Slab-Quality Prediction with In-Depth Metallurgical Modeling

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Defects in continuous casting are caused by parameters which can be modeled through computations and on the basis of water-model investigations. The results have led, for example, to a 9% reduction in necessary slab-end scarfing to remove transverse cracks caused by AlN precipitation, a better understanding of mould powder entrapment, and have shown that a slower filling rate of the tundish following ladle exchange reduces ladle slag inclusions in the cast slab.

INTRODUCTION

Careful monitoring of the process parameters influencing quality during continuous casting is indispensable for finding the origins of slab defects and for continuous quality improvements. Additional parameters which influence quality can be derived by applying computational metallurgical models that describe the casting process more precisely and which show good correlations with the actual defects. Such computational modeling is likely to play an increasing role in generating deeper process understanding as advances in both computer hardware and software are making the modeling tools more powerful[1].

Work carried out on computational modeling in a joint project between the Austrian steelmaker voestalpine and the plant builder VAI tested the computer models for continuous casting and were used on-line for quality prediction. The results of three quality-improvement investigations are outlined in the following sections.

APPLICATION 1 ALUMINUM NITRIDE PRECIPITATION

Transverse cracking is a serious problem in the continuous casting of steel and negatively affects the final product quality. These surface defects are believed to arise during the straightening of the strand[2] from the vertical plane as it exits the mould to the horizontal run-out table. Figure 1 illustrates this type of defect.

The cracks are intergranular and meander along the prior austenite grain boundaries. Strand straightening is performed in the temperature range between 700–1000 °C. This coincides with the temperature interval in which steel exhibits a minimum in ductility as demonstrated in laboratory hot-tensile tests that shows a fall in reduction of area (RA) – an indicator of ductility. Increasing the N or Al content of the steel extends both the depth and width of the low ductility trough in such tests due to increasing precipitation of aluminum nitride (AlN) which supports microvoid coalescence.

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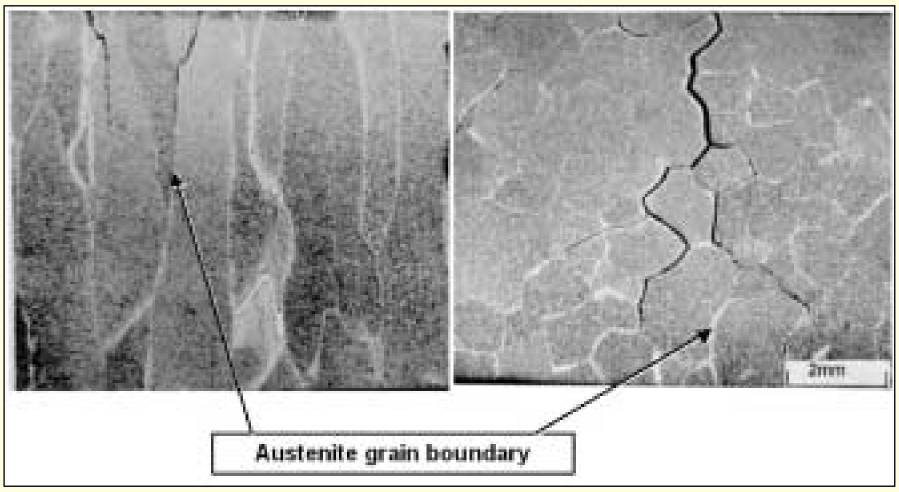

Figure 1: Surface Cracks on Continuously Cast Slabs at the Austenite Grain Boundaries.

More detailed investigations have shown a strong influence of nitride- and carbonitride- precipitation kinetics on the hot-ductility behavior of steels, especially with respect to particle density, particle size and the amount of precipitation. The shape and appearance of these ductility curves are determined by the chemical composition of the steel and its cooling history[3]. For example, coarse precipitation is less harmful than fine precipitation of an equal volume fraction.

The target of this investigation project was to develop a computer model capable of describing precipitation kinetics during the casting of steels containing Al, V, Nb nitrides and carbonitrides[4]. This model provides quantitative information on the nitride and carbonitride precipitation for each individual cast. Consequently the prediction of the surface quality of the strand is more reliable.

