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HYBRID COMPUTER SYSTEM FOR THE DESIGN OF FLAT ROLLING TECHNOLOGY – CASE STUDY FOR MULTIPHASE STEEL

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Abstract

Creation of the system for optimization of semi product and product properties in metal forming industry was the objective of the paper. This system is demonstrated in application to Advanced High Strength Steels (AHSS), which are innovative materials used by automotive industry. The hybrid computer system joins functionality of numerical simulations, material modelling and optimization to minimize costs related to design of production technologies and maximize semi and final product properties. The paper presents design and functionality of this system, which includes all mentioned functional modules for the design of flat rolling technology. The architecture of the proposed system is described in details, as well as material models applied in numerical simulations. The system was validated and tested using optimization of multiphase cycle of rolling of complex phase steel strip as an example.

Key words: hybrid computer system, numerical simulations, multiphase steel

1. INTRODUCTION

Optimization of semi product and product properties in metal forming industry becomes highly sophisticated nowadays. This is mainly caused by application of innovative materials, e.g. Advanced High Strength Steels (AHSS), in connection with advanced production technologies. Difficulties in prediction of material properties after forming are usually related to expensive experimental trials, which do not guarantee optimal parameters of production technology. This justifies creation of a computer system joining functionality of numerical simulations, material modelling and optimization to minimize costs related to design of production technologies and maximize semi and final product properties. Development of such a hybrid computer system and application of this system to the design of rolling of Complex Phase (CP) steel strip was the objective of the present work.

2. HYBRID COMPUTER SYSTEMS

2.1. General information

Hybrid computer systems are usually defined as software covering more than one different functionalities e.g. optimization, numerical simulation and support in the form of embedded expert system. Such hybrid systems supporting design of production technology are a part of bigger group of production planning systems (PPS), which play important role in industry. These systems manage supply chains, optimize work of employees, maximize incomes or plan space of warehouses. Commercial versions of such systems were developed in early 1990s and were based on task schedulers or management of Gantt

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charts (McKey & Black, 2007). This simple functionality was constantly developed by implementation of the following ideas (Cheng et al., 1993): mass production, flexible manufacturing, computer integrated manufacturing, lean manufacturing and material resource planning (MRP). These steps were necessary to achieve the milestone in the lifecycle of planning systems, i.e. from mentioned earlier MRP to Enterprise Resource Planning (ERP) conversion. Further evolution of the functionality of PPS systems focused on implementation of methods supporting concurrent engineering and, finally, to agile manufacturing. The latter systems were created to manage production processes held in unstable environment and to satisfy individual fast changing customer needs.

Following the PPS development, systems were modified and extended by including algorithms based on artificial intelligence and soft computing, to create so called Intelligent Manufacturing Systems (IMS). One of the first examples, proposed by Giachetti (1998), was based on formal multi-attribute decision model and relational database. The created system was helpful in selection of materials and manufacturing processes, however, its functionality became out of date very fast. Nowadays, such approaches often use expert systems (Mahl & Krikler, 2007) or knowledge bases (Halevi & Wang, 2007). Former propose a framework to create customize rule based system, using semantic net and edges between its nodes. Computation of semantic hulls allows to obtain solution and to determine the optimal decision. Halevi and Wang (2007) suggests to create a knowledge-based "road-map", which facilitates decision making in production planning by introducing flexibility and dynamics of the manufacturing process.

IMS are crucial, especially in branches where a scale of production reaches high level and each, even small change in production chain, influences final efficiency of a company. Such branch may be represented, among the others, by the metal forming companies, producing millions of tons of steel products annually. The available PPS systems and the mentioned needs of metal forming branch inspired the Author to create system based on numerical simulations of industrial processes and feedback data received directly from such processes. System is dedicated to the pilot rolling mill LPS described in Garbarz et al. (2012). Since prediction of properties of products is essential for effectiveness of such systems, advanced modelling methods based either on internal variables or on discrete techniques should be applied. Selection of the relevant method and presentation of the details of modelling are particular objectives of the paper. The functionality of the system modules is discussed, as well, and the results of calculations are presented.

