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OPTIMIZATION OF CHEMICAL COMPOSITION OF THE MOULD POWDER FOR CASTING Ø 170 mm BILLETS FROM C45 STEEL

Physico-chemical properties of mould powders and assumed casting parameters for the particular steel grade influence the way of lubricating the surface of the skin of concast billets formed in the mould, as well as heat transfer along its circumference.

The paper presents research which main aim was to improve the surface quality of continuous casting round billets (Ø 170 mm) cast from C45 steel. Improvement of the surface quality can be obtained by designing the chemical composition of mould powder for local casting conditions and the technical and technological parameters of CC equipment. Based on the experimental casting from C45 medium carbon steel it was found that there are relationships between the physicochemical properties of mould powder and intensity of skin lubrication and heat transmission to the mould wall.

Keywords: CC process, mould powder, lubrication, round billets

1. Introduction

Good quality of a billet depends upon appropriate course of many physical and chemical processes in the mould. The processes affect, among others, heat and media exchange (liquid steel, mould slag), change of physical state of steel and mould powder, friction associated with the mechanical extraction the billet from the mould etc. (Fig. 1).

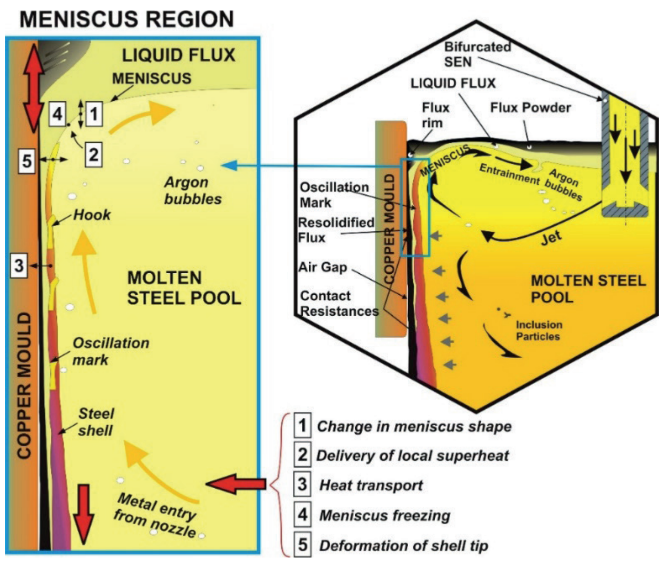

Fig. 1. General figure of the mould flux in continuous casting [2, 3]

Careful selection and monitoring of these processes determine the possibility of obtaining defects-free billets.

During casting the billet is exposed to mechanical stresses due to friction of the mould, pulling forces, bulging, bending and straightening [1]. Schematic distribution of stresses acting upon the growing shell of the billet during solidification in the mould is shown in Fig. 2.

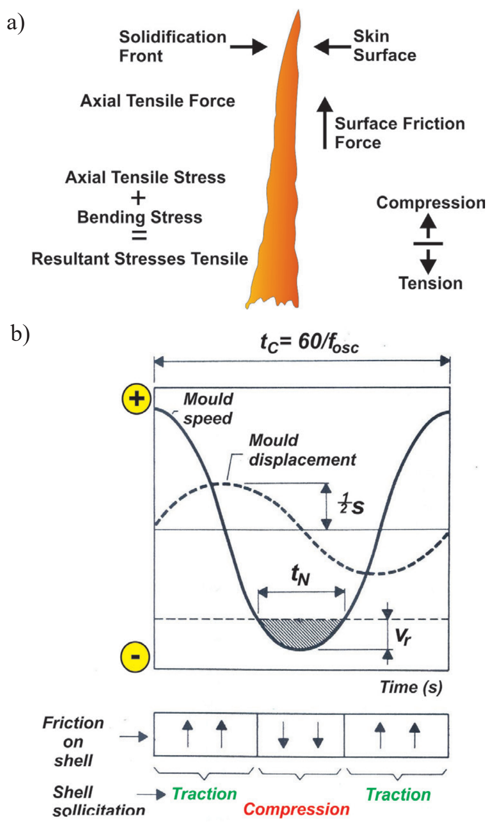

Fig. 2. Distribution of axial and bending stresses in solid shell resulting from friction in the mould (a); schematic representation of negative stripping time (t_N) and maximum speed difference (b) [4, 5]

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Oscillating motion of the mould acts as mechanical impact on the phenomena which accompany the formation of the billet in the mould. The oscillating motion of the mould and changes in the formation of a steel meniscus, directly affect the following processes: steel coagulation, liquid flux supply, and its pressure changes in the interfacial layer i.e., lubrication of the billet and regulation of the heat flow - Fig. 2b.

