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## IMPACT OF MOULD POWDER DENSITY ON SURFACE QUALITY AND NEAR-SURFACE ZONE MICROSTRUCTURE OF CAST SLAB

### WPLYW GĘSTOŚCI ZASYPKI KRYSZALIZATOROWEJ NA JAKOŚĆ POWIERZCHNI I MIKROSTRUKTURĘ STREFY PRZYPOWIERZCHNIOWEJ WLEWKA CIĄGŁEGO

The modifications of physicochemical properties of mould powders are usually obtained by control of their mineralogical composition. Depending on the mould powder form and grain size the thermal insulating changes within the mould. Thus, the mould powder density has a significant impact on heat exchange in mould. The experiments were carried out to increase the pulverised mould powder density by forming it into uniform shape blocks. Using the industrial continuous casting machine the experimental casting of slab ingots from low-carbon steel with pulverised, granulated and formed mould powder with identical mineralogical composition was carried out. The highest calculated consumption values  $Q_s$  ( $\text{kg}/\text{m}^2$ ) were obtained for the formed mould powder. The microscopic examinations of subsurface zone of the slabs cast with formed mould powder revealed the existence of hooks with smaller length and depth of penetration into slab structure than those in the slabs cast with granulated and pulverised mould powder. The results of the experiments have indicated that the use of formed mould powders allows increasing the casting speed without deterioration in quality of surface and subsurface zone of the continuous slab.

*Keywords:* density mould powder, microstructure slabs, OM, hooks

Celem uzyskania odpowiednich właściwości fizykochemicznych zasypki krystalizatorowych przeprowadza się zwykle przez regulację ich składu mineralogicznego. W zależności od postaci zasypki i wielkości ziaren zmienia się izolacyjność w krystalizatorze. Lepszą izolacyjnością charakteryzują się zasypki proszkowe, a gorszą zasypki granulowane. Gęstość zasypki wpływa zatem w sposób istotny na wymianę ciepła w krystalizatorze. Przeprowadzono eksperymenty polegające na zwiększeniu gęstości zasypki proszkowej z  $0,83 \text{ g}/\text{cm}^3$  do  $1,23 \text{ g}/\text{cm}^3$  przez dodanie lepiszcza i uformowanie w jednolite kształtki. Na przemysłowym urządzeniu COS przeprowadzono doświadczalne odlewanie wlewków płaskich ze stali niskowęglowej pod zasypką proszkową, granulowaną i formowaną o jednakowym składzie mineralogicznym. Najwyższe obliczone wartości wielkości zużycia  $Q_s$  ( $\text{kg}/\text{m}^2$ ) uzyskano dla zasypki formowanej. Pomiary znaków oscylacyjnych za pomocą profilometru ujawniły wpływ postaci zasypki krystalizatorowej na topografię powierzchni wlewków ciągłych. Nieznacznie obniżona lepkość i zwiększona gęstość zasypki formowanych wpłynęła na układ cieplny wokół menisku, powodując ukształtowanie znaków oscylacyjnych o nieznacznie większej głębokości. Badania mikroskopowe strefy podpowierzchniowej wlewków odlanych pod zasypką formowaną, ujawniły natomiast pod znakami oscylacyjnymi występowanie zawijaków o mniejszej długości i głębokości wnikania w strukturę wlewków, niż we wlewkach odlanych pod zasypką granulowaną i proszkową. Stwierdzono ponadto, że wlewek odlany pod zasypką formowaną posiada w strefie podpowierzchniowej najbardziej jednorodną i drobnoziarnistą mikrostrukturę; we wlewkach odlanych pod zasypką proszkową i granulowaną występują w strefie przy powierzchniowej obszary o zróżnicowanej mikrostrukturze: drobnoziarnistej i gruboziarnistej. Wyniki przeprowadzonych eksperymentów pozwalają na sformułowanie następującego wniosku praktycznego: stosując zasypki formowane o mniejszej izolacyjności i polepszonym smarowaniu, możliwe jest zwiększenie prędkości odlewania bez pogorszenia jakości powierzchni i strefy podpowierzchniowej wlewków ciągłych.

