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UNSTEADY MODEL-BASED PREDICTIVE CONTROL OF CONTINUOUS STEEL CASTING BY MEANS OF A VERY FAST DYNAMIC SOLIDIFICATION MODEL ON A GPU

PREDVIDEVANJE KONTROLE KONTINUIRNEGA LITJA NA PODLAGI NERAVNOTEŽNEGA MODELA Z ZELO HITRIM DINAMIČNIM MODELOM STRJEVANJA NA GPU

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The aim of the paper is to develop and test a model-based predictive control system for continuous casting of steel billets with an emphasis on unsteady casting situations, often accompanied by abrupt changes in the casting speed. A very fast dynamic solidification model was developed for this purpose. This fully 3D model runs on graphics processing units, GPUs, and it is significantly faster than the recently used commercial models. Therefore, a scenario approach can be utilized, which means that the control system, in real time, predicts and evaluates the thermal behavior of cast billets for various scenarios of the control strategy. The concept of the effective casting speed was utilized for the proposed control strategies. The results show that the developed control system can provide an effective control of the casting process and brings new control possibilities for continuous steel casting.

Keywords: continuous casting, model-based predictive control, effective casting speed, dynamic solidification model, GPU, computing

Namen prispevka je razvoj in preizkušanje nadzornega sistema kontinuirnega ulivanja gredic, ki temelji na modelu napovedovanja, z upoštevanjem neenakomernih razmer pri litju, pogosto spremljanih z nenadnimi spremembami hitrosti ulivanja. Za ta namen je bil razvit zelo hiter dinamičen model strjevanja. To je popoln 3D-model, ki teče na grafičnih procesnih enotah GPU in je bistveno hitrejši kot pred kratkim uporabljani komercialni modeli. Zato se lahko uporabi scenarijski način, kar pomeni, da sistem nadzora v realnem času napoveduje in ocenjuje toplotno vedenje litih gredic pri različnih scenarijih strategije kontrole. Za predlog nadzornih strategij je bil uporabljen koncept učinkovite hitrosti ulivanja. Rezultati kažejo, da razviti sistem nadzora ponuja učinkovito metodo nadzora procesa litja in prinaša nove možnosti nadzora pri kontinuirnem ulivanja jekla.

Ključne besede: kontinuirno ulivanje, napovedovanje na osnovi modela, efektivna hitrost litja, dinamični model strjevanja, GPU, računalništvo

1 INTRODUCTION

Recently, the optimum control of continuous casting has been among the main objectives of steelmakers around the world. A proper control, especially in the secondary cooling with water or air-mist cooling nozzles, is an essential issue directly related to productivity and quality. Various techniques and approaches can be used for this purpose. An experimental setup of a casting machine is seldom used due to a large complexity of the problem and due to fallible results. Instead, many researchers and steelmakers use numerical dynamic solidification models. These systems enable the calculations of the temperature field of a cast blank and its solidification and they can be, therefore, used for the casting control,[1,2] its optimization[3–5] and for investigating the thermal behavior.[6,7]

The crucial issue of dynamic solidification models in relation to casting control is their computational demands limiting their wider use in the production control process. In particular, a dynamic solidification model usually computes the transient heat transfer and the temperature distribution of an entire cast blank in specified points, in the so-called computing grid. This procedure generates a large amount of calculations (in order of billions) determining the transient temperature field of cast blanks. The recently used commercial dynamic solidification models use the state-of-the-art CPU computing and perform these calculations within tens of minutes. Nevertheless, tens of minutes are rather long times to utilize the solidification models for the real-time control or optimization of a casting process. However, a new computing approach has recently become available for highly parallelizable problems. This technique, called the GPGPU (general-purpose computing on graphics processing units), utilizes the computing on graphics cards, GPUs. A GPU, though primarily intended for the use in computer graphics and gaming, consists of a large number (from hundreds to thousands) of rather simple processors allowing a huge computing performance that can be used for solving various scientific and technical problems. The GPGPU has been mainly used for the simulations of molecular dynamics,[8] image processing[9] and Monte Carlo simulations.[10] In spite of this, only a few papers relating to heat-transfer problems have been published[11] by researchers and none of these covers continuous casting. However, Klimes and Stetina[12,13] recently published papers on the use of the GPGPU for a parallel dynamic solidification model of continuous casting on a GPU and the results show that the GPGPU can greatly enhance the computing performance of solidification models, allowing a significant reduction in the computing time and, therefore, new opportunities for the use of solidification models in the optimum casting control have become available.