In addition to mechanical stresses there are thermal stresses. If, as a result of thermo-mechanical stresses the yield strength of the given steel grade in the solidified structure of the billet shell is exceeded, defects can occur in the form of subsurface micro cracks.

Most of the surface defects of billets originate in the mould and it is usually the result of higher values of the parameters directly affecting the start of solidification process of the steel. One of the most important factors responsible for the formation of the changing conditions of solidification of steel in the mould is lubrication, or its lack. In case of inadequate lubrication, the friction forces F_r generated in the mould affect the billet surface quality depending on the physicochemical properties of the mould powder and casting parameters (Fig. 3).

Factors influencing the frictional force shown in Fig. 3 should also include the following:

- intensity of electromagnetic stirring
- immersion depth of immersion nozzle (SEN/SES) in the mould

The frictional forces of the liquid in the mould are proportional to:

- slag viscosity
- thickness of liquid flux layer
- difference between the maximum mould speed and casting speed

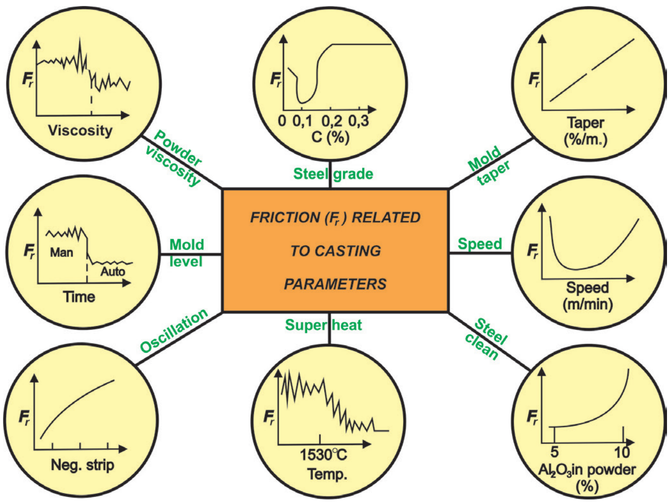


Fig. 3. Schematic presentation of casting parameters that influence friction in mould [6]

The change of thickness in liquid flux layer and its viscosity may cause the change of friction forces Fr [kN] in the mould, which can be calculated from the equation [7]:

$$F_r = \frac{\eta_s \cdot v_r \cdot s_A}{d_l} \tag{1}$$

where:

η_s – slag viscosity [P]

v_r – relative speed of mould movement [m/min]

d_l – thickness of liquid flux layer in air gap [mm]

s_A – contact surface between billet and mould [mm] (equation 2)

$$s_A = \frac{2 \cdot l_M \cdot (a + b)}{l_M \cdot a \cdot b} \tag{2}$$

where:

a – mould width [m]

b – mould thickness [m]

l_M – active mould length [m]

The above equation shows that frictional forces in the mould increase with the decrease in the thickness of liquid flux layer and the increase of its viscosity. Therefore, the properties of mould powder are among the most important factors responsible for the intensity of lubrication of the billet in the mould.

Chemical composition of the majority of powders produced and used is based on two basic components SiO_2 and CaO which generally constitute approx. 70% of powder mixture with slight percentage of Al_2O_3. Small amounts of MgO may be present instead of CaO and alkali oxides. The group of fluidifying additives (lowering the melting point and viscosity) may include alkaline earth oxides and fluorine (MnO, Na_2O, K_2O, Li_2O, Fe_2O_3, FeO, CaF_2, MgF_2, NaF, LiF). During casting of high-alloy steel TiO_2 and ZrO_2 are also introduced to mould powders composition. Free carbon is used as a regulator of melting speed of mould powders. Graphite, carbon black or coke powders are used as carriers for free carbon.

