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Mould powder selection for thin slab casting

J.A. KROMHOUT*, A.A. KAMPERMAN†, M. KICK†, and J. TROUW*
**Corus Research, Development and Technology*
†Corus Strip Products IJmuiden, Direct Sheet Plant

Mould powders play an important role in the stability of the continuous casting process. The main functions of mould powders are to provide sufficient lubrication and to control the horizontal heat transfer. Because process control of thin slab casting is more stringent, it is generally assumed that mould powder properties become more critical as well.

In 2000, the Direct Sheet Plant at Corus IJmuiden (DSP) was commissioned, incorporating a thin slab caster designed for casting speeds up to 6 m/min. During commissioning, several operational problems with mould powders were encountered i.e. insufficient liquid pool depth and the formation of rims/lumps.

To investigate the operational mould powder problems, some of the mould powders were characterized using physical and mineralogical methods. The results were linked to operational experiences.

It was concluded that for thin slab casting, a stable slag formation is obtained with a proper choice of free carbon and an even distribution of the carbon particles within the granules. The physical properties of mould powders are not as critical as expected when the additional mineralogical requirements are taken into account.

Keywords: mould powder, characterization methods, thin slab casting.

Mould powders for thin slab casting

Mould powders play an important role in the stability of the continuous casting process. The main functions of mould powders are to provide sufficient lubrication and to control the horizontal heat transfer. Several authors have reviewed the design, properties and operational experiences of mould powders for (conventional) slab and billet casting[1–2].

Because process control of thin slab casting is more stringent, it is generally assumed that mould powder properties become more critical as well. So, a further understanding of mould powder composition and physical properties is needed. In recent years, some authors reviewed mould powder applications, including operational experience for thin slab casting[3–5]. In general, mould powders for thin slab application are derivatives of powders used for conventional slab casting. The improvements are mainly based on trial and error. Lubrication and mould heat transfer are considered to be important parameters[6].

Before commissioning of the Direct Sheet Plant (DSP) at Corus IJmuiden in 2000, mould powder criteria for thin slab casting were defined. Infiltration of mould slag, resulting in sufficient lubrication of the strand and uniform heat transfer, was considered a key process. Therefore, mould powder selection concentrated on the melting behaviour (melting point, melting speed), mould slag viscosity and the solidification of the mould slag (basicity, crystallization point). With this in mind, the commissioning of the DSP started.

During the early stages of operation, serious problems with mould powders were encountered. It was not possible to tackle these problems with the existing knowledge and characterization methods. An additional method, based on optical microscopy was used.

In this paper, operational experience and the results of mould powder characterization at the DSP are described.

Thin slab casting at Corus IJmuiden

Production of strip by means of thin slab casting and direct rolling became a major technology during the past decade and is now being practised at over thirty locations worldwide. From the early days, Corus identified this integrated technology as being an excellent route for producing strip of a thinner gauge than that usually produced in conventional slab caster-hot strip mill combinations[7–8]. In October 1997 it was decided to build the Direct Sheet Plant on the Corus IJmuiden site. (See Figure 1.)

The DSP completes the transformation to 100% flat products production in IJmuiden. It forms a second route to flat products in addition to the conventional casters and hot/cold strip mills. (See Figure 2.) The rolling mill, directly fed from the thin slab caster, is dedicated to the production of thin gauge and this is reflected in its capability for (semi-) endless rolling. In addition, the mill is optimized for ferritic rolling, which offers an extra flexibility towards controlling the properties of the end product. The most important grades will be galvanized and pickled and oiled. The steel for the DSP is received from BOS No. 2 in 300 tonne heats. In BOS No. 2 an additional programme was executed to increase the output to a level of 6.5 Mtonne/year, which is adequate for both the existing conventional slab casting route and the DSP. For feeding the DSP, a ladle furnace has been installed and forms the logistical buffer between the steel plant and the DSP. It also provides adequate temperature control, composition control and a reproducible clean steel practice including Ca-treatment.