## 1. Introduction

Mould powder plays an important role in the continuous casting process not only as the lubricating agent, but also as the agent to control heat flow into mould walls

and absorb non-metallic inclusions. Mould powders that are widely used in the continuous casting process include pulverised and granulated mould powders. Pulverised mould powders show good thermal insulation and flexibility when coating the steel surface under un-

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favourable conditions in the mould (turbulent movement and large fluctuations in liquid steel level). Under such conditions, granulated mould powders have a tendency to go down towards the lower levels as a result of their good floatability – Fig. 1, which may lead to surface exposure and secondary oxidation of liquid steel. Table 1 presents the advantages and disadvantages of pulverised and granulated mould powders.

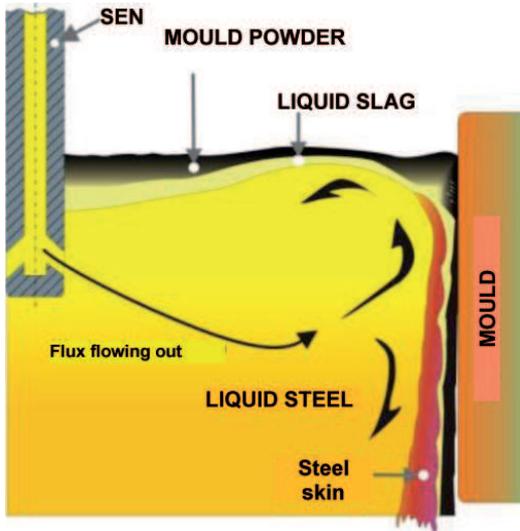


Fig. 1. Minimum mould powder coating with a narrow wall as a result of turbulent movement of steel in mould

## 2. Preliminary investigations

Before the investigations the mould powder of increased density (formed) was assumed to have the physical and chemical properties as much similar to those of the base mould powder (pulverised) as possible. The base mould powder used for production of formed mould powder was the powder commonly used for lubricating the mould walls of the continuous casting machine that the industrial studies were planned to be carried out in. The pulverised mould powder was selected because of its low price and possibility of “improvement” with regard to limitation of dustiness and segregation of components as well as enhancement of the environmental and working conditions for operation of the continuous casting machine.

The purpose of the investigations was to obtain the working material combining the advantageous features of both the pulverised and granulated mould powders.

The pulverised mould powder for laboratory investigations and industrial studies was obtained from Metallurgica by the courtesy of its representative.

As a part of the laboratory experiments, multi-variant tests of blending together the base mould powder (pulverised) with various binders were carried out. After verification of the formed mould powder samples, for the best variants a wide range of tests to determine their physical and chemical properties and melt-down rate were carried out. The melt-down tests were performed in the laboratory induction furnace. Based on the analysis of the results of the tests and measurements the most advantageous variant of formed mould powder was selected and the pre-production batch in the form of uniform 425×205 plates was manufactured – Fig. 2.



Fig. 2. Plates of formed mould powder for industrial studies

TABLE 1

Characteristics of pulverised and granulated mould powders [1]

Item	Pulverised powder	Granulated powder
Price	○	■
Thermal insulating power	○	■
Floatability in cold state	●	○
Flexibility in mould	○	■
Control of chemical composition	■	○
Effect on environmental protection	●	○

○ – good, ■ – quite good, ● – poor

It is the grain size and thickness of unmelted mould powder layer that affect the thermal insulation of metal surface. Density of mould powder along with the amount and size of carbon grains is one of the main factors to control the rate of melting mould powders down.

This article presents the results of investigations and experiments to determine the extent to which the increase in density of mould powder will affect heat exchange in the mould, lubrication of mould walls as well as surface quality and subsurface microstructure of cast slabs.

Samples were taken from the batch of Scorialit SL 470/M mould powder in the pulverised and granulated form and from one formed mould powder plate. The samples were put to investigations to determine their physical and chemical properties. The remaining plates

were used in the industrial studies. The weight of a single plate varied from 3.1 to 3.3 kg.

### 3. Industrial studies

The industrial steel casting tests using a single grade of mould powder with different densities (pulverised, granulated and formed) were originally planned to be carried out with Scorialit SL 470/M mould powder. However, because of depletion of the granulated mould powder reserves its ALSICAL equivalent, i.e. ALSIFLUX GS-C7.3, was used.

The experiments were carried out on SMS two-strand continuous casting machine during casting of low-carbon steel with C content  $<0.07\%$  into strand cast slabs of  $220 \times 1030$  mm.

