Dynamic superheat determination in a continuous casting machine - process, practice and benefits

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There is an increasing need to accurately control the parameters associated with casting liquid steel in a continuous casting machine. One of the main parameters is superheat, which is defined as the elevated temperature of the liquid steel above its liquidus. Liquidus is defined as being the first point of freezing. Accurate measurement of this elevated temperature is required to reliably control the casting speed of the machine. and in order to reflect the conditions in the Continuous Casting mould, which is where the liquid steel actually freezes at the start of the solid product forming process. A sensor mounted close to this and continuously monitoring the temperature is the superior solution. In order to complete the superheat picture, an accurate assessment of the liquidus must be provided in conjunction with continuous temperature. The uncertainty in the liquid steel temperature and the uncertainty in the liquidus calculation has led to a situation where liquid steel is sent to be cast with excessive superheat with a resultant over use of energy and materials. Heraeus Electro-Nite (HEN) have developed CasTemp Superheat package as a means for enhancing the visualisation of dynamic Superheat during casting, and ultimately helping to improve the control of casting through optimal use of the features included in the package. An overview and early adoption of the system is given highlighting the potential benefits for controlling superheat thereby reducing energy requirements and improving the associated process control parameters.

KEYWORDS: SUPERHEAT, LIQUIDUS, PRODUCTIVITY, ENERGY SAVING, PRODUCT QUALITY, OPTIMISATION, PROCESS CONTROL;

INTRODUCTION

There are significant pressures on steel makers and casters to ensure that their plants are operating to achieve several objectives. Amongst many factors these are some of the key: safety, productivity, low cost, environmentally friendly – low emissions, high yield, excellent product quality, minimal scrap. Once the steel has been processed through primary and secondary refining then the casting machine must ensure that the steel is cast with all aforementioned factors in mind and accurately control the parameters associated with casting liquid steel in a continuous casting machine. One of the main parameters is superheat, which is defined as the elevated temperature of the liquid steel above its liquidus. Liquidus is defined as being the first point of freezing and solidus as the last point. These points and the freezing range are defined by the steel chemistry with the carbon content being the most significant factor.

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Accurate measurement of this elevated temperature can be achieved by several methods. In order to reflect the conditions in the Continuous Casting mould, which is where the liquid steel actually freezes at the start of the solid product forming process, a sensor mounted close to this and continuously monitoring the temperature is the superior solution. In order to complete the picture, an accurate assessment of the liquidus must be provided in conjunction with Continuous temperature measurement to provide a reliable, accurate and dynamic superheat[1].

As a result of some investigations into how much effort was put into regular understanding of superheat by different steel makers, it became apparent that it is not an area of regular examination. Indeed, several plants used do not review their liquidus practice and the basis of understanding was often not evident. Many plants are using methodologies for calculating liquidus based on equations and formulae derived in the middle of the 20th century, perhaps with some empirical adjustment over the intervening decades. The current situation is that there appears to be no common standard and variation in the liquidus calculation has led to significant process issues, particularly when plants are making high carbon and / or more highly alloyed steels. The future steel grade markets are continually evolving, and, as an example, electrical steels are becoming more in demand to service the electric car market. These are high in silicon (~3%) and outside the usual product range for a standard carbon steel producer.

In terms of practical solutions, it seems therefore that a system that delivers superheat rather than relying an ever-changing model (for calculating liquidus) would be of significant benefit to steel makers and casters. Delivery of improvements to process control via productivity, energy savings (and emission reductions), and product quality can simultaneously be achieved. The traditional method of calculating the liquidus is through an analysis of a chemical sample and by use of a mathematical formula, equation or model that has limitations due to accuracy of analysis, validity of method model and timeliness. A new CasTip sensor has been developed to precisely measure the liquidus in the CC tundish which is instantaneous and accurate to +/- 0.5oC. The system includes integration of the CasTip direct reading liquidus sensor to measure tundish liquidus and hence offer a current dynamic superheat and a forward prediction towards end of cast. The system is available through software control and integration of inputted plant data. There is an excellent correlation between CasTip and liquidus calculated from equivalent reference samples across a range of carbon and some low alloy steels. Ultimately, there should be one liquidus value for a given heat of steel, and HEN believe that the CasTemp Superheat system (1) focusses closer to this value than previous approaches, particularly in higher carbon steels. This allows for a dynamic superheat to be available which gives the operator the potential to optimise the casting process control.

