Slab and strip quality control through metallurgical modelling

Use of metallurgical models of casting and rolling, based on measured process data, enables prediction of the quality properties of the cast and rolled steel, the control of these properties within close limits, and the ability to make decisions in the case of quality deviations.

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Extensive experience with on-line quality control for slab and strip production has been gained over many years from joint developments between voestalpine and VAI. These developments started in 1984 with the slab quality control system, VAI-Q Slab; with the quality control for hot rolling, VAI-Q Strip being developed in 1997. Today both products are successfully used in daily production at voestalpine and other steel plants.

The latest collaboration includes in-depth metallurgical modelling of precipitation, phase transformation and scale formation. The resulting model implementations have become an integral part of the computer-aided quality control solutions: VAI-Q Slab and VAI-Q Strip. Both automation solutions cover process engineering by simulation, on-line quality control prior to shipping certification, and evaluation of actual quality results. Selected examples are presented and demonstrate the benefits of comprehensive metallurgical modelling, including improved quality prediction accuracy and savings in conditioning and inspection costs.

COMMON CONCEPTS OF VAI-Q SLAB AND VAI-Q STRIP

The aim of both systems is to predict quality properties of the cast and rolled steel based on measured process data, to control those properties within close limits, and to make decisions in the case of quality deviations. The following common functions are:

- Detailed data recording during production
- Computational metallurgical modelling of expressive parameters in terms of quality
- Prediction of quality properties of the slabs/strip based on process parameters and model results
- Closed loop control of the process to achieve the required quality
- Initiating product inspection, sampling and re-grading in the case of predicted quality deviations
- Tools for process engineering by simulation

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METALLURGICAL MODELLING

VAI-Q Slab predicts various defects that may occur on the produced slabs and then makes a decision with regard to inspection and scarfing. For this prediction a combined approach consisting of empirical knowledge stored in the computer and metallurgical modelling is used. The prediction is based on detailed process data recording at 0.5m sections of the strand. VAI-Q Slab is linked with VAI-Q Strip to provide information about steelmaking and the casting process. The advances in computer hardware have enabled computational metallurgical models to be applied on process computers and to use the results for on-line process control. This has led to the development of metallurgical models calculating more expressive quality parameters from the measured process data.

The VAI-Q Slab system can optionally be extended by various physical and metallurgical models including liquid steel inter-mix calculation, initial shell formation in the mould followed by strand temperature and solidification calculation, as well as determination of austenite/ferrite phase transformation and precipitation. Since almost all metallurgical processes are time/temperature controlled,
and during cooling of the coil, are all covered by VAI-Q Strip. The solution of the coupled partial differential equations in the two dimensions of time and thickness, is done by highly sophisticated numerical methods. Thus, detailed information is available for every strip position and provides a full insight into the metallurgical processes.

Figure 2 shows the time/temperature development of a single strip segment from exiting the roughing mill until the end of the finishing mill, as a function of time (transformed to position) and position across strip thickness.

**PRECIPITATION MODELS**

Even though the thermodynamic process of precipitation is, in principle, identical for casting and rolling, the impact on these two processes is completely different.

**Precipitation in VAI-Q Slab** Depending on the content of precipitation-forming elements, complex nitride and carbonitride precipitations will form, in a temperature range from 1,000 to 700°C. This coincides with the temperature range in which steel exhibits a ductility minimum and the strand shell is subject to straightening loads. The amount and distribution of these precipitates in the strand is seen to be in close relationship to the surface crack-susceptibility of slabs.

Predominantly, aluminum nitrides in Al-killed steels, and Nb-, V- and Ti-carbonitrides in microalloyed steel grades will precipitate. Typically, these particles are situated along austenite grain boundaries where they support microvoid coalescence as a primary crack initiator. In Figure 3, the surface of a typical intergranular crack can be seen. In the dimples, which are distinctive of plastic crack formation, various precipitates can be found. In VAI-Q Slab, the individual surface crack sensitivity is rated by calculating the precipitation parameters and
comparing them with critical limits. Within this model, the precipitation amount and the particle density etc., are determined for each half-metre segment of the strand. These expressive parameters, which describe one of the root causes of surface crack formation, display and summarise the impact of several process parameters influencing each other; for instance time/temperature history as a result of secondary cooling, casting speed, superheat and steel composition.

**Process optimisation by precipitation modelling** In addition to quality rating, the precipitation model can be used as a simulation program for process optimisation. Simulations may help to identify critical casting situations and it can be a useful tool to quantify the efficiency of countermeasures (eg, changing the secondary cooling practice). Slabs produced during unsteady casting conditions (eg, SEN or tundish exchanges) are well-known to be more susceptible to surface cracking. Figure 4 shows the amount of AlN precipitation, as calculated for the cast strand at the position of entering the straightening zone versus time. A precipitation peak occurs for that strand section which was cast just before a tundish exchange. With the simulation tool, process practices can be developed to keep the precipitation level below a certain limit and consequently reduce the cracking risk.

