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THE INFLUENCE OF THE NEAR-MENISCUS ZONE IN CONTINUOUS CASTING MOLD ON THE SURFACE QUALITY OF THE CONTINUOUS CASTING INGOTS

WPŁYW STREFY PRZYMENISKOWEJ W KRYSTALIZATORZE COS NA JAKOŚĆ POWIERZCHNI WLEWKÓW CIĄGŁYCH

The physical, chemical and mechanical phenomena which take place in the near-meniscus zone of continuous casting mold are the significant factors influencing the quality of CC ingot and especially the quality of its surface. Such phenomena consist of the following processes: lubrication of the ingot surface by the liquid slag-forming phase of mold powder, creation of meniscus, formation of the specific kind of galvanic cell and connected with this cell ions migration of liquid mold powder. Application of the mold powders is the commonly used lubrication method of the surface of CC ingots in mold (in near-meniscus zone). According to the ionic structure theory of the liquid metallurgical slags the following thesis can be formulated: the liquid slag-forming phase of mold powder is the ionic liquid. The ionic liquid occurs between two metals: the copper wall of mold and the steel surface of ingot can create a specific kind of galvanic cell in the upper part of mold (the near-meniscus zone of mold). The paper presents results of industrial research of low-carbon steel continuous casting. The electromotive force of galvanic cell situated in the upper (near-meniscus) part of CC mold was measured. Moreover, the influence of applied powders with different alkalinity on the character of oscillatory marks forming on the ingot surface was considered. The galvanic cell, which is created in the upper part of mold in the near-meniscus zone, can cause the essential change of the chemical composition of electrolyte (liquid phase of mold powder) in the near-electrodes zones. So in the process the condition of lubrication and character of obtained oscillatory mark can also be changed.
Keywords: quality of CC ingot, oscillation marks, galvanic cell, near-meniscus zone in mold

Istotnym czynnikiem wpływającym na jakość wlewka ciągłego a zwłaszcza jakość jego powierzchni są zjawiska fizyczne, chemiczne i mechaniczne zachodzące w strefie przymeniskowej krystalizatora COS. Do zjawisk tych należy między innymi zaliczyć: „smarowanie" powierzchni wlewka ciekłą fazą żużlotwórczą zasypki, powstawanie menisku, tworzenie się specyficznego rodzaju ogniwa galwanicznego i związana z nim migracja jonów ciekłej zasypki. Powszechnie stosowaną metodą smarowania powierzchni wlewka ciągłego w krystalizatorze – w strefie przymeniskowej – jest stosowanie zasypek krystalizatorowych. Powołując się na teorię jonowej budowy ciekłych żużli metalurgicznych można postawić tezę że ciekła żużlotwórcza faza zasypki krystalizatorowej jest cieczą jonową. Występując między dwoma metalami – miedzianą ścianką krystalizatora i żelazną (stalową) powierzchnią wlewka może utworzyć szczególny rodzaj ogniwa galwanicznego w górnej części krystalizatora (strefa przymeniskowa krystalizatora). W artykule przedstawiono wyniki badań przemysłowych siły elektromotorycznej ogniwa usytuowanego w górnej (przymeniskowej) części krystalizatora COS podczas ciągłego odlewania stali niskowęglowej. Przedstawiono również wyniki badań przemysłowych wpływu stosowanych zasypek krystalizatorowych, różniących się zasadowością, na charakter znaków oscylacyjnych powstających na powierzchni wlewka ciągłego. Występowanie ogniwa galwanicznego w górnej części krystalizatora w tzw. strefie przymeniskowej może w istotny sposób powodować zmianę składu chemicznego elektrolitu (ciekłej fazy zasypki) w obszarach przyelektrodowych a tym samym warunków smarowania i charakteru otrzymywanych śladów oscylacyjnych.

1. Meniscus area in a mold

The term "meniscus area" is used to name the top part of the mold, at the surface of liquid steel (Fig. 1). Geometrical parameters of the meniscus (its radius and height) affect essentially the process of creating a solidified ingot layer, and at the same time the quality of an ingot surface.