By means of a nucleation/ growth model[5,6], density, size and the total amount of particles per volume are predicted as a function of the concentration of micro-alloying elements and the temperature profile. The model introduces a thermodynamic approach to determine precipitation parameters, taking into account the mutual interaction between the alloying elements and dissolution of precipitates as a consequence of strand reheating. Zener's steady state approximation was employed for the description of the growth of spherical particles[7].

Modeling Precipitation Parameters

The main aim of the model is to improve the product quality and quality prediction results. Therefore, correlations between quality and precipitation parameters have to be established. Data recorded by VAI on caster start-ups was used to reconstruct thermal histories of slabs where surface defects had been observed and correlated to AlN precipitation. From this, the behavior and kinetics of precipitation were determined. Low-carbon aluminum-killed peritectic grade steels were selected based on the assumption these offered stable casting conditions. By employing VAI's in-house developed computer software the surface temperature history was calculated as well as the precipitation parameters for particle density, particle size and the number of particles.

Results

A typical result of such a simulation of precipitation kinetics for a continuously cast slab containing 60 ppm N and 450 ppm Al is shown in Figure 2 in the form of a calculated Precipitation-Time-Temperature (PTT) diagram. The surface temperature of the slab is superimposed on the precipitation curve as well as the region where straightening of the slab takes place. The straightening operation coincides with a maximum precipitation rate. Grain boundaries weakened by precipitates are exposed to mechanical deformation processes and, as a consequence, surface cracks occur.

The results of a statistical evaluation of calculated precipitation and quality data is presented in Figure 3. Mean values and standard deviation of precipitated AlN are indicated for good and cracked samples. Whereas defective slabs had precipitated approximately 260 ppm AlN as a mean value, slabs free of defects had precipitated only a mean of 140 ppm. A strong correlation is evident.

This model was implemented at the caster process computers and integrated with the existing computer-aided quality control system[8]. The benefit was 9% reduced scarfing of slab ends compared to the previous rate. It should be noted that prediction of surface cracks by this model is limited to cracks caused by precipitation. There are also several other metallurgical phenomena leading to this kind of defect, one of which is pre-eutectic ferrite precipitation[9].

In conclusion, the following can be stated:

- Ductility of Al-killed steels is affected by AlN precipitation
- Additional extended models have been developed to include the precipitation of niobium carbonitrides and vanadium nitride for the analysis of microalloyed steels
- Surface quality shows a dependency on the precipitation parameters, density, size and quantity
- Crack prediction seems possible and more effective using the physical AlN precipitation model
- Pre-eutectic ferrite precipitation is not covered by the present model and will be the next step of development.

Figure 2: Calculated PTT Diagram Including Surface Temperature History.

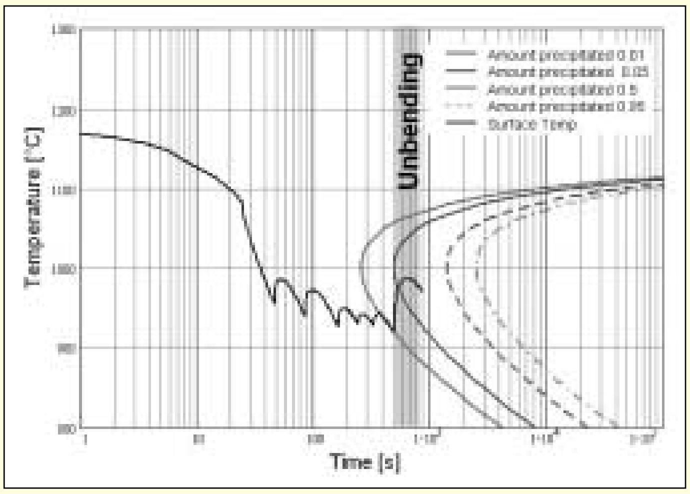

Figure 3: AlN Precipitation vs. Strip Quality.