2.2. System requirements and architecture

Primarily, the system was implemented to be used by single user. Nevertheless, to support multi-user and multi-access functionality, the system was designed on the basis of Client-Server architecture (figure 1), supporting two versions of the implementation i.e. thick and thin Client. In the case of computationally demanding simulations, the latter version of the software was applied, where calculations take part at the server side leaving Client computer unloaded and stable. Otherwise, while simulations are simplified and the network communication is unprofitable, thick Client architecture is implemented. In both cases the Client part of the system is responsible for gathering information about parameters of simulated process and used material. Server side always maintains a centralized database, which keeps information about users, their projects, materials, etc. Such solution allows effective exchange of data among people in different remote locations.

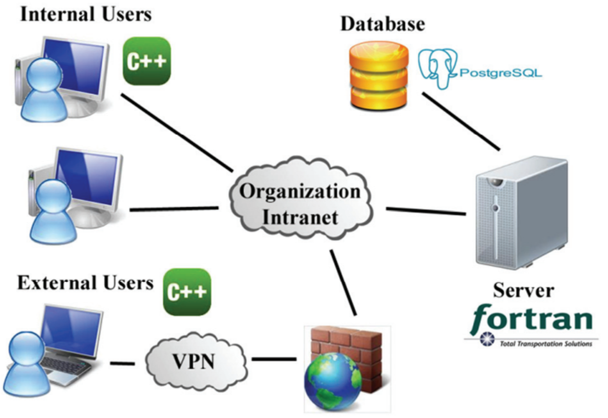

Fig. 1. Deployment of the hybrid computer system.

2.3. Implementation details

The main purpose of the computer system is to support the work of technologists by enabling the design of the rolling technology for flat and long products, optimal material selection or the use of the expert system. Therefore, the functionality of the system includes both the ability to define new and to modify already defined processes, as well as the use of material database and optimization procedures. Therefore, the developed system has a modular structure (figure 2), where each module is an autonomous part of a separate dedicated functionality such as: Graphical User Interface (GUI), knowledge based support or numerical simulations. This architecture will greatly facilitate implementation of the system and the introduction of subsequent modifications to the software source code.

