

Continuous casting mould powder and casting process interaction: why powders do not always work as expected

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Why does a continuous casting mould powder, which works successfully on a particular caster with respect to semi quality, fail to perform on a caster of a similar design utilizing liquid steel from a similar route for an identical product without some tuning of its make-up and composition? In casting sequences of the same steel grade, why do some apparent random heats produce poor surface quality with respect to cracking when otherwise good surface quality is realized? The answer to these questions lies in the interaction of the mould powder, the casting hardware, and the casting process variables. Using, as examples, data collected from within Corus UK and during collaborative work on the assessment of mould powder performance and its effects on surface quality, the interaction of the mould powder, the casting hardware and the casting process variables is explored. The steelmaking route and its associated alumina load, unexpected changes to slag chemistry, infiltration of the slag into the mould strand gap, and the nature of the slag film are all shown to affect powder performance.

Keywords: continuous casting, mould powders, alumina, slag films

Introduction

Mould powders for continuous casting have been developed over the past twenty-five years such that the casting of many varied sections is now considered routine. This development has been by what many may consider to be ‘trial and error’, taking a mould powder from a similar plant, casting similar products and fine-tuning this powder to the demands of the new application. The fine-tuning has been seen as a ‘black art’ and as such meant that the powder manufacturer and supplier have been in a strong position when defining and supplying to a particular plant, albeit that there has always been significant discussion between the parties. Some of the strength of the manufacturer and supplier has been eroded over recent years as plants introduce mould thermal monitoring systems, which are able to measure the heat transfer conditions and thus help define the powder and slag requirements. Even with such aids, mould powders do not always transfer easily, with many powders working successfully on one plant but not working on a similar plant under seemingly identical conditions. Within Corus UK, and prior to the merger British Steel, the caster operators constantly review mould powder selection and performance. As a consequence there are regular contacts with mould powder manufacturers and suppliers. Information from these contacts, plus data generated from the company’s own powder development programme and research activities¹⁻³ are used in this paper to review why some mould powders do not transfer from one caster to another.

The continuous casting mould is described as the heart of the process and not without reason, as it is recognized that the origin of the majority of surface defects is at, or within, 25 mm of the meniscus in the mould. Whether the defects propagate into cracks depends on the heat transfer in the remainder of the mould and events and conditions at and

below the mould exit. For optimum surface quality, uniform and consistent mould heat transfer is essential for uniform solidification together with consistent lubrication through the mould. Both heat transfer and lubrication are affected by the design of the mould powder, design and condition of the mould itself, and events within the mould that affect meniscus stability. Thus it may be said that it is the interaction of the mould powder and the caster and process variables that determines surface quality. This interaction explains why in some casting sequences of the same steel grade, apparent random heats produce poor surface quality with respect to cracking when otherwise good surface quality is realized, and vice versa. The current paper examines some of these interactions using as examples data collected within Corus UK, and prior to the merger British Steel¹⁻¹⁰, supported by selected examples taken from recent literature.

Data source

The examples reported are taken from work done at the Corus UK plants but concentrate on the slab casters at Scunthorpe and Teesside. Details of the powder type designations, their usage with respect to steel type and mean powder chemistry for the powders investigated at Scunthorpe and Teesside are given in Table I.

During the period of data collection at Scunthorpe almost two hundred casts were monitored and during almost half of these mould top slag samples were taken between 10 to 30 minutes throughout the cast. In order to remove some of the variability in the dataset, only casts made to a mid-peritectic carbon steel composition in 1 830 mm wide slab format were used in the analysis reported here.

