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New Developments for Process Modelling of the Continuous Casting of Steel

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ABSTRACT: Casting process simulation programs are designed to offer the engineer a powerful tool for a virtual optimisation of casting processes. Due to the complexity and variety of physical phenomena driving the continuous casting process of steels, the requirements for an integrated simulation tool are challenging. In a cooperative effort, the Department of Ferrous Metallurgy (IEHK), RWTH Aachen University and a developer of professional process simulation software (MAGMA) have joined forces with theoretical and practical expertise. In this paper, two aspects of continuous casting modelling will be discussed: First, the prediction of the liquid pool depth and second, possible causes of crack formation during the entire process. In both cases primary process parameters and required boundary conditions for a comprehensive simulation of the entire process route are discussed. The results of thermal and mechanical calculations are presented. The evaluation of results shows the strong influence of process parameters like casting speed and spray cooling on the depth of the liquid pool. Analyzing crack formation, special focus is put on the mechanical properties at high temperature as an input variable. The discussed developments will be part of an integrated and practical tool for the engineer to optimise his processes and his productivity.

1. Introduction

Continuous casting has proven to be a universal production method for steel billets of different sizes and steel grades. Nevertheless continuous casting is a very sensitive process that requires deep knowledge of the amount of heat to be removed during solidification. In addition to the heat removal in the mould, the size of the water cooled area and the position of the spray nozzles as well as the casting speed are the most important parameters that may be modified. Here again the simulation can avoid expensive tests on the production line, especially when the producer wants to optimise the casting speed and therefore the productivity, or when the slab size and grade are to be changed. Due to the reliability of modern simulation algorithms and the power of the actual computer generation the virtual optimisation is much cheaper and much faster than real modifications of the production line.

In this paper the simulation of continuous casting of steel billets with different cooling strategies is presented, taking into account the thermal and mechanical requirements. The base of this simulation is an accurate calculation of the temperatures during casting. Finally, an example is shown how an existing production line can be adapted to another steel grade.

2. High temperature Material Properties

During solidification steel has to go through several typical temperature zones. These temperature zones depend on the chemical composition of the material. Above zero strength temperature (ZST), the steel has no strength and no ductility and behaves as a liquid. Below the solidus temperature the steel shows a minimum in ductility due to microsegregation. The temperature at which the steel can sustain almost no tensile strain is called zero ductility temperature (ZDT). A second minimum in ductility occurs below 1300 °C caused by precipitations of sulphides, nitrides and carbonitrides on the grain boundaries. These temperature zones of reduced ductility are determined in hot tensile tests. The ductility of a test specimen is measured by the reduction of area RA, that implies certain amount of plastic strain. For higher plastic strains the risk of cracks increases drastically. In literature the critical strain is indicated with values between 0.5 to 3.8 % at various carbon contents and strain rates [1]. Many efforts are made to predict the mechanical properties such as the critical strain in dependency of the chemical composition and the casting parameter [2]. Actually the characteristic temperatures of low ductility and the flow curves at high temperature are determined by the Trebel hot tensile testing machine at the IEHK and implemented into the continuous casting simulation. The experimental approach is an in situ melt tension test, where cylindrical samples of 20 mm diameter and 130 mm in length are heated to approx. 20 K above liquidus temperature. The sample is melted partly over a length of 30 mm, is then cooled to test temperature and drawn until fracture. For the chosen steel the characteristic temperatures are listed in table 1. The solidus and liquidus temperature were calculated with a thermodynamic software tool.

ST52	Temperature (°C)
$T_{liquidus}$	1506
$T_{solidus}$	1468
ZST	1488
ZDT	1460
ZDT(RA<75%)	1422; 900 to 1000

Tab. 1: Characteristic temperatures for a simple construction steel determined by hot tensile tests.

3. SET UP OF THE SIMULATION

3.1 Modelling the spraying nozzles of a production line

Before the simulation of the solidification can take place, the local thermal boundary conditions must be modelled. Since the spraying is the main mechanism of heat withdrawal during continuous casting, the accuracy of the nozzle definition is decisive for the success of any further calculation.

Every nozzle is defined by their water charged area and by the amount of water, that is sprayed on this area within certain time. In simulation, the nozzles are replaced by corresponding heat transfer coefficients. These are calculated according to the amount of sprayed water and apply for the whole sprayed area. The position of the nozzle and the diameter of the area must agree with the production line. When two nozzles are overlapping, for the intermediate section a different heat transfer coefficient has to be defined. Since there are a lot of nozzles between the mould and the cutting section the correct definition of the areas and the heat transfer coefficients is the most time consuming part of the modelling.

