1. Introduction

Mould fluxes play an important role in the continuous casting of steel. Twenty years ago mould fluxes were regarded by many as “black magic” since there were seen to work but there was little scientific understanding as to how they worked. However, nowadays we know much more on how they work. In large part, this is due to the efforts of Japanese research workers and the manufacturers of fluxes.

Mould powders are fed onto the top of the mould. As they gradually move down the mould the carbon in the powder reacts with any air present to form a reducing atmosphere of CO (g) to protect molten steel from oxidation. Then the oxide components form a sintered layer and eventually, they melt to form a liquid flux pool (Fig. 1). Liquid slag from the pool infiltrates into the mould/strand channel and lubricates the newly-formed, steel shell.

However, most of the first liquid entering this channel freezes against the water-cooled, copper mould and forms a glassy, solid slag film (typically ca. 2 mm thick). The thin, liquid slag film (ca. 0.1 mm thick) provides liquid lubrication to the shell. In time, the glassy slag may transform into a crystalline layer in the hotter regions of the solid slag film (i.e. on the shell side of the solid film). Some crystallisation of the slag film can occur on the mould side if the film is left undisturbed for a long time. It is generally considered that the liquid slag film travels with the strand and the solid slag film remains in contact with the mould. It has been suggested by some workers that the solid slag film also travels down the mould. If it does then it must travel at a much slower speed than that of the liquid film.

The mould flux must fulfil the following functions:

1. Protect the steel meniscus from oxidation.
2. Absorb inclusions floating up from the steel.
3. Provide thermal insulation to prevent the steel from freezing.
4. Provide the optimum level of horizontal heat transfer between shell and mould.
5. Provide lubrication of the steel shell.

In this study we will focus primarily on the last two functions and will show that mould flux performance is controlled by certain physical properties, namely,

(i) the viscosity (usually at 1573 K)
(ii) the % crystalline phase developed in the slag film and
(iii) the thickness of both the liquid and solid layers of the slag film which are, in turn, dependent on the break temperature ($T_{br}$) or solidification temperature ($T_{sol}$) of the flux.

We will see that there is a hidden but underlying logic to the selection of mould flux compositions since about 90%
of the fluxes have property values which are consistent with those derived from empirical rules. Thus there is simplicity in the way that mould fluxes perform the required functions.

The complexity arises from the huge range of “in mould conditions” that the flux has to deal with. The large number of variables in the continuous casting process and their effect on both the surface quality of the product and on process control are shown in Fig. 2. The mould flux is expected to compensate for many of the variations in casting conditions by being “flexible” and “forgiving”. Given the large differences in the casting conditions at different plants, it is not surprising that fluxes known to work successfully on one plant, frequently do not perform so well on another plant.

The principal factors affecting flux performance are:

- Casting conditions (casting speed, \( V_c \), oscillation characteristics).
- Steel grade and mould dimensions.
- Mould level control (which can lead to depressions etc.).
- Metal flow since turbulent flow can lead to several problems eg gas and slag entrapment.

In this study we will examine the effects of mould flux on lubrication and heat transfer and how flux performance is affected by both casting conditions and steel grade being cast. Then we will look at how the mould flux is expected to deal with problems caused by turbulent metal flow in the mould and how recent developments affecting metal flow control may help to simplify the tasks carried out by mould fluxes.

2. Mould Flux Lubrication

The liquid mould flux lubricates the steel strand. It is important that there is liquid lubrication throughout the strand since problems (such as star cracking) can occur if the flux crystallises completely in the lower half of the mould and liquid lubrication is lost.\(^5\) The liquid friction \((F_l)\) is given by Eq. (1) where \(V_m\) is the velocity of the mould. It can be seen that the friction decreases as the viscosity \((\eta)\) decreases and the liquid flux film thickness \((d_l)\) increases.

\[
F_l = \frac{\eta V_m - V_m}{d_l} \tag{1}
\]