BACKGROUND

Why is Superheat necessary?[2]

In ideal conditions, steel would be cast with the minimum amount of superheat for that grade to achieve low energy cost, best product quality and productivity recognising the superheat is a balance between metallurgy and productivity within the machine design constraints. In ideal circumstances maximum casting speed would be maintained at all times, which would mean minimum steel residence time during casting if the superheat is correctly positioned to allow for safe draining of the ladle and continuance of the sequence. However, there is uncertainty of the measurements in a traditional setting and there is the constant operational battle to keep plant and equipment online and available to produce steel to meet the casting times. These uncertainties refer not only to temperature measurement but also to weighing of ladle and tundish contents and accounting for unknown variables such as slag. A small deviation from the expected can lead to ladles emptying earlier than expected or overrunning and this can cause major disruption back through secondary refining and onto to the primary refining furnace.

In fact, the caster design is usually predicated on optimum product quality at maximum casting speed so that full benefits of product quality and productivity are achieved simultaneously. The imperative should therefore be to cast at maximum speed for that grade. However, because a ladle's previous thermal history cannot always be accounted for, then there is an empirical adjustment based usually on a discretionary subjective analysis of this thermal load which accounts for a part of the uncertainty.

How does superheat influence the casting parameters?
Good metallurgical knowledge – theoretical and practical to ensure that robust casting techniques are applied at minimal cost and a desire to utilise the machine effectively. Low superheat is a desirable aim to cast steel because of the inherent better as cast product quality derived from equiaxed zones in the as cast product. There are the practical constraints of ensuring the maximise yield from each heat and specifically ensuring enough superheat to allow a controlled changeover to the next heat without jeopardising the sequence continuity. In fact, the observations seen in a majority of steel plants is that steel is presented to the caster with excessive superheat. Generally, this amount of superheat is far in excess of a sensible and controlled quantity for a known and predictable period of casting:

Variability in the reliability of steel assets over many years has led many steel makers and management to regard the continuation of a sequence and the buffer of excess superheat in case of local difficulties to override the sum of constraints identified such as energy cost, productivity and indeed a potential impact on product quality. The desire for liquid tonnes can seem to be the only imperative that matters and as long as the caster is casting there is a knowledge that production is occurring. Indeed, metal in mould is often a key benchmark. Efficiency, cost management and quality are often deemed lower priorities leading to sub optimal use of the machine and potentially producing steel with lower than expected quality at slower rates. Excess superheat; uncertainly in measurement and lack of consistency and standardisation lead to sub-optimal performance. Most of the casting is generally broken down into a simple relationship between superheat and casting speed. The higher the former, the slower the latter. The principle is robust to ensure that the strand product emerges from the mould with enough shell thickness to retain the liquid and solidifying core. As the mould and machine can extract only a finite amount of heat at any speed then excessive heat has to be removed by exposing the strand to a lengthier cooling period.
The liquidus temperature is grade dependent, varying in commercial carbon steels from about 1450°C to 1530°C dependent upon steel chemistry. It is normally modelled via linear formula from the steel chemistry, each plant favouring its own derivation of formula. Superheat will vary in the range (+00C) to +700C. Low superheat indicates an increased risk of freezing, and high superheat indicates an increased risk of breakout. There are several areas of improvement for the casting operator to address through improved control of superheat. These include productivity, product quality, energy reduction, operational control.

