

Looking into continuous casting mould

K. C. Mills^{*1,2}, P. Ramirez-Lopez³, P. D. Lee², B. Santillana⁴, B. G. Thomas⁵ and R. Morales⁶

When you look into the continuous casting mould you can see very little. Consequently, steelmakers have had to rely on plant trials, simulation experiments and physical property measurements on fluxes and steels to gain an understanding of the mechanisms responsible for process problems and product defects. However, in recent years, mathematical modelling has advanced to the stage where they can provide us with great insight into these mechanisms. As a non-mathematical modeller, I was initially sceptical of some of the predictions of the mathematical models. However, I have been completely won over by the ability of these models to simulate accurately the mechanisms responsible for various defects, such as slag entrapment, oscillation mark formation, etc. Mathematical modelling literally allows us to 'see' what is happening in the mould. It is a remarkable tool.

Keywords: Continuous casting, Metal flow, Defects, Mechanisms, Mould oscillation

Introduction

If you look into the continuous casting mould (Fig. 1), you can see very little of what is going on inside the mould. This is because the surface of the steel is covered with casting powder, which masks any movements in the mould. In fact, continuous casting, as viewed from the top of the mould, appears to be a very peaceful process. However, this is very deceptive since at high casting speeds V_c the powder hides a seething, fluctuating maelstrom.

Since it is not possible to see into the continuous casting mould, other techniques have had to be used to gain an understanding of what is going on inside the mould. This is especially so when exploring the underlying causes of process problems and product defects. Knowledge of the underlying causes of product defects (e.g. longitudinal cracking) and process problems (e.g. sticker breakouts and hot tearing) has been principally deduced from:

- (i) the results and observations of plant trials (e.g. factors determining heat transfer in the mould)^{1,2}
- (ii) water modelling studies (e.g. slag entrapment)^{3,4}
- (iii) measurements of the physical properties of casting powders (e.g. determination of empirical rules for powder consumption)^{5,6}
- (iv) mathematical modelling of in-mould behaviour.⁷⁻¹⁰

It is my belief that mathematical modelling has now developed to the stage where it literally allows us to see into the continuous casting mould; it is the equivalent of close circuit television (CCTV) looking inside the mould. This is a personal account of how a sceptical experimentalist has become convinced of the great benefits that mathematical modelling can bring to our understanding and control of the continuous casting process.

Mathematical modelling of processes effectively started in the 1980s. My scepticism of its predictive powers arose from anecdotal stories of 'if you do not get the right answer change the mesh size'. There was also the case of the powder consumption (Q_s , which is a measure of the lubrication supplied to the steel shell), where mathematical models predict an increase in Q_s with increased frequency of mould oscillation, but plant data show the opposite trend. This will be discussed below at the end of the section on 'New mechanism for Oscillation mark formation'.

My co-authors are all mathematical modellers. Although I had some

scepticism about the accuracy of some predictions, I did realise it was capable of shining a torch into the interior of the continuous casting mould.

Consequently, P. Lee and I started our collaboration on modelling various aspects of the continuous casting process.⁷ We were later joined by P. Ramirez-Lopez and then by B. Santillana of Tata Steel. Much of the work described below arose from that collaboration.¹⁰⁻¹² However, in paying tribute to the way that mathematical modelling has developed to the stage where it provides us with a CCTV to see into the mould, it is only fitting to acknowledge the outstanding contributions made by B. Thomas and R. Morales to bring us to the present situation. My co-authors have provided me with case studies below, all showing how modelling allows us to see into the mould.

Continuous casting process

Continuous casting is a highly successful process, and more than 1 billion tonnes of steel are cast per year by this method. Steel from the ladle is poured into a tundish and then flows through a submerged entry nozzle (SEN) into a water cooled copper mould (Fig. 2a). The molten steel solidifies to form a shell (Fig. 2b). The sticking of the shell to the mould is prevented by (i) adding a casting flux (which forms a liquid layer between the steel shell and the mould) and (ii) oscillating the mould. Casting powder is added to the top of the mould, where it sinters (and forms a



1 Image of view of continuous casting mould from top (courtesy of Dr B. Stewart, Tata Steel)

¹Department of Materials, Imperial College, London, UK

²Rutherford Appleton Laboratory, University of Manchester, Didcot OX11 0FA, Manchester, UK

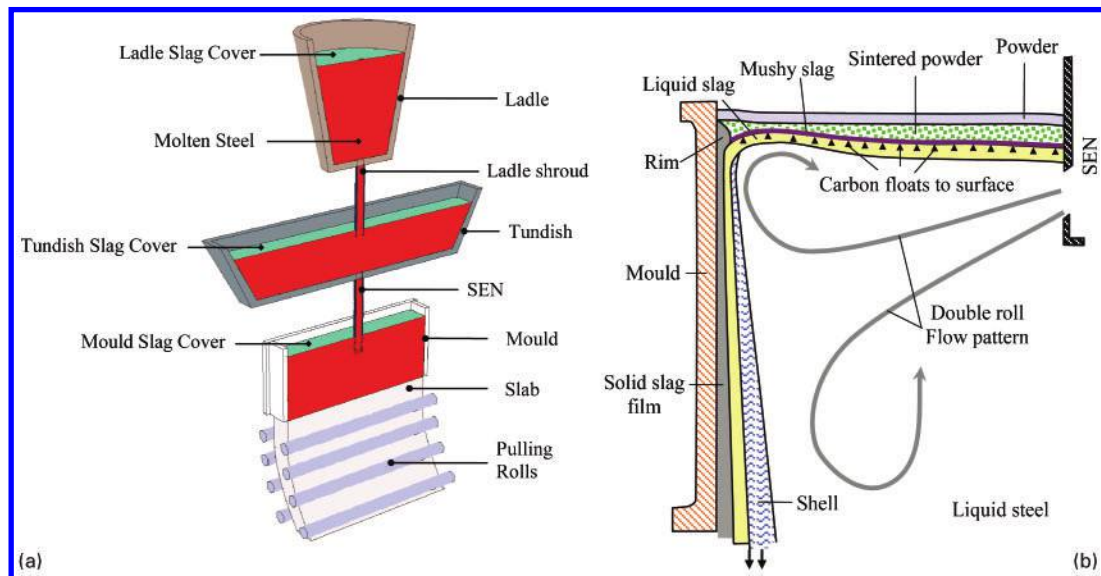
³Swerea, MEFOS, Aronstorpsvägen 1, Luleå SE 974 37, Sweden

