

POWDER CONSUMPTION AND MELTING RATES OF CONTINUOUS CASTING FLUXES

S Sridhar^(a,b) KC Mills^(a) and ST Mallaband^(c)

(a)Department of Materials, Imperial College STM, London SW7 2BP, UK

(b) Currently, Dept. Materials Science, Carnegie Mellon University, Pittsburgh, PA

(c) Metallurgica (UK), Bath Road, Stourbridge, West Midlands, UK

ABSTRACT

Plant data from steelworks throughout the world have been analysed to determine :

- (i) the effects of mould dimensions on powder consumption
- (ii) the factors affecting the required melting rates of the fluxes
- (iii) the reliability of empirical rules to predict both powder consumption and the optimum casting conditions
- (iv) the relation between *Break temperature* and the type of steel being cast

The results are discussed with special reference to thin slab casting

INTRODUCTION

Mould powders play an important part in the successful continuous casting of steel. They are placed on the top of the mould where they gradually decarburize, then sinter, form a mush and eventually produce a pool of liquid slag (Figure 1)

The mould flux provides the following functions:

- (a) It must form a liquid slag pool, which protects the surface of the liquid steel from oxidation.
- (b) The liquid slag should infiltrate into the mould/strand channel and provide liquid lubrication throughout the mould.
- (c) The liquid slag freezes against the water-cooled, copper mould and forms a solid slag (usually with glassy and crystalline layers) which must provide the right level of heat transfer for the steel grade being cast.
- (d) The liquid slag pool should absorb non-metallic inclusions since this is the last chance for removing inclusions from the metal.

The mould flux must perform all these functions satisfactorily. However, it is important that the melting rate of the powder should match the demand for molten slag to lubricate the steel strand. The melting rate is usually controlled through the presence of carbon particles, which retard the agglomeration of molten slag globules.

Wolf [1] proposed that it was possible to achieve optimum casting conditions which could provide both good surface quality of the product and good process control, free of problems like sticker breakouts, where molten steel can pour out of the mould. Wolf proposed that the frictional forces were at a minimum and the heat transfer was at an optimal level when

$$\eta v_c^2 = 5 \pm 2 \text{ dPa s (m min}^{-1}\text{)} \quad (1)$$

where η = slag viscosity at 1300 °C and v_c = casting speed .

Ogibayashi et al [2] proposed that the fluctuations in slag infiltration were at a minimum (ie. the slag infiltration is most stable) when :

$$\eta v_c = 2.5 \pm 1 \text{ dPa s (m min}^{-1}\text{)} \quad (2)$$

Thus the viscosity of the molten slag is important since it may help to define the optimum casting conditions.

1.1 Powder Consumption

The powder consumption (Q) is a measure of the amount of liquid slag infiltrating into the mould/strand channel. Wolf [3] pointed out that it was used only to monitor the cost of the

mould flux per unit tonne of steel and was determined as Q_t in kg powder (tonne)⁻¹ but it could be converted to kg powder (m² of mould)⁻¹ which was a measure of the liquid lubrication and hence was a valuable process control parameter.

Wolf [3] converted Equations (1) and (2) into relationships involving Q_s .

Wolf:
$$Q_s (\text{kg m}^{-2}) = 0.7 / \eta^{0.5} v_c \quad (3)$$

Ogibayashi :
$$Q_s (\text{kg m}^{-2}) = 0.6 / \eta v_c \quad (4)$$

Jenkins [4] proposed an alternative relationship :

$$Q_s (\text{kg m}^{-2}) = (\rho_{\text{slag}} / v_c^{0.5} \cdot 6000) \{1 + [\rho_{\text{slag}} \cdot g / 9 \cdot 10^5 \eta v_c^2]\} \quad (5)$$

Where ρ = density of liquid slag and this can be reduced to

$$Q_s (\text{kg m}^{-2}) = (0.433 / v_c^{0.5}) \{1 + [2.83 \cdot 10^{-2} / \eta v_c^2]\} \quad (6)$$

Several other relations have been proposed for the optimal powder consumption, these have been reviewed by Wolf [3] who pointed out that Q_s increases with decreasing oscillation frequency and increasing stroke length. Wolf [3] also pointed out that there is little agreement on how Q_s is dependent upon the oscillation characteristics. Consequently, we have only tested relationships which excluded the oscillation characteristics (Equations 3 to 5).