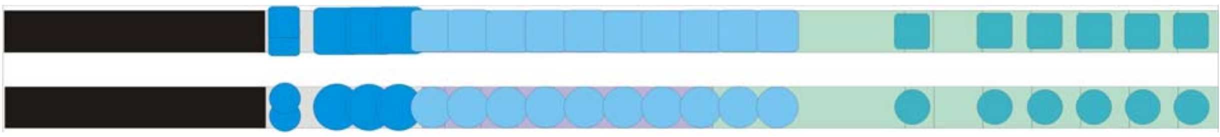

Fig. 1a: Nozzle distribution for circular and square nozzles. The nozzle areas below the mould are overlapping.

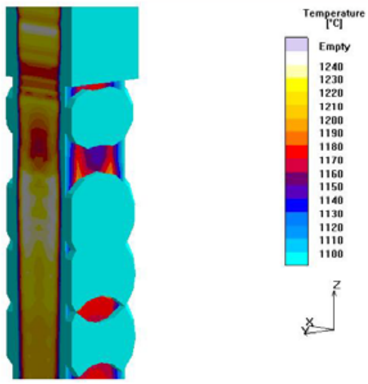

Fig. 1b: Temperature distribution for circular nozzles. The nozzle areas below the mould are overlapping.

3.2 Depth of the liquid pool

Once the nozzles are defined one can proceed with the thermal calculations, with a special focus on the main points of interest. The most critical parameter of continuous casting is the depths of the liquid pool. It is formed when the production line starts to move from the mould down to the cutting section and remains almost stable during the further production of billets. Therefore it is necessary to simulate the whole thermal history until the final cut of the billet on the whole cast, not only on a moving disk. Due to the thermal heat conduction there is no separated heat balance under each spraying nozzle, they strongly influence each other.

The depths of the liquid pool depends on the way how the solidification is ruled by spraying. The outer sections of the cast will always solidify quite soon during spraying, forming some kind of insulation for the inner sections. The centre of the billet will therefore solidify much later, when the strand has already passed the bending mechanism. The depths of the liquid cool is the point when the centre of the billet passes the solidus temperature. For security reasons this point should lay at least one meter in front of the cutting section, because otherwise the cut of the billet will produce an outflow of liquid steel. For the prediction of the depth of the liquid pool it is essential to model the temperature dependent feeding properties of the steel, the isostatic pressure, the latent heat and the morphology of solidification. Secondary effects like reheating and recrystallization must also be taken into account.

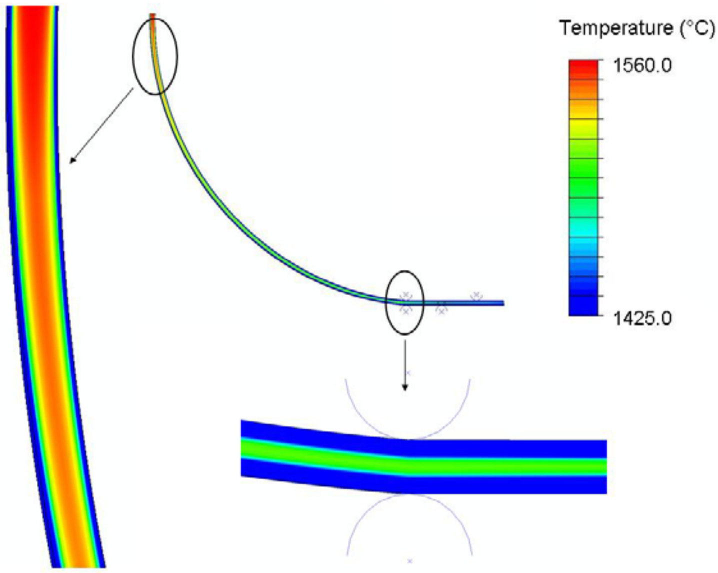

Fig. 2: Simulated temperature distribution in the billet center from the mould to the bending rolls