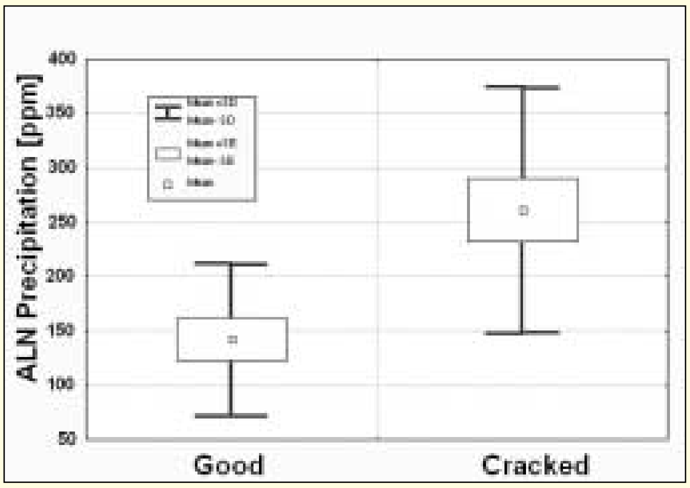

Figure 4: Macroetched Sample with Inclusion Defect Near Oscillation Mark.

APPLICATION 2
MOULD POWDER ENTRAPMENT

One of the quality problems encountered for the casting of low-carbon steel and IF (interstitial-free) steel is the entrapment of mould powder slag near the surface of the slab and in the vicinity of "hooks"[10] formed by the strand shell due to mould oscillation. Figure 4 shows such an inclusion on an etched slab sample[11].

It is assumed that the hook depth as well as the number of entrained slag particles both influence the frequency of the defect occurring on the coil, together with other casting parameters. The project therefore focused on:

- Empirically estimating the hook depth on process parameters
- Modeling mould-steel flow using the commercially available CFD code 'FLUENT', verified by physical water modeling on a 1:1 scale mould to estimate the probability of slag entrainment.

Modeling of Hook Depth

Based on experiments carried out by voestalpine and others earlier[11,12], an empirical hook-depth model could be set up according to the oscillation parameters, carbon content and casting speed.

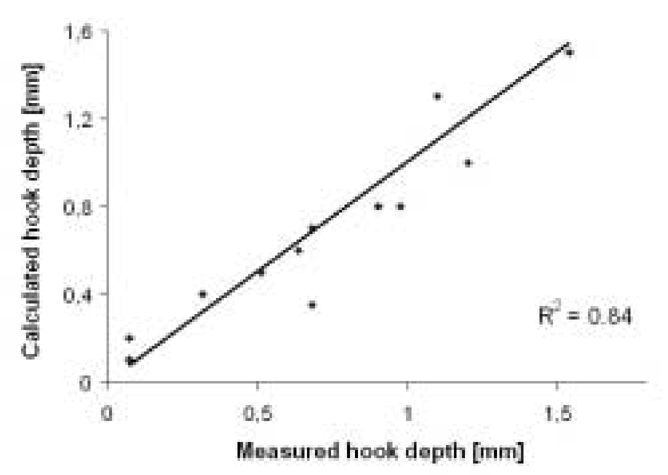

Figure 5: Calculated Versus Measured Hook Depth.

