Chapter 2
Slag Infiltration, Lubrication and Frictional Forces

Abstract It is essential to lubricate the shell since inadequate lubrication leads to defects in the steel product (e.g. longitudinal cracks, sticker breakouts and star cracks). The liquid layer of the slag film, formed between the shell and the mould, lubricates the newly formed shell; the lubrication increases with increasing liquid slag thickness ($d_l$). Lubrication is usually represented by the powder consumption ($Q_s$ in units of kg slag (or powder) m$^{-2}$) which is related to liquid film thickness ($d_l$). However, there are several terms used for powder consumption and these terms are interrelated (e.g. $Q_s$, $Q_t$ and $Q_{MR}$). The frictional forces acting on the shell are highest in the centre of slabs and thus slabs need more lubrication. The required powder consumption, $Q_s$ increases with increasing distance from the corner and thus $Q_s^{\text{slab}} > Q_s^{\text{bloom}} > Q_s^{\text{billet}}$. The required powder consumption can be calculated from the relation, $Q_s^{\text{req}} = 2/(R^* - 5)$ where $R^* = \{2(w + t)/w \cdot t\} = \text{(surface area/volume) of the mould}$. However, the powder consumption, $Q_s$, is also affected by other parameters, namely, the casting speed ($V_c$), slag viscosity ($\eta$), the break temperature of the slag and the oscillation frequency ($f$) and stroke ($s$). There is general agreement that $Q_s$ decreases with increasing casting speed and viscosity (e.g. empirical rules, $Q_s^{\text{req}} = 0.55/\eta^{0.5} \cdot V_c$). There is some dispute with regard to the effect of $f$, $s$ and $T_{br}$ but most plant studies indicate that $Q_s^{\text{req}}$ decreases as $f$, $s$ and $T_{br}$ increase. The required values of powder consumption and viscosity can be calculated for the given casting conditions using empirical rules. The predictions of a mathematical model indicate that slag infiltration into the model/strand channel occurs when the mould and slag rim are descending but little powder consumption occurs when the mould is ascending. The changes in mould direction are accompanied by periods of confused flow in the mouth of the channel and little slag infiltration occurs in these periods. Frictional forces and the factors affecting them are also discussed; it was found that liquid friction increased with increasing mould dimensions, slag viscosity, casting speed and ($V_m - V_c$). Plots of liquid friction ($F_l$) versus casting speed exhibit a minimum since $F_l$ increases with increasing $V_c$ but decreases with decreasing ($V_m - V_c$).
Symbols, Abbreviations and Units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area (m$^2$)</td>
</tr>
<tr>
<td>%C$_{\text{free}}$</td>
<td>Percentage of free carbon</td>
</tr>
<tr>
<td>%C$_{\text{total}}$</td>
<td>Percentage of total carbon</td>
</tr>
<tr>
<td>%LOI</td>
<td>Percentage of loss on ignition</td>
</tr>
<tr>
<td>D$_C$</td>
<td>Mean particle size of the carbon</td>
</tr>
<tr>
<td>D$_{\text{corn}}$</td>
<td>Distance mould corner to centre (m)</td>
</tr>
<tr>
<td>D$_l$</td>
<td>Thickness of liquid slag film (m)</td>
</tr>
<tr>
<td>F$_i$</td>
<td>Frictional force (N)</td>
</tr>
<tr>
<td>f</td>
<td>Frequency (Hz or cycles min$^{-1}$)</td>
</tr>
<tr>
<td>f$^*$</td>
<td>Fraction of powder forming slag</td>
</tr>
<tr>
<td>Q$_{\text{cycle}}$</td>
<td>Powder consumption (kg m$^{-1}$ cycle$^{-1}$)</td>
</tr>
<tr>
<td>Q$_{\text{MR}}$</td>
<td>Melting rate (kg/min or kg/s)</td>
</tr>
<tr>
<td>Q$_s$</td>
<td>Powder consumption (kg/m$^2$)</td>
</tr>
<tr>
<td>Q$_t$</td>
<td>Powder consumption (kg/tonne$^{-1}$)</td>
</tr>
<tr>
<td>R$^*$</td>
<td>Mould (surface area/volume) (m$^{-1}$)</td>
</tr>
<tr>
<td>s</td>
<td>Stroke length (m)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature ($^\circ$C)</td>
</tr>
<tr>
<td>T$_{\text{br}}$</td>
<td>Break (or solidification) temperature</td>
</tr>
<tr>
<td>t</td>
<td>Time (s) or thickness of mould (m)</td>
</tr>
<tr>
<td>t$_{\text{cycle}}$</td>
<td>Time for one cycle (s or min)</td>
</tr>
<tr>
<td>t$_n$</td>
<td>Negative strip time (s)</td>
</tr>
<tr>
<td>t$_p$</td>
<td>Positive strip time (s)</td>
</tr>
<tr>
<td>V$_c$</td>
<td>Casting speed (m/min)</td>
</tr>
<tr>
<td>V$_{\text{in}}$</td>
<td>Velocity of mould (m/min or m/s)</td>
</tr>
<tr>
<td>w</td>
<td>Width of mould</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Slag viscosity (dPas)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg/m$^3$)</td>
</tr>
</tbody>
</table>

Superscripts

- $^{\text{powd}}$: Refers to powder
- $^{\text{slag}}$: Slag formed from powder

2.1 Introduction

The newly formed steel shell is lubricated as it progresses down the mould by a flow of liquid slag from the slag pool (Fig. 2.1). This flow of slag helps to reduce the frictional forces acting on the shell. The liquid frictional force ($F_i$) operating on the shell can be calculated using Eq. 2.1 where $V_{\text{in}}$ and $V_c$ are the velocities of the mould and the casting speed, respectively, $A$ is the active surface area of the mould, $\eta = \text{slag viscosity}$ and $d_l$ is the liquid slag film thickness.
Thus the liquid frictional force decreases as the:

- Thickness of the liquid film increases.
- Surface area of the mould decreases.
- Viscosity decreases.
- With a decrease in the difference between the velocities of mould and steel strand.

It will be seen below that the thickness of the liquid slag film \(d_l\) is related to the powder consumption \(Q_s\) (with units of kg/m\(^2\)). In addition to the liquid friction forces there are also solid friction forces which tend to occur in the lower mould.

The powder consumption, \(Q_s\) (in kg/m\(^2\) of mould) is often used as a measure of the lubrication supplied by the liquid slag since it is linearly related to \(d_l\) (see Eq. 2.4).

### 2.2 Powder Consumption (Q)

The powder consumption \((Q)\) can be expressed in several ways, each term having different units. The most common form for powder consumption is \(Q_t\) (in kg/t steel) which is the mass of powder consumed per tonne of steel cast. This provides a measure of the cost of the casting powders in continuous casting.
It should be pointed out that the mould powder contains carbon, carbonate and other volatiles which burn off and, hence, do not contribute to lubrication by the slag. Some billet fluxes contain up to 25% free carbon and consequently, it is necessary to differentiate between mould powder and slag. This is denoted here by attaching the superscripts, \textsuperscript{powd} and \textsuperscript{slag}, respectively, to the various consumption terms. It is possible to calculate one term from the other by calculating the fraction of powder forming slag (\(f^*\)) by Eq. 2.2 and using either the free carbon (\(%C_{\text{free}}\)) and total carbon contents of the powder (\(%C_{\text{total}}\)) or alternatively, the loss on ignition (\(%\text{LOI}\)) which are usually supplied by the powder manufacturer.

\[
\begin{align*}
  f^* &= \left[100 - (%C_{\text{free}}) - \{(44/12)(%C_{\text{total}} - %C_{\text{free}})\}\right]/100 = (100 - %\text{LOI})/100 \\
  \text{(2.2)}
\end{align*}
\]

The powder consumption of slag can be calculated from the relation:

\[
Q_{s}^{\text{slag}} = f^* Q_{t}^{\text{powd}}. \quad \text{(2.3)}
\]

### 2.2.1 Various Powder Consumption Terms

As mentioned above, the powder consumption can be expressed in various ways, each with different units; the various terms can be calculated from one another, e.g. \(Q_s\) and \(Q_t\) by Eq. 2.4.

\[
Q_s^{\text{slag}} (\text{kg/m}^2) = \left(f^* 7.6 Q_{t}^{\text{powd}} \right)/R^* = \rho d_l \approx 2550 d_l. \quad \text{(2.4)}
\]

where \(R^*\) = (surface area/volume) of mould = \(\{2(w + t)/ \text{w} \cdot \text{t}\}\) (and has units of \(\text{m}^{-1}\)) \(w\) = width of the mould (m), \(t\) = thickness of the mould (m) and \(\rho\) = the density (\(\text{kg/m}^3\)) of the molten slag. 7.6 is the density of steel in \(\text{t/m}^3\). Equation 2.4 also shows the link between \(Q_s\) and the thickness of the liquid slag film (\(d_l\)).