Since there is direct contact of mould powder with the surface of liquid steel, the changes of the surface properties of steel occur. Moreover, it plays the role of a lubricating agent. Mould powders are introduced into the mould from the top onto surface of the liquid steel, then gradually move down to the mould. Liquid flux, the outcome of molten mould powder, forms on the surface of the liquid metal a layer feeding the space (air gap) between the mould and billet of cast steel and lubricating the shell of a newly formed billet [8].

Lubrication of a billet and walls of the mould requires the provision of an appropriate amount of liquid flux to the air gap (Fig. 4) with an appropriate viscosity η and solidification temperature T_{sol}. Depending on the basicity (B_0=CaO/SiO_2) and the chemical composition of the mould powder, liquid flux solidifies at different temperatures. The higher the basicity of the powder (B_0>1) causes the higher solidification point of the slag. The stability of slag coating can be maintained only by the continuous supply of liquid flux into the space between mould and billet. It is mainly controlled by the depth of the liquid flux layer dp on the surface of liquid steel in the mould [10]. Therefore, one of the criteria for assessing the intensity of lubrication Q_s of a billet shell is the measurement of the depth of the liquid phase of the slag dp. In addition, this measurement can also determine the degree of influence of the selected technological parameter on the lubrication process of the billet surface.

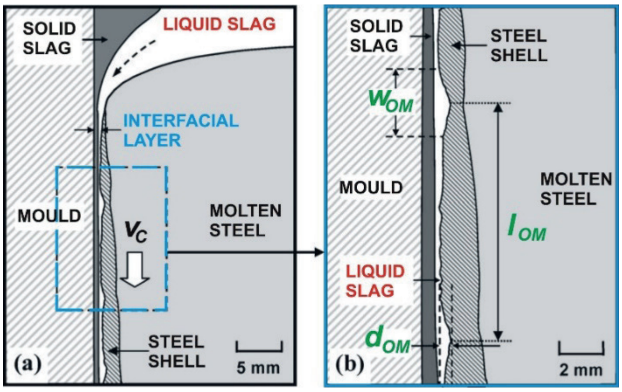


Fig. 4. Schematic diagram of interfacial gap between the mould and solidifying shell in continuous casting process [9]

2. Object of study

The surface quality of round billets cast from steel C45 does not always correspond to the requirements of the customers. The surface of billets is characterized by heavy reciprocation marks and false wall. Periodically occurring problems with the maintenance of the required surface quality of billets cast from steel C45 meant that actions were taken to improve them.

Round billets Ø 170 mm are cast on three strands CC device with a curvature radius R = 6 m. Two electromagnetic stirrers M-EMS and F-EMS are installed on each strand. Steel in grade C45 is cast in the full protection of the stream by submerged entry nozzles into Convex type moulds.

Composition of steel C45 is shown in Table 1, and the current cast parameters of Ø 170 mm round billets for this steel are given in Table 2.

The following equations were used to calculate the physical parameters of the powder

1) The amount of crystalline phase of the slag (NBO/T) [7]:

$$NBO/T = \frac{2X_{CaO} + 2X_{BaO} + 2X_{CaF_2} + 2X_{Na_2O} + 2X_{Al_2O_3} + 6X_{Fe_2O_3} + (2X_{MgO} + 2X_{MnO})}{X_{SiO_2} + 2X_{Al_2O_3} + X_{TiO_2} + 2X_{B_2O_3} + (X_{MgO} + X_{MnO})} \quad (3)$$

where:
X - the mole fraction of slag components

The transition point (transition) occurs for the NBO/T = 2.0. Below this point the slag is completely glassy or with a very low percentage of crystallization.