Casting of slabs with granulated, formed and pulverised mould powder was conducted at constant values of the casting parameters, which were as follows:

- casting rate:  $V_c = 1.04$  m/min
- steel superheating temperature above  $T_{liq.} = 13.2$  °C
- oscillation stroke:  $s = 6$  mm
- oscillation frequency:  $f = 97.2$  cycles/min
- convergence of mould walls:  $\beta = 0.5^\circ/\text{wall}$
- oscillation coefficient:  $K = 1$

In order to obtain the identical thermal conditions in the mould, the experiments were conducted on a single strand. Mould powders (Table 2) were loaded during casting of the first two melts in the following sequence see Table 2.

During the casting of experimental melts, casting parameters from the computer-assisted control system of the continuous casting machine were archived, thickness measurements of the mould slag liquid phase were taken and thermal camera image of the surface of formed mould powder plates and surface of strands upon leaving the secondary cooling chamber was recorded.

The lowest mould powder consumption was obtained during the casting of experimental melts with use of formed mould powder and it was  $Q_t = 0.56$  kg/t. The consumption of pulverised mould powder was highest and amounted to  $Q_t = 0.78$  kg/t. According to the Steel Mill's data, the average consumption of granulated mould powders is  $Q_t = 0.6$  kg/t.

1 – granulated mould powder ALSIFLUX GS-C7

2 – formed mould powder Scorialit SL 470/M

3 – pulverised mould powder Scorialit SL 470/M

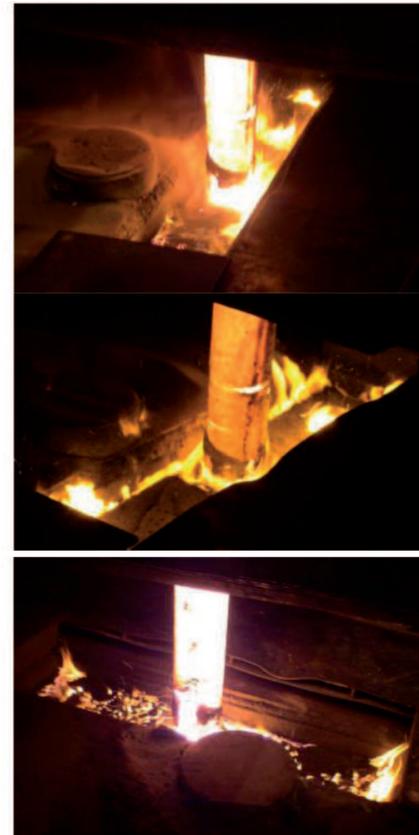


TABLE 2

Physical and chemical properties of ALSIFLUX GS-C7.3 and Scorialit SL 470/M mould powders used in the experimental melts

	Granulated ALSIFLUX GS-C7.3	Formed Scorialit SL 470/M	Pulverised Scorialit SL 470/M
CaO	27.00%	26.50%	29.76%
Al <sub>2</sub> O <sub>3</sub>	4.70%	4.56%	4.44%
SiO <sub>2</sub>	34.4%	31.66%	32.21%
MgO	3.90%	1.52%	1.51%
Fe <sub>2</sub> O <sub>3</sub>	1.60%	0.93%	0.95%
F	9.00%	8.62%	7.88%
Na <sub>2</sub> O+K <sub>2</sub> O	11.80%	9.33%	8.79%
TiO <sub>2</sub>	0.24%	0.21%	0.21%
C <sub>free</sub>	3.60%	8.31%	5.96%
CO <sub>3</sub> <sup>2-</sup>	7.70%	11.90%	12.90%
* Density $\eta_{1300}$	1.08 dPa·s	1.1 dPa·s	1.1 dPa·s
Bulk density	<b>0.50 g/cm<sup>3</sup></b>	–	<b>0.83 g/cm<sup>3</sup></b>
Apparent density	–	<b>1.23 g/cm<sup>3</sup></b>	–
Open porosity	–	** 42,3 %	–
Grain size	0.20 - 0.60 mm	plate 425x205 mm	below 0.045 mm
CaO/SiO <sub>2</sub>	0.79	0.84	0.92
Melting point	1050°C	*** 1090°C	*** 1090°C
Flow temperature	1070°C	*** 1150°C	*** 1180°C
Thickness of mould powder liquid phase, d <sub>l</sub>	24 mm	** 28.8 mm	25 mm

\* – absolute viscosity calculated with the use of Riboud's formula,

\*\* – average value based on the measurements,

\*\*\* – the measurements were taken using the measurement equipment PR-37/1600 at the Department of Metallurgy of the Silesian University of Technology in Katowice.