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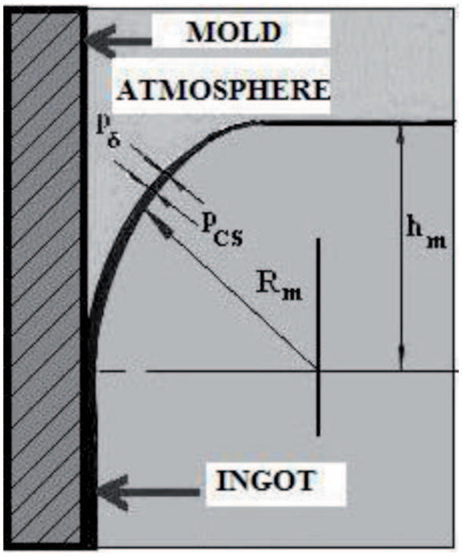

Fig. 1. A convex meniscus of liquid steel near the mold wall [1]

From the equivalence of the surface tension pressure P_σ and the ferrostatic pressure P_{CS} of steel at the meniscus surface we can determine the meniscus radius R_m [2]:

$$R_m \cong 1,699 \cdot \sqrt{\frac{\sigma_{CS}}{g \cdot \rho_{CS}}} \qquad (1)$$

where: σ_{CS} – surface tension of liquid steel , $N{\cdot}m^{-1}$,

ρ_{CS} – density of liquid steel, $kg{\cdot}m^{-3}$.

As a result of a cooling effect of the mold and the surrounding atmosphere the ingot skin begins to form as early as when at the meniscus surface. Under the influence of the ferrostatic pressure of liquid steel the skin is straightened along the mold. Covering the top surface of steel in the mold with the molten slag, produced as a result of melting the casting powder, causes the surface properties of the liquid steel to be changed. In such the case its radius is defined with the expression:

$$R_m^Z \cong 1,699 \cdot \sqrt{\frac{\sigma_{CS-Z}}{g \cdot (\rho_{CS} - \rho_Z)}} \qquad (2)$$

where: $\sigma_{CS-\dot{Z}Z}$ – interphase tension at the boundary between the liquid steel and the liquid phase of the casting powder, $N{\cdot}m^{-1}$,

$\rho_{\dot{Z}Z}$ – density of liquid phase of the casting powder, $kg{\cdot}m^{-3}$,

g – acceleration of gravity, $m{\cdot}s^{-2}$.

As can be seen from the analyses of the formulas (1-2), there is a possibility to affect the meniscus parameters by means of liquid phase of the casting powder. The lower meniscus radius means also its lower height and a lower probability of forming the superficial defects of concast ingots, such as folds, curling dies and fractures.

2. Galvanic cell of the Cu/casting powder liquid phase/Fe type

From the thermodynamic point of view the upper part of the mold (the zone of contact of liquid steel and liquid phase of the casting powder, together with the copper wall of the mold) creates a special kind of a galvanic cell (Fig. 2). The source of electromotive force of such the cell is a difference of potentials of iron (the steel ingot) and copper (the mold wall) – resulting from the electromotive series of metals – as well as a difference of potentials resulting from the temperature differences at the border between two different metals (a thermoelectric force).