2) The percentage of crystallized slag [8]:

$$\%\ \text{crystallized slag} = 141.1\ (NBO/T) - 284.0 \quad (4)$$

3) The equivalent thermal conductivity λsys at temperature 1200 °C for mould powder, [W/mK] [9]:

$$\lambda_{sys(1200°C)} = 2.03 - 0.459 \cdot \left(\frac{\%"CaO"}{\%"SiO_2"}\right) - 0.1695\ \%FeO - 0.0348\ \%Al_2O_3 \quad (5)$$

where:
$\%"CaO" = \%CaO + \%MgO + \%MnO\% + \%K_2O + \%Na_2O + \%LiO_2$
$\%"SiO_2" = \%SiO_2 + \%B_2O_3$

In order to determine the current lubrication conditions of Ø 170 mm billets cast under mould powder Scorialit SPH-C 189/E1, the following measurements were conducted:

- depth measurements of liquid phase of mould slag
- measurements of surface topography of the billet
- calculation of frictional force occurring in the mould by equation (1)

Measurement of the depth of liquid mould slag is a simple method to monitor *lubrication intensity* of a billet shell. It is applied during tests of new powders when the assessment of current state of lubrication conditions is necessary or when defects on billets occur. Depth measurement of liquid slag depth in the mould is performed by means of two wires - steel and copper- which are simultaneously immerse under

TABLE 1

Chemical composition of steel C45 [weight %]:

C	Mn	Si	P	S	Cr	Ni	Cu	Al	Sn	As	Pb
0.45	0.70	0.20	0	0.020	0.15	0	0	0.018	0	0	0
0.49	0.80	0.30	0.025	0.030	0.20	0.25	0.25	0.025	0.030	0.005	0.003

TABLE 2

Cast parameters of steel C45casting into Ø 170 mm billets

Mould powder	Metallurgica granular powder Scorialit SPH-C 189/E1
Nominal casting speed	v_C = 1.7 m/min
Oscillation parameters:	Stroke, s = 5 mm
	Rate of oscillation, cpm = 105
	Frequency f_{osc} = 172 cycle/min (c/min)
Parameter M-EMS:	Intensity 260 A
	Frequency 4.5 Hz
Water flow in the mould	1650 l/min

TABLE 3

Physical and chemical properties of mould powder Scorialit SPH-C 189/E1

Chemical composition [weight %]:									
SiO_2	CaO+MgO	Al_2O_3	Na_2O+K_2O	Fe_2O_3	MnO	C_{free}	CO_2	$C_{tot..}$	F
31.0	19.5	4.5	10.0	1.0	< 0.1	18.0	5.5	20.0	4.0
33.0	21.5	6.0	12.0	2.5		20.5	6.5	22.0	5.0
Basicity (CaO/SiO_2)			0.53 ÷ 0.65		Humidity ($H_2O_{600°C}$)			< 0.8	
Physical properties									
Bulk density, ρ_m					0.50 ÷ 0.70 kg/dm^3				
Pour point T_{soft}					$1000^{\pm 30}$°C				
Melting point, T_{fluid}					$1080^{\pm 20}$°C				
Dynamic viscosity at 1300°C, η_{1300}					5.6 P				
1) Amount of crystalline phase of the slag, NBO/T					1.84				
2) Percentage of crystallized slag					-24.2 %				
3) Equivalent thermal conductivity, $k_{sys(1200°C)}$					1.85 W/mK				

TABLE 4

Mean values of steel C45 casting parameters into Ø 170 mm billets

Mould powder grade.	Water flow in mould	Casting speed, v_C	ΔT mould	Mould oscillation			M-EMS	
				s	cpm	f_{osc}	Intensity	Frequency
Sc 189/E1	1653 l/min	1.6 m/min	9.5°C	5 mm	105	172 c/min	260 A	4.5 Hz

slag surface into liquid steel. Steel wire melts in liquid steel whereas copper wire melts in liquid slag. The length difference between tips of both wires is taken as the measurement of the depth of liquid phase of mould slag (d_p).

The measurements carried out at the cast of steel C45 proved that the depth of liquid phase of mould slag falls in the range of **d_p = 2÷3 mm**. Table 4 presents values of casting parameters at which the measurements were performed.

The performed measurements of the depth of mould slag liquid phase show that the shell lubrication practically does not exist or is extremely weak. The values of a parameter ΔT = 9.5 °C seem to prove it. Large difference in temperatures of in-floating and out-floating water testifies the extensive heating of the mould walls being the result of downward friction of the billet against the wall of oscillating mould.

