Summary of EU Supported Mould Powder Research

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Introduction

Mould powders are essential to crack free casting and there has been a number of European funded projects dedicated in whole or part to the study of mould powder behaviour.

These projects have aimed at better understanding the role of mould fluxes and how they interact with and steel as it is cast and evolve as a result of that interaction.

The projects have involved a significant amount of trial based study and both physical and numerical modelling

Introduction

European Funded Projects involving Mould Powders

Acronym	Title	Year	Report Number
7210-PR/273	Mould powder consumption, melting and lubrication and their effects on mould heat transfer and subsequent surface quality of continuously cast slab	2005	EUR 21907
FOMTM,	Application of fibre optical thermal monitoring at CC billet mould for improved product quality, Report number,	2007	EUR 28466
FLUXFLOW	Enhanced steel product quality & productivity by improved flux performance in the mould through optimising in the multiphase flow conditions & special regard to melting & entrapment	2008	EUR 23182
PRECIPITATION	Precipitation behaviour of micro-alloyed steels during solidification and cooling,	2010	EUR 24024
SLAGFILMOWL	Optimising slag film properties and determination of operational windows for lubrification, mould heat transfer and shell formation	2011	EUR 24988
LSSEMIQUAL,	Reduction in surface cracking in as cast low sulphur and calcium treated steels, Report number,	2013	EUR 25885
LUBRIMOULD,	Identification of optimal mould lubrification conditions through an innovative hot and cold simulation method, Report number,	2013	EUR 26173
TRANSIENT,	Effect of transients on quality of continuously cast product, Report Number,	2014	EUR 26399
INNOSOLID	Investigation of innovative methods for solidification control of liquid steel in the mould	2019	EUR 29549
NNEWFLUX	Non-Newtonian mould fluxes - a smart viscosity response to enhancing production flexibility of steel grades prone to entrapment	Ongoing	Ongoing
OPTILOCALHT	Optimisation of Local Heat Transfer in the CC Mould for Casting Challenging and Innovative Steel Grades	Ongoing	Ongoing
RealTimeCastSupport	Embedded real-time analysis of continuous casting for machine-supported quality optimisation	Ongoing	Ongoing

7210-PR/273 - Mould powder consumption, melting and lubrication

2005

The aim of this project was to develop an understanding of mould powder consumption, melting and lubrication, and their effects on mould heat transfer and subsequent slab surface quality. This was achieved through a combination of plant measurements, laboratory studies and mathematical modelling.

Mould powder consumption is heavily dependent of section size and consumption reduces as section size increases. For a fixed section the most direct influence on powder consumption is casting speed. A secondary correlation was established with carbon content and more significantly carbon equivalent.

Models for predicting flux consumption were developed by CSM and Corus. The CSM model can be used to specify the melting range and viscosity required in a mould powder. The Corus model determine powder consumption rate.

The consumption rates calculated were used to control a new automated powder feeder with promising results.

7210-PR/273 - Mould powder consumption, melting and lubrication

2005

The effect of oscillation strategy on powder consumption, the slag pool depth and the thickness of the slag film in the mould/strand gap and their consequence for heat transfer, lubrication and slab surface quality was investigated via laboratory simulation at Corus IJTC. Predicted shell thickness was in good agreement with the measured values and the correlation between measured slag layer thickness and the values predicted from powder consumption were greatly improved.

A study was made of published empirical mould powder models. This indicated a strong relationship between mould powder consumption and viscosity.

CSM investigated the relationships between glass/crystalline ratio and thermal diffusivity. These were used in the development of the model of heat flux in the mould. It was found that the thermal diffusivity of the slag film could be predicted from the glass/crystalline ratio provided that the prediction is limited to powders having similar chemistries exposed to similar heat exchange conditions.

FLUXFLOW - Enhanced steel product quality & productivity by improved flux performance in the mould through optimising the multiphase flow conditions & special regard to melting & entrapment.

2008

The main objective was to provide more detailed information on the interrelation between melting conditions of the flux layer and steel flow. What flow conditions are needed in the mould to guarantee a sufficient layer and to avoid flux entrapment.

Extensive trials were performed concerning flux melting and entrapment for flat products. Modelling results were verified and finally optimum conditions were determined.

