Continuous Casting Powders and Their Effect on Surface Quality and Sticker Breakouts

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Recent publications concerning mould powders have been reviewed. This investigation confirms Wolf's contention that the powder consumption rate is a valuable process variable since it provides a measure of the lubrication supplied to the mould. The relations between powder consumption with the heat transfer and the frictional forces are explored. The mechanisms responsible for longitudinal cracking and depressions, star cracking, transverse cracking, slag and gas entrapment and sticker breakouts are examined and related to powder consumption, heat transfer and lubrication characteristics of the mould flux.

1. INTRODUCTION

Initially, mould powders were regarded as a form of *black magic*, since they sometimes worked well but little was known about how they worked and why some performed better than others. This is no longer the case since over the last twenty years considerable research effort has been devoted to mould powder research and how their performance affects surface defects and sticker breakouts.

Successful continuous casting demands that the mould powders should perform satisfactorily at each of the various stages shown in Figure 1; failure to do so at any of these stages could lead to inferior surface quality of the product. Of all these various stages, the infiltration of slag into the mould/strand gap is considered to be the most critical, since it provides the necessary lubrication and also affects the heat transfer between steel and mould, both of which are important in avoiding surface defects and sticker breakout.

Powder consumption provides a reasonable measure of the thickness of the liquid slag film infiltrating into the mould/strand gap. Wolf [1] pointed out that powder consumption had in the past been regarded as a measure of powder costs but did, in fact, provide a very useful measure of process control ie an index of the lubrication supplied.

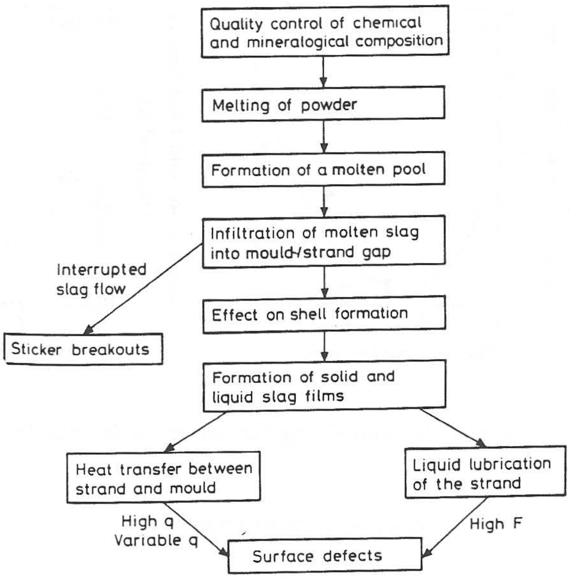

Figure 1 Key processes for mould powders in continuous casting and their effect on surface quality.

Wolf [2] proposed that (i) the most stable infiltration occurred when the parameter ηV_c^2 had a value of around 5 dPas (m min^{-1}) where η is the viscosity and V_c is the casting speed and (ii) the heat flux and the frictional forces were at a minimum in this regions (Figure 2).

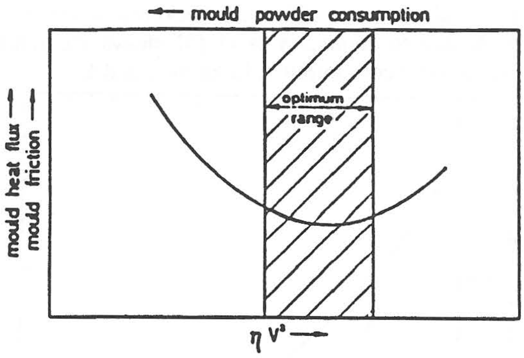

Figure 2 Optimum powder consumption range.

Ogibayashi et al [3] proposed that the *fluctuations* in molten slag infiltration were at a minimum when the parameter ηV_c has a value in the range 1-3 dPas m min^{-1} and that *variations* in heat flux and friction force [4] were also at a minimum in this region. (Figure 3).