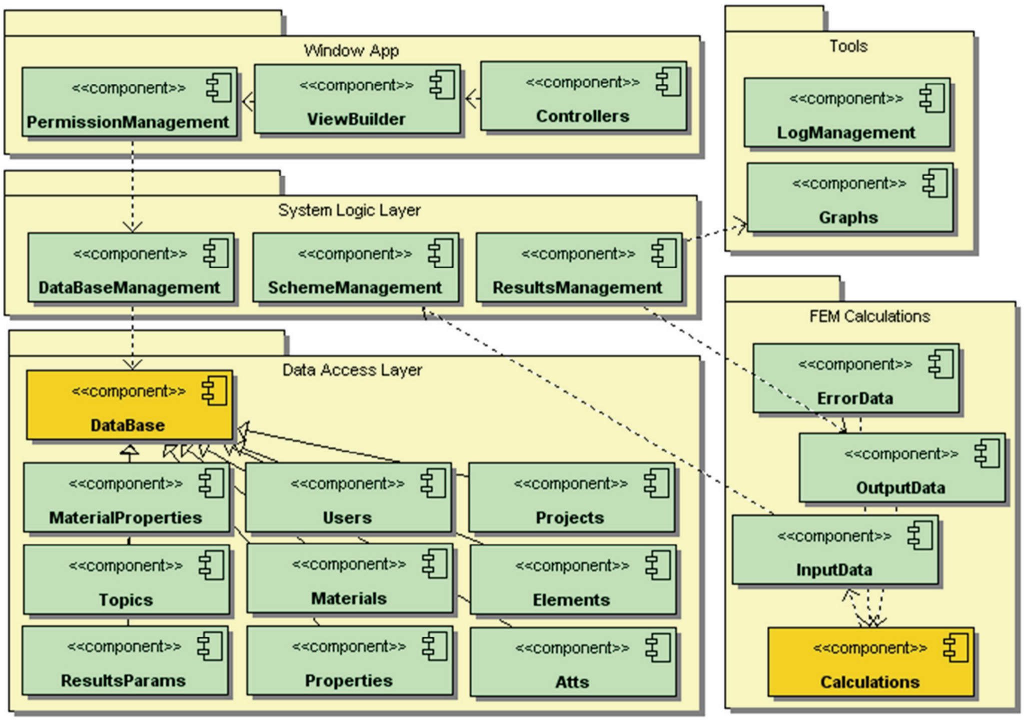

Fig. 2. *Diagram of components implemented in the hybrid computer system.*

The database is composed of several tables used for gathering all necessary information about users and their projects. Object-Relational Mapping (ORM) technique was applied, therefore each table in the database has its equivalent component implemented in Data Access Layer (figure 2). Materials, Properties, Elements (rolling mill equipment) and Projects are the most important components for numerical simulations, which are mapped onto the proper tables in the database i.e. *dbo_material*, *dbo_element*, *dbo_property* and *dbo_project*. The main table in the database is *dbo_project*, which joins together all other functional tables besides *dbo_config*, which gathers information about system configuration. The design of the database is presented in figure 3, where main functional tables are expanded presenting the most important fields and minor tables are toggled into icons e.g. table *dbo_materialitem*, connecting *dbo_project* and *dbo_material*. The following list presents detailed information about records of the tables:

- *dbo_project* – contains data about projects, which are setup by system users at the beginning of the work. The main fields in the table are project name, description, date of modification and owner,
- *dbo_material* – gathers records of materials including their name, models, grade and ids of chemical components, which are stored in *dbo_chemelement*,
- *dbo_element* – contains data about devices on the semi industrial or industrial production line e.g. rolling mills, descalers, crops. These devices are described by their properties (*dbo_properties*),
- *dbo_properties* – stores data of devices' properties e.g. number of passes, velocity of rolling, pressure of water in laminar cooling. Specific values of these properties are set in *dbo_elementproperty*, which connects projects, elements and their properties together,
- *dbo_result*, *dbo_resultfile* – gathers results of numerical simulations in plain text and external files,
- *dbo_user* – is just a storage of system's users divided into two groups, i.e. administrators and normal users.

There is additional group of tables, which consists of *dbo_bookchapter*, *dbo_chaptercontent* and *dbo_attachment*. Book chapters related to users and materials are used as structured knowledge base of expert system supporting technology design according to advanced technological aspects of hot rolling and specific materials. Users are able to extend the knowledge by modification of existing or creation of new content.