The thickness of the flux layer depends strongly on the powder used. This can lead to entrapment of powder which has a great impact on the occurrence of defects remaining on the steel surface.

Trials were performed involving parameters important with regard to flux melting and entrapment for long products. Modelling results were verified, and finally optimum conditions were determined.

The powder properties of most concern are the viscosity and the melting rate. The carbon content, on which melting rate depends strongly, plays a significant role.

It was found that the flux layer thickness decreases with increasing immersion depth. Deeper immersion also makes the meniscus more ‘quiet’ and less risky for slag entrapment. At the Sidenor Basauri plant, an increase of the nozzle immersion depth improved billet quality by preventing mould powder entrapment.

2008

Physical and mathematical modelling approaches were developed and applied successfully with regard to simulation of:

- flux melting rate and layer thickness
- 3-dimensional fluid flow in the mould including electromagnetic stirring
- multiphase flow in the mould, evolution and formation of liquid flux layer and entrapped flux droplets

Strong flow fluctuations in the mould caused by fluctuations of casting parameters can result in horizontal flow velocities in the melt. These can exceed a value identified as critical for flux entrapment.

Guidelines for sufficient melting of flux and avoidance/minimisation of flux entrapment were produced

2008

For both flat and long products optimum casting speed and immersion depths were found and mould powder with a low free carbon content should be used. Mould level stability is essential to avoid entrapment due to fluctuations. A high risk of entrapment is given when the of liquid flux layer thickness falls below a critical value.

The effect of SEN geometry on slag entrapment were investigated:

- For flat products changes in SEN geometry due to wear or clogging must be minimised.
- For stainless steel long products a modified SEN geometry with a five ports was identified to reduce entrapment

Overall the investigations showed clearly that unsteady operating conditions are the main cause for flux entrapment. The first heats of a casting sequence are the most prone to slag entrapment. It takes time for the mould powder to reach stable conditions in terms of lubrication. This makes the choice of the powder properties very important.

Precipitation - Precipitation behaviour of microalloyed steels during solidification and cooling

2010

The effect different mould powders have on precipitates and consequential surface quality was investigated using data and samples from the 4 industrial casters; pilot plant and laboratory investigations. This was supported by thermodynamic, numerical and kinetic modelling.

Trials using different mould powders were carried out on a peritectic C Nb and Ti microalloyed steel grades. An optimum combination of basicity and viscosity of the mould powder is essential to change the carbonitrides precipitated at the surface within the mould for an optimum surface quality.

An instrumented mould was used to record the hot face temperature and evaluate the effect of mould powder on horizontal heat transfer under steady state casting conditions. Powder which had a relatively low basicity and high thermal conductivity, provides hard cooling (i.e. high hot face temperature) as compared to high basicity powder was seen to refine the dendrite arm spacing near the surface.

Trials were carried out using mould powders with low and high basicity in combination with low and high viscosity. Using mould powders of high basicity (mould soft cooling) and medium viscosity (1.0 to 1.5 dpas) a high quality of as-cast surface is achieved.

SLAGFILMOWL - Optimising slag film properties and determination of operational windows for lubrication, mould heat transfer and shell formation

2011

The project aimed to improve the surface and sub-surface quality of continuously cast carbon and stainless steel by the development of an understanding of the events and conditions at the meniscus that affect slag infiltration and conditions in the mould strand gap resulting from the properties of the slag film.

Mould top slags and slag films from industrial casters were characterised and correlated with plant operational and surface quality data which was fed into numerical modelling to increasing understanding of the relationship between powder composition and powder behaviour.

Numerical modelling at BFI of early solidification and the effect of deformation and stresses on the shell and slag infiltration into the mould strand gap was in good agreement with physical phenomena and resulting surface quality observed in operational practice. Near corner cracking was reproduced particularly well. Operational windows for lubrication, mould heat transfer and shell growth were developed.

SLAGFILMOWL - Optimising slag film properties and determination of operational windows for lubrication, mould heat transfer and shell formation

2011

Sidenor successfully developed a new higher speed casting practice and optimised the automatic powder feeder based on the powder properties, viscosity and the melting rate whilst maintaining and even improving surface quality

A greater understanding of the formation of crystals in slag films was developed. Two different crystal types were found in the film. Dendritic close to the steel shell and angular close to the mould. The influence of basicity on crystallisation rate was clearly shown and its impact on film thickness which in turn regulates the heat flux - the greater the degree of crystallisation the thicker film thickness.

