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DIGITAL TWINS AS A MODERN APPROACH TO DESIGN OF INDUSTRIAL PROCESSES

The objective of the paper was to describe the concept of a virtual, digital equivalent to a physical process. The basic idea of the virtual counterpart for the process called a digital twin is described first. Following this the hybrid computer system dedicated to the design of the optimal manufacturing technology for thin steel strips is presented. The models used in the system and the database are described. Numerical tests showing capabilities of the system recapitulate the work.

1. INTRODUCTION

A digital twin (DT) is a digital representation of a real-world entity or system. Usually, DT is used in the context of Internet of Things (IoT), where twins are linked to real-world objects and offer information on the state of the counterparts, their functionalities and response to environmental changes. In industry DTs are mainly responsible for virtual description of physical devices and materials, but also for monitoring and analysis of data gathered from online sensors during the process. Such an integration of physical and virtual worlds gives powerful analytical tool covering entire lifecycle of a process or product. It is expected that digital twins will exist for billions of things in the nearest future. In the short term, however, digital twins should offer added value in operational efficiency and insights into how products should be manufactured, how they are used and how can be improved.

Although scientific publications dealing with development of computer systems for design of industrial processes are common now in the literature (see examples for steel strips manufacturing [1–4]), those dedicated to Digital Twins are still scarce. Few review papers which describe general idea of the DTs are available [5–7]. The objectives of the present paper are twofold. The first is presentation of the general idea of a DT using manufacturing of Advanced High Strength Steel (AHSS) strips as an example. The second is presentation of the capabilities of the hybrid computer system as far as design of the optimal manufacturing technology is considered.

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2. DIGITAL TWINS

A digital twin is a virtual representation of a physical product or process, used to understand and predict their performance. DTs are used throughout the product lifecycle to simulate and optimize the production system before investing in physical prototypes. By incorporating multi-physics and multiscale simulations, big data mining and machine learning capabilities, DTs are able to show the impact of design changes, manufacturing routes and other variables. In consequence, the need for physical prototypes can be eliminated, development time can be reduced and quality of the product can be improved.

To ensure accurate modelling over the entire lifetime of a product or its production, digital twins use data from sensors installed on physical objects to determine the object real-time performance and operating conditions. Using this data, the DT evolves and continuously updates to reflect any change to the physical counterpart throughout the product lifecycle, creating a feedback in a virtual environment that enables to optimize the products, production and performance at minimal cost. The potential applications for a DT depend on what stage of the product lifecycle it models. There are three types of digital twin: product, production and performance, which are discussed in the literature. The combination and integration of the three DTs as they evolve together is known as the digital thread [8]. This is a data-driven architecture that links together information generated from across the product lifecycle. Though DT is a communication framework used to design manufacturing processes in order to improve efficiency. There is still no a principled mathematical formulation describing the manner in which DT can be used for critical design decisions. The contribution of this paper is to present such a formulation from the context of a data-driven design and decision problem. This formulation accounts for the fact that the design process is highly iterative and not all information is available at once. Output design decisions are made not only on what data to collect but also on the costs and benefits involved in experimentation and sensor instrumentation to collect that data.

Digital thread is a wide system composed of sensors, computer systems, servers, communication hubs and network storages. The present work is constrained to the description of the hybrid computer system for the design and optimization of the production of AHSS strips. To prove the DT concept a cyber-physical virtual rolling mill was developed as an output of the Research Fund for Coal and Steel (RFCS) project VirtRoll [9], which gathered University research team, research Institutes IMZ in Poland and CEIT in Spain and industrial partner ArcelorMittal. At this stage the system does not have a feedback from the production line and can be considered an example of the model-based manufacturing. The strengths and weaknesses in the current, industry strategies for implementing model based enterprise are discussed in [10].

