THE MELTING SPEED OF MOULD POWDERS, DETERMINATION AND APPLICATION IN CASTING PRACTICE

J.A. Kromhout, D.W. van der Plas

Corus Research, Development & Technology, formerly Hoogovens Research and Development, IJmuiden, The Netherlands

Controlled melting of mould powder on top of the meniscus is essential for proper mould flux performance. This paper presents two complementary methods to determine the melting speed of a mould powder. One method measures the displacement of a pre-pressed cylinder of mould powder at a fixed temperature. This method yields qualitative, but reproducible results which can be related to flux composition. In the second method, a sample of mould powder is melted on top of a steel bath. The data are interpreted with the help of an improved theoretical melting model, resulting in quantitative values of melting speed and thickness of the molten flux layer. The results of both methods agree well with measured plant data.

1. Introduction

In the continuous casting process, controlled melting of the mould powder is essential to minimise break-out occurrence and to optimise surface quality of the cast product. The required melting speed of a mould powder depends on caster design and on casting speed. Mould powder suppliers use carbon to control the powder melting speed. In addition to this inorganic components which are present in the powder may influence the melting behaviour[1,2].

Although the melting speed of a mould powder is considered a key parameter, this property is not measured regularly and so far no standardised assessment method exists[3]. Knowledge on the melting behaviour of the powder is mainly based on practical experience

With the demand to increase the casting speed for conventional slab casting and the higher casting speeds common for thin slab casting, a proper assessment of the mould powder melting speed is even more essential[4,5]. At Corus IJmuiden, two complementary methods were developed to obtain the melting speed.

2. Softening Method

2.1 Method

In the softening method a pre-pressed cylinder of mould powder is put into a furnace at a given temperature. The softening of the mould powder is registered as a function of time. The result can be seen as an indication of the melting speed. The method is schematically illustrated in Figure 1.

In more detail the measuring procedure is as follows:

- 25 grams of mould powder are cold pressed uniaxially to a cylindrical shape. The pressing force is 20N/mm^2. The dimensions of the cylinder are 30 mm (diameter) and approximately 25 mm (height).
- The cylinder is placed into a furnace with a temperature of 1400°C, which is above the melting point of the mould powder.
- A rod of alumina (20 mm diameter) is placed on top of the cylinder. As a result of the softening of the mould powder the rod will be displaced. This displacement is registered as a function of time.
- In this manner every powder is tested twice.

It should be mentioned that nearly all methods to obtain the melting speed of mould powders are experimental methods based on visual observations. An important advantage of the softening method is that the obtained results are based on well defined measured values resulting in reproducible numbers.

2.2 Results

The displacement of the aluminium rod starts slowly, gradually increases and ends with a sharp increment. The results of the characterisation of different powders for slab-, billet- and thin slab casting are given in figures 2 to 6 and are summarised in tables 1 to 4.

2.2.1 Carbon and MgO content

As mentioned in section 1, the free carbon content is considered an important parameter to control the powder melting speed with inorganic components having secondary effects.

It was found that free carbon as well as the MgO content of the powder has an influence on the melting speed. So in the first place, the obtained results were related to the carbon content in the mould powders which did not contain MgO. At a given displacement (20%), the free carbon content in the mould powder (C_{free}) is plotted as a function of time, see figure 2. It is clear that the amount of carbon has an important influence on the melting speed of a mould powder [4,6]. However, the amount of carbon is not the only influencing parameter.

2.2.2 Slab casting: comparison with plant data

In the slab casters of BOS No.2 of Corus IJmuiden, standard mould powders as well as test mould powders were applied in full scale trials. The powders were also characterised using the softening method. The results are presented in Figures 3 and 4 and in Tables 1 and 2. Note that in the tables the free carbon content is given as well as the measured liquid pool depth during casting.

It can be seen that a mould powder with a small amount of carbon (470/LC6 for casting ULC grades) results in a faster displacement than several universal powders or mould powders for casting low carbon grades (470/M, 220A, 221/14A6). Based on the standard powder 221/14A6, the test powder 221/A6 was developed with an increased free carbon content to avoid excessive rim formation. It is assumed that the risk of rim formation is decreased when the melting speed of this test powder is decreased.