Powder consumption provides a measure of the lubrication supplied and it is very dependent upon mould size since the friction increases as the distance from the corner increases.\(^5\) Thus frictional forces are much larger in slabs > blooms > billets. Powder consumption \((Q_s)\) is usually measured as kg flux (tonne steel)\(^{-1}\). However, \(Q_s\) can be converted to \(Q_t\) with units of kg flux m\(^{-2}\) (of mould) using Eq. (2),

\[
Q_t = f^* Q_s \frac{7.6}{R} = d_l \rho \tag{2}
\]

where \(f^*\) is the fraction of powder producing slag, \(\rho\) the density of the liquid slag and \(R\) is the surface area to volume of the mould and is given by \(2(w+t)/w\) where \(w\) and \(t\) are the thickness of the mould. The effect of mould dimensions on powder consumption, \(Q_t\) can be clearly seen in Fig. 3 since \(R\) has values of <10 for slabs, 10–15 for blooms, >20 for billets and >30 for thin slabs.
We have collected plant data from steel plants all round the world when casting slabs, blooms, billets and thin slabs. The following data were included: powder consumption, which work well enough in practice but do not fit the requirements derived from the empirical rules. Wolf subsequently converted these into empirical rules to derive the required powder consumption.6,7) Wolf subsequently converted these into empirical rules to derive the required powder consumption.6,7) However, powder consumption is also dependent upon other casting parameters such as the oscillation characteristics, solidification or break temperature etc. The various empirical rules8–18) reported for powder consumption are summarised in Table 1. Itoyama17) reported a model where the Q_s contained contributions from (i) flow emanating from the molten pool, (ii) flow between parallel plates (mould and strand), (iii) the oscillation of the mould and (iv) slag trapped in oscillation marks (Q_s). In order to test the validity of these various relationships we have collected plant data from steel-plants all round the world when casting slabs, blooms, billets and thin slabs. Database 1 was collected from plant data from single trials for billet-bloom-slab and thin slab-casting in >30 steelworks. The following data were included: powder consumption, Q_s or Q_m, mould dimensions, casting speed, steel composition and flux chemical composition, viscosity and break temperature, T_br. The variation in powder consumption values for runs carried out under similar casting conditions is around ±10–15%,19) Database 2 contained all the information listed for Database 1 plus the oscillation characteristics, frequency (f) and stroke length (s). Mean powder consumption values were derived in trials with identical casting conditions but allowing a ±10% variation in the casting speed. The variation of averaged powder consumption values is less than that in Database 1. The performances of the various relationships were checked by comparing the calculated Q_s against the measured Q_s; the results are given in Fig. 4. It can be seen from Fig. 4 and Table 1 that

\[ Q_s = 2.6 \times (1 - s) \]  

(iii) there are deviations from these relations for billet-casting where frequently high-viscosity fluxes are used to minimise problems related to turbulent metal flow (e.g. slag entrapment) because the lubrication requirements for billets are low. It should also be noted that low powder consumption can occur when casting steels containing Ti, due to the copious formation of TiN which prevents the infiltration of liquid slag into the mould/strand gap.

Table 1. Summary of powder consumption studies.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type of investigation</th>
<th>Results (R^2 value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolf6</td>
<td>Analysis of plant data</td>
<td>( Q_s = 0.7 \gamma /\rho'V' ) ; modified ( Q_s = 0.55 \gamma /\rho'V' ) (R^2=0.74)</td>
</tr>
<tr>
<td>Ogihara et al.7</td>
<td>Analysis of plant data</td>
<td>( Q_s = 0.6 \gamma /\rho'V' ) (R^2=0.48)</td>
</tr>
<tr>
<td>Nakajima8</td>
<td>Analysis of plant data</td>
<td>( Q_s = 0.433 \gamma /\rho'V' + 0.00283 \rho'V' ) (R^2=0.55)</td>
</tr>
<tr>
<td>Jenkins10</td>
<td>Direct observation of OM formation</td>
<td>( Q_s = 10000 \gamma /\rho'V' ) (R^2=0.81)</td>
</tr>
<tr>
<td>Tsutsumi11</td>
<td>Laboratory experiments</td>
<td>( Q_s = 0.015.8 \gamma /\rho'V' ) (R^2=0.85)</td>
</tr>
<tr>
<td>Itoyama17</td>
<td>Model and analysis of plant data</td>
<td>( Q_s = 0.4 \left( \frac{1}{\sqrt{A}} + \frac{f}{s} \right) \gamma /\rho'V' + 0.22 ) (R^2=0.80)</td>
</tr>
<tr>
<td>Maeda18</td>
<td>Analysis of plant data</td>
<td>( Q_s = 0.015.8 \gamma /\rho'V' ) (R^2=0.85)</td>
</tr>
<tr>
<td>Kwan19</td>
<td>Analysis of plant data</td>
<td>( Q_s = 0.015.8 \gamma /\rho'V' ) (R^2=0.85)</td>
</tr>
</tbody>
</table>