In recent years there has been a considerable amount of work published on powder consumption and its relation to heat transfer and lubrication and how these parameters affect the surface quality of steel product. This paper attempts to collate this information.

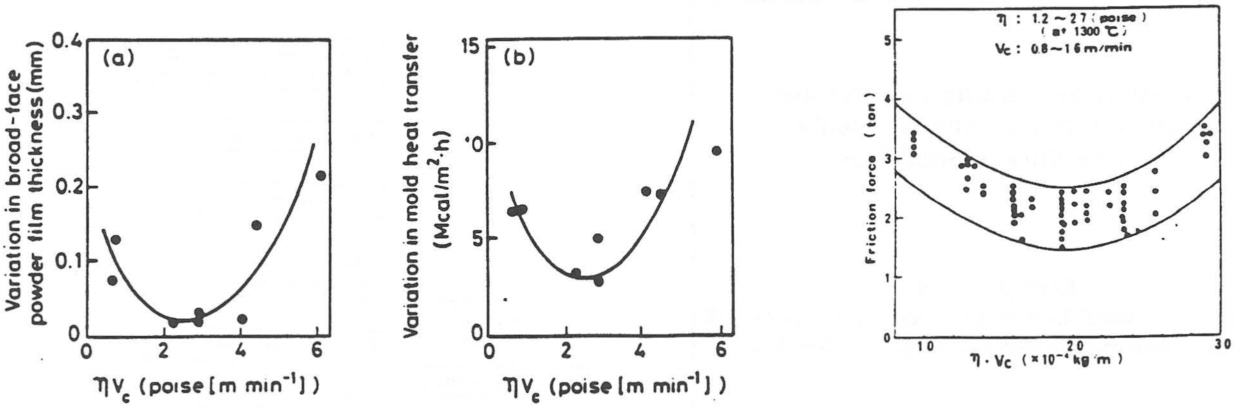

Figure 3 (a) Liquid slag film thickness (b) heat flux and (c) frictional forces as functions of parameter ηV_c.

2. POWDER CONSUMPTION

Powder consumption (Q_t) used to be reported as kg (tonne steel)$^{-1}$. However, it also provides a measure of the liquid film thickness and can be regarded as a lubrication index. Consequently, in more recent years, it is more commonly cited in terms of the surface area of the mould, Q_s, ie as kg m^{-2}. The two terms are related through the surface area/volume ratio, R [5] which can be calculated from Equation (1).

$$R = \frac{2(w+t)}{wt} \qquad (1)$$

where w and t are the width and thickness of the mould. Figure 4, due to Neumann et al [5] shows the relation between powder consumption, in kg m^{-2}, and R.

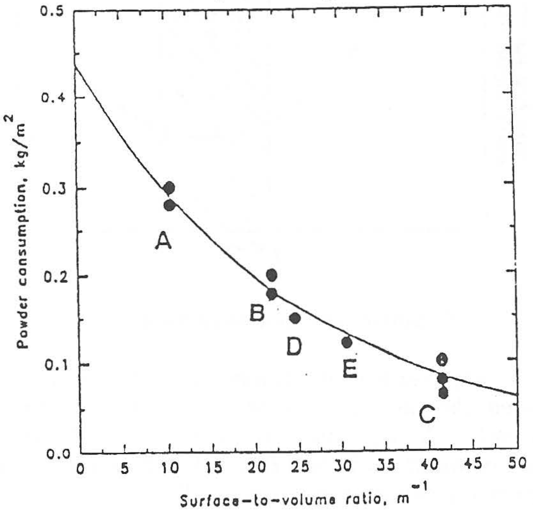

Figure 4 Powder consumption (kg m^{-2}) as a function of the ratio of (surface area/ volume) R for different mould geometries where A = 220 x 1500 mm (V_c = 1.5); B = 100 x 1000 mm (V_c = 4-5); C = 50 x 1300 mm (V_c = 4-5); D = 160 x 160 mm (V_c = 1.5); E = 130 x 130 mm (V_c = 1.8); V_c values in m min^{-1}.