1.2 Melting Rate

The melting rate of a mould powder is affected by a series of factors (i) the carbon content. (ii) The particle size and the nature of the carbon used. (iii) the vertical heat flux (which depends upon casting speed, turbulence, steel temperature etc) and (iv) the presence of exothermic agents in the powder.

Kawamoto et al [5] have related the melting rates of powder to the C % and the carbonate content.

1.3 Heat Transfer

The first influx of molten slag into the mould/strand gap freezes against the water-cooled, copper mould and forms a glassy solid layer which tends to crystallise with time (on the side nearest to the steel shell) as can be seen from Figure 1. The horizontal heat transfer across the three-layered (glass/ crystalline / liquid) slag film is important. The thermal resistance across the film can be treated as an Ohm's Law analogue in series.

$$R_{\text{total}} = R_{\text{st/sl}} + R_l + R_{\text{crys}} + R_{\text{gl}} + R_{\text{Cu/sl}} \quad (7)$$

Where R is the resistance, the subscript l, gl, and crys refer to the liquid, glass and crystalline phases st, sl and Cu to the steel shell, slag and copper interfaces.

This can be rewritten as:

$$R_{\text{total}} = R_{\text{st/sl}} + \frac{d_l}{k_l^{\text{eff}}} + \frac{d_{\text{crys}}}{k_{\text{crys}}^{\text{eff}}} + \frac{d_{\text{gl}}}{k_{\text{gl}}^{\text{eff}}} + R_{\text{Cu/sl}} \quad (8)$$

where d = thickness, k = thermal conductivity and eff = effective.

With medium -carbon (MC) grades, there is a 4% difference between the shrinkage coefficients of the δ and austenite Fe phases and this produces stresses in the newly-formed shell which can only be relieved by longitudinal cracking. The strategy to overcome this problem is to minimize the horizontal heat transfer to keep the shell as thin as possible so as to minimize the stresses. Thus for MC grades it has been found best to control the heat flux through the use of "soft cooling", i.e. create a thick, solid, slag layer ($d_{\text{crys}} + d_{\text{gl}}$) with a high crystalline content to minimize radiation conduction through the slag.

In contrast, high carbon (HC) steel grades tend to have low strength and thus it is necessary to strengthen the shell by making it thicker. Thus the strategy adopted to combat sticker breakouts (which usually occur because of inadequate lubrication ie powder consumption) is to create a thicker shell by increasing the horizontal heat flux, which is achieved by producing a thin, glassy slag film.

The thickness of a solid slag film can be increased by increasing solidification temperature of the slag flowing into the steel/mould channel. It is our contention that there are similarities between the flow of slag in the channel and that in a viscometer (except the molten slag flows vertically in the channel and rotates in the viscometer. For this reason we consider that the break temperature (T_{br}) obtained in the viscometer (ie. the point where the viscosity increases dramatically on cooling i.e. where liquid lubrication breaks down) provides the best parameter to represent the thickness of the slag formed in the channel.

2. EXPERIMENTAL

Two types of powder consumption data were obtained in plant trials. *Specific powder consumption* data were obtained for fixed conditions of mould dimensions, casting speed, steel grade and *global* where *average* powder consumption values were obtained and where the various parameters were allowed to range between certain values. The specific powder consumption data are preferred. All the plant data were obtained by Metallurgica, GmbH from trials carried out on continuous casting plants throughout the world. No data for the oscillation characteristics were available.

Viscosity and break temperature data were also supplied by Metallurgica who made measurements using a rotating cylinder viscometer and using a Bahr 403 viscometer and platinum alloy crucibles. The measurements were carried out dynamically using a cooling rate of 10 C min^{-1} .

3. ANALYSIS OF PLANT DATA

The following assumptions were made :

- (i) That the powder consumption was due entirely to the liquid layer moving downwards with the strand whilst the solid slag remained in contact with the mould.

- (ii) That all the plants were operating with near-optimum casting conditions.

Then first assumption may not be justified since Jenkins [4] has suggested that the solid slag film moves down the mould at a rate of about 10% that of the liquid slag film.