2.2.3 Billet casting

Three standard powders for billet casting, used at BOS No.1 (Corus IJmuiden) were characterised. The results are presented in Figure 5 and in Table 3. Comparing figures 3 and 4 with figure 5, it can be seen that mould powders for billet casting have a slower melting speed than mould powders for slab casting due to the increased amount of carbon (C_{free}).

2.2.4 Thin slab casting

Three typical mould powders for thin slab casting have been characterised. Results are shown in Figure 6 and in Table 4. In comparison with conventional slab casting, it can be seen that for thin slab casting the mould powders give the same or higher results i.e. a longer time to melt indicating the influence of the (increased) carbon content (C_{free}).

3. Powder Melting Method

3.1 Experimental set-up

The second method, the powder melting method, is illustrated in figure 7. Powder samples held in a steel cup (diameter 70mm) are melted on top of the steel meniscus in a laboratory scale induction furnace. The bottom of the cup is replaced by an aluminium foil (thickness 0.05 mm) which completely dissolves in the steel within less than a second when the cup is immersed into the steel bath through a refractory tube. The temperature of the melt is continuously measured via an immersed thermocouple and can be controlled manually. A video system is used to record the melting process. For a given mould powder the melting time is measured using different samples with varying weight (between 10 and 100g).

Unlike other testing methods for the melting speed of mould powders, samples can be used without prior preparation. Furthermore, actual casting conditions such as fluid flow at the steel/slag interface and flotation of argon bubbles can to some degree be addressed in the experimental set-up, e.g. by gas injection and inductive heating (stirring). Thus, the testing conditions relate better to the situation in the casting mould.

3.2 Melting model

Melting of solid flux on top of a liquid flux layer is an endothermic reaction. The reaction rate will depend on: (1) the kinetics of the melting process; (2) the transport of heat from the steel through the liquid slag layer, to the solid/liquid interface.

In the case where the melting process itself is the rate limiting factor, the melting speed is constant and independent of the thickness of the liquid slag layer. In this situation the time required for complete melting of a sample in the laboratory trials will increase linearly with the sample weight.

In the case where the heat transport to the interface is rate limiting, the melting speed will decrease with increasing slag layer thickness, and the time required for complete melting increases more than linearly with the sample weight.

While a constant melting speed would imply a very straightforward interpretation of the measured values, a more intricate model is required in case the process is limited by the heat transfer. An example of the latter was developed by Nakano et al[7]. However, as the Nakano model did not include heat transfer by radiation, very high values of heat conductivity in the liquid slag had to be assumed to obtain realistic results. Thus it was decided to improve the Nakano model by adding heat transfer by radiation.

Various approaches for the heat transfer by radiation exist. The one most apt for the current situation (a large temperature gradient and thin layers i.e. $a_l.z>>1$ is not satisfied) is the grey gas approximation[8]. The uncertainties in the physio-chemical properties of the slag justify a simplified approach, bearing in mind that the amount of heat dissipated at the interface is almost one order of magnitude larger than the heat dissipated in the growing liquid slag layer.

The total heat consumed in melting, Φ_1, is then given by (see table 5 for the definition of symbols):

$$\Phi_1 = \rho_l.(C_p.(T_{fus}-293)+H_{fus}).dz/dt \qquad [1]$$

Furthermore, the heat Φ_2 required to maintain the temperature profile in the liquid slag layer as its thickness increases can be approximated as:

$$\Phi_2 = \rho_l.C_p.(T_i-T_{fus}).(dz/dt)/2 \qquad [2]$$

Finally, an assumption has to be made about the heat loss to the surroundings on top of the powder layer. Considering that the heat flux consumed in melting will be very high for a thin liquid slag layer, we assume as a first approximation that this heat loss is negligible as long as there is still powder present on top of the liquid layer. The melting speed is then calculated as:

$$\Phi_1 + \Phi_2 = \Phi_{tot} = \Phi_{rad} + \Phi_{cond} \qquad [3]$$

$$\Phi_{cond} = \lambda.(T_i-T_{fus})/z \qquad [4]$$

$$\Phi_{rad} = [n_l^2/(3a_l.z/4+1/\varepsilon_i+1/\varepsilon_{fus}-1)].\ \sigma.(T_i^4-T_{fus}^4) \qquad [5]$$