3. MANUFACTURING OF ADVANCED HIGH STRENGTH STEEL STRIPS

Manufacturing of flat products in the form of hot and cold rolled thick and thin strips is presently the second largest (after long products) assortment of products obtained with the use of the rolling technology. A part of these products is directly used for various constructions (e.g. shipbuilding or power industry), but a significant majority is used as semi-products for further processing in e.g. sheet forming and bending. Advanced rolling technologies must ensure not only required geometry (e.g. flatness) but also required mechanical properties, which are obtained mainly by using new advanced grades of steels. The automatization and robotization of the production processes as well as modelling play crucial role in reaching described aims. As far as rolling of thin strips is considered, the most important challenges can be summarized in four groups, as follows:

- Dimensional accuracy, which involves problems of homogeneity through the width and through the length of the strip, as well as stability of rolling.
- Low level of residual stresses, which can be obtained by controlling the laminar cooling and coiling parameters.
- Improved microstructural parameters and mechanical properties, which are obtained by thermomechanical rolling and complex cooling strategies.
- Rolling of new materials with exceptional properties – Advanced High Strength Steels are used as an example in the present paper.

There are, in general, two strategies in development of hot strip mills. The first is focused on conventional rolling mills (Fig. 1a), which are generally composed of furnace, descaler, roughing train, roller table, finishing train, laminar cooling and coiler. These mills are developed by an increase of the power of motors, new gauge control systems and complex cooling strategies including ultra-fast cooling. The second strategy involves compact hot mills (CSP – Compact Strip Production), which is a novel technology developed in 1980s for casting-hot-rolling of thin slabs [11]. The former strategy is considered in the present paper.

Hot rolled strips can be either used directly for manufacturing final products or can be subjected to further cold rolling process (Fig. 1b). In the former case the final microstructure is obtained by applying complex cooling strategies in the laminar cooling. In the latter case hot rolled strips are subjected to typical cooling cycles resulting in ferrite-pearlite microstructures. *VirtRoll* computer system covers the whole manufacturing of thin strips.

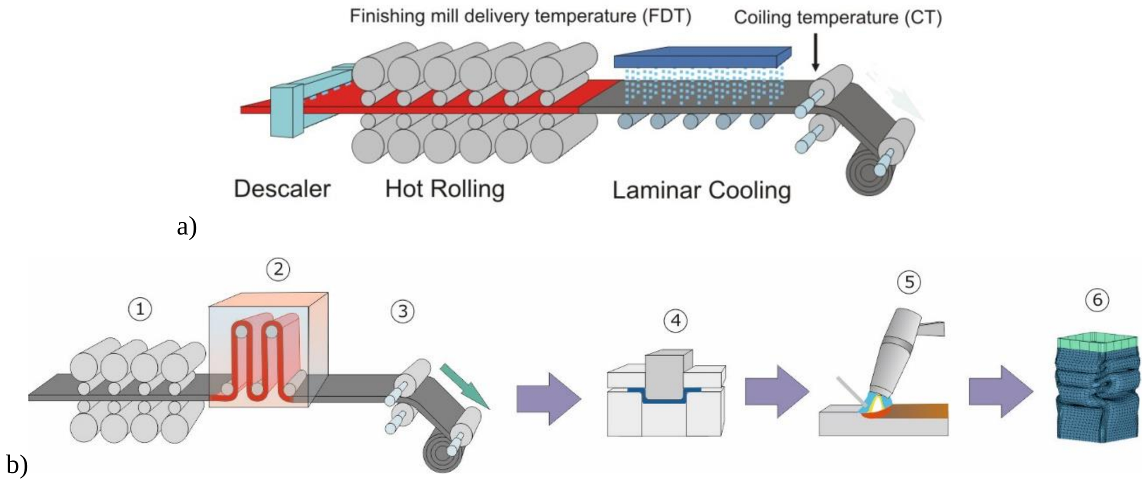
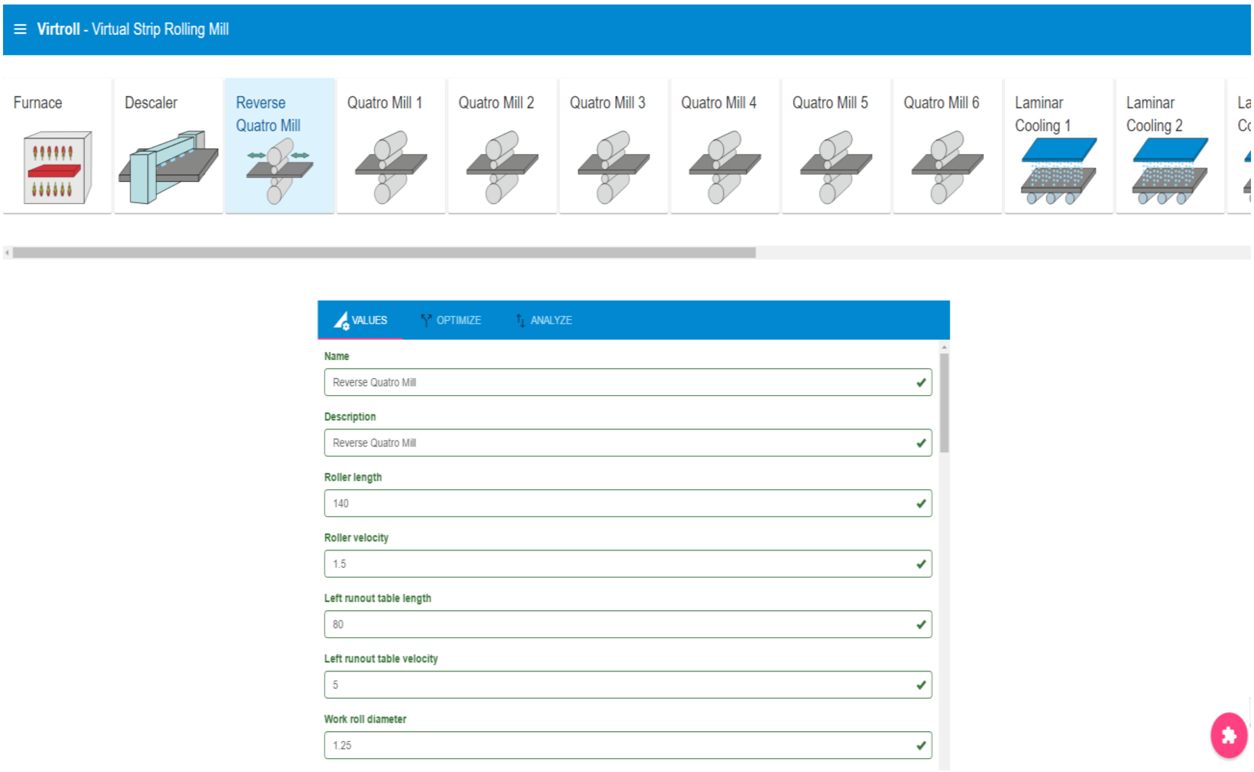


