CONTINUOUS CASTING MOULD POWDER EVALUATION

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ABSTRACT

A continuous casting mould powder must satisfy various requirements including thermal insulation, chemical insulation, inclusion absorption, lubrication and promotion of uniform heat transfer from the solidifying steel strand to the continuous casting machine copper mould. The relative importance of these properties varies according to the type of steel cast, the prevailing casting conditions and the end steel requirements.

Development of mould powders in Corus UK Limited involves plant-based trials of different powders whose properties influence the above characteristics of which heat transfer is a major consideration. Particular use is made of mould thermal monitoring which although primarily designed for sticker breakout detection is now finding increasing use as an investigative tool in mould slag assessment. Both static and dynamic data are now available relating mould slag heat transfer performance to casting conditions and this paper describes some recent investigative work carried out by the Aluminium & Steel Casting Department of Teesside Technology Centre, Corus UK Limited. Proving that using a combination of plant based observation and laboratory analysis a greater depth in understanding of mould powder performance can be realised, yielding important information for future powder development.

1. INTRODUCTION

A continuous casting mould powder must satisfy various requirements including thermal insulation, chemical insulation, inclusion absorption, lubrication and promotion of uniform heat transfer from the solidifying steel strand to the continuous casting machine copper mould as detailed in figure 1. The relative importance of these properties varies according to the type of steel cast, the prevailing casting conditions and the end steel requirements.

This paper demonstrates, through the use of three case studies, the relative merits of combining in-mould thermal data monitoring and laboratory based characterisation to develop a methodology of mould powder assessment as carried out by the Aluminium & Steel Casting Department based at Teesside Technology Centre.

2. ASSESSMENT OF MOULD POWDER DURING CASTING

Planned technical support to the several Corus UK Limited business units includes assistance with mould powder development which incorporates plant-based trials of new or improved existing mould powders. These involve maintaining a presence on site during the trial period and retrospective analysis of powder performance using a variety of laboratory and computer based applications.

2.1 PRACTICAL OBSERVATIONS

The standard method for mould powder assessment requires that a prospective powder be trialled against a control, i.e. a powder normally used on that particular caster, under the same casting conditions. To facilitate this both trial and control powders are used on adjoining strands of the same machine and careful checks are made to ensure that, as far a practically possible, both strands are subject to the same operational conditions.

2.2 MOULD THERMAL MONITORING

The on-line prediction of continuously cast product quality is an important factor in the production of prime product for hot charging and direct rolling. Over a number of years Corus UK Limited Teesside Technology Centre has developed a system, utilising thermocouples in mould plates, which can provide information related to mould conditions and the occurrence of surface defects. This Mould Thermal Monitoring system (MTM) allows the real-time assessment of thermal conditions and provides a valuable input for on-line grading, enabling modifications to mould practice to be assessed scientifically. Since high machine utilisation is also essential in continuous casting, the system includes the feature of sticker breakout detection and has the potential for detection of other types of breakout. All UK based Corus UK Limited slab casting machines are equipped with MTM.

2.2.1 Principles of Operation

The water-cooled copper mould lies at the heart of the continuous casting process and regardless of the section size or caster machine design, the mould has a primary influence on surface quality of the as-cast semi-finished product.
It is essential that the casting powder slag layer between the steel shell and copper plate is uniform and stable during casting. This provides lubrication and most importantly forms an interface with high thermal impedance ensuring smooth controlled transfer of heat from the steel shell.

A strong, uniform, shell surface at the mould exit offers potential for a high quality continuously cast product if operating conditions in the rest of the machine are appropriate. A weak, uneven or distorted shell at the mould exit cannot readily be corrected as it travels through the remainder of the machine and is likely to lead to quality defects and breakouts.

Thermal conditions are assessed using thermocouples installed in the mould copper plates just below the meniscus position and around the whole of the mould perimeter. Additional thermocouples are installed lower in the mould to monitor slag film development down the length of the plates and for sticker breakout detection. In addition to prevention of sticker-type breakouts, development of MTM has been based on the following objectives:

- Assess mould conditions in real time.
- Allow casting practice development, e.g. trial casting powders, new grades, with greater confidence.
- Key information provider to on-line grading or quality prediction systems.

The raw data obtained from the system, when interpreted, can yield useful information as to the relative thermal stability of the solidifying steel strand and thus the mould slag's performance can be inferred. Analysis of the relevant data from the trial casts consists of thermal contour maps and thermocouple temperature separation investigation.

2.3 LABORATORY BASED INVESTIGATION

To assess the thermochemical behaviour of mould powder, a combination of simultaneous scanning calorimetry and thermogravimetic testing at high temperatures (termed STA) is used. The equipment at Teesside Technology Centre is a Polymer Laboratories STA 1500H thermal analyser, which heats a powder sample to a maximum of 1500 °C in a controlled atmosphere whilst recording the sample weight and heats of reaction, both exothermic and endothermic. Information available from this type of analysis includes the amount of water present, both moisture and chemically bound (OH^-), reactions of powder constituents, phase changes and crystallinity reactions and percentage weight loss over a melting/solidification cycle. This allows determination of the onset of chemical reactions and phase changes pertinent to the behaviour of the powder during its melting and solidification in the continuous casting mould. Figure 2 shows an idealised trace from an STA test combining thermogravimetic (TG) and differential scanning calorimetry (DSC).