From the above, the total time for complete melting of the sample is given by:

$$t_{Zmax} = \rho_l.(C_p.(T_{fus}/2+T_i/2-293)+H_{fus})\ .\ {}_0\!\int^{Z\_max} (\Phi_{cond}+\Phi_{rad})^{-1}dz \qquad [6]$$

Table 5 shows the reference values for the powder and slag properties employed. Note that the model is 1-dimensional, which is justified by the large diameter to thickness ratio used in the experiments.

The model described above not only enables the appropriate physical and chemical properties to be derived from the experimental results, but also enables translation of the experimental results into casting practice, as it defines the relation between melting speed and thickness of the liquid slag layer.

3.3 Results

3.3.1 Melting speed and rate limiting step

Figure 8 shows the melting curves of three different mould powders as obtained by the melting method. The melting time of a sample is defined by the instant that the first bare spot on top of the powder layer is observed in the experiment. Figure 9 shows experimental data and calculated results for the powder 470/LC6 as an example. The dashed curve is a linear regression on the measured data, assuming that the melting kinetics is rate limiting. The solid curve assumes heat transfer limitation, as discussed in §3.2. The figures indicate that the melting process is controlled by the heat transfer to the interface. Linear regression results in melting times that are too long for small samples and too short for the larger ones. A second justification is that the linear approach would result in a flux melting speed in the order of 0.1 mm/s, irrespective of liquid flux layer thickness.

As the true values of a_l, n_l and H_{fus} for the mould powders investigated are not known beforehand, two out of the three entities were set to a common literature value (table 5), and the third was fitted to the experimental results. As discussed in §2.2.1, several agents (carbon, MgO) influence the melting speed. These additions hardly affect the liquid phase (C escapes as gas), i.e. n_l and a_l. Theoretically, the most proper fit might be therefore to vary H_{fus}, as this is the only parameter that really influences the melting process as such.

Table 6 gives the values of H_{fus} obtained from best fits to the experimental data. One uncertainty in the experiment is the actual temperature of the steel/slag interface. As the heat extracted at the meniscus by the melting powder is considerable, the temperature at the meniscus may well be below the average temperature of the melt. Thus, assuming the average melt temperature at the interface, the heat transfer through the liquid slag layer is overestimated, i.e. H_{fus} is overestimated and the powder melting speed under operational conditions will be underestimated. On the other hand, assuming steel solidification temperature at the steel/slag interface, this gives the minimum value of H_{fus} and the maximum value of the melting speed under operational conditions.

3.3.2 Melting speed and liquid flux layer during casting

The experimental results depicted in figure 8 were transformed into the melting speed as a function of liquid slag layer thickness. This is shown in figure 10. Based on the actual powder consumption (BOS No.2) melting rates between approx. 0.01 and 0.06 mm/s were calculated resulting in liquid slag thickness of 3 to 25 mm for the powder 234/16Mg. The liquid slag layer for powder 470/LC6 will be about twice as thick.

3.3.3 Influence of melting furnace operation

Inductive heating results in melt stirring. This might cause increased temperature at the steel/slag interface and increased heat transfer through the liquid slag layer. It was observed that melting times decreased by a factor two when the induction heating was varied from zero to maximum power.

4. Discussion

Attempts have been made to relate the results of the softening method with the liquid pool depth. The liquid pool depth is determined by the melting speed of the mould powder, actual

flow conditions in the mould and the balanced values of the mould powder feeding rate and the mould powder infiltration rate.
At the start of the project the liquid pool depth ranged from 5 to 25 mm. Since 1997 the measured liquid pool depth at the IJmuiden slab casters had values ≤10 mm.
One of the explanations given for the decrease in the liquid pool depth as measured in BOS No. 2 over the last few years is the reduction of turbulence at the meniscus

The powder melting method has shed some light on the relation between process conditions and melting speed. By the stirring action of the induction heater at full power, the melting time could be halved with respect to a completely calm interface. In casting practice, the effects observed in the melting experiment may be enhanced by meniscus waviness, instationary behaviour, and the effect of argon bubbles escaping at the meniscus. Clearly, more experiments are needed, including argon bubbling, to quantify the effects and relate them to the casting practice.