Fig. 1. Schematic illustration of the investigated process: a) hot rolling (only finishing part is presented for simplicity), b): cold rolling (1), followed by continuous annealing (2), coiling (3), stamping (4), welding (5) and final product (6)

4. HYBRID COMPUTER SYSTEM VIRTROLL

The *VirtRoll* system combines models, data and knowledge bases and inverse approach to design of optimal processes. It allows design of rolling line composed of basic equipment like furnace, descalers, rolling stands, laminar cooling, coilers, etc. The typical strip mill with 6 finishing stands shown in Fig. 1 can be reproduced in this system. However, beyond this typical application, the system enables an arbitrary combination of various devices and design any configuration of the rolling mill. Graphical User Interface (GUI) allows to design an arbitrary sequence of devices using drag and drop technique, see Fig. 2. The system connects selected devices in one sequence and runs calculations for the whole line.



Name
Reverse Quatro Mill ✓

Description
Reverse Quatro Mill ✓

Roller length
140 ✓

Roller velocity
1.5 ✓

Left runout table length
80 ✓

Left runout table velocity
5 ✓

Work roll diameter
1.25 ✓

Fig. 2. Graphical User Interface of the *VirtRoll* system

Depending on selected materials specific numerical models can be loaded by the system. The main loading procedure is based on the workflow idea and is supported by software framework for workflow design, creation and performance. This approach was integrated with the steel modelling workbench, which is an open software environment, where various models can be linked and run to allow the modular development of integrated models of various stages of the manufacturing. The integration was based on the common data flow model. An overview of the system along with main steps of the workflow is shown in Fig. 3. Numerical simulations of different hot rolling aspects are an essential part of studying rolling-related processes.