3. CASE STUDIES

3.1 TEESSIDE (MTM)

Several plant trials have been carried out to determine the suitability of a new smaller design of submerged entry nozzle tube changing device (TCD) for use on Teesside slab machines when casting ‘narrow’ section sizes. This case study summarises Teesside Technology Centre personnel’s observations and analysis from one particular trial highlighting the use of MTM data to assess in-mould conditions.

3.1.1 In-Mould Observations

Overall the mould condition was satisfactory. Figure 3 shows acceptable mould level, tundish stopper position and casting speed during a TCD change over. A slight surface ripple was evident travelling towards both end plates, but this was not deemed excessive. Excessive mould powder burn-off was evident midway through the cast near one mould end plate (south) and initially, a suspected air leak on the mould level sensor head situated nearby was thought to be the cause. However, it was later realised that the TCD itself was off centre, approximately 25mm towards south plate and 10mm towards west plate (fixed). Post cast examination of the TCD revealed an immersion depth of 120mm, which was within specified limits, with the mould powder consumption calculated at 0.534 kg/tonne, which was at the lower end of the range historically seen for the particular powder in use at Teesside (0.544 to 0.692 kg/tonne).

3.1.2 Mould Thermal Monitoring Data

Interrogation of mould thermal monitoring data yielded no significant difference in mould level and stopper position variation between the penultimate and final ladles. (Note: Alumina flush evident at 363m cast length old TCD design in figure 3.)

The TCD misalignment noted earlier should be visible in the thermal contour maps as preferential flow towards the south end plate. Figures 4 and 5 detail the fixed and loose broad plate upper thermocouples for the penultimate and final ladles respectively and higher thermocouple temperatures are evident towards the south and fixed plate, confirming the SEN misalignment. Upon examination of the contour maps, there appears no significant difference in performance between the old and new TCD designs. Nevertheless it should be noted that the smaller TCD design does show greater temperature uniformity across the broad plates, even with non-optimal casting conditions such as SEN misalignment.

3.1.4 Conclusions

Examination of the in-mould conditions by both direct observation and retrospective analysis of mould thermal monitoring data of the trials gave encouraging results for the new smaller TCD. This resulted in additional trials and the new design has now entered extended production trials.

3.2 PORT TALBOT (LABORATORY BASED)

This case study summarises the results of simultaneous thermal analysis and chemical analysis carried out on mould powder samples from Port Talbot. A discussion of the results and proposed future investigative work is also given.

In general terms, mould powder slags with increased crystallinity reduce the heat transfer across the mould slag / copper plate interface and this is often intentionally used to "soften" the cooling of crack sensitive grades. To investigate the high temperature properties STA was used to characterise the mould powder.

3.2.1 Simultaneous Thermal Analysis

The standard STA test procedure calls for a representative sample to be taken from the material supplied which is then pulverised to improve sample homogeneity. Table 1 details the summary results for melting and solidification for supplied batches of powder over several STA runs, prepared as above, and as received granular material.

Upon examination of table 1, the melting characteristics remain similar for all STA tests. Unfortunately the same cannot be said of the solidification / crystallisation regimes experienced by each batch of powder. The results for the samples of batch number 1 and 4 are in close agreement. Initial solidification occurs close to 1160°C and a distinct crystallisation peak is evident between 1118°C and 1125°C. This compares unfavourably with results obtained for samples of batch number 4. Here initial solidification starts around 1250°C and a distinct crystallisation peak is evident around 1190°C.

To investigate possible granular material inhomogeneity, a granulated sample of batch 1 was subjected to STA testing. The melting characteristics were similar to previous results. However, the granulated material did not exhibit a distinct solidification peak and the resultant slag residue was indeed a glassy material. Previous experience has shown that pulverised and granulated forms of the same powder exhibit similar melting and solidification characteristics. The difference observed in this instance has implications on powder performance within the mould, as differing solidification regimes would give rise to localised inconsistency of slag rim formation and strand gap infiltration with associated detrimental effects on lubrication and mould heat transfer.

The apparent disparity in STA results suggests that the powder samples of batch 3 have a higher crystallisation potential and therefore mould heat transfer and frictional forces between the mould plate and solidifying steel shell may be affected. Furthermore, the STA results indicated that a potential variation exists in the solidification characteristics between samples of powder and this will give irregular mould heat transfer and lubrication, which could influence surface cracking levels.

With reference to potential surface quality problems, the difference in STA results has implications upon slag rim formation and mould slag performance at the steel meniscus. Increased slag rim formation allied to non-optimum mould level control could give rise to non-metallic inclusions being introduced to the solidifying steel shell at the meniscus area. Viscosity of the mould slag would be the prime consideration here and the STA results suggest that batch 3 would exhibit a higher "break point" (onset of solidification/crystallisation) than say batch 1 or 5. This increase in break point means that the slag will more readily chill against the mould plate giving a potential increase in rim formation for that given powder. Correspondingly, the higher break point would vitiate strand lubrication as infiltration of the slag to the mould strand gap would be compromised for a given mould oscillation practice.