The dataset from Teesside contains information on over 450 casts, the samples being taken on both of the slab casters. Unfortunately, at Teesside there are no set slab

Table I
Mould powder designation, usage and chemistry

Powder	Powder Usage	Powder Analysis (wt%)							Calculated Viscosity at 1300°C
		CaO	SiO ₂	Al ₂ O ₃	MnO	K ₂ O	Na ₂ O	CaF ₂	
SB	Standard <0.17%C Steels	32.30	40.69	8.38	0.12	0.12	5.378	11.69	7.351
SD	Tri-Peritectic Carbon Steels	33.76	34.45	5.44	0.13	0.35	6.59	12.65	2.340
SH	Tri-Peritectic Carbon Steels	32.00	38.95	6.20	0.16	0.44	7.43	14.23	2.840
TA	<0.085% C Steels	23.90	41.71	5.74	0.06	0.70	9.98	15.53	3.724
TB	>0.145% C Steels	29.98	41.75	4.82	0.06	0.66	8.13	13.62	3.430
TC	Peritectic Carbon Steels	33.19	38.4	8.60	0.04	0.12	5.23	11.33	6.767
TG	>0.15% C Steels	23.26	40.93	5.31	0.09	0.66	10.24	15.93	3.22
TH	Peritectic Carbon Steels	34.96	38.61	5.36	3.79	0.18	5.19	9.76	10.090

widths as at Scunthorpe, the practice being to utilize the mould width adjustment during casting to meet the customer's requirements. Thus to reduce the variability in the dataset, slab widths between 1 750 and 1 830 mm were selected (the dataset containing data on widths as small as 1 090 mm). Again only mid-peritectic carbon steel compositions were selected.

Several different steelmaking routes were utilized to make these monitored casts and these are:

- F Ladle flush and trim analysis at BOF
- Fi Ladle, deep ladle injection
- FS Ladle, stir and final trim at the casters
- FH Ladle, ladle furnace
- FD Ladle, vacuum degas
- FHD Ladle, ladle furnace, vacuum degas
- FHiD Ladle, ladle furnace with deep ladle injection, vacuum degas.

As a critical aspect of the investigations was changes to slag chemistry during casting, data on all casts were removed where ladle to tundish shrouding was a problem, i.e. alumina pick-up and slag Fe₂O₃ increase.

The Corus mould thermal monitoring (MTM) system is installed on the casters at the two plants. A general description of the system, its analysis tools and how it is used for analysis of mould powder performance and surface quality is given elsewhere^{1,11-14}. Also, for both plants the surface defect investigated was broad face longitudinal crack.

Powder transfer from one caster to another

Steelmaking route and alumina load

During the powder development programme for the slab caster at Scunthorpe Works, three trials were carried out using powder SD as a prospective replacement for the standard powder SB. The concern and driving force for Scunthorpe at the time was that major efforts to reduce the incidence of longitudinal cracking had been so successful that the gross cracks had been eliminated but very fine cracks, typically three to four oscillation marks long, were now a problem as this type was so difficult to observe on inspection. The manufacturer of powder SD made an initial recommendation based on the results from two similar European casters producing equivalent long product peritectic grades. Data from the three trials were varied and could be related to the alumina picked up in the slag pool. Where the alumina pick-up was low and reported to be significantly lower than the European plants, longitudinal cracking worsened, a consequence of what was thought to

be poor lubrication¹⁵. Where the alumina pick-up was at a similar level to that of the European plants (VFS route at Scunthorpe compared with VFH route) then the longitudinal cracking was neither better nor worse.

In an attempt to overcome the apparent alumina problem, the manufacturer provided a modified version (powder SH, already a production powder and in routine use elsewhere within Europe) with a higher level of alumina and also changed levels of fluxing agents to provide a slightly higher viscosity slag. Two four-ladle casting sequences were undertaken with powder SH; in every slab longitudinal cracking was extensive, even though the alumina pick-up was at similar levels to the European plants where the powder was in routine use. Thus, an alternative mechanism was required to explain why the powder did not work.

Mould design

During a collaborative European research programme¹ several mould slag and slag film samples were taken from the strip grade slab caster at Sidmar, Belgium, using its routine powder SH during the casting of peritectic grades. Longitudinal crack performance was excellent and in the few instances where light cracking was noted, it correlated well with periods of high thermal variability in the mould. At the Corus Teesside Works, powder SH has also undergone significant testing, with varied results. Although no heavy longitudinal cracking was noted, there were periods where light cracking required surface rectification at significantly higher levels than when using the routine powder. Alumina pick-up was at similar levels to Sidmar and Scunthorpe. As stated above, the performance at Scunthorpe was poor.