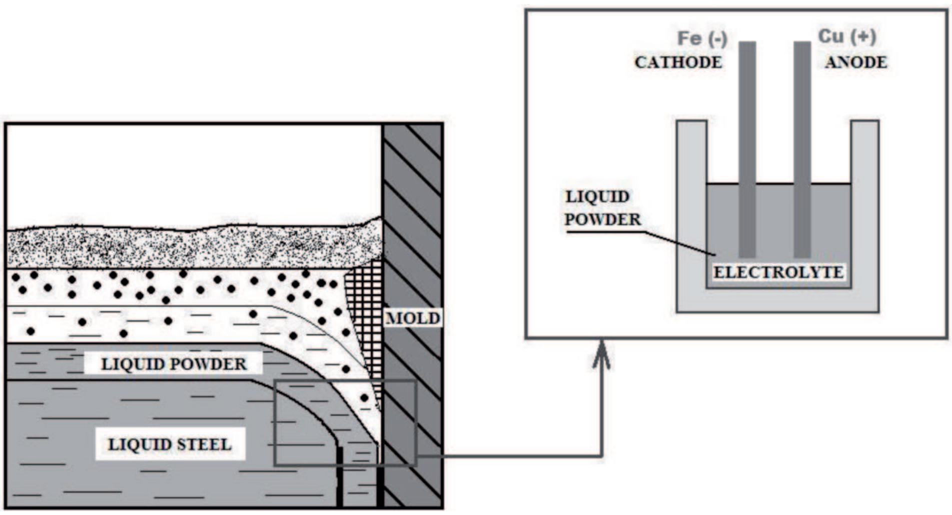

Fig. 2. Schematic diagram of a galvanic cell at the meniscus area in a mold

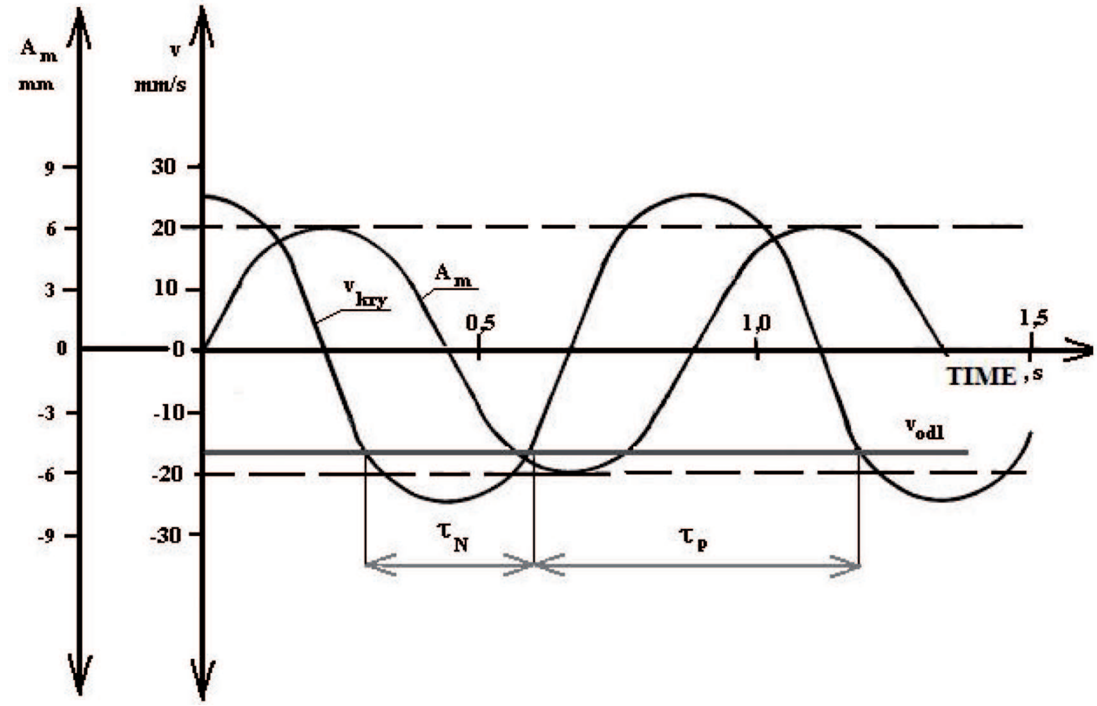

Fig. 3. Diagram of a mold oscillation [1]

The role of electrolyte, according to ionic theory of the metallurgical slug structure, is played by the liquid phase of the casting powder, filling the space between the solidifying ingot and the mold wall.