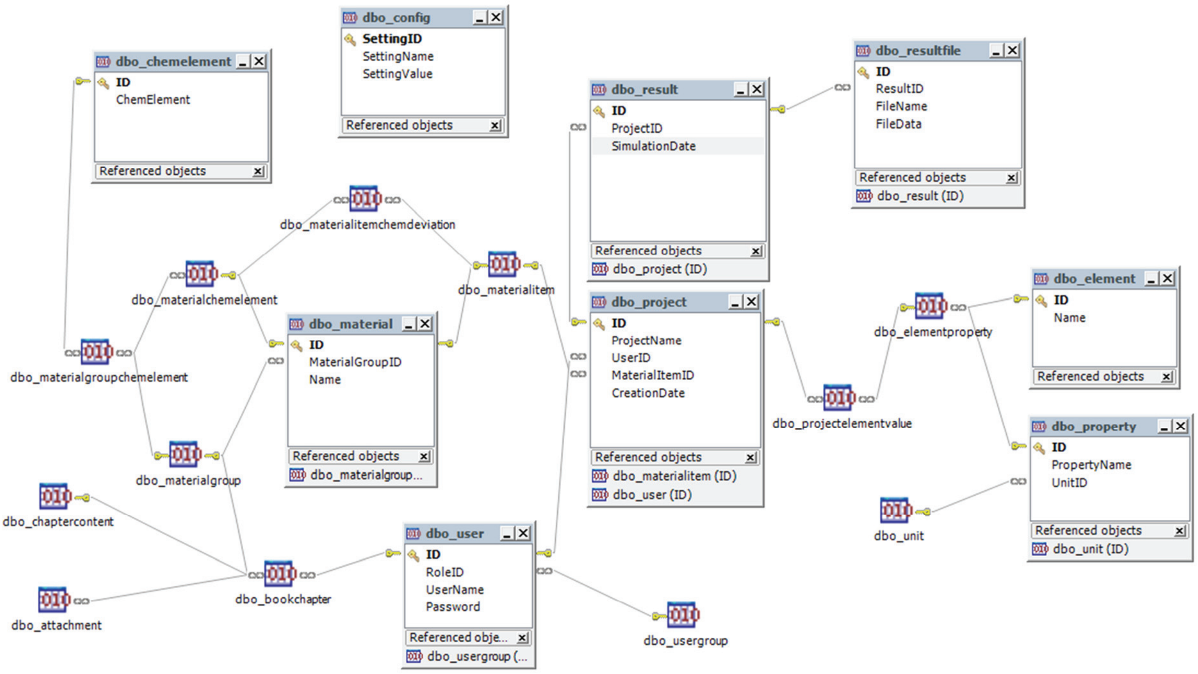

***Fig. 3**. Diagram of the database implemented in the proposed hybrid computer system.*

The design of the rolling technology begins from definition of the project, which joins together all parameters of the rolling mill and material models. Selected material and a fixed set of its characteristics is assigned to initially designed rolling process. First run of the expert system is to predict number of passes and drafts to optimize energy supplied to stands. It works twofold, i.e. on the basis of optimization procedures and data collected in the knowledge base, covering materials and practice of experienced engineers. This knowledge can be developed by adding new comments and rules to dbo_bookchapter table in the database.

Additionally, the system supports optimization of finishing rolling and laminar cooling. The finishing rolling is optimized by minimization of temperature differences along a rolled material to obtain acceleration of material in last mill stand. Laminar cooling is setup to optimization with the objective function based on assumed volume fractions of phases leading to the best material properties. Phase transformation models are used in the optimization. Applied material models are described in subsequent chapter. Finally, the calculation results are visualized using the appropriate temperature charts.

3. MODELS

The system was tested by comparison results of simulations with the experimental data. Complex phase (CP) steel containing 0.09%C, 1.5%Mn, 0.45%Si, 0.4%Cr, 0.26Ni, 0.009%P, 0.01%S, 0.18%Cu, 0.035%V, 0.12%Ti, 0.041%Al, 8(ppm)O and 34(ppm)N was selected for the analysis. The process models and the material models for this steel are given below.

3.1. Thermomechanical model

Thermomechanical model is based on the slab method and thermal part is based on 1D finite element (FE) solution of the Fourier equation (Lenard et al., 1999). This is a well-known approach and it is not discussed here. Flow stress of the investigated CP steel is (Rauch et al., 2012):

$$\sigma_p = 5189.3\varepsilon_i^{0.267}\exp\left(-0.3436\varepsilon_i\right)\dot{\varepsilon}_i^{0.112}\exp\left(\frac{-3.32T}{1000}\right) \tag{1}$$

where: T - temperature in $^{\circ}$C, ε - effective strain, $\dot{\varepsilon}_i$ - effective strain rate.