Productivity
The casting machine should be run at the designed maximum speed for the relevant grade in order to generate tonnes and minimise casting time and if not, then why not? There is always a scheduling constraint between primary and secondary refining, where heats are batch processed in fixed quantities (dependent on ladle size) and continuous casting. The latter is unconstrained by heat size but has its own constraints in terms of design: throughput / casting speed being chemistry grade related and the metallurgical length will define what is the practical casting speed (particularly in a slab caster) and the dimensional requirements of the customer output. Logistical constraints can also impact but in principle the caster should be driven at the maximum possible for the grade to maximise productivity but also benefit from the

design characteristics of the machine in terms of product quality. As an example of a small increase in casting speed, by casting at 1.05 m/min rather than 1.0m/min, this 5% uplift in speed could generate 50,000 tonnes of output per annum (in a million tonnes output caster). Another way to view this is to consider a 5% speed increase would reduce the casting time and empty the same ladle weight in 95.2% of the original time. For a 120tonne ladle casting in one hour (at 2t/min) this would take 57 minutes (at 2.1t/min) generating a 3 minutes saving. For a 20-ladle sequence approximately one hour is saved, enabling one additional cast to be made in the same overall time period. This improves output, refractory utilisation, yield and product quality. A further reduction in superheat is then available to be taken advantage of as the casting time is reduced as the ladle does not take so long to be emptied.

As this is a critical area of control it is often considered just another piece of data and Fig.1 – Casting Parameters, shows how variation in liquid steel temperature can be displayed on a typical steel plant amongst other casting parameters. This type of display, although full of useful information, masks the critical temperature infections that occur and does not aid the operator in making important and timely decisions.

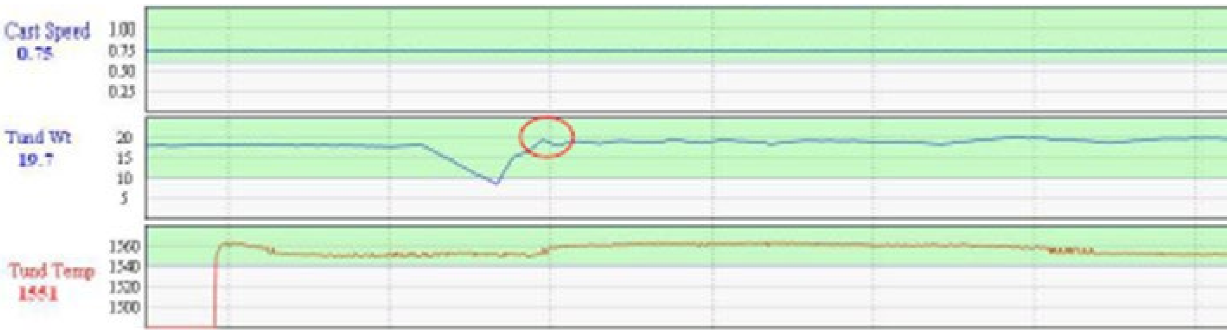

Fig.1 - Casting Parameters.

Product quality

As product quality is related to superheat, a lot of effort has gone into caster machine design to ameliorate the impact of superheat control to some extent. Soft reduction has allowed casters to significantly improve internal segregation and Electromagnetic stirring (EMS) can have a similar effect. However, to address the superheat control where action can be taken is a considered way forward. Product quality is linked to caster design and casting speed. Segregation is more likely to occur in steel casting with higher superheat. This is a result of the formation of a smaller area of equiaxed zone and a larger dendritic area potentially leading to intercolumnar quality issues. Although EMS has mitigated these effects to some extents, not all casting machines are fitted with this technology which is capital and operationally expensive to install and maintain and the effects are more beneficial at lower superheat. As the sump is determined by metallurgical length then the designed location is positioned when stable casting at maximum speed occurs.

Energy

Energy costs are a significant part of the steelmakers' cost base. The actual makeup of the energy will vary from site to site and the cost will indeed vary according to the season, day and time. However, the fundamental factor of raising the one tonne of liquid steel by 1 degree is not insignificant. A simplified calculation attempts to outline the main cost factors (see Figure 2 Cost factors in Steel Plant Energy).

