INTEGRATED MULTISCALE SIMULATION OF CONTINUOUS CASTING OF STEEL

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Abstract

This work copes with a simulation system for modeling of steady-state and transient temperature, velocity, and concentration fields on micro and macro level in continuously cast steel strand (billet, slab, bloom) as a function of the process parameters. The numerical solution of coupled partial differential equations is based on recently developed meshless technology, involving collocation with radial basis functions. The system is designed for estimation of influence of process parameters on strand conditions and development of casting of new materials. The options of simulation system, which enable the technologist automatic setup of process parameters, are described. The regulation coefficients of the casting machine control system can be calculated based on this system. Regulation coefficients are used for compensation of the changes of process parameters that are difficult to control (casting temperature, temperature of cooling water, heat transfer in the mold) with the easily controlled parameters (coolant water flow, casting speed) in such way that the surface temperature and liquid pool depth remain invariant. The on-line and off-line sub-modules of the system are elaborated. The on-line module helps the technologist in monitoring of the status of the main process parameters and safety related issues. The off-line post-processing module is based on the simulation system and real process parameters data base, and helps the technologists in estimation of the reasons for possible casting defects and suppression of them. The implementation of the simulation system in billet caster of Steelworks Štore-Steel, Štore, Slovenia – one of the major European producers of spring steels, is elaborated.

Keywords*:* Continuous casting of steel, simulation system, temperature, velocity, concentration, microstructure, properties, regulation.

Božidar Šarler. Professor of Materials Science and Engineering and Head of Laboratory for Multiphase Processes at the University of Nova Gorica, Slovenia. His research interest is focused on development of mesh reduction numerical techniques for solid and fluid mechanics problems, solid-liquid phase change, and development of industrial simulation systems for continuous casting of steel and aluminium alloys. He led several major modernisations in Slovenian aluminium and steel industry connected with information of the production and intruduction of simulation tools for process yield, safety, and quality optimisation.

1 Introduction

The Štore Steel company is a successor of ironworks which started with the company Berg und Hüttenwerk Štore in the year 1851. State owned Jeklo Štore has been sold to Inexa from Sweden and Unior from Slovenia in 1999 and renamed to Inexa Štore. Unior bought shares from Inexa and sold its previous shares to Slovene partner companies Kovintrade and Dinos Celje in year 2003. The company afterwards received his present name Štore - Steel. It has around 490 employees and is ranking on the place fifty among Slovenian companies regarding the quantity of export towards developed markets. The production focus is on rounds and flats of small and medium size. Plant capacities enable a long - term production of 120.000 to 140.000 tons per year. Such quantities are not sufficient to achieve cost efficiency on the basis of economies of the scale but are ideal for covering of market niches where special needs exist. The company is respectively producing a huge spectrum of different high quality steels in relatively small amounts. The company has a long tradition in delivering top quality steels to the major European spring and automotive producers. Every third truck, produced in Europe, is respectively driving on the springs, produced from the Štore - Steel semi-products. The Company is an ISO-9001 certified mini-mill using steel scrap as the main resource for steel production. The steel plant consists of EAF furnace, ladle furnace VOD-VD, and three-strand bow type CC machine. The business strategy of the company has the following basic goals: (I) to increase selling of company products and services, based on higher quality and productivity, (II) permanent restructuring and modernisation of the company, (III) just in time strategy, (IV) optimisation of the efficiency and effectiveness of the human resources, (V) minimisation of the environmental impact, (VI) stimulation of the in - factory and global technological development through major expansion of research and development on local and European level. In year 1999 the company started a major CC billet caster modernisation programme. The final goal of the programme which has been completed within the EU project COST-526: Automatic Process Optimisation in Materials Technology (APOMAT) in 2005 is the state-of-the-art information [1] of the caster. The following four general strategies have been chosen in order to improve the quality of the product and the safety and the economy of the continuous casting process at Štore - Steel: (I) better understanding of the process, (II) better insight into the process, (III) better influence on the process, (IV) better organization of the work around the process.