3.2. Microstructure evolution models

Microstructure evolution model was based on the fundamental works of Sellars (1979) with coefficients determined on the basis of experimental tests for the CP steel:

- kinetics of static recrystallization

$$X_{st} = 1 - \exp\left(\ln(0.5)\left[\frac{t}{t_{0.5}^{st}}\right]^{n_{st}}\right) \qquad (2)$$

- time for 50% recrystallization

$$t_{0.5}^{st} = 1.6\times10^{-9}\varepsilon^{-0.305}\dot{\varepsilon}^{-0.443}D_0^{0.625}\exp\left(\frac{150713}{RT}\right) \quad T<1000^{\circ}\mathrm{C}$$

$$t_{0.5}^{st} = 1.77\times10^{-19}\varepsilon^{-3.127}\dot{\varepsilon}^{-0.23}D_0^{0.625}\exp\left(\frac{375926}{RT}\right) \quad T\geq1000^{\circ}\mathrm{C}$$

- grain size after static recrystallization

$$D_{st} = 23.378\varepsilon^{-0.073}D_0^{0.137}\exp\left(-\frac{6521.8}{RT}\right) \qquad (3)$$

- kinetics of metadynamic recrystallization

$$X_{md} = 1 - \exp\left(\ln(0.5)\left[\frac{t}{22.34\,Z^{-0.819}\exp\left(\frac{241449}{RT}\right)}\right]^{1.2}\right) \qquad (4)$$

- grain size after metadynamic recrystallization

$$D_{md} = 62.01Z^{0.0303} \qquad (5)$$

- grain growth

$$D_{gr}^2 = D_{st}^2 + 10^A t \qquad A = 9.5 + \frac{10920}{T} \qquad (6)$$

where: $n_{st} = 0.723$ for $T < 1000^{\circ}$C and $n_{st} = 0.836$ for $T \geq 1000^{\circ}$C, D_0 – austenite grain size prior to deformation, Z – Zener-Hollomon parameter.

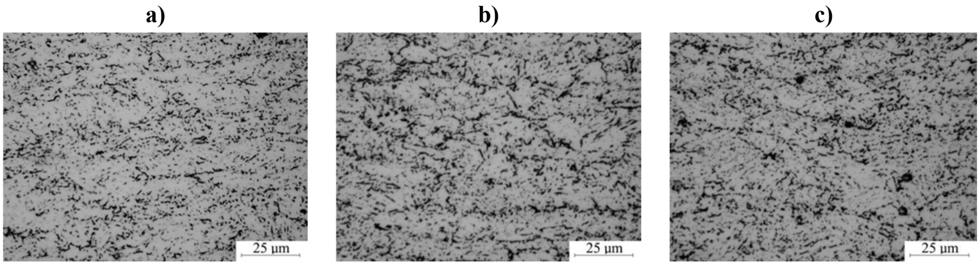

Fig. 4. Microstructures after three investigated cooling schedules.

3.3. Phase transformation models

Transformation model is based on the Avrami equation:

$$X = 1 - \exp\left(-kt^n\right) \qquad (7)$$

Details of this model are given by Pietrzyk and Kuziak (2012). Briefly, a constant value of coefficient n in equation (7) was used. On contrary, value of the coefficient k varied with temperature. A modified Gaussian function was used for ferritic transformation and exponential functions were used for pearlitic and bainitic transformations. Koinstinen-Marburger (1959) equation was used for martensitic transformations.

4. EXPERIMENT

4.1. Dilatometric and Gleeble tests

Dilatometric tests were performed to identify the coefficients in the phase transformation model (Rauch et al., 2012) for results. Gleeble 3800 physical simulations were performed to supply data for validation of this model. The following three cooling schedules were selected for presentation in the paper:

a) 923°C ⇒ 450 (50°C/s) ⇒ 430 (0.01°C/s) ⇒ RT (5°C/s)
b) 923°C ⇒ 450 (20°C/s) ⇒ 430 (0.01°C/s) ⇒ RT (5°C/s)
c) 923°C ⇒ 450 (50°C/s) ⇒ 430 (0.01°C/s) ⇒ RT (5°C/s)

where RT means Room Temperature. Microstructures after these three schedules are shown in figure 4. These microstructures are composed of allotriomorphic ferrite, bainite and martensite.