3.3 Prevention of Crack formation

Possible cracks in a strand are the second limitation for continuous casting production lines. Cracks can be caused by the development of local thermal stresses and plastic strains in strand which exceed the materials strength. Reasons are for example a non-uniform shell growth in the mould caused by the casting stream and/or casting flux. Longitudinal surface cracks in billet casting for example may arise below the mould caused by a too strong cooling. In this paper the focus is put to internal cracks that appear beneath the surface, but the basic mechanism is the same as for some surface cracks, which emerge from internal cracks and open to the surface. Thermal stresses are caused by non-uniform thermal shrinkage of inner and outer section and therefore depend on the spray nozzle arrangement. It has already been mentioned that at the beginning the outer sections cool faster than the inner sections. During this period one will find tensile stresses in the outer sections and compressive stresses in the inner sections, because the outer sections are shrinking onto the inner ones. Later on the inner sections are cooling faster than the outer sections. This will cause a change in sign of the residual stresses, ending up with compressive stresses in the outer sections and tensile stresses in the inner section, because now also the inner sections try to shrink, but the outer sections are already too rigid.

For proper evaluation of residual stresses a nonlinear, temperature dependent material model is required. It should be able to accumulate plastic strains caused by thermal shrinkage, even during reheating and recrystallization, because cracks of all type occur when the plastic strains exceed a critical value. This value dependents on temperature. The critical amount of plastic strain is extremely low in the temperature range of the first minimum of ductility, close to the solidus temperature. Generally tensile stresses are supposed to be more dangerous, because in this case the whole strength has to be transported via interdendritic connections. The ductility and strength are connected to the state of microsegregation and precipitation which can be estimated on metallurgical basis [3]. When therefore in areas close to the Zero Ductility Temperature plastic tensile strains arise, the danger of cracks is immanent. This applies both to outer cracks that become visible when the billet has cooled down completely and to inner cracks. Since a nonlinear stress calculation of the whole casting takes a lot of computation time for this kind of calculations a different model has to be used. This time a movable disk may be used in conjunction with proper boundary conditions instead of the whole casting, because the shear stresses along the casting are supposed to be very small (plain strain definition). The temperatures calculated during the evaluation of the depths of the liquid pool have to be mapped successively onto this disk, determining the local material properties at each time step. With this sequence and a nonlinear material model it is possible to calculate the accumulated plastic strains, that may be compared with the critical amount of plastic strain.

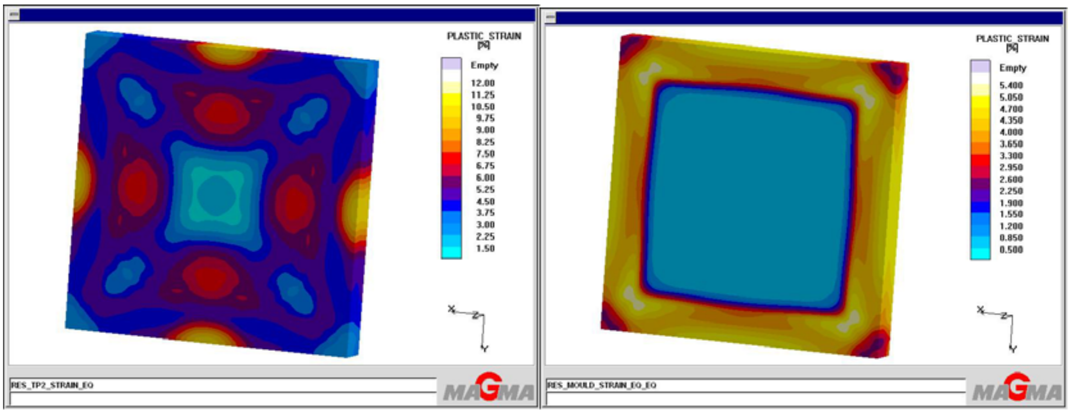

Fig. 3: Simulated plastic strains caused by thermal shrinkage at the bending roll (left picture) and just under the permanent mould (right picture).

In Figure 3 it may be seen how the corner sections are already very rigid and show almost no strains. A maximum of plastic strains is found in the middle between the liquid center and the outer section of the billet. These areas have to be compared with the critical value for plastic strains.

4. EXAMPLE

As an example the production of a bloom with a square section of 160 x 160 mm shall be analysed. The thermo physical properties of a steel grade St52 for the simulation where taken from the database of MAGMASOFT. The information of zero strength and zero ductility temperatures are results from the IEHK. This temperatures will be used for the interpretation of the calculated stress results with focus on crack formation. Six cooling zones with different heat transfer coefficients in each zone were modelled. In addition to full cone nozzles a second cooling plan with square nozzles was calculated. As casting speed 3 m/min and 3.5 m/min were chosen. The results of the simulated depths of the liquid pool are visualised in Fig. 4.