Furthermore, the melting rate of the mould powder, \(Q_{MR}^{\text{powd}}\) (in units of \(\text{kg/min}\) or \(\text{kg/s}\)) can be calculated from \(Q_s^{\text{slag}}\), by Eq. 2.5 where \(V_c\) is the casting speed (\(\text{m/min}\)).

\[
Q_{MR}^{\text{slag}} (\text{kg/s}) = f^* Q_{MR}^{\text{powd}} = 2(w + t)Q_{s}V_c/60 \quad \text{(2.5)}
\]

The melting rate should match the powder consumption (\(Q_s\)) needed to provide good lubrication of the shell. There are a number of variables which affect the melting rate but it is primarily controlled through the free carbon content (\(%C_{\text{free}}\)) and the mean particle size of the carbon (\(D_{C_{\text{free}}}\)) of the powder (i.e. \(Q_{MR}^{\text{slag}}\) is \%\(C_{\text{free}}\) and \(D_{C_{\text{free}}}\)).

The powder consumption per oscillation cycle, \(Q_{\text{cycle}}^{\text{slag}}\) (kg/cycle) can be calculated from \(Q_s\) via Eq. 2.6 where \(f\) = oscillation frequency (in \(\text{Hz}\)).
All of the above parameters can be derived by considering a liquid slag film of uniform thickness \((d_l)\) distributed around the mould and by assuming \(A_{\text{shell}} = A_{\text{mould}}\).

### 2.2.2 Measurement of Powder Consumption

The powder consumption, \(Q_t^{\text{powd}}\), is frequently determined as the number of bags \((N)\) of known mass of casting powder \((m)\) used in the entire cast, for which the total mass of steel cast \((m_{\text{steel}})\) is known. Thus \(Q_t^{\text{powd}}\) can be calculated \((Q_t^{\text{powd}} = Nm/m_{\text{steel}})\).

Powder consumption rates for different periods during a cast can be determined by measuring the mass of powder dispensed from the hoppers in a known time period. However, these measurements are affected by the height of the powder in the hopper and thus measured rates are affected by recharging the hopper; for true significance, the measurements should refer to the same height of powder in the hopper. There is some variability in the consumption values. Some of this variability probably arises from small variations in the casting conditions (e.g. changes in casting speed) through the cast.

The most precise method for measurement of mould powder consumption, when, for example, performing plant trials with new mould powders, is to use a bucket with known amount of mould powder and count the number of buckets needed for the casting.

Powder consumption data for 32 casts of the same steel under the same conditions (where any casting speed variations were <\(\pm 10\%\)) is shown in Fig. 2.2. The mean \(Q_t\) value was 0.63 kg/t, the maximum range in values was 0.24 kg/t and the uncertainty was calculated as \(\pm 12\%\) [1, 2].

Studies where the powder supply was monitored at nine positions between the centre and the edge of the mould showed that consumption (i) was highest at the edge (presumably because it has to feed the narrow face too) and (ii) went through a minimum located midway between the edge and the centre [3].

The powder consumption at different periods of the cast is shown in Fig. 2.3, it can be seen that the powder consumption appears to be higher at the beginning of the cast and gradually decreases to a steady value.

### 2.2.3 Methods Used to Understand Slag Infiltration Mechanisms

Several techniques have been used to gain an understanding of the mechanisms responsible for slag infiltration, they are:
2.2.3.1 Analysis of Plant Data

Plant trials are carried out where powder consumption is measured as one variable (for instance, as a function of casting speed or slag viscosity) is changed while all the other variables are held constant. Most of the empirical relations were derived in this manner (see Table 2.3). One major problem with this approach lies in determining the effects of oscillation characteristics where it is common practice to operate with a fixed negative strip ratio. Thus if the frequency is increased, it is common practice to alter the stroke (s) or casting speed to ensure that negative strip time remains the same. Thus there are few plant trial data carried out where only one oscillation parameter (say frequency, f) is varied systematically.

Fig. 2.2  Histogram of powder consumption (kg/t) in similar trials where a variation of <±10% in casting speed was allowed (courtesy of Fox [2])

Fig. 2.3  Powder consumption at different periods of the cast (courtesy Fox [2])

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An alternative approach was taken by Saraswat et al. [4]; they carried out a statistical analysis for a large database of powder consumption data from various steel plants in order to identify those variables (Vc, η, f, s, Tbr) which had a statistically significant effect on Qs.

### 2.2.3.2 Physical Modelling Studies

In physical models, the effect of changing one variable is studied by observation of the slag flow. The physical models can be divided into three types, given below, and details of the various studies are given in Table 2.1:

(a) *Cold (or water) models* which are usually carried out at near-ambient temperatures. In some cases the slag rim is represented by a solid ledge [5] and other cases by freezing of the water representing the slag [6]. The main problem with these tests is that they tend to be isothermal whereas the conditions in the mould are not isothermal.

#### Table 2.1 Details of some physical modelling studies of slag infiltration and factors affecting powder consumption

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Metal</th>
<th>Slag</th>
<th>Comments, findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anzai [12]</td>
<td>CM</td>
<td>Rubber belt</td>
<td>Paraffin</td>
<td>Pressure measured in mould/shell gap; mould = oscillating plate, shell = moving belt</td>
</tr>
<tr>
<td>Jenkins [6]</td>
<td>CM</td>
<td>Ice</td>
<td>Glycerol/water</td>
<td>Rim = solid ledge; Measures pressure (p) in gap. Predicts (a) Qs↓ as f↓ as s↑ and η↑. (b) P versus η plot goes through maximum at 2 dPas</td>
</tr>
<tr>
<td>Tsutsumi [7]</td>
<td>HM</td>
<td>Sn/Pb</td>
<td>Stearic acid</td>
<td>Slag infiltration occurs in both tn and tp but more in tp—slag inflow occurs at end of tn. Qs↑ as Vc↓, η↑, f↑, s↓ Tsol↓ Friction measured</td>
</tr>
<tr>
<td>Itoh [7], Nebeshima [7]</td>
<td>HM</td>
<td>Cu</td>
<td>Mould flux</td>
<td>Qs dependent upon (tn + 0.5tp). No η dependence for Qs.</td>
</tr>
<tr>
<td>Kajitani [5]</td>
<td>CM</td>
<td>Moving polyester belt</td>
<td>Silicone oil</td>
<td>Mould = oscillating acrylic plate; Mould/ shell gap monitored. Gap profile is important. If gap narrows (as go downward) Qs↑ as Vc↑, η↑; if gap widens Qs↓ as Vc↓, η↓ suggests gap widens downward</td>
</tr>
<tr>
<td>Badri [9, 10]</td>
<td>M Sim</td>
<td>Steel</td>
<td>Mould slag</td>
<td>Oscillating mould. Principally focused on shell profile, heat flux and OM formation</td>
</tr>
</tbody>
</table>

*CM* cold model; *HM* hot model; *M Sim* mould simulator
(b) *Hot models* use low-melting metals, like copper or tin, to represent the steel shell and the effects of changing variables are observed visually [7, 8].

(c) *Miniature continuous casters* [9–11] are, bench-top versions of a continuous casting machine; they are fully instrumented to provide information about powder consumption, heat flux, friction, etc. The apparatus (see Sect. 3.2.4.2) consists of (i) a water-cooled copper mould which is inserted in a bath of steel covered with mould powder (the mould is in *inverse mode*, i.e. where the mould is surrounded by a slag film and a steel shell) (ii) an extraction system to provide continuous casting (iii) mould level control (iv) sinusoidal oscillation of the mould and (v) sensors to provide mould and steel temperatures, shell and mould displacements [9–11].

### 2.2.3.3 Mathematical Modelling Studies

The importance of the slag infiltration process is reflected in the number of mathematical models developed to predict the powder consumption; these models mostly make use of the Navier–Stokes equation [1, 13–25]. Billany et al. [26] and Gray [27] compared the predictions of the earlier models with plant data and observations. They found that:

- The models predicted the correct trends with casting speed, viscosity, etc.
- The models tended to slightly underestimate powder consumption.

However, one common problem with the model predictions is that they predict that $Q_s$ increases with increasing frequency whereas most experimental data indicate the reverse relation, i.e. $Q_s$ and $Q_t$ decrease with increasing frequency (see Sect. 2.2.6.4) (Fig. 2.4).

![Fig. 2.4 Powder consumption as a function of frequency](permission granted ISIJ [28], re-drawn)
There are two approaches to modelling powder consumption. The first considers the powder consumption in its entirety. In the second approach, the various contributions to powder consumption are calculated individually [7, 19, 20] and collated. For instance, Meng and Thomas [19] consider that the powder consumption ($Q_s$) is made up of the following contributions:

- Liquid slag consumption ($Q_l$).
- Solid slag consumption ($Q_{sol}$) caused by any downward movement of the solid slag film.
- Powder consumption ($Q_{OM}$) caused by liquid slag trapped in the oscillation mark.

In some cases, $Q_{sol} + Q_l = Q_{lub}$ is assumed [7]. The powder consumption which is trapped in the oscillation mark ($Q_{OM}$) has been derived from calculations of the mean depth and the pitch of the oscillation mark [19] or from the relation, $Q_{OM} = 0.001f t_n \rho_t (t_n + 0.5t_p)$ [20].