The STA test is used regularly but in this instance an additional test was carried out to determine if the equipment was functioning within desired tolerances. Figure 6 shows the derived curve for samples of the same powder tested at different times and clearly shows acceptable temperature reproducibility for both tests, implying the STA equipment is performing satisfactorily. (Note: Variations in derivative intensities are to be expected due to the age difference in samples)

3.2.2 Chemical Analysis

Summary chemical analysis was been carried out on samples from batches 1 and 3 and the results are compared in table 2.

Whilst the two analysis appear to be generally similar, attention should be drawn to the differences between the two submissions particularly CaO and SiO_2 levels. The CaO and SiO_2 levels are smaller in batch 3 than those in 1 and this has implications on the basicity (CaO/SiO_2) of the powder. Although the calculated value does not vary significantly, the potential difference in mineralogical content could explain the disparity in solidification between the two powders. However, it does not explain the contrast in solidification between pulverised and granulated material. With increased solidification temperatures the resultant mould slag would solidify more readily against the mould copper plate and thus form a comparatively larger slag rim with the potential of surface quality problems as outlined earlier. Other elemental differences do not appear significant. The exception is S, as when combining with Ca it would also alter the basicity of the powder.

3.2.3 Discussion and Proposed Further Work

Examination of the predominant binary and ternary phase diagrams(1) did not suggest a mineralogical composition near a phase boundary which would explain the disparity of solidification experienced with the powder, i.e. slight compositional changes giving rise to significantly different crystallisation potentials. Unfortunately, when considering this type of effect it is usual that the melting characteristics would also vary significantly with mineralogical content and not, as in this case, just the solidification. Discussion with colleagues yielded suggestions on the varying effects of volatile losses from the slag. Evaporation of F and S is known to affect the degree of crystallisation seen in the solidifying slag, but again not to the degree exhibited in these samples. There may be a cumulative effect at work, but without high temperature X-ray diffraction to identify the phases present this is pure speculation.

Confidence in the STA equipment giving reproducible results was high, as reproducibility problems were not previously encountered and calibration checks were passed. Nevertheless, the small sample size used in the actual STA test (~25mg) is a possible source of variation and this has been highlighted by the different results obtained between pulverised and granulated samples. However, this does not answer satisfactorily the question of the difference in crystallisation between batches when solidification reactions are evident. X-ray diffraction analysis of the base powder may yield important information as to the mineralogical composition of the powders and was therefore recommended as additional work.

3.2.4 Conclusions

In conclusion more tests were deemed necessary, since the apparent variation in powder solidification, if a real effect, has implications upon the performance of the powder during actual casting operations. Results from these extended tests fall outside the remit of this case study. However, it should be noted that this study highlights the need for mould powder users to have adequate resources for independent powder testing and in-mould performance determination, enabling constructive debate between end user and suppliers over whether a powder is the optimum solution for a particular application.

3.3 SCUNTHORPE (INTEGRATED APPROACH)

3.3.1 Pulverised versus Granulated Powders:

The lower price of pulverised powders, £250-£350 per ton as opposed to £400-£600 per ton for granulated, is offset by the much greater dust losses. It is this dust loss which leads to the biggest disadvantage of pulverised powders: poor working environment. Pulverised powders do exhibit good thermal insulation and flexibility during adverse mould conditions (assuming they are correctly formulated in terms of carbon content[(2)]) and the existing pulverised powder had served Scunthorpe well over the years in this respect. Granulated powders are superior products in terms of chemical uniformity and cold flowability and also have better insulating ability. A comparison by Diehl[(3)] of the relative merits of different types of mould powder is given in table 3.

Unfortunately, previous work[(4)] states that conventional spherical granules as produced in the past, have not been as forgiving in the mould as powders during turbulent conditions as mould level variations and rolling often occur near the narrow face. Spherical granules tend to flow to lower levels in the mould because of their good flowability which can expose the liquid flux or the steel shell near the narrow face. This can result in sticker alarms and reoxidation effects. By contrast pulverised powders, by virtue of having less flowability, tend to hold their position better when turbulence occurs, resulting in a small reduction in powder thickness, ensuring adequate powder depths are maintained for chemical and thermal insulation of the meniscus area.

3.3.2 Mould Observations During Trials:

In all the trials carried out, the tundish and submerged entry nozzle (SEN) / mould alignment was in general satisfactory prior to the start of cast. However, during one trial the control strand was a little suspect with the SEN being slightly closer to the loose mould plate, which could have promoted non-symmetrical steel flow into the mould. During the casts observed both the control strand and trial strand exhibited good in-mould conditions, that is to say no excessive turbulence with respect to mould level and argon flow was evident. Throughout the trial period, powder was added as per instructions (little and often) maintaining a black practice on both strands, thus ensuring protection against reoxidation effects of the steel. Mould slag samples were taken from the meniscus area and were subject to subsequent simultaneous thermal analysis.