⁴Tata Steel RD&T, IJmuiden, The Netherlands

⁵Department of Mechanical and Industrial Engineering, University of Illinois, Urbana-Champaign, IL, USA

⁶Department of Metallurgy, National Polytechnic Institute ESQIE, Apdo 75-874, Mexico

*Corresponding author, kcmills@talktalk.net



2 Schematic diagram showing *a* continuous casting process and *b* various phases formed in mould^{6,9}

bed) and then melts to form a molten slag pool. Molten slag infiltrates into the mould/shell gap and forms a slag layer consisting of a liquid slag film (~ 0.1 mm thick) and a solid slag layer (~ 2 mm thick), as shown in Fig. 2*b*. The thicknesses of the liquid d_l and solid slag layer d_s determine, respectively, the level of lubrication supplied to the shell and the magnitude of the horizontal heat flux between shell and mould. The powder consumption $Q_s = \rho d_l$, where ρ is the density of molten slag ~ 2600 kg m⁻³ is often used as a measure of the lubrication supplied.

Continuous casting is a complex process involving a large number of parameters (metal flow, heat transfer, oscillation characteristics, thermomechanical properties of the steel). These parameters are strongly interdependent. For instance, if the casting speed is increased to increase productivity, this will affect the slag infiltration (i.e. lubrication) and the heat transfer between shell and mould, increase turbulence in the metal flow and perhaps cause thinning of the shell in the region where the metal flow impacts with the shell. Each of these can, in turn, have a collateral effect on the process.

Mathematical model

The metal flow in the mould is very important, and several defects (such as slag entrapment, oscillation mark (OM) formation and SEN erosion) are directly traceable to the flows of metal and slag in the mould. Ideally, the metal flow should form a 'double roll' as depicted in Fig. 2.

Model details

The model of Ramirez-Lopez *et al.*¹⁰⁻¹² provides most of the examples cited in this paper; the model couples the following:

- (i) the fluid flow in both metal and slag phases
- (ii) the heat transfer from shell to mould (which involves the resistance of the slag film and the interfacial resistance caused by the shrinkage of the slag with crystallisation)
- (iii) the solidification of the shell.

The model makes no assumptions concerning the following:

- (i) the formation of solid and liquid slag films
- (ii) the meniscus shape (some models assume a Bikerman profile)

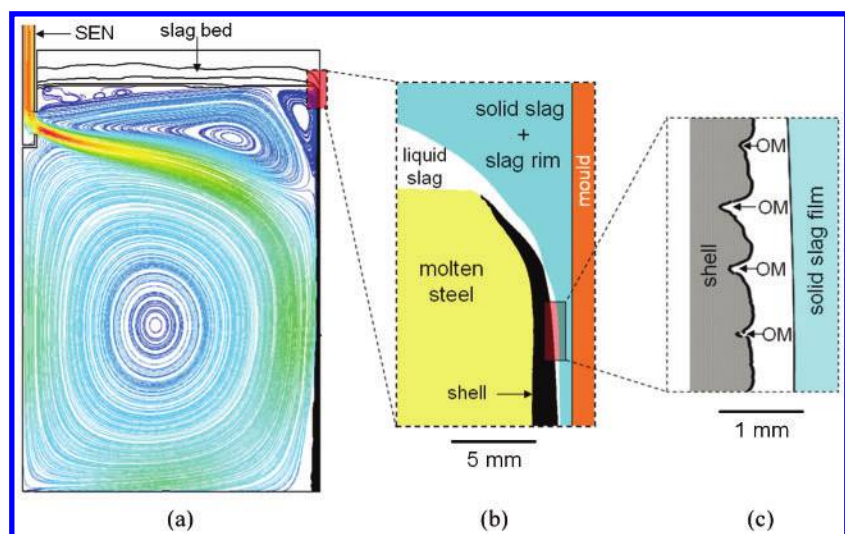
- (iii) the formation of a slag rim (shown in Fig. 2*b*) that helps to push the liquid slag into the shell/mould gap.

