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THE OFF-LINE COMPUTER SYSTEM FOR DESIGN OF THE HOT ROLLING AND LAMINAR COOLING TECHNOLOGY FOR STEEL STRIPS

The objective of this work was development of the computer system *VirtRoll*, which allows designing of the arbitrary rolling line and performing numerical simulations using high efficiency hardware architectures. Selection of the mechanical, thermal, microstructural and phase transformation models, which allow decreasing the computing costs while the accuracy of simulations is maintained on the reasonable level, was one of the objectives of the paper. Thus, metamodel was applied in the mechanical part and a simple finite element approach was used in the thermal part of the hot rolling model. Simulations of microstructure evolution in hot rolling and phase transformations during the laminar cooling were based on modified Avrami equation. The system was designed in the client-server architecture, in which client part is in the form of the graphical interface. This interface allows to design of rolling line. The server part is composed of: i) controllers which prepare computing tasks, ii) middleware layer responsible for launching and monitoring of the computing tasks, iii) the layer of numerical computations. Deal.II library dedicated to solve partial differential equations was used for the time step adaptations. All these parts led to short computing times and additionally allowed parallel solution of the optimization tasks. Simulations of thermal-mechanical-microstructural phenomena were performed for the rolling-cooling sequence and the results allowed validation of the system.

1. INTRODUCTION

Design of manufacturing processes often involves time consuming computations, in particular when multi iteration optimization techniques are applied. Hot strip rolling is an example of such manufacturing process, in which particular operations (rolling, laminar cooling, coiling) are controlled by a number of the design variables. The objective of this work was development of the computer system, which allows designing of the arbitrary rolling line and performs numerical simulations using high efficiency hardware

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architectures. This system called *VirtRoll* is described in the paper. Selection of the mechanical, thermal, microstructure evolution and phase transformation models, which allow decreasing the computing costs while the accuracy of simulations is maintained on a reasonable level, was one of the objectives of the paper. Beyond computational efficiency, particular emphasis was put on accuracy of simulation. Thus, selection of models was based on the trade-off between computing costs and predictive capabilities of models [1]. All material models describing flow stress, microstructure evolution and phase transformation were identified on the basis of experimental tests, and were implemented in the FE thermal code using multiscale approach.

2. MODELS

Details of all models implemented in the *VirtRoll* system can be found in earlier publications and they are collected in the book [2]. The basic features of these models are repeated briefly below for completeness of the paper.

2.1. MECHANICAL MODEL

Originally finite element (FE) model described in [3] was used to calculate strains, stresses, forces, torques and temperatures. Even if a simple stationary FE model with a coarse mesh is used in simulations of metal flow in rolling, the computing time for one pass is about 2-3 minutes. Since a lot passes have to be simulated to determine one value of the objective function in, the decision was made to search for alternative models, which can accelerate optimization. Application of the metamodel is such an alternative. Metamodel of the process or phenomenon is a certain abstraction created on the basis of the lower level model developed using mathematical techniques. Thus, any approximation of the basic model, which gives reasonably realistic description of the process, can be considered a metamodel. Metamodel allows for significant decrease of the computing time.

Various techniques can be used to build metamodels. Artificial Intelligence (AI) methods, in particular Artificial Neural Networks (ANN), are the most common. When the cost of computations for training data is not so high and large training data sets can be created, application of the ANN is efficient and even very complex relationships can be accurately described by the metamodel. Contrary, when the FE method is used to generate training data, the costs of computations of one set of data are high and other metamodelling techniques should be searched. The surface response method was used in the present work to calculate mechanical parameters including strains, stresses, forces and torques. Additional advantage was made of the fact that the material flow stress is the main factor, which decides about the accuracy of calculation of force parameters and an influence of the geometrical parameters is of lesser importance. Therefore, the emphasis was put on accurate identification of the flow stress model. Plastometric tests were performed for each material in the database and flow stress models were identified using inverse analysis [4]. Relation between the flow stress (σ_p) and the average pressure (p_{av}) in rolling has to account for so called “friction hill” and this relation was described by the surface response method. The metamodel follows the idea of Sims [5], who introduced coefficient Q representing average pressure-to-flow stress ratio ($Q = p_{av}/(a\sigma_p)$, where $a = 2/\sqrt{3}$). Large number of calculations was performed using FE program [3] for different reductions (ε), roll radius (R) and friction coefficients (μ). This data were used to find polynomial relation describing function $Q = f(\varepsilon,R,\mu)$. However, sensitivity analysis has shown that the effect of the design variables can be combined together by introduction of one variable $\xi = \mu/\Delta$, where Δ is the shape factor defined as h_{av}/l_d, $h_{av} = (h_1 + h_2)/2$ is an average thickness, $l_d = \sqrt{Rh_1\varepsilon}$ is the length of the arc of contact. Several FE simulations were performed for various process parameters and it was found in [6] that for a wide range of strip thicknesses and reductions the relationship between Q and ξ is linear. In consequence, the following equation was obtained by approximation of results of the FE simulations:

$$F = \sigma_p l_d w \left(1 + 0.572\frac{\mu}{\Delta}\right) \tag{1}$$

where: w - width of the strip, F – rolling force.