The powder consumption, Q_t is measured in kg powder (tonne steel)⁻¹ and can be converted to Q_s in kg powder (m² of mould)⁻¹ by use of Equation 9, where R = ratio of the (surface area/volume of the mould), thus for a rectangular mould $R = \{2(w + t) / wt\}$ where w and t are the width and thickness of the mould in metres.

$$Q_s \text{ (kg m}^{-2}\text{)} = \frac{7.6 Q_t}{R} \quad (9)$$

Casting fluxes contain varying amounts of carbon in the form of carbon and carbonate and these vaporize as CO₂ or CO gas and do not form liquid slag. Consequently, in order to calculate the powder consumption it is necessary to correct the carbon and carbonate losses using Equations 10 and 11.

$$f = \left[1 - \frac{\%C_{\text{free}}}{100} - \left(\frac{44}{12} \times \frac{(\%C_{\text{total}} - \%C_{\text{free}})}{100} \right) \right] \quad (10)$$

$$Q_s^{\text{corr}} = f \cdot Q_t \cdot 7.6 / R \quad (11)$$

The average thickness of the liquid slag, assuming no loss of solid slag can be calculated from Equation 12.

$$\bar{d}_l = \frac{Q_s^{\text{corr}}}{\rho_{\text{slag}}} = \frac{\rho_{\text{Fe}} Q_t}{\rho_{\text{slag}} \times 1000 R} \quad (12)$$

The average mass flow rate of liquid slag (M) can be calculated from Q_s , using Equation 13 and this must be equal to melting rate (MR).

$$M = MR = (w + t) Q_s v_c \quad (13)$$

4.RESULTS AND DISCUSSION

4.1 Empirical Rules for Optimum Casting

The empirical rules for optimum casting due to Wolf [1] and Ogibayashi [2] were checked and are presented in Figure 2. It can be seen that :

- (i) Most of the specific plant data fall between the curves representing the Wolf and Ogibayashi relationships but the global or averaged plant data (not shown) tended to be closer to the $\eta v_c = 2.5 \pm 1 \text{ dPa s (m min}^{-1})$ curve.
- (ii) A large amount of the data for billet and high speed billet - casting do not conform to these rules since, as discussed later, powder consumption demands are not stringent for billet casting and thus high viscosity powders can be used to overcome problems (such as slag entrapment) turbulence in the mould and high SEN erosion rates
- (iii) There is a tendency for the Ogibayashi [2] rule ($\eta v_c = 2.5 \pm 1 \text{ dPa s (m min}^{-1})$) to underestimate the relation, this may be due to the practice of selecting a powder for the maximum casting speed and then subsequently operating at lower existing speeds (i.e. the casting conditions plotted in Figure 2 may not be optimal).

On the basis of the data shown in Figure 2, and ignoring the high viscosity powders used for billet - and high speed billet-casting the following relation would give a better fit.

$$\eta V c^{1.5} = 3 \pm 1.5 \text{ dPa s (m min}^{-1})^{1.5} \quad (14)$$

4.2 Powder Consumption

Neumann et al [6] noted that the powder consumption, Q_s was a function of the parameter R i.e. the (mould area/volume) ratio. Sridhar et al [8] confirmed this relation. The result of the specific powder consumption, Q_s as a function of R. The magnitude of the parameter R.

- (i) is in the hierarchy : thin slabs and billets > blooms > slabs
- (ii) decreases with increasing slab width

The results for powder consumption, Q_s and liquid slag film thickness, (d_1) as functions of R are given in Figures 3a and b

It can be seen that:

- (a) there is relatively little scatter in the results and the results agree well with the relation $Q_s = \{2/(R-5)\}$ proposed by Sridhar et al [8]
- (b) thin slabs have Q_s values very similar to those for billets.
- (c) the powder consumption values from the curve due to Neumann et al [6] are slightly higher than those obtained here but Neumann et al. did not correct for the carbon and carbonate losses (i.e. f value) and would agree very well with the present curve when $f = 0.95$ and $f = 0.85$ for slabs and billets, respectively, were applied.
- (d) the powder consumption demands for billet- and high speed billet-casting are not as stringent as they are for slabs and consequently high viscosity powders have been used to

minimize problems due to turbulence i.e. slag entrapment and high SEN erosion rates; it has been suggested that this practice may lead to problems downstream [7] .

Wolf [3] proposed that the relations $\eta v_c = 5 \pm 2 \text{ dPa s (m min}^{-1})^2$ and $\eta v_c = 2.5 \pm 1 \text{ dPa s (m min}^{-1})$ could be converted into powder consumption expressions, namely, $Q_s \text{ (kg m}^{-2}) = (0.7 / \eta^{0.5} v_c)$ and $(0.6 / \eta v_c)$, respectively. The calculated values (Q_s^{calc}) and measured (Q_s^{corr}) values (x and y axes, respectively) are compared for these relations in Figures 4 a and b, respectively. In addition, the results obtained using the Jenkins relation (Equation 6) are shown in Figure 4.