Based on the literature review, researchers have recently used various approaches to the optimum control of the continuous casting process: frequently by applying PI or PID controllers,[1] probabilistic metaheuristics (e.g., simulated annealing[2]), heuristic searches,[3] fuzzy logic techniques[4] or mathematical programming methods[5]. However, several issues may appear when these methods are used or intended for a practical use in steelworks. One of the most important issues of PI and PID controllers is that they regulate a process according to the history of that process. Considering a system delay, it means that the regulation may react improperly. Heuristic methods and, particularly, the approaches via mathematical programming suffer from huge computational demands, usually because of the repeated computations of the model. This issue can, therefore, significantly prolong the regulation process and, for this reason, the use of these methods is often limited in a real-time regulation.

Due to the above reasons and encouraged by the computational performance of the developed parallel dynamic solidification model running on a GPU, the aim was to propose a new control approach for continuous casting. For this purpose the model-based predictive-control (MPC) approach was selected. One of the features of the MPC is that it uses a model as a numerical sensor to predict the future evolution of a controlled process under certain conditions.

2 PARALLEL DYNAMIC SOLIDIFICATION MODEL RUNNING ON A GPU

Nowadays, commercial dynamic solidification models for continuous steel casting utilize the state-of-the-art computing on central processing units (CPUs). These models usually solve heat transfer and solidification of cast blanks in discretized points (in a number of hundreds of thousands or millions) and these models require tens of minutes to compute the stationary state under constant casting conditions.[12] These models are, therefore, rather awkward for a fast and real-time regulation due to time-consuming computations. However, many computational problems with a possibility to be parallelized can be computed more efficiently with the use of GPGPU techniques and graphics processing units (GPUs).[14] The GPGPU divides a computational problem into independent parts that can be computed concurrently in a parallel manner. For this reason a GPU consists of many simple computing units that are designed to process an identical code, but on different data. The number of units depends on the type of the GPU, generally varying between several hundreds and several thousands.

The transient heat transfer and the solidification of cast blanks can be modeled with the Fourier-Kirchhoff equation:

$$\frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T) + v_z \frac{\partial H}{\partial z} \qquad (1)$$

where H is the volume enthalpy (J m^{-3}), T is the temperature (K), t is the time (s), k is the thermal conductivity (W m^{-1} K^{-1}), v_z is the casting speed (m s^{-1}) and z is the spatial coordinate (m) in the direction of casting. The mass-transfer and fluid-flow phenomena inside a blank are usually neglected, but they can also be considered, e.g., with the use of the effective heat-conductivity approach. The volume enthalpy that appears in Equation (1) is used to include the latent heat released during the solidification.[15] This thermodynamic function can be defined as:

$$H(T) = \int_0^T \left(\rho c - \rho L_f \frac{\partial f_s}{\partial \theta} \right) d\theta \qquad (2)$$

where ρ is the density (kg m^{-3}), c is the specific heat (J kg^{-1} K^{-1}), L_f is the latent heat (J kg^{-1}) and f_s is the solid fraction (1).