Several flow stress models are implemented in the system. All these models are described in [2] and they are not repeated here. Hensel-Spittel model [7] was used in the case study in Chapter 0 of this paper:

$$\sigma_p = A\varepsilon^B \exp\left(-C\varepsilon\right)\dot{\varepsilon}^D \exp\left(-ET\right) \tag{2}$$

where: ε – strain, $\dot{\varepsilon}$ – strain rate, T – temperature in °C, A, B, C, D, E - coefficients.

Similar metamodel was developed to calculate strain distribution through the thickness of the strip. Numerous FE simulations were performed for various parameter Δ and it was found that following function describes strain distribution with good accuracy:

$$\varepsilon\left(y\right) = \frac{2}{\sqrt{3}}\ln\left(\frac{h}{h_1}\right)\left[1 + 3\left(\frac{0387y\Delta}{y_{\max}}\right)^2\right] \tag{3}$$

where: h_1,h – entry and current thickness of the strip, respectively, y – coordinate through the thickness ($y = 0$ in the centre and $y = y_{\max} = h/2$ at the surface.

Equation (3) allows to calculate strain at each location along the roll gap and through the thickness of the strip. Equation (1) allows further to calculate rolling torque (M_r) as well as electric current (I) and power (P) of the motor:

$$M_r = \psi F l_d \tag{4}$$

$$M_b = 2\mu_b F R_b \tag{5}$$

$$M_M = \frac{M_w + M_b + M_{bj}}{\eta_D \eta_M i} \tag{6}$$

$$P = M_s\omega \tag{7}$$

where: ψ – arm of the torque calculated using equations in [8], i – gear ratio, M_b – friction torque in bearings, M_N – nominal torque of the motor, M_{bj} – idle torque assumed as equal to $0.05M_N$, R_b – radius of the bearing, μ_b – friction coefficient in the bearing, ω, ω_N – current and nominal angular velocity of the motor, i – transmission ratio.

Equations describing components of the total torque were taken from [8]. The electric current of the motor was calculated from the electric power, depending on the type of the motor. For alternative current motors it was:

$$I = \frac{P}{U \cos(\varphi)} \tag{8}$$

where: U – voltage, φ – power factor defined as the cosine of the phase angle between voltage and current.

Equations presented in this section are used in the system to calculate all mechanical parameters as well as power and electric current required to run the rolling mill. These equations are coupled with thermal and microstructural models.

2.2. THERMAL AND MICROSTRUCTURAL MODELS

1D solution of the Fourier equation was used to calculated temperature distribution through the thickness:

$$\frac{\partial}{\partial x}\lambda\frac{\partial T}{\partial x} + Q = \rho c_p \frac{\partial T}{\partial t} \tag{9}$$

where: T – temperature, λ – conductivity, x – coordinate along the thickness, ρ – density, c_p – specific heat, t – time.

Equation (9) has to satisfy the boundary condition on the top and bottom surface:

$$\lambda\frac{\partial T}{\partial x} = \alpha\left(T - T_a\right) \tag{10}$$

where: T_a – ambient temperature, α – heat transfer coefficient selected according to the current location of the strip.

Microstructure evolution model was based on works of Sellars in the University of Sheffield [9]. This model includes equations describing recrystallization and grain growth. The model is executed depending on strain and recrystallized material fraction according to the diagram presented in Fig. 1. The diagram contains general approach for the austenite microstructure evolution simulation during the hot rolling process.

Coefficients in microstructure evolution equations for each steel in the database of the system were determined on the basis of stress relaxation tests or 2-step compression tests. Equations of the microstructural model with the coefficients for the DP600 steel investigated in the present work were given in [10] and they are not repeated here.

1D thermal model allows to obtain very fast and reliable calculations, which do not require parallelization. On the other hand, micro scale models are attached to selected integration points in hierarchical semi- or fully coupled way.