Analysis of the data suggested it was the contribution of the mould design that had resulted in the differences in performance. This was supported by other research^{6,16-18} into the thermal and mechanical behaviour of slab moulds where the design of the cooling water slots in the copper plate and the mounting bolt location to the overall mould plate, especially with respect to the cooling slots, was shown to affect temperature isotherms and mould plate distortion.

Variation of performance within and between sequences

Steelmaking route and alumina load

Table II shows the alumina pick-up by the mould slag and variability in mould heat transfer by steelmaking route for the Scunthorpe data for the standard mould powder SB. It is

Table II
Alumina pick-up and mould thermal variability by steelmaking process route for scunthorpe standard powder SB

Steelmaking route	Al ₂ O ₃ pick-up		Mould thermal variability	
	Mean	Std. Dev	Mean	Std. Dev
F	1.873	0.430	2.312	0.875
FS	1.658	0.416	2.003	0.783
FH	1.496	0.468	2.064	0.878
FD	1.520	0.444	1.826	0.369
FHD	0.8235	0.557	1.524	0.349
Steelmaking route effect of cast position in sequence	Al ₂ O ₃ pick-up		Mould thermal variability	
	Mean	Std. Dev	Mean	Std. Dev
F in sequence FS, FS, F, F	2.340	0.497	2.640	0.894
F in sequence FD, FD, FD, F	2.264	0.782	2.693	0.899
FS in sequence FD, FS, FD, FD	1.715	0.470	2.314	0.657
FS in sequence FD, FD, FS, FD	1.839	0.357	2.354	0.754
FS in sequence FD, FD, FD, FS	1.987	0.642	2.460	0.875
FS in sequence FD, FD, FS, FS	2.064	0.659	2.598	0.953
FH in sequence FD, FH, FD, FD	1.530	0.499	2.156	1.006
FH in sequence FD, FD, FD, FH	1.592	0.533	2.005	0.904
FD in sequence FHD, FHD, FD, FD	1.489	0.494	2.645	0.840

obvious that for the routes involving secondary steelmaking practices, ladle furnace and/or degassing, both alumina pick-up and mould thermal variability are lower. Previous experience of the analysis of thermal variability in the mould has shown a strong correlation with longitudinal crack^{1,11-14}. Unfortunately, for these Scunthorpe data there was only a very weak correlation with steelmaking route, alumina pick-up, thermal variability and longitudinal cracking. However, the correlation became very strong when the data were considered on a sequence basis where the steelmaking route changed cast-by-cast throughout the sequence, i.e. FD, FD, FS, and FD. Table II shows also the alumina pick-up by the mould slag and variability in mould heat transfer for the sequence heats produced by different steelmaking routes. It can be seen from the table that for the simpler process routes, F, Fi, and FS, intermixed with casts from a more sophisticated steelmaking route, the effect is to increase both the mean and standard deviation of the data. These increases correspond to increased longitudinal cracking. The relatively high levels of alumina pick-up in casts produced via the ladle furnace and degasser are thought to be a consequence of the data being influenced by the occasional late aluminium addition. Some anomalies, identified as a consequence of unexpected changes to the levels of fluxing agents in the mould top slag, have been removed from the data set; these will be discussed later.

Batch-to-batch variation in powder chemistry

There were several incidents within the former British Steel where part way through a casting sequence a new batch of powder was started on the caster and this has had dire consequences on the security of the caster (breakouts) and surface quality. In one incident⁹, transverse cracking was noted to have increased significantly; the cracking being more of an intrinsic hot tear, which is indicative of a loss of lubrication. Routine chemical analysis revealed no difference in the chemical composition of this powder from the previous batches. XRF analysis, however, revealed a possible change in the wollastonite source used as part of the base of the powder. The manufacturer confirmed this,

but more significantly, the manufacturer stated that the free carbon had changed to a different mix from different sources. This had changed the melting characteristics of the powder. In a second incident where the deterioration was observed over a period of time, longitudinal cracking and sub-surface defects resulting in sliver-type defects were noted to have increased during the casting of peritectic strip grade steels. Again simple chemical analysis revealed no difference between batches, but simultaneous thermal analysis (STA) revealed a significant difference in the crystallization characteristics of the molten slag¹². Following significant discussion, the manufacturer admitted a change in the mineralogical make-up of the powder.