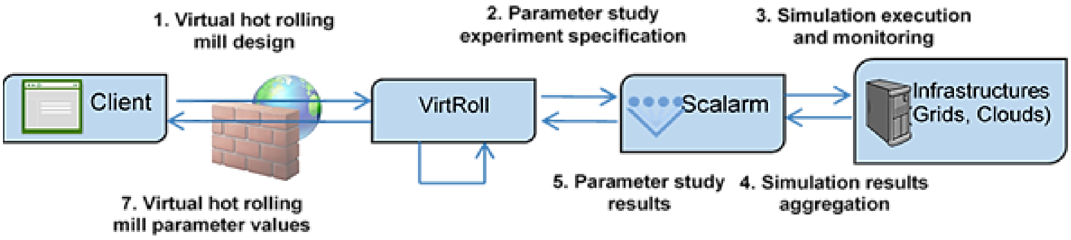


Fig. 3. An overview of a system supporting studying workflow of hot strip rolling processes

As it has been mentioned, combination of models with the data and knowledge bases and with the inverse approach to design of optimal processes is the main advantage of the *VirtRoll* system, which distinguishes this system from the existing ones. Development of the database and application of the inverse analysis to identification of various material models was crucial for the functionality of the system.

Database. The work was started with the analysis of the software architecture, which was used as a fundamental element of the *VirtRoll* system dedicated to flexible material modelling, large scale computations, sensitivity analysis and optimization. All the analysed aspects of the architecture influence final design and implementation of the database including: authorization and authentication, process design and parameters selection, materials management, computing jobs performance, monitoring and many others. This also includes storing of common data used by all subsystems, which are crucial for using modern e-infrastructures [12].

Methodology. The technology involved in the creation of the data base and the system concerns three main elements: the *VirtRoll* system development, the integration between the system and the *Scalarm* platform [13] as well as numerical simulations of rolling-related processes. *VirtRoll* is composed of two parts [4] i.e. a web-based module allowing design of rolling mill and computing module dedicated to numerical simulations of designed manufacturing cycle. Information about materials and devices available for hot rolling mill designers is stored in the database, being the aim of this paper. The idea was to design the database to be as flexible as possible, therefore, MongoDB database management system was used in the first implementation. The selection of MongoDB was justified by its capability of object oriented design and implementation convergent with model layer in application. It gave the compatibility of the database with the server side of the system and the maintenance of flexible data modelling of the process, i.e. support for new materials and devices, characterized by different parameters.

Models. The following models were already implemented in the *VirtRoll* system: i) Finite Element (FE) 1D model of deformation during rolling, ii) Flow stress model, iii) microstructure evolution model describing static and dynamic recrystallization as well as grain growth, iv) Phase transformation model, v) Models describing ii) Detailed description of all the models implemented now in the *VirtRoll* system and coefficients in these models for four groups of steels are given in [12]. All coefficients in the models were determined using inverse analysis for the experimental tests performed for bainitic steels, HSLA (High Strength Low Alloyed) steels and AHSS (Advanced High Strength Steels). The experiments were performed by industrial partners in the VirtRoll project. The experiments included uniaxial compression tests, stress relaxation tests and dilatometric tests and they are described in [9]. The set of models offers following functionalities:

- The models account for the effect of microalloying elements in the new generation steels (AHSS, bainitic and HSLA).
- The models are able to describe complex material behaviour and they can be easily applied in numerical simulation of various hot rolling processes, where temperatures, strains and strain rates are changing in the whole sample. This allows predictions of heterogeneous material properties, depending on configuration of virtual manufacturing process.
- The parameters of models were identified by using full inverse analysis, which means that they can be used in robust simulations integrated with FE modelling. In consequence, material properties in different material points can be predicted. Moreover, robust modelling assures high quality of obtained results, which was validated by laboratory tests [9].

The user can select any model from the data base and use either coefficients for grades in the base or use his own coefficients. Beyond this, the user can define his own models and compile them with the system.

Sensitivity analysis (SA). The *VirtRoll* system allows to perform the sensitivity analysis. The SA can be used to assess the relative importance of input parameter values to the observed output [14]. In the *VirtRoll* system, the sensitivity analysis is performed to find which rolling parameters contribute most to the final microstructure and properties of product. The response, y, for the sensitivity analysis is taken as the value of the selected property (hardness, yield stress) or microstructural parameter (grain size, phase fractions). Assuming that general relation of the output parameter y on process parameters $\mathbf{x} = \{x_1, \dots x_n\}$ has a form $y = y(\mathbf{x})$, the sensitivity factor for the parameter x_i is calculated as:

$$\xi\left(x_i\right) = \frac{y\left(x_1,\dots,x_i+\Delta_i,\dots x_n\right) - y\left(x_1,\dots,x_i,\dots x_n\right)}{\Delta_i} \tag{1}$$