The developed parallel dynamic solidification model for continuous casting of steel billets (**Figure 1**) based on Equation (1) and the necessary initial and boundary conditions was created using the control-volume method and explicit time discretization.[12,13] The heat withdrawal from the mould, within the secondary cooling zones with the cooling nozzles and other casting conditions, can be adjusted through the initial and boundary conditions. The explicit discretization in time is an essential condition for the parallel model, allowing it to run on GPUs. Basically, the calculations related to various control volumes are solved concurrently by various computing units of a GPU.[12,13] The CUDA C/C++ computing architecture was

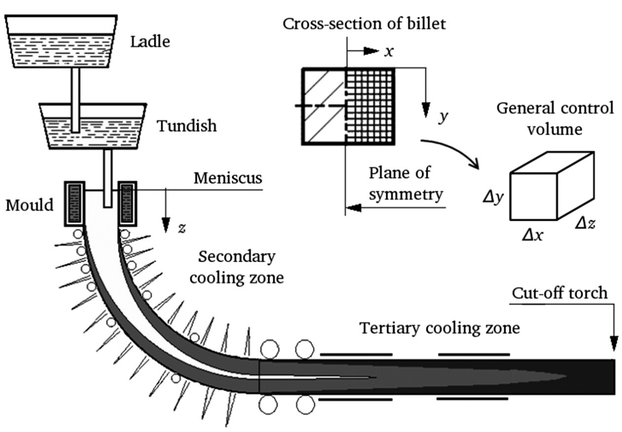

Figure 1: Billet caster and the mesh definition
Slika 1: Naprava za ulivanje gredic in določanje mreže

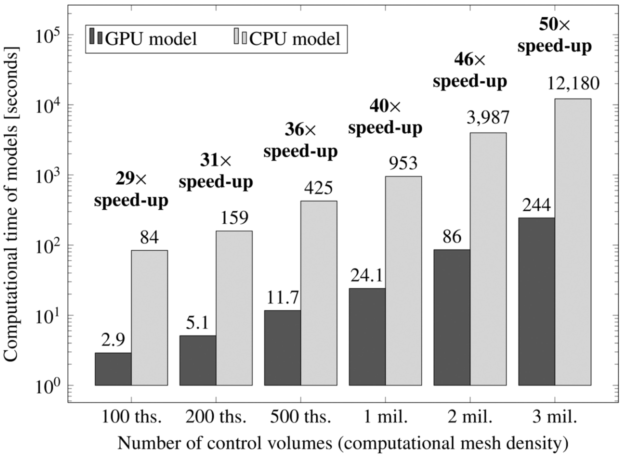

Figure 2: Comparison of computational performances between GPU and CPU dynamic solidification models

Slika 2: Primerjava računske zmogljivosti med GPU in CPU pri dinamičnih modelih strjevanja

used for the development of the presented solidification model.[16]

A comparison of the computing performances between the developed parallel solidification model running on a GPU and an identical model utilizing the state-of-the-art computing on a CPU is shown in **Figure 2**. The results are presented for various numbers of control volumes (i.e., for various computational mesh densities) and identical casting conditions.[12] GPU NVIDIA Tesla C2075 having 448 computing units was used as the representative of GPUs. The CPU model was run on a computer with Intel Core 2 Quad CPU with 4 cores, each having a frequency of 2.4 GHz. As can be seen from **Figure 2**, the GPGPU computing can greatly enhance the computational performance of the solidification models. For the mesh with 100000 control volumes, the GPU model processes the computations in only about 3 s which is 30-times faster than in the case of the model running on a CPU. Moreover, with an increasing mesh density the parallelism and the computational performance of the GPU become more significant: in the case of 3 million control volumes, the model running on a GPU is even about 50-times faster than the CPU model. In this case, the GPU model performs all the computations with a very fine mesh in only 4 min. On the contrary, the CPU model needs more than 200 min to do the same job. These results unambiguously prove the benefits of the parallel GPU solidification model, opening new possibilities for its real-time use in continuous-casting control.