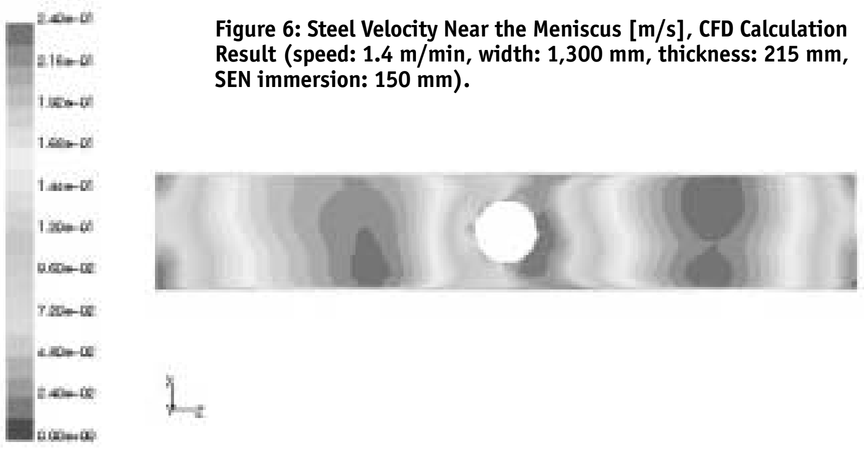

Figure 6: Steel Velocity Near the Meniscus [m/s], CFD Calculation Result (speed: 1.4 m/min, width: 1,300 mm, thickness: 215 mm, SEN immersion: 150 mm).

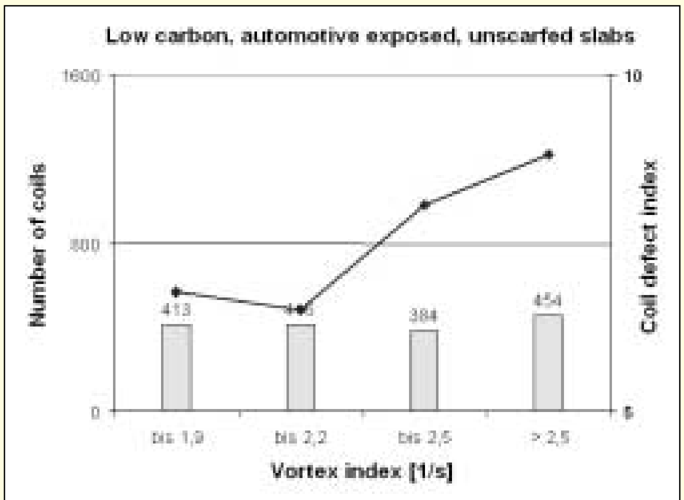

Figure 7: Frequency of Coil Defects vs. Calculated CFD Vortex Index.

This was in good agreement with the experimental results (Figure 5). The model is calibrated for sinusoidal oscillation, but future work will adapt the model for non-sinusoidal oscillation, a feature installed in recent casters and achieved by means of hydraulic oscillators.

Mould Flow by CFD

Modeling the flow of metal in the mould considers the main parameters; mould width, casting speed, SEN immersion depth and the flow of argon applied to the stopper. Since these parameters can change during casting, a study was carried out for different casting situations. The steel flow velocity near the meniscus as well as the probability of vortex formation were calculated. These parameters may be significant for slag entrainment and have been investigated in detail[13,14].

Figure 6 shows a typical CFD result for the casting parameters 1) speed: 1.4 m/min, 2) width: 1,300mm, 3) thickness: 215 mm and 4) SEN immersion depth: 150 mm. The CFD calculation for the different casting situations were approximated by regression analysis to allow the calculation of these parameters during on-line casting operations.

Water Modeling

Using a 1:1 scale water model of the mould, the steel flow patterns in the mould for the various conditions modeled by CFD were compared. Particles with a specific density close to that of water were added to the water to demarcate the flow. Four ultrasonic sensors were positioned on top of the mould to measure level fluctuations as well as the average mould levels under various flow rates. The levels recorded were compared with the calculated values derived from the CFD analysis.

The experiments were documented by video camcorder and afterwards the frequency at which vortexes occurred were counted for each trial. The vortex index derived from the CFD calculations showed good agreement with the observed vortex frequency and the location of the vortex.

Results

The modeled parameters were correlated with the defects identified during strip inspection. As an example, Figure 7 shows good correlation of the CFD vortex index and the frequency of actual defects on the inspected coils.

Due to the statistical nature of the turbulent steel flow and transient flow phenomena[15], an exact prediction of the location of the defects on the coil proved impossible. However, on the basis of the model results the frequency of the defects can be predicted and casting situations avoided where there is a high probability of defect formation. Furthermore, the acquired know-how is useful for evaluating new SEN designs.