Full details are given elsewhere.¹⁰⁻¹²

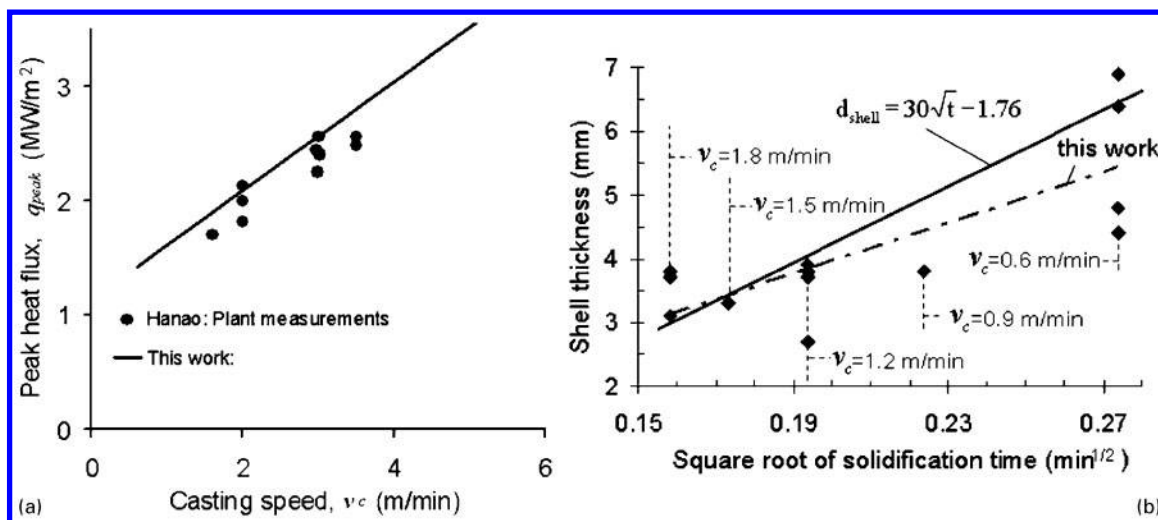
Model validation

The model was found to correctly predict the occurrence of the following:

- (i) solid and liquid slag films (d_s and d_l) with thicknesses close to those removed from the mould and also show a reasonable shell meniscus profile and slag rim (Fig. 3*b*)
- (ii) heat fluxes q and shell thicknesses (Fig. 4) and powder consumption Q_s in excellent agreement with the values measured on plant
- (iii) a double roll metal flow (Fig. 3*a*) and the meniscus



3 Model predictions of *a* double roll metal flow, *b* slag rim and slag film and *c* OM formation in shell^{10,11}



4 Model predictions^{10,11} of a heat flux (line) against plant measurements (•) as function of casting speed and b shell thickness (dash dot line=model values) against measurements (=♦ and solid line) as function of (solidification time)^{9,5} (Ref. 13)

wave formed by the rebound of the metal flow from the mould wall (narrow face) and in some cases vortices (Fig. 5a and b)

- (iv) natural phenomena such as slag entrapment and OM formation (Fig. 3c).

Model prediction of defect mechanisms

Metal and slag flows can cause a variety of defects and process problems. Several examples of the way in which mathematical modelling can be used to provide insights into the mechanisms underlying these defects and problems are given below.

Slag entrapment

The demand for ever higher production rates has led sequentially to higher casting speeds, greater turbulence in the metal flow and more slag entrapment. Water modelling studies have shown that slag entrapment can occur by several mechanisms;^{3,4} these are outlined in Fig. 6a. The mechanism (A) of 'necking and detachment' (Figs. 6b and 7) is a result of the velocity of metal flow being much greater than that of the slag. A video of the metal and slag flows was prepared and revealed clear evidence of necking and detachment occurring in the mould. Any scepticism about the reliability of the predictions of mathematical modelling was dispatched when this mechanism was seen in the video of the predicted flows. This was a key moment.

Furthermore, the video of model predictions also showed the formation

of Karman vortices (Fig. 5b), which is another cause of slag entrapment (denoted as B in Fig. 6a). Thus, the model was clearly predicting situations where slag entrapment occurred.

Fluctuations in the metal flow initiate in the SEN. When the metal strikes the base of the SEN, it rebounds and forms a vortex (Fig. 8a), and this vortex interferes with the flow from the two ports. The spin of the vortex favours the flow from one port or the other at different times; this gives rise to continual fluctuations in the metal flow. Torres-Alonso and co-workers¹⁵ studied the mechanism responsible for periodic clusters of entrapped slag in billets. A straight nozzle (SEN) with no base plate is used in billet casting. Mathematical and water modelling were used in this study,¹⁵ and it was shown that even with straight nozzles the fluctuations in the metal flow result from periodic formation of eddies and back flows with consequential slag entrapment (Fig. 8b).

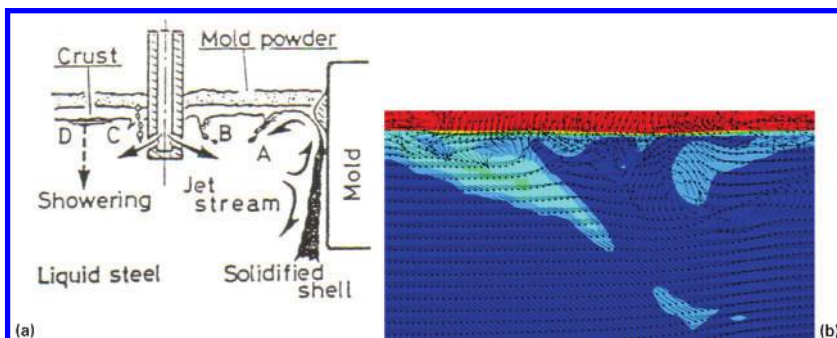
Thus, the model is acting like a CCTV to monitor the metal flow in the mould.

Electromagnetic braking (EMBR)

Metal flow turbulence near the surface is the principal factor affecting slag entrapment and surface defects. The EMBR is used to reduce both metal flow turbulence and to maintain a double roll metal flow in the mould. However, it is necessary to optimise the settings on the EMBR, and this is not easy because of our inability to see into the mould. However, with a reliable, validated mathematical model, it is possible to optimise the settings for the conditions.¹⁶ Figure 9 is made up of frames taken from videos of the model predictions. These frames show the flow patterns formed with no EMBR (Fig. 9a), EMBR setting 91 mm (Fig. 9b) and EMBR setting 121 mm (Fig. 9c).¹⁶ Figure 9a indicates that with no EMBR, the surface flow is very slow, which means there is a possibility of the metal surface freezing (i.e. skull formation). Figure 9b shows that the application of EMBR across the nozzle ports does create a double roll flow, but in this case the flow is very unsteady and lapses occasionally into 'asymmetric flow', which is