Itoyama et al. [20] divided the powder consumption ($Q_s$) into the following contributions:

$$Q_s = Q_m + Q_g + Q_f + Q_{OM}.$$  (2.7)

where $Q_m (= \rho d l/2)$ and $Q_g (= g \rho^2 d l^3/12 \eta V_c)$ are associated with the pressure drop for parallel plates and the effect of gravity on the flow, respectively, $Q_f$ is the flow associated with mould oscillation ($Q_f = (L_u/L_e) \rho sf L_e \sin(\beta/V_c)$) and $Q_{OM} = A_{OM} \rho f' V_c$ where $\beta$ is the mould taper, $L_e =$ effective length of mould) and $L_u =$ relative, decreasing, distance when mould is ascending and $A_{OM} =$ area of oscillation mark.

Saraswat et al. [4] calculated the values of $Q_{OM}$ (denoted $Q_{OM}^{\text{calc}}$) and compared them with a database of powder consumption values recorded in different steelworks ($Q_{OM}^{\text{total}}$). It was found that all of these models tended to seriously over-calculate $Q_{OM}$, i.e. ($Q_{OM}^{\text{calc}}/Q_{OM}^{\text{total}}$) > 1 and frequently with values of 2 or more for this ratio.

Details of the various mathematical models are summarised briefly in Table 2.2.

### 2.2.3.4 Empirical Rules

A number of empirical equations have been deduced from analysis of plant data or from observations made in simulation tests. These are discussed in detail in Sect. 2.2.6. The equations and the effects of changes in the various factors are summarised in Table 2.3.
### Table 2.2: Details of some published mathematical models covering slag infiltration

<table>
<thead>
<tr>
<th>References</th>
<th>Model details</th>
<th>Comments, findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niggel [13]</td>
<td>Initially oscillation excluded. Assumes solid slag film adheres to mould; liquid moves down. Thermo-mechanical approach</td>
<td>Two regimes (i) $Q_{MR} \leq Q_{MR}^{TOL}$; (ii) $Q_{MR} \geq Q_{MR}^{TOL}$ Model predicts $Q_s$ versus $V_c$ exhibits a maximum</td>
</tr>
<tr>
<td>Schwerdtfeger [18]</td>
<td>Based on N–S eqn. for slag flowing between parallel plates. Needs data for $d_{s+l}$ at meniscus and parallel plate regions Calculates velocity profile and $P$ in gap</td>
<td>Shear stress and Friction calculated from velocity profile. Predicts shell bent away from mould during descent of mould and towards mould during ascent of the mould</td>
</tr>
<tr>
<td>Kor [14]</td>
<td>Based on N–S eqn. for slag flowing between two parallel plates— (1) moving at constant velocity and (2) oscillating</td>
<td>Must provide value of $d_{s+l}$ and no account of thermal effects in the slag film</td>
</tr>
<tr>
<td>Hill [29]</td>
<td>Model to calculate slag flow, $d_{OM}$ Max. vol flow rate, $Q_{s}^{\text{max}} = (2/3) \frac{\eta}{\Delta \rho g}^{0.5} V^{1.5} - N$–S Eqn.</td>
<td>Predictions for $d_{OM}$: $d_{OM} \uparrow$ as $s \uparrow$ as $\eta \downarrow$</td>
</tr>
<tr>
<td>Nippon Steel [15, 16, 30]</td>
<td>Values of $d_s$ and $d_l$ not needed. Assumes mould oscillation affects viscosity. Rheological approach to calculate slag film thickness and velocity profile</td>
<td>Predicts (i) $d_l \uparrow$ as $\eta \uparrow$ and as $f \downarrow$ (ii) $Q_s \uparrow$ as $V_c \uparrow$ as $\eta \downarrow$ [26]. In agreement with plant data</td>
</tr>
<tr>
<td>Meng [19]</td>
<td>Couples transient slag flow model with solid slag stress and FD model of heat transfer. Uses Slag fracture and TTT data. Validated via Friction measurements on plant</td>
<td>Models used to check effects of $V_c$ and $\eta$, $F_1$ gives negligible stresses. Slag film Fracture occurs near meniscus for crystalline and near mould exit for glass phase</td>
</tr>
<tr>
<td>Okazawa [17]</td>
<td>Uses Reynolds eqn, not N–S eqn. Steady state Unsteady state</td>
<td>Mould/shell gap widen as mould ascends; gap narrows during the ascent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gap opened during ascent and closed during descent of mould</td>
</tr>
<tr>
<td>Ojeda [22]</td>
<td>Couples, FF and HT. Values assumed for $d_s$, $d_l$; men shape = Bikerman</td>
<td>Steel overflows at end of $t_p$. Rim exerts positive pressure. Positive $Q_s$ during (t_n to early $t_p$) and negative $Q_s$ during $t_p$, when $V_m$ is high</td>
</tr>
<tr>
<td>Ramirez–Lopez [21]</td>
<td>Couples FF, HT and solidification. No assumptions re: $d_s$, $d_l$ or men. shape</td>
<td>Follows $Q_s$, $q$, $d_{shell}$, $d_l$ through osc. cycle, $Q_s$ increases as mould/rim descends with max. in early $t_p$. Related to direction of flow in slag pool- downward-descending; outward-ascending</td>
</tr>
<tr>
<td>Jonayat [25]</td>
<td>Couples transient flow of metal and slag phases with heat transfer and solidification models Validated against plant data for $Q_s$</td>
<td>Parametric data: $Q_s \uparrow$ as $V_c \downarrow$, as $s \uparrow$ as $x' \uparrow$ relation with $f$ complex; $Q$ (kg m$^{-1}$cycle$^{-1}$) $\downarrow$ as $f' \uparrow$</td>
</tr>
</tbody>
</table>

*FF* fluid flow in slag and metal; *HT* heat transfer; *men* meniscus; *osc* oscillation cycle; *N–S* Navier–Stokes; *P* pressure; $Q_{MR}^{TOL}$ is required $Q_s$ value; $x'$ modification ratio.
### Table 2.3 The predicted effect (increase ↑ or decrease, ↓) on $Q_s$ with an increase in parameter (e.g. $f$)

<table>
<thead>
<tr>
<th>References</th>
<th>Equation, $Q_s$</th>
<th>$V_c$</th>
<th>$\eta$</th>
<th>$f$</th>
<th>$T_{sol}$</th>
<th>$T_{liq}$</th>
<th>$S$</th>
<th>$t_p$</th>
<th>$t_n$</th>
<th>$t_{cycle}$</th>
<th>$\rho_{ slag}$</th>
<th>$d_l$</th>
<th>$d_{OM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolf [62]</td>
<td>$Q_s = 0.1 + 0.55 \times (60/\eta)^{0.5} V_c$</td>
<td>↓</td>
<td>↓</td>
<td></td>
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<tr>
<td>Ogibayashi [42, 43]</td>
<td>$Q_s^{powd} = 0.60/\eta V_c$</td>
<td>↓</td>
<td>↓</td>
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<tr>
<td>Wolf [41, 42], Fox [1]</td>
<td>$Q_s^{powd} = 0.70/\eta^{0.5} V_c$</td>
<td>↓</td>
<td>↓</td>
<td></td>
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<tr>
<td>Kwon [51]</td>
<td>$Q_s = 0.22 + 0.4 \times (60/0.5 \cdot s)^{0.3} \eta^{0.5} V_c$</td>
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<td>Maeda [49]</td>
<td>$Q_s = 0.15 \cdot f \cdot t_p/ (\eta \cdot V_c)$</td>
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<tr>
<td>Nakajima [52]</td>
<td>$Q_s = 205400 V_c^{-0.628} \cdot T_{liq}^{-0.866} \cdot s^{0.341} \cdot t_{cycle}^{-0.076} \cdot t_p^{-0.116}$</td>
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<td>Sridhar [45]</td>
<td>$Q_s = 0.3/ (\eta^{0.48} V_c)$</td>
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<tr>
<td>Wolf 5 [63]</td>
<td>$Q_s = 0.5 \cdot (s/\eta \cdot V_c/1000)^{-0.5}$</td>
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<td>Jenkins [6]</td>
<td>$Q_s = (0.433 \times V_c^{0.8} \cdot (1 + 0.023/\eta V_c))$</td>
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<tr>
<td>Fox-modified [2]</td>
<td>$Q_s = (0.369 \times V_c^{0.8} \cdot (1 + 0.1564/\eta V_c^{-2}) - 0.123$</td>
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<td>Nebeshima [7]</td>
<td>$Q_s = \left(\rho_{OM} \cdot d_2 V_c + \rho_{d_2 h}\right)$</td>
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<td>Tsuchumi [53, 64]</td>
<td>$Q_s = (k_b \cdot s^{0.4} \cdot T_{sol}^{0.5} \cdot V_c) \cdot \cos^{-1} \left[1000V_c/2\pi f_s\right]$</td>
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<td>Emi [65]</td>
<td>$Q_s = 0.6\eta^{-0.15}$</td>
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<tr>
<td>Nakato [66, 67]</td>
<td>$Q_s = \rho_{ slag}(0.143 - 0.003 \eta)$</td>
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<tr>
<td>Kitagawa [57]</td>
<td>$Q_s = 0.0085 \cdot t_p/ V_c$</td>
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<td>Noguchi [68]</td>
<td>$Q_s = 10^{-3} \cdot (1952 - 246V_c - 44\eta - 1.07T_{liq})$</td>
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<td>Kobayashi [69]</td>
<td>$Q_s = 0.003(\cdot t_{cycle} + t_p)^{1.5} \cdot f/V_c$</td>
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<tr>
<td>Shimizu [70]</td>
<td>$Q_s = f \cdot t_p \cdot (0.0184(T_s - T_{liq}) - 2.58) / 10 V_c$</td>
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<tr>
<td>Itoyama [20]</td>
<td>$Q_s = Q_m + Q_s + Q_t + Q_{OM}$</td>
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<tr>
<td>Shin [23]</td>
<td>$Q_s = \left[0.025 \cdot \rho_{f} \cdot k_{43} \cdot \left(2\Delta T/ \Delta \rho_{g}\right)^{0.5} \cdot 0.556 \cdot L_{n}^{-0.389} \cdot \nu_s^{1.49} + 0.507 \cdot e^{3.59\rho_{f}} \right] \cdot (f/\nu_s)$ where $\nu_s = V_c \cdot 10^3 / 60$</td>
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<tr>
<td>Saraswat [4]</td>
<td>$Q_s = e^{28.8^{V_c^0.46}} \cdot f^{3.49} \cdot s^{1.37} \cdot T_{br}^{0.48}$</td>
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when casting a LC steel where $f$: frequency; $s$: stroke; $t_p$: negative strip time; $t_p$: positive strip time; $Q_m$, $Q_f$, $Q_s$ defined in Sect. 2.2.3.1 (iii); $P$: analysis of plant trial data; $Sim$: simulation expts; $StA$: statistical analysis of plant data
2.2.4 Problems Arising from Poor Powder Consumption