The following concluding remarks can be made:

- A prediction model for hook depth was established and fitted to the measured results.
- The steel flow in the mould could be characterized by model parameters such as steel-flow velocity near the meniscus, vortex index and steel temperature at the meniscus.
- On the basis of the modeled results the casting practice was adjusted to avoid unfavorable operating parameters.
- Future investigations will focus on finding new measuring techniques to better characterize the mould steel flow as well as mould-level fluctuation.

APPLICATION 3
LADLE SLAG CARRY OVER

Slabs cast during a ladle exchange have an inferior quality with respect to steel cleanliness in comparison with the slabs

cast using steel from a single ladle. In earlier work it has been shown that the inclusions causing defects in deep-drawn products are often particles consisting of ladle slag, approximately 0.1 mm in diameter.
The task of the investigations were therefore to evaluate different ladle exchange conditions and to determine the strand length with an inferior quality arising from ladle slag inclusions. Three evaluation methods were applied:

- Physical water modeling of the tundish flow
- Plant trials and slab sampling
- Combined CFD modeling of tundish and strand.

Water Modeling of Tundish

Using a 1:1 scale water model of the voestalpine tundish at caster CC5, a pulse of particles was injected into the shroud. The tundish water content as well as the filling rate and casting rate were varied for the different experiments. The particles arriving in the mould were collected periodically, dried and weighed.
Figure 8 shows a cloud of white particles dispersing throughout the tundish after injection into the shroud.

Plant Trials and Slab Sampling

From a slab cast during a ladle exchange a total of 48 samples were cut and rolled using a laboratory rolling stand. The rolled samples were assessed in the laboratories of voestalpine by means of ultrasonic inspection. Figure 9 shows the measured cleanliness index versus strand length. The cleanliness of the steel begins to decrease before the current ladle is closed. The decrease of cleanliness continues for more than 10 meters of strand length after the new ladle is opened for the next heat.

CFD Model

The calculated results of a CFD model of the steel flow in the tundish and strand were calibrated with the results of water modeling of the same region using particle floatation. Figure 10 shows a typical result of the CFD calculations carried out with using the proprietary CFD code "FLUENT"[16]. The particle size for the calculation was 110 µm. The contour plot shows the concentration of particles related to the injected concentration.
Furthermore, a combined numerical 'mix-box' model of the tundish and the strand was set up and adjusted to fit the results of the water model trials, plant trial (Figure 9) and CFD simulations. This numerical mix-box model was then fed into the continuous casting process computer for an on-line determination of the strand length with inferior steel cleanliness arising during a ladle exchange.

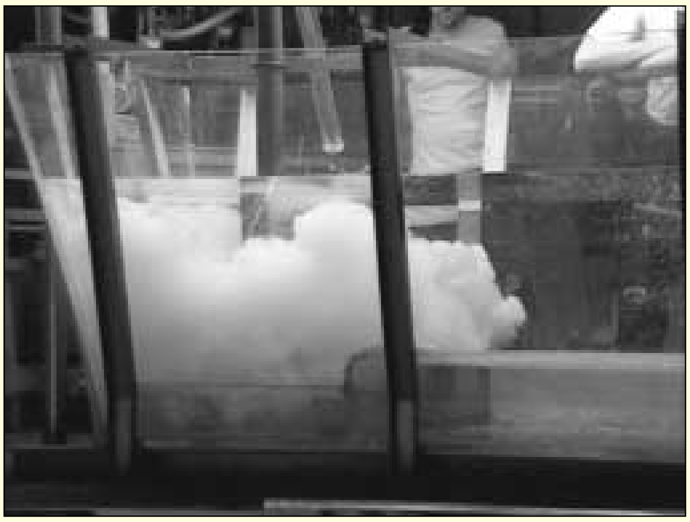

Figure 8: Particle Injection into Tundish Water Model through Shroud.