2 New Control System

The control system of the Štore - Steel caster has been designed in order to address the second and the third principal tasks. The system consists of four elements: (I) operator control console with man -machine interface (MMI), (II) programmable logic controller (PLC), (III) associated custom software, and (IV) field devices (sensors, actuators). The benefits of the installed control system include: (I) increased productivity through controlled, repeatable cast starts and stops and ability to develop and optimise casting practices, (II) increased recovery through reduced operator error, (III) improved safety due to the controlled cast starts, stops and emergency procedures, (IV) increased consistency of metal properties from cast to cast, (V) most importantly, the casting control system is based on intimate knowledge and a thorough understanding of the CC machine, gained in the last twenty years of operation. The details of the system are given in [2]. All sensors of the CC machine have been renewed, replaced or upgraded. Additional sensors have been installed in order to achieve a detailed insight into casting temperature, velocity, mould oscillation, mould level, primary and secondary coolant system flows, pressures, and temperatures. On-line pyrometers have been installed before unbending region and several more are planned in upwards direction. All the cooling system flows have been made controllable from the man-machine interface and no manual valve operations are needed any more. Because the system has been developed in collaboration with the plant process engineers and a domestic automation company, several modifications of the system already took place and additional might be planned in a most straightforward and easy manner.

3 Process Modelling

Mathematical process models can be applied in several different ways to serve industry by inducing beneficial changes to process operation. CC process modelling [3,4] has been introduced at ŠTORE STEEL in order to improve quality, reduce production cost, and improve safety. Like most commercial material processes, the continuous casting involves many interacting phenomena of great complexity. Because of this complexity, no model can include all of the involved phenomena at once. Two following two types of models are continuously under development: off-line and on-line CC model.

3.1 The off-Line CC Model

3.1.1 Temperatures

The off-line CC model calculates the steady temperature distribution in the strand as a function of the following process parameters: billet dimension, steel grade, casting temperature, casting velocity, primary, and two secondary cooling systems flows, pressures, temperatures, type and quantity of the casting powder, and the (non)application of the radiation shield and electromagnetic stirring. The Bennon-Incropera mixture continuum formulation is used for the physical model, solved by the Voller-

Swaminathan iterative scheme. The recently developed meshless Local Radial Basis Function Collocation Method (LRBFCM) [5,6,7,8] is used for the solution of thermal and stress-strain fields with non-uniform mesh discretization in all three dimensions. In this novel numerical method, the domain and boundary of interest are divided into overlapping influence areas. On each of them, the fields are represented by the multiquadrics radial basis function collocation on a related sub-set of nodes. Time-stepping is performed in an explicit way. The governing equations are solved in its strong form, i.e. no integrations are performed. The polygonisation is not present and the method is practically independent on the problem dimension. Scheme of the simulation system is depicted in Figure 1. Different steel material properties generation packages [9,10] might be directly attached to the temperature and stress field solver. The thermal conductivity of the liquid phase is artificially enhanced to account for the forced and natural convection effects in the melt. The simulation output is represented in graphical (around 50 pictures) and alphanumeric form. The results include plots of the used steel grade enthalpy, specific heat, thermal conductivity, density, thermal contraction, differential thermal contraction, dynamic liquid viscosity, liquid phase fraction, a log file of all generated material properties, and a schematic caster geometry plot. The temperature and phase field graphics include corner, centreline, and average temperatures of the four billet surfaces, longitudinal and transversal temperatures and phase fractions of the billet and an overview of all other typical technological strand data in alphanumeric form. The alphanumeric output includes maximum, average and minimum temperatures of billet surfaces and edges at different longitudinal caster segments. The heat transport mechanisms in the mould take into account the heat transport mechanisms through the casting powder, across the air-gap (if it exists), to the mould surface, in the mould, and from the mould inner surface to the mould cooling water. The heat transport mechanisms in the secondary cooling zone take into account the effects of the casting velocity, strand surface temperature, spray nozzle type, spray water flow, temperature and pressure, radiation and cooling through the rolls contact. Different types of the rolls are considered (driving, passive, centrally cooled, externally cooled, etc.). The mentioned basic heat transfer mechanisms are modified with regard to running water and rolls stagnant water at relevant positions. All involved heat transport mechanisms have been implemented as generic at the first stage of the simulator development. They have been systematically replaced by the plant specific ones through data from the plant measurements and laboratory measurements [11].

3.1.2 Temperatures and velocities

The velocity model has been recently added to the temperature model by incorporating the solution of the coupled heat, mass and momentum transport. The governing equations are based on the mixture continuum formulation of the solid and the liquid phase. The model takes into account the pure liquid, nucleation and movement of the globulitic solid phase, formation of the rigid porous solid matrix, and complete solid. The most simple zero-equation Prandtl mixing-length theory turbulence model is incorporated into the momentum equation [12]. This models allows for more precise simulation of the heat transfer in the mould as a function of the submerged entry nozzle position.