Empirical rules for the selection of fluxes for “optimum casting” in terms of casting speed and flux viscosity have been developed.6,7) Heat transfer in the mould can be conveniently classified into vertical and horizontal heat transfer. Decreased vertical heat transfer has been reported20) to reduce (i) the number of pinholes and (ii) the depth of oscillation marks by reducing the length of steel meniscus. However, it is the horizontal heat transfer between steel shell and mould which is more important since it has such a significant effect on the surface quality of the steel. Horizontal heat transfer is complex involving two mechanisms, namely, lattice or phonon conductivity (k_l) and radiation conductivity (k_r). Radiation conductivity involves absorption and re-emission of radiated energy and can be the dominant mechanism in glassy materials at high temper-
peratures. However, $k_R$ can be significantly decreased by the presence in the slag film of (i) crystallites which scatter the radiation and (ii) transition metal oxides (e.g. FeO) which absorb the radiation. It has been estimated that $k_R/\mu_1005$ for heat transfer across slag films formed during slab casting. However, it may be much more significant in glassy slag films formed using high-viscosity fluxes for billet casting. The overall resistance to thermal transfer ($R_{*\text{total}}$) between shell and mould can be regarded as a series of resistances as shown in Fig. 6 and Eq. (4).

$$R_{*\text{total}} = R_{*\text{Cu/sl}} + (d/k)_l + (d/k)_g + (d/k)_{cry}$$ (4)

where $R_{*\text{Cu/sl}}$ is the interfacial resistance and $d$ and $k$ are the thickness and thermal conductivity of the layers in the slag film and subscripts $l$, $g$, and $cry$ denote the liquid, glass, and crystalline layers, respectively.

Yamauchi introduced the contribution from radiation conduction as a parallel resistance. The most significant terms affecting ($R_{*\text{total}}$) are (i) $R_{*\text{Cu/sl}}$ and (ii) the thickness of the solid slag film i.e. $d_{solid} = d_g + d_{cry}$. The interfacial resistance $R_{*\text{Cu/sl}}$ was found to increase with (i) increasing solid slag thickness, $d_{solid}$ and (ii) increasing crystallinity. This is best understood as an increase in $R_{*\text{Cu/sl}}$. Results from an increase in the thickness of an air gap, formed as glass transforms into the more-dense, crystalline phase ($r_{cry} > r_g$). Thus the two key parameters are (i) the thickness of the solid slag film ($d_{solid}$) and (ii) the % crystalline phase developed in the slag film.

Longitudinal cracking in medium carbon (MC) steels results from the 4% mismatch in the thermal shrinkage coef-
ficients for the $\delta$ and $\gamma$ phases\textsuperscript{24} which results in stresses which can only be relieved by cracking. The stresses can be minimised by keeping the shell as thin and as uniform as possible. This is achieved by reducing the horizontal heat transfer by using a thick slag film with a significant crystalline fraction.

In contrast, sticker breakouts are caused by lack of lubrication. They occur prevalently, when casting high-carbon (HC) steels since the constrained shell does not have sufficient strength to withstand the ferro-static pressure.\textsuperscript{25} One possible strategy to minimise stickers is to make a thicker, stronger shell by increasing horizontal heat transfer. This is achieved by forming a thin, glassy slag film.