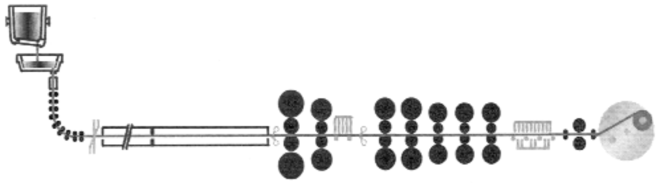

Figure 1. Lay out of Corus's direct sheet plant (DSP)

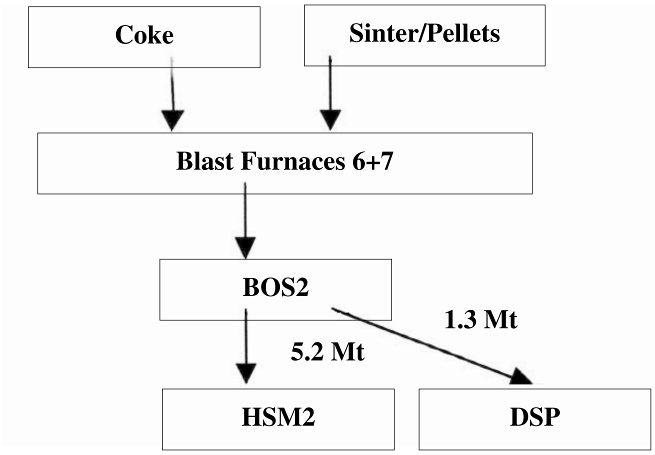

Figure 2. Corus IJmuiden production route

A consortium made up of SMS-Demag from Germany and Mitsubishi-Hitachi Metals Machinery from Japan supplied the equipment for the DSP, whose main specifications are listed in Table I.

Operational experiences

Since the start-up of the DSP, several mould powders have been used both with high and low basicity (CaO/SiO_2). The performance of a representative selection of mould powders is discussed and will be related to mould powder characterization. In Table II an overview is given of the chemical composition of the mould powders. Mould powders A and B have been used for longer periods as standard powders. The powders C to F were used for trial purposes only. Mould powder G is a conventional slab casting variant and is given as a reference material.

Mould powders C and D are the same but originate from different batches and are closely related to mould powder A. Mould powder E is a further development of mould powder A with the aim of improving slag formation during casting. Finally, mould powder F is designed to reduce the horizontal heat transfer, especially in the meniscus area. With the exception of mould powder B, all thin slab casting powders have a high basicity ($CaO/SiO_2>1$). (See Table II.)

The performance of a mould powder was evaluated using several operational criteria, including slag formation i.e. the liquid pool depth and rim/lump formation behaviour, uniformity and ratio of the heat transfer per side of the mould, friction, and meniscus stability. The liquid pool depth was obtained by immersing a steel sheet in the mould. At the meniscus, the sheet melts and the liquid slag solidifies on the sheet. The operators observed the formation of rims and lumps. The friction of the strand was obtained by the hydraulic oscillation system of the DSP. The meniscus stability was measured using a radiometric system. Based on operational experience, windows for meniscus stability and friction were defined. Mould heat transfer was calculated using mould cooling water temperatures.

In Table III an overview of the operational performance of the selected mould powders at the DSP is given.

Casts with mould powder A were characterized by serious operational problems like an unstable meniscus, a high mould friction, an unstable heat transfer, bridge formation, and even breakouts. These problems were mainly initiated by insufficient slag formation (i.e. too low liquid pool depth and excessive rim/lump formation) and infiltration. Minor changes were made (powder C), which successfully overcame these problems. For a longer trial, a new batch of this mould powder was ordered and tested at the DSP (powder D). However, this time the powder behaved like mould powder A: excessive rim/lump formation, causing serious operational problems. Differences between powder C and D could not be explained using conventional tools only—chemical analysis, viscosity and melting behaviour—and so additional characterization methods based on optical microscopy were considered. These will be discussed in Section 4.

Mould powder E is a further improvement of powder A with the aim of improving slag formation during casting. This powder performed better than powders A and D but

Table I
Summary targets Direct Sheet Plant

Steel grades	Low carbon Constructional (light alloys)
Strip thickness	0.7 mm–2.5 mm
Strip width	1 000 mm–1 560 mm
Thickness control	± 1 %
Crown	Cr. (40): ≤ 1 %
Flatness	Max. 25 I-units
Width/Thickness	Up to 2 000
Coil weight	Max. Specific weight: 21 kg/mm Max. weight: 33 tonnes
Annual capacity	1.3 M/year of hot rolled coils

Table II
Chemical analysis (wt.%) of mould powders for thin slab casting (DSP) and reference material, as measured at Corus IJmuiden