It can be seen that (a) slabs (A,B) have much higher powder consumption requirements than billets (D,E) and (b) the requirements for thin slab casting (C) are similar to those for billet casting (D,E). Wolf [1] noted the following:

(i) powder consumption decreased as casting speed increased

(ii) the minimum powder consumption (Q_{min}) for successful casting depended upon the grade being cast: for *crack-sensitive grades*: Q_{min} = 0.25 kg m^{-2} for round billets and 0.4 kg m^{-2} for heavy-plate medium, C grades (0.10-0.15%C): for *sticker-sensitive grades*: high V_c, low C, Q_{min} = 0.3 kg m^{-2} and for high C, low V_c, 0.4 kg m^{-2}

(iii) the maximum powder consumption (Q_{max}) was controlled by the melting rate and the need to maintain a liquid slag reservoir of sufficient depth.

Wolf [1] reviewed the various empirical equations proposed to calculate the powder consumption rates, the principal factors are (i) viscosity, (ii) casting speed, (iii) slag solidification temperature, T_{sol} and (iv) the oscillation characteristics.

The optimum infiltration relations involving ηV_c^2 and ηV_c, (Figures 2 and 3, respectively) can be expressed in the form of optimum powder consumption (Equations 2 and 3).

$$Q_s = 0.7\,(\eta V_c^{2})^{-0.5} \qquad (2)$$

$$Q_s = 0.6\,(\eta V_c)^{-1} \qquad (3)$$

Noguchi et al [6] proposed an empirical equation involving the solidification temperature T_{sol} this is shown in Equation (4).

$$Q_t = 1.952 - 0.2461\, V_c - 0.044\eta - 0.00107\, T_{sol} \qquad (4)$$

Kohtani et al [7] related viscosity, solidification temperature and casting speed for the optimum casting of slabs of low C steel (Figure 5). Wolf [1] showed that the various combinations shown in this figure led to a constant powder consumption, Q_s of 0.30 kg m^{-2}.

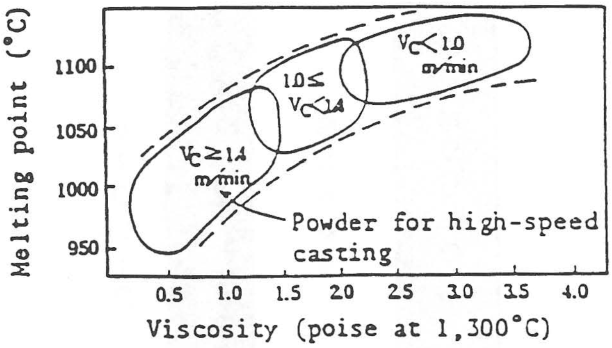

Figure 5 Empirical relation between viscosity, solidification temperature and casting speed for slab casting of low C steels [7].

The greatest variability lies in the expressions used to describe the effect of oscillation characteristics on the powder consumption. The molten slag is drawn into the mould/strand gap when the mould is travelling faster than the strand, thus a relation with negative strip time, t_N, might be anticipated. A relation between Q and reciprocal frequency (f) has been reported [8] this inverse relationship was attributed to a shorter t_N. However, other investigators [9] have suggested that slag infiltration occurs during positive strip time (t_p). Other workers [10] have used a compromise by assuming powder consumption is related to the total cycle time. Wolf [1] considered that total cycle time may provide a measure of the relative velocities of strand and mould which would account for any slag infiltration in negative strip time and upward drag of slag in the positive strip time. The upward drag can be reduced by extending the share of the positive strip time which is accomplished by either using either a (short stroke/low frequency) strategy for sinusoidal oscillation or non-sinusoidal oscillation. As to the stroke length, a reduction of 8 to 6 mm was found [11] to change Q by < 10%. At the present time there does not appear to be a reliable equation covering all of the factors known to affect powder consumption viz casting speed, viscosity, T_{sol}, and the oscillation characteristics.