3.3.3 Simultaneous Thermal Analysis

Tests were carried out on the granulated mould slag samples and compared with those of the existing pulverised material to determine cast suitability. Figure 7 details the STA results for both samples with the chemical composition of the powders analysed listed in table 4.

Powders for casting peritectic grades of steel require a high crystallinity in the slag layer between the mould and the solidifying steel strand to reduce the heat flow into the copper plates. This crystallinity is evident as distinct exothermic peaks, attributable to solidification, and the formation of a highly crystalline phase in the solidified slag, in both powders' cooling cycle. The slight difference in melting characteristics evident can be attributed to differences in mineralogical composition between powders and does not effect the weight loss, which was around 30% for both powders. Overall the powders appear comparable and well suited to the proposed application.

3.3.4 MTM Thermal Contour Maps

Figures 8 and 9 show thermal contour maps for the upper row of thermocouples in the broad plates of both trial and control strands for a particular trial cast. They detail the thermal activity across the mould plate and thus qualitative heat transfer can be inferred.

Overall both strands are comparable in terms of uniformity of heat transfer across the broad plates. However, in this example, the trial strand does show hotter thermocouple temperatures just east of the SEN on the loose plate, with confirmation on the fixed plate (not shown). This effect is probably due to the slight misalignment noted in SEN position. Nevertheless, it should be noted this thermal inconsistency could give rise to localised modification of the slag film, for example differing levels of crystallinity due to different cooling rates, resulting in non-uniform heat transfer and potential associated surface quality problems.

It would be expected that uniformity in mould heat transfer be reflected in the temperature separation of upper and lower thermocouples. Unfortunately, direct comparison of the thermocouple temperature separations for control and trial strands is of limited value as the validity of direct comparison is compromised by the inherent differences between strands, varying mould hot face to thermocouple tip distances for example. Nevertheless, applied appropriately, this type of analysis is still useful in providing additional information on the relative mould thermal history during a cast

3.3.5 End Plate Thermocouple Separation Data

End plate MTM thermocouple data provides information relating to in-mould steel flow conditions and is usually used to confirm other observations. Figure 10 details the average thermocouple separations plotted against cast length during the trial cast. In this case both strands exhibit clear separation values, suggesting uniform heat transfer is conferred by both powders' resultant slag films. Note the higher values obtained with the trial strand loose plate are significant as, due to the SEN misalignment, this region would have greater thermal energy and yet the slag film has allowed a proportionally greater heat flow. This suggests that the granulated powder is suitable for a wider range of casting speeds than the pulverised material.

3.3.6 Conclusions

In the trial work referenced, overall the granulated material performed well and was considered to be a suitable alternative/replacement to the existing pulverised material, with the associated environmental and potential productivity benefits.

4. OVERALL CONCLUSIONS

The mould is at the heart of the continuous casting process and a casting powder's high temperature performance has great influence on semi product surface quality. Using a innovative combination of plant based observation and laboratory analysis a greater depth in understanding of mould powder performance can be realised, yielding important information for future powder development.

No information has been given on as-cast semi surface quality in the foregoing descriptions of trials. Slabs for critical grades are currently either proof scarfed or fully surface scarfed but MTM data are being related to surface quality assessment of such slabs. Ideally surface quality data would be included in the mould powder assessment process, unfortunately the reporting timescale often does not allow this. MTM is a key tool in the slab quality grading scheme being implemented on slab casters and although primarily designed for sticker breakout detection, it is now finding increasing use as an investigative tool in mould slag assessment when combined with laboratory STA.

5. REFERENCES

1. VDEh "Slag Atlas - 2nd Edition" ISBN 3-514-00457-9

2. R.Bommaraju, “Optimum Selection and Application of Mould Fluxes for Carbon Steels” 74th Steelmaking Conference, Washington, 1991