It can be seen from these three figures that:

- (i) there is considerable scatter in the results which may reflect the effect of oscillation parameters on the powder consumption or that some of the plants were not operating under optimal conditions for powder consumption (which is certainly the case for much of the billet casting).
- (ii) the Wolf relation ($Q_s = 0.7 / \eta v_c$) tends to overestimate Q_s ; on the basis of the data obtained here $Q_s = (0.55 / \eta v_c)$ would provide a better fit.
- (iii) the Ogibayashi relation ($Q_s = 0.6 / \eta v_c$) has a tendency to underestimate Q_s ; one possible reason is that frequently a mould flux viscosity is selected to operate at the maximum casting speed but is frequently used for casting at lower speeds
- (iv) The Jenkins relation performed similarly to the Wolf relation and tended to overestimated the powder consumption.

4.3 Melting Rate

The principal factor affecting melting rate is the carbon content; the melting rate (MR) has been plotted against %C in Figure 5a .It can be seen that the melting rate decreases with increasing carbon content and that that high melting rates are needed for casting slabs. To reflect these findings the melting rate was plotted in Figure 5b as a function of the parameter ($R / \%C$) .It was found that the following melting rates were needed : billets (0.1 kg min^{-1}) blooms (0.2 kg min^{-1}) slabs and thin slabs ($0.4 - 0.8 \text{ kg min}^{-1}$) .Thus for thin slabs the powder consumption, Q_s , should be similar to that for billets but the melting rate should be similar to that for slabs.

4.4 Heat transfer

The horizontal heat transfer, as mentioned above , is largely controlled through the thickness of the solid which ,in turn ,is dependent upon the break temperature. Kohtani et al [9] introduced a plot of melting temperature (at 1300°C) as a function of the viscosity. Sridhar et al [8] substituted the break temperature for the melting temperature (Figure 6) and showed that the upper curve should be used to select mould powders for casting Medium Carbon (MC) ,crack -sensitive steel grades and the lower curve for sticker- and bulging-sensitive (HC) steel grades and values between these bounds for all other grades

When the data for thin slabs and high speed billet casting in a similar manner, it can be seen from Figure 7 that the break temperatures of fluxes for thin slabs are about 100 °C higher than those being used for slabs. This suggests that in order to minimize problems with longitudinal cracking in thin slab casting, powder manufacturers have increased the thickness of the solid slag film by increasing the break temperature.

However, the break temperature decreases with increasing cooling rate. The T_{br} values shown in Figures 7 and 8 were obtained at a cooling rate of 10 °C min⁻¹ but cooling rates in the mould / strand channel are of the order of 600 -2000 °C min⁻¹. Thus, it is possible that the T_{br} values for the mould conditions may be 100 °C lower than those shown in Figures 7 and 8.

The break temperatures can be predicted [10] to ± 20 °C (for a cooling rate of -10 °C min⁻¹) from chemical composition using Equation 15.

$$(T_{br} - 1120 \text{ }^{\circ}\text{C}) = -8.43 \% \text{ Al}_2\text{O}_3 - 3.3 \% \text{ SiO}_2 + 8.65 \% \text{ CaO} - 13.86 \% \text{ MgO} - 18.4 \% \text{ Fe}_2\text{O}_3 \\ - 3.2 \% \text{ MnO} - 9.2 \% \text{ TiO}_2 + 22.8 \% \text{ K}_2\text{O} - 3.2 \% \text{ Na}_2\text{O} - 6.47 \% \text{ F} \quad (15)$$

4.5 Chemical composition

Sridhar et al.[3] showed that there was little difference in the chemical compositions of mould fluxes used to cast billets, blooms and slabs. However, there were small, but systematic, differences in compositions used to cast certain grades. For example, since more crystalline slag films are needed for casting MC, crack-sensitive grades the fluxes tend to be lower in SiO₂ and Al₂O₃ contents and higher in F and Na₂O. In contrast, the glassy slag films needed for casting HC, sticker-sensitive grades tend to be higher in SiO₂ and Al₂O₃ contents. On the basis of the results shown in Figure 7, mould fluxes for thin slabs would tend to be basic, low in SiO₂ and Al₂O₃ and may contain exothermic agents to ensure a high meniscus temperature [11] and good infiltration.