3. HEAT TRANSFER

The first liquid slag to infiltrate into the mould/strand gap solidifies against the water-cooled mould. Thus slag film consists of three layers, a glassy layer (ca 1 mm thick) adjacent to the mould, a crystalline layer (ca 1 mm thick) and a liquid film (ca 0.1 mm thick). Heat transfer occurs by two mechanisms in glasses viz lattice and radiation conduction. At high temperature the radiation conductivity (k_R) can be an order of magnitude higher than the lattice conductivity (k_c). Some workers [12,13] have proposed that $k_R > k_c$ for heat transfer across the slag film formed in the mould/strand gap. However, recent studies, [14-16] have indicated that for basic slags, the crystalline layer scatters the radiated energy and that k_R is < 20% of k_c. Thus the crystalline layer is important in reducing the heat transfer from the steel to the mould. A method of measuring the amount of crystallinity in the slag film has been proposed which determines the amount of glassy phase present from comparing the Cp increase in the film with that of the glassy slag at the glass transition.

Another factor affecting heat transfer is the thickness of the solidified slag film which is, in turn, dependent upon the solidification temperature. Thus the heat flux can be reduced by increasing the solidification temperature. However, the thickness is also affected by the casting speed (V_c) for example an increase in V_c will increase the heat flux and cause melt back of the solidified slag film. The other factor affecting heat transfer is the magnitude of the heat transfer coefficient of the air gap formed at the mould/slag interface ($h_{Cu/slag}$) especially in the meniscus region.

Recently longitudinal and star cracking have both been related to the *variability* in the strand/mould heat transfer [17,18] and this according to Figure 3 is related to *fluctuations* in slag infiltration.

4. LUBRICATION, FRICTIONAL FORCES

Liquid frictional forces operate in the upper part of the mould but solid/solid frictional forces may arise in the lower part of the mould. If it is assumed that the velocity gradient between the strand and the mould is linear the liquid frictional force, F_l is given by Equation 5 where A is the area of mould/strand contact and V_m is the velocity of the mould.

$$F_l = \frac{\eta(V_m - V_c)A}{d_l} \qquad (5)$$

Thus the frictional forces will decrease with decreasing viscosity and increasing liquid film thickness (ie increasing powder consumption rate). This assumes Newtonian behaviour but it is possible that with a (solid + liquid) region that the behaviour is non-Newtonian.

Ogibayashi et al [19] have calculated the apparent frictional coefficients and found that the values decreased from 0.3 to 0.15 as the liquid film thickness (d_l) decreased from 0.160 to 0.230 mm. These coefficients are higher than those calculated for liquid lubrication and this was attributed to either variations in liquid film thickness or to non-Newtonian behaviour by the mould flux.

Sorimachi et al [20] pointed out that frictional forces tended to be measured over the entire shell but when sticker breakouts occurred it was the local friction forces at the meniscus which were important. They developed a simulation experiment in which the upper graphite plate (slab) was rotated unidirectionally and the lower graphite plate was oscillated sinusoidally (f = 100 to 400 cpm) and the 2 mm gap separating the plates contained mould flux with $\eta_{1300\,°C} = 3.9$ Pa.s. It was concluded that (i) mould fluxes behave as Maxwell viscoelastic fluids with a coefficient of elasticity = 10 Pa at 0.28 Pa.s and 50 Pa at $\eta = 2.3$ Pa.s, and (ii) that the frictional forces working on the shell were lower than those calculated assuming Newtonian behaviour.

It would appear that further work is needed here since in one case the apparent frictional coefficients exceeded those derived assuming Newtonian behaviour whilst in the other case they were lower than Newtonian values.

5. SURFACE DEFECTS

5.1 Longitudinal Cracking

Longitudinal cracking is a particular problem when casting either medium C (0.08 - 0.15%) steels or low C grades at high casting speeds. Cracking is considered to be caused by the thermal stresses in the shell resulting from the differences in the thermal contraction coefficients of the δ ferrite and austenite phases. These cause, sequentially, (i) wrinkles in the shell, (ii) variable air gaps and heat transfer coefficients which result in local hot spots which concentrate the tensile strains and lead to (iii) longitudinal cracks. Consequently the aim is to produce a shell which is both thin and uniform; this can be achieved by reducing the heat flux.