A mathematical model to predict the formation of solid phases from a given mould powder and mould slag as a function of temperature was produced. The goal was to determine the crystallisation and melting temperatures of the real slag present in the mould strand gap, derived from the original powder after chemical interaction with steel components.

SLAGFILMOWL - Optimising slag film properties and determination of operational windows for lubrication, mould heat transfer and shell formation

2011

The mathematical and thermal models of CSM were successfully integrated in order to describe the distribution of the heat flux and predict local thermal gradient in the steel at the interface with the slag film. The model was shown to be applicable to different casting conditions and mould geometries.

A model of mould flux evolution was created and applied to casting conditions of Sidenor and the comparison with the experimental evaluation of slag film samples showed good agreement between calculated and measured values. The steel metallurgy greatly affects the chemical composition of the slag which can be dramatically changed by minor variations in steel composition.

SLAGFILMOWL - Optimising slag film properties and determination of operational windows for lubrication, mould heat transfer and shell formation

2011

A full linear model describing the relationships between mould friction and operational parameters was obtained from the data, developed by KIMAB. Significant improvements in the deep longitudinal cracking of duplex stainless steels at Avesta were achieved through application of the model.

GMH has implemented the operational windows developed through industrial trials and the numerical simulations of BFI. The improvements were achieved by modifying the viscosity of the mould powder, the casting speed and the mould taper.

Overall this project has made a very significant contribution to improving the surface quality of a range of steels relevant to European steel producers, the development of new casting practices, increasing knowledge and understanding of mould powder properties and behaviour and the development of new and more powerful tools for powder selection.

LUBRIMOULD - Identification of optimal mould lubrication conditions through an innovative hot and cold simulation method

2013

The objective was the enhancement of the as-cast surface quality of carbon and stainless steels by the optimization of mould flux. To do this complete characterisation of the mould powders and related fluxes in terms of physico-chemical and thermal properties was carried out.

For selected steel grades, standard powders were sampled and tested. Mould slag films from industrial trials were also taken and analysed. A comparison was made between the chemical composition of the casting powder before use and those of the slag films collected in the casting machines. This indicated that during use there is a change of flux composition and hence properties. Laboratory measurements of the temperature dependant properties: thermal conductivity, heat capacity and thermal diffusivity of all the powders were also carried out.

The activities of CSM focused on the evaluation of the depolymerisation index (NBO/T) in comparison to the usual basicity index. The NBO/T index was shown to be a parameter for evaluation of the flux behaviour than the commonly used basicity index.

LUBRIMOULD - Identification of optimal mould lubrication conditions through an innovative hot and cold simulation method

2013

Physical models of the gap between strand and mould were used which use silicon oils to simulate the infiltration of liquid slag relative to casting conditions. The TATA model for slabs and the CSM model for billets. The models show high potential for the simulations of current and new conditions. The results show the optimal infiltration conditions are achieved when the channel between strand and mould has a correct taper. The influence of the oscillation parameters has also been evaluated.

This project emphasises the importance of mould taper. Incorrect mould taper has a significant influence on the consumption and effectiveness of mould flux.

The CSM mathematical models calculated the heat flux between mould and shell and thickness of the different layers in the gap. This was applied to assess the evolution of the liquid and solid slag layers along the mould vertical axis. These were transferred to the Thermo-fluid-dynamics model at Kimab which then simulated shell formation in the mould including a description of the heat transport. The model was used for the identification of thickness of the mushy zone, for the definition of the rim and for the estimation of the thickness of the shell at the exit of the mould.

LUBRIMOULD - Identification of optimal mould lubrication conditions through an innovative hot and cold simulation method

2013

During Billet trials the largest temperature fluctuations are seen in the vicinity of the meniscus due to the effect of mould powder addition on the steel level variation, and to the rim morphology changes during casting.

Trials were carried out to study the influence of the casting speed, mould friction between billet and mould and the effect of mould powder addition. Typically, the heat flux increases with the increase of the casting speed.

The friction between mould and billet is the most directly measurable parameter that can be used to describe the billet/mould interaction and the powder lubrication. Sudden changes of the friction signals can be linked with lubrication problems and subsequent product defects.