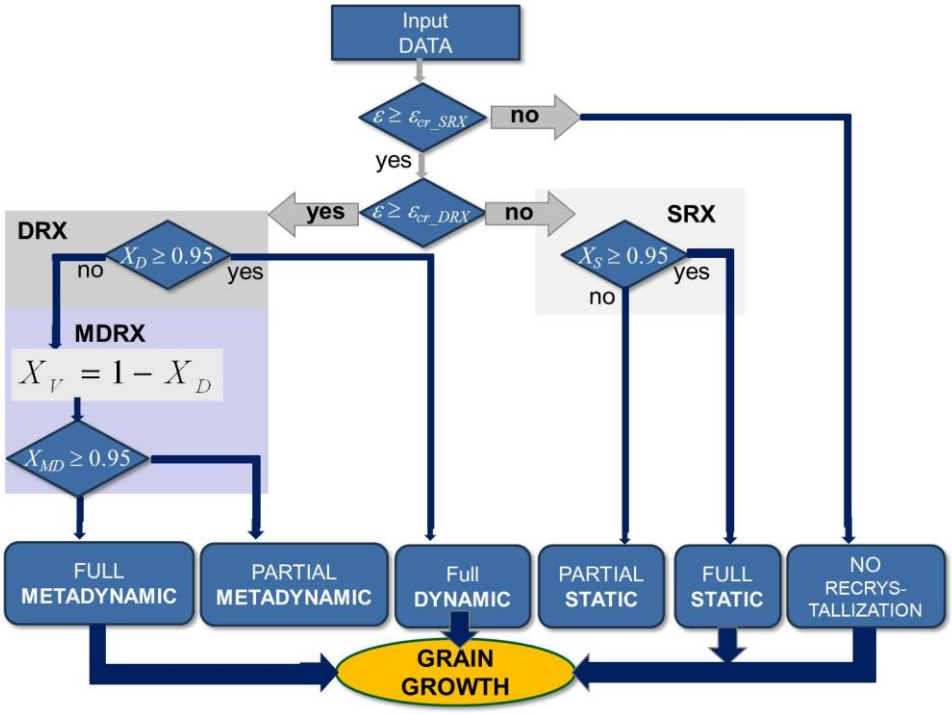


Fig. 1. Flow of calculations in simulations of microstructure evolution (SRX, DRX and MTDRX – static, dynamic and metadynamic recrystallization, respectively)

Such implementation offers very flexible way of distribution of calculations onto HPC infrastructures, as well as facilitates collection of results. The algorithms used in micro scale can be designed and implemented on the basis of different approaches, depending on the needs. This gives another possibility of parallelization on the level of multicore computing devices e.g. GPGPUs or dedicated co-processors. Additionally, the computational module contains two numerical libraries: i) optimization library dedicated to determine optimal parameters for rolling mill devices; ii) sensitivity analysis library allowing investigation of particular parameters influence on final properties of the product.

2.3. LAMINAR COOLING AND PHASE TRANSFORMATION MODELS

An arbitrary laminar cooling equipment can be designed in the *VirtRoll* computer system. The most typical laminar cooling composed of two sections was considered in the paper. There were 40 boxes in each section and the length of each box was 1m. Sections were divided into 12 zones of three types: intensive zone, normal zone and trimming zone. Distance between the sections was 20m. Schematic illustration of this laminar cooling system is shown in Fig. 2. Number of boxes in each zone is given in the figure, as well as in Table 1. Maximum water flux in various zones is also given in Table 1. Maximum heat transfer coefficient for the laminar water cooling was calculated on the basis of equation proposed in [11]. This heat transfer coefficient was decreased proportionally to the water flux decrease. More details on this laminar cooling system are given in [12].

Table 1. Number of boxes and maximum water flux in each zone of the laminar cooling (I – intensive, N – normal, T – trimming)

Zone	1 I	2 I	3 N	4 N	5 I	6 I	7 N	8 T
boxes	12	8	6	14	12	10	10	8
W, m^3/h	860	580	300	680	860	860	340	250

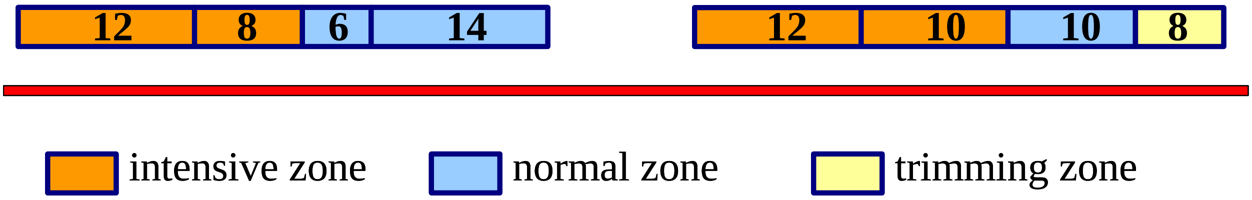


Fig. 2. Schematic illustration of the laminar cooling system investigated in the paper

Temperature distribution in the strip during laminar cooling was calculated using the model described in section 2.2. Prediction of the kinetics of phase transformations and volume fractions of phases after cooling was the main task of the laminar cooling model. Modified JMAK equation was used to reach this task. The basic form of this equation is:

$$X = 1 - \exp\left(-kt^{n}\right) \tag{11}$$

where: X – volume fraction of a new phase, k, x – coefficients, t – time.

Modification of equation (11) included introduction of the coefficient k as a function of the temperature. Various functions k= f(T) were used for ferritic, pearlitic and bainitic transformations, see [13] for details.

Mechanical, thermal, microstructure evolution and phase transformation models described briefly in this Chapter and in detail I publications were implemented [5-13] in the *VirtRoll* system and used for simulations of hot rolling processes.

3. *VirtRoll* SYSTEM

The *VirtRoll* system is dedicated to flexible modelling of material behaviour in rolling mills of an arbitrary configuration. The system enables large scale computations, sensitivity analysis and optimization. Before designing the system, an analysis of the software architecture which should be used as a fundamental element of this system, was performed. All the considered aspects of the architecture influence final design of the system 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 (e.g. *Scalarm* [15]), which are crucial for using modern e-infrastructures. Main features of the *VirtRoll* system are described in this Chapter.

3.1. METHODOLOGY

Studying rolling processes by building a virtual hot rolling mill can be considered as a multi-step workflow involving: design of a virtual hot rolling mill, simulation of the rolling process with the parameter study approach, and output data exploration with sensitivity analysis methods to discover relationships between the hot rolling mill parameters and the obtained thermo-mechanical properties in final product [17]. Each of these steps has different requirements regarding easiness of use, computing power and progress monitoring. Designing and developing a system supporting this multi-step workflow was the objective of the presented work. An overview of the system along with main steps of the workflow is shown in Fig. 3.