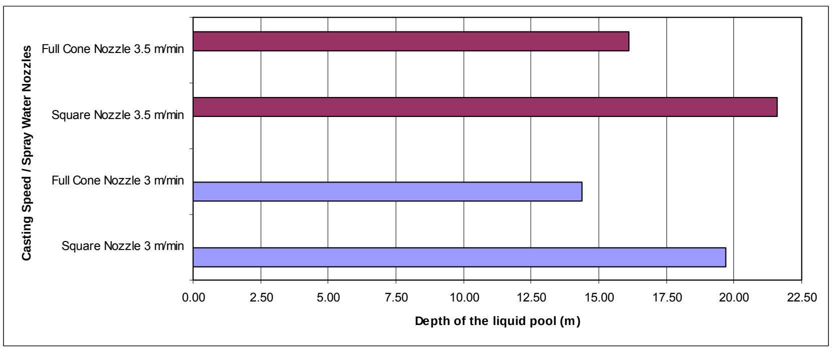

Fig. 4: Depth of the liquid pool for the different process conditions

In the model virtual thermocouples where used to show the effect of the secondary cooling with water. The typical shape of cooling curves for this reheating phenomena is shown in Figure 5.

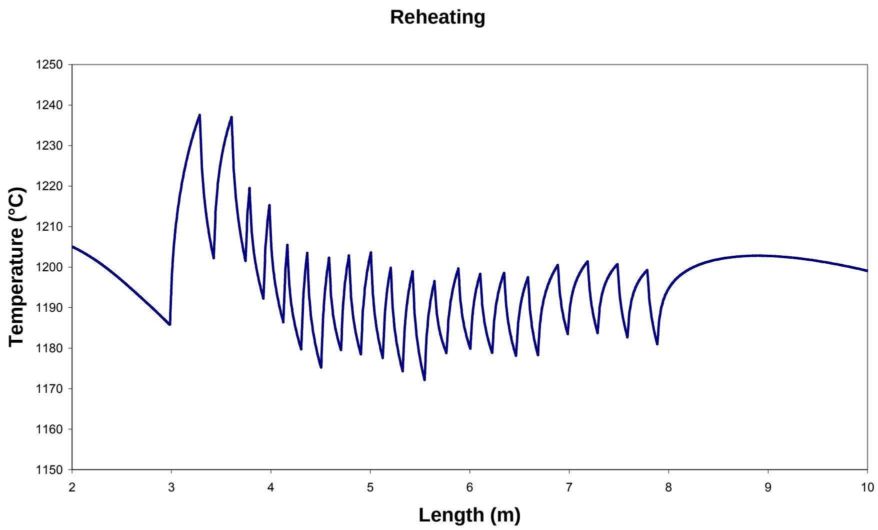

Fig. 5: Simulated temperature curve showing the reheating between the spraying nozzles

The main focus of the here described simulations was the detection of cracks with the help of the integrated thermal and mechanical simulation with MAGMAcont [7]. The idea was to use the results of plastic strain and to find critical areas in the range between the zero strength and zero ductility temperature.