LUBRIMOULD - Identification of optimal mould lubrication conditions through an innovative hot and cold simulation method

2013

A series of criteria for the characterisation of the physico-chemical properties of the mould powders and related fluxes developed in previous projects have been applied in an integrated approach.

This project demonstrated that a more accurate and technically solid approach can be made easily accessible at industrial level. The project demonstrated that modelling can be used to experiment with new conditions in terms of modification of the casting parameters and powders.

TRANSIENT - Effect of transients on quality of continuously cast products

2014

The transient project studied the causes and effects of transient conditions on surface and internal quality.

The effect of mould heat flux and friction variations on surface quality and breakouts for microalloyed billets was studied. Increased probability of breakout was found when casting certain grades at casting speeds above 1.35m/min using the standard mould powder. A relationship between high mould friction, poor surface quality and breakouts was established.

Plant trials with a lower viscosity mould powder were carried out which demonstrated consistently lower friction at the mould surface at higher casting speeds. Off corner cracking was also reduced. Mould friction measurements became more variable at casting speeds below 1.20m/min and there was a negative effect on surface quality when casting below 1.35 m/min using the improved powder. Plant procedures were changed to use the lower viscosity powder for all microalloyed medium carbon steel grades and maintain casting speeds within the range 1.35 to 1.50 m/min.

TRANSIENT - Effect of transients on quality of continuously cast products

2014

An on-line monitoring system was developed to look at the interactions between mould powder, gas stirring and powder melting at the meniscus during transient conditions. The system used cameras, filters and bespoke software to provide enhanced imagery of the mould surface which clearly shows when the mould powder surface breaks up.

Plant trials on a slab caster showed asymmetric mould powder feeding could cause mould powder break up which was significantly improved using automatic powder feeders and granulated mould powder. Permanent installation of mould powder feeders and use of granulated mould powder resulted in an 8% reduction in mould powder consumption.

INNOSOLID - Investigation of innovative methods for solidification control of liquid steel in the mould

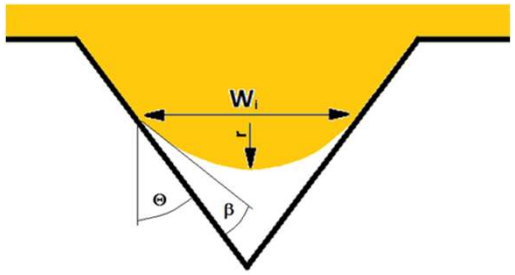
2019

The aim of the project was to improve product quality using innovative concepts for an optimized heat transfer for slab casting. The structured copper plate concept (*SCPC*) had a strong mould powder element.

A surface profile was applied to the mould copper surface. The profile allows the solidified slag layer to thicken locally increasing the thermal resistance in the grooved area.

The optimum surface profile was selected by numerical simulation and physical laboratory trials.

There was a significant influence of the viscosity, i.e. penetration into the grooves was increased with decreasing viscosity.



Trials were carried out on the mould of a pilot caster at Tata Steel. There was a clear improvement of surface quality linked with the mould surface profiling for peritectic grade casts.
It was not possible during the timescale of the project to move to industrial trials.

Summary

- The majority of cracking is initiated in the mould during initial solidification. The performance of mould powders has a significant effect on initial solidification.
- Techniques have been devised to provide data including consumption measurement, slag sampling, thickness of flux layers and retrieval of slag rim samples.
- The composition thus properties of a mould powder and can alter during casting due to composition changes as a result of absorption of inclusions from the mould.
- Best practice for powder feed is consistency of application either by applying the powder ‘little and often’ or using automated continuous feed.
- Mould powder consumption rate increases as the viscosity and break temperature of the flux decreases. The melting rate of a powder must be sufficient to maintain a liquid slag depth of greater than the oscillation stroke length. The melting rate controls the liquid slag depth.
- Flux entrapment occurs when the horizontal velocity of steel at meniscus is high. The first heat of a sequence is more prone to slag entrapment until the flux reaches stable conditions in terms of lubrication.