3. S. Diehl et al, “Improved Spherical Granular Mould Flux”, 78th Steelmaking Conference, Nashville, 1995

4. R.J Philips et al, “Prevention of Broad Face Sticking”, 73rd Steelmaking Conference ISS, Detroit, MI 1990)

6. FIGURES

Figure 1.- Continuous Casting Mould and Powder Requirements

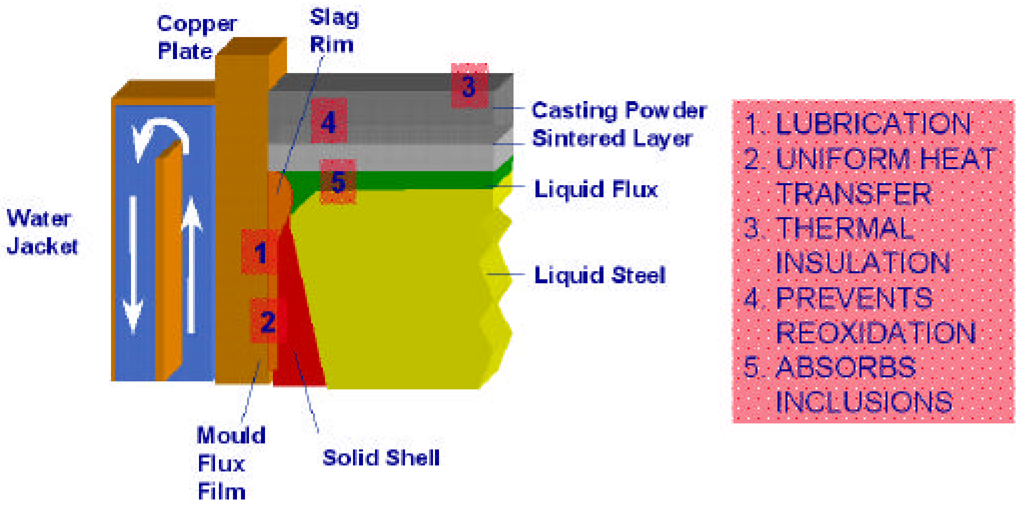


Figure 2. - Idealised STA Results

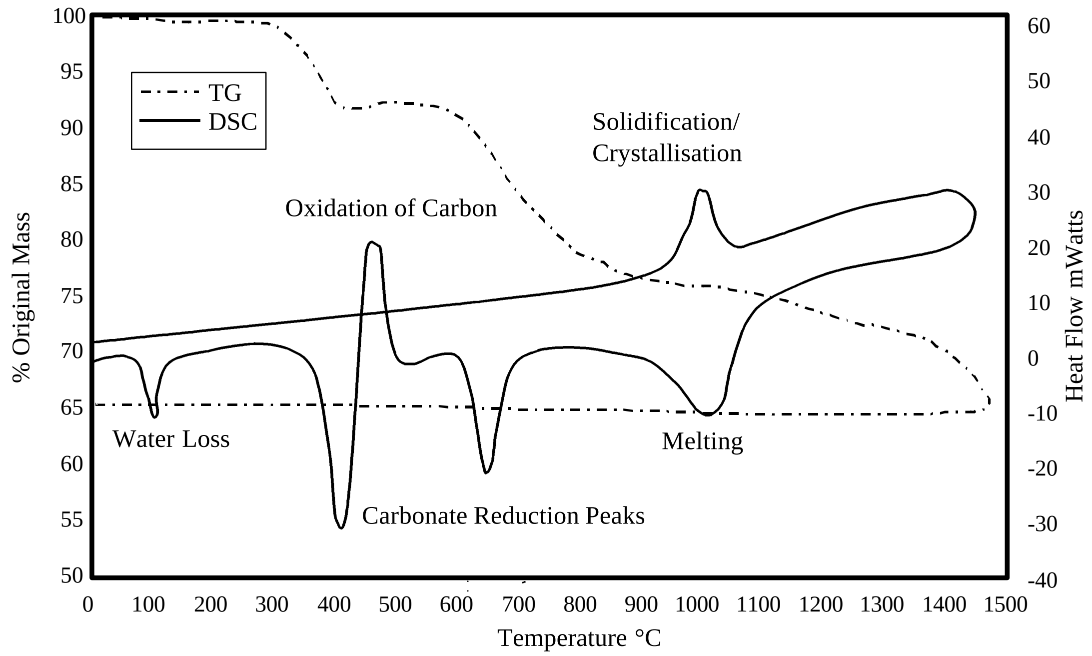


Figure 3. - Casting Parameters

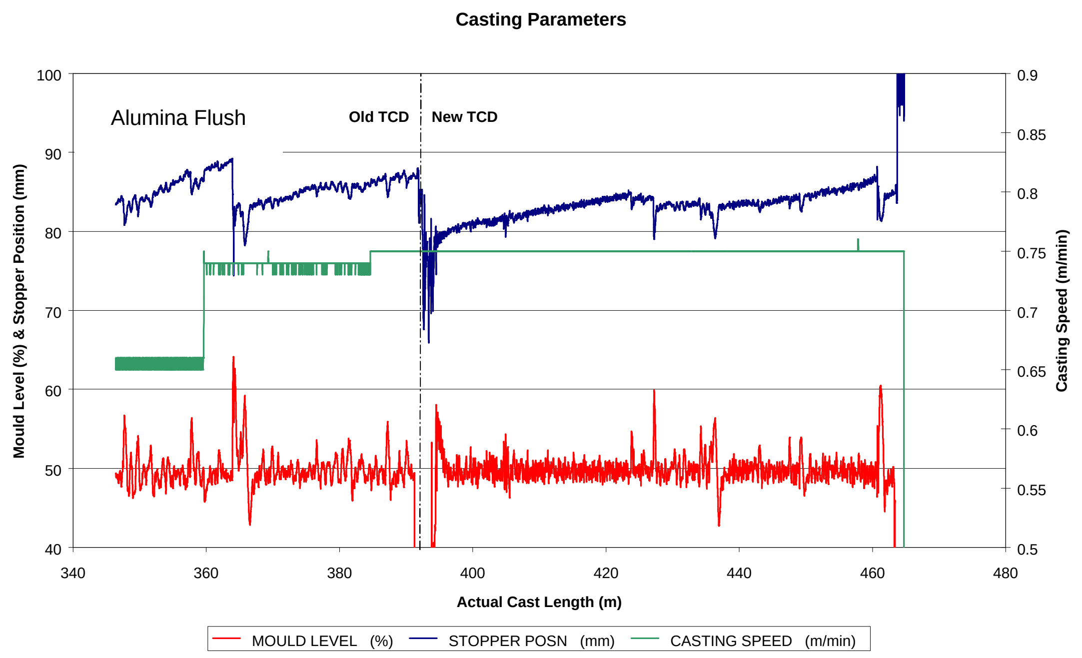