The first step of the workflow is design of a virtual hot rolling mill including selection of devices, their location, and configuration parameters. The *VirtRoll* system supports this step by providing a virtual workplace with a graphical drag&drop editor of the rolling mill and a toolbox of available configurable devices. The user can either prepare a mill design from the scratch or select an existing project of a mill. Moreover, the user can save the work at any given moment and return to it in the future.

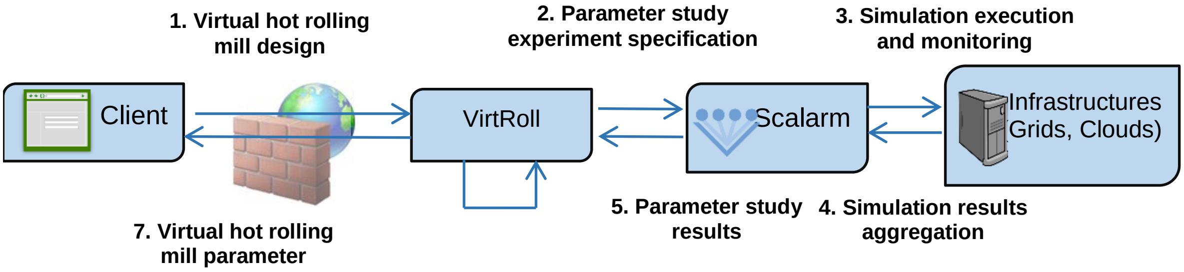


Fig. 3. An overview of a system supporting studying workflow of hot rolling processes

The second step is numerical simulation of the rolling process in a parameter study manner. The user prepares a parameter space involving material parameters, devices configuration and process conditions. Briefly, the parameter study includes:

- computational tasks scheduling to high performance computational infrastructures,
- on-line progress monitoring of the simulations with capability to adjust computing power or extend the parameter study interactively,
- collecting simulation results and further analysis.

These functionalities are attained by integrating the *VirtRoll* system with the *Scalarm* platform described in [14],[15] and extending it where required.

The third step of the workflow is exploration of the simulations results. The objective of this step is to reach a better understanding of the rolling process and discover pros and cons of the designed virtual rolling mill in terms of properties of the final product. The conducted parameter study provides sufficient data to perform a meaningful sensitivity analysis and to discover relationship between simulation input and output.

3.2. DESCRIPTION OF THE TECHNOLOGY OF THE SYSTEM DESIGN

The technology used in the paper uses three main elements: the Graphical User Interface (GUI) of the *VirtRoll* system, the middleware in form of the *Scalarm* platform as well as numerical simulations of rolling/cooling processes. The GUI created as a web-based module facilitates access from different operating systems and devices. Application of modern web technologies, e.g. AJAX and HTML5, fulfils requirements regarding various operating systems, interactivity and easiness of use. Information about materials and devices available for rolling mill designers is stored in the database, see next section for details. In contrast to web-based high-level solutions, the *VirtRoll* computing module, used to simulate rolling cycles, was developed as a high performance parallel application. It was dedicated to be executed on High Performance Computing (HPC) systems. As it has been mentioned, the *Scalarm* platform was applied to ensure interoperability between the *VirtRoll* web-based module and *VirtRoll* numerical simulations. Both systems follow the lightweight Service Oriented Architecture (SOA) approach. They are loosely coupled services, deployed on separated hosts, and exchange information with a REST-based API accessible via the HTTP protocol. Security is an important aspect of such integration and HTTPS was used for secure communication between the user and the system and between the system and the *Scalarm*. Another aspect of the application security is authentication. The OpenID technology was used to provide the Single Sign-On functionality and to enable users to use their existing accounts. This influences design of the data structures, which are dedicated to store users' data like login, password or other credentials.

3.3. *VirtRoll* INTEGRATION WITH SCALARM

Scalarm is domain-agnostic, i.e. it supports all types of simulations and can be used to conduct experiments from various science disciplines. To date, *Scalarm* has been utilized to study security forces strategies, parallel programming algorithms, and optimization problems and more information about *Scalarm* can be found in authors previous works [14],[15]. In this work *Scalarm* is a comprehensive platform for parameter studies. It supports following three steps necessary to conduct experiments based on the parameter study:

- Input space specification – values necessary to be explored are specified for each input parameter and constitute an experiment input parameter space; each element of such space is a vector of values for a single simulation run.
- Simulation – a single experiment may require substantial computational resources, possibly collected from different infrastructures. Thus, *Scalarm* provides a reliable middleware layer for uniform accessing heterogeneous computational infrastructure.
- Results collecting and exploration – each simulation returns a set of results describing the studied process. *Scalarm* aggregates the results from all the simulations and enables data exploration and visualization with various charts.

Scalarm provides two user interfaces: a web-based application and REST API. The former is dedicated to scientists who run their simulation codes manually on various infrastructures and would like to facilitate this cumbersome process. The latter supports the integration of third-party tools with *Scalarm* using a programming language communication protocol HTTP and a data representation format JSON. The integration of the *VirtRoll* system with *Scalarm* was based on this approach. JSON was used to store information in the data and knowledge bases, as well as in internal communication of all the subsystems.