Fig.2 - Cost factors in Steel Plant Energy.

Emissions are directly related to energy consumption and as current technologies are carbon based, a reduction in energy consumption will lead to a reduction in emissions.

Operational Control

Modern caster control requires sophisticated knowledge of the casting process. To maximise casting speed to design levels then a good understanding of the process and the metallurgy is required. Of course, there may be significant factors that constrain the caster: metal supply (timeliness), previous practice influencing how the change process is implemented along with other regulations and ways of working. However, by avoiding plant critical events, such as breakouts and freeze offs, improvement is possible[3].

METHODOLOGY

What is the CasTemp Superheat system?

There are 3 main components to achieve an accurate reliable and dynamic superheat:

- CasTemp – a sensor to reliably and accurately measure the liquid steel temperature
- CasTip - to reliably and accurately measure the liquidus of that heat of steel
- Delivery platform – to marshal the information via an easy to use, digital and accurate instrument system for operator control

This equipment is shown in Fig.3 – Equipment for CasTemp Superheat

Fig.3 - Equipment for CasTemp Superheat.

The traditional model for relying on a potentially outdated model in order to calculate the liquidus and to measure the liquid steel temperature with a single isolated dip is not sufficient to ensure that the modern-day caster can perform to its optimum capability. The dip measurement is replaced by continuous temperature measurement and a sensor mounted close to the tundish outlet provides real time and accurate information to the operator, see Fig.4 – Cross section of Tundish showing temperature profile. This sensor can measure from before the start of preheating until the end of casting without any further interaction from the casting operator crew which significantly improves the safety of continuous caster area by removing the need for personnel to take dips and for dipping equipment to be readily available nearby to the tundish, causing a hazard in itself, see Figure 5 to show the close proximity of the installed sensor to the tundish outlet.

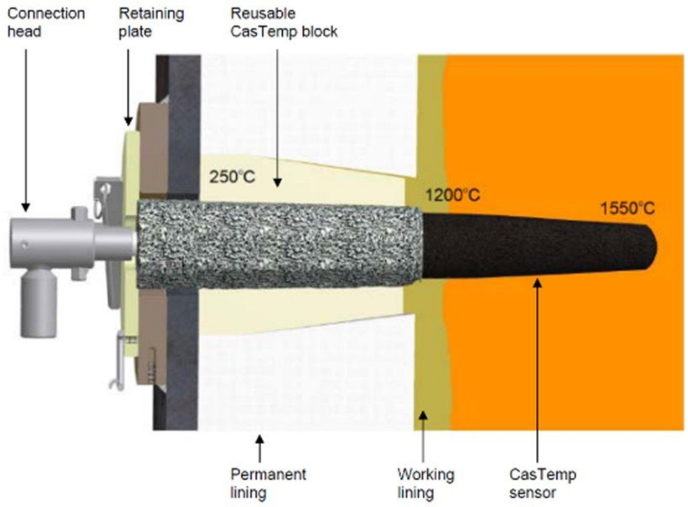

Fig.4 - Cross section of Tundish showing temperature profile.

Fig.5 - CasTemp Sensor Installed in a Tundish.

It is clear from the installation that the thermocouple is measuring the liquid steel temperature without any undue influence from other refractory bodies within the tundish as a minimum clearance is calculated. Once the safe, reliable and accurate CasTemp continuous temperature measurement system is installed and measuring then the liquidus is taken via the CasTip sensor. This liquidus measurement is necessary every heat as there can be a change from heat to heat and sometimes a difference can be noted. This can be due to a variety of factors in the steel making process from incorrect alloy additions to insufficient mixing or some problem with the alloying system. It is therefore more likely that higher alloyed steels are more likely to differ in liquidus values on a heat by heat basis. Once the CasTip is taken it will be displayed on the instrument screen alongside the ongoing CasTemp measurement and be readily observable for the remainder of that heat and into the start of the next heat as the inter heat mixing is completed, usually around 10 minutes. In addition, once a CasTip is taken, a customer defined and configurable, critical action limit, is displayed. The time that this will be reached as well as a predicted end of heat superheat value will also be advised if the algorithm for the prediction is activated. To achieve all this, the system must communicate bi-directionally with the plant level 2 via an established network link and display effectively to the operator via
Fig.6 – CasTemp Superheat Operator Display.