The horizontal heat transfer is controlled by the nature of the slag film the dominant factors being $d_{\text{solid}}$ and $\%$ crystalline phase. It is very difficult to predict a priori the amount of crystalline phase developed in a slag film. Consequently, we assumed (i) that the thickness of the slag was the dominant factor and (ii) that $d_{\text{solid}}$ could be represented by the break temperature $T_{\text{br}}$ or ($T_{\text{sol}}$). Some support for these assumptions is provided by Fig. 7 due to Yamauchi.\textsuperscript{23}

The $T_{\text{br}}$ values in Database 1 for slab-, bloom- and billet casting were plotted against the viscosity of the flux at 1,573 K in Fig. 8. It was found that:

(i) $T_{\text{br}}$ values for MC-crack sensitive grades fell on the upper curve.

(ii) $T_{\text{br}}$ values for HC-sticker-sensitive grades fell on the lower curve.

(iii) $T_{\text{br}}$ values for all other grades fell between these two curves.

Thus the selected value of $T_{\text{br}}$ is determined by the steel grade being cast and the flux viscosity which is, in turn, determined by the casting conditions and the mould dimensions. Mould powder selection by the flux manufacturers was carried out in an ad hoc manner. However it is obvious there is an underlying, but hidden, logic in the selection process ie a successful cast can be obtained by specifying the break temperature and viscosity required for the specific conditions and steel grade. This applies to 80–90\% of the fluxes we have studied. There are, however, a few fluxes which are reported to perform satisfactorily but whose viscosity and $T_{\text{br}}$ values deviate from predicted values. Further work is needed to determine why this so.

In Sec. 2 we saw that the lubrication requirements could be specified in terms of the required viscosity and $T_{\text{br}}$ for the casting conditions. In this section we have seen that the required heat transfer can be specified in terms of the $T_{\text{br}}$ and $\%$ crystallinity of the slag film. This suggests that mould flux behaviour is essentially very simple and that a mould flux can be selected for the casting conditions, steel grade and mould dimensions in terms of three factors, namely, viscosity, break temperature and degree of crystallinity developed in the slag film. A flow diagram for a model to calculate required powder consumption, viscosity and break temperature is shown in Fig. 9.\textsuperscript{19}

4. Problems and Defects

4.1. Control of Metal Flow

The complexity in mould flux performance arises when we try to use the flux to combat problems other than those related to lubrication and heat transfer. One example is using the mould flux to deal with problems arising from turbulent metal flow (e.g. slag and gas entrapment and SEN erosion). One way of reducing these problems is to use a high-viscosity flux but this has the disadvantage that it reduces powder consumption.
Metal flow velocities can have a significant effect on surface quality and process control problems. The “double roll flow” patterns (Fig. 10) are considered to be the most satisfactory for successful casting.\(^{28}\)

Turbulence causes the formation of a standing wave and this was found to increase with increasing casting speed.\(^{29}\) The metal flow is affected by (i) SEN positioning, (ii) SEN port designs and (iii) Ar flow rates. Ideally, the metal flow should be laminar. Tai et al.\(^{30}\) noted that the “white band” (caused by negative segregation) tended to be shallower in the corners due to delayed solidification, resulting from impingement of the metal flow. High-viscosity fluxes (with low powder consumption) are frequently used to combat problems associated with in-mould turbulence (e.g. slag and gas entrapment) in billet casting where powder consumption requirements are low.

It is not easy to eliminate turbulent metal flow since it is not possible to “see into” the mould. Consequently, we must rely on one of the following:

- Water modelling or mathematical modelling.
- “Dip plate” or nail board to test determine the size of the standing wave.
- Observations of low-melting metals, e.g. Sn.

Consequently, it is not surprising that the mould flux has been used to alleviate the problem rather than dealing with the source of the problem, i.e. the metal flow. It has been proposed\(^{31}\) that slag entrapment could be reduced by increasing either the metal/slag interface tension \(\gamma_{ms}\) or the flux viscosity. The usual practice is to increase viscosity but this will reduce the powder consumption, which is not good practice (at least for slabs and blooms). The problem is that we have no proved way of increasing \(\gamma_{ms}\) although some workers have tried removing all Na compounds from the flux.\(^{32}\) Selection of a flux to maximise \(\gamma_{ms}\) may lead to the use of a flux with an inappropriate viscosity or \(T_{br}\) value.

Recent research has shown that the following targets would bring benefits to continuous casting:

- To promote solidification of the shell at lower positions in the mould to avoid oscillation mark (OM) formation.
- This has the additional advantage that the shell is formed far away from the turbulent areas near the meniscus and should avoid problems like gas and slag entrapment (and the need for high viscosity fluxes with low powder consumption).
- To slow down the metal flow velocities in the mould.