5. Conclusions

1. The softening method can be used to qualitatively assess the melting speed of mould powders for slab-, billet- and thin slab casting, as a function of free carbon and MgO.
2. The powder melting test can be used to characterise the melting behaviour of a mould powder in a comparable situation as in the actual casting mould.
3. The melting speed is limited by the heat transport through the liquid slag layer. Quantitative values for the melting speed as a function of the thickness of the liquid slag layer can be obtained, enabling the thickness of the liquid slag layer on top of the meniscus to be calculated under operational conditions.
4. The powder softening method and the powder melting method must be regarded as complementary. Whereas the former gives reproducible, but qualitative figure for a well described but artificial set-up, the latter yields a quantitative figure that can be translated to casting practice.
5. Mould powders for billet casting have slower melting speeds due to the increased amount of carbon, compared with mould powders for slab casting. Mould powders for thin slab casting yield the same or longer melting times as compared with conventional slab casting. If needed, the melting speed of mould powders for billet casting and thin slab casting can be increased by lowering the carbon content.
6. Turbulence at the steel/slag interface enhances the melting speed. This effect can partly explain the thin layers of liquid slag measured in plant trials. Still, more research is necessary to clarify this observation to a satisfactory extent.

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6. References

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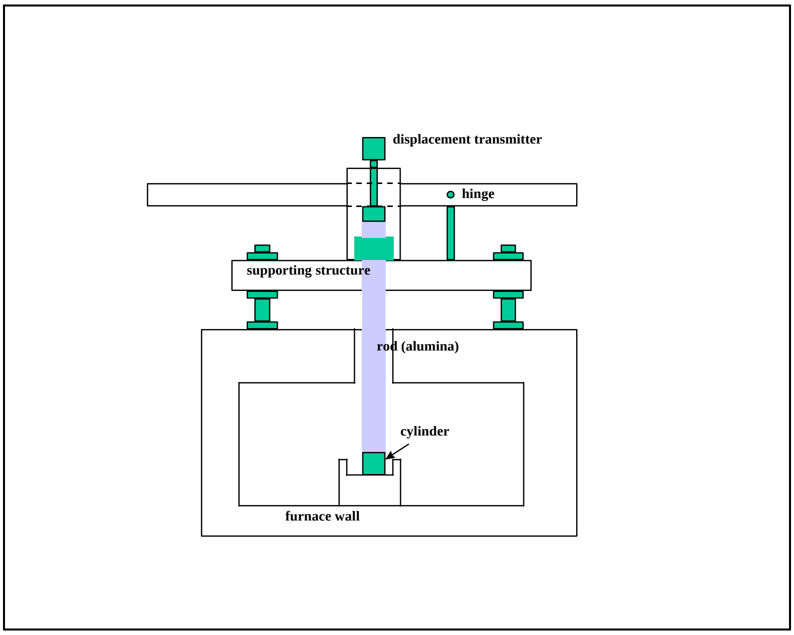