	Powder type						
	A	B	C	D	E	F	G
CaO/SiO_2	1.31	0.98	1.27	1.27	1.32	1.15	0.80
SiO_2	25.3	33.4	27.2	26.7	26.0	30.3	32.8
CaO	33.1	32.7	34.4	34.0	34.3	34.7	26.5
MgO	3.7	0.4	3.7	3.4	3.6	3.7	1.2
Al_2O_3	3.9	3.2	3.8	3.7	3.9	2.9	5.1
Fe_2O_3	0.57	0.49	0.27	0.27	0.36	0.81	1.6
Na_2O+K_2O	8.83	12.49	8.62	8.32	8.19	9.6	12.62
Li_2O	0.8	0.01	0.7	0.7	0.93	0.01	0.01
F	9.9	7.7	10.5	10.0	11.5	5.9	9.1
C_{free}	6.7	4.0	5.9	5.6	5.4	5.0	4.4
CO_2	7.36	7.21	7.18	8.16	8.44	8.1	7.71
C_{total}	8.72	5.98	7.86	7.83	7.70	7.2	6.52
LOI (1000°C)	18.7	13.4	15.4	15.2	16.0	14.8	15.0

Table III
Mould powder performance at the DSP

	Powder type					
	A	B	C	D	E	F
Period used	03-’00/10-’00	11-’00/06-’03	trial/1 seq.	trial/9 seq.	trial/4 seq.	trial/4 seq.
Liquid pool depth	1–2 mm	4–8 mm	6–8 mm	–	2–5 mm	4–20 mm
Rim/lump formation	excessive	negligible	negligible	excessive	negligible	negligible
Meniscus stability	unstable	stable	stable	unstable	stable	stable
Friction	high	low	–	high	medium	medium
Heat transfer uniformity	bad	good	–	bad	good	good
Heat flux ratio*	70–80%	90–100%	–	70–80%	65–80%	90–100%

Heat flux ratio*: heat flux narrow face/average heat flux broad faces. The heat flux calculations are based on the increase of mould cooling water temperatures per side

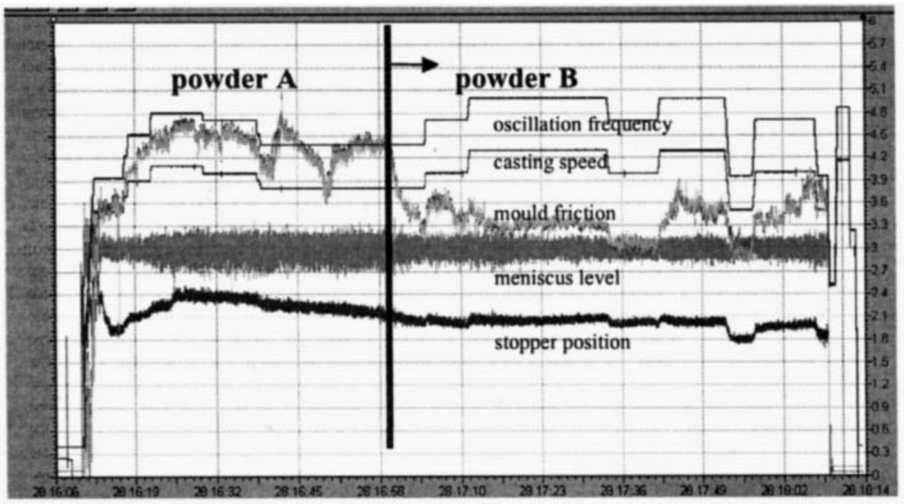

Figure 3. Mould powder trial at the DSP

still showed insufficient liquid pool depth. Furthermore, the colour of the mould slag was black, which indicates the presence of carbon in the liquid slag i.e. an insufficient combustion of the carbon particles during slag formation. Summarizing, mould powders A and D showed comparable operational problems that were closely related to the slag formation during casting. Mould powder E showed some improvements. Only powder C gave good operational results, but another batch of this powder (powder D) did not show the required behaviour. In Figure 3 an example of a cast is shown.

On the other hand, mould powder B was successfully used over a very long period. In this period the average casting speed increased to 5.0 m/min, with an increasing casting time from 3 to 8 hours using the same refractory material of the submerged entry nozzle (SEN) and the same mould level control system. From these experiences it can be concluded that a liquid pool depth > 5 mm is sufficient. However, incidentally lower values were measured during longer periods of casting without operational problems.

