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IMPACT OF MOULD POWDER ON SLAB LUBRICATION

WPŁYW ZASYPKI KRYSTALIZATOROWEJ NA SMAROWANIE PŁASKIEGO WLEWKA CIĄGŁEGO

The paper presents results of industrial experiments with application of mould powders characterized with similar chemical composition, with different density and form: pulverized, granulated and formed. Impact of mould powder form on intensity of lubrication and its consumption is defined on the basis of the results of industrial tests of continuous casting of low carbon steel, 1030×220 mm format.

Keywords: mould powder, continuous casting, steel, lubrication

W niniejszym artykule przedstawiono wyniki eksperymentów przemysłowych z zastosowaniem zasypki krystalizatorowej posiadającej jednakowy skład chemiczny lecz różniącej się postacią i gęstością: proszkowa, granulowana i formowana. Wpływ postaci zasypki krystalizatorowej na intensywność smarowania i jej zużycie określono na podstawie wyników przemysłowych odlewania na urządzeniu COS stali niskowęglowej w formacie 1030×220 mm.

1. Introduction

Surface quality of concast slab depends mostly on geometry and frequency of oscillation marks presence [1], [2], [3] as well as formation of the so called hooks in the subsurface layer [4]. Following rolling these may result in formation of surface defects in final product. such as cracks, teeming arrest, or pinholes (skinholes) [5], [6]. Oscillation marks are crosswise cavities along strand circumference, formed when the mould is in top position. A hook often accompanies the oscillation mark, however it is characterized with various microstructural features in the subsurface layer [7], [8], [9] and depends on steel grade and casting parameters [10]. Hook dimensions increase along with reduction in the content of carbon in steel, low frequency of oscillations f and casting velocity V_c. Hooks demonstrate the tendency to capture mould slag and impact the outflow of non-metallic inclusions and gas bubbles [7], [8].

Oscillation of the mould prevents the solidifying skin from sticking (jamming) to mould walls. During each full cycle of oscillation, when the falling mould moves faster than the strand, the so called "negative strip advance – t_N" occurs during which the mould slag flows into the gap between the mould wall and the steel skin, thus resulting in lubrication thereof. Properly selected parameters of mould oscillation (stroke – s, frequency – f, oscillation ratio – *cpm*), in that negative strip advance sizing constitute a basis for stable continuous casting of steel [11], [12] and control of friction force between the solidifying skin and mould wall. Elongation of oscillation stroke increases consumption of mould powder [13], [14], [15]. Araki and Ikeda [16] combine these observations with the concept of negative strip advance, claiming that longer stroke and higher oscillation ratio should improve lubrication of the mould by increasing the negative strip advance, while Kawamoto with collaborators [17] interpret this effect with increasing pressure on the way to the bottom of the mould. One of the more important parameters of mould powder consumption is negative strip advance time. During the said time, during oscillation of the mould, friction force changes from tension to compression. Defined consumption of powder per unit of mould length proves that in each oscillation cycle the consumption increases significantly along with increase in negative strip advance time [18], [19], [20]. Calculations of slag flow in an interphase gap during mould oscillation imply that slag is used not only during the negative strip advance but also during reverse slip t_P despite increase in the pressure in the gap. As a result

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of research on formation of oscillation marks based on direct observations, Itoh and collaborators [21] have arrived at the conclusion that consumption of mould powder depends both on t_N and t_P, and occurs both during negative strip advance cycle and half of reverse time of the mould (t_N+ 0,5t_P).