Plant operational practice and in-mould conditions

It is accepted that no matter how stable the ladle to tundish shrouding, at ladle change, there will be an increase in the alumina load of the steel and a consequential pick-up of alumina by the mould slag. Alumina entering the system will generally mean clogging of the tundish to mould refractory holloware; the extent to which this occurs will dictate how the flow patterns within the mould are affected. Breaking away of the alumina and its flushing into the mould will affect mould level control and will change the mould slag properties in terms of viscosity and crystallization. Should clogging be greater in one port of the SEN than the other, then asymmetric flow will result. An example from Teesside Works on meniscus stability at the slab end plates resulting from the onset of asymmetric flow is illustrated in Figure 1; the meniscus profiles were measured by the plate dipping method¹⁷. The figure shows that as a consequence of the asymmetry a rolling meniscus had developed approximately 40 mm from the end plate; the effect of the meniscus being to starve the end plate of slag. Asymmetry has been correlated with poor slab edge shape, broad face corner guttering and off-corner longitudinal cracking.

In addition to alumina clogging, throttling of the steel flow by the stopper or slide gate, argon input into the holloware, SEN immersion depth and slab width changes

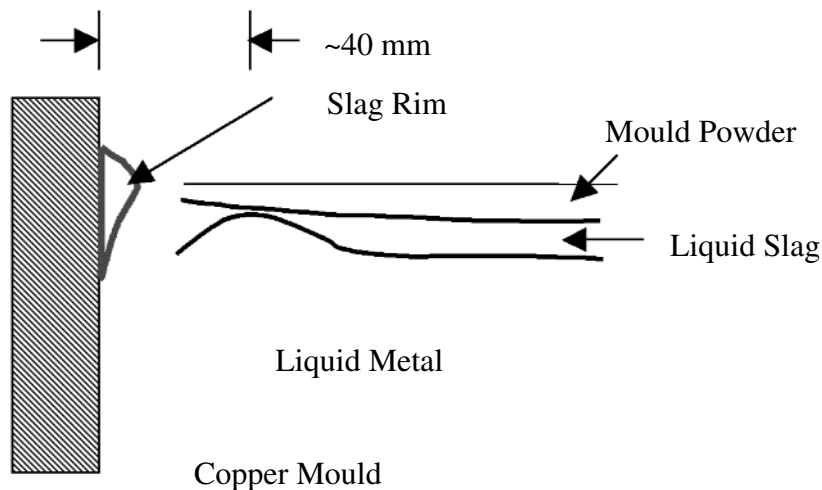


Figure 1. Schematic of the effect of a rolling meniscus at the slab end plate

during casting also affect the flow patterns in the mould. Thus, any change to operational practice during a cast or casting sequence may affect mould powder performance and surface quality. A further example from Teesside Works is that of an inward width change during casting where the operational window of the SEN (with respect to slab width) has been lost and severe narrow face turbulence introduced, producing an effect similar to that of asymmetry (Figure 1) but at both narrow faces of the mould.

Unexpected chemistry changes in liquid slag

There have been several investigations undertaken where the chemistry of the mould top slag has been monitored throughout a casting sequence. There is a general pattern to the changes in slag chemistry as described below:

- Start of cast pick-up of Al_2O_3 and MnO falling to a value typical for the powder after 10 to 15 minutes
- Ladle change pick-up of Al_2O_3 and MnO falling after 5 to 15 minutes but to a higher level compared with the preceding cast
- Large decrease in fluorine and other fluxing agents on the first cast, the level of loss decreasing during the progression of the cast
- A gradual increase in the fluxing agents throughout the casting sequence.