Summary

New and more powerful tools for powder selection have developed using numerical and computational modelling. Models developed have included:

- Prediction of flux properties from powder composition including crystallisation and melting temperatures
- Evolution of the slag composition due to contact with liquid steel which potentially will lead to a change in flux properties
- Formation of liquid flux layers
- Flux layer thickness
- Flux flow in moulds
- Flux consumption
- Heat transfer through different flux layers
- Liquid fraction in the mould
- Stresses in the solidified shell and crack formation

COMPUTATIONAL AND PHYSICAL MODELLING

Summary of modelling performed over the last 20 Years

Company	Project	Topic	Technique	Success	Comments
CSM	7210-PR/273	Predicting flux consumption.	Calculation based on viscosity and melting temperature	good agreement with measured values	
Corus	7210-PR/273	Predicting flux consumption	Calculation based on thermal and mechanical behaviour of flux and steel	Uncalibrated with plant data	
CSM	FLUXFLOW	Flux layer thickness and the flow conditions in moulds for long products	CFD numerical simulation	Correlated with plant data	
BFI	FLUXFLOW	Formation of liquid flux layer	Physical water model and CFD numerical simulation (FLUENT)	validated operational observations	

COMPUTATIONAL AND PHYSICAL MODELLING

Summary of modelling performed over the last 20 Years

Company	Project	Topic	Technique	Success	Comments
BFI	SLAGFILMOWL	In-mould conditions liquid fraction in the mould and stresses in the solidified shell and crack formation- special steel blooms. 3D	CFD numerical simulation. Finite Volume Method for the fluid-mechanical Finite Element Method for the thermo-mechanical	Good agreement with physical phenomena and to published literature	Could be expanded for other steel grades and casting conditions
CSM	SLAGFILMOWL	Evolution of the slag composition during solidification. Determination of crystallisation and melting temperatures	Thermodynamic calculation and ThermoCalc	Compared to mould powders and slags taken from industrial casters.	
KIMAB	SLAGFILMOWL	Heat transfer through the slag film	2D model, with COMSOL Multiphysics Finite Element Method	Validated by plant trials	Shell thickness model was not completed. Given continued supported by the Swedish government.
CSM	SLAGFILMOWL	Thermal model of heat transfer to calculate the thicknesses of the vitreous, crystalline and liquid layers and the different thermal conductivity values of each single layer of the slag film	Numerical and thermal model	Validated against plant data. Valid for different casting conditions and mould geometries.	

COMPUTATIONAL AND PHYSICAL MODELLING

Summary of modelling performed over the last 20 Years

Company	Project	Topic	Technique	Success	Comments
CSM	LUBRIMOULD	Physical model using scale model of the billet mould including oscillation, silicon oil to simulate liquid flux and moving belt to simulate the moving strand	Physical Simulation	Requires correlation with industrial casters	
TATA	LUBRIMOULD	Physical model using scale model of the slab mould including oscillation, silicon oil to simulate liquid flux and moving belt to simulate the moving strand	Physical Simulation	Requires correlation with industrial casters	
CSM	LUBRIMOULD	Calculating the heat flux between mould and shell and thickness of the different layers in the gap as a function of the thermo/physical properties of steel	Numerical model	Model can assess evolution of the liquid and solid slag layers for comparison to mould thermocouple data	
Kimab	LUBRIMOULD	Taking input from CSM layer thickness model simulation of shell formation and heat transfer. Estimation of the thickness of the shell at the exit of the mould. Visualisation of flow pattern in melt and mould slag	Thermo-fluid-dynamics using with COMSOL Multiphysics		
BFI	LUBRIMOULD	The fluid-flow and the dynamic behaviour at the meniscus formation of meniscus interface perturbations and lack of liquid flux feeding	physical and numerical (FLUENT) modelling	Physical model was used to validate numerical results	

COMPUTATIONAL AND PHYSICAL MODELLING

Summary of modelling performed over the last 20 Years

Company	Project	Topic	Technique	Success	Comments
BFI	FOMTM	Heat transfer model to evaluate different sensor positions with respect to the investigated boundary conditions	numerical	Validated against operational practice	
Tata UK	INNOSOLID	Predict the development and change of the phases formed during solidification of the liquid flux	Factsage		Performed using standard commercially available software
VAS	INNOSOLID	Simulation of heat transfer and infiltration of proposed grooved copper surface profile	Finite element	Infiltration confirmed by laboratory simulation	Project specific

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BFI

Thank you for your attention.

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Research Fund for Coal & Steel