*Heat flow into mould*

The amount of heat transferred between the band and the mould walls while casting with various forms of mould powder can be calculated, approximately, based on heat exchange in the mould according to the following formula:

$$\Phi = c * p * \Delta t \quad (1)$$

where:

$\Phi$  – flux of heat transferred from the band to the mould (kJ/s)

$\Delta t$  – difference in temperature between water flowing into and out of the mould, (K)

$c$  – specific heat of water (kJ/kg\*K)

$p$  – water flow in the mould (kg/s).

For the calculated values, see Table 3.

On the basis of the obtained results of calculation of heat exchange  $\Phi$  and differences in temperatures of water for cooling the mould –  $\Delta t$ , it can be found that the form of the applied mould powder had no signifi-

cant influence on horizontal heat exchange between the mould walls and the band. The analysis of the measurement results recorded with the thermocouples installed in the mould walls also did not reveal any significant differences in the course of temperature with regard to the form of mould powder used in the research melts.

TABLE 3

Average values of heat flux transferred from the band to the mould walls obtained during casting with pulverised  $\Phi_{powd}$ , granulated  $\Phi_{gran}$  and formed  $\Phi_{form}$  mould powder

Heat flux	Mould wall				Unit
	right	left	loose (front)	fixed (rear)	
$\Phi_{gran}$	904,5	913,5	5069,2	4851,0	kJ/s
$\Phi_{form}$	860,8	865,9	4917,7	4754,9	kJ/s
$\Phi_{powd}$	865,6	890,2	4919,0	4682,1	kJ/s

The visual observation of metal surface fluctuations in the mould confirmed the assumptions that formed mould powders stabilised any disorders on metal surface caused by turbulences of fluxes flowing out of the submerged nozzle and oscillation movement of the mould. This stabilisation is highest until the original shape of formed mould powder is maintained and is slightly reduced upon cracking of the plates.

#### *Surface condition and subsurface structure of cast slabs*

The surface quality of strand cast slab made in the continuous process to a large extent depends on geometry and density of the oscillation marks (OM) [3,4] and hooks formed in the subsurface layer [5]. The oscillation marks and hooks may result in defects such as cracks, hulls and punctures (blisters) [6,7] in the final product after rolling.

Samples were taken from the slabs cast with mould powders of different densities for metallographic tests and surface smoothness measurements with the profile measurement gauge Form Talysurf 50. After the samples had been cut out of the cast slab sections, their surfaces were put to sand blasting to remove scale – Fig. 3.

The slab surface topography measurements were taken on 54 sand blasted samples and on samples for metallographic tests. The microstructure investigations and surface topography measurements were conducted

on samples taken from the side surface of slab where the oscillation marks were intact. The cast slab surface measurements were taken with the profile measurement gauge and their purpose was to measure the pitch ( $L_m$ ) (– distance between OMs) and depth ( $d_{OM}$ ) of the oscillation marks. For measurements of depths of the oscillation marks the boundary value below which no measurements were taken ( $<0.30$  mm) was adopted. The microsections were made in the plane perpendicular to the course of oscillation marks. For evaluation of the level of steel contamination with non-metallic inclusions the microscopic observations were conducted on non-etched microsections. The microstructure of slabs was revealed by nital etching of microsections. The hooks were revealed by special etching of microsections using another reagent.

The measurement of characteristic features of the hooks and oscillation marks – Fig. 4, was taken with a straight edge and protractor on light microphotographs.

Based on the metallographic examinations and measurements with a profile measurement gauge, it was going to determine whether there is a relationship between the influence of mould powder density on one hand and the surface quality and microstructure of cast slab on the other.

Fig. 5 presents the examples of hooks in the examined samples.

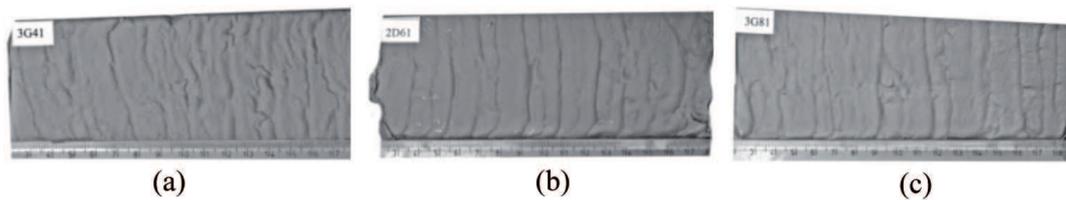


Fig. 3. Cleaned surfaces of samples taken from the sections of slabs cast with: (a) granulated mould powder, (b) formed mould powder, (c) pulverised mould powder