Where the above pattern is not followed, generally the explanation is one of a perturbation in the casting practice, i.e. a breakdown of ladle to tundish shrouding, tundish slag carry-over (however minor) or major disturbance of the mould powder and slag cover. However, there have been several instances where a sudden and unexpected change in the slag chemistry has been measured and this has correlated with surface quality problems. Some examples are (neglecting the effects of alumina flushes):

- > 5 per cent pick-up of Fe_2O_3 and > 2 per cent pick-up in fluorine: in these two samples there was increased copper plate temperature and heat transfer variability and an increased incidence of longitudinal, and transverse corner crack, an indication of a possible reduction in the mould-strand gap slag film thickness due to a loss of viscosity
- > 1.5 per cent loss of fluorine: associated with an increase in longitudinal cracking. There was some

speculation that the fluorine loss could be attributed to an incorrect in-cast change to the stopper and tube changer argon inducing more turbulence around the SEN

- > 3 per cent pick-up of MnO and >1 per cent loss of MnO : both examples resulted in significant changes to mould heat transfer variability but only the latter to a worsening of surface quality
- > 0.5 per cent pick-up in Cr_2O_3 : an unexpected pick-up in the mould top slag as Cr_2O_3 , originating from the ladle gate well filler¹⁹, is normally only found in the tundish cover slag. The pick-up was associated with a decreased mould heat transfer variability and copper face temperature but an increased level of longitudinal cracking, including off-corner longitudinal cracking.

Such unexpected changes in slag composition were reported for the slab casters at IJmuiden¹⁰ on work done prior to the merger, albeit there were no slab surface quality data reported.

Conditions at the meniscus and within the mould strand gap

It is accepted that events and conditions in the mould that affect the ability of the mould top slag to infiltrate the mould-strand gap will affect surface quality. Such events and conditions include:

- Mould oscillation characteristics^{3,5,20,21}
- Mould level surges and mould level control^{1,3,7}
- Flow patterns in the mould²²
- Development, consumption and removal of the slag rim
- Mould powder consumption^{3,5,20,21}
- Mould powder melting rate^{3,5,20,21}
- Changes to slag chemistry that modify the slag viscosity¹

The effects of several of these have been highlighted in the previous sections. One event of particular interest is the development, consumption and removal of the slag rim. Generally a slag rim will develop and remain in relative equilibrium throughout a casting sequence. However, sometimes the rim will grow, until a size is reached where the rim will collapse onto the meniscus and be consumed; a new slag rim will then form. Analysis of slab quality data from Scunthorpe suggests that during the collapse, consumption and re-growth of the rim star cracking

worsens, indicating a breakdown in lubrication. Longitudinal and star cracking and, especially, mould powder entrapment result from the rabbling of the rim into the mould. Large heavy rims prior to collapse may also starve the mould-strand gap of slag as more slag attaches and solidifies to the rim or prevent feeding of slag into the gap as the mould level fluctuates.

A recently completed ECSC project has shown that the growth and structure of the slag rim differs for different mould powders and steel grades²². In addition, the slag rim has been shown to interact with the meniscus and influence the initial shell to be formed. The work also proposed that variations on the structure of the slag film from the mould-strand gap were a consequence of oscillation induced movement of the slag rim with respect to the mould wall.

Within the mould-strand gap, the role of the slag is to ensure consistent and uniform mould heat transfer. This means that the slag film has to be of a constant thickness around the periphery of the mould and have constant heat transfer properties.

Figure 2 shows the variation in slag film thickness for mould powders:

- SB
- TA, used for peritectics²
- TA, used for >0.15 per cent C steels¹
- TC, used for peritectic grade steels⁵
- TH, current peritectic grade powder.

The slag films were collected at Scunthorpe by removing the slag rim, which had attached up to 150 mm of slag film. At Teesside, the slag films were collected using three methods, a wire mesh basket at mould exit, from the cooling grids at the end of a cast or sequence, or from breakouts. The collection of samples at the mould exit meant that there were no data on their exact location within the mould.

Figure 2 shows that scatter of slag film thickness for powder SB is low, reflecting the good long-term performance of this powder. For powder TA (for both peritectic carbon steels and > 0.15 per cent C steels) there is considerable variability in the thicknesses. The variability in slag film thickness for peritectic steel reduces in the order TA, TC, TH. It is interesting to note that the mean film thickness for the powders is different. The performance of powder TH is far superior with respect to longitudinal cracking.