3 MODEL-BASED PREDICTIVE CONTROL FOR CONTINUOUS CASTING

3.1 Model-based predictive control systems

On the basis of the literature review, the model-based predictive control approach[17,18] was chosen to be utilized with the developed GPU model for the optimum control of continuous casting process. Though primarily utilized in the petroleum industry, the model-based predictive control has been recently used in many engineering applications, mainly due to a rapid development of computers and their performance.[17–19] The main principle of the general model-based predictive control (MPC) system is as follows: in defined consecutive time instants with the measurements of the current and past process outputs and with the past values of the control inputs, the control inputs for the current and future instants are determined with the model, so that these control inputs minimize the differences between the predicted controlled outputs and the required reference values, the so-called set-points over a certain control horizon[17]. In other words, the MPC utilizes the model of the process to predict the behavior of the system resulting from the changes in the inputs and to evaluate the consequences of these modifications. This is actually an opposite to the PI and PID controllers that control and regulate the process according to the known behavior in the past. A very illustrative comparison between the PI and PID versus the MPC is as follows: the PI and PID controlling is like driving a car using the rear-view mirror. On the other hand, the MPC approach, in the context of driving a car, is like the normal driving using the windshield of the car.[17]

Inspired by the described idea of the MPC, we propose an MPC system for the continuous casting of steel utilizing the developed, very fast GPU model. The scenario approach and the effective casting speeds are then used for determining the control inputs.

3.2 Proposal of the model-based predictive control system for continuous steel casting

The main idea of the proposed MPC system for continuous steel casting is based on using the developed parallel GPU model as a numeric sensor of the real casting machine. However, due to the developed, very

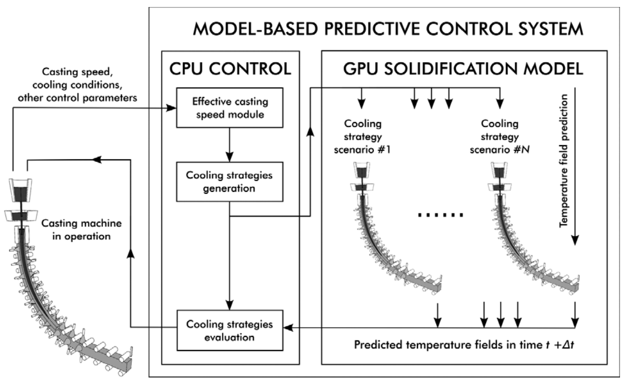

Figure 3: Concept of the model-based predictive control system for continuous casting using a very fast dynamic solidification model running on a GPU

Slika 3: Zasnova kontrolnega sistema napovedovanja na osnovi modela pri kontinuirnem ulivanju z uporabo modela zelo hitrega dinamičnega modela strjevanja, ki teče na GPU fast dynamic solidification model running on a GPU, the concept of the MPC can be extended and modified. The entire concept of the control system is presented in **Figure 3**. The main idea is to use the scenario approach. It means that in every time step the MPC system retrieves the actual casting parameters (e.g., the casting speed, the casting temperature, etc.) from the casting machine. The control system then generates several control strategies, the so-called control scenarios in order to control the process. Each of these scenarios represents a possible control of the casting machine, particularly the cooling setup (i.e., the water-flow volume) of the cooling nozzles in the cooling circuits within the secondary zone. The control scenarios are generated making use of the experiences provided by the experts, the traditional relationships between the water-flow volume through the nozzles and the casting speed, and the concept of the effective casting speed[20]. The control system then predicts the future thermal behavior of cast billets for a certain future-time horizon and for all the generated control scenarios. This task can be performed in real time (between tens of seconds and several minutes depending on the number of scenarios) solely due to the very fast GPU dynamic solidification model. The control system consequently analyses the results of the scenario thermal behaviors and chooses the resultant control strategy used for the real casting process. The main objective of the resultant control strategy is to ensure that the surface temperatures of cast billets fit the predefined temperature intervals (to avoid subcooling or overcooling because of a low ductility of steel[21] resulting in surface defects, e.g., cracks) and that the metallurgical length fits the defined range.[3,4] The control loop is, thereby, closed and the procedure is repeated in the next time instant.