3.1.3 Temperatures, velocities and concentration

The inner structure of the continuously cast billets has a great importance from the point of view of further processing and application. The main reason for this is the very direct effect of the inner structure's features (ie. porosity, macrosegregations, geometry of primary dendrites) on the technological characteristics of further processing (ie. crack sensitivity, formability, etc.). The columnar to equiaxed transition position and the extent of macrosegregation are being included in the form of semi-empirical correlations, developed in [13].

3.1.4 Microstructure

A physically and mathematically more sound approach is being recently adopted through coupling of the macroscopic temperature and velocity fields with the cellular automaton approach to incorporate the phase transformation kinetics effects and thus predict the size and orientation of the grains [14]. A basic goal of simulation of microstructures is to be able to calculate microstructure features of the billet as a function of process parameters and to optimize casting conditions regarding required microstructures. According to that, a stochastic model was developed to predict the solidification grain structures and was coupled with cellular automaton (CA) techniques. An attention was focused on the theoretical concept of two processes occurring during the solidification: nucleation and growth.

A two dimensional model for simulation of the solidification system was used for the calculation of the columnar to the equiaxed transition (CET), which was analyzed in detail [15]. The solidification process was divided into two steps [16]:

Nucleation is assumed to occur randomly in the calculated space. In the present study we adopted continuous nucleation model in which the different Gaussian distributions were considered at the surface and in the bulk liquid respectively. The rate of nucleation depends on the undercooling temperature. Once a nucleus is formed the *growing* process begins. Growing kinetics was accounted for with Kurz-Giovanola-Trivedi (KGT) model. The preferential growth direction coincides with the heat flow (which drives the crystallographic orientation) and the growth velocity is determined by the local undercooling and the thermodynamic properties of steel.

The off-line CC model from the Štore Steel company described above was used to calculate the steady temperature distribution. Temperature in the nodes of the macroscopic heat transfer grid was interpolated using a simply equation [17] to obtain the temperature field in the solidifying region and to define initial CA micro cells state. The CA transformation rules, which are responsible for the CA cell state change, are set in the form of the nucleation and grain growth process models. Free parameters of the method have been adjusted with respect to the experimental microstructure.

Numerical algorithm: In the simulation, depicted in Figure 2 the calculation domain (14cm x 14cm) is divided into square macro cells. Each macro cell includes around 1000 micro cells which are characterized by different variables and state (liquid or solid). At the beginning of simulation all the nucleation cells are liquid and their state index is set to zero. As nucleation proceeds, some of the cells become solid and their index is changed to an integer larger that zero. Nucleation conditions are checked. Once a cell has nucleated it will grow according to the heat flow, with respect to the preferential direction corresponding to its crystallographic orientation, having a growth velocity determined by the local undercooling and the thermodynamic parameters of the steel (KGT model). Each of new nucleuses grows with randomly chosen configuration during each time step. During nucleation three probabilities are used: one for cells located at the surface and in the bulk to nucleate during each micro time step and also during the growth stage to check if the nearest neighbours will be trapped by the closed cell using randomly generated number (Figure 2). The process has been repeated as long as all CA cells are occupied by solid [18].

3.1.5 Thermomechanics

One of the major problems encountered in continuous casting process is the formation of surface and internal cracks and the shape deformation [19]. These cracks are results of thermo-mechanically induced strains and stresses due to high temperature gradients and density changes, effects of ferrostatic pressure, gravitational self-loading of the billet and other mechanically (straightening machine) induced loads. In 2004 a programme of complementing the thermal calculations with the mechanical ones started. Thermo-mechanically induced strains can be calculated as a sum of the strains induced by temperature and phase changes, the ferrostatic pressure and the mechanical loadings (gravitational, etc), respectively. In the same manner, the calculations can be divided in the three main entities: calculation of the thermal and phase-change induced strains, calculation of the strains induced by the ferrostatic pressure and the calculations of the strains induced by the gravitational and other mechanical loadings. The ferrostatic pressure, which depends of the “height” of the liquid metall is also a mechanical load, but its calculation is separated for better understanding of particular effects. On the other hand, at high temperatures, the material behaviour is highly nonlinear, so the nonlinear elastic - viscoplastic temperature dependent material model has to be used. As the thermal and mechanical problems are strongly coupled, their calculation could not be separated in a general case. For example, the mechanical state variables depend on the temperature field and heat transfer coefficients in the mould depend on the air gap, which makes temperature field strongly dependent on displacement. Thus, the calculation of the distribution of temperature, strains and stresses have to be calculated in a time-dependent iterative manner in the future [20]. All the details mentioned above enlarge complexity of the model and computational costs. At this stage, only the steady-state elastic calculations were made. The deformation model of the billet in the mould, which is currently the sole simulation system integrated mechanical module, is used as a help for technologists in order to decide about the appropriate mould taper. The simulation system has a user-friendly self-explanatory Windows application for generation of the simulation and plot input data as well a self-explanatory plot results browser. A dynamic model of the strand with the dynamic plot browser is available as well.

