COUPLING MICROSTRUCTURE EVOLUTION MODEL WITH Fe CODE FOR NUMERICAL SIMULATION OF ROLLING-COOLING SEQUENCE FOR RAILS

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Abstract

The paper deals with modelling of rolling and controlled cooling processes for rails. Coupling microstructure evolution model with the thermal-mechanical finite element (FE) code is the basis of the model developed by the Authors. Microstructure evolution in this model is simulated using closed form equations describing grain size and recrystallization kinetics, as well as kinetics of phase transformations. Properties of final products are predicted as functions of microstructural parameters such as pearlite grain size, colony size and interlamellar spacing. FE software Larstran was used in simulations of the rail rolling process. The objective of the paper was presentation how user procedures in Larstran can be used for implementation of microstructure evolution model in the FE code. Structure of the Larstran software and schematic diagram of the user producers are demonstrated. The program was tested and validated and selected simulations results are presented. It is shown that coupling of the FE Larstran software with the microstructure evolution model creates an efficient tool for simulation and optimization of the rail manufacturing process.

Keywords: FE software, users procedures, manufacturing of rails, cooling, microstructure evolution

1. INTRODUCTION

A constant development in rail transport sector has been observed in the last decades. The progress involves implementation of technological solutions complying with the strict safety requirements and environment protection [1-3]. The rail transport capacities depend on the track parameters such as car stability, geometry of the contact with running wheel, and possibility to sustain greater loads. To enable application of greater axle load and increase train speed, there is a need to improve quality of rails characterized by the abrasive wear strength, fatigue strength and resistance to contact-fatigue defects [4]. Improvement of these properties is achieved by an application of special cooling sequence to the rail after hot rolling process,. That approach provides smaller distance between the cementite lamellae S_0 around 0.10-0.12 μm, comparing to the structure after a natural cooling in the air (S_0 = 0.2-0.3 μm) [4]. Design of the best parameters of the rails manufacturing can be more efficient when numerical simulation of the whole process is applied. Several models of rolling-cooling sequence for rails were developed. The model describing microstructure evolution and properties of pearlitic steels was proposed at the AGH [5-8]. Preliminary research on microstructure evolution during hot forming of pearlitic steels are described in [5]. Details of the whole model and identification of coefficients for the rail steel are given in [6]. Validation of the model by comparison with the physical simulations of controlled cooling of rails is presented in [7]. Finally, recent paper [8] presents numerical tests of the model and sensitivity analysis. The optimization task is formulated in that last paper, as well. The main goal of the present work, which is a continuation of [9], is preparation of the simulation consisting of hot rolling integrated with external software and controlled cooling in one simulation task. This goal was reached by using Larstran finite element (FE) software for hot rolling integrated with Authors' external software for simulation of controlled cooling with implemented pearlitic steel microstructure evolution and phase transformation models.

2. MODELS

Details of the microstructure evolution model for rail steels are presented