3. Oscillation of the mold

The oscillation of the mold prevent the ingot skin adhering (sticking) to the copper walls especially in its upper part, the so-called meniscus area. The principle of the oscillation of the mold consists in its regular raising and dropping with the predefined amplitude and frequency, independently of the motion of the concast slab, drawn down the mold with a constant speed. Many years research works have proven that the mold downward motion with a speed higher than the speed of the ingot drawing from the mold (the continuous casting speed) results in improvements in quality of the surface of the manufactured concast ingots: the skin is detached from the mold walls under the influence of the low compressive stress and is not subjected to tensile stresses. With the use of the casting powders (as lubricating material) and the immersion nozzles, feeding liquid steel to the mold, a special role in the oscillation of the mold is played by advance time (a negative strip time) τ_N – Fig. 3:

$$x\tau_{\mathrm{N}} = \frac{60}{\pi \cdot \mathrm{f_{kry}}} \cdot \arccos \frac{1000 \cdot \mathrm{v_{odl}}}{\pi \cdot \mathrm{A_m} \cdot \mathrm{f_{kry}}} \tag{3}$$

where: A_m – oscillation amplitude (stroke), mm,

f_{kry} – frequency, stroke/min

v_{odl} – casting speed, m/min.

The higher the value of the mold advance time (the negative strip time) is, the thinner the layer of the slag formed between the ingot surface and the copper wall occurs. The values of the advance time used in practice are within the interval from 0.08 to 0.15 s. The casting powder consumption and the depth of oscillation marks on the concast ingot surface depend on the positive strip time τ_P, defined by the formula:

$$\tau_{\mathrm{P}} = \frac{60}{\mathrm{f_{kry}}} - \tau_{\mathrm{N}} \tag{4}$$

The lower the positive strip time gives the lower consumption of the casting powder and the lower depth of oscillation marks. Parameters of the oscillation of mold are one of the factors affecting the characteristics of oscillation marks on the concast ingot surface.

4. Oscillation marks on concast ingots surfaces

The oscillation of the mold in CC devices contributes to forming oscillation marks on concast ingot surfaces. The oscillation marks are parallel to each other on the ingot surface and perpendicular to the direction of the ingot drawing from the mold (Fig. 4).

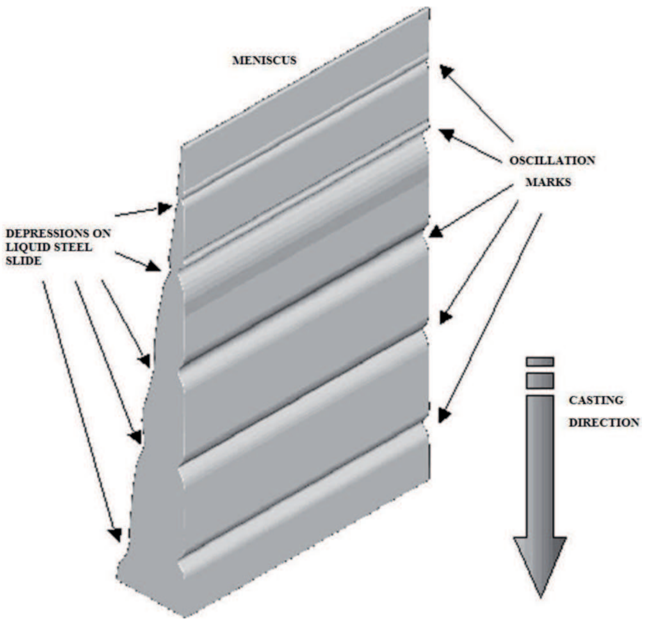

Fig. 4. Schematic representation of oscillation marks on ingot surfaces [2]

A distance l between oscillation marks on concast ingot surfaces is defined by the formula (5):

$$l = \frac{V_{odl}}{f_{kry}}, \mathrm{m} \quad (5)$$

The oscillation marks can create defects on ingots surface in the process of continuous casting. The mechanism of creating the oscillation marks is very complex and is a result of overlapping effects of many physical phenomena, which vary in time in the meniscus area (Fig. 5): fluctuations in liquid steel pressure, melting of casting powder, variations in metal-slag interphase tension, heat dissipation, deformations in the skin formed during oscillations.

There is however a common opinion that the main casting process parameter, affecting the mark creating, is the negative strip time – its increase results in larger depth of the oscillation marks on the ingot surface. The decrease in viscosity of the casting powder (increase in its level of alkalinity) causes improvement in lubrication between the ingot surface and the copper mold wall, and generates smaller oscillation marks on the ingot surface. With increase in viscosity the slag-forming phase of the crystallizer's powder finds more difficulties when flows into the gap between the solidifying ingot and the crystallizer's wall. However, when the viscosity is too high, then the slag layer is thin and incoherent. The optimum viscosity of the slag of the casting powder is closely connected with the sort of casted steel, the casting speed and oscillation.