3.2 The on-line CC model

3.2.1 Automation

The on-line CC model is used exclusively in automation of the CC machine. It controls the mould oscillation, electromagnetic stirring, casting speed, and spray flows as a function of format, steel grade, casting temperature, start and stop of the cast. The regulation algorithm is based on the sensitivity coefficients derived from the off-line CC model. The principal control strategy is based on compensation of the process parameters that are difficult to control (casting temperature, cooling water temperature, mould heat extraction) with the casting parameters that are more easy to control (casting speed, spray water flow) in order to preserve the reasonable similar surface temperature and metallurgical length. The regulation coefficients of the on-line CC model are calculated from the off-line CC model of the temperature field.

3.2.2 Monitoring of process parameters

The on-line “caster status model” was developed and implemented on the plant that shows the current status of the casting machine, particularly the temperature at the unbending point, metallurgical length and the thickness of the solid shell at the outlet of the mould. This graphical presentation is entirely based on the regulation coefficients.

3.3 Post - processing

The post-processing of the stored caster process parameters data is made in two different ways. In the first way, the "caster status model" is run after the casting with the realistic casting data and the technological parameters are graphically represented as a function of time or casted length. In the second approach, the full transient temperature model in realistic geometry is run with realistic casting data and a full transient presentation of the casting temperature field is made.

4 Process Optimisation

Continuously cast billets are subject to several different types of quality problems. Their quality is determined by the desired composition and cleanliness of the melt, by the expected shape and surface smoothness of the final product, and by as low as possible cracking, macro- and micro-segregation. The experience gained during continuous casting of steel evolved in empirical metallurgical cooling criteria for the process [21]. Present authors have further developed this criteria for several years from the basic set [22] and what follows represents their fourth improved and enhanced generation. They are listed in quality, safety, economy, ecology and maintenance categories: Quality: (I) maximum depth of the liquid pool, (II) maximum billet surface cooling rate in the spray cooling zone, (III) maximum billet surface reheating rate in the spray cooling zone, (IV) maximum billet surface temperature in the unbending region, (V) maximum negative billet surface deviation at given axial position, (VI) maximum positive billet surface deviation at a given axial position; Safety: (VII) minimum safety thickness of the steel crust at the mould outlet, maximum safety depth of the liquid pool; Economy: (VIII) maximum casting speed, (IX) minimum superheat; Ecology: (X) minimum consumption of spray water; Maintenance: (XI) minimum forces on the rolls and unbending machine. It is believed that the consideration of the listed criteria leads to the best product quality, best caster safety, best caster economy, best caster ecology, and longest caster maintenance intervals. Based on the calculation of the temperature distribution in the billet, the metallurgical cooling criteria can be explicitly evaluated. The technologist has an opportunity to search for the weak points of the process parameter setting. Using the simulator, he is able to properly tailor all process parameters. This is much easier, safer and cost-effective than real-word experimentation. Such simulation is of pronounced importance when designing the process parameter settings for the continuous casting of new materials. With the heat transfer model, the design changes on the plant such as change of the rolls, spray nozzle type, etc., can be easily tested. The heat transfer model can straightforwardly answer to some of the important safety questions. For example, can a pressure drop in one of the cooling systems cause a breakout, etc. In addition, it is extremely useful for training of the caster operators. The simulation system has been already successfully employed for casting practice design and for the design modifications of the secondary cooling system. These modifications include installation of additional spray nozzles which suppressed the corner cracking in some of the steel grades and dimensions. As the number of possible process parameters is high and the criteria are highly conflicting, determining appropriate values is not trivial. A novel approach [23] to process parameter optimisation is in the implementation in the presented simulation system. The approach relies on the heat transfer model, metallurgical cooling criteria and a genetic algorithm, which is a stochastic optimisation method from the field of evolutionary computation. The system iteratively and automatically improves the parameter settings: the genetic algorithm guides the search through the parameter space and activates the heat transfer model to evaluate the candidate parameter settings. The continuous casting process has a substantial optimisation potential because the process involves many input parameters which are almost impossible to set optimally through experimentation only. Despite the developed very sophisticated and comprehensive automatic process optimisation framework, only two automatic process model options are currently implemented in practice: automatic set-up of process parameters that yields predetermined metallurgical length or surface temperature.