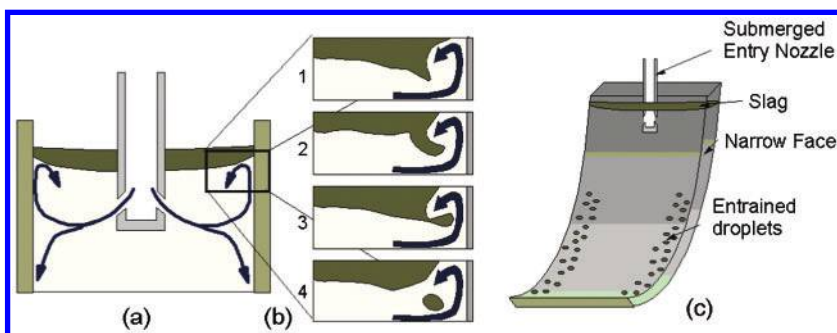
5 Model predictions showing a surface waves on metal meniscus and b formation of vortex^{10,11}



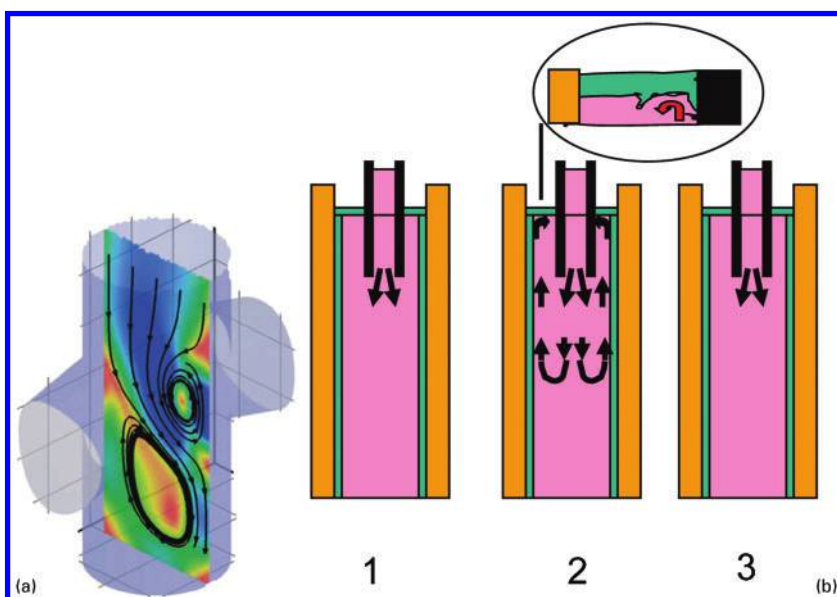
6 a Schematic diagram showing various mechanisms involved in slag entrapment and b model prediction showing necking and detachment of slag^{10,11}

undesirable. Figure 9c shows a much more satisfactory and stable 'double roll' flow with the EMBR positioned lower, below the nozzle ports. Thus, once more, mathematical models allow us to inspect the flow patterns in the mould and to optimise the flow conditions.

Modelling the effects of EMBR has also been carried out at Tata Steel;¹⁷ their work showed that EMBR improved the metal flow pattern and the swirl in the sump of the SEN was found to bias the flow, preferentially, towards the loose, wide face of the mould (Fig. 10).¹⁷



7 Schematic drawing showing mechanism a, showing a metal flow in mould, b mechanism of necking and detachment and c location of slag entrapment on slab¹⁴



8 Schematic drawings showing a vortex formed in sump of SEN, b flow from straight nozzle in billet casting showing downward flow in periods 1 and 3 and periodic formation of eddies, back flows and slag entrapment in period 2¹⁵

Effect of argon flow

Argon is streamed into the metal flowing through the SEN in order to minimise clogging of the ports by inclusions, and it also aids the removal of inclusions to the slag pool. There is anecdotal evidence that the metal flow in the mould is sensitive to the argon flowrate. There have been a few independent modelling studies carried out on this topic in recent years.^{17–19}

Mathematical models have shown that when argon is bubbled into the metal, the larger bubbles tend to escape near the SEN and the smaller bubbles emerge farther away from the SEN¹⁹ and the Ar bubbling tends to 'cushion' the metal flow.¹⁹

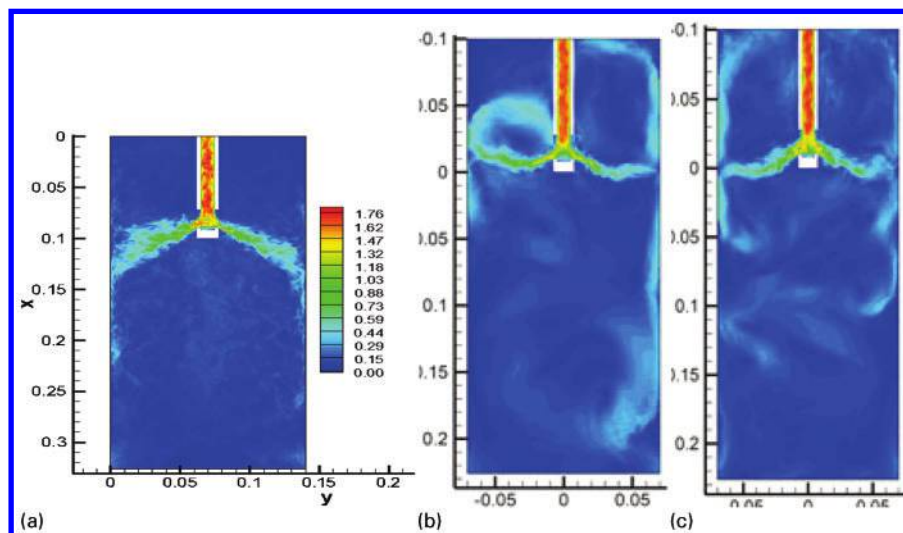
A recent modelling study indicated that for $V_c = 1.2 \text{ m min}^{-1}$ and an Ar flowrate of 4 L min^{-1} a double roll pattern with the upper roll flowing inwards along the surface towards the SEN was produced (Fig. 11a).¹⁸ When the Ar flowrate was increased to 5 L min^{-1} , the increased Ar bubbling created a vertically upward flow of bubbles along the SEN that induced an outward, surface flow from the SEN (i.e. the increased Ar flowrate reversed the direction of the surface (metal) flow; Fig. 11b). This finding agreed with plant experience, which indicated that the Ar flowrate should not exceed 4 L min^{-1} . In order to verify the modelling results, a simulation trial was carried out where the surface of the metal was covered with oil. With an Ar flowrate of 4 L min^{-1} , the Ar bubbling induced an inward flow (Fig. 11c), but when the flowrate was increased to 5 L min^{-1} , the bubbles emerged near the SEN, and the surface flow direction was reversed (Fig. 11d).