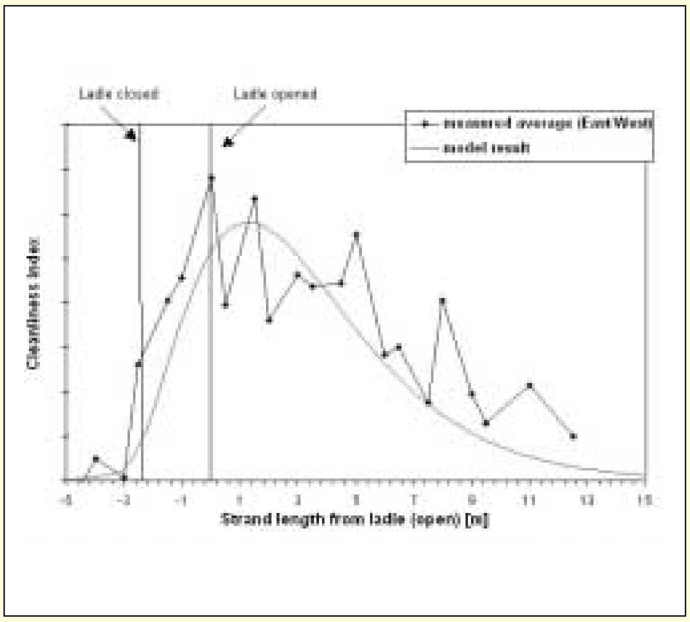

Figure 9: Cleanliness Index vs. Strand Length (Measured & Model Results).

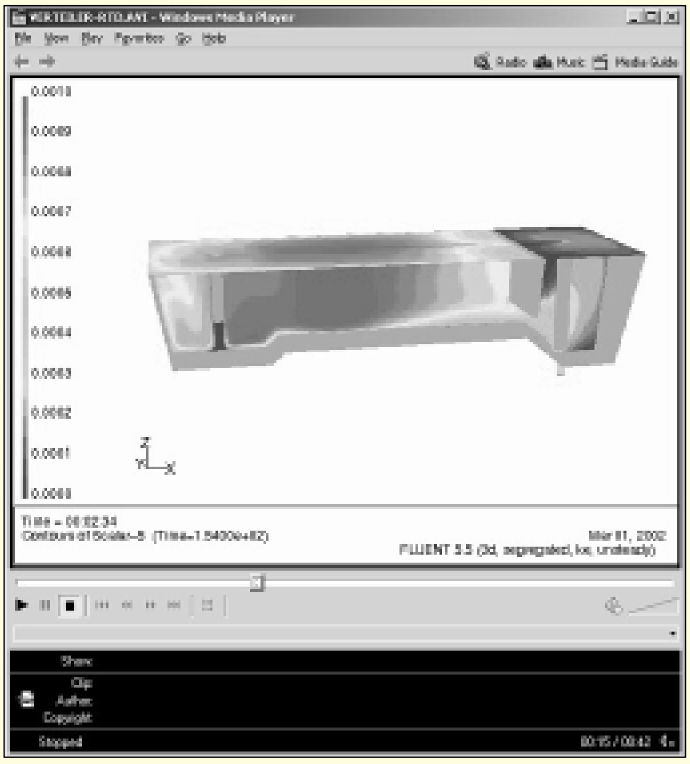

Figure 10: CFD Simulation (unsteady) of a Particle Pulse Propagating through the CC5 Tundish at voestalpine, Linz.

As an immediate result of these trials and simulations, the ladle exchange practice was changed at voestalpine. Special care is now taken not to fill up the tundish too rapidly. As a next step, the inclusions found in the slab samples will be analyzed to determine their chemical composition. Future work will correlate the on-line mix-box model prediction results with quality feedback information from the final product.

The following concluding statements can be made:

- Because the particles of interest are large, but relatively rare, samples taken from the liquid steel or from the hot-rolled coil could not be successfully evaluated. Ultrasonic inspection of slab samples was sufficient.
- Particle entrapment in a mould could be illustrated on the basis of investigations in a full-scale water model.
- Selection of the type of material and particle size used in the water model was difficult. Future work will focus on improving the particle size distribution and the method of measuring the quantities of particles reaching the mould.
- A combined CFD model for the tundish and strand could be set up. The CFD calculation has proven to be important in the investigation of multiple ladle changes because plant trial sampling is time consuming and costly.
- The ladle exchange practice was changed and quality improvements are expected.

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