5 Further Process Automation

The primary task of further plant automation represents development and calibration of the simulator (experimental programme) and proper, steel specific definition of optimisation criteria as well as proper definition of optimisation problem as a whole (interaction of different optimisation categories in order to achieve optimum yield). The optimiser, based on the hybrid evolutionary computation approach, developed in [24] will be used. The dynamic process parameters setting in continuous casting is a task first achieved almost 20 years ago [25], however, the dynamic optimum control of the process parameters setting is a task yet to be achieved. For this purpose new, very fast simulation and optimisation algorithms have to be developed in order to achieve the computing times of one to five seconds per optimisation/regulation step. The development of such algorithms in realistic geometry is representing one of the principal ongoing research tasks.

6 Conclusions

The described information of the Štore – Steel billet caster substantially improved the process performance [26]. Successful model implementation requires skills in at least two different fields: practical understanding of the industrial process and computer modelling. In the present case the developments represent results of six research teams: the first is specialised in numerical modelling and computer graphics connected to the casting processes, the second in plant specific technology and expert knowledge, the third in industrial automation, the fourth in optimisation procedures, the fifth in plant and laboratory measurements, and the sixth in the development of optimisation criteria. The described elements of the upgrades, particularly full of- and on-line automatic optimisation, will be stepwise implemented in the near future. The described elements of the caster information will be demonstrated in detail at the conference.

7 Acknowledgement

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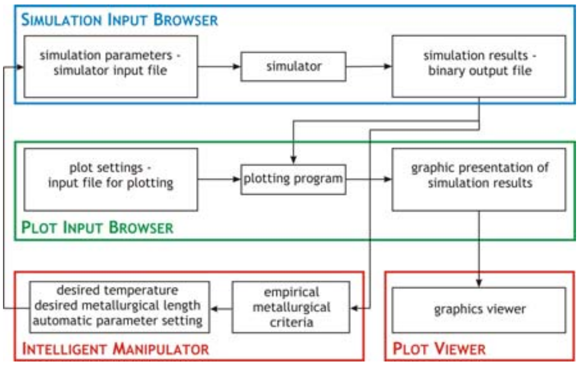
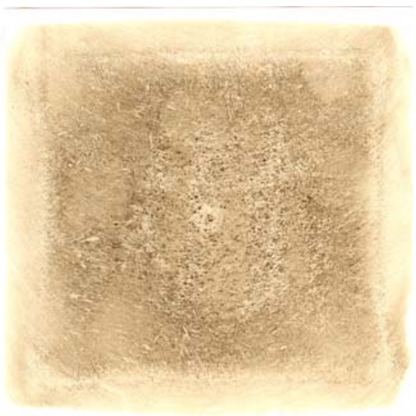


Fig. 1 General scheme of the simulation off-line simulation system.



a) Measured microstructure

b) Simulated microstructure by CA

Fig.2 Example of measured and calculated microstructure

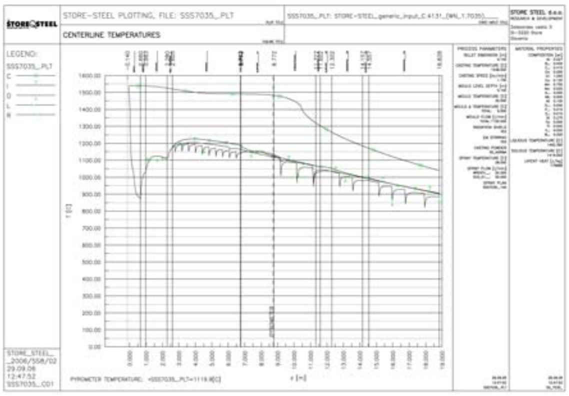


Fig. 3 Example of the off-line CC casting simulation: billet centreline temperatures.