The integration is transparent from the end user point of view. The following list describes the most important methods of the API for computation delegation from the *VirtRoll* system to actual computational infrastructure:

- Registering a simulation scenario – it is a prerequisite of conducting a parameter study with *Scalarm*. The registered simulation scenario includes simulation binaries/codes, a description of input parameters and a set of so called adapters to transform input/output of the simulation from the *Scalarm* form to the simulation specific-form.
- Starting a new experiment – it includes identification of a previously registered simulation scenario and input space specification, i.e. parameterization types and specific attributes for each selected parameterization type.
- Scheduling computations – the user can specify how much computing power and from which infrastructure should be used to execute simulation runs in a form specific for each infrastructure, e.g. a grid job or a virtual machine instance.
- Getting information about experiment’s progress – at any given time the user can check how many simulations are running and how many of them were completed.
- Download results – an integrated third-party tool can download results of the already completed simulations (e.g. as CSV file) to enable further analysis with more domain-oriented tools.
- Extending an experiment – based on the analysis of results it may be necessary to explore additional parameter spaces or to study interesting cases, not included previously.
- Stopping an experiment – when all simulations were completed, the experiment can be stopped and marked as historical. In such a case the results are stored in the platform and can be explored.
- Removing an experiment – when the results are no longer necessary, the experiment can be removed from the system.

Each of these methods is executed by the *VirtRoll* system on behalf of an actual user. The authentication and authorization process is facilitated by the OpenID mechanism. The user authenticates himself only at the trusted OpenID provider. In return, the *VirtRoll* system obtains a proxy certificate, which enables infrastructure permissions delegation in the grid infrastructures context. This proxy certificate is passed to the *Scalarm* platform, which handles computation scheduling and monitoring.

Moreover *Scalarm* allows selection of an adequate computational infrastructures and scheduling software. Solutions for executing metallurgical-related numerical simulations in data farming and task farming manner on High Performance Computing (HPC) infrastructures were analysed, e.g. Pegasus, Taverna, and the UNICORE Workflow system. More specifically capabilities related to the following aspects were evaluated:

- support for parameter space specification for conducting parameter studies,
- integration with such computational infrastructures as clusters, grids and clouds,
- simulation output collecting for further analysis in an automatic manner,
- fault-tolerant and reliable execution of computations.

Besides provided functionality, the survey involved analysis of non-functional aspects, namely scalability and elasticity of the solutions with regard to efficient execution of numerous simulations in parallel and computational resources management. In addition, available Application Programming Interfaces were evaluated regarding dynamic resources scaling and providing virtual clusters on demand to execute large-scale numerical simulations, in the context of Grid middleware solutions (QosCosGrid, Unicore and gLite), Computing Clouds (Amazon Elastic Compute Cloud, Google Compute Engine and Microsoft Windows Azure).

3.4. DATABASE AND KNOWLEDGE BASE

The design of the database was prepared to be flexible, thus object-oriented MongoDB engine was used. This choice was dictated by the necessity of a flexible data model of the process, i.e. support for new materials and devices characterized by different parameters. The material parameters included in the database compose coefficients in the flow stress models, microstructure evolution models and phase transformation models and they are combined with the chemical composition of steel. Thermophysical and thermodynamic parameters are gathered in the database, as well.

Advanced materials and new manufacturing technologies bring new theoretical and practical knowledge, which should be stored inside the *VirtRoll*, as well. This leads to the advantage that the results gathered with several experiments will be available to other users in the company. The knowledge is therefore stored and will be still available even if the experts, who were the sources of this knowledge, leave the company or retire. The knowledge base to be used in *VirtRoll* fulfils the following demands:

- The user friendly interface. It has to be usable for technologists who are not always IT experts.
- An integrated support for the integration of graphics, formulas as well as bibliographical references in usual styles (e.g. integration in bibtex format).
- Since export to PDF and a layout by means of TEX were made available, the information stored in the knowledge base can be also used for a paper reports.
- The structure of the knowledge base is designable by means of processes or plant types.
- The option to search inside the documentation was added.

The direct connection between the documentation inside the knowledge base and the simulation system was made. The results can be easily interpreted if the experiments are processed directly with given parameters used to reach the results. This offers the possibility to the user to change some parameters and run the experiment again. The new results can be compared to the documented ones to see the influence of some parameters. The solution used for *VirtRoll* takes all the above mentioned demands into account. To reach this functionality the data analysis tool for JMatPro EDA (Extended Data Analysis) software developed by METATECH [18] was selected as platform for the *VirtRoll*. This tool can be used to analyse hundreds of JMatPro calculations. EDA is a web oriented data system for analysis and processing of virtual material data. It fulfils all the demands as defined above. EDA consists of two platforms: DATA and DOCS. Material data and bibliography are stored in DATA and one can perform various tasks, calculations or curve fitting. Various regression methods were made available to reach this goal. DOCS, which is based on Markdown syntax for editing (simplified html), is a wiki-similar platform where the results of data analysis and processing can be integrated in structured documents. DOCS has a toolbar and a preview window. It uses also MathJax, so that equations and mathematical symbols can be written in the Tex-Syntax. DOCS is a multimedia platform so that external images, references links, etc. can be embedded in documents.