4.2. Rolling in the LPS pilot mill

Main parameters of the pilot mill (Garbarz et al., 2012) were work roll radius 300 mm, back-up roll radius 600 mm and rotational velocity of work rolls 17 rpm. Cast slabs measuring 60×150×1020 mm were used as a stock material. Roughing rolling to 30 mm was performed first and it is not discussed in this paper. Finishing rolling to 9.8 mm was performed in 5 passes with 5s intervals between passes. Parameters of this process are given in table 1 (h – thickness, r – reduction, T – temperature, F – rolling force, M – roll torque, D – austenite grain size).

Table 1. *Rolling parameters.*

Pass	*h*, mm	*r*	*T*, °C	*F*, kN	*M*, kNm	*D*, µm
-	30	-	1150	-	-	80.0
1	25	0.167	1050	664	5	90.1/27.1
2	19	0.24	1033	975	7	30.3/22.3
3	15	0.211	995	943	6	24.3/21.4
4	11.8	0.213	940	1062	6	22.3/20.6
5	9.8	0.169	920	965	5	21.0/20.2

4.3. Case study

Primary validation of the phase transformation model was performed by calculations for the three cooling schedules in section 4.1. Volume fractions of ferrite equal 0.183, 0.376 and 0.58 for schedules a), b) and c) respectively were obtained. These values are in agreement with microstructure analysis. Simulation of experimental rolling process performed on the LPS line (Garbarz et al., 2012) was carried out next to validate the whole system.

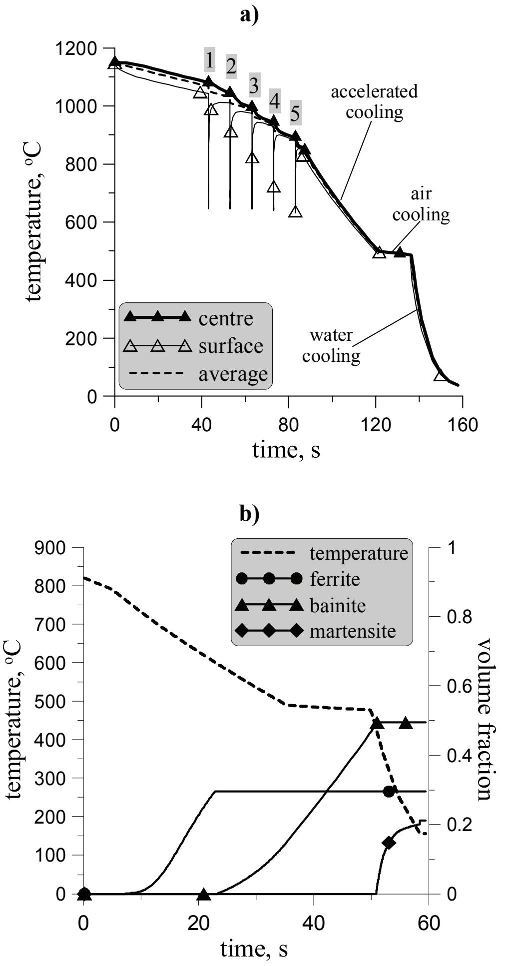

Fig. 5. *Time temperature profile for hot rolling and laminar cooling of the CP steel (a) and kinetics of transformations during laminar cooling (b).*

Calculated forces and austenite grain size are given in table 1. Figure 5 shows results of calculations of temperature for the whole process. Laminar cooling of the CP steel should lead to microstructure composed of ferrite, bainite and martensite. Developed system was used for the design of the optimal laminar cooling schedule. The objective was to obtain 30% of ferrite, 50% of bainite and 20% of martensite in the microstructure. The optimal parameters of the cooling were found as 35 s of accelerated cooling in air followed by 15 s of slow free cooling in air and water cooling to the room temperature.

5. CONCLUSIONS

Hybrid computer system for the rolling technology design for the pilot mill LPS was presented in the paper. Design and functionality of the system compose of optimization, numerical simulation and support in form of embedded knowledge base. System is user friendly and enables arbitrary configuration of the rolling process. The microstructure evolution model and phase transformation model are implemented in the system.