Mould powder F is designed to reduce the horizontal heat transfer. The powder has been used supplementary to mould powder B. With mould powder F several successful trials were performed, and it is considered to be a good alternative for casting crack sensitive steel grades. However, up to now all low alloyed steel grades can be cast with mould powder B and therefore at present there is no need to use mould powder F.

During casts with various mould powders, it became clear that the mould slag basicity is not a key parameter in the observed in-mould behaviour.

Based on the current operational practice, slag samples showed no significant changes in composition (i.e. Al_2O_3, CaO and SiO_2 contents).

Mould powder characterization

Introduction

Physical characterization plays an important role in the selection procedure and the operational evaluation. In general, the chemical composition (Table II), the viscosity including the start of crystallization, and the melting behaviour are considered. This information proved insufficient to understand the slag formation process, which is critical in thin slab casting. Therefore, optical microscopy and X-ray diffraction were used as additional characterization methods with the aim of focusing on the composition and especially on the free carbon sources of the mould powders.

Viscosity

The viscosity of a mould slag influences the infiltration of mould flux during casting. In general, infiltration increases with a decreased viscosity of the mould slag for the same operational conditions, and this tendency is used for thin slab casting. Operational windows for the viscosity are mainly based on rules of thumb, but other demands such as the control of slag entrapment also play an important role when defining the required viscosity of a mould powder[9].

The viscosities of the two standard powders (A and B) and the reference material (G) were determined using the rotating cylinder method. At IJmuiden, this method has been used as a standard test for many years. The measured viscosity at 1300°C and the so-called crystallization point are considered as characteristic values. Results are shown in Table IV and Figure 4.

Melting behaviour

The melting behaviour of a mould powder strongly influences both the liquid pool depth and the sensitivity towards rim/lump formation. The melting behaviour can be described by the melting trajectory and the melting speed. In both cases, additions of free carbon (C_{free}) are considered to be a principal factor[10–11]. The other main parameter is the flow condition in the mould i.e. the meniscus stability during casting. The liquid pool depth results from the balanced values of the feeding and the infiltration of the mould powder.

Melting trajectory

The melting trajectory of the mould powders was determined using a hot stage microscope. Results are given as values for the softening, the melting and the flow temperature (Table V).

Melting speed

The melting speed of mould powders was determined using the so-called softening method[12]. With this method, the displacement of a prepressed cylinder of mould powder is measured as a function of time at a fixed temperature (1400°C). The method yields qualitative results that can be related to the mould powder composition i.e. the free carbon content of a mould powder. Results are shown in Figure 5 and summarized in Table VI. Mould powder A did not show any softening and melting during heating in the furnace i.e. nearly no slag was formed and no displacement was measured. Instead, the mould powder sintered and no results could be obtained.

Table IV
Viscosity (Pa.s) at different temperatures and crystallization point (°C) as measured at Corus IJmuiden

	Powder type		
	A	B	G
T (°C) = 1350	0.09	0.15	0.18
1300	**0.11**	**0.17**	**0.21**
1250	0.12	0.22	0.27
1200	0.13	0.28	0.37
1150	0.17	0.38	0.51
1100	2.45	0.54	0.77
Tcryst (°C)	**1133**	**1106**	**1078**

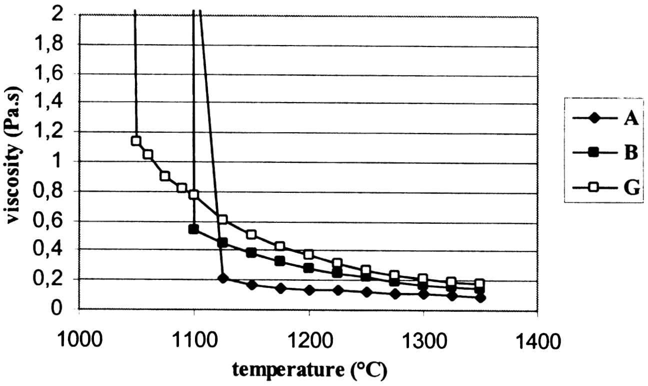

Figure 4. Viscosity

Optical microscopy

Based on casting experience at the DSP and the subsequent characterization of the mould powders using the conventional methods, the observed melting behaviour and the slag formation could not be explained.