Casting velocity is the most evident parameter influencing powder consumption. Numerous regression equations based on measurements of powder consumption in the industry have quantitatively determined that drops in consumption of powders are related to higher casting velocity [13], [15], [22], [23]. Tsutsumi and collabrators [14] have ascertained that consumption of mould powder changes inversely to the casting velocity, provided that properties of mould powder and conditions of oscillations are constant. Researchers claim [17] that gravity is the main driving force responsible for slag consumption, while others are of an opinion that consumption depends on interphase friction between mould wall and skin, especially at high velocity. Nakato and collaborators [24] have found that friction force for the specific range of casting velocity has its minimum level depending on the properties of mould powder. Using the model of thermal flow and stresses in the interphase gap, Meng and Thomas [25] discovered that the critical volume of powder consumption and lubrication efficiency depends on friction force. In view of that, achievement of proper lubrication of the mould is so crucial in continuous casting of steel, especially during casting of steel at high velocity.

2. Measures of mould powder consumption

Wolf [22] as one of the first researchers has indicated that consumption of mould powder is mostly the variable controlling the lubrication process. Consumption of mould powder expressed in kg/t of cast steel is a measure of the consumed quantity of powder Q_t, while consumption of powder expressed in kg/ unit of mould surface Q_s is a "measure of lubrication", which may be calculated knowing the volume of total consumption of the powder Q_t [26], [27], using the Eq. (1)

$$Q_s = \frac{7,6 \cdot f_s^* \cdot Q_t}{R} \tag{1}$$

where: Q_s – lubrication measure, kg/m^2
Q_t – powder consumption, kg/t
f_s^* – friction of slagforming powder
R – ratio of the surface area to volume of the mould, mm

$$R = 2 \cdot (a + b)/(a \cdot b) \tag{2}$$

where: a – width of the narrow wall of the mould, mm
b – width of the broader wall of the mould, mm

Itoyama [28], on the other hand, has suggested that total consumption of mould powder contains a range of constituents which constitute an Eq. (3)

$$Q_s = Q_m + Q_g + Q_f + Q_{om} \tag{3}$$

where: Q_m – constituent stemming from the pressure put by liquid slag pool
Q_g – constituent stemming from drop of pressure on parallel walls of the mould
Q_f – constituent stemming from the movements of mould oscillator
Q_{om} – constituent related to supply of slag to oscillation marks

Particular constituents of equation (3) are depicted by Eq. (4-7)

$$Q_m = \frac{\rho \cdot d_l}{2} \tag{4}$$

where: ρ – density of liquid slag, kg/m^3
d_l – depth of liquid slag pool, mm

$$Q_g = \frac{g \cdot \rho^2 \cdot d_l^3}{12 \cdot \eta \cdot V_c} \tag{5}$$

where: g – gravitational acceleration, m/s^2
η - slag viscosity, P
V_c – casting velocity, m/min

$$Q_f = \frac{L_u}{L_m} \cdot \rho \cdot s \cdot f \cdot L_m \cdot \sin\left(\beta/V_c\right) \tag{6}$$

where: L_m – effective length of a mould, mm
L_u – scope of change in steel surface level, mm
s – oscillation stroke, mm,
f – oscillation frequency, Hz
β – mould draft, °/wall
V_c – casting velocity, m/min

$$Q_{om} = A \cdot 0,5\rho \cdot f/V_c \tag{7}$$

where: A – surface of oscillation mark (relationship no. 9)

$$A = \frac{d_Om \cdot w_Om}{L_Om} \tag{8}$$

where: d_Om – depth of oscillation mark, mm
w_Om – width of oscillation mark, mm
L_Om – scale of oscillation marks, mm

One of the approaches [26], [29] to the issue of mould powder consumption assumes that Q_{om} is constant for majority of cases of casting and therefore the average thickness of liquid slag film may be calculated based on total consumption of powder, according to the equation (9), adopting the density of liquid slag as 2600 kg/m^3

$$d_l = \frac{Q_s}{\rho} \approx \frac{Q_s}{2600} \tag{9}$$

In the case of the present paper, based on measurements conducted during previous research, the value of liquid slag density was adopted as ρ_l = 2700 kg/m^3

3. Internal research

Tests of surface and subsurface layer of concast slabs were conducted on samples taken from slabs, dim. 1030×220 mm, cast under various forms of mould powder: pulverized, granulated and formed in form of homogenous plates the physic-chemical properties of which are presented in table 1. Low carbon steel of chemical composition presented in table 2 was selected for research.