**Precipitation in VAI-Q Strip** In hot rolling, microalloying elements and their precipitates significantly affect the properties of HSLA steels via influence on grain growth, recrystallisation kinetics, transformation behaviour and precipitation strengthening. It is, therefore, necessary to describe the amount of alloying elements in solution and the type, fraction, composition and size of precipitates, respectively. A well-known feature of the complex carbonitrides of Ti, Nb and V is that they are unstochiometrically and mutually soluble, which can be described by:

\[ N_b N_T i V (C , N) \]

Other particles such as MnS, TiS and AlN can also be formed. In order to describe the thermodynamic equilibrium at reheating temperature, the Hillert-Staffanson model was used for the molar free energy \( G^f \) of the carbonitrides in the form:

\[ G^f = (1 - \beta(x \Delta G_{C,39}^{f,39} + y \Delta G_{N,39}^{f,39} + z \Delta G_{V,39}^{f,39})) + \beta(x \Delta G_{C,39}^{f,39} + y \Delta G_{N,39}^{f,39} + z \Delta G_{V,39}^{f,39}) - T \cdot S^f \]

where \( \Delta G_{C,39}^{f,39} \) and \( \Delta G_{N,39}^{f,39} \) are the standard Gibbs energies for the formation of pure binary carbides and nitrides at a given austenitisation temperature \( T \), and \( G^f \) is the integral molar entropy of mixing, and is the integral excess molar free energy of mixing. According to the sublattice model, where Ti, Nb and V occupy one sublattice, and C, N and vacancies occupy the other, one can write the following equation for the entropy:

\[ S^f / R = x \ln x + y \ln y + z \ln z + \alpha \ln(\alpha / (\alpha + \beta)) + \beta \ln(\beta / (\alpha + \beta)) \]

Simpler equations can be written for AlN, MnS and TiS.

For the description of the mutual influence of alloying elements on the activities, temperature-dependent Wagner interaction parameters are used. Together with mass balance equations, where the mole fraction of precipitates is an extra parameter, the whole non-linear equation set of 15 equations is simultaneously solved by the Newton-Raphson method. As a result, the equilibrium chemical composition of the matrix and the precipitates, as well as their volume fraction, is predicted as a function of temperature and particle size. These thermodynamic calculations for the maximum equilibrium precipitation volume of the complex, NbTiV(CN), were taken into account for the contribution of the precipitates to the mechanical properties only at representative points of the manufacturing process. For AlN, however, the kinetic equations are solved as part of the coupled differential equations.

**RESULTS OF PRECIPITATION MODELLING**

**VAI-Q Slab** A clear goal of the precipitation model is to improve the quality rating of VAI-Q Slab. Therefore, extensive correlation investigations between precipitation parameters and slab quality have been carried out to define critical parameter limits. Concentrating on slabs of surface crack-sensitive steel grades with unsteady state casting conditions, quality rating rules have been established in close cooperation with voestalpine. Figure 5 shows one performance result for a six-month slab data set. Slabs rated as 'bad' (without the model) but which are actually 'good', as verified by inspection, cause unnecessary scarfing costs and a decrease in yield. With the additional use of precipitation modelling for the slab rating, the proportion of slabs belonging to this category was reduced by 68%.
When simulating the dependency of the mechanical properties as a function of finishing temperature and coiling temperature, a remarkable difference between structural and microalloyed steels is evident (see Figures 6 and 7). In the case of structural steels (S235-type), the final rolling temperature has little influence on the mechanical properties, and changing the coiling temperature by approximately ±60°C suffices to compensate for ±20 MPa in the yield point.

The situation is, however, very different in the case of microalloyed steels. If the hot strip mill is operated at (or just under) optimum coiling temperature, an increase in strength of +10MPa can only be achieved by increasing the final rolling temperature by +15°C. This optimum coiling temperature, where there is maximum contribution to the yield stress, is determined by the precipitation of the microalloying elements, and is thus dependent on steel analysis. Too high coiling temperatures will result in coarse particles, which are also inefficient for strengthening, whereas too low coiling temperatures will not give the microalloying elements enough time to precipitate.

CONCLUSIONS AND OUTLOOK
Automatic quality control systems applied to slab casting and hot rolling are operating successfully at voestalpine, based on the following models:

- Thermal tracking
- Precipitation
- Re-crystallisation
- Phase transformation
- Scale formation

Metallurgical modelling and its implementation in the process computers for on-line prediction of slab and strip quality, has proven to be useful. The results are encouraging us to develop additional models in the near future. MS

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