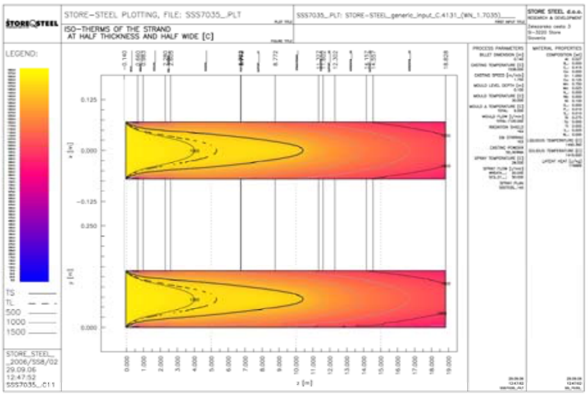


Fig. 4 Example of the off-line CC casting simulation: iso-therms of the strand at half thickness and half wide.

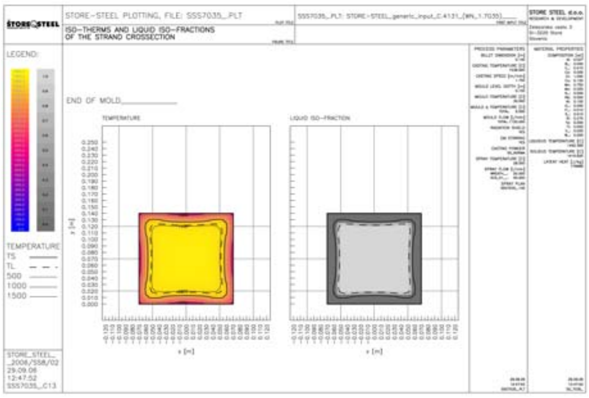


Fig. 5 Example of the off-line CC casting simulation: iso-therms and iso-liquid fractions of the strand cross-section at the end of mould.

Fig. 6 Scheme of the validation of the simulation system by the infrared thermography.

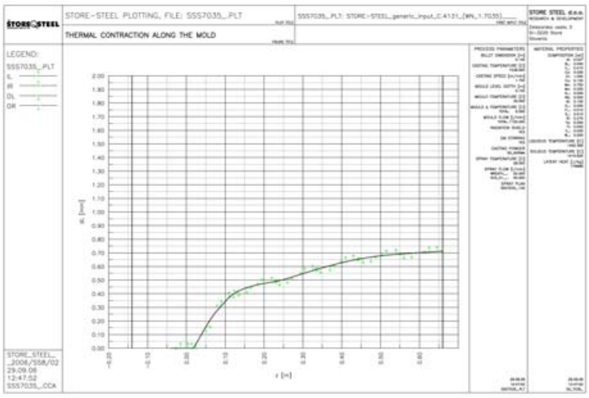
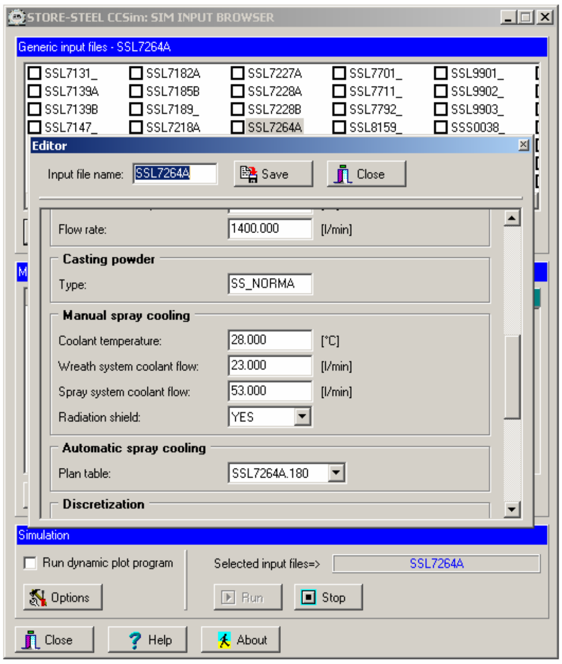


Fig. 7 Example of the off-line CC casting simulation: thermal contraction along the mould.