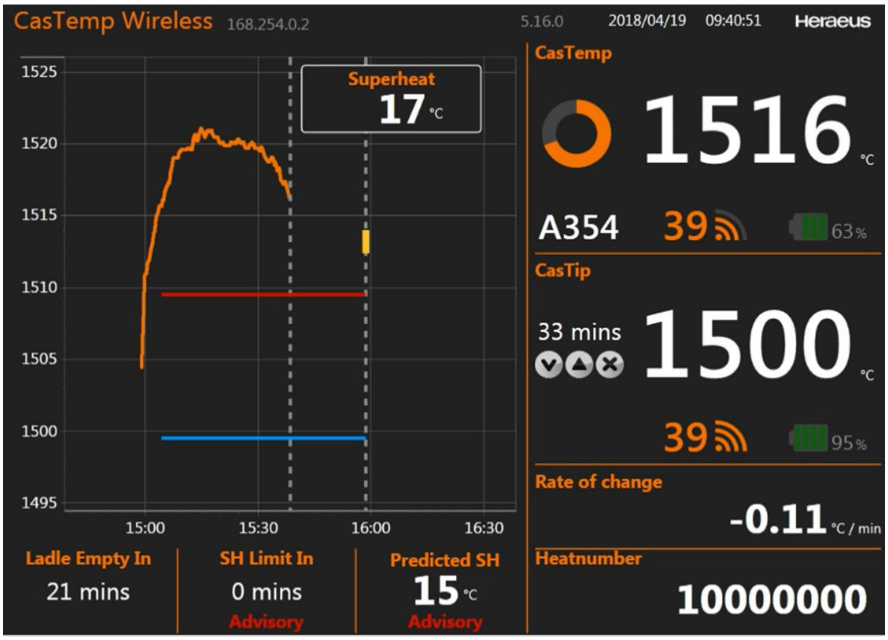

Fig.5 - CasTemp Superheat Operator Display.

The following features are available to the operator

- Liquidus evaluation via CasTip measurement
- Dynamic Superheat determination
- Rate of change determination
- Visual trending
- Visual forward prediction of superheat to end of cast
- Critical limits indication
- Displays available in the control room and on the casting floor

This then gives the operator at the caster (and elsewhere in the steel shop) to be given guidance as to the likely course of the Superheat during the casting of the heat. As the process is dynamic then any changes in parameters, such as the casting speed, are reflected through to the prediction and new advice can acted upon.

RESULTS

In the initial phase of trial work the customer needs to have the system proven. This is understandable, the CasTemp continuous temperature measurement system is a new way of working and is often felt to be counter intuitive to best practice. However, the system is proven to operate extremely well and improves the overall safety of the caster operations by removing the need for manual temperature operations every 10 to 20 minutes throughout the casting periods of many hours and every day.

Once CasTemp is proven the customer will then refer to their traditional practices and try to draw comparisons even though the measurement systems are in completely different zones of the tundish. As CasTemp measures as close as possible to the exit of the tundish then it is a very close approximation to the steel temperature within the mould. The mould is where solidification begins and the constraints within the mould such as consistent flow patterns and zones of temperature variation do not make this a sensible position for temperature measurement. The liquid steel flow through the tundish and the introduction of furniture can significantly affect what temperature is actually measured because of the residence time in the tundish of the steel can be affected. Fast flow and the absence of flow control can lead to short circuiting of hot steel straight into the mould.