Figure 1: Set-*up of the softening method*

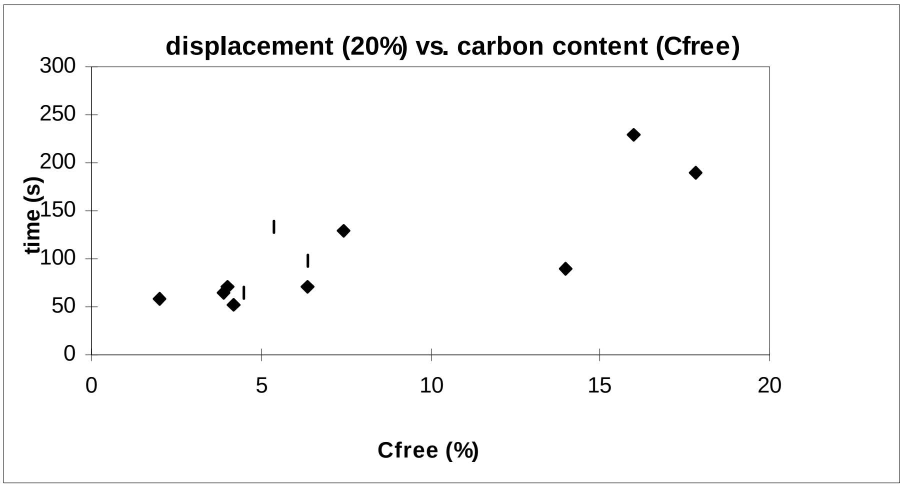

Figure 2: *Displacement time as a function of the carbon content (C_{free})*

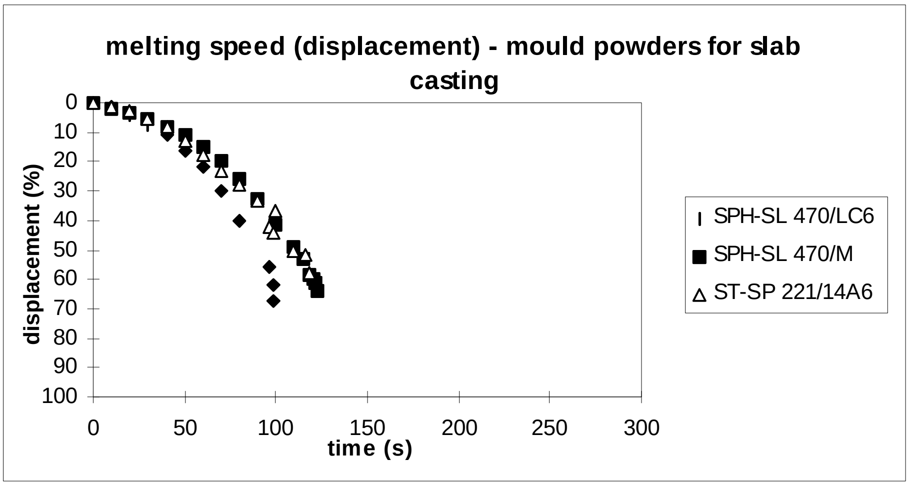

Figure 3: *Melting speed (displacement) - mould powders for slab casting*

Figure 4: *Melting speed (displacement) - mould powders for slab casting (test powders)*