For these reason other methods were needed which could give more insight into the mould powder composition. Main points of interest were the choice of carbon sources (free carbon) and the distribution of free carbon particles within the granules. The mould powders were examined

Table V
Melting trajectory as measured at Corus IJmuiden

Melting stage	Powder type						
	A	B	C	D	E	F	G
Softening temperature (°C)	930	918	874	827	913	1068	1010
Melting temperature (°C)	1120	1110	1040	1005	1014	1169	1068
Flow temperature (°C)	1163	1126	1185	1134	1054	1169	1090

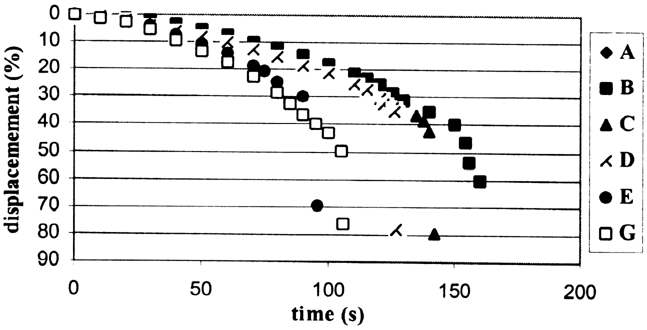

Figure 5. Melting speed (displacement)

Table VI
Melting speed (displacement vs. time) of mould powders, as measured at Corus IJmuiden

Displacement (%)	Melting time (s) and powder type					
	A	B	C	D	E	G
10	–	70	57	60	49	41
20	–	117	95	95	74	65
40	–	150	139	126	85	95
60	–	160	141	127	90	105
C_{free} (%)	6.7	4.0	5.9	5.6	5.4	4.4

No results are available for mould powder F using reflected light microscopy and the results were compared with the in-mould behaviour of each individual mould powder. Summaries of the results are given in Tables VII and VIII. To support the optical examinations, X-ray diffraction analysis of the mould powders was performed.

The investigations revealed that for some mould powders up to five carbon sources are used and that in nearly all cases the distribution of the carbon particles within the granules was poor or very poor. Only powders B and F showed an even distribution of carbon particles based on carbon black, which in general combusts more easily than graphite or coke (Figure 6). In mould powder F, a minor supplement of one grade of fine coke is present.

Surprisingly, mould powders B and F also showed stable slag formation during casting. With a poor carbon distribution the requirements for the in-mould behaviour could not be met. The relatively high combustion rate of carbon black also may enhance a uniform slag formation.

Maybe even more important, it became clear that an even carbon distribution is impossible to obtain when more than two carbon sources are used. The application of one fine grade of carbon black, possibly supplemented with one grade of fine coke, is therefore recommended.

X-ray diffraction

To support the optical examinations, X-ray diffraction was performed, giving information about the choice of raw materials. Before analysing, the powders were crushed (<60 µm). A summary of the results is given in Table IX. Differences among the powders can be seen, for instance in the use of spodumene, albite and magnesite.

Current status at the DSP

The caster output shows a continuous improvement from the moment of commissioning onward, which was accelerated by the introduction of mould powder B. An overview of the achievements can be found in Table X. At present (Q2, 2003) approximately 69% of the targeted quarterly output of 350 000 tonnes of slab is reached. Since Q4 of 2001 the stability achieved in the process allowed an increase in casting speed, still using mould powder B. During Q1 of 2003 the maximum casting speed was set at 5.4 m/min and was operated for long casting periods, using the EMBR with a fixed current of 280 A. Over 50% of the slabs were cast at average speeds of 5 m/min and above in Q1-2003. The target for 2004 is to increase the casting speed to 6.0 m/min.

Sequence length was raised stepwise from 600 to 2 400 tonnes during the past years, resulting in an average sequence length of 1 200 tonnes in the second quarter of 2003. The casting time per sequence is increased to a maximum of 12 hours at present.

Discussion

All the mentioned mould powders for thin slab casting were used with the same or comparable operational casting practices i.e. casting speed and width, oscillation and taper settings, SEN etc. So all the operational experiences are fully comparable. However, conventional characterization methods provided insufficient information to explain the observed in-mould behaviour. Especially, the slag formation required further investigations using mineralogical characterization methods.

As a result, it was concluded that free carbon additions are very important in controlling the melting behaviour of a mould powder. In addition to this, carbonates also affect the melting of mould powders. During casting, carbonate generates CO_2 and this increases the melting speed due to stirring the powder layer[13]. Considering an uneven distribution of carbon particles, the effect of carbonate probably does not promote the melting of these powders, but enhances the formation of rims/lumps. This can be a further explanation for the bad performance of some of the mould powders and will be a point of attention during future developments.