The next phase of trial work is for the CasTemp superheat to be evaluated by the customer. Again, the first comparison will be to consider any existing liquidus calculation and do a direct comparison with the CasTip measurement. In general, for most low carbon, lightly alloyed steels this gives good agreement, usually with 2-4 degrees C. However, for some steels there is a significant difference. E.g. electrical and high carbon steels. This is fundamentally because the liquidus models are outdated and require significant effort to be maintained with the developing steel grades. However, the most important consideration is not the absolute value of the liquidus as determined by CasTip but the Superheat, which is difference between the CasTemp and CasTip.

Fig.7 – Historical data Trends shows the detail of the first few heats of a sequence when considered historically. It is clear that there is considerable amount of superheat and some scope for reduction, which then makes the need for end of casting prediction far more relevant, see Fig.8 – Superheat.

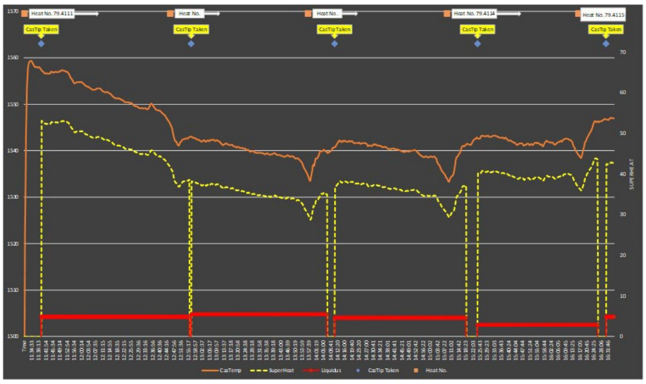

Fig.7 - Historical data Trends.

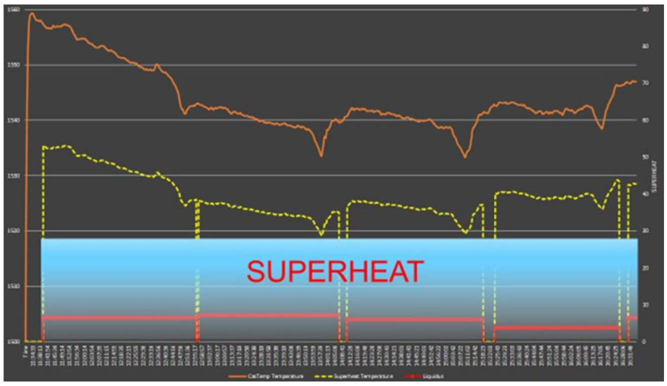

Fig.8 - Superheat.

Fig.9 – CasTip difference from evaluated liquidus, shows how by measuring the superheat and understanding how an incorrect calculation from traditional techniques, particularly on highly alloyed steels (in this case carbon) leads to an excess of superheat during the critical start up period of the first ladle and in this case resulted in a strand breakout on the billet caster.

In many cases Superheat can be seen to be in the range 30 to 50 degrees, with many examples exceeding this. The requirement to then reduce the Superheat can be a lengthy management process and despite identifying key factors as identified earlier, such as productivity, energy saving and difficulties with casting some grade, e.g. high carbon, customers seem reluctant to make changes to practice on a small scale to identify routes to improvement. There is a preference to remain with existing practice despite knowing it could be improved.