3.3 Effective casting speed

The concept of the effective casting speed was adopted for the determination of the control cooling strategies in secondary cooling.[20] When the actual casting speed rapidly varies in time (e.g, due to a change of tundishes), the determination of the water-flow volume through the nozzles as a function of the actual casting speed may result in inappropriate cooling, particularly in the cooling circuits far from the mould.[20] Researchers and steelworkers usually tend to use the dependencies of the water-flow volume in the cooling circuits as the quadratic functions of the casting speed.[20] The mentioned problem can be overcome with the use of the effective casting-speed approach, based on considering the dwell time that a blank divided into slices spends in each of the cooling circuits. The effective casting speed $v_{e,i}$ for the i-th cooling circuit (m min^{-1}) can be calculated as:

$$v_{e,i} = \varepsilon_i v_{a,i} + (1-\varepsilon_i) v_z \tag{3}$$

where ε_i is the weight coefficient (1), v_z is the actual casting speed (m min^{-1}) and the average casting speed $v_{a,i}$ for the i-th cooling circuit (m min^{-1}) is determined as:

$$v_{a,i} = \frac{n_i L_i}{\sum_{j=1}^{n_i} t_{r,i,j}} \tag{4}$$

where n_i is the number of slices, L_i is the distance from the mould (m) and $t_{r,i,j}$ is the residential time (s).[20] **Figure 4** shows the effective casting speed for the fluctuating actual casting speed and for the casting machine with three cooling circuits within the secondary cooling zone.

As can be seen from **Figure 4**, the effective casting-speed approach can be suitably used for the characterization of the fluctuating casting conditions. Particularly in the cooling circuits far from the mould, the effective casting speed has a smoothness effect, which fairly corresponds to the reality.

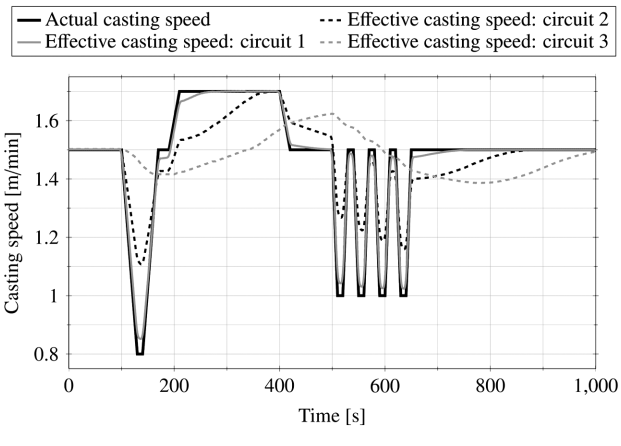

Figure 4: Concept of the effective casting speed
Slika 4: Zasnova učinkovite hitrosti litja

4 USE OF THE CONTROL SYSTEM, RESULTS, DISCUSSION

The developed MPC system was tested for the control of the secondary cooling in the case of a temporary change in the casting speed, e.g., due to the change of tundishes. The dynamic solidification model was configured for a caster with 6 cooling circuits within the secondary cooling incorporating 180 JATO cooling nozzles of several types. The caster casts 200 mm × 200 mm steel billets, normally with the casting speed of 1.5 m/min. The temporary drop in the casting speed from 1.5 m/min to 0.8 m/min was assumed for 6 min as depicted in **Figure 5** where the effective casting speeds for each of the cooling circuits are presented as well.

The aim of the control was to determine the cooling strategy of the cooling nozzles within the secondary cooling so that the surface temperatures on the cast billets would be maintained as close as possible to the surface temperatures in the case when no change is made to the casting speed. Thereby, the steady-state surface

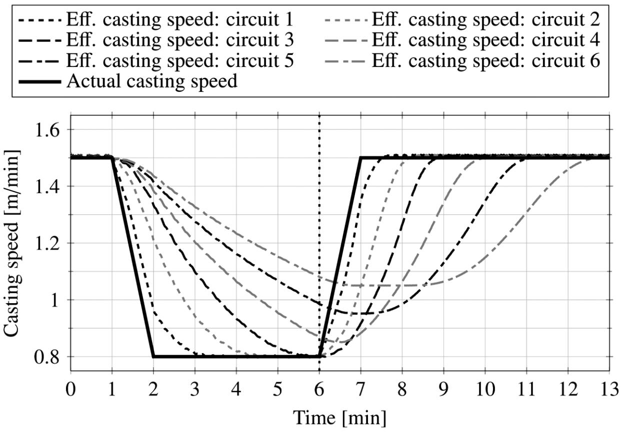

Figure 5: Actual casting speed and the corresponding effective casting speeds for all the cooling circuits
Slika 5: Dejanska hitrost litja in ustrezne hitrosti litja za vse hladilne kroge