Figure 4. - Thermal Contour Map Fixed Broad Plate Upper Thermocouples

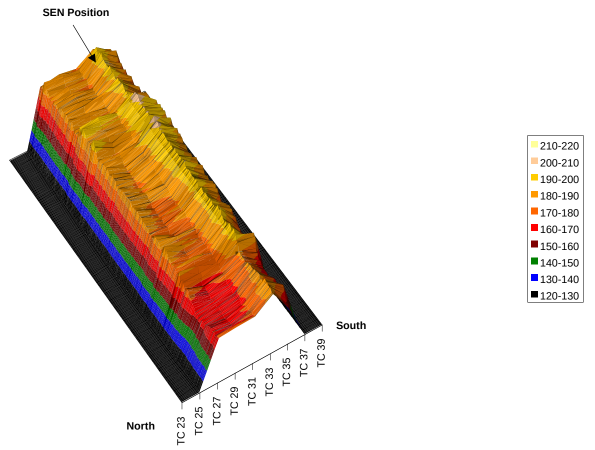


Figure 5. - Thermal Contour Map Loose Broad Plate Upper Thermocouples

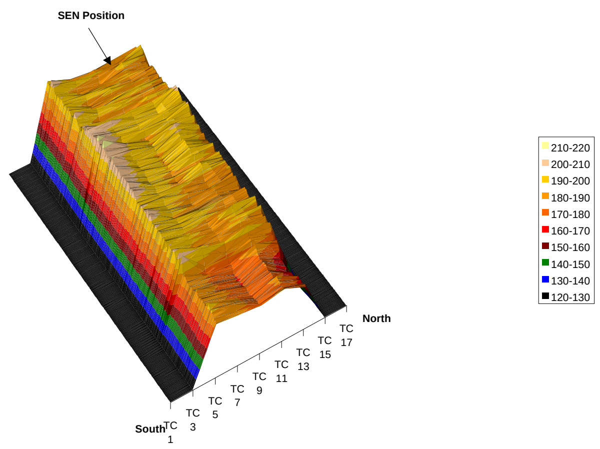


Figure 6. - STA Derived Curves for the Same Powder

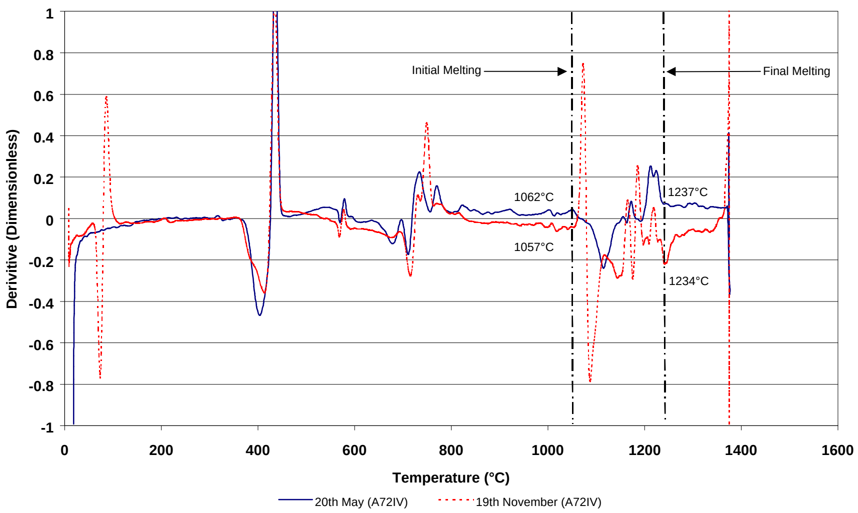


Figure 7. - STA Results for Granulated and Pulverised Powder

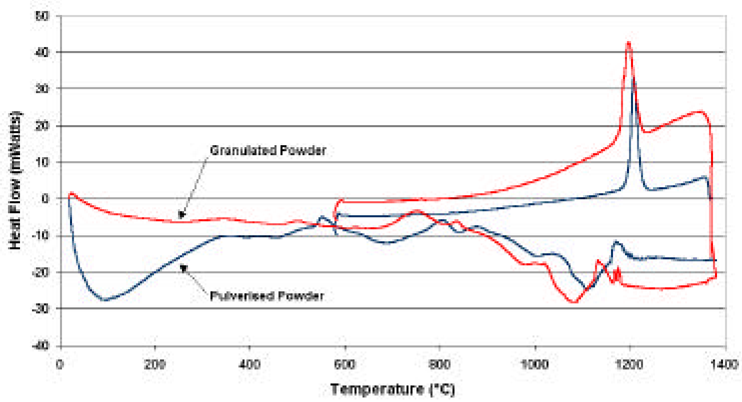


Figure 8. - Thermal Contour Map Loose Broad Plate Upper Thermocouples (Trial)