Local and global SA can be calculated in the *VirtRoll* system. Local sensitivity factor $\xi(x_i)$ is calculated from equation (1) for all remaining parameters constant. Global SA is performed using Morris method [15]. Morris design is a screening method that is based on the one-at-a-time approach. In this method, each model execution allows to measure local impact (relative output difference) by changing one parameter at a time. Estimation of global impact is a result of many local measurements. The elementary effect is defined by equation (1). The components x_i ; $i = 1 \dots n$ can take k discrete values in the set $\{0;\ 1/(k-1);\ 2/(k-1);\ \dots.;\ 1\}$. The SA investigation domain is then a n-dimensional k-level grid. The value of Δ_i depends on k and should be the smallest element in the grid $1/(k-1)$ or its multiplicity. Finally, two estimators of the global impact are determined based on local measurements, that is the mean value (μ) and standard deviation (σ). The mean value represents sensitivity of the model output with respect to the ith input parameter. High values of standard deviation indicate non-linear parameter influence. In consequence, the importance of the considered parameter in the whole domain of investigated parameters is determined.

Optimization. Few optimization tasks are available in the *VirtRoll*. In general, it was assumed that obtaining required level of properties as well as homogeneity of these properties was the objective in all optimization tasks. Therefore, the general objective function was defined as:

$$\varphi = \sqrt{\sum_{i}^{n_i}\sum_{j}^{n_j} w_{ij}\left(\frac{p_{ij}-p_{iav}}{p_{iav}}\right)^2 + \sum_{i}^{n_i}\sum_{j}^{n_j} w_{ijex}\left(\frac{p_{ij}-p_{iex}}{p_{iex}}\right)^2} \tag{2}$$

where: p_{ij} – value of *i-th*-property in *j-th*-point in the material (along a strip or in depth), n_j – number of points in the sample, n_i – number of properties in the objective function, p_{iav} – average value of the *i-th*-property, p_{iex} – expected value of the *i-th*-property, w_{ij}, w_{ijex} – weights.

The following optimization tasks were formulated:

- *Task* 1 (level of difficulty – easy). Objective: uniform distribution of temperature along the strip after cooling and before coiling. p_{1j}, p_{1ex} – temperature in *j-th* point on the surface of the strip and expected value of this temperature, respectively. The optimization variable is acceleration of the finishing mill within a range of <0.01–0.04> m/s^2. The problem is 1D and does not require any advanced optimization methods.
- *Task* 2 (level of difficulty – medium). Objective: specific phase fractions in each material point after cooling in a coil. p_{1j}, p_{1ex} – ferrite fraction in *j-th* point and expected value of this fraction, respectively. p_{2j}, p_{2ex} – martensite fraction in *j-th* point and expected value of this fraction, respectively. p_{3j}, p_{3ex} – bainite fraction in *j-th* point and expected value of this fraction, respectively, where sum of p_{ex} is equal 1. The optimization variables are water fluxes on cooling boxes in laminar cooling and rolling schedule in finishing mill, which influences austenite grain size before cooling. The problem is multidimensional and requires nature inspired optimization method.
- *Task* 3 (level of difficulty – advanced). Objective: specific distribution of temperature along the strip before coiling, which allows to minimize microstructure heterogeneity. p_{1j}, p_{1ex} – temperature in *j-th* point and expected value of this temperature, respectively. The latter is different in different points along the strip, to obtain uniform distribution in the coil. The temperature should be higher at the beginning and the end of the strip to keep higher temperature in internal (near mandrel) and external areas of the coil, which are exhibited to faster cooling than internal parts. The optimization variables are the same as in *Task* 2. The problem is multidimensional and requires nature inspired optimization method and modelling of coiling.

All these optimization tasks are accessible from the GUI and the user does not need to formulate the objective function.