In order to obtain appropriate lubrication of steel billet shell in the mould, the minimum depth of liquid slag d_p should be bigger than the length of the stroke of oscillating motion. Depending on the casting conditions, the depth of liquid slag layer at the cast of small billets should fall in the range of d_p = 6÷12 mm [11].

Calculations of the friction force in a mould at the casting process of Ø 170 mm billets.

With casting and dynamic viscosity parameters of Scorialit SPH-C 189/E1 powder in equation (1) the following result of friction force was obtained:

$$Fr = 7.5 \text{ kN}$$

where:

- dynamic viscosity of slag η_{1300} = 5.5 P,
- layer depth of liquid slag d_p = 3 mm,
- surface area versus billet volume in the mould s_A = 47.1 m^{-1}
- difference between mean speed of the mould and cast speed: $v_r = v_m - v_c$ = 0.085 m/min.

On the basis of the carried out investigations and measurements [6] of the casting process of various steel grades into Ø 150 mm billets it was found that the change in friction force, in relation to mould oscillation, is regular and ranges from -1 to +2 kN. Friction force symbol is negative or positive and defines the direction of the moving mould. Positive friction force was interpreted as the force which causes traction of the surface of a billet shell which results in the formation of surface defects. However, negative friction force which occurs at the positive step, is responsible for the pressure exerted upon the billet surface and contributes to closing the surface defects. In the course of the performed tests it was found that in some cases, in an upper position of the mould, the level of friction force could reach positive values approaching 5 kN [12].

Friction force values obtained for Ø 170 mm billet were significantly higher than those mentioned in the literature [12].

2.1. Physical and chemical properties of powder for casting process of Ø 170 mm billets

The measurements of the liquid phase depth of mould slag and the values of friction force proved that Scorialit SPH-C189/E1powder does not ensure proper conditions for adequate lubrication of billet shell.

On the basis of the recently elaborated empirical equations [13, 14] as well as the computation method for calculation of chemical composition of mould powders presented in the paper [15], the authors proposed optimal values of physicochemical parameters of the powder which would be most suitable at the casting process of Ø 170 mm billets made of C45 steel.

Firstly, basicity of C/S contents - two basic oxides CaO and SiO_2 of powder and their relations were determined.

Then, on the basis of the assumed dynamic viscosity and crystallization temperature of mould slag, Al_2O_3, CaF_2 and alkaline oxides contents were determined. Finally, the content of free carbon in powder was defined.

Taking into consideration the attestation of manufacturers, physical and chemical properties of mould powders used in the metallurgical plant were analyzed. The powder, the properties of which were the closest to the expected, were (was) selected. Scorialit SPH-C176/ALS 9 (Table 5) was to substitute so far used Scorialit SPH-C189/E1. New type of powder is characterized by higher basicity and lower thermal conductivity. Moreover, it features higher value of dynamic viscosity than the powder used so far.

Main factors which decided about the choice of ScorialitSPH-C176/ALS 9 for commercial tests were the values of two parameters close to optimal values. Optimal value of dynamic viscosity of slag was η_s = 7.4 P, whereas basicity C/S = 0.8 ÷ 0.9. The content of free carbon is too low in relation to the assumed (optimal) which should equal C_{free} = 23.5%.

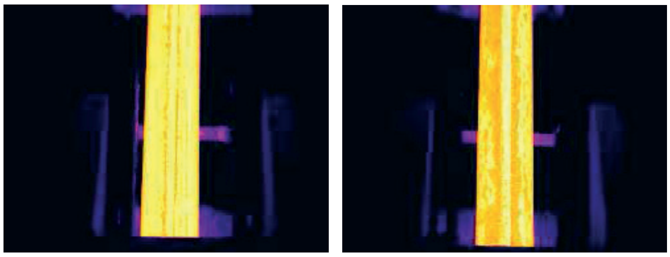
2.2. Experimental casts with new mould powder application

It was assumed that casting of experimental heats would be carried out on one strand (no. 3) under new powder - Scorialit SPH-C176/ALS 9 – whereas the other two (no. 1 and 2) under- Scorialit SPH-C189/E1.Technological parameters were archived and depth measurements of slag liquid phase were performed. Thermographic measurements of billets surfaces were done on strands 2 and 3 after they left the secondary cooling chamber. The measurements were repeated on the cooling bed. Sections were taken from the selected billets the surfaces of which after sandblasting were subjected to topography measurements and metallographic studies. Table 6 presents the casting parameters of experimental heats.