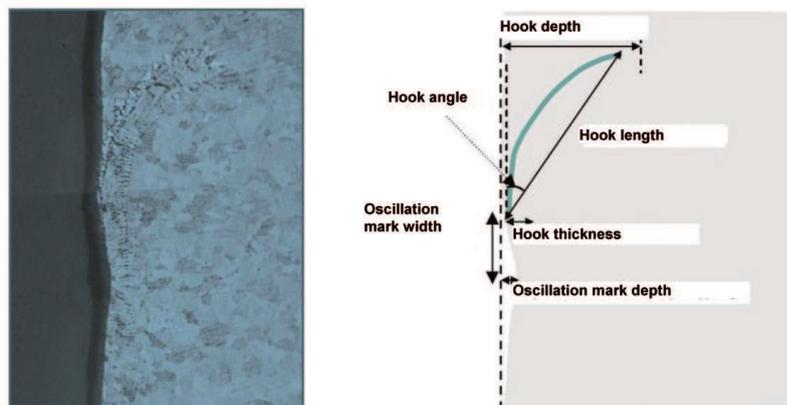


Fig. 4. Characteristics of oscillation mark and hook

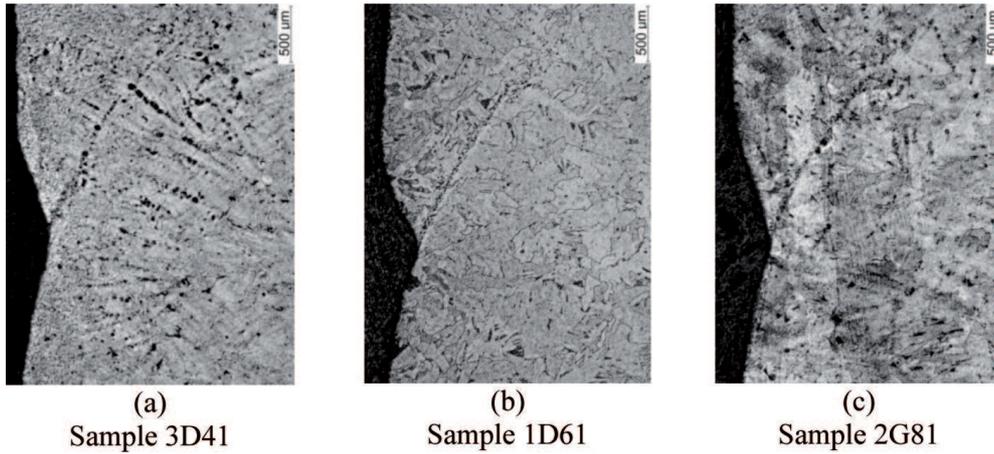


Fig. 5. Structure of samples with visible hooks. Sample from slab cast with: (a) granulated, (b) formed, (c) pulverised mould powder

By analysing the depths of oscillation marks (OM), it can be found that the surface depression depth caused by oscillation marks is highest on the slab cast with formed mould powder. The average OM depth for this slab is approx. 0.5 mm, i.e. by approx. 0.1 mm higher than the results obtained on slabs cast with loose (granulated and pulverised) mould powders.

The situation with regard to hooks is different. The most advantageous characteristics of hooks are observed on the slab cast with formed mould powder. Both the lengths and depths of hook penetration into the cast slab subsurface layer for samples taken from the slab cast with formed mould powder are lower than for samples taken from the slab cast with pulverised and granulated mould powder. Below are the average values obtained based on measurements of lengths, depths and penetration angles of hooks:

TABLE 4

Mould powder form	Average value from measurements of hook length, mm	Average value from measurements of hook penetration depth, mm	Average value from measurements of hook penetration angle, °
granulated	1.48	1.13	30.0
formed	1.12	0.82	24.2
pulverised	1.36	0.93	28.6

The penetration angle of hooks in samples taken from the slab cast with formed mould powder is lowest

(the lower penetration angle of hook the lower risk of defects).