Easy access to the data and knowledge bases is the main advantage of the *VirtRoll*. It was reached by using the Model-View-Controller (MVC) pattern, which was used to design the web-based part of the *VirtRoll* system. In object-oriented programming development, MVC is the name of a methodology or design pattern for efficient relating the GUI to underlying data and models. The MVC is widely used in development of programs in Java, Smalltalk, C, and C++ and it has been heralded by many developers as a useful pattern for the reuse of object code and a tool that allows them to reduce the time necessary to develop applications with user interfaces. The MVC pattern proposes three components or objects:

- A Model, which represents the underlying, logical structure of data in a software application and the high-level class associated with it. This object model does not contain any information about the user interface.
- A View, which is a collection of classes representing the elements in the user interface (all of the things the user can see and respond to on the screen, such as buttons, display boxes, and so forth).
- A Controller, which represents the classes connecting the model and the view, and is used to communicate between classes in the model and view.

The View layer allows to design any configuration of rolling mill, which is passed further to controller responsible for serialization of the design into a JavaScript Object Notation (JSON) file. Additionally, users are able to setup the possible ranges of values for different parameters of the process. This allows to generate the proper sampling of parameter space and save such configuration of samples in a Comma Separated Values (CSV) file. The final design of a hot rolling mill is stored in the *VirtRoll* database, while the files in JSON and CSV formats are passed further to Scalarm.

Controller is a part of specific business logic of the *VirtRoll* system, which is integrated with the Graphical User Interface. A Model layer is a set of classes which are created according to the rules of Object-Relational Mapping (ORM). This mechanism makes it possible to address, access and manipulate objects without having to consider how those objects relate to their data sources. ORM allows programmers to maintain a consistent view of objects over time, even as the sources that deliver them, the sinks that receive them and the applications that access them change. Based on abstraction, ORM manages the mapping details between a set of objects and underlying relational databases, XML repositories or other data sources and sinks, while simultaneously hiding the often changing details of related interfaces from developers and the code they create. ORM hides and encapsulates change in the data source itself, so that when data sources or their APIs change, only ORM needs to change to keep up—not the applications that use ORM to insulate themselves from this kind of effort. This capacity lets developers take advantage of new classes as they become available and also makes it easy to extend ORM-based applications. In many cases, ORM changes can incorporate new technology and capability without requiring changes to the code for related applications.

3.5. IMPLEMENTATION OF MATERIAL MODELS

The man part of the system is encapsulated in separated computational module responsible for numerical modelling of macro and micro properties of material. The macro scale simulations of temperatures are realized by using FE method coupled with mechanical and microstructural models, see Chapter 0. Material models described in Chapter 0 are stored in designed database (Section 3.4). Flexibility of *VirtRoll* system assumes that user can add new material models through the GUI. Therefore, initial library was created, which contains abstract classes. These classes are proposed in multi-level hierarchy, which can be directly inherited. The classes already implemented are as follows:

- *Model* – root class of the whole hierarchy, containing calculation method. The method is responsible for execution of calculations specific for selected model.
- *RheologicalModel* – the main class for rheological models. Currently all models discussed in [2] are implemented.
- *StaticRecrystallizationModel* – the main class for SRX models [2].
- *DynamicRecrystallizationModel* – the main class for DRX models [2].
- *MetadynamicRecrystallizationModel* – the main class for MTDRX models [2].
- *FerriteTransformationModel* – the main class for ferrite phase transformation models.
- *PearliteTransformationModel* – the main class for pearlite phase transformation models.
- *BainiteTransformationModel* – the main class for bainite phase transformation models.
- *MartensiteTransformationModel* – the main class for martensite phase transformation models.

3.6. SUMMARY OF *VirtRoll* CAPABILITIES

Due to application of innovative materials in connection with advanced production technologies, optimization of semi products and product properties in metal forming is highly sophisticated nowadays. Prediction of material properties after rolling and cooling usually requires expensive, long lasting experimental trials, which do not guarantee identifying the optimal technological parameters. Thus, the *VirtRoll* model-based computer system described in this section joins functionality of numerical simulations, material modelling (metamodelling), multi scale modelling, inverse analysis and optimization to minimize costs of design of production technologies and maximize semi and final product properties. The system is equipped with advanced numerical models for advanced steels (AHSS, modern bainitic steels, HSLA). *VirtRoll* combines developed models with database, knowledge base and inverse solution coupled with optimization techniques in one hybrid computer system. The main advantages and unique functionalities of the system can be summarised as follows:

- The user friendly interface (GUI), which is usable for engineers who are not IT experts.
- Advanced physical and numerical models to predict behaviour of advanced steels.
- Guidelines for unconventional production methods.
- A graphical drag&drop editor which supports flexible design of rolling mill.
- Database and knowledge base, which essentially support design of rolling technology.
- Sensitivity and inverse analyses to support flexible design of strip rolling technology.
- Combining developed models, database, knowledge base and inverse into one hybrid computer system.

4. CASE STUDY

Modern bainitic steel with the chemical composition in Table 2 was selected to demonstrate capabilities of the *VirtRoll* system. Experiments performed to supply data for identification of material models included plastometric tests (flow stress), two step compression tests (microstructure evolution) and dilatometric tests (phase transformations). All experiments were performed in the Institute for Ferrous Metallurgy in Gliwice, Poland. Experimental data were subjected to the inverse analysis [2] and coefficients in material models were determined. These coefficients were loaded to the *VirtRoll* database.