The slag film controls heat transfer from the shell to the copper mould. It has been reported that the interfacial resistance to heat flow increases with increasing crystallinity and increasing slag film thickness^{23,24}. The work of Riaz²⁴ has also shown that distribution of the crystalline phase also affects the interfacial resistance. These observations are particularly important when the structure of the slag films is examined. Figures 3 and 4 show two slag films from powder TH taken from adjacent strands of slab caster No. 1 at Teesside. It is unknown whether these structures were typical of those around the periphery of the mould, but the slab surface quality from strand 2 was worse than strand 1. It should be stated that the in-mould conditions with respect to turbulence, argon input and asymmetry, were also worse on strand 2. The structures observed from the microscopic examination of the slag films can be summarized as:

- Porosity variable across the thickness of the sample
- Porosity often associated in bands between glassy and crystalline phases
- Pore size generally between 2 and 20 microns but some pores greater than 50 microns
- Crystallization appears to have nucleated on some pores
- Multiple bands of crystallized/glassy phases
- The bands of crystallized/glassy phases in many combinations between the mould and shell, i.e. glassy/crystalline, crystalline/glassy/crystalline etc., and not always as reported in the literature
- Presence of many metal droplets in the slag film, these were distributed randomly
- Voids associated with solidification shrinkage.

These observations suggest that a slag film of a particular powder may take many forms and thus affect the mould heat transfer differently. The form of the slag film may be a consequence of the in-mould conditions, the local powder melting rate (vertical heat transfer) and elemental pick-up on a local scale. If there is a change in the slag film structure locally around the mould periphery, then it has been suggested that this should be detected via thermocouples in the mould. It is possible, however, that the structure may be so localized that its effects cannot be detected by an individual thermocouple. If this is the case, it also may be argued that local variations in the slag film structure may not affect surface quality.

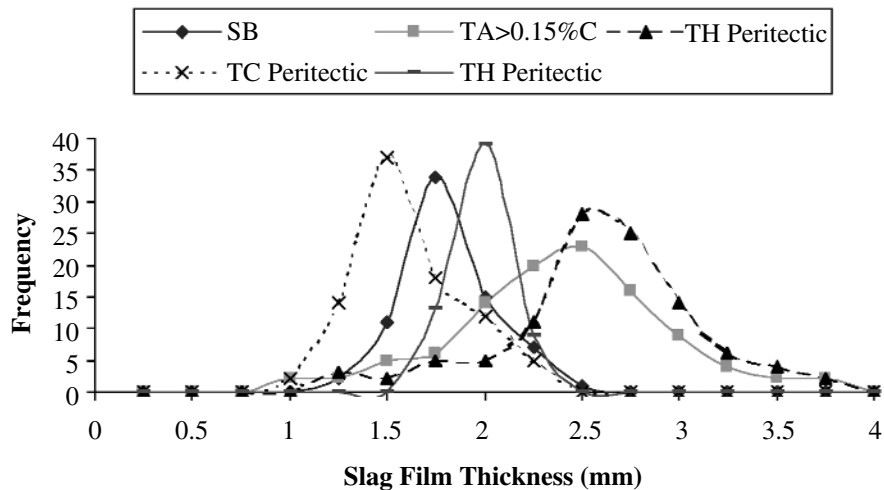


Figure 2. Frequency distribution for thickness of slag films from mould-strand gap for powders SB, TA, TC, and TH