temperatures were considered as the optimum target temperatures. The resultant surface temperatures on the top (small-radius) surface of the control process are shown in **Figure 6**. These temperatures for the cooling circuits 4, 5, 6 are plotted for the time when 5 min have elapsed from the beginning of the change in the casting speed (depicted by the vertical dotted line in **Figure 5**) and when the actual casting speed begins to increase from 0.8 m/min back to 1.5 m/min.

As for the described control problem of the temporary change in the casting speed, the developed model-based control system generated 15 cooling scenarios for the cooling strategy within the secondary cooling. These scenarios were generated taking into account the effective casting speeds. The system then predicted the future thermal behavior (calculating the complete temperature distribution) for all these cooling scenarios. The computations were performed for a computational mesh with 1 million control volumes and all these computations for all the cooling scenarios were performed within 1 min

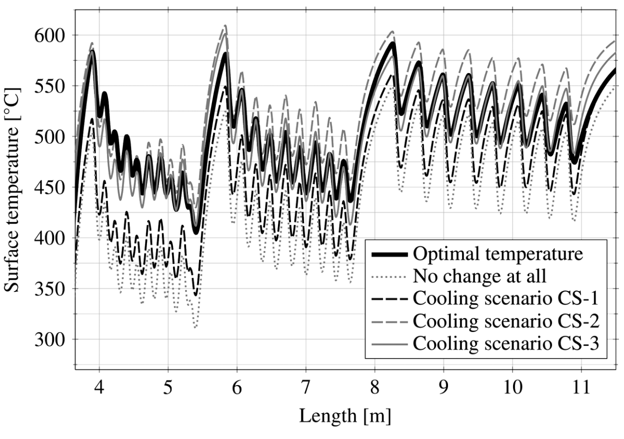

Figure 6: Surface temperatures on the top (small-radius) surface resulting from the use of the MPC system
Slika 6: Temperature površine na vrhu gredic (manjši polmer), ki so dobljene z uporabo MPC-sistema

using GPU NVIDIA Tesla C2075. The temperature distributions for three representative scenarios (denoted as CS-1, CS-2, and CS-3) are plotted in **Figure 6** together with the optimum steady-state temperature distribution and with the temperature distribution for the case when no change in the cooling strategy is performed. As can be seen from **Figure 6**, when no change in the cooling strategy is considered, a significant subcooling occurs within the secondary cooling. Further, the generated cooling strategy CS-1 is also rather inappropriate due to the subheating, mainly occurring within the fourth cooling circuit. Similarly, the cooling strategy CS-2 is also rather inconvenient owing to the overheating, especially in the fifth and sixth cooling circuits. But in the case of the cooling strategy CS-3, the distribution of the temperature is very close to the target temperature distribution in all three cooling circuits plotted in **Figure 6**. The cooling scenario SC-3 can, therefore, be considered as the optimum cooling strategy for the investigated situation.

5 CONCLUSION

The paper presents a proposal for a model-based predictive control system for the continuous casting of steel. The system is based on the dynamic solidification model as the numerical sensor for predicting the future thermal behavior of cast billets under specific casting conditions. The control system utilizes the developed very fast dynamic solidification model that runs on graphics processing units, GPUs. The solidification model, using the concepts of the scenario-based cooling strategies and the effective casting speed was then used for the optimum control of continuous casting. The control system was tested for the case of a temporary drop in the casting speed and the results show that the proposed system is a promising tool for solving these control problems. The next research will aim at tuning up the developed control system and testing it in various production control situations in the continuous casting of steel.

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