5. Research of the influence of the casting powder on the character of oscillation marks forming on the ingot surfaces

The research works have been carried on in industrial conditions in Ferrostal Łabędy Metallurgical Plant in Gliwice, Poland, within the framework of the process of continuous casting of 31MN4 steel of the following chemical composition: C = 0.29%, Mn = 0.90%, Si = 0.30%, P = 0.02%, Cu = 0.30%, S=0.012%, on the triple-channel CC device (Fig. 6) of the following characteristics:

- A_m– oscillation amplitude 10 mm,
- f_{kry}– frequency, 200 stroke /min,
- v_{odl}– casting speed 1,91 m/min,
- negative strip time 0,09÷0,12 s

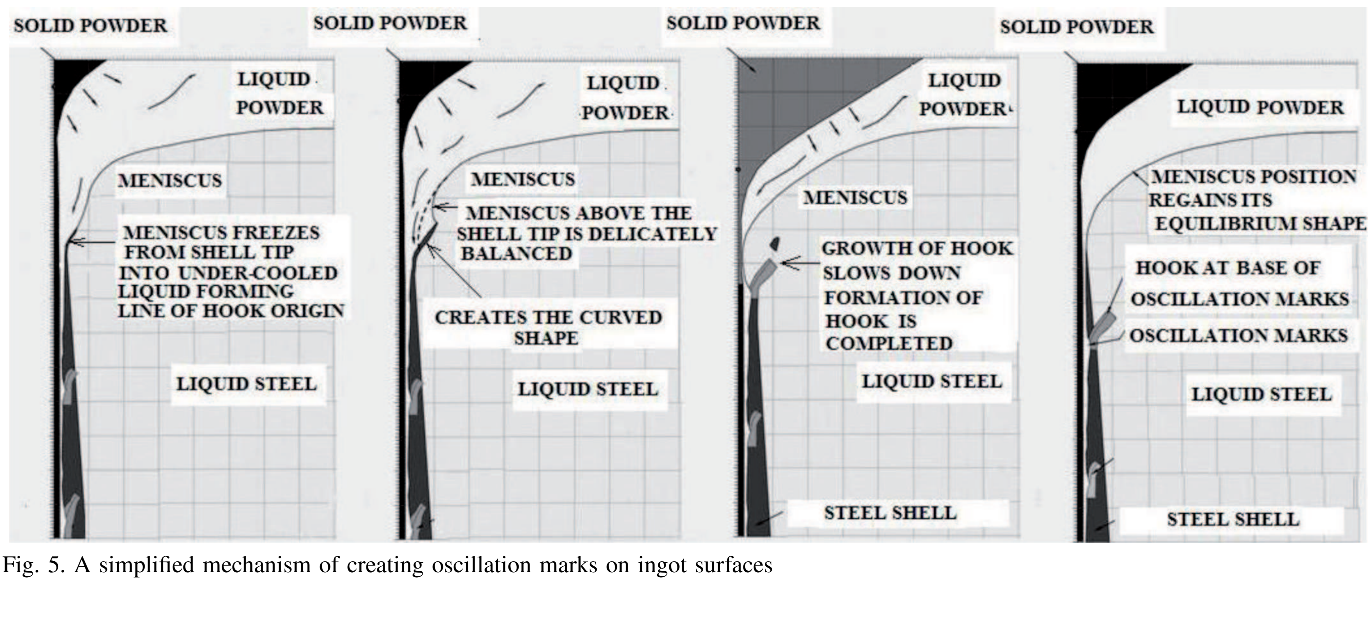

Fig. 5. A simplified mechanism of creating oscillation marks on ingot surfaces

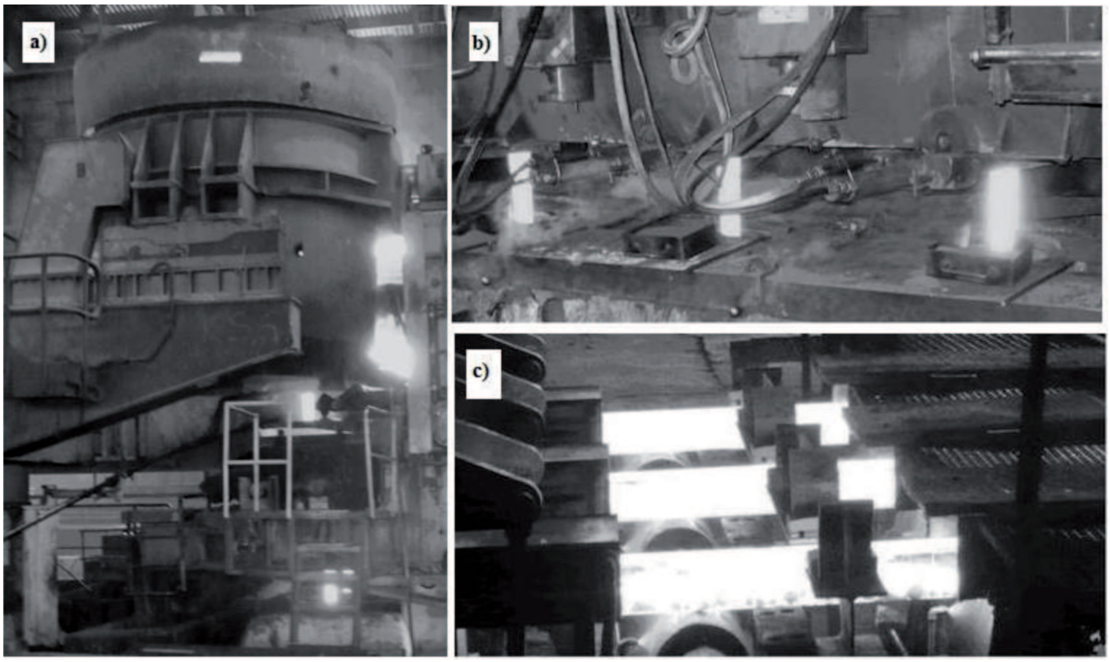

Fig. 6. View of Ferrostal Łabędy CC device: a) general view, b) immersion nozzles, c) casted ingots

The steel has been casted into ingots of 140×165 mm cross-section area. During the process of casting in two channels of mold we have used at the same time two casting powders, differing in chemical composition (Table 1).