Murakami et al [21] dipped a water-cooled copper plate into molten steels with variable carbon contents (0.054, 0.146 and 0.276%). They observed that the shell formed by the medium C shell had hexagonal-pattern depressions which were absent for the steels with C contents of 0.054 and 0.276%. These depressions formed air gaps between the shell and the chill plate and resulted in uneven solidification.

It has long been known that longitudinal cracking can be reduced by lowering the total heat flux through imposition of softer water cooling or by changing the mould powder [22]. However other studies [18] have indicated that they could identify no correlation between the level of longitudinal cracking and total heat flux but could establish a correlation with the variability in heat flux.

If there is a variable air gap, the heat transfer coefficient ($h_{cu/sl}$) between mould and slag will be large (in some regions) and variable. We can consider the heat transfer as an analogue of Ohms Law with the heat flux density and temperature gradients as analogues of the potential difference and current, respectively. The thermal resistance (R) is given by Equation 6 where d is thickness, k the thermal conductivity and the subscripts gl, cry and liq refer to the glassy, crystalline and liquid layers.

$$R = \frac{1}{h_{cu/sl}} + \frac{d_{gl}}{k_{gl}} + \frac{d_{cry}}{k_{cry}} + \frac{d_{liq}}{k_{liq}} \qquad (6)$$

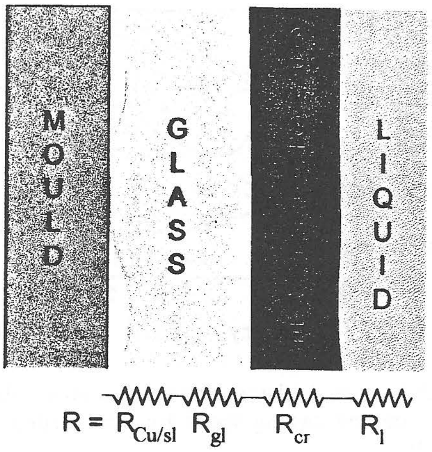

Figure 6 Schematic diagram showing the thermal resistance contributions of the various layers in the slag film.

If the solid layer is thin ($1/h_{cu/sl}$) could be the dominant term and the heat flux would be very variable in both transverse and longitudinal directions for medium C steels and this would cause longitudinal cracking. However if we increase the thickness of slag film the ($1/h_{cu/sl}$) term becomes less dominant and the heat transfer becomes more uniform.

The customary ways of reducing the heat flux through the mould powder selection are:

- increase the solidification temperature to create a thicker solid slag film
- decrease radiation conduction by creating slag films with a developed crystalline layer (ie increased CaO/SiO_2 ratio).

Ogibayashi et al [23] pointed out that the meniscus temperature was also important since it influenced (i) powder melting and slag infiltration, (ii) the formation of the slag rim and (iii) the thickness of the solid slag film in the meniscus region. Thus any changes which will improve the uniformity of the meniscus temperature will help to overcome longitudinal cracking. These include

(i) reducing the temperature variations in the transverse and longitudinal direction through use of electromagnetic stirring (EMS) and breaking (EMBr) and using low-thermal conductivity SENs

(ii) increasing the meniscus temperature (by EMBr) which increases the uniformity of both slag infiltration and meniscus temperature

(iii) good mould level control

(iv) minimising turbulence through improved SEN design and positioning since turbulent flow can create a standing wave on the surface of the steel (Figure 7) which affects slag infiltration.