A similar modelling study was carried out at Tata Steel,¹⁷ and the findings agreed with those described above, i.e. the metal flow direction is sensitive to the Ar flowrate.

New mechanism for OM formation

In the examples cited above, inspection of the videos of model predictions was sufficient to identify the problem. In the following example, it was necessary to couple inspection of the videos of model predictions with other information from the model in order to identify the mechanism responsible for OM formation.

Oscillation marks are regular indentations in the surface of the steel (Fig. 12a) and are dependent upon the oscillation characteristics of the mould. Oscillation marks are regarded as defects



9 Frames from video of model predictions for *a* no EMBR, *b* EMBR setting 92 mm (across nozzle) and *c* EMBR setting 121 mm (below nozzle)¹⁶

because segregation and cracking tend to occur in the base of the mark, and the severity of the problem increases with increasing OM depth d_{OM} .

Mould oscillation is usually characterised in terms of negative t_n and positive strip times t_p . The negative strip time is the portion of the oscillation cycle when the mould is descending faster than the withdrawal rate (i.e. $V_m > V_c$), which is depicted as a gray box in Fig. 12b; the positive strip time is the remainder of the oscillation cycle (i.e. $t_p + t_n = t_{cycle}$). However, mould oscillation can also be characterised in terms of the position of the mould (shown as a dotted red line in Fig. 12b). It can be seen that the mould and slag rim are at their highest position in late positive strip t_p^{late} , the

mould and slag rim are at their lowest position in early positive strip time t_p^{early} and the mould is descending throughout t_n .

It was found that the model predicted regular marks on the steel surface (Fig. 3c). These marks were proved to be OMs when it was shown that the pitch of these marks was identical to the theoretical pitch for OMs ($=V_c/f$, where f is the oscillation frequency). This showed that the model was predicting the formation of OMs.

Two mechanisms have been proposed for the formation of OMs. In the overflow mechanism, the molten steel overflows the steel meniscus leaving a hook or (nail) (Fig. 13a); in some cases there is remelting of the hook (Fig. 13b). In the folded

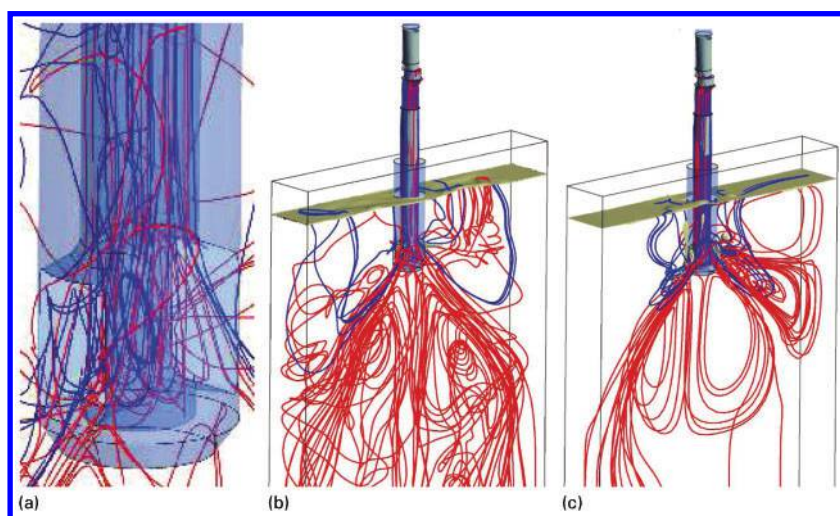
mechanism, the thin shell is bent backward by ferrostatic pressure to form the mark (Fig. 13c).

The mathematical model was used to track the following parameters through the oscillation cycle:

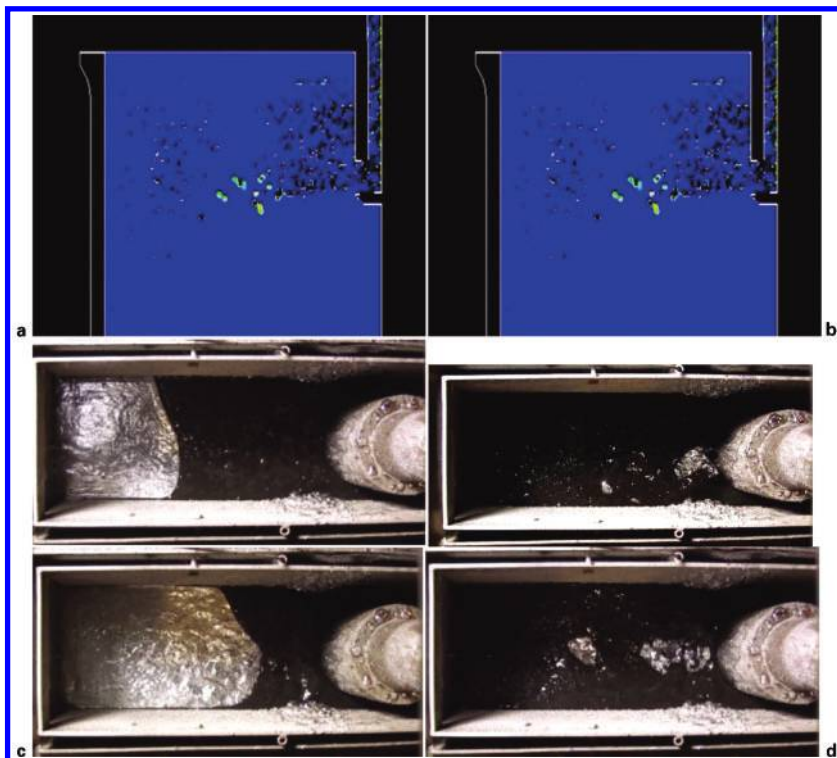
- (i) powder consumption ($Q_s = \rho \cdot d$)
- (ii) horizontal heat flux q (from shell to mould)
- (iii) shell solidification d_{shell}
- (iv) OM formation d_{OM} .