CONCLUSIONS

- (i) A much thicker film of liquid slag is needed for casting slabs than for casting thin slabs and billets.
- (ii) Empirical rules for the prediction of required powder consumption (a) based on the casting speed and the flux viscosity (b) for differing mould dimensions were found to be reasonably consistent with plant data.
- (iii) Much higher melting rates are needed for slabs and thin slabs than for billets and blooms
- (iv) Break temperatures should be adjusted to the type of steel grade being cast and it would appear that T_{br} values used for thin slabs are currently 100 °C higher than those used for thin slabs
- (v) The powder consumption demands for billet casting are not stringent and frequently high viscosity fluxes are used to combat slag entrapment and high SEN erosion rates

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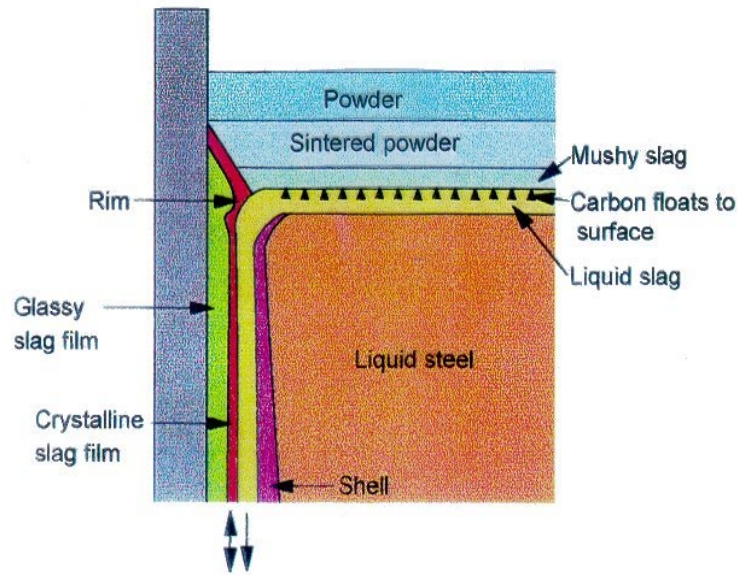


Figure 1 Schematic representation of the various layers of flux formed in the continuous casting mould.

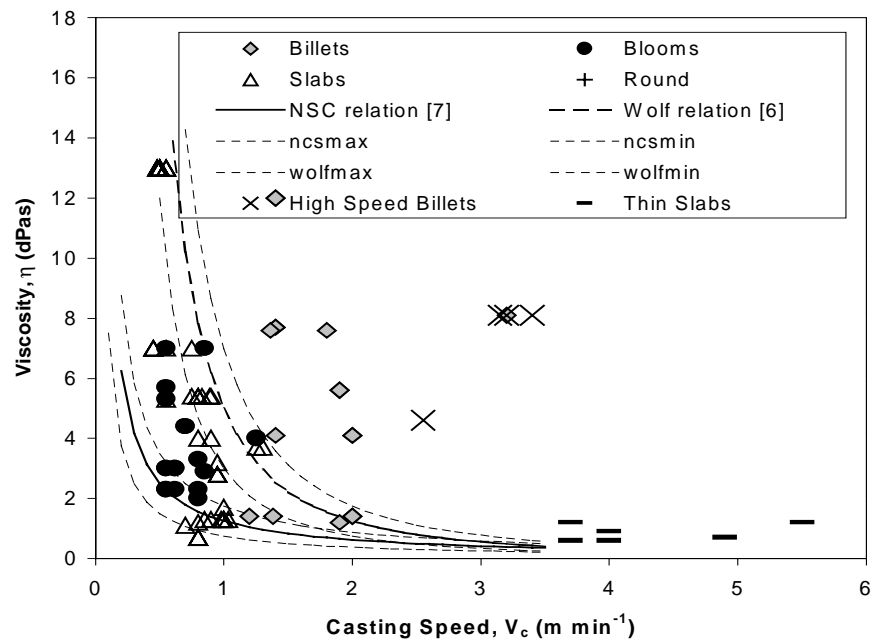


Figure 2 The viscosity of mould fluxes at 1300 °C as a function of casting speed; - - -, Wolf relation ; - . . . , Ogibayashi relation ; - - - , bounds of the two relations.