5. CASE STUDIES

Different manufacturing routes were investigated for each group of steel grades. Selected results for the bainitic steels are presented below. Numerical simulations follow physical simulations using plane strain compression (PSC) tests. The tests were performed in the Institute for Ferrous Metallurgy in Gliwice and the full set of results is presented in [9]. Two variants of physical simulations were considered in the present paper. In variant 1 lower temperatures of deformation were applied. Variant 2 is characterised by higher temperatures. Grain size prior to the first deformation (after soaking) was 67 μm. Cooling from the last deformation temperature to the holding temperature was at the rate of 20°C/s. Three holding temperatures during cooling, 400, 500 and 600°C were used for each variant. Both variants were reproduced in the *VirtRoll* system. PSC deformation was replaced by rolling with the same reduction of the height. The particular emphasis was put on adjusting the models to be capable to simulate experimental manufacturing routes. The following aspects were of particular importance: i) Capability to predict material behaviour and product properties accounting for different finish rolling temperatures, ii) Capability to predict product properties for multi-phase microstructure, accounting for the properties and morphology of the component phases. In numerical simulations the same roll pass schedule was used for all steels and the results for one steel only are presented.

Various finishing rolling temperature. Two cases were considered, conventional with the finish rolling temperature of 950°C (Variant 2) and a new route assuming additional fast cooling device before last two deformations (Variant 1). Calculated time-temperature profiles for both variants are shown in Fig. 4a and changes of the austenite grain size are shown in Fig. 4b. These data were used as starting point for further simulations of laminar cooling variants. The results for versions with CT = 500°C and CT = 600°C are shown in Fig. 5. These results were compared with experimental data and good predictive capabilities of the model were confirmed.

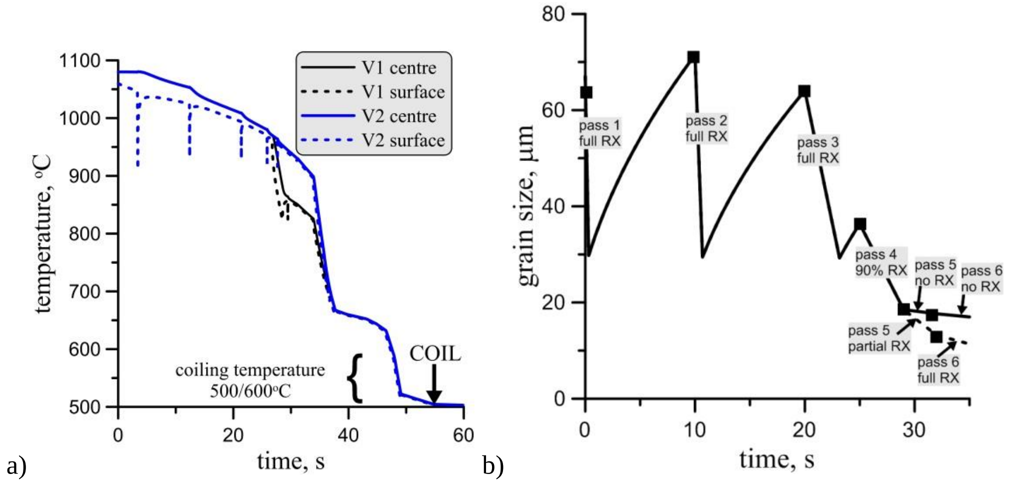
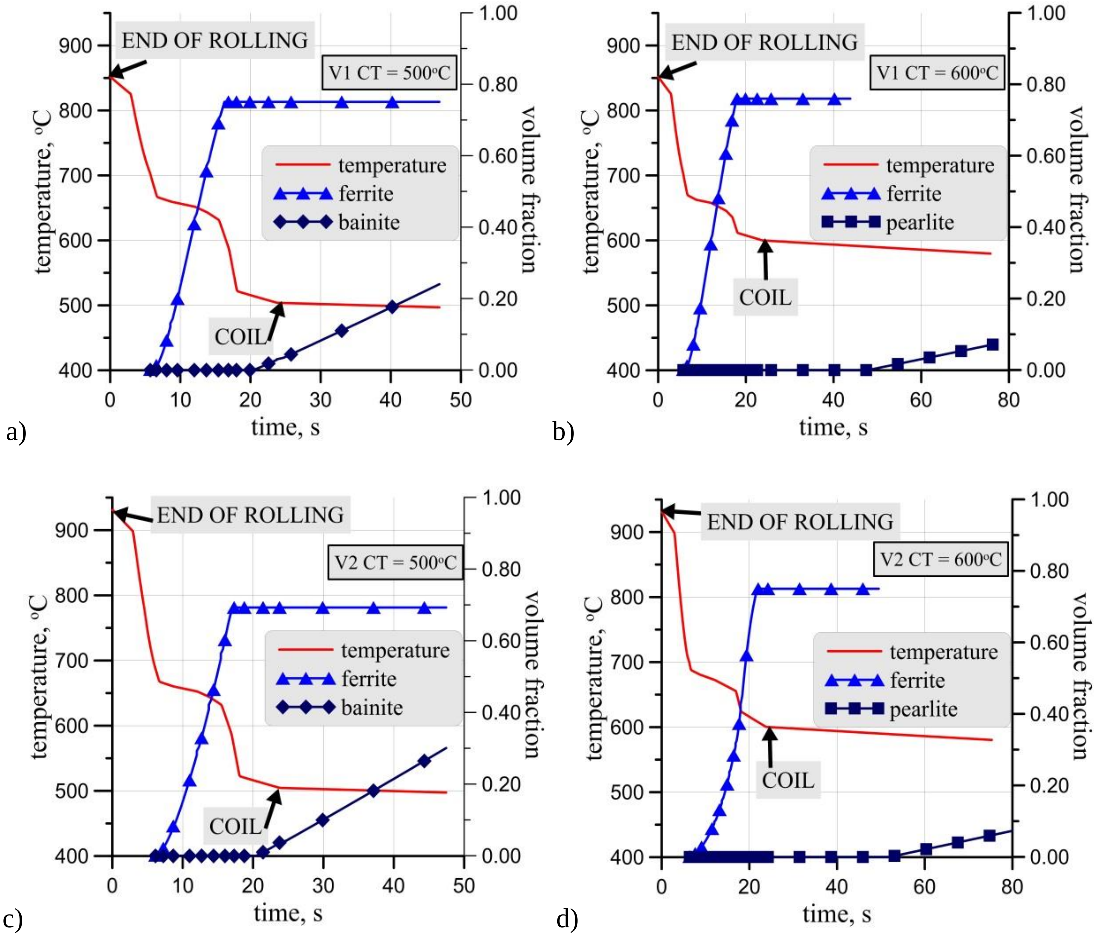