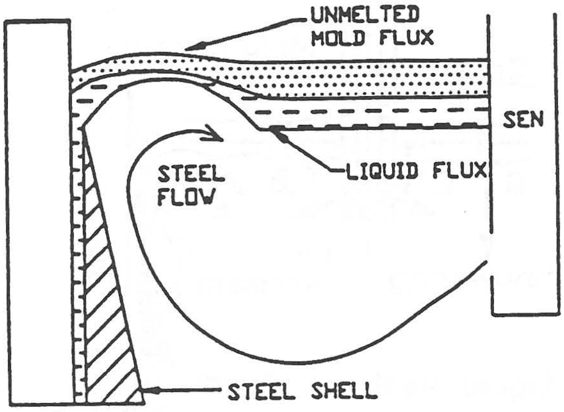

Figure 7 Schematic drawing showing formation of a standing surface wave.

Ogibayashi [19] developed a mathematical model of frictional forces and their effect on longitudinal cracking. There is shrinkage of the meniscus in the transverse direction and the frictional force is greatest at the centre of the slab where the shell is thinnest. They concluded that longitudinal cracking occurred

(1) as a consequence of poor lubrication at high casting speeds and

(2) through irregular growth of the initially-solidified shell at lower casting speeds.

However, recently, Kawamoto et al [22] have reported that in their plant trials longitudinal cracking showed better correlation with the total heat flux than with temperature variations in the transverse and vertical directions.

5.2 Longitudinal Depressions

Longitudinal depressions, typically (50-500 mm) long x (1-2)mm x (0.3-1)mm deep are encountered and sometimes evolve into scrape marks. The depressions were sometimes found with entrapped scums. It can be seen from Figure 8 that the depressions are associated with mould level instability. This problem has been studied by both Kim et al [24] and Jenkins et al [25]. It was noted that the depressions coincided with peaks in the mould level and troughs in the heat flux [24]. They noted that the pressure at the meniscus increased as it approached the slag rim which suggests that deepening oscillation marks may be a feature of rising mould level and that slag infiltration was cut off near the slag rim. They proposed the following mechanism, shown in Figure 9, for the formation of longitudinal depressions.

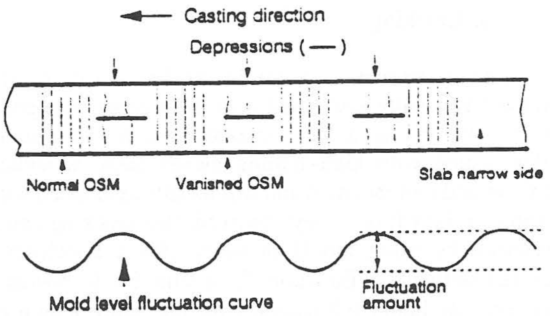

Figure 8 Schematic diagram showing the relation between positions of depressions and mould level fluctuations [24].

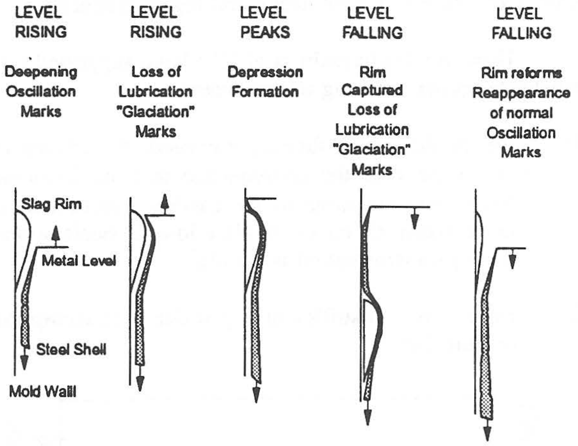

Figure 9 Schematic diagram outlining the proposed mechanism for longitudinal depressions [25].

Deep oscillation marks are formed as the mould level and the slag rim moves closer to the slag rim. This results in increased pressure on the liquid slag which increases the bending forces on the shell [25].

Depressions are formed as a result of either (a) metal solidifying against the slag (above the slag rim) leaving the imprint of the slag rim or (b) by the capture of the slag film by the shell [25].

This is another example of poor surface quality occurring when lubrication is cut off.

