones within ingots cast in each steel strand.

Developed research methodology of ingots’ macrostructure was divided into two stages:

- taking of samples from cast strands (templets),
- metallographic tests.

Taking samples from ingots were synchronized with temperature measurements of liquid steel in tundish and molds. This was done by cutting templets using gas cutting machines in these zones of cast strands, in which previously were measured the temperatures (start, middle and end of smelting). Parameters of casting and cooling in all strands were identical. Metallographic tests of samples was conducted by deep digestion. Exemplary results of metallographic researches are shown in Fig. 8. These present samples taken from WB1 smelting.

Metallographic researches analysis of the results indicated, that while ingots cast in strands 2 and 3, columnar crystals zone dimensions are similar ingots cast in the strand 1 have significantly smaller zone. The values of the percentage share of columnar crystals area in each ingots are shown in Table 3.

TABLE 3
Percentage share of the columnar crystals zone on the surface of metallographic microsection

Cast symbol	**Share of the columnar crystals zone, %**			
		Strand 1	**Strand 2**	**Strand 3**
WB1	beginning of cast	25,93	39,32	44,53
	middle of cast	19,60	42,30	33,31
	end of cast	25,61	37,95	35,41

The obtained results allow to conclude that the hydrodynamic conditions prevailing in the tundish of CC device, characterized by improper proportions of individual flow zones: too small area of of the piston and turbulent flow, while a considerable area of dead flow, are the cause of uneven distribution of temperature fields in the working space of tundish, and in consequece, differences in the crystallization zone sizes compared to cross-sectional area of ingots cast in each strands of CC device. This situation is also disadvantageous from the point of view of the energy balance of the steel casting process,

strand 1 strand 2 strand 3

Fig. 8. Macrostructure of ingots’ cross-section measuring 140×140 mm, middle of WB1 smelt

because it requires a higher degree of steel overheating before casting to prevent steel freezing in the furthest outlet.

7. Conclusions

On the basis of tests performed following conclusions were formulated:

1. Homogenization processes occuring in the working space of tundish have a significant impact on the formation of crystallization zones in ingots' primary structure cast in individual veins.
2. From the thermal point of view, the main parameter of CC process, having an influence on range of the formation of columnar crystals zone in ingots' primary structure is steel overheating temperature.
3. The higher the degree of steel overheating, the greater the range of columnar crystals zone in ingots' primary structure.
4. A particular problem during ingots casting in devices equipped in asymmetrical multi-outlets tundishes, is getting ingots' with similar character of primary structure in terms of crystallization zones range.
5. Much longer time needed for steel to reach the furthest strand (strand 1) of asymmetrical three-way tundish, than the other strands (2 and 3) enforces the use of a higher overheat degree of steel in ladle. This fact negatively affect the CC process from two points of view:
   - energy losses of the process,
   - obtained ingots in strands 2 and 3 are characterized by a greater range of columnar crystals zone, than ingots from strand 1.
6. Applying appropriate liquid steel flow regulators in the working space of the tundish, which provide optimal homogenization favors the formation of similar in terms of individual crystallization zones range of ingots primary structure in each strand of CC device equipped with asymmetrical tundish.

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