The application of Scorialit SPH-C176/ALS 9 instead of Scorialit SPH-C189/E1 resulted in the change of lubricating conditions of billets surfaces. With the same casting parameters on both strands, the measurements of the depth of slag liquid phase showed that larger growth in depth (from 3÷4 mm to 12÷13 mm) was achieved when Scorialit SPH-C176/ALS 9 was used. Scorialit SPH-C176/ALS 9 intensified the supply of liquid flux into the air gap which significantly improved the lubricating conditions of the billet shell and reduced friction to F_r =2.2 kN. More intensive infiltration of the space between shell and mould wall (air gap) with liquid flux improved lubricating conditions and heat removal. Lower thermal conductivity of the powder resulted in significant difference in temperature growth of water which was cooling the mould (ΔT) of ca. 2°C (Table 7).

Visual observation and thermographic images (Fig. 5) of billets leaving the secondary cooling chamber showed pronounced difference in the amount of solidified mould slag upon the billets surfaces between strands 1 and 2 and strand 3.

Thermographic measurements of billets surfaces after they left the secondary cooling chamber and those on the cooling bed confirmed the difference in surface temperatures on each individual strand. The surface temperatures for billets cast under standard powder Scorialit SPH-C189/E1 was ca. 10°C lower than for those under new powder (Fig. 6).



(a) Strand 2 (Scorialit SPH-C189/E1) (b) Strand 3 (Scorialit SPH-C176/ALS 9)

Fig. 5. Thermographic images of the surface of billet leaving secondary cooling chamber

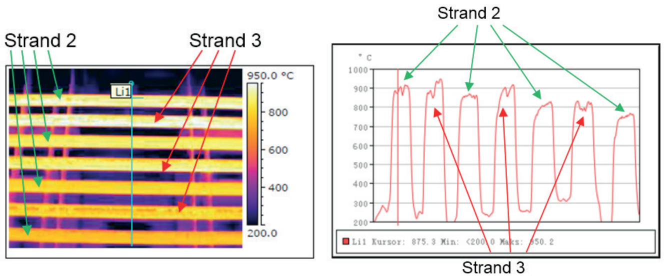


Fig. 6. Thermographic image of billets on cooling bed

Measurements of billets surface topography were done with Form Talysurf 50, Taylor Hobson Ltd. Figs. 7 and 8 show exemplary measurement results.

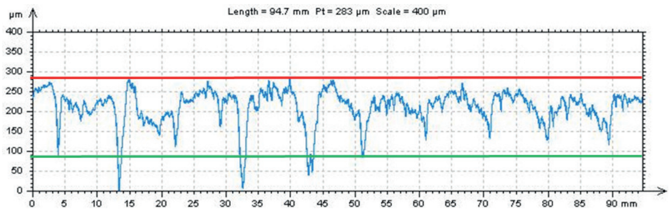


Fig. 7. Topography of billet surface cast from C45 steel under Scorialit SPH-C 189/E1

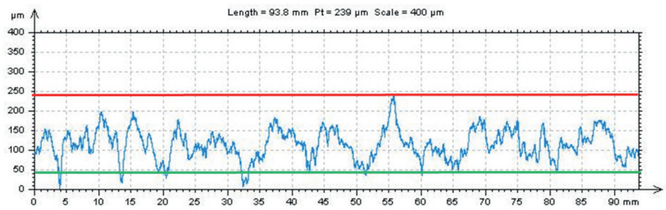


Fig. 8. Topography of billet surface cast from C45 steel under SPH C 176/ALS 9

On the basis of the carried out measurements it was possible to state that the mean value of the reciprocation marks for Ø170 mm billets cast under Scorialit SPH-C189/E1 is $\mathbf{d_{OM}}$ **= 0.28 mm,** whereas for those under SPH-C176/ALS 9 $\mathbf{d_{OM}}$ = **0.23 mm.**