*Microstructure in the subsurface zone*

In every case, the microstructure of slabs cast in the experimental melts was of ferritic-pearlitic type, with a very small amount of pearlite (a few per cents). In the subsurface zones of slabs, the microstructure was diverse with regard to ferrite grain size – Fig. 6. The subsurface zones generally showed highly refined ferrite grains, however thickness of the zones in individual samples was not uniform and varied from 0 to a few millimetres.

The most uniform zone with fine-grained microstructure occurred in the slab cast with formed mould powder. In this slab, thickness of the zone with fine-grained structure varied from approx. 1 mm to 5 mm. The average ferrite grain size in the subsurface zone was approx. 30 µm, while the average ferrite grain size in the slab beyond this zone was approx. 150 µm. In the slab cast with pulverised mould powder, thickness of the zone with fine-grained structure was more diverse. On certain samples from this slab only large ferrite grains, comparable to the size of grains in the further part of the slab, were found in the subsurface zone, while on the other samples there were alternate zones with large and fine ferrite grain at the surface. In the slab cast with pulverised mould, the size of ferrite grains in the near-surface zone changed similarly to that in the slab cast with pulverised mould powder. At the surface of this slab, there were alternate areas with fine- and coarse-grained structure.

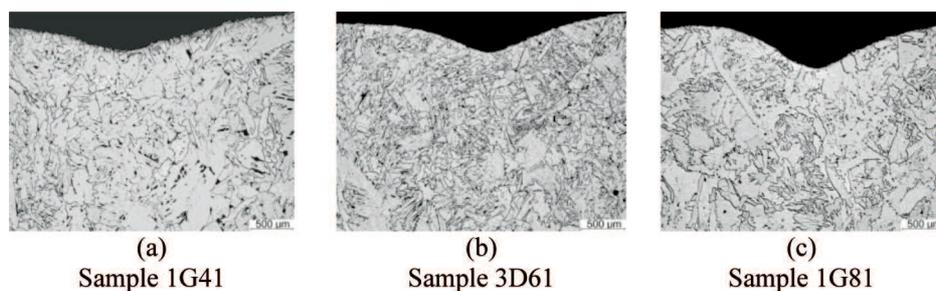


Fig. 6. Microstructure of near-surface zone of slabs cast with (a) granulated, (b) formed, (c) pulverised mould powder

#### 4. Summary and conclusions

As a result of the metallographic examinations it was found that the most uniform subsurface zone with fine-grained microstructure occurred in the slab cast with formed mould powder. The average ferrite grain size in the subsurface zone was approx.  $30\ \mu\text{m}$ , while the average ferrite grain size in the slab beyond this zone was approx.  $150\ \mu\text{m}$ . In slabs cast with pulverised and granulated mould powder, thickness of the zone with fine-grained structure was more diverse and there were alternate areas with fine- and coarse-grained structure at the surface.

The uniform fine-grained structure in the slab cast with mould powder of increased density (formed) signifies greater vertical heat flow as a result of the use of this powder than in case of using lower density powders (granulated or pulverised). Lower insulating power of the formed mould powder resulted in reinforcement and probably thickening of the slab skin in the mould on one hand and reduction in its plasticity on the other hand. Lower plasticity of steel skin in the mould caused less susceptibility of the skin top to bending during the oscillation movement of the mould. Thus, lower length and depth of hook and smaller angle of its penetration into the cast slab were obtained. The increased heat flow through the formed mould powder probably reinforced and thickened the skin in the mould on one hand and contributed to the increase in density of liquid steel as a result of reduction in temperature on the other hand, which was reflected in formation of a little bit deeper oscillation marks on the cast slab surface.

The experiments and results of investigations allow the following conclusions to be formulated:

- a new direction of experiments using formed mould powders and concerning the ability to affect the primary structure of the cast slab in the mould with density of mould powders was identified,
- the use of formed mould powders had an advantageous effect on the working environment, as dustiness and related material losses were eliminated,
- lower consumption of formed mould powder in relation to the loose mould powders was obtained; the introduction of binder into the composition of the

- powder slightly reduced its viscosity, which allowed obtaining better wall lubrication with mould slag,
- the metallographic examinations of subsurface zone of the slabs cast with formed mould powder revealed the existence of hooks with shorter length, lower depth and smaller penetration angle than in slabs cast with granulated and pulverised mould powder.

The results of the investigations, examinations, measurements and analyses have allowed the following practical conclusion to be formulated: thanks to their lower thermal insulating power and improved lubrication the formed mould powders allow significant increase in the casting speed without deterioration in quality of surface and subsurface zone of the continuous slab.

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