The advantages of three recent developments are summarised in Table 2.

These devices will either slow down the metal flow in the meniscus region or will move the site of metal solidification lower down the mould away from the turbulent interface. Treating the problem of turbulent metal flow with these devices frees the mould flux so that it can concentrate on optimising lubrication and horizontal heat transfer.

### 4.2. Environmental Concerns

In recent years the main aims in steel-related research have been to reduce both the volume of slag produced\(^{36}\) and the amount of fluorine in these slags. In continuous casting, fluorine emissions cause erosion of plant, acidification of the cooling water and are a potential health and safety hazard. It is our belief that if F-free powders are to be used, then the replacement (F-free) powder should have the same viscosity, \(T_{br}\) and % crystallinity in the slag film as those in the original powder. It can be seen from Table 3 that if you replace CaF\(_2\) with, say B\(_2\)O\(_3\), that the latter would bring about the decrease in both viscosity and \(T_{br}\) but would have the reverse effect to CaF\(_2\) on the % crystallinity. So great care must be taken with the formulation of the F-free flux composition.

### 4.3. Defects

Table 4 lists various defects,\(^{37}\) the possible causes of these defects and possible remedies to combat them.

### 5. Conclusions

(1) More than 80% of mould powders work in a way which conforms to empirical rules; so there is a logic in the way that fluxes work but this logic is frequently hidden.
There is a basic simplicity in the way fluxes work since there are only three properties determining the optimum lubrication and heat transfer for the given casting conditions, mould dimensions and steel grade, namely, the viscosity, break temperature and % crystallinity in the slag film. When the mould flux is used to combat other problems (e.g. slag entrapment due to turbulent metal flow) this frequently leads to the use of fluxes which do not provide optimal lubrication and horizontal heat transfer.

Several new devices could help to reduce turbulence in the metal flow and if these were successfully implemented they would allow the mould flux to concentrate on providing optimum lubrication and horizontal heat transfer.

(2) There is a basic simplicity in the way fluxes work since there are only three properties determining the optimum lubrication and heat transfer for the given casting conditions, mould dimensions and steel grade, namely, the viscosity, break temperature and % crystallinity in the slag film.

(3) When the mould flux is used to combat other problems (e.g. slag entrapment due to turbulent metal flow) this frequently leads to the use of fluxes which do not provide optimal lubrication and heat transfer.

(4) Several new devices could help to reduce turbulence in the metal flow and if these were successfully implemented they would allow the mould flux to concentrate on providing optimum lubrication and horizontal heat transfer.

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Nomenclature

\[ d : \text{ Thickness (m)} \]
\[ f : \text{ Frequency of oscillation (Hz)} \]
\[ f^* : \text{ Fraction of powder containing slag} \]
\[ Q : \text{ Powder consumption (kg \cdot m}^{-2}\text{)} \]
\[ Q \] : Powder consumption (kg (tonne steel) \(^{-1}\))

\[ R \] : Ratio of mould surface area/volume

\[ R^* \] : thermal resistance (m\(^2\) K W\(^{-1}\))

\[ s \] : Stroke length (m)

\[ t \] : Thickness of mould (m)

\[ T_{\text{break}} \] : Break temperature (K)

\[ T_{\text{solidification}} \] : Solidification temperature (K)

\[ V \] : Casting speed (m min\(^{-1}\))

\[ w \] : Width of mould

\[ \gamma_{\text{int}} \] : Interfacial tension (N m\(^{-1}\))

\[ \eta \] : Viscosity (dPa s)

\[ \rho \] : Density (kg m\(^{-3}\))

EMC : Electro-magnetic casting

HC, LC, MC : High, low, medium carbon steel

OM : Oscillation mark

SEN : Submerged Entry Nozzle

SF : Swirling flow (SEN)

\( \uparrow \) : Increase; \( \downarrow \) : Decrease; \( \rightarrow \) : Leads to

Subscripts

\( l \) : liquid

\( gl \) : glass

\( \text{cry} \) : crystalline

REFERENCES

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