Inadequate powder consumption has been reported to cause:

- Longitudinal cracking [31].
- Sticker breakouts (which are associated with a thin shell and poor lubrication).
- Deep oscillation marks [32, 33].
- Transverse cracking [34].
- Off-corner cracking [35, 36].
- The formation of depressions (when poor mould level control leads to the capture of the slag rim and the simultaneous cutting off of slag infiltration) [37–39].

Furthermore, heat flux (or mould temperature) variations were found to increase with decreasing powder consumption (Fig. 2.5) [40]. One of the principal causes of heat flux variations is the creation of a corrugated shell which is prevalent when casting peritectic, MC steels. The powders used to cast these steels are designed to give a thick, crystalline slag film to reduce the horizontal heat transfer. This is achieved by increasing \( T_{\text{br}} \) for the slag. However, a high \( T_{\text{br}} \) slag tends to create in a thin liquid slag film (\( d_l \)) which results in a low \( Q_s \) value. Corrugated shells are less common in other steel grades and so slags tend to have lower \( T_{\text{br}} \) values and hence higher \( Q_s \) values. Thus mould temperature fluctuations tend to exhibit an inverse relation with powder consumption (Fig. 2.5).

2.2.5 Optimum Casting Conditions

Wolf [41, 42] proposed that there was an optimum range for casting (i.e. the minimum friction and the optimum horizontal heat flux) which was defined in terms of the parameter \( (\eta V_c^2) \). This is shown in Fig. 2.6. The optimum conditions were found to occur when \( (\eta V_c^2) = 5 \pm 3 \text{ dPas (m min}^{-1})^2 \).

![Fig. 2.5 Fluctuations in mould temperature as a function of powder consumption when using different casting powders (permission granted, ISS/AIST, [40])](image-url)
Ogibayashi et al. [43] reported that fluctuations in molten slag infiltration and mould temperature (heat flux) were at a minimum when the parameter, $\eta V_c$, had a value in the range $1 - 3$ dPas m min$^{-1}$ (Fig. 2.7a, b). A similar figure, involving fluctuations in the frictional force, also exhibits a minimum in this region (Fig. 2.7c) [44]. Thus the minimum fluctuations (i.e. optimum casting) occurs when $\eta V_c = 2 \pm 1$ dPas m min$^{-1}$.

It can be seen from Figs. 2.5 and 2.6 that the equations, $\eta V_c^2 = 5 \pm 3$ dPas (m min$^{-1}$)$^2$ and $\eta V_c = 2 \pm 1$ dPas (m min$^{-1}$) that powder consumption increases with decreasing viscosity. A plot of the viscosity of the casting slag as a function of the casting speed for mould fluxes used in a large number of steel plants revealed that the bulk of the data fell between the curves representing the Wolf [42] and Ogibayashi [43, 44] relations (Fig. 2.8 [45]). The outliers in the figure all relate to high-viscosity powders used in high-speed billet casting and this behaviour will be discussed in Sect. 2.2.6.10.
2.2.6 Factors Affecting Powder Consumption

There are a number of factors affecting powder consumption, these are outlined below. These factors can be classified as following: (i) casting conditions, (ii) characteristics of the mould powders and slags and (iii) conditions arising from process problems.

2.2.6.1 Mould Dimensions

It was noted above in Eq. 2.1 that the frictional force increased as the surface area of the mould increased. Neumann et al. [46] proposed the powder consumption \( Q_s \) could be represented as function of the parameter, \( R^* \) (Fig. 2.9a, Eq. 2.8). This term represents the ratio of the (surface area/volume) for the mould. Alternatively, it can be regarded as the ratio of (the surface area of shell/volume of steel in the mould). It can be calculated from Eq. 2.9 where \( w \) and \( t \) are the width and thickness of the mould. The parameter, \( R^* \), was used in Eq. 2.4 to calculate \( Q_s^{\text{slag}} \) from \( Q_t^{\text{powd}} \).
Subsequently, a similar study based on a much larger database and found that the data shown in Fig. 2.9b could be represented better by Eq. 2.10 [45, 47].

\[ Q_s = 0.44 \exp^{-0.44R^*} \]  
\[ R^* = 2(w + t)/w \cdot t \]  

Typical \( R^* \) values are for Slabs 9–15; for Blooms 10–18; for Billets 22–30, Thin slabs 40. It can be seen from Fig. 2.9b that the required powder consumption is much greater for slabs than that for billets. Ogibayashi [34] pointed out that frictional forces on the broad face tended to increase as the distance from the corner increased. Consequently, Fox [2] derived an alternative relation for powder consumption, \( Q_t f^* \), in terms of distance from the corner, \( D_{corn} \) (Fig. 2.10 and Eq. 2.11); note \( (Q_t f^*) \) was calculated to avoid using \( R^* \) in the conversion of \( Q_t^{\text{powd}} \) to \( Q_s^{\text{slag}} \).

\[ (Q_t f^*) = 0.615 D_{corn}^{0.586} \]  

The overall conclusion is that mould dimensions have a marked influence on the required powder consumption, regardless of whether the parameters \( R^* \) or \( D_{corn} \) is used. However, with thin slabs the high value of \( R^* \) suggests thin slabs require little powder consumption whereas the fact the \( D_{corn} \) is quite large suggests that a high powder consumption is needed. It is also true that powder consumption values tend to be low in thin-slab casting. The shell in thin-slab casting tends to be very thin.
because of the short residence time in the mould and thus shell shrinkage and the size of the gap tend to be low also. Some support for this view is that 400 mm thick slabs at Dillinger (where the shrinkage is high) tend to have high powder consumption (Figs. 2.9b and 2.10).

2.2.6.2 Effect of Casting Speed

The effect of casting speed on powder consumption has been investigated by a large number of workers [1, 3, 4, 20, 21, 23, 25, 32, 42, 46–52].

In Sect. 1.4 above, it was pointed out that Wolf [41, 42] proposed that optimum casting was obtained when \( \eta V_c^2 = 5 \pm 3 \text{ dPas (m min}^{-1})^2 \) and that Ogibayashi et al. [43] found the fluctuations were at a minimum, (for both slag film thickness and heat flux) when \( \eta V_c = 2 \pm 1 \text{ dPas (m min}^{-1}). \) Subsequently, Wolf [42] converted these relations into optimum powder consumption equations, i.e. Eqs. 2.12 and 2.13, respectively.