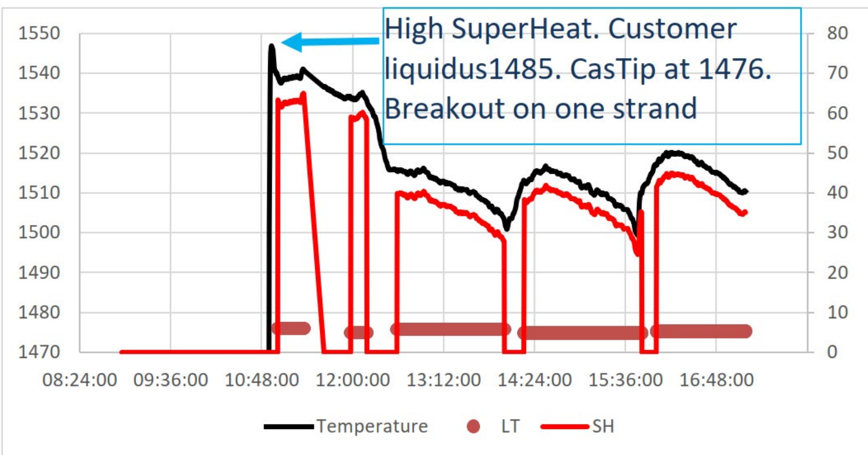

Fig.9 - CasTip difference from evaluated liquidus.

Figures 10 and 11 are real examples of steel grades split into a general high carbon group and non-high carbon group where the CasTemp Superheat system has been routinely employed. Table 1 shows both groups exhibit high maximum but also high end of ladle superheat. The preparation of the steel during steel making needs to be adjusted to aim for lower values. The impact on product quality has not been assessed but it is clear that there are demonstrable energy savings (with comparative cost savings) derived from avoiding attaining high superheat and then having to remove it during casting.

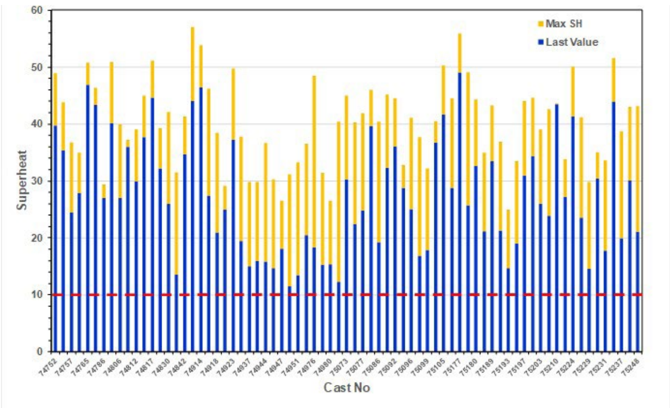

Fig.10 - High Carbon Grades Superheat Maximum and EOL.

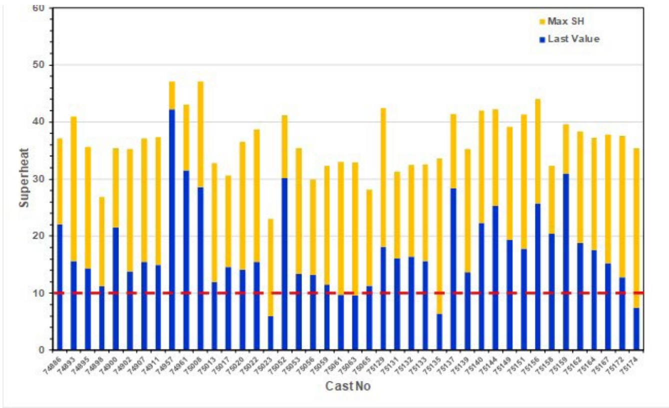

Fig.11 - Non-High Carbon Grades Superheat Maximum and EOL

Tab.1 - CSummary of maximum Superheat and EOL for High Carbon and Non-High Carbon steel grades.

	High Carbon grades	Non-High Carbon grades
Number of Ladles	77	197
Max SH average	37.8	40.8
End of Ladle SH average (EOL)	19.8	28.1
Average drop in SH	18.0	12.6
% casts below 10°C SH EOL	7.8% (6)	2.5% (5)

DISCUSSION

An analysis therefore must take account of a wide body of information, these include:

- Maximum superheat during casting and at the end of ladle
- Duration of casting time

To incorporate the temperature management system to take account of the thermal history of the ladle would be of benefit to the casting machine but even without this knowledge a significantly improved process control package to take account of delivered liquid steel is available to dynamically deliver the superheat., thus:

- Evolution – improved control at caster to back feed to ladle furnace and to primary steelmaking
- Prediction of events should lead to improved planning and control
- Margin for unexpected misjudgements are reduced
- Virtuous cycle of casting shorter time requires a lower superheat.