The research results, in form of images presenting the oscillation mark cross sections, as well as their dimensions (especially the mark's depth) are presented in Fig. 7 and Fig. 8. Basing on the presented microscopic images of the oscillation marks we can state that the use of Scoriolit casting powder in the process of steel casting in the mold causes the oscillation marks to be shorter and of lesser depth than in case of use Accutherm casting powder (when the oscillation marks are longer and of greater depth). This fact can be probably explained by differences in alkalinity levels of the casting powders used, connected with powder's viscosity and SiO_2 contents.

TABLE 1

Chemical composition and selected properties of the casting powders used within the frameworks of the industrial research works

Powder's chemical composition [%]	Powder Scorialit SPH-C 411-81/E	Powder Accutherm ST-SP/521-GL-1
SiO_2	25,0÷27,0 %	29,3÷32,3 %
CaO + MgO	23,0÷25,0 %	
CaO		17,1÷20,1 %
MgO		0,9÷1,9 %
Al_2O_3	10,0÷11,5 %	4,3÷5,8 %
$Na_2O + K_2O$	4,0÷5,5 %	
Fe_2O_3	2,5÷4,0 %	<1,5 %
Na_2O		8,3÷9,8 %
K_2O		<1,0 %
Li_2O		<0,3 %
C_{total}	18,0÷20,0 %	21,1÷23,6 %
F	4,5÷6,0 %	5,0÷6,0 %
Level of alkalinity CaO/SiO_2	0,82÷0,94	0,55÷0,65