Casting parameters for all forms of mould powders were as follows:

- Casting velocity: V_c = 1.04 m/min
- Steel overheating temperature = 13.2 K
- Oscillation stroke: s = 6 mm
- Oscillation frequency: f = 97.2 cycles/min
- Draft: β = 0.5° /wall
- Effective length of mould: L_m = 710 mm
- Oscillation ratio: K =1

TABLE 1

Physico-chemical properties of mould powders used during research

	Granulated ALSIFLUX GS-C7.3	Formed Scorialit SL 470/M	Pulverized Scorialit SL 470/M
CaO	27.00%	26.50%	29.76%
Al_2O_3	4.70%	4.56%	4.44%
SiO_2	34.4%	31.66%	32.21%
MgO	3.90%	1.52%	1.51%
Fe_2O_3	1.60%	0.93%	0.95%
F	9.00%	8.62%	7.88%
Na_2O+K_2O	11.80%	9.33%	8.79%
TiO_2	0.24%	0.21%	0.21%
C_{free}	3.60%	8.31%	5.96%
CO_3^{2-}	7.70%	11.90%	12.90%
* Viscosity η_{1300}	0.47 dPa·s	0.34 dPa·s	0.45 dPa·s
Bulk density	0,50 g/cm^3	–	0.83 g/cm^3
Apparent density	–	1.23 g/cm^3	–
Open porosity	–	** 42.3 %	–
Grain size	0.20–0.60 mm	plate 425×205 mm	below 0.045 mm
CaO/SiO_2	0.79	0.84	0.92
Melting point	1323 K	*** 1363 K	*** 1363 K
Flow temperature	1343 K	*** 1423 K	*** 1453 K
Depth of slag liquid phase, d_l	24 mm	** 28.8 mm	25 mm

* dynamic viscosity calculated according to Riboud's formula,
** average value from measurements,
*** measurements were conducted at the Silesian University of Technology in Katowice, using measurement equipment PR–37/1600 manufactured by PIE in Warsaw

TABLE 2

Chemical composition of steel cast during research

Mass share of elements, %	
C	0.04 - 0.070
Mn	0.20 - 0.30
Si	0.00 - 0.03
P	0.00 - 0.014
S	0.00 - 0.014
Cr	0.00 - 0.08
Ni	0.00 - 0.10
Cu	0.00 - 0.08
Al_{total}	0.025 - 0.065
Mo	0.00 - 0.05
N	0.0025 - 0.0065
As	0.00 - 0.03

TABLE 3

Consumption of mould powder Q_t

Form of powder	Length of stand cast under powder, m	Weight of steel cast under powder, Mg	Volume of supplied powder, kg	Powder consumption, kg/t
Granulated (in that ALSIFLUX GS-C7.3)	–	–	–	*0.6
Dextrin Formed Scorialit SL 470/M	13.0	23.17	13.1	0.56
Pulverized Scorialit SL 470/M	7.2	12.82	10.0	0.78
* from exploitation material balances as provided by the plant				

Consumption of mould powder was determined in two ways: as measure of mould lubrication in kg/t, determined as ”dry” – Q_t consumption of powder, as well as in reference to the unit of mould area in kg/m^2, defined as “wet” – Q_s consumption of powder. The measure of ”dry” lubrication, expressed in kg/t, for particular forms of powders is presented in table 3. For the purpose of calculations, weight of 1m of slab of dimensions 1030×220 mm M_{COS} =1791,9 kg was adopted. A formula developed by Itoyama (4) was used for calculation of the measure of lubrication expressed per unit of mould area. In order to define the volume of slag transferred by oscillation marks Q_{om}, the area of oscillation mark (A) was calculated using the relationship 9. Table 4 presents the values characterizing oscillation marks and results of calculations.