Fig. 4. Variant 1 (a) and variant 2 (b) of physical simulations

Various laminar cooling parameters. In the former case the laminar cooling parameters were changed only to change the coiling temperature. In the present set of calculation more flexibility was added to the cooling system. Ultra-fast cooling device was added between the last stand and the typical laminar cooling. The optimization *Task* 2 was realized in the *VirtRoll* system. The objective was to obtain 82% of bainite (O1) and

72% of bainite (O2) without martensite in the microstructure. The results for the two objective functions are presented in Fig. 6.



a) b)

c) d)

Fig. 5. Kinetics of transformations for Variant 1 (a,b) and Variant 2 (c,d) and for coiling temperatures 500°C (a,c) and 600°C (b,d)

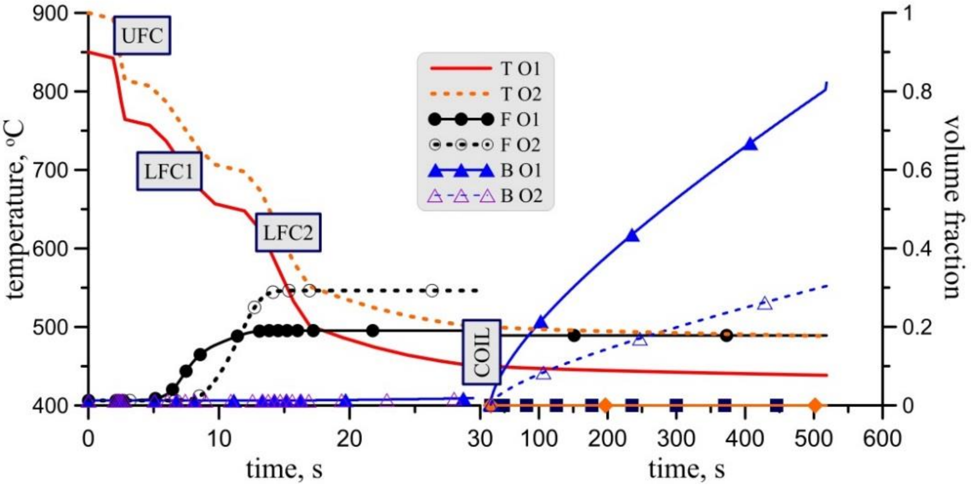


Fig. 6. Kinetics of transformations for optimal cooling strategies (F – ferrite, B – bainite)