5.3 Star Cracking

This is known to occur in the lower half of the mould and is usually associated with the melting of copper. However, Billany et al [17] reported that it occurred in moulds coated with high-melting metals such as nickel, chromium and molybdenum and was usually associated with variations in heat flux. They observed, that cracking could be reduced by using mould powders with a Lubrication Index (LI defined in Equation 7) around 1.0 ie powders which provide liquid lubrication over the entire length of the mould.

$$LI = \frac{\text{Distance meniscus to point where } T = T_{sol}}{\text{Distance meniscus to bottom of mould}} \qquad (7)$$

5.4 Transverse Corner Cracking

Transverse corner cracking is usually associated with oscillation marks, the severity increasing with increasing depth of the depression. The cracking can be minimised by avoiding the low ductility region at 820 °C which frequently coincides with the temperatures in the corner regions at the time of straightening. The development of a thinner slag in the corner regions may be an alternative to the usual remedy of using a shorter stroke and higher frequency.

However Ogibayashi et al [19] have suggested that transverse corner cracking occurs when:

(i) the mould narrow face taper exceeds the amount of shrinkage with the consequence that the frictional forces become large in the casting direction (it is more likely to occur in ultra low C steels where $\delta \rightarrow \gamma$ transformation is small).

(ii) there is insufficient powder consumption (Figure 10).

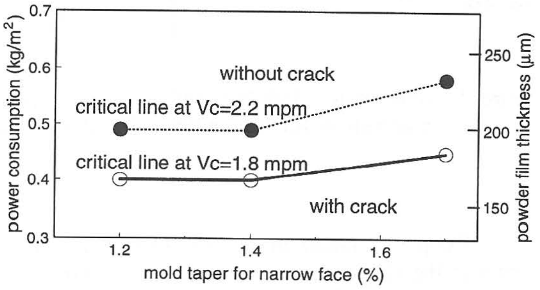

Figure 10 Critical powder consumption required to avoid transverse cracks as a function of mould taper.

5.5 Gas and Slag Entrapment

Slag and gas entrapment occurs in the early moments of solidification of the meniscus and leads to entrapped scums, blow holes and subsurface inclusions. This problem has attracted a lot of attention in recent years and most of these studies have involved physical modelling of the entrapment mechanism. Four mechanisms for slag entrapment proposed by Nakato et al [26] are shown in Figure 11.

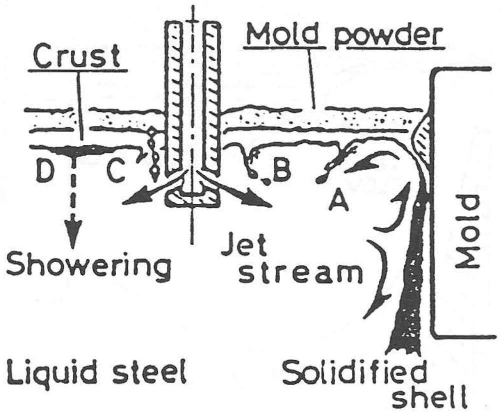

Figure 11 Schematic representation of four mechanisms of slag entrapment; A = shearing of a *neck* of molten slag by a reverse flow; B = shearing of a *neck* of molten slag in the vortex in the SEN region; C = disturbance of metal/slag interface bubbling; D = showering of mould powder crusts when steel temperature is too low [26].

Recently, Emling et al [27], Feldbauer and Cramb [28] and Herbertson et al [29] have reviewed the mechanisms and the factors responsible for slag entrapment. Most of the factors affecting slag entrapment are process variables such as positioning of the SEN, port design of the SEN, metal velocity, Argon flow rate, electromagnetic breaking, mould level control and the clogging of SEN. There are only two properties of the mould powder which affect slag and gas entrapment, viz mould slag viscosity and slag/metal interfacial tension. Feldbauer and Cramb [28] have suggested that viscosity is unlikely to have a large effect since their modelling studies indicated a dependence on $\eta^{0.22}$. However, steelmakers report that slag entrapment can be reduced by using a powder with a high viscosity.