The lowest consumption of mould powder was achieved during casting of experimental melt with use of formed powder, and it reached the level of Q_t = 0.56 kg/t, while consumption of pulverized powder was the highest and reached Q_t = 0.78 kg/t. According to data provided by the steel plant where research was conducted, consumption of granulated powders is Q_t = 0.6 kg/t. Material balance implies therefore that the most economically efficient is application of the powders of higher density, i.e. formed powders.

It is assumed that the ”measure of lubrication” expressed in kg/m^2 of mould is a ratio which most completely expresses proper effect of mould walls and skin lubrication. As it stems from calculations of Q_s, presented in table 5, the highest level of lubrication is obtained for formed powder. Literature analysis as well as analysis of the obtained results imply that the result of such situation is mainly lower viscosity of formed powder as compared to pulverized powders. The second, less important reason is the area of oscillation mark which has minor impact on the constituent Q_{om}. It was found that addition of the binding agents in formed powders result

TABLE 4

Results of measurements and calculations of the surface of oscillation marks

Form of powder	d_{OM}, *mm*	w_{OM} *mm*	L_{OM}, *mm*	$A = \frac{d_{OM} \cdot w_{OM}}{L_{OM}}$	*A*, *mm*
	Average values from measurements			*mm*	*avg.*
Granulated ALSIFLUX GS-C7.3	0.49	2.06	8.9	0.112	0.117
	0.52	2.06	9.4	0.113	
	0.44	2.06	8.4	0.106	
	0.47	2.06	7.8	0.125	
	0.75	2.06	11.8	0.131	
	0.52	2.06	9.4	0.113	
Dextrin formed Scorialit SL 470/M	0.80	2.10	10.9	0.153	0.129
	0.48	2.10	10.5	0.095	
	0.63	2.10	8.1	0.163	
	0.57	2.10	9.5	0.125	
	0.54	2.10	9.2	0.123	
	0.49	2.10	9.2	0.111	
Pulverized Scorialit SL 470/M	0.68	1.99	11.3	0.120	0.111
	0.97	1.99	12.1	0.159	
	0.47	1.99	9.0	0.104	
	0.43	1.99	9.6	0.090	
	0.45	1.99	10.8	0.084	
	0.52	1.99	9.6	0.107	
Measurement method	Profile measurement gauge	Manual from metallographic specimen	Profile measurement gauge		
Theoretical scale of oscillation mark $L_{OM} = V_c/f = 10.7$ *mm*					

in reduction of their viscosity, thus contributing to higher efficiency of mould walls lubrication by formed powder as compared to pulverized powders. Based on analysis of the results of temperature measurement by means of thermocouples installed in the walls of the mould, no difference was found in horizontal heat flow between casting under a pulverized, granulated or formed powder.

4. Summary

Consumption of mould powder which is related, *inter alia* to thickness of liquid and solid slag film as well as sizing of oscillation marks is a parameter controlling the manner of mould walls lubrication. Values of the said factors are related to technological parameters such as: viscosity of mould slag, casting velocity, frequency and mould stroke, etc.

As a result of the conducted research it was found that:

– utilization of powder of higher density formed powder – in form of homogenous plates, has resulted in an increase in vertical flow of heat in the mould and achievement of deeper slag pool on the surface of metal as compared to loose powders (pulverized and granulated),

– consumption of formed powder Q_t = 0.56 kg/t is lower as compared to pulverized powder Q_t = 0.78 kg/t and granulated powder Q_t = 0.6 kg/t,

– introduction of binding agent to the composition of the formed powder in order to manufacture a homogenous plate has decreased its viscosity, which allowed to improve lubrication of walls with mould slag,

– the highest level of Q_s was achieved for formed powder,

– slabs cast during industrial tests under pulverized, granulated and formed powder were free of surface and subsurface defects. All the slabs were successfully rolled into sheets in line with the customer's order.

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