6. VIRTROLL AS A PART OF THE DIGITAL TWIN FOR STRIP MANUFACTURING PROCESS

The most important part of innovative DTs is a module of data/measurements analysis equipped with innovative Machine Learning (ML) methods. The module integrates together sensors (giving the data directly from the process), analysis (based on Artificial Intelligence and Soft Computing) and decision support (responsible for control of the process). Thus, the integration is a cycle starting from and finishing with the production process. Moreover, modern manufacturing systems are complex networks of workers and machines interacting in a multitude of ways. So called "Smart Factory", based on real systems and their DTs, embraces large amounts of data both inside and outside the production environment across the whole production lifecycle. Efficient and effective use of this data enables the manufacturing process to become more agile, increases reliability in products and helps to ensure that resources are used more efficiently. Thus manufactures are empowered to become more competitive.

The vision of the VirtRoll as a part of DT relies on the integration of advanced ML techniques and Cyber-Physical Systems (CPSs) across the whole product lifecycle. This integration is increasingly focused on the appropriate and innovative use of Big Data tools, managing in an intelligent way how information is generated, captured, stored and used for decision making across the factory from shop floor employees to senior business managers and external suppliers.

The vision in this system is to develop solutions to support the transformation from data generated by CPS networks, to useful information and strategic knowledge using simulation and decision support methods to improve both the factory floor operation and integration with the wider Enterprise systems.

CPSs are the next generation of embedded ICT systems, interconnected through technology associated with the concept of the Internet of Things (IoT) and endowed with data gathering functions and output capabilities. Due to their integration in the user environment they can track a wide variety of production environment data. Cyber-Physical Production Systems (CPPSs) is the branch focused on industry. CPPSs make the most of the gathered data in order to allow improved agility in the manufacturing process by presenting increased possibilities for improved flexibly and efficiency in the process.

VirtRoll aims to provide algorithms and software tools to improve the manufacturing process chain by collecting and federating data and then generating information and knowledge from that data using data analytics. This will benefit the product life cycle during the design, production and product use cases. The data analytics and numerical simulation are the crucial part of innovation and contain smart software to conduct functionalities such as prediction, anomaly and trends detection, motive discovery, novelty, clustering and classification that can be used to optimise production capacity and quality and improve predictive maintenance.

At the Enterprise level, connecting with factory floor data enables improved integration with higher-level business functions such as logistics with low-level activity on the production line. Big Data analytics will drive the integration and use of low-level and Enterprise data to establish a more direct interactive relationship and knowledge. Analytics and integration of low-level and high-level data within the organization offers manufacturers the ability to perform predictive maintenance, optimization of the supply chain and service delivery as well as obtaining insights into how, when and where devices are being used. Taking advantage of these opportunities will result in cost savings and will expedite product innovation.

7. CONCLUSIONS

The paper presents idea of VirtRoll system application as a digital twin of hot rolling production line. Besides the description of the system functionality and the possibilities of its practical usage, the idea of machine learning module capabilities and implementation was given. The module has crucial impact on the consistency of the whole solution by integration of the production process as a data source, the module of ML analysis and decision support offering new propositions of process input and control parameters. The proposed system has also a huge influence on:

- Increased productivity – improvement of productivity by ensuring improved resource usage in the manufacturing supply chain. Via the use of algorithms, tools and device integration improved knowledge of the manufacturing process chain will be achieved. This knowledge will form the basis on which the process can be better planned and react faster to process changes / reconfigurations.
- Improved cost efficiency and accuracy, reliability and performance of simulation techniques for manufacturing processes and/or full complex products – the system provides a holistic approach, where simulations are integrated with process data analytics for improving simulation effectiveness and reliability.
- Enhanced interoperability of integrated product and factory design systems and global state monitoring enabling new type of services related to the data analysis, simulations and visualization techniques in each manufacturing stage.
- The future work with the system assumes design and implementation of specific ML algorithms and performance of numerical tests for selected case studies.

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