Table 2. Chemical composition of the investigated steel, wt%.

C	Mn	Si	P	S	Ti	Mo	Al	N
0.11	1.95	0.98	0.020	0.007	0.18	0.20	0.022	0.004

Selected results of identification of material models are shown in Fig. 4. Flow stress curves for various temperatures and the strain rate of 1 s-1 are shown in Fig. 4a. Coefficients in equation (2) determined using inverse analysis are: A = 10539, B = 0.435, C = 0.789, D = 0.112, E = 0.00355. Fig. 4b shows comparison of measured and calculated force during the two-step compression test. Optimized microstructure evolution model was used in this simulation and the results confirm good accuracy of this model. There was almost no softening for lower temperature (1000^{o}C) and lower strain in the 1st step (0.2) while almost full softening was observed for higher temperature (1100^{o}C) and higher strain in the 1st step (0.3). Prediction agree well with the experimental data.

Dilatometric tests were performed for identification of the phase transformation model and coefficients in the model were identified. Results of validation of this model are shown in Fig. 5. Equilibrium carbon concentration at austenite-ferrite ($c_{\gamma\alpha}$) and austenite cementite ($c_{\gamma\beta}$) boundaries are shown in Fig. 5a, where c_0 is carbon concentration in the steel. Fig. 5b shows comparison between measured and calculated start and end temperatures for phase transformations. It is seen that very good agreement between predictions and measurements was obtained when coefficients of the model were determined using inverse analysis of dilatometric tests.

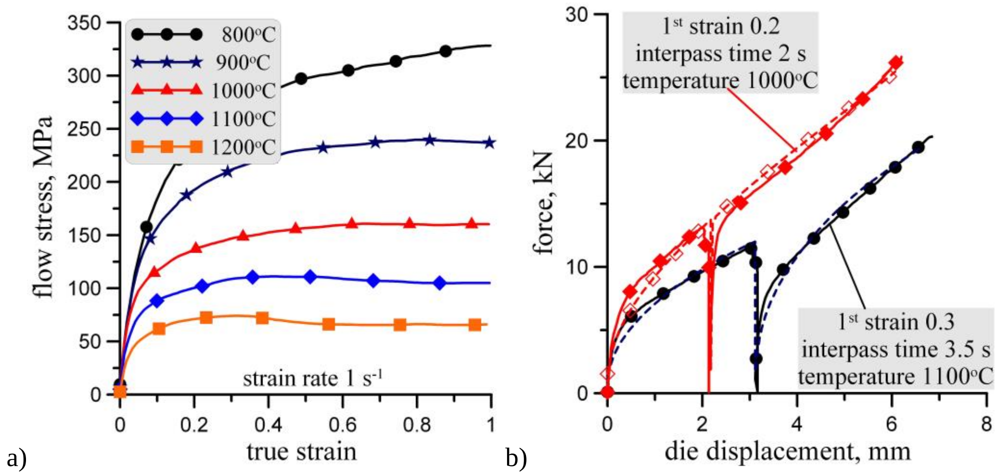


Fig. 4. An overview of a system supporting studying workflow of hot rolling processes

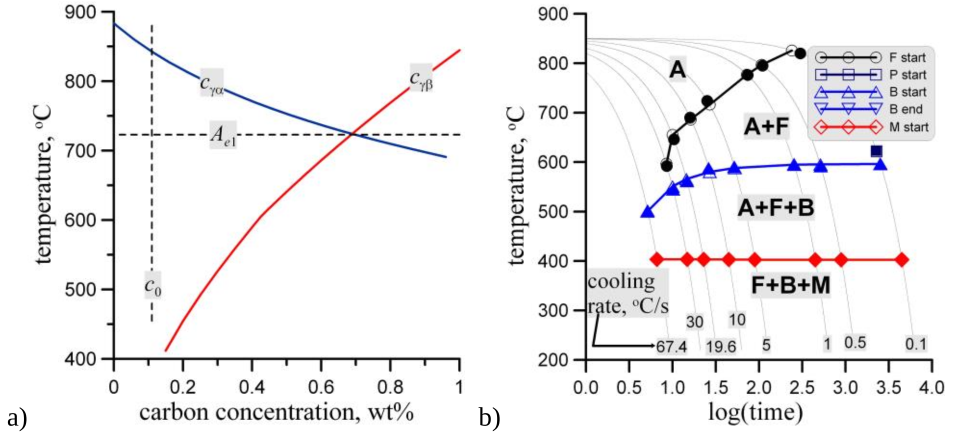
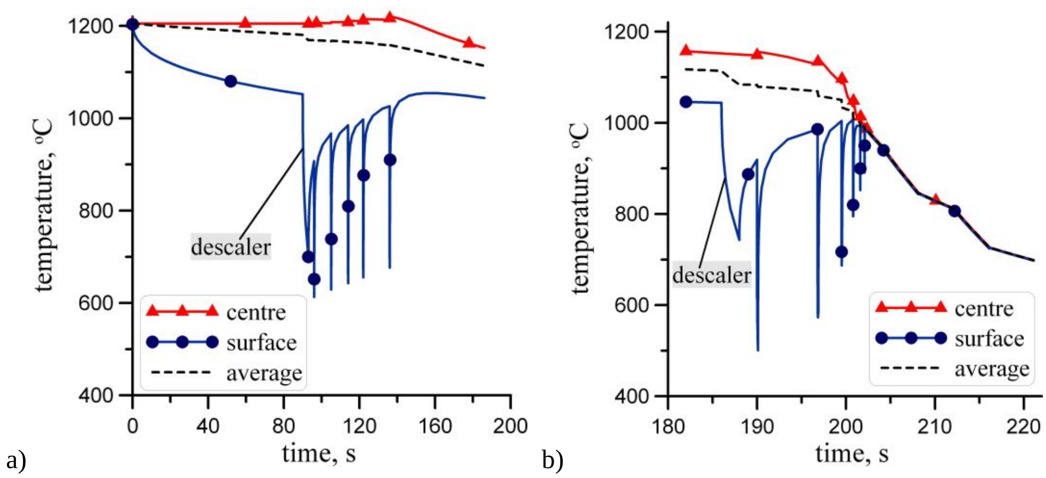