Better control leads to improved safety reduction in break out events and as importantly freeze off events as it is clear what the direction of travel is and how long it will take to get there.

It can help to define what is the correct endpoint superheat of a ladle. Each will have its own characteristic dependent upon the thermal history; refractory content and type and planned / actual duration of casting. The steel grade, residence time and the processes that have been undertaken and for how long: such as stirring, heating and alloying. The slag content and heat enthalpy will also be a variable effect as will lidding a ladle and the point at which this is done, for example either at end of processing or only during the casting process.

An isolated Dip is unverifiable and by itself gives no indication until the Dip measurement is taken. A continuous trend can start to indicate trends within a short period of time as the datapoints are produced typically on a 15 second interval. Therefore, over a casting sequence of 24 hours then 5000datapoints can be generated compared with approximately 4 or 5 per hour with a Dip measurement. Each continuous datapoint is then a fraction the cost of a single Dip type measurement.

What will the future hold for the evolution of steel grades?

From earlier it is clear that changing market conditions – e.g. light weighting; EVs; packaging requirements that there will continue to be a need to innovate in the steel grade but the basic tenets of steel casting will remain fundamentally the same but the technological and operational imperative to ensure safe and efficient casting will progress. CasTemp Superheat is designed to assist the casting operator to achieve those aims.

The use of CasTemp for reliability to ±1 degree for liquid steel measurement and a high degree of accuracy in liquidus too is required to provide accurate and reliable superheat.

There are several scenarios where superheat control can be significantly improved:

New grades of steel - Technological evolution and market changes has driven the need for new grades of steel, greater light weighting in vehicular traffic and packaging leads metallurgists to develop different grades of steel. Grades for electric car batteries are significantly different in chemistry from existing grades that a steel maker is required to make. High silicon content can alter the liquidus value by a large amount. Using existing models and testing methodology can lead the steel maker to develop casting practices that are not compatible with current practice. This might mean slower casting reducing productivity and affecting the economics of the plant and the grade being produced.

Unexpected consequences can also occur such as unexpected freezing using a model that as shown can provide a significant variation from reality[4]. Other grades now moving into the commercial arena are TWIP,

TRIP, Corrosion resistant rebar and high manganese. Most of these newer grades are significantly different in metallurgical chemistry and will therefore require refinement. This places a challenge for the caster to keep pace with developments and maintain optimal casting productivity.

Product quality

It is well known that superheat affects the solidification structure and there is a compromise with ideal and practical casting conditions. Some of this can be mitigated by utilising, for example EMS in the mould or strand but these have their own extra costs associated with capital investment, operation and maintenance.

In the caster of the future there will be more demand from close control of the superheat to match the product quality. Indeed, heating in the tundish may well become more prevalent.

CONCLUSIONS

Dynamic superheat control of a ladle casting is a valuable and useful tool for the operator to accurately control the process parameters. There are significant benefits in terms of productivity, product quality, energy, and operational control.

Some investigations have shown that only a few steel companies regularly review their liquidus and superheat practices although it is considered to be essential to have robust practices for successful casting. Trials at several plants have shown that superheat is higher than is optimum leading to sub optimal practices of casting slower than desired for throughput and product quality reasons. A considerable amount of effort is required throughout the whole steel making and casting process to ensure the delivery of ladles of steel that can be cast in the desired superheat range.

The CasTemp superheat system has the ability to forward predict the superheat towards the end of the ladle with a high degree of precision. This allows the operator to cast at a lower superheat with the confidence that even with a small error in delivery temperatures, the process can be managed through the casting cycle to maintain sequence casting effectively and efficiently. The uncertainty surrounding previous systems is effectively eliminated.

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