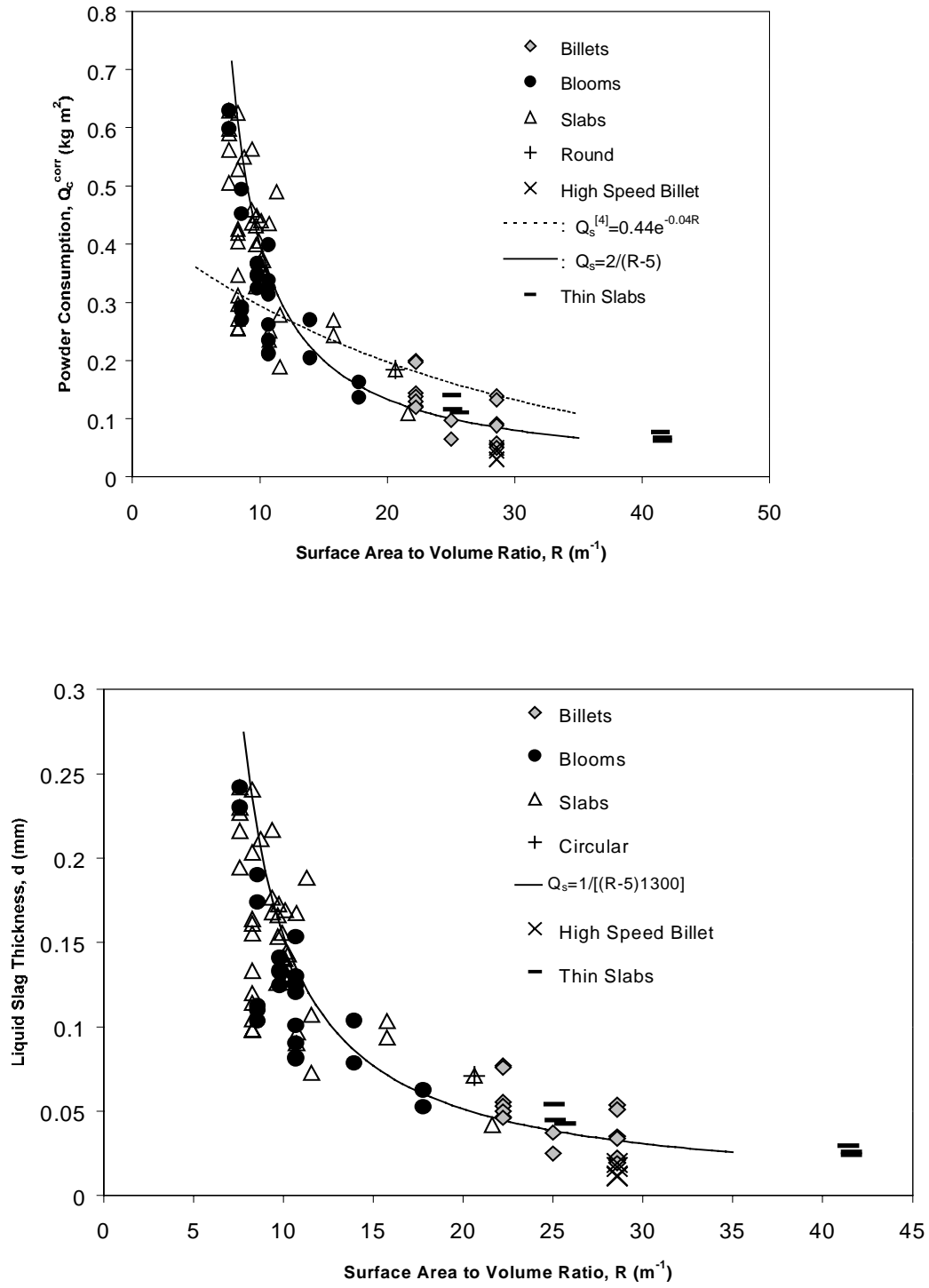


Figure 3a&b: Results for powder consumption, Q_s and liquid slag film thickness, (d_l) as functions of R .