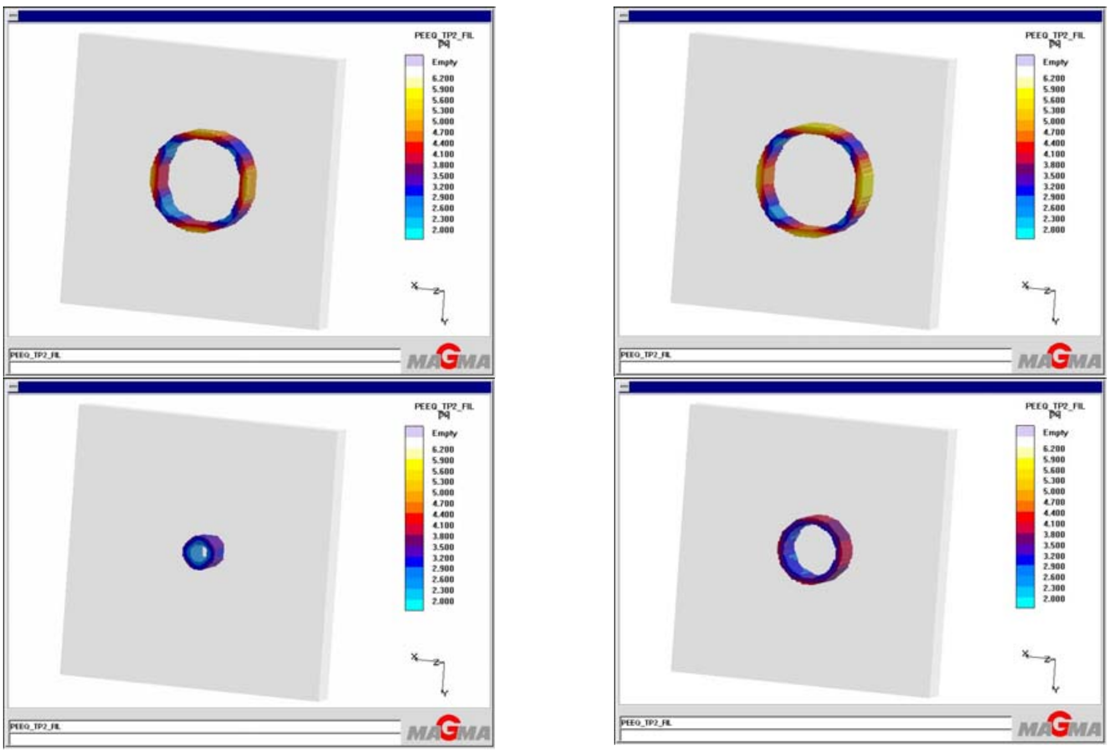

Fig.6: On the left, plastic strains within the zero ductility temperature for 3.0 m/min, on the right for 3.5 m/min. The results on top correspond to square nozzle cooling, the result on the bottom to circle cooling

All results were calculated at the second bending roll, showing also the diameter of the liquid pool. Obviously there is a strong influence of the spraying conditions to the risk of crack formation.

5. CONCLUSIONS AND OUTLOOK

Today simulation of continuous casting is able to show the sensitivity of critical parameters like the depth of the liquid pool and the risk of crack formation in dependence to the spraying and the casting speed, when the geometry and the external boundary conditions are modelled with sufficient accuracy. For the calculation of the depth of the liquid pool the whole casting from the mould to the cutting mechanism must be taken into account using a temperature dependent feeding and crystallization model. For the check of the crack formation the calculated temperatures may be mapped on a moving disk.

This capability may be used for the optimisation of the productivity or for adapting an existing production line to a different steel grades or strand sizes. This is much cheaper than tuning the spray nozzles on the production line. The discussed developments will be part of an integrated and practical tool for the engineer to optimise his processes and his productivity.

6. BIBLIOGRAPHIES

[1] Won, Y.M., Yeo, T.-J., Seol, D.J., Oh, K.H.: A New Criterion for Internal Crack Formation in Continuously Cast Steels", Met. Mat. Trans B (2000), pp.779-794

[2] Stratemeier, S., Senk, D., Böttger, B., Göhler, K.: „ Simulation and Modelling of Hot Ductility for Different Steel Grades", Proc. 2nd Int. Conf. on Simulation of Steel Making 2007, Graz

[3] Senk, D., Safi, M., Hamadou, H.: "Effect of Mould Flux on the Solidifying Steel in the Meniscus Region of Continuous Casting Mould", 5th European Continuous Casting Conference 2005, Nizza, La Défense: Revue de Métallurgie 2005 (CD-ROM)

[4] Horský, J. - Raudenský, M.: "Experimental Study of Nozzle Cooling in Continuous Casting." In. 2nd International Conference Continuous Casting of Billets, Třinec, 1997, Oroc. pp. 107-116.

[5] Deisinger, M. – Tacke, K.-H.: "Unbending of continuously cast slabs with liquid core", Ironmaking and Steelmaking, 1997, Vol 24 No.4, pp. 321-328

[6] Válek, L.- Pospíšil, J. – Moravec, R.: "Numerical Simulation of Steel Solidification as a Tool for Secondary Cooling Optimization of the Continuous Casting Machine", Proc. 1st Int. Conf. on Simulation of Steel Making 2005, Brno, Proc. pp. 147-161

[7] MAGMAcont User Manual: Technical Documentation of the Release 4.4, Aachen, 2006; see also www.magmasoft.de