Compared with mould powders for thin slab casting, the successful conventional slab casting powder showed a poorer distribution of free carbon. This indicates that slag formation at lower casting speeds (<1.9 m/min) and/or thicker slabs (225 mm) is less critical.

Table VII
Carbon sources (free carbon) in mould powder granules, as measured at Corus IJmuiden

Free Carbon source	Powder type						
	A	B	C	D	E	F	G
Graphite	+	0	+*	+*	0	0	0
Coke (fine)	+	0	+	+	+	+	+
Coke (metallurgical, recycled)	+	0	+	+	+	0	+
Carbon black (lumps)	+	0	+	+	0	0	0
Carbon black (fine)	+	+	+**	+**	+	+	+**

+: present
+*: traces
+**: probably present
0: not present

Table VIII
Distribution of carbon particles (free carbon) in mould powder granules, as measured at Corus IJmuiden

Carbon distribution	Powder type						
	A	B	C	D	E	F	G
Distribution	very poor	good	poor	very poor	poor	good	poor

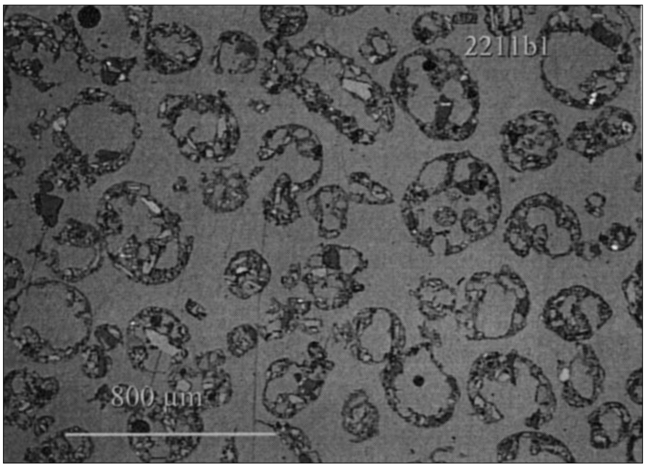

Figure 6. Mould powder B showing a good carbon distribution

Table IX
Mould powder composition (X-ray analysis), as measured at Corus IJmuiden. The numbers are related to the heights of the peaks of the constituents (scale 1–10)

Mineral	Powder type						
	A	B	C	D	E	F	G
Fluorite (CaF_2)	8	7	6	5	10	5	10
Cryolite (Na_3AlF_6)	0	0	1	1	0	0	0
Wollastonite ($CaSiO_3$)	3	4	6	6	5	8	3
Spodumene ($LiAlSi_2O_6$)	2	0	0	0	2	0	0
Magnesite ($MgCO_3$)	2	0	2	2	2	0	0
Forsterite (Mg_2SiO_4)	0	0	0	0	0	2	0
Albite ($NaAlSi_3O_8$)	0	2	0	0	0	0	0
Calcite ($CaCO_3$)	0	0	0	1?	1?	1	2
Soda (Na_2CO_3)	1	1	1	1	1	1	1
Corundum (Al_2O_3)	0	0	0	0	0	0-1	0
Carbon	1	1	1	1	1	1	1
Quartz (SiO_2)	0	T*	0	0	0	T*	T*
Amorphous	5	8	6	6	6		5

T*: traces
1?: probably present

Table X
Summary achievements Corus DSP (status up to May 2003)

Slab production	[kton]	387
Coil production	[kton]	364
Casting speed (max)	[m/min]	5.4
Casting speed (avg)	[m/min]	5.0
EMBR current	[A]	280-350
Cast time (max.)	[hr]	12
Sequence length (max)	[ton]	2400
Sequence length (avg)	[ton]	1200
Breakout ratio	[1/10 kton]	0.47

Conclusions

- The free carbon source and an even distribution within the granules are essential to guarantee a stable slag formation. This can be obtained by using one grade of fine carbon black, possibly supplemented with one grade of fine coke
- The physical properties of mould powders are important, but not as critical as assumed before commissioning of the DSP
- A liquid pool depth > 5 mm is recommended to ensure good lubrication and homogeneous heat transfer
- Differences in the mould slag basicity are not a key parameter in the observed in-mould behaviour
- In addition to conventional characterization methods, optical microscopy proved to be essential for better explanation of the observed in-mould behaviour.

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