The measurement results of surface topography of billets cast under Scorialit SPH-C176/ALS 9 showed that the depth

TABLE 5

Physical and chemical properties of mould powder Scorialit SPH-C 176/ALS 9

Chemical composition [weight %]:									
SiO_2	CaO+MgO	Al_2O_3	Na_2O+K_2O	Fe_2O_3	MnO	C_{free}	CO_2	$C_{tot..}$	F
27.5	30.0	5.0	2.0 ÷ 3.5	2.0	2.5	16.0	5.5	17.5	1.0
29.5	32.0	6.5		3.0	4.0	18.0	6.5	19.5	2.0
Basicity (CaO/SiO_2)			0.99 ÷ 1.11		Humidity ($H_2O_{600°C}$)			< 1.0	

Physical properties	
Bulk density, ρ_m	0.70 ÷ 0.90 kg/dm^3
Pour point, T_{soft}	1070 $^{\pm 30}$°C
Melting point, T_{fluid}	1140 $^{\pm 20}$°C
Dynamic viscosity at 1300°C, η_{1300}	7.2 P
1) Amount of crystalline phase of the slag, NBO/T	1.65
2) Percentage of crystallized slag	-51.4 %
3) Equivalent thermal conductivity, $k_{sys(1200°C)}$	1.72 W/mK

TABLE 6

Mean values of parameters for casting of experimental heats

Strand no.	Mould powder grade	Casting speed vC, [m/min]	Water flow in mould [l/min]	Mould oscillation			M-EMS	
				s, [mm]	cpm	f_{osc}, [c/min]	Intensity, [A]	Frequency, [Hz]
2	**Sc 189/E1**	1,9	1657	5	105	199	260	4.5
3	**Sc 176/ALS**	1,9	1655	5	105	199	260	4.5

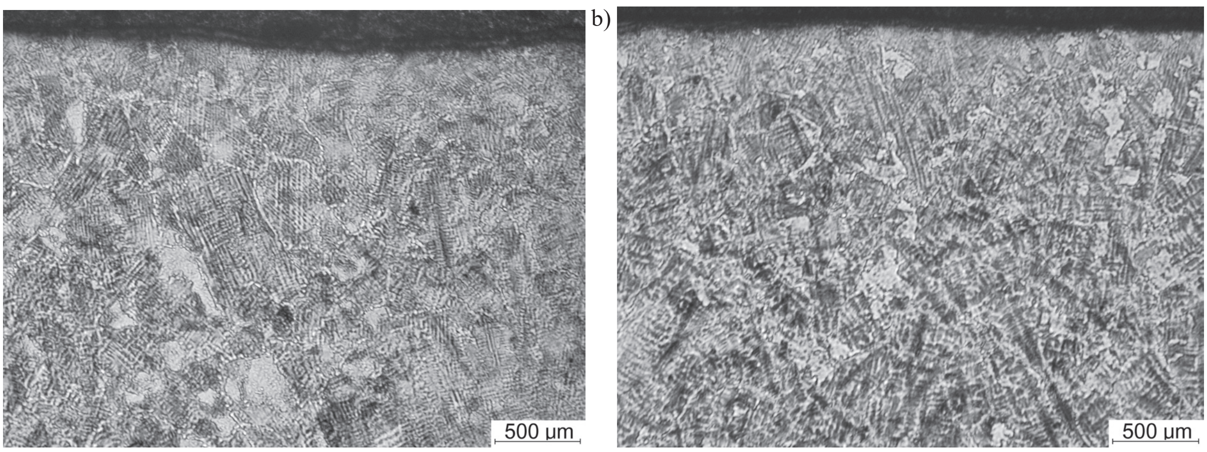


Fig. 9. Dendritic structure in the surface area of billets from experimental heats: strand 2 (a) and strand 3 (b) [16]

of reciprocation marks was ca. 20% shallower in comparison with billets cast under Scorialit SPH-C189/E1.