Wolf:

\[
Q_{\text{req powd}}^{\text{powd}} = 0.7/\eta^{0.5} \cdot V_c
\] (2.12)

Ogibayashi:

\[
Q_{\text{req powd}}^{\text{powd}} = 0.6/\eta \cdot V_c
\] (2.13)

An investigation using a much larger database of \( Q_s \) values, subsequently indicated a modified version of Eq. 2.12 (given in Eq. 2.14) provided a better fit with plant data [1, 48].

\[
Q_{\text{req slag}}^{\text{slag}} = 0.55/\eta^{0.5} \cdot V_c
\] (2.14)

These equations all indicate that powder consumption decreases as the casting speed increases.
2.2.6.3 Slag Viscosity

The effect of viscosity on powder consumption has been studied by a number of investigators [1, 15, 20, 21, 25, 31–33, 38, 45, 49–54]. It can be seen from Eqs. 2.12 to 2.14 that powder consumption increases with decreasing viscosity. The powder consumption values obtained on plant with high-viscosity fluxes used in high-speed billet casting are significantly lower than required $Q_s$ values calculated with Eqs. 2.12–2.14. This is discussed in Sect. 2.2.6.10. Low consumption values are also recorded on plants casting Ti-stabilised stainless and LC steels. This is thought to be due to the blocking off of slag infiltration by accretions of Ti(CN) or perovskite (CaO-TiO$_2$) at the mouth of the shell/mould channel (see Sect. 2.2.6.9). The minimum powder consumption providing acceptable levels of lubrication has been discussed [42]. Recommended values of $Q_s$ for casting sticker sensitive steel grade are 0.3 and 0.4 kg m$^{-2}$ for round billets and HC steel grades, and for crack-sensitive grades, values of 0.25 and 0.4 for round billets and heavy plate, respectively [42]. For high-speed casting, minimum values of $Q_s = 0.1$ kg m$^{-2}$ have been recommended [55]. The minimum levels of powder consumption required to avoid solid friction (which causes fracture of the slag film) has also been discussed [19]. Values of $Q_s$ for non-Newtonian mould slags have been compared with those for conventional slags ($Q_{s\text{ conv}} < Q_{s\text{ non-Newt}}$) since the high shear forces in the infiltration region result in a reduction of their viscosity [56].

2.2.6.4 Oscillation Parameters

The effects of the various oscillation parameters have been investigated by a number of workers [1, 4, 20, 21, 23, 31, 32, 42, 49, 51–53, 57–61]. Various equations have been reported for the calculation of powder consumption; these involve a number of variables (e.g. casting speed, frequency, etc.). A number of the reported equations are given in Table 2.3; the effect of an increase in the variable on the powder consumption is also given. Inspection of Table 2.3 indicates:

- There is reasonable agreement that increases in casting speed, viscosity and break temperature ($T_{br}$) all result in a decrease in powder consumption.
- There is little agreement on the effect of other variables controlling powder consumption.
- There is no agreement on the effects of the oscillation characteristics; it should be pointed out that some workers considered slag infiltration to occur during negative strip time $t_n$, (i.e. when the mould is descending faster than the shell) which results in increased pressure produced by a descending slag rim. In the other school of thought, slag inflow is considered to be difficult in $t_n$ (since the channel gets blocked by the bending of the shell in this period) and thus slag infiltration largely occurs in positive strip time, $t_p$, (where $t_p + t_n = t_{cycle}$). It has been reported that $Q_s$ exhibited a stronger correlation with $t_p$ than with $t_n$ [25].
Some of the experimental studies indicate that $Q_s$ decreases with increasing frequency (Fig. 2.4) but as can be seen from Table 2.3 other studies show the reverse relation with frequency (i.e. $Q_s \uparrow$ as $f \downarrow$)

Wolf [42] examined plant data where all casting variables were kept constant except the stroke length which was altered (i.e. $t_n$ and $t_p$ will change) and found that as the stroke increased $Q_s$ increased ($Q_s \uparrow$ as $s \downarrow$) as shown in Fig. 2.11. This is supported by plant data from Oxelösund Steelworks which exhibited a strong relationship between stroke length and mould powder consumption. However, a statistical analysis of plant data showed the reverse trend ($Q_s \uparrow$ as $s \downarrow$) and a parametric study suggested that increasing stroke only had a slight effect on $Q_s$ [25].

### 2.2.6.5 Non-sinusoidal Oscillation

Several workers have reported that non-sinusoidal oscillation increases powder consumption [25, 49, 53, 60, 64, 71]. It can be seen from Fig. 2.12 that the use of non-sinusoidal oscillation leads to a 10% increase in powder consumption.

### 2.2.6.6 Solidification (or Break) Temperature ($T_{br}$)

The effect of break (or solidification) temperature on powder consumption has been studied by a number of investigators [4, 16, 20, 51–53, 64].

It can be seen from Table 2.1 that those equations which involve $T_{br}$ (or $T_{sol}$ or $T_{liq}$) all agree that an increase in $T_{br}$ results in a decrease in powder consumption ($Q_s \downarrow$). This can be seen in Fig. 2.13. This is consistent with intuition since it can be
seen from Fig. 2.14 that an increase in $T_{br}$ leads to a decrease in thickness of the liquid film ($d_{l\downarrow}$) and an increase in solid film thickness ($d_{s\uparrow}$).

The mathematical model reported by Ramirez–Lopez [1, 21, 54] indicated that the horizontal heat flux increased gradually in the period of the oscillation cycle where the mould was descending. The increased heat flux, in turn, caused solid slag to melt, resulting in an increase in liquid film thickness ($d_{l\downarrow}$) and a decrease in the solid film thickness ($d_{s\uparrow}$). This process was reversed when the mould ascended. Thus, the liquid layer increased at the expense of the solid layer when the heat flux was increasing and vice versa when the heat flux was decreasing.
2.2.6.7 Melting Rate

It was pointed out in Sect. 2.2.1 that powder consumption (in kg min$^{-1}$ or kg s$^{-1}$) in Eq. 2.5 ($Q^{\text{slag}}_{\text{MB}}$) can be viewed as the melting rate. The powder consumption has been found to increase with increasing slag pool depth ($d_{\text{pool}}$) [72] and $d_{\text{pool}}$ is affected by the melting rate. In practice, the melting rate is controlled by the amount of free carbon and, to a lesser extent, by the size of the carbon particles (see Sect. 4.3). Consequently, it is important that powder consumption is close to the required $Q_{s}$ for the given casting conditions (mould dimensions, casting speed, etc.), i.e. it is not restricted by an excessively high carbon content of the mould powder. A few casting powders have a carbon content which is too high and thus leads to a restricted slag infiltration.

2.2.6.8 Superheat ($\Delta T$)

The effect of superheat on powder consumption has been studied by several investigators [1, 3, 16]. Increasing superheat results in increased powder consumption. On the basis of Eq. 2.12 or Eq. 2.13 increases in superheat will lead, sequentially, to an increase in slag temperature, a lower viscosity and a higher value of $Q_{s}$.

2.2.6.9 Argon Flow

It has been reported that powder consumption increases with increasing argon flow rate [73] (Fig. 2.15). One possible reason for this behaviour is that an increased Ar flow rate causes more convection and hence, a higher vertical heat flux which, in turn, increases the melting rate. A high Ar flow rate is known to affect the metal flow patterns in the mould.

Fig. 2.14 Schematic drawing showing effect of increasing $T_{br}$ on the thicknesses of solid and liquid films, where $T_{br(b)} > T_{br(a)}$ (note relative thickness values are not to scale)
2.2 Powder Consumption (Q)

2.2.6.10 Continuous Casting of Steels Containing Ti

It has been observed that powder consumption is frequently lower than predicted when casting steel grades containing Ti. This is thought to be due to the formation of TiN or Ti(C, N) which has a low solubility in the slag pool and thus, tends to exist as solid particles [74, 75]. These particles agglomerate through turbulent collisions and the agglomerates restrict the slag flow when they are sited in the mouth of slag/mould channel (Fig. 2.16) [74, 76]. The solid particles also increase the slag viscosity and thus, decrease $Q_s$. Alternatively, TiO$_2$ particles can form perovskite (CaO.TiO$_2$) which has a high melting temperature and thus reduces both the thickness of the liquid slag film ($d_l$) and $Q_s$. It is necessary to keep the basicity, (C/S) < 1.0 to avoid perovskite formation [77].

2.2.6.11 High-Viscosity Powders

The powder consumption data for most powders follow the empirical rules based on the viscosity and casting speed [2, 42, 43] the only exceptions are the high-viscosity ($\eta_{1300} = 10–30$ dPas) powders used for high-speed billet casting [2] and those used in casting steel grades containing Ti. In high-speed billet casting, considerable turbulence is generated which results in significant levels of slag entrapment. One way of reducing slag entrapment is to increase the slag viscosity. However, the reduction in slag entrapment levels comes at the expense of a significant decrease in powder consumption. Fortunately, the powder consumption required for billets is low (since the distance from centre line to corner is low and, furthermore, R* has values > 22) which means this practice is widely used to minimise slag entrapment.

It has been suggested that these high-viscosity slags will form super-cooled liquids (scl) rather than crystallites during cooling. The scl, although viscous, will move in response to any stress applied by the ferro static pressure, the downward movement of the shell or the oscillating motion of the mould; hence, the slag (scl).
will supply some lubrication to the shell. The importance of retaining some glass phase in the slag film has been pointed out by Hanao et al. [78].