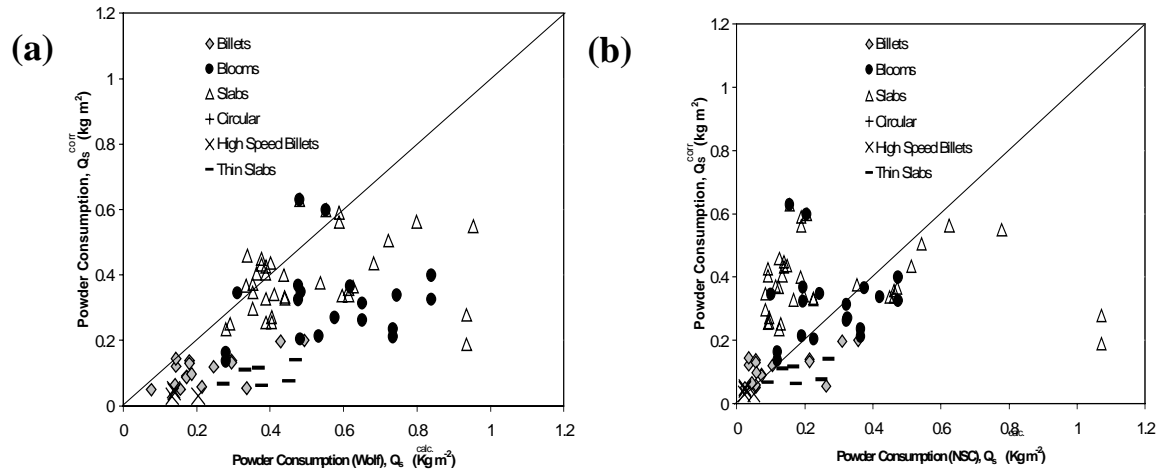


Figure 4 Measured powder consumption as a function of the parameter R; ratio of (surface area / volume) for the mould

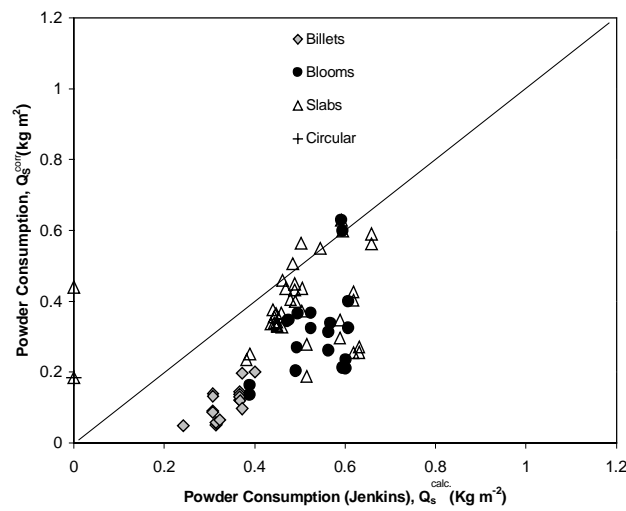


Figure 4 c Measured powder consumption as a function of calculated powder consumption for (a) the Wolf relation, and (b) Ogibayashi relation.

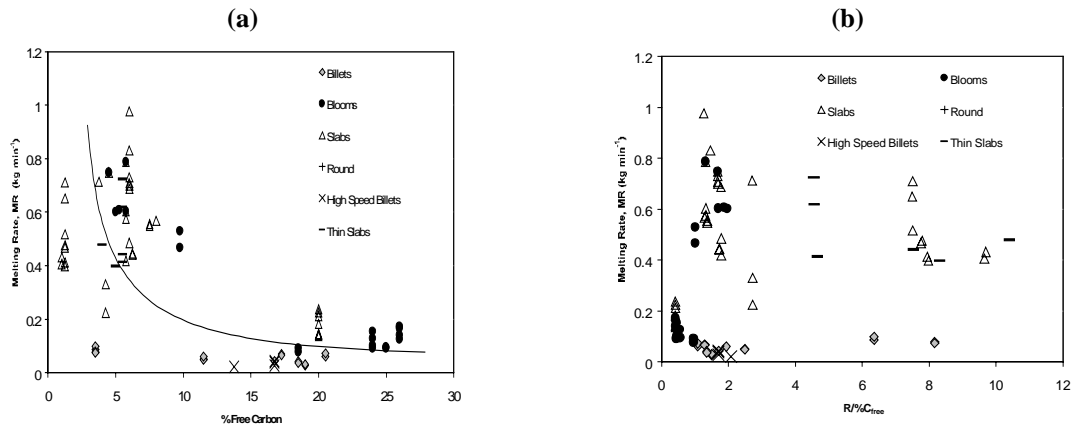


Figure 5 Melting rate of mould fluxes as a function of (a) % C in the flux (b) the parameter (% C / R)