The results shown in Fig. 13b indicate that Q_s , q , d_{shell} and d_{OM} all increase through t_n and are at a maximum in early t_p , i.e. when the mould is at its lowest position.

A video of the movement in the slag phase revealed that the direction of flow changed during the oscillation cycle (Fig. 14a).¹² When the mould was ascending (Fig. 14a(i)) the slag flow is radially outward; this flow will be warm (tropical) since it passes across the steel interface. There is little slag flow into the mould/strand gap. At the beginning of the mould's descent (Fig. 14a(ii)), the flow is still warm and outward, and there is little slag flow into the gap. However, when the mould is halfway through its descent (Fig. 14a(iii)), it can be seen that the slag flow direction is downward, and there is strong flow into the gap. This downward flow is cold because it is coming from a cooler (Arctic) region. This Arctic flow causes both rapid shell growth and increased heat flux, both of which increase rapidly as the mould descends towards its lowest position (in early t_p). Finally, when the mould and rim start to ascend, the slag flow reverts to a warm, outward flow (Fig. 14a(iv)). The



10 Predicted metal flow patterns showing *a* vortex formed in sump of SEN, *b* single roll formed with no FC (=no EMBR) and *c* double roll formed with FC and flow bias toward loose, wide side of mould when using a sliding gate¹⁷



a model predictions showing bubbles and metal flow pattern for Ar flowrate of 4 L min^{-1} (with flow pattern of outward movement followed by vertical and then inward flow along surface); **b** for Ar flow of 5 L min^{-1} (showing upward flow along SEN followed by outward flow along surface); **c** images showing metal (bright section on left) pushing oil (dark phase) towards SEN; **d** image showing bubbles emerging near SEN and being swept along by outward flow (of oil=dark phase) from SEN¹⁸

11 Effect of Ar flowrate on metal flow pattern for casting speed of 1.2 m min^{-1}

slag flow is very confused during tide changes, and there is very little slag infiltration into the gap in these periods.

The following was proposed:¹²

- (i) shell solidification and increased heat flux occurred when the cold (Arctic) downward, convective, flows were initiated when the mould

was descending (during t_n); shell solidification and heat flux both peaked when mould and slag rim were at their lowest position

- (ii) slag infiltration (i.e. lubrication) principally occurred when the slag flow was downward (i.e. when the mould was descending)

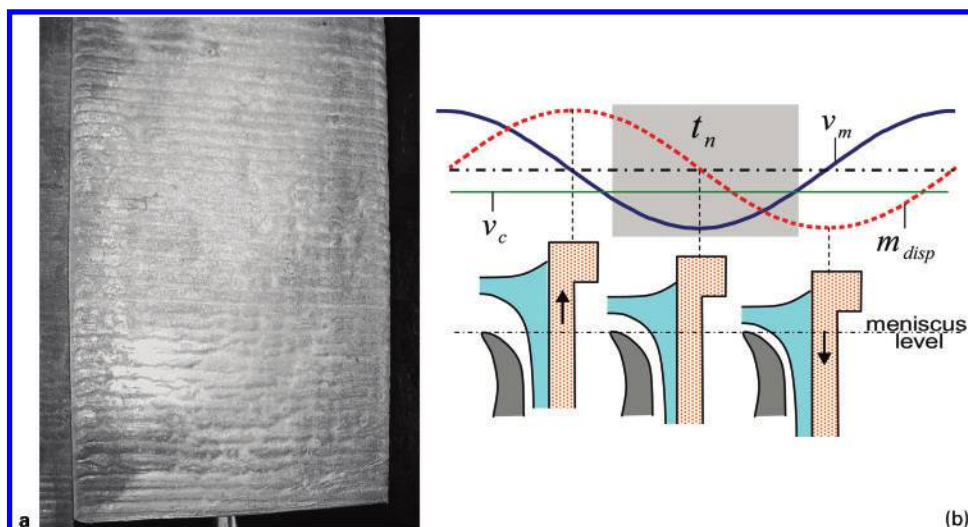
- (iii) oscillation marks were formed by the joint action of a downward slag flow that created a dimple in the liquid metal adjacent to the shell tip (see circle in Fig. 14b) and the rapid freezing of the steel (due to the arctic flow) at low positions of the mould and rim
- (iv) tide changes in the slag flow were followed by periods of confused flow in which little slag infiltrations took place.

Thus, a new mechanism for OM formation was proposed in which OMs were formed from the joint action of the creation of a dimple in the liquid steel adjacent to the shell tip and the sudden freezing that were both caused by the downward slag flow during the mould's descent.