TABLE 7

Values of technological parameters obtained in experimental heats for mould powder grades

Mould powder grade	Scorialit SPH-C189/E1	Scorialit SPH-C176/AlS9
Liquid flux depth d_p	*3 ÷ 4 mm	13 ÷ 14 mm
ΔT of mould	9.1 °C	6.6 °C
Friction force F_r	7.5 kN	2.2 kN
Dynamic viscosity of powder η_{1300}	5.6 P	7.2 P

* - lower immersion depth of billets in mould resulted in the increased depth of liquid phase of mould slag to d_p = 7 mm.

Metallographic investigations proved that sphere size of crystals frozen in the billets which were cast on strands 2 and 3 is similar. Mean size of the sphere is about 5 mm. Billets cast of strands 2 and 3 show different size of dendrites in surface area which is presented in Fig. 9.

In case of a billet cast under Scorialit SPH-C189/E1 main dendrites and their branches are intensively shredded in comparison with those cast under Scorialit SPH C176/AlS9. This might mean that the new powder Scorialit SPH C176/AlS9 used for the cast of C45 steel Ø170 mm billets, featuring very good quality of billets surfaces and much more advantageous lubricating conditions in the mould in comparison with Scorialit SPH-C189/E1, produces far too large amount of mould slag. Such big amount of slag produced with the application of Scorialit SPH C176/AlS9 which is

TABLE 8

Suggested physicochemical properties of mould powder designed for C45 steel cast into Ø 170 mm billets

Chemical composition, % mas.							
SiO_2	CaO + MgO	Al_2O_3	$Na_2O + K_2O$	Fe_2O_3	MnO	C_{free}	F
~ 30.5	~ 25 (1.5 MgO)	~ 8	~ 9.5	~ 1,5	< 0,1	23,5	~ 3
Basicity (CaO/SiO_2)		0.8		Humidity ($H_2O_{600°C}$)		< 0.6	
Physical properties							
Dynamic viscosity at 1300°C, η_{1300}				5.6 P			
1) Amount of crystalline phase of the slag, NBO/T				1.76			
2) Percentage of crystallized slag				-34.8 %			
3) Equivalent thermal conductivity, $k_{sys(1200°C)}$				1.83 W/mK			

deposited on the billet surface acts as an insulator blocking the heat flow into the mould walls. This leads to steel temperature growth and expansion of dendrites. At the same time low thermal conductivity of slag ($k_{sys(1200°C)}$ = 1.72 W/mK) or too low content of free carbon in Scorialit SPH C176/AlS9 i.e. C_{free} = 17% may also be significant decisive factors here. Free carbon content calculated with the method elaborated in the paper [15] was C_{free} = 23.5% which should reduce the melting speed of powder upon liquid steel surface of the mould, respectively.

Tests performed with the new mould powder showed that the large improvement of both surface quality of billets and lubricating conditions of mould walls were obtained. However the excess of dendrites growth in the subsurface area of the billet showed that in case of C45 steel cast into Ø170 mm billet it is more advisable to set the chemical composition somewhere between Scorialit SPH-C189/E1 and Scorialit SPH C176/AlS9. The latter, with some corrections for the following components: increased addition of Al_2O_3 and Na_2O+ K_2O about ca. 2-3%, 1% increase of Fe_2O_3 and F, elimination of MnO, may constitute the base chemical composition for such powder.

Table 8 shows suggested modification of Scorialit SPH-C176/AlS9.

3. Conclusions

Investigations, measurements and commercial findings on the casting process of C45 steel under the new mould powder into Ø170 mm billets make it possible to formulate the following conclusions:

- depth of the phase of liquid flux formed from molten mould powder show the strongest impact on the value of friction force in mould
- appropriate depth of liquid flux in the mould can be obtained through optimal physicochemical properties of mould powder
- application of mould powder characterized by close to optimal physicochemical properties helps obtain lower depth of reciprocation marks and better heat removal into mould walls
- good surface quality of Ø170 mm billets made of C45 steel may be obtained improving lubrication of shell by applying the mould powder with modified physicochemical properties

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