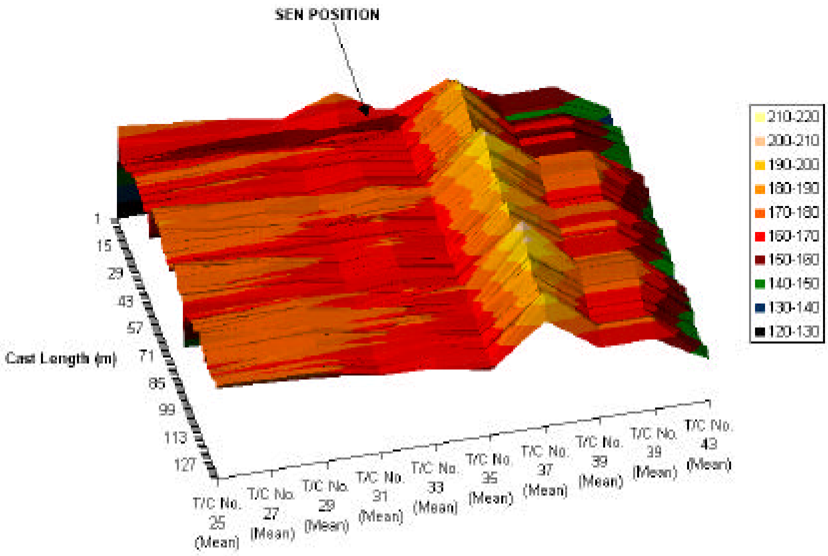


Figure 9. - Thermal Contour Map Loose Broad Plate Upper Thermocouples (Control)

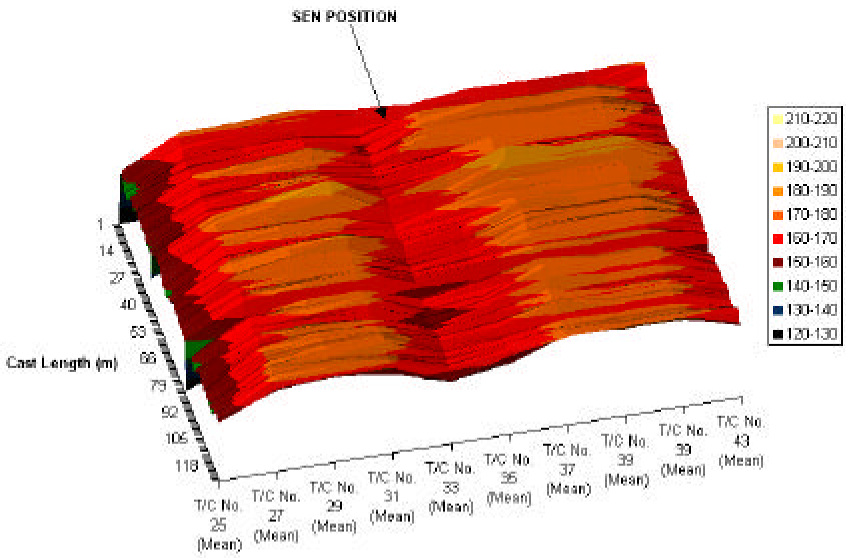
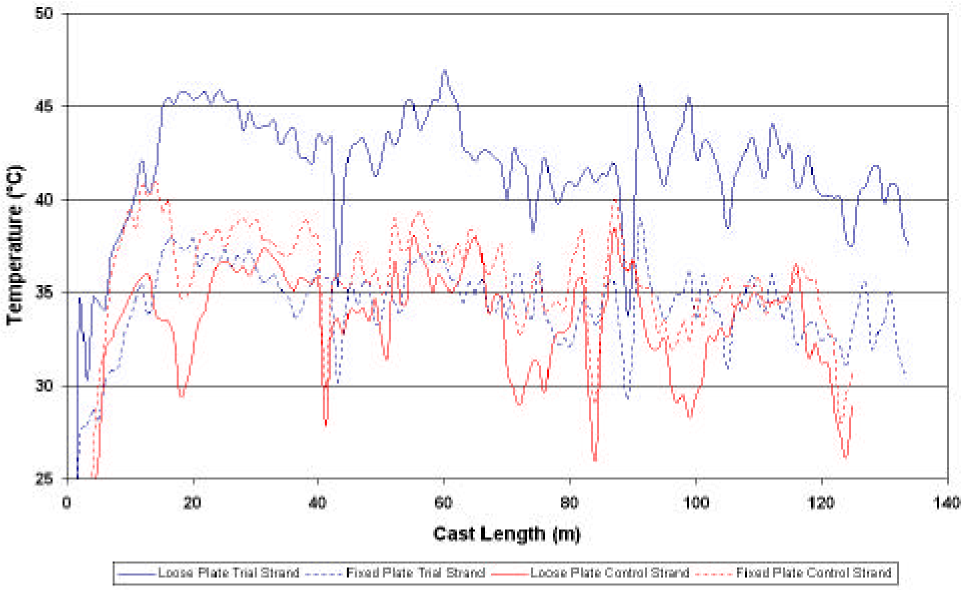