A high slag/metal interfacial tension would hinder the necking and shearing of the slag. However, the dominating factor in the interfacial tension (γ_{ms}) is the surface tension of the steel and this is largely controlled by the S content of the steel. Feldbauer and Cramb [28] pointed out that with respect to the mould slag (i) the trend of increasing TiO_2 and MgO contents to reduce viscosity and T_{sol} could result in a decrease in γ_{ms} and (ii) the practice of reducing the Na_2O content in mould powders to increase γ_{ms} may not be warranted since Na_2O content was found to have little effect on γ_{ms}. It is known [30] that mass transfer across the slag/metal interface results in a sudden decrease in γ_{ms} to a very low value which would encourage the shearing and emulsification of the slag. It is possible that these conditions prevail in the mould during continuous casting.

6. STICKER BREAKOUTS

Sticker breakouts are caused by lack of lubrication. Several mechanisms have been proposed [31-33] which relate to interruption of the flow of molten slag resulting from either a blockage at the meniscus level or by the slag rim.

High C steels (> 0.4%) are particularly sensitive to sticker breakouts as a consequence of the low strength of the shell near the meniscus due to enhanced microsegregation of ferrite between austenite grains.

It has been proposed [33] that two events are necessary for a breakout to occur:

(i) some hinderance to the flow of slag into the mould/strand gap

(ii) the pick-up of carbon which leads to a high C, low-melting meniscus which does not repair sufficiently during negative strip time and which results in the shell sticking to the mould.

In order to minimise sticker breakouts (and steel grades prone to bulging below the mould) it is necessary to increase the heat transfer from shell to mould to create a thick shell. This is carried out by selecting mould powders with (i) a low T_{sol} which produce a thin solid slag layer and (ii) a low CaO/SiO_2 ratio to create a glassy slag which promotes radiation conduction.

There is some evidence that ZrO_2, derived from the SEN, causes sticker breakouts [35]. It has been suggested that since ZrO_2 has a limited solubility in the slag, the ZrO_2 particles act as nucleation sites to give a slag with a high solidification temperature [36].

It should be noted that the mould powder requirements for sticker steel grades are the opposite to those needed for crack sensitive grades. Bommeraju [37] has pointed out that there is an operation window for the mould powder to work in (Figure 12) in order to avoid both sticker breakouts and longitudinal cracking.

Figure 5 can be used to select approximate values for the viscosity and solidification temperature of a candidate mould powder. If the steel is likely to be prone to longitudinal cracking, the upper bound can be used to give the required T_{sol} and viscosity. Conversely, if the steel is sticker sensitive the lower bound can be used to select these properties.

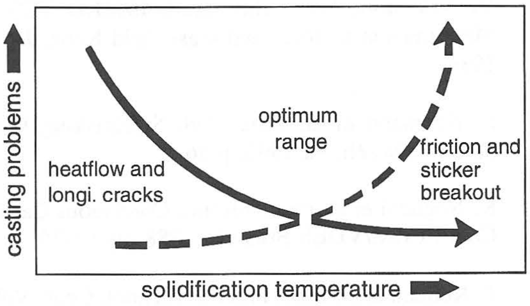

Figure 12 Operation window for continuous casting.

The importance of the solidification temperature suggests that the data obtained for the *softening*, *melting* and *fluidity* temperatures on the heating cycle should be replaced by solidification or 'break' temperatures determined by DTA and viscosity measurements, respectively, for the cooling cycle.

7. CONCLUSIONS

1. Recent research investigations have shown the importance of (a) the stage which involves the infiltration of molten slag into the mould/strand gap and (b) powder consumption as a valuable process variable.

2. Most recent work confirms the view that longitudinal cracking results from heat flux variations in the transverse and longitudinal directions of the mould; cracking is best overcome by using mould slags with a high solidification temperature and a well-developed crystalline layer.

3. Sticker breakouts and bulging problems are best overcome by using mould powders which produce a glassy slag with a low solidification temperature.

4. There is a case for replacing the *softening*, *melting* and *fluidity* temperatures cited for the melting range with solidification or break temperatures measured on the cooling cycle.

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