Fig. 5. Equilibrium carbon concentration at austenite-ferrite ($c_{\gamma\alpha}$) and austenite cementite ($c_{\gamma\alpha}$) boundaries (a) and comparison between measured (filled symbols) and calculated (open symbols with lines) start and end temperatures for phase transformations (b).

All optimized coefficients of models were implements in the database of the *VirtRoll* and simulation of the hot rolling process were performed. Typical hot strip mill composed of the reverse roughing mill and 6-stand finishing train was selected for the analysis.

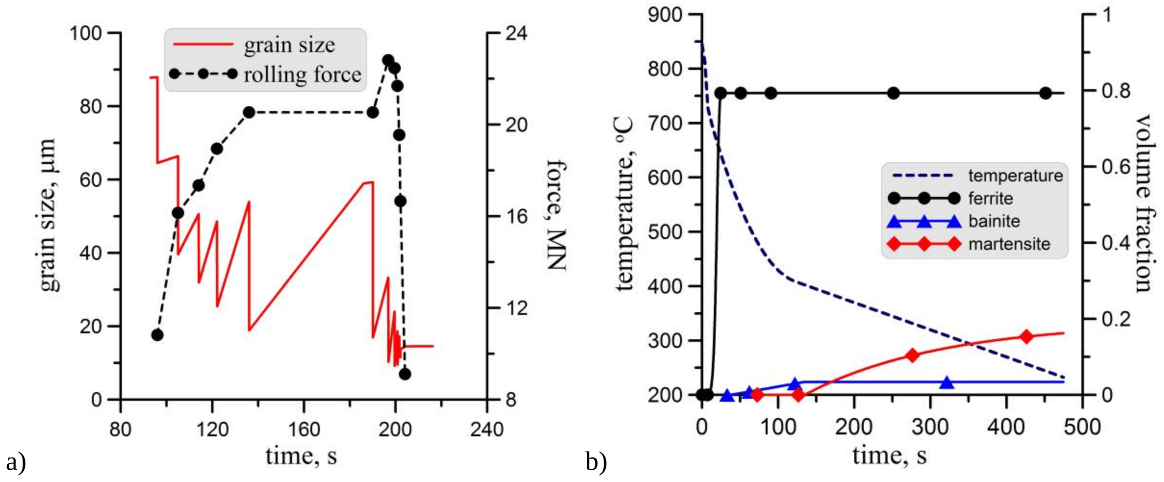
Configuration of the rolling mill was introduced in the system using drag&drop editor in the GUI. The basic process parameters were as follows: temperature in the furnace 1205^{o}C, slab dimensions 250×1500×7000 m, time of transport of the slab between the furnace and the roughing mill 90 s, rolling velocity in the roughing mill 2 m/s, time intervals after roughing passes 9, 9, 8, 14, and 40 s, rolling velocity in the last finishing stand 10 m/s and rolling schedule in the finishing train 66.1 $\rightarrow$ 40.6 $\rightarrow$ 19.1 $\rightarrow$ 9.4 $\rightarrow$ 5.43 $\rightarrow$ 3.58 $\rightarrow$ 2.9 mm. Selected results of simulations are presented in Fig. 6 and Fig. 7. Fig. 6 shows calculated temperature in the two location at the cross section and an average temperature.



a) b)

Fig. 6. Calculated temperatures in roughing mill (a) and during finishing rolling and laminar cooling (b)

Fig. 7a shows calculated forces and austenite grain size. Fig. 7b shows results of simulations of the laminar cooling process. It is seen that predominantly ferritic microstructure was obtained with small amounts of bainite and martensite.



a) b)

Fig. 7. Calculated forces and austenite grain size in subsequent passes (a) and results of simulations of kinetics of transformations during laminar cooling (b)

Presented results confirm good predictive capabilities of the *VirtRoll* system. Configuration of the arbitrary rolling mill is easy and fast. The system automatically prepares input data for simulations and executes simulations. The results are presented in the communicative way.

5. CONCLUSIONS

Computer system *VirtRoll* dedicated to technology design for hot strip rolling has been presented in the paper. The main features of the system are presented in Section 3.6. Numerical tests performed in Chapter 0 confirmed extensive capabilities and functionalities of the system. *VirtRoll* is flexible and open what means that new models and optimization methods can be implemented by the user.

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