Generic input files - SSL7264A

☐ SSL7131_
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☐ SSL7139B
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☐ SSL7264A
☐ SSL7701_
☐ SSL7711_
☐ SSL7792_
☐ SSL8159_
☐ SSL9901_
☐ SSL9902_
☐ SSL9903_
☐ SSS0038_

Editor

Input file name: SSL7264A

Flow rate: 1400.000 [l/min]

Casting powder

Type: SS_NORMA

Manual spray cooling

Coolant temperature: 28.000 [°C]
Wreath system coolant flow: 23.000 [l/min]
Spray system coolant flow: 53.000 [l/min]
Radiation shield: YES

Automatic spray cooling

Plan table: SSL7264A.180

Discretization

Simulation

☐ Run dynamic plot program

Selected input files=> SSL7264A

Fig. 8 User friendly input/output browsers of the simulation system.

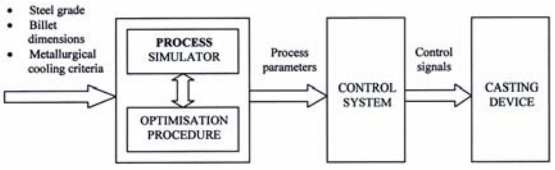
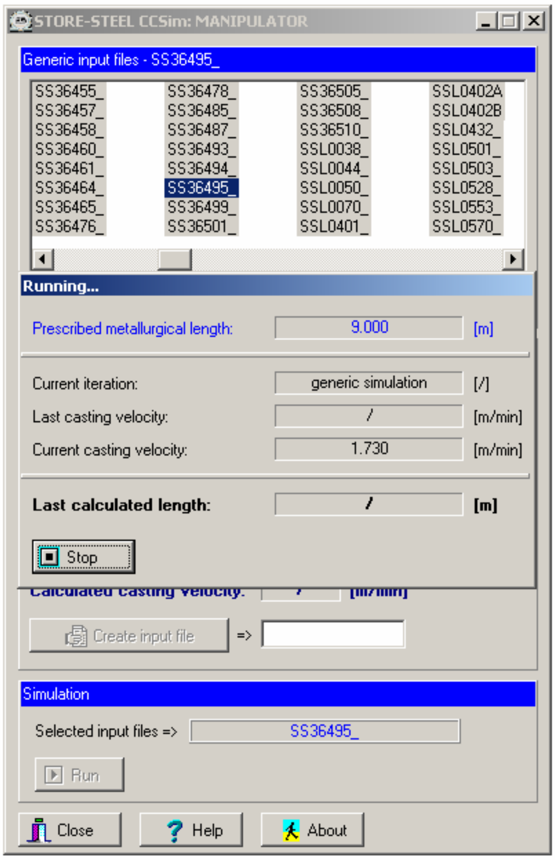


Fig. 9 Scheme of the automatic process optimisation strategy.



Generic input files - SS36495_

SS36455_
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SS36510_
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SSL0044_
SSL0050_
SSL0070_
SSL0401_
SSL0402A
SSL0402B
SSL0432_
SSL0501_
SSL0503_
SSL0528_
SSL0553_
SSL0570_

Running...

Prescribed metallurgical length: 9.000 [m]

Current iteration: generic simulation [/]
Last casting velocity: / [m/min]
Current casting velocity: 1.730 [m/min]

Last calculated length: / [m]

Calculated casting velocity: / [m/min]

Simulation

Selected input files => SS36495_

Fig. 10 User friendly input/output browsers of the automatic off-line optimisation.

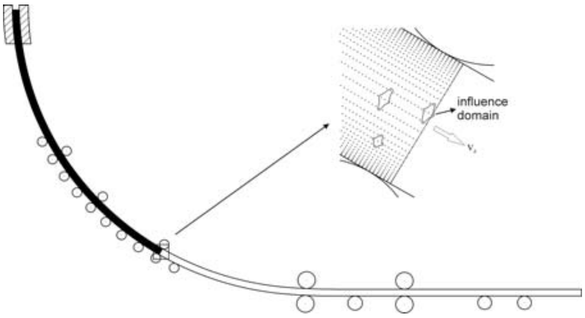

Fig. 11 Node arrangement with influence domains for calculation of the transient thermal fields with moving material boundaries by using a meshless method.

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