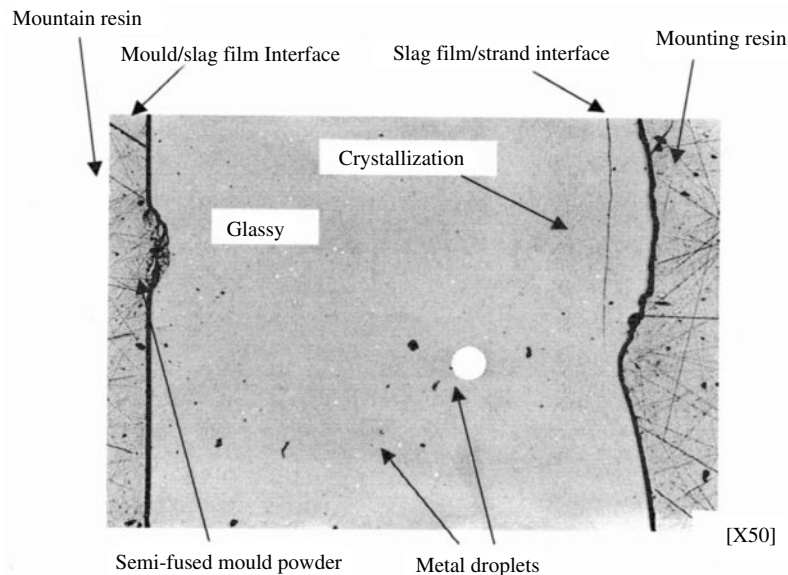


Figure 3. Slag film from peritectic grade cast at Corus Teesside works strand 1 using powder 'TH'

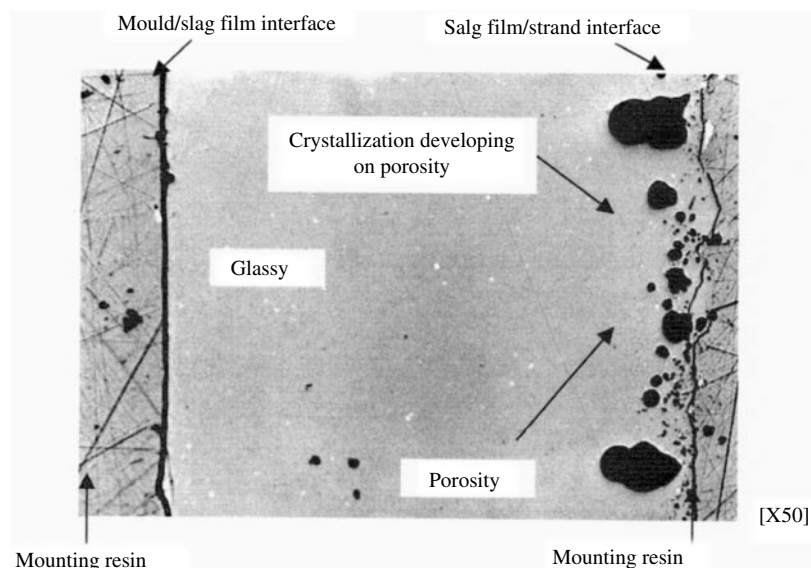


Figure 4. Slag film from peritectic grade cast at Corus Teesside works strand 2 using powder 'TH'

There have been several investigations reported in the recent literature on the nature of slag films^{24–28} and most illustrate non-uniform structures. It is unclear from these investigations, as with the Corus data, as to just how localized are these structural changes. Hooli²⁸ has also shown the nature of the slag film changes as casting progresses.

Conclusions

Many factors are known to affect the performance of the mould powder. In this paper the interaction of the mould powder with the casting process variables has been reviewed, using data collected during investigations and powder development work undertaken by Corus UK personnel, to investigate why mould powders do not always work as expected.

The transfer of a mould powder operating successfully on

one caster to an apparently similar caster, producing identical steel grades manufactured by a similar process route is not always successful. In this respect it has been shown that the alumina load from the steelmaking practice and the design of the mould itself will affect the powder performance.

During some sequences of casting the same steel grade, apparent random heats produce poor surface quality with respect to cracking when otherwise a good surface quality is realized, and vice-versa. Also, between sequences of the same steel grade there is a step-change in surface quality, either for better or for worse. These observations have been explained by the effect of the steelmaking route and variations in its associated alumina load, batch to batch variation in the mineralogical make-up of the powder, unexpected changes to the slag chemistry, conditions within the mould especially at the meniscus, and the nature of the slag film within the mould-strand gap.

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