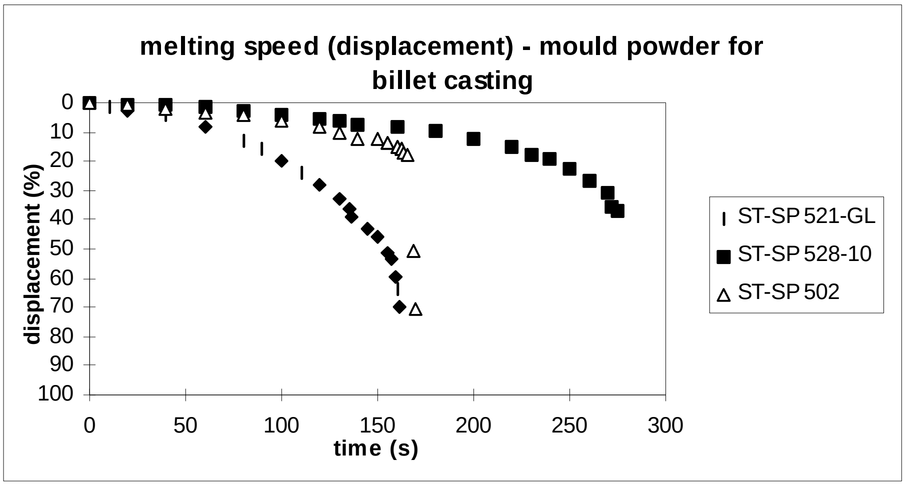

Figure 5: *Melting speed (displacement) - mould powders for billet casting*

Figure 6: *Melting speed (displacement) - mould powders for thin slab casting*

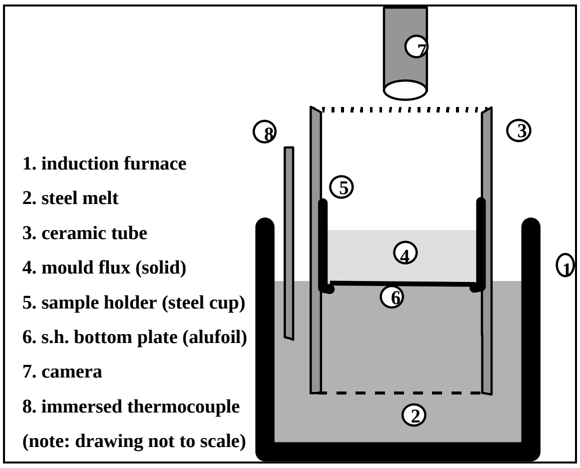

Figure 7: *Experimental set-up at the start of the experiment.*

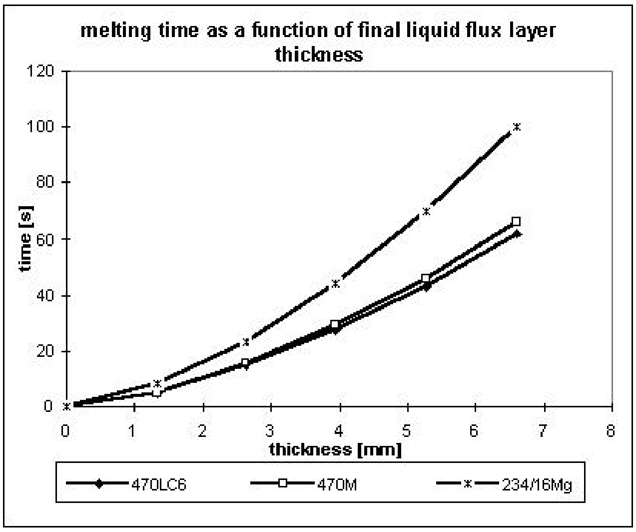

Figure 8: *Melting curves obtained from the melting experiment*

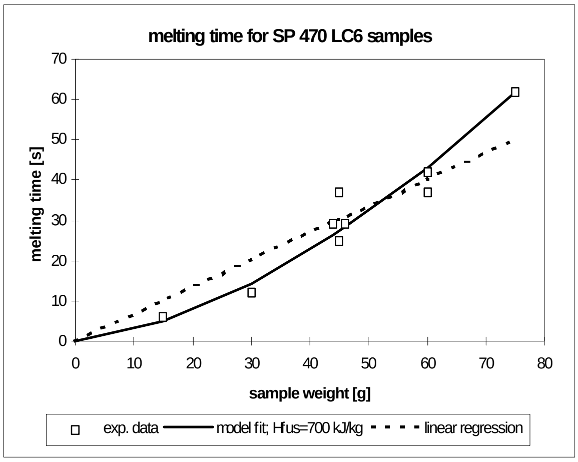

Figure 9: R*esults of melting experiments; powder 470LC6*

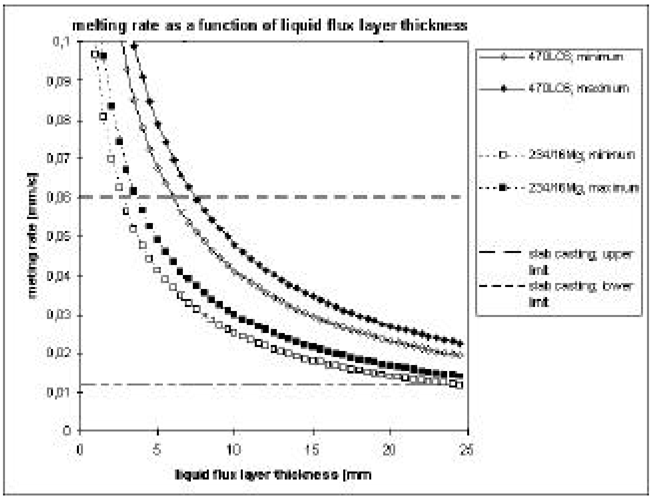

Figure 10: *Melting speed versus flux layer thickness.*

Table 1: *Melting speed (displacement vs. time), standard mould powders for slab casting*