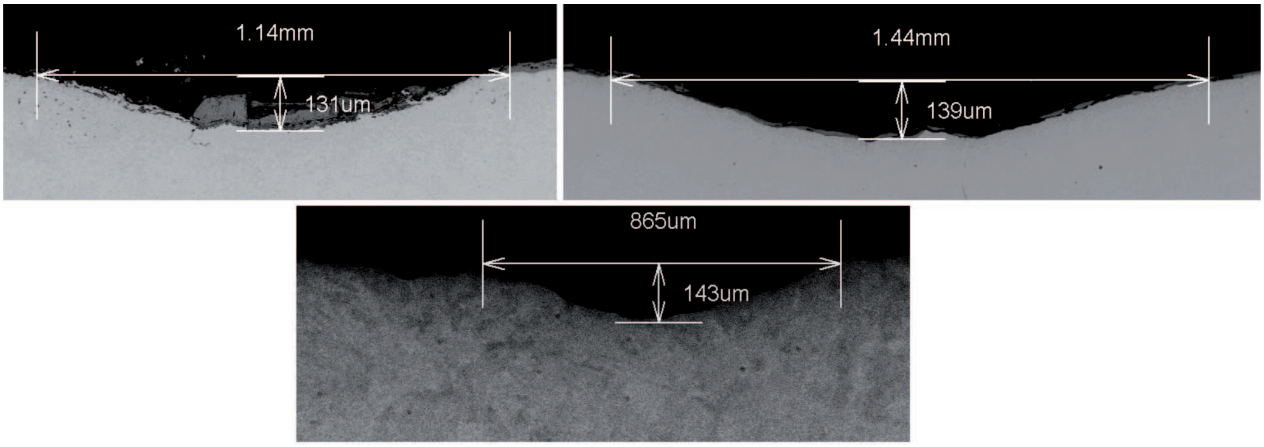

Fig. 7. A microscopic image of oscillation marks on the surface of ingot casted with the use of Scorialit SPH-C 411-81/E casting powder

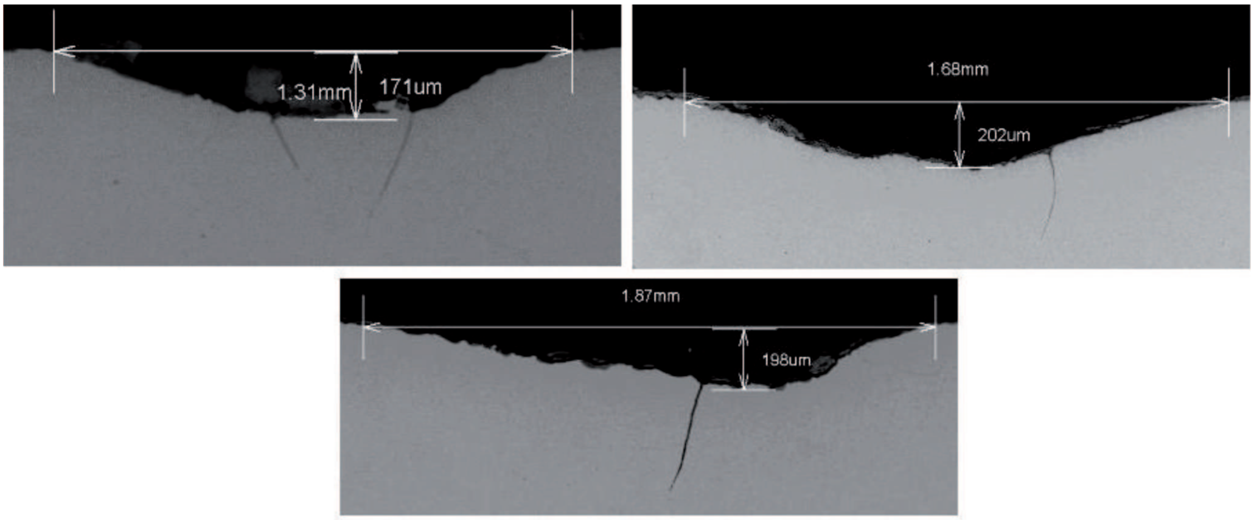

Fig. 8. A microscopic image of oscillation marks on the surface of the ingot casted with the use of Accutherm ST-SP/521-GL-1 casting powder

6. Research of the electromotive force in the Cu/casting powder liquid phase/Fe galvanic cell in industrial condition

The research works have been carried out during continuous casting of carbon steel in double-channel VOEST ALINE CC device in steel works of Gonar-Bis Sp. z o.o. (Gonar-Bis, Ltd), Stalownia Baildon Department, Katowice, Poland. Steel surface in the mold has been covered with Accutherm ST-SP/500-18(NW) casting powder, manufactured by Stollberg company and designed for low carbon steel casting (Table 2). Measurements of the electromotive force have been made in accordance with the schematic diagram presented below (Fig. 9).