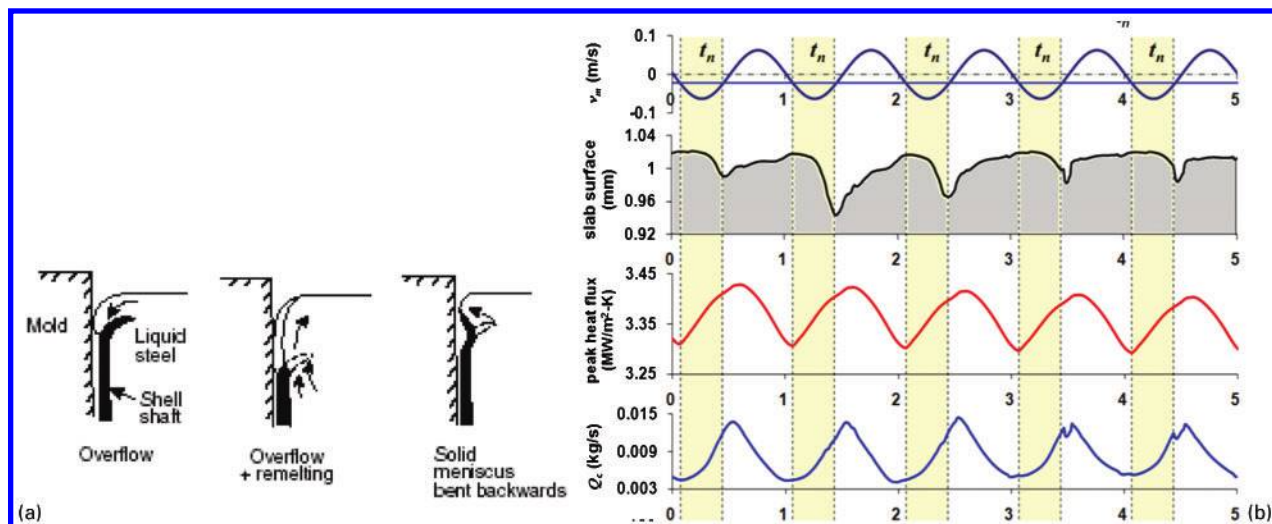
One possible reason for why mathematical models wrongly predict the relation between powder consumption and oscillation frequency f could be related to the points covered in (iv) above. Take the example of $f=1 \text{ Hz}$, and then increase it to 2 Hz . In the case of 1 Hz , there will be two tide changes per second where very little slag infiltration occurs. However, with 2 Hz , there will be four tide changes per second in which little slag infiltration occurs. Thus, there will be less slag infiltration when you increase the frequency. The mathematical models have not taken the effects of tide changes into account.

Discussion

It is obvious from the examples given above that a reliable, validated mathematical model allows us to 'see' into the mould and provides us with a



12 a Image showing OMs on surface of steel slab and **b** schematic drawing showing negative strip time (=grey box) and positive strip time (=remainder of cycle): solid line=mould velocity; dotted line=mould position



13 a Schematic drawing proposed mechanisms of OM formation, from the left, overflow with hook formation, overflow mechanism with remelting of the hook and folding mechanism, respectively **b** model predictions, from top, for mould velocity, OM formation, powder consumption in kg s⁻¹ and heat flux, respectively, over 5 oscillations

way of deducing the mechanisms responsible for defects and process problems.

The examples above also highlight the complex interactions that go on in the mould (literally 'everything counts'). For example, if it was decided to increase the casting speed to counter star cracking; this would result in the following:

- (i) increased heat flux density (resulting in a thinner solid slag film and possibly longitudinal cracking)
- (ii) more turbulence in the metal flow (leading to possibly more slag entrapment)
- (iii) lower powder consumption Q_s , thereby providing less lubrication to the mould
- (iv) lower negative strip time (leading to shallower OMs)

Each of these actions will have repercussions for the process.

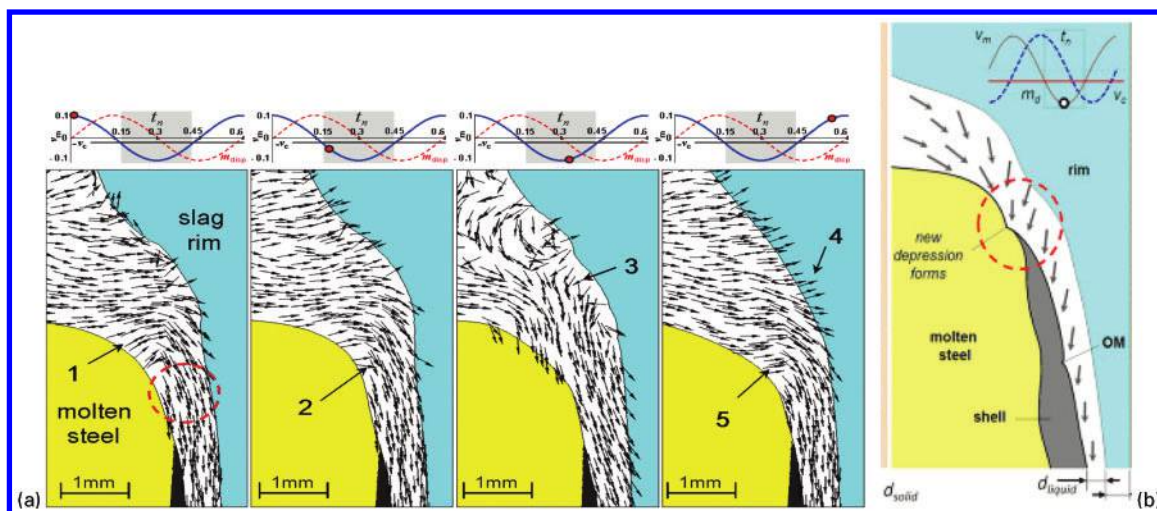
It is exceedingly difficult for the steelmaker to take all these complex interactions into account when he alters a parameter like casting speed or oscillation frequency. Given the complexity of the interactions, it is apparent that steelmakers have proved exceedingly smart in controlling the casting process so effectively. However, it is obvious that in the future the current models will have to be developed to control the continuous casting process since only a model can take all the interactions into account.