Figure 10. - Average Thermocouple Temperature Separations



7. TABLES

Table 1. - Melting and Solidification Temperatures

Batch Number	Powder Form	Melt Start	Melt Finish	Initial Solidification	Initial Solidification Peak	Secondary Solidification	Secondary Solidification Peak
1	Pulverised	1137	1290	1160	1118	1216*	1160*
2	Pulverised	1135	1300	1253	1203	1170	1135
1	Granular	1121	1306	No Solidification peak evident			
3	Pulverised	1116	1307	1247	1185	1130	1110
4	Pulverised	1143	1294	1151	1125	1213*	1157*
5	Pulverised	1147	1290	1190	1158	1131	1108
6	Granular	1126	1269	No Solidification peak evident			

* Denotes slag information

Table 2. - Chemical Analysis for Submitted Mould Powders

Batch No.	1	3	Absolute Difference
Fe (Total)	0.62	0.93	0.31
CaO	38.75	38	0.75
SiO_2	39.57	38.24	1.33
C/S	0.98	0.99	0.01
MgO	5.05	5.66	0.61
Al_2O_3	4.6	4.72	0.12
P	0.72	0.873	0.153
P_2O_5	1.66	2	0.34
Mn	0.09	0.07	0.02
MnO	0.11	0.09	0.02
S	0.19	0.392	0.202
SO_3	0.48	0.979	0.499
K_2O	0.44	0.65	0.21
V_2O_5	0.01	0.009	0.001
TiO_2	0.12	0.185	0.065
BaO	0.01	0.052	0.042
ZnO	0.01	0.003	0.007
PbO	0.03	0.021	0.009
Na_2O	2.06	2.293	0.233
Cr_2O_3	0.01	0.009	0.001
C	1.15	1.15	0
F	3.55	3.67	0.12
LOI	3.16	3.19	0.03

Table 3. - Comparison of the Merits of the Different Types of Mould Fluxes[2]

ITEM	POWDER	EXTRUDED GRANULE	SPHERICAL GRANULE
PRICE	Good	Fair	Fair
THERMAL INSULATION	Good	Poor	Fair
COLD FLOWABILITY	Poor	Fair	Good
MOULD FLEXIBILITY	Good	Fair	Fair
CHEMICAL CONTROL	Fair	Good to Fair	Good
ENVIRONMENTAL	Poor	Good	Good

Table 4. - Chemical Analysis of Mould Powder Tested

Powder Type	Fe (Total)	Fe_2O_3	CaO	SiO_2	MgO	Al_2O_3	P	P_2O_5	Mn	MnO
Pulverised	5.64	8.06	37.47	35.41	0.51	8.91	0.006	0.014	1.539	1.987
Pulverised	0.43	0.61	40.4	37.21	0.56	10.48	0	0	1.842	2.378
Granulated	0.58	0.83	40.03	36.14	0.74	7.42	0.006	0.014	3.143	4.058
Granulated	0.39	0.56	40.29	36	0.8	6.7	0.008	0.018	3.371	4.353
Granulated	1.02	1.46	38.4	35.58	0.84	6.03	0.015	0.034	3.285	4.242
Granulated	0.94	1.35	39.26	35.21	0.83	6.02	0.021	0.048	3.232	4.173
Granulated	0.96	1.38	39.48	35.16	0.88	6.64	0.011	0.025	3.375	4.358
Granulated	1.05	1.5	39.06	35.75	0.83	6.42	0.02	0.046	3.062	3.954
Powder Type	**S**	**K_2O**	**V_2O_5**	**TiO_2**	**Na_2O**	**Cr_2O_3**	**ZrO_2**	**LOIa**	**C**	**F**
Pulverised	0	0.1	0.003	0.669	4.47	0.01	0.1	0.14	1.4	5.24
Pulverised	0	0.105	0	0.862	4.82	0.009	0.1	0.27	0.16	5.34
Granulated	0.003	0.13	0.005	0.679	4.06	0.011	3	0.04	0.1	5.7
Granulated	0.005	0.164	0.006	0.62	3.93	0.015	3.8	0.03	0.075	5.93
Granulated	0.026	0.136	0.005	0.512	3.72	0.013	3.8	0.93	0.73	5.83
Granulated	0.038	0.15	0.008	0.503	4.39	0.017	4	1.71	1.7	5.97
Granulated	0.028	0.14	0.004	0.59	3.71	0.013	3.9	-0.16	0.16	5.9
Granulated	0.036	0.146	0.007	0.528	3.83	0.016	4	1.45	1.55	5.88