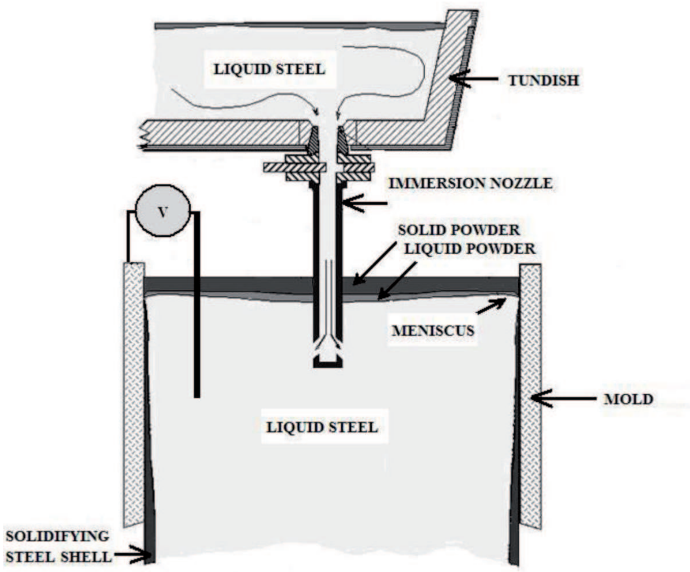

Fig. 9. Schematic diagram of EMF measurements in a Cu/casting powder liquid phase/Fe galvanic cell in industrial conditions

TABLE 2
Properties of ACCUTHETM ST-SP/500-18(NV) casting powder manufactured by STOLLBERG company

Chemical composition	
SiO_2	34,20 %
CaO	28,20 %
MgO	2,90 %
Al_2O_3	4,20 %
Fe_2O_3	0,70 %
Na_2O	4,10 %
C_{free}	18,04 %
F	4,50 %
Properties	
Level of alkalinity CaO/SiO_2	0,82
Melting temperature	1240°C (1513 K)

Results of electromotive force measurements are as follows:

– initial stage of a melt casting → 0,8 V
– intermediate stage of a melt casting → 1,3 V
– final stage of a melt casting → 1,9 V

The research was conducted to demonstrate the existence of electromotive force in the mold.The obtained results of measurements of the electromotive force in a Cu/casting powder liquid phase/Fe galvanic cell in industrial conditions are approximately the same as results of measurements in laboratory conditions. First of all, when taking into account the much higher temperature of electrolyte (liquid slag-forming phase of the casting powder) in the researched galvanic cell in industrial condition, compared with the temperature of laboratory cell electrolyte, one should expect higher values of the electromotive force of the galvanic cell formed in the mold.

7. Conclusions

Basing on the research mentioned above along with the description of results, it was concluded that:

1. The meniscus area in the mold plays important role in forming quality of surface of concast ingots. The physical, chemical and mechanical phenomena, occurring in this area, together with the oscillation substantially affect the form and depth of the oscillation marks.
2. Proper selection of physical and chemical properties of the used casting powders affects the process of lubrication of the mold walls and finally affects quality of the manufactured concast ingots.
3. It has been stated that there is the influence of the level of alkalinity of casting powders on the character of oscillation marks on the surface of concast ingots. The use of powders of the lower levels of alkalinity results in longer and deeper oscillation marks on ingot surfaces than with the use of powders of higher levels of alkalinity.
4. The existence of a Cu/casting powder liquid phase/Fe galvanic cell in the crystallizer's meniscus area causes the electrolyte inhomogeneity in the electrode's neighbouring areas, what in consequence changes lubrication conditions and affects quality of surface of concast ingots.

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