	Melting Time (s) and Powder Type		
Displacement (%)	SPH-SL 470/LC6 (ULC)	SPH-SL 470/M (LC)	ST-SP 221/14A6 (PERITECTICS)
10	40	49	40
20	59	70	65
40	82	98	105
60	92	118	120
70	100	--	--
C_{free} (%)	2.00	4.00	3.90
Liquid pool depth (mm)	2-15	2-10	2-10

Table 2: *Melting speed (displacement vs. time), test mould powders for slab casting*

	Melting Time (s) and Powder Type				
Displacement (%)	ST-SP 234/16Mg (ULC)	ST-SP 234/W-DT (ULC)	ST-SP 220A (LC)	ST-SP 221/A6 (PERITECT.)	SPH 176/M1 (PERITECT.)
10	40	60	46	66	50
20	60	90	65	98	70
40	95	135	94	135	105
60	120	165	116	148	135
70	135	170	125	--	140
C_{free} (%)	1.70	2.00	4.5*	6.38	6.40
MgO (%)	5.50	3.80	--	--	--
Liquid pool depth (mm)	3-10	1-9	2-12	5-10	1-10

Table 3: *Melting speed (displacement vs. time), mould powders for billet casting*

	Melting Time (s) and Powder Type		
Displacement (%)	ST-SP 521-GL	ST-SP 528-10	ST-SP 502
10	50	160	110
20	90	230	190
40	--	--	--
60	--	--	--
C_{free} (%)	14*	16*	17.80

Table 4: *Melting speed (displacement vs. time), mould powders for thin slab casting*

	Melting Time (s) and Powder Type		
Displacement (%)	SPH-SL 481	SPH-SL 188/GA3	ST-SP 221/BC3
10	31	85	90
20	52	130	134
40	85	--	--
60	--	--	--
C_{free} (%)	4.19	7.44	5.38

*: based on data sheets (supplier)

Table 5: *List of symbols and Reference values for physical properties of mould fluxes*

Parameter	Symbol	Value	Remarks
Emission coefficient powder/slag interface	ε_{fus}	1.0	full absorption assumed
Emission coefficient steel meniscus	ε_I	0.8	generally accepted value
Heat transfer coefficient liquid slag	λ_l	1.0 $W.m^{-1}.K^{-1}$	literature values 0.4-1.0 $W.m^{-1}.K^{-1}$; see refs.[7,9,10].
Absorption coefficient liquid slag	a_l	500 m^{-1}	literature values 250-500 m^{-1}; see refs. [9,10]
Powder melting enthalpy (sum of all contributions apart form Joule heating)	H_{fus}	500 $kJ.kg^{-1}$	assumed equal to heat of fusion; see ref.[10]
Specific heat of powder/slag	C_p	1.1 $kJ.K^{-1}.kg^{-1}$	assumed equal for powder and liquid slag; see ref. [10]
Density liquid slag	ρ_l	2800 $kg.m^3$	
Refraction index liquid slag	n_l	1.6	Kawamoto et al.[11]
Flux melting temperature	T_{fus}	1363 K (1090 °C) 1418 K (1145 °C) 1358 K (1085 °C)	measured data for 470 LC6 measured data for 234/16Mg measured data for 470 M
Steel temperature (meniscus)	Ti	1843 K (1570 °C)	controlled
Stefan-Bolzman constant	σ	$5.6*10^{-8}$	
Time	t		
Temperature	T		
Thickness of liquid slag layer (melting method)	z		
Heat flux, - by conduction, - by radiation	Φ, Φ_{cond}, Φ_{rad}		

Table 6: *Experimentally obtained melting enthalpy of mould powders*

Mould powder	H_{fus} from melting experiment [kJ/kg]
SPH-SL 470/LC6	400 - 700
SPH-SL 470/M	500 - 850
ST-SP 234/16Mg	1200 - 1700