2.2.6.12 Electromagnetic Braking (EMBr) and Casting (EMC)

Electromagnetic devices are reported to increase powder consumption. The application of electromagnetic braking (EMBr) results in a 30% decrease in vertical heat transfer [79] from the steel, resulting in a ca. 10 °C increase in meniscus temperature [80–83]. This increased meniscus temperature results in a lower slag viscosity and higher powder consumption. EMBr is widely used in high-speed, thin-slab casting where powder consumption tends to be low [84].

Increases of 20% in $Q_s$, have been reported when using pulsative, Electromagnetic casting (EMC) [85]; it is known that the pinch force in EMC reduces the horizontal heat transfer, which, in turn, results in increases in both meniscus temperature and $Q_s$. 

---

**Fig. 2.16** Schematic drawing showing formation of agglomerates of Ti(C, N) when casting steels containing Ti; (permission granted, ISS/AIST [74])
2.2.6.13 Liquid Slag Feeding to the Mould

Some high Al- and Mn-steels have low-melting temperatures, so the vertical heat flux is insufficient to melt the mould powder. Consequently, liquid slag feeding technology has been developed to provide liquid slag to the steel surface. It is reported that powder consumption is increased with liquid slag feeding [86].

2.3 Slag Infiltration During the Oscillation Cycle

A number of empirical rules have been proposed to calculate the powder consumption. These are given in Table 2.3 and are based on plant observations and physical modelling results. It was mentioned above that there is general agreement that the powder consumption increases as the casting speed ($V_c$), slag viscosity ($\eta$) and break temperature ($T_{br}$) all decrease. However, there is no consensus as to (i) which of the various oscillation parameters affect $Q_s$ or (ii) the way in which they affect $Q_s$. Furthermore, there are two schools of thought concerning the period of the oscillation cycle where slag infiltration occurs;

- The first identifies $t_n$ as the primary period of slag infiltration, where the descending slag rim increases the pressure on the molten slag which responds by infiltrating into the shell/mould channel and
- The second considers $t_p$ as the principal period of infiltration, since infiltration is restricted in $t_n$ because the bending-back of the shell is considered to block off the slag flow during this period; thus slag infiltration is restricted to $t_p$ where the shell does not interfere with the infiltration.

The infiltration mechanism has been studied in (i) plant trials [3, 55, 87–89] (ii) cold modelling studies [5, 6, 12, 58, 90] (iii) hot modelling studies [7, 53, 91] and (iv) mathematical modelling of the heat and fluid flow [1, 12, 16, 21, 22, 25, 36, 92, 93].

Mathematical models based on Navier–Stokes equations do provide a reasonable description of the effects of casting speed, slag viscosity and $T_{br}$, but, for the most part, they also predict that $Q_s$ increases with increasing frequency which disagrees with most experimental observations, e.g. Fig. 2.4. In an attempt to explain these discrepancies, mathematical models have been developed to explore in which part of the oscillation cycle the slag infiltration takes place [1, 21, 22, 25, 54].

It is customary to characterise oscillation in terms of negative and positive strip times ($t_n$ and $t_p$, respectively) where $t_n$ represents the time when the mould is descending faster than the shell and $t_p$ constitutes the remainder of the cycle (i.e. $t_n + t_p = t_{cycle} = 60/f$ where $f$ is in cpm). However, the oscillation cycle can also be characterised in terms of the position of the mould. The mould and the slag rim will be at their highest position in late $t_p$ (denoted $t_p^{late}$). It descends throughout $t_n$ and reaches its lowest position in early $t_p$ ($t_p^{early}$). The mould will then ascend steadily through $t_p$. 

---

2.2 Powder Consumption ($Q$)
The findings of the two studies due to Ojeda [22] and Ramirez–Lopez [1, 21, 54] are in good agreement with both proposing that slag infiltration occurs during the descent of the mould/rim covering the period \(t_n - t_p^{early}\) and that there is little slag infiltration during the ascent of the mould (in \(t_p\)). This can be seen in Fig. 2.17c and it was also noted that the rate of slag flow into the shell/mould channel is at its highest when the mould/slag rim was at its lowest position (i.e. between \(t_n^{late}\) and \(t_p^{early}\)).

The directions of flow in the slag pool at different periods of the oscillation cycle have also been studied in the several investigations [1, 21, 22, 54] and are shown in Fig. 2.18. It can be seen when the mould and slag rim are at their highest position (Fig. 2.18a) that the slag flow into the mouth of the channel is radially outward and upward. As the mould/rim descends the slag direction changes to downward and there is evidence of a vortex in the region of the mouth (Fig. 2.18b). When the mould and slag rim reach their lowest positions (in \(t_p^{early}\)) the flow is strongly downward into the channel (Fig. 2.18c). Finally, halfway through \(t_p\) the flow changes direction to radially—outward and upward (Fig. 2.18d). Thus the direction of the flow in the slag pool plays a significant role in the slag infiltration into the shell/mould channel and this is affected by the direction of movement of the mould and slag rim.

The slag rim acts like a piston and helps to inject slag into the channel. However, the movement of the mould alone will cause some downward flow of slag but the slag rim certainly accentuates the downward slag flow.

Just after the mould reaches its highest position there is a tide—change in the slag flow (radially outward and upward to downward) which results in a period of “confused flow” (the remnants of which are shown in Fig. 2.18b). There is a similar period of confused flow after the mould and rim reach their lowest points. There is very little slag infiltration during these periods of confused flow. It has been suggested that the lack of slag infiltration in the periods following a tide-change is responsible for the failure of the models based on the Navier–Stokes equation to predict the correct \(Q_s\) dependency on frequency (namely, \(Q_s \downarrow\) as \(f\)) observed on plant [1]. For example, if \(f = 60\) cpm and is increased to 120 cpm, there will twice as many tide-changes per unit time. Since little powder consumption occurs during these tide-changes, the increased number of tide-changes per minute will result in an overall decrease in \(Q_s\). A parametric study showed [25] indicated that a 60% increase in frequency resulted in only 2% change in \(Q_s\) (where both increases and decreases in \(Q_s\) were recorded for different stroke lengths). However, it was found \(Q_{cycle}\) (kg m\(^{-1}\)cycle\(^{-1}\)) decreased by 35% with a 60% increase in \(f\).

In summary, slag infiltration occurs through the downward flow of slag resulting from the downward movement of the mould; the slag rim accentuates this slag flow. The size of the slag rim is dependent upon the steel grade being cast, with high basicity (C/S) slags (used for MC steels) forming large rims and low-(C/S) slags forming smaller rims (see Fig. 1.4).
Fig. 2.17 Mathematical model predictions of a profile of strand surface, b heat flux, c powder consumption in kg s$^{-1}$, d liquid film thickness $d_l$, e solid slag film thickness, $d_s$ and f pressure during five oscillation cycles [1, 21, 54] the dotted, vertical lines indicate the onset (left) and end (right) of negative strip periods of each cycle (0–5). Note that peaks in $Q$ and $d_l$ lie in early $t_p$; (permission granted, ISIJ, [21])
2.4 Empirical Equations for Calculating Powder Consumption

A number of empirical rules have been proposed to calculate the powder consumption; the proposed equations are given in Table 2.3. Fox [2] carried out an evaluation of the various empirical equations. This evaluation compared predictions with plant measurements contained in an extensive database of powder consumption and casting variables for a large number of trials carried out at different steelworks casting slabs, blooms, billets and thin slabs. It should be pointed out that the database contained powder consumption for high-viscosity billet powders used to minimise slag entrapment at high casting speeds; $Q_s$ data for these slags are much lower than for other powders and tend to distort the fit. The performance was judged from $\Delta_{RMS}$ which is calculated from Eqs. 2.15 and 2.16 where $N$ = the number of mould slags. The best performing models for this database were found to be in the hierarchy, Ogibayashi [42, 43] > Kobayashi [69] > modified Wolf [1, 2] > Maeda [49]

$$\delta = 100\left(\frac{Q_{\text{meas}} - Q_{\text{pred}}}{Q_{\text{meas}}}\right)$$  \hspace{1cm} (2.15)

$$\Delta_{RMS} = \left\{ \frac{\sum(\delta_1^2 + \delta_2^2 + \delta_3^2 + \cdots)}{N} \right\}^{0.5}$$  \hspace{1cm} (2.16)

Analysis of plant data for powder consumption for slab-, bloom- and billet-casting indicated that $Q_t^{\text{slag}} \ (= f^* \cdot Q_t^{\text{powd}})$ is reasonably constant at 0.48 kg (tonne steel)$^{-1}$ except for the “high-viscosity billet powders” mentioned above in Sect. 2.2.6.10.
2.4.1 Frictional Forces

Frictional forces \( F \) acting on the shell contain contributions from the liquid frictional \( (F_l) \) and solid frictional \( (F_s) \) forces (Eq. 2.17).

\[
F = F_l + F_s \tag{2.17}
\]

It was pointed out in Eq. 2.1 that the liquid frictional force was inversely, dependent on the thickness of the liquid layer \( (d_l) \). Since \( d_l = (Q_s / \rho_l) \) Eq. 2.1 can be re-written as

\[
F_l = A \cdot \eta (V_m - V_c) \rho_l / Q_s. \tag{2.18}
\]

It can be seen that the liquid friction force is inversely dependent upon the powder consumption and directly related to the slag viscosity and the difference between the velocities of the mould and the strand.

