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 (tₙ) and maximum speed difference (b) [4, 5]

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

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

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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 \( F_r \) [kN] in the mould, which can be calculated from the equation [7]:

\[
F_r = \frac{\eta_l \cdot v_t \cdot s_A}{d_l}
\]  

where:
- \( \eta_l \) – slag viscosity [P]
- \( v_t \) – 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)

\[
s_A = \frac{2 \cdot l_M \cdot (a + b)}{l_M \cdot a \cdot b}
\]  

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 \( \text{SiO}_2 \) and \( \text{CaO} \) which generally constitute approx. 70% of powder mixture with slight percentage of \( \text{Al}_2\text{O}_3 \). 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,O, K,O, Li,O, FeO, 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 \( \eta \) and solidification temperature \( T_{sol} \). Depending on the basicity (\( B_0=\text{CaO}/\text{SiO}_2 \)) 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.
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]:

\[
NBO/T = \frac{2X_{CaO} + 2X_{MgO} + 2X_{SiO_2} + 2X_{Al_2O_3}}{X_{CaO} + 2X_{MgO} + 2X_{SiO_2} + 2X_{Al_2O_3} + (X_{MgO} + X_{Al_2O_3})}
\]

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]:

\[
\% \text{ crystallized slag} = 141.1 \times (NBO/T) - 284.0
\]

3) The equivalent thermal conductivity $\lambda_{sys}$ at temperature 1200 °C for mould powder, [W/mK] [9]:

\[
\lambda_{sys} = 2.03 - 0.459 \times \left( \frac{\% \text{CaO}}{\% \text{SiO}_2} \right) - 0.1695 \% \text{FeO} - 0.0348 \% \text{Al}_2\text{O}_3
\]

where:
- $\% \text{CaO}$ = $\% \text{CaO} + \% \text{MgO} + \% \text{MnO} + \% \text{K}_2\text{O} + \% \text{Na}_2\text{O} + \% \text{Li}_2\text{O}$
- $\% \text{SiO}_2$ = $\% \text{SiO}_2 + \% \text{B}_2\text{O}_3$

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...
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 (dp).

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 $dp = 2\div3 \text{ mm}$. 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 $\Delta T = 9.5 \degree\text{C}$ 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 $dp$ 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 $d_p = 6\div12 \text{ mm}$. Table 4 presents values of casting parameters which at the measurements were performed.

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**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:

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

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

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].

Fricion 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/E1 powder 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, Al₂O₃, CaF₂ 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, 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 Scorialit SPH-C176/ALS 9 for commercial tests were the values of two parameters close to optimal values. Optimal value of dynamic viscosity of slag was ηₕ = 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 Cₑₗₑₑₑ = 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 Fₑ = 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).

![Thermographic images of the surface of billet leaving secondary cooling chamber](image)

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

![Thermographic image of billets on cooling bed](image)

**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.

![Topography of billet surface cast from C45 steel under Scorialit SPH-C 189/E1](image)

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

![Topography of billet surface cast from C45 steel under SPH C 176/ALS 9](image)

**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 dₑₗₑₑₑ = 0.28 mm, whereas for those under SPH-C176/ALS 9 dₑₗₑₑₑ = 0.23 mm.

The measurement results of surface topography of billets cast under Scorialit SPH-C176/ALS 9 showed that the depth
of reciprocation marks was ca. 20% shallower in comparison with billets cast under Scorialit SPH-C189/e1.

### Table 7

<table>
<thead>
<tr>
<th>Mould powder grade</th>
<th>Scorialit SPH-C189/E1</th>
<th>Scorialit SPH-C176/Als9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid flux depth dₜ</td>
<td>*3 ± 4 mm</td>
<td>13 ± 14 mm</td>
</tr>
<tr>
<td>ΔT of mould</td>
<td>9.1 °C</td>
<td>6.6 °C</td>
</tr>
<tr>
<td>Friction force F,</td>
<td>7.5 kN</td>
<td>2.2 kN</td>
</tr>
<tr>
<td>Dynamic viscosity of powder η</td>
<td>5.6 P</td>
<td>7.2 P</td>
</tr>
</tbody>
</table>

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

### Table 5

<table>
<thead>
<tr>
<th>Chemical composition [weight %]:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>CaO+MgO</td>
</tr>
<tr>
<td>27.5</td>
<td>30.0</td>
</tr>
<tr>
<td>29.5</td>
<td>32.0</td>
</tr>
<tr>
<td>Basicity (CaO/SiO₂)</td>
<td>0.99 ± 1.11</td>
</tr>
<tr>
<td>Humidity (H₂O600°C)</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical properties</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Bulk density, ρₘ</td>
<td>0.70 ± 0.90 kg/dm³</td>
</tr>
<tr>
<td>Pour point, Tₙₚₚ</td>
<td>1070 ± 30°C</td>
</tr>
<tr>
<td>Melting point, Tₙₚₚ</td>
<td>1140 ± 20°C</td>
</tr>
<tr>
<td>Dynamic viscosity at 1300°C, η</td>
<td>7.2 P</td>
</tr>
<tr>
<td>1) Amount of crystalline phase of the slag, NBO/T</td>
<td>1.65</td>
</tr>
<tr>
<td>2) Percentage of crystallized slag</td>
<td>-51.4 %</td>
</tr>
<tr>
<td>3) Equivalent thermal conductivity, kₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑ euler</td>
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### Table 6

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</thead>
<tbody>
<tr>
<td>2</td>
<td>Sc 189/E1</td>
<td>1.9</td>
<td>1657</td>
<td>5 105 199</td>
<td>260 4.5</td>
</tr>
<tr>
<td>3</td>
<td>Sc 176/Als</td>
<td>1.9</td>
<td>1655</td>
<td>5 105 199</td>
<td>260 4.5</td>
</tr>
</tbody>
</table>

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

![Fig. 9. Dendritic structure in the surface area of billets from experimental heats: strand 2 (a) and strand 3 (b) [16]]
SPH-C176/AlS9. The latter, with some corrections for the following conclusions:

- deposition of crystalline phase of the slag, NBO/T
- percentage of crystallized slag - 34.8%
- equivalent thermal conductivity, \( k_{sys(1200^\circ C)} \) 1.83 W/mK

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 according to Table 8. C45 steel may be obtained improving lubrication of mould powder with modified physicochemical properties.

### Table 8

<table>
<thead>
<tr>
<th>Chemical composition, % mas.</th>
<th>Physical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>CaO + MgO</td>
</tr>
<tr>
<td>~ 30.5</td>
<td>~ 25 (1.5 MgO)</td>
</tr>
<tr>
<td>Basicity (CaO/SiO₂)</td>
<td>0.8</td>
</tr>
<tr>
<td>Dynamic viscosity at 1300°C, ( \eta_{1300} )</td>
<td>1) Amount of crystalline phase of the slag, NBO/T</td>
</tr>
<tr>
<td>2) Percentage of crystallized slag</td>
<td>-34.8 %</td>
</tr>
<tr>
<td>3) Equivalent thermal conductivity, ( k_{sys(1200^\circ C)} )</td>
<td>1.83 W/mK</td>
</tr>
</tbody>
</table>

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[16] H. Kania i zespół, Zastosowanie symulacji fizycznej i numerycznej do opracowania podstaw technologicznych ciągłego odlewnia wlewków stalowych o przekroju kołowym na urządzeniu o małym promieniu luku, Projekt rozwojowy nr N R07 0021 06, niepublikowane.