Developed system was tested for the complex phase steel. All models for this steel were identified on the basis of plastometric tests, stress relaxation tests and dilatometric tests. Validation confirmed good accuracy of the models.

System was tested for the 5 pass hot rolling followed by controlled cooling of the CP steel strip. Capability of the system to perform optimization with the phase composition used as the objective function was confirmed.

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REFERENCES

Cheng, K., Harrison, D.K., Pan, P.Y., 1998, Implementation of agile manufacturing – AI and Internet based approach, *Journal of Material Processing Technology*, 76, 96-101.

Garbarz, B., Burian, W., Woźniak, D., 2012, Semi-industrial simulation of in-line thermomechanical processing and heat treatment of nano-duplex binite-austenite steels, *Steel Research International*, spec. issue conf. Metal Forming, 1251-1254.

Giachetti, R.E., 1998, A decision support system for material and manufacturing process selection, *Journal of Intelligent Manufacturing*, 9, 265-276.

Halevi, G., Wang, K., 2007, Knowledge based manufacturing system (KBMS), *Journal of Intelligent Manufacturing*, 18, 467-474.

Koistinen, D.P., Marburger, R.E., 1959, A general equation prescribing the extent of the austenite-martensite transformation in pure iron-carbon alloys and plain carbon steels, *Acta Metallurgica*, 7, 59-69.

Lenard, J.G., Pietrzyk, M., Cser, L., 1999, *Mathematical and physical simulation of the properties of hot rolled products*, Elsevier, Amsterdam.

Mahl, A., Krikler, R., 2007, Approach for a rule based system for capturing and usage of knowledge in the manufacturing industry, *Journal of Intelligent Manufacturing*, 18, 519-526.

McKey, K.N., Black, G.W., 2007, The evolution of a production planning system: A 10-year case study, *Computers in Industry*, 58, 756-771.

Pietrzyk, M., Kuziak, R., 2012, Modelling phase transformations in steel, in: *Microstructure evolution in metal forming processes*, (eds), Lin, J., Balint, D., Pietrzyk, M., Woodhead Publishing, Oxford, 145-179.

Rauch, L., Gołąb, R., Kuziak, R., Pidvysots'kyy, V., Pietrzyk, M., 2012, Zastosowanie komputerowego systemu eksperckiego do projektowania technologii walcowania na gorąco blach w LPS, *Prace IMŻ*, 1, 104-109 (in Polish).

Sellars, C.M., 1979, Physical metallurgy of hot working, in: *Hot working and forming processes*, (eds), Sellars, C.M., Davies, G.J., The Metals Soc., London, 3-15.

HYBRYDOWY SYSTEM KOMPUTEROWY DO PROJEKTOWANIA TECHNOLOGII WALCOWANIA WYROBÓW PŁASKICH – STUDIUM PRZYPADKU DLA STALI WIELOFAZOWYCH

Streszczenie

Celem pracy było stworzenie systemu dla optymalizacji wytwarzania półwyrobów i wyrobów w przemyśle przetwórstwa metali. System przedstawiono w zastosowaniu do stali AHSS, które są nowoczesnymi materiałami wykorzystywanymi przez przemysł samochodowy. System łączy funkcjonalność symulacji numerycznych, modelowania materiałów oraz optymalizację, co pozwala na minimalizację kosztów związanych z projektowaniem technologii produkcyjnych oraz umożliwia uzyskanie optymalnych własności półwyrobów i wyrobów. Niniejszy artykuł przedstawia projekt i funkcjonalność hybrydowego systemu komputerowego, posiadającego wszystkie wymienione powyżej moduły funkcjonalne niezbędne do projektowania technologii walcowania wyrobów płaskich. Architektura zaproponowanego systemu została szczegółowo opisana, podobnie jak modele materiałowe wykorzystane w testowych symulacjach numerycznych. System został zweryfikowany dla przypadku optymalizacji cyklu walcowania produktów ze stali wielofazowych.

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