The frictional forces tend to be highest when casting MC steels because the corrugated shell formed increases both \( A \) and \( F_l \) and \( d_l \) tends to low because high \( T_{br} \) slags are used to cast these steels. The friction forces measured when casting with mould powders are lower than those for oil casting [94]. Longitudinal cracking has been correlated with high frictional forces [95]. Frictional forces tend to decrease as the cast proceeds [95].

Solid friction (between the shell and the solid slag) tends to occur in the lower half of the mould. The formation of star and spongy cracks (Sect. 11.7) is associated with solid/solid friction and the consequent spalling of the solid slag film which can even result in the pick-up of copper by the strand. However, solid friction may also occur in the upper mould in the corner regions if the corners are overcooled [4].

Since solid friction can occur in the bottom of the mould it is important to ensure that all of the mould receives liquid lubrication [96]. A lubrication index (LI) was proposed by Billany et al. [96] which is a measure of the fraction of the mould enjoying liquid lubrication; this index is defined in Eq. 2.19. Ideally, the parameter, LI, should have a value of 1.0.

\[
LI = \frac{\text{Distance from meniscus to point where } T = T_{br}}{\text{Distance from meniscus to mould exit}} \tag{2.19}
\]

If solid friction is a problem in the lower half of the mould, probably the best measure is to increase the casting speed. In theory, a decrease in the flow rate of the cooling water would also be beneficial but in practice, the remedial effect is small.

Sorimachi et al. [97] have pointed out that:

- The frictional forces refer to the entire mould wall and not to the local frictional forces in the meniscus region which is of key importance in the formation of sticker breakouts.
- The measured friction is that acting on the mould wall and is not that acting on the shell.
2.4.1.1 Measurement of Frictional Forces

Measurements on frictional forces have been derived using plant trials, simulation experiments and mathematical modelling of the frictional forces.

Plant Measurements of Friction

In the past, a number of investigators have measured frictional forces by using load cells attached to the oscillating mechanism and then applying Fourier analysis of the signals produced [27, 71, 98]. Alternatively, frictional forces can be measured using the MLTEKTOR system [99]. These devices have been used for the detection of defects and longitudinal cracks [44, 100, 101].

Friction Measurements in Simulation Tests

Several tests have been devised to simulate the frictional forces acting on the shell when using different mould fluxes. Short descriptions of these tests are given below.

Rotating Cold Finger Test

In this test, a water-cooled, copper finger (representing the mould) is rotated in a steel crucible (representing the strand) containing the molten mould flux [98]. The copper finger becomes covered with a solid slag film of ca. 3 mm thickness and a thin liquid layer. The frictional forces are measured by determining the torque developed on the steel crucible as the finger is rotated at constant velocity (10–50 rpm). The apparatus is shown in Fig. 2.19a.

Oscillating Cold Finger Test

This test resembles the rotating cold finger test but the cold finger is oscillated vertically instead of being rotated [9, 11, 53, 102].

![Fig. 2.19](image-url) Schematic drawings showing the apparatus used in a the rotating cold finger test [98] and b the oscillating pad method [27, 103] (permission granted, Europ. Comm. Sci. and Tech. Publ. [27])
Oscillating Pad Test

In these tests, a water-cooled copper pad (mould), which can be oscillated at different frequencies, is lowered onto a heated steel block (strand) covered with molten mould slag (Fig. 2.19b). The block is then withdrawn at a fixed speed and the frictional force exerted by the pad is measured as it bears down on the strand by using a load cell mounted on the oscillation arm. The thickness of the molten slag layer (ca. 0.3 mm) was monitored using a displacement transducer [27, 103].

Rotating and Oscillating Pads Test

A simulation test was reported by Sorimachi et al. [97] and is shown in Fig. 2.20. In this test a graphite disc (representing the strand is rotated unidirectionally). A second, lower, graphite disc (representing the mould) contains a 2 mm deep liquid, mould slag of known viscosity; and this disc is oscillated sinusoidally. The torque is measured continuously.

Miniature Continuous Caster

Friction measurements have been carried out in a miniature continuous caster [91]. In order to view the solidification process of the shell the steel was replaced by Sn–5%Pb, the mould slag by stearic acid with Al₂O₃ particles to act as tracers and one side of the oscillating, 50 mm², Cu mould was replaced by silica to facilitate viewing [91]. The friction between mould and shell was measured by load cells sited
below the mould. The frictional force per unit area between mould and shell was taken as $\Delta F/A = (F_{\text{max}} - F_{\text{min}})/A$ where $A$ = surface area and the subscripts max and min represent the maximum and minimum load in any one cycle, respectively. Values of $\Delta F/A$ were found to decrease as liquid film thickness ($d_l$) increased and $(V_m - V_c)/d_l$ decreased (i.e. $\Delta F/A \downarrow$ as $d_l \uparrow$ and as $(V_m - V_c)/d_l \downarrow$) [91]. Friction measurements can be made in a similar manner in mould simulators [9–11].

2.4.1.2 Mathematical Modelling of Friction in Mould

Mathematical modelling of the frictional forces in the mould has been reported [12, 18, 53, 97]. Schwerdtfeger and Tacke [18] derived a relation for the shear stress in the liquid slag based on computations of the velocity. The frictional force was calculated by multiplying the calculated stress by the area wetted by the slag.

2.4.2 Factors Affecting Frictional Forces in the Mould

It can be seen from Eq. 2.18 ($F_l = A \eta (V_m - V_c) \rho_l Q_s$) that the liquid friction force ($F_l$) is inversely dependent upon the powder consumption ($Q_s$); thus it follows $F_l$ will increase as $Q_s$ decreases ($F_l \uparrow$ as $Q_s \downarrow$). However, $Q_s$ is dependent upon other factors, e.g. casting speed; the effect of the various parameters are given below.

However, high friction measurements recorded on plant (i.e. 10–20 kPa) have been attributed to (i) movement of the solid slag layer (ii) excessive taper and (iii) mould misalignment [19]. At low casting speeds the critical consumption is high so variations in consumption, $Q_s$, can lead to slag film fracture and high, solid friction forces. In contrast, at high casting speeds the principal causes of high frictional forces are excessive taper (see Fig. 1.48) and mould misalignment [19].

2.4.2.1 Casting Speed ($V_c$)

The powder consumption, $Q_s$, is dependent upon $(V_c)^{-1}$ (Eqs. 2.12–2.14). Using the modified Wolf relation ($Q_s = 0.55/\eta^{0.5} V_c$) to demonstrate the effect of casting speed, it can be seen that Eq. 2.18 can be re-written as

$$F_l = A \eta (V_m - V_c) \rho_l \eta^{0.5} V_c / 0.55$$  \hspace{1cm} (2.20)

Similar relations could be derived with other relationships for $Q_s$. It can be seen from Eq. 2.20 that an increase in casting speed causes a decrease in the $(V_m - V_c)$ term, in addition, to the increase in the $V_c$ term. These conflicting responses to a $V_c$ increase, result in a minimum ($V_c^{\text{min}}$) in the $F_l$–$V_c$ plot shown in Fig. 2.21 reported by D’Haeyer [99]. It can be seen that the $(V_m - V_c)$ is dominant at low speeds and the $V_c$ term tends to dominate at higher casting speeds.
Tsutsumi et al. [91] carried out simulation experiments and reported that $F_{l}$ decreased:

- As casting speed increased ($F_{l}$ as $V_c$) indicating, $V_c < V_c^{\min}$ in their experiments.
- As the liquid slag film thickness ($d_l$) increased ($F_{l}$ as $d_l$).
- As the velocity gradient ($\frac{(V_m - V_c)}{d_l}$) decreases.
- With the introduction of non-sinusoidal oscillation.
2.4.2.2 Viscosity (η)

According to Eq. 2.20 the liquid frictional force is a function of ($\eta^{1.5}$) and the Ogibayashi [42, 43] relation (Eq. 2.13) leads to $F_l$ exhibiting a dependence on ($\eta^2$). Thus the frictional forces increase with increasing viscosity. Wolf [42] reported a minimum in the $F_l - (\eta^{0.5} V_c)$ plot (Fig. 2.6) at $5 \pm 2$ (dPas)$^{0.5} \cdot \text{m min}^{-1}$; the equivalent plot for the Ogibayashi relation for $Q_s$ leads to a minimum at $2 \pm 1$ dPas. m min$^{-1}$ as shown in Fig. 2.7c [44].

Hering et al. [104] reported that the liquid frictional force increased with increasing Al$_2$O$_3$ content in the casting slag (Fig. 2.22a). This is presumably due to the increase in viscosity with increasing Al$_2$O$_3$ content. However, Hering et al. [104] found that this was not always the case, (as can be seen from Fig. 2.22a) and proposed that the friction was affected the nature of the mineralogical phase formed. It is possible that with the wollastonite/gehlenite curve in Fig. 2.22b could be explained by a lowering of $T_{br}$ with increasing Al$_2$O$_3$ which offsets the effect of increasing viscosity.