Some further model development will be necessary. For instance, at the present time, the strength of the solidified shell is not taken into account, which will be of great importance in

predicting when hot tearing and some types of sticker breakout will occur. At the present time, a thermomechanical model is being developed with a view to incorporating it into the present model.** Furthermore, the first steps are being taken to model the microstructure of the solidified shell to explore how it affects hot tearing.**

It should be pointed out that the current models do not tell you what is happening in the mould at the present time. The models predict the theoretical actions and reactions that can occur in the mould as a result of the casting conditions. The major challenge for the modellers in the future will be in modifying the theoretical models so that

** RFCS-funded project: Direct Defect Toolbox (DDT), for further details contact pavel.ramirez.lopez@mefos.se.



14 a Model predictions of slag flow for different mould positions, from the left, halfway up, at its highest position, halfway down and halfway up, respectively and **b** schematic drawing showing formation of 'dimple' by cold downward flow when mould is near its lowest position¹²

they can represent the actual mould in real time. This will be a major step in developing closer control of the process.

Conclusions

1. In the eyes of a sceptic of mathematical modelling, it is obvious that the models have developed to the stage where literally they allow us to 'see' what is going on in the continuous casting mould.

2. These models give us valuable insights into the mechanisms responsible for various defects and process problems.

3. The interactions occurring in the mould are so complex that it seems inevitable that mathematical models will be used in the future to determine what remedial actions should be undertaken.

4. Some development of the models is still required, such as coupling in a thermomechanical model to the current model in order to take the strength of the shell into account.

5. The major challenge for the future will be how to bridge the gap between a theoretical model of the actions and reactions occurring as a result of the casting conditions and the real time conditions in the actual mould.

Acknowledgements

My Bessemer lecture was a non-modeller's view of the fantastic modelling achievements made possible in continuous casting and based on the work of the following researchers: P.

Ramirez-Lopez (Swerea, Sweden), P. D. Lee (University of Manchester, UK); B. Santillana (Tata Steel, The Netherlands), B. G. Thomas (University of Illinois, USA) and R. Morales (National Polytechnic Institute ESQUIRE, Mexico). I am greatly indebted to their contribution to the lecture and the production of this paper.

References

1. S. Hiraki, K. Nakajima, T. Murakami and T. Kanazawa: Proc. 77th Steel-making Conf. held Chicago, IL 1994, 397–403 publ ISS Warrendale PA.
2. M. Hanao and M. Kawamoto: *ISIJ Int.*, 2008, **48**, 180–185.
3. S. Feldbauer, I. Jimbo, A. Sharan, J. Harman and A. W. Cramb: Proc. 78th Steelmaking Conf., Nashville, TN, USA, April 1995, 655–667. ISS, Warrendale PA.
4. K. Tsutsumi, K. Watanabe, M. Susuki, M. Nakada and T. Shiomi: Proc. 7th Int. Conf. on 'Molten slags, fluxes and salts', Capetown, South Africa, January 2004, SAIMM, 803–807.
5. M. Wolf: *AIME Elect. Furn. Proc.*, 1982, **40**, 335.
6. S. Ogibayashi, T. Mukai, Y. Nagano, K. Yamaguchi, T. Takahashi, K. Koyama and T. Nakano: *Nippon Steel Tech. Rep.*, 1987, **34**, 1–10.
7. R. Saraswat, D. M. Majer, P. D. Lee and K. C. Mills: *ISIJ Int.*, 2007, **47**, 96–104.
8. B. G. Thomas, A. Moitra and R. McDavid: *Ironmaking Steelmaking*, 1996, **23**, (4), 57–70.8. see also L. C. Hibbeler, B. G. Thomas, B. Santillana, A. Hamoen and A. Kamperman: *Metall. Ital.*, 2009, **6**, (2), 1–10.
9. R. Morales, A. Ramos-Banderas, L. Garcia-Demedices, M. Diaz-Cruz: *ISIJ Int.*, 2003, **43**, 653–666.
10. P. E. Ramirez-Lopez, P. D. Lee and K. C. Mills: *ISIJ Int.*, 2010, **50**, (3), 425–434.
11. P. E. Ramirez-Lopez, P. D. Lee, K. C. Mills and B. Santillana: *ISIJ Int.*, 2010, **50**, (12), 1797–1804.
12. P. E. Ramirez-Lopez, K. C. Mills, P. D. Lee and B. Santillana: *Metall. Mater. Trans. B*, 2012, **43B**, (1), 109–122.
13. M. Hanao and M. Kawamoto: *ISIJ Int.*, 2009, **49**, 365–374.
14. W. Emling, T. P. Waugaman, S. P. Feldman and A. W. Cramb: Proc. 77th Steelmaking Conf., Chicago, IL, USA, March 1994, ISS, 371.
15. E. Torres-Alonso, R. D. Morales, S. Hernandez-Garcia and J. Palafox-Ramos: *Metall. Mater. Trans. B*, 2008, **39B**, 840–852.
16. R. Choudhary, B. G. Thomas and S. P. Vanka: *Metall. Mater. Trans. B*, 2012, **43**, (3), 532–553.
17. E van Vliet, D. W. van der Plas, S. P. Carless, A. A. Kamperman and A. E. Westendorp: Proc. 7th Eur. Conf. on 'Continuous casting', Dusseldorf, Germany, June 2011, Session 4.
18. P. Ramirez-Lopez: unpublished results, Mefos, Lulea, Sweden, 2013.
19. K. Pericleous: private communication, University of Greenwich, Greenwich, UK, 2009.