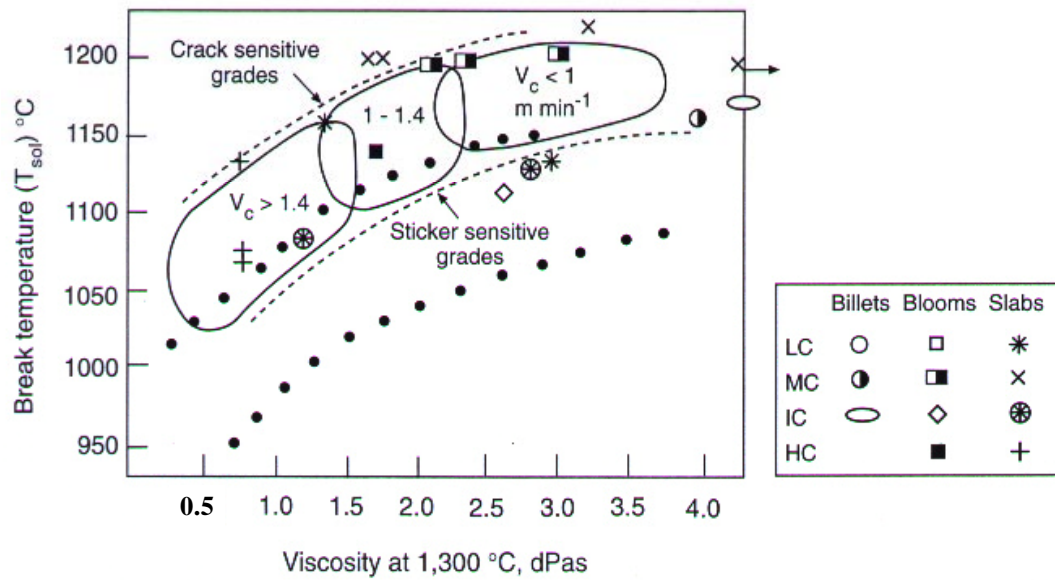


Figure 6 Break temperature as a function of viscosity at 1300 °C for mould fluxes ; - - -, bounds for casting crack-sensitive (upper) and sticker-sensitive (lower) steel grades;, curve for melting temperature used by Kohtani[9].

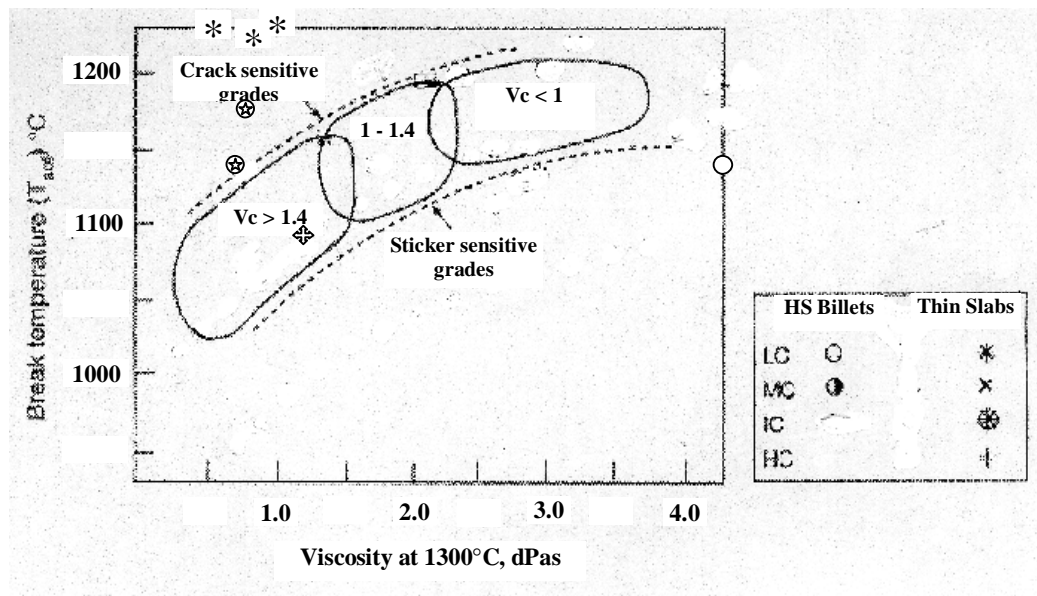


Figure 7. Break temperature as a function of the viscosity of the of the mould flux at 1300 °C for thin slab- and high-speed billet casting.