**Fig. 2.22** Frictional force as function of a Al$_2$O$_3$ content and b viscosity (cited in Pas, thus multiply by 10 for dPas [104]); (permission granted, Stahl Eisen, [104], re-drawn)
2.4.2.3 Mould Dimensions and Surface Area (A)

It can be seen from Eq. 2.1 and Fig. 2.20 that the liquid frictional force ($F_l$) increases as the surface area of the mould (or shell) increases. Ogibayashi et al. [105] pointed out that the shrinkage of the steel will be greatest at the centreline, the point where the shell is at its thinnest. Ogibayashi et al. [105] also pointed out that in peritectic MC steels the shell (in the meniscus region) tends to become uneven or corrugated; this unevenness increases the surface area of the shell. Consequently, the friction coefficient tends to increase as the unevenness of the shell increases (Fig. 2.23).

2.4.2.4 Break (or Solidification) Temperature ($T_{br}$)

Increases in break temperature would be expected to reduce the thickness of the liquid slag film ($d_l$), as shown in Fig. 2.14; this would result in higher frictional forces ($F_l$ as $T_{br}$). Furthermore, increasing $T_{br}$ will also enhance the amount of solid friction. Thus on both counts the friction will tend to increase as $T_{br}$ increases.

Measurements of friction and friction coefficient are shown in Fig. 2.24a, b, respectively. These figures show that there is a sharp increase in friction at a temperature slightly below the break temperature, $T_{br}$, this may imply that the cooling rates in the friction experiments were slightly higher than those used in the viscosity experiments, since $T_{br}$ decreases with increasing cooling rate. These figures show that relatively small amounts of solid friction can have a significant effect on the total friction. The rate of friction rise was much greater in some cases, denoted. Type A, e.g. Powder J with sharp $T_{br}$ temperatures) than in others (Type B i.e. more “glassy” slags, e.g. Powder A).

2.4.2.5 Frequency (f)

Since most plant observations indicate that powder consumption $Q_s$ decreases as $f$ increases, it is expected that an increase in frequency would increase the liquid
friction ($F_1 \uparrow$ as $f \uparrow$). This relationship ($F_1 \uparrow$ as $f \uparrow$) has been confirmed by several investigators [53, 64, 106]. It should be noted that an increase in frequency also increases the velocity of the mould ($V_m$) and it can be seen from Eq. 2.18 that an increase in $V_m$ will result in an increase in friction.

### 2.4.2.6 Stroke Length (S)

It can be seen from Table 2.3 that there is no consensus on the effect of the stroke length (s) on the powder consumption, $Q_s$. The statistical analysis of plant data due to Saraswat et al. [4] indicates that $Q_s$ decreases as the stroke increases ($Q_s \downarrow$ as $s \downarrow$); on this basis, $F_1$ would be expected to increase (i.e. $F_1 \uparrow$ as $s \uparrow$). Other workers have reported that $Q_s$ increases with increasing stroke ($Q_s \uparrow$ as $s \uparrow$) [53, 64] which would result in ($F_1 \downarrow$ as $s \downarrow$). However, $Q_s$ (or $d_l$) is not the only factor affecting friction forces and an increased stroke would lead to increased values for $V_m$ and ($V_m - V_c$) and $F_1$. Thus no relation between $F_1$ and $s$ can be recommended at this stage.

### 2.4.2.7 Negative and Positive Strip Time ($T_n$ and $T_p$)

As mentioned above, there has been considerable debate as to whether powder consumption occurs in negative strip time or positive strip time. Mathematical models [1, 21, 22] indicate that slag infiltration occurs predominantly in the period when the mould (plus rim) are descending, with the infiltration rate being at its highest in late $t_n$ and early $t_p$. Thus it may be concluded that increased negative strip would increase $Q_s$ and hence decrease $F_1$. 

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**Fig. 2.24 a** Frictional force [98] and **b** Coefficient of friction [27, 103] as functions of temperature derived in rotating cold finger and oscillating pad tests, respectively (permission granted, Europ. Comm. Sci. and Tech. Publ. [27, 98])

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![Frictional force and Coefficient of friction graphs](image-url)
However, Tsutsumi et al. [53, 64] reported that in their simulation experiments that increased positive strip resulted in a decrease in $F_l$. It has also been reported that the correlation of powder consumption with $t_p$ is stronger than that with $t_n$ [25].

### 2.4.2.8 Steel Temperature

It has been reported that a decrease in steel temperature results in increased friction measurements, presumably due to the effect of the slag viscosities (which increase at lower temperatures) on the friction.

### 2.4.2.9 Non-sinusoidal Oscillation

Non-sinusoidal oscillation has been reported to reduce liquid friction [60, 71, 99, 106–108], however, the reverse relation ($F_l\uparrow$ as NSO↑) has been found in trials in Sweden [109]. Mizukami et al. [60] reported that non-sinusoidal oscillation can result in a 40% decrease in liquid friction compared with conventional, sinusoidal oscillation (Fig. 2.25a) but only resulted in a 5% decrease in solid friction ($F_s$).

**Fig. 2.25** Frictional force, $F_l$, as a function of casting speed $V_c$, showing differences between sinusoidal (---●--) and two modes of non-sinusoidal oscillation (—△— and —□—) and $F_l$ in relation to tensile strength ($\sigma_B$, $\sigma_{surf}$ in N mm$^{-2}$) denoted in curves, for both the average shell temperature (△) and the surface temperature (o) [60] (permission granted, ISIJ, [60] re-drawn)
Non-sinusoidal oscillation results in a decrease in \((V_m - V_c)\) which leads to a concomitant decrease in the liquid friction \((F_l)\) as shown in Eqs. 2.18 and 2.20. The frictional forces were compared with the tensile strength of the steel (Fig. 2.25a) from which it was concluded that the upper limit for the casting speed when casting with an oscillating mould, lay between 5 and 8 m \(\text{min}^{-1}\) [60].

2.5 Summary

The following observations were made concerning the lubrication of the shell and the frictional forces acting on it:

(i) Inadequate lubrication of the shell leads to various defects in the steel product, such as, longitudinal cracks, sticker breakouts and star cracks.

(ii) The lubrication is supplied by the liquid slag infiltrating into the channel between mould and shell; this occurs principally in the period where the mould (and slag rim) are descending and \(Q_s\) increases gradually through this period with maximum infiltration corresponding with the lowest position of the mould.

(iii) Changes in mould direction are accompanied by periods of confused flow where little slag infiltration occurs.

(iv) The powder consumption, \(Q_s\) (in kg m\(^{-2}\)) provides a good measure of the lubrication supplied and is related to the thickness of the liquid slag layer in the slag film \((Q_s^{\text{req}} = \rho \cdot d_l)\) where \(\rho\) is the density of the liquid slag.

(v) Several powder consumption terms are used and these terms are interrelated; the melting \((Q_{MR})\) rate must match the required powder consumption.

(vi) Since mould powders contain carbon and volatile materials it is necessary to distinguish between powder and slag \((Q_s^{\text{slag}} = f^* Q_s^{\text{powd}})\) where \(f^*\) is the mass fraction of the powder forming slag.

(vii) Analyses of plant data for powder consumption revealed that \(Q_s^{\text{req}}\) increases:

\(-\) with increasing mould surface area, \((Q_s^{\text{req}} = 2/(R^* - 5))\)

\(-\) with decreasing casting speed and slag viscosity

\(-\) with decreasing oscillation frequency and stroke (although these relations are disputed by some workers); these effects are smaller than those above.

\(-\) with increasing Argon flow rate.

(viii) The required values of viscosity, break temperature and \(Q_s^{\text{req}}\) can be calculated for the given casting conditions using empirical rules.

(ix) High frictional forces in the mould arise from (i) fracture of slag films at low casting speeds and (ii) excessive taper and mould misalignment at higher casting speeds.

(x) Liquid friction increases with the:
– Increasing surface area of the shell (including any shell corrugations)
– Increasing viscosity, casting speed and \((V_m - V_c)\); the plot of \(F_l\) versus \(V_c\) exhibits a minimum due to the conflicting responses to increasing \(V_c\) on \((V_m - V_c)\) and \(F_l\) with \((V_m - V_c)\) dominant at low casting speeds and the \(V_c\) effect being dominant at high speeds.
– Increasing oscillation frequency but there is no consensus regarding the effect of stroke length.
– With decreasing non-sinusoidal oscillation.

References

73. T. Mallaband, Metallugica. UK, private communication cited in AB Fox thesis [1].
76. H Lei, Y Zhao, DQ Geng, ISIJ Intl., 54, 1629, (2014).
92. H Steinruch, C Rudischer, W Schneider, Non-linear Analysis, Theory, Methods and Applications, **30** (8), 4915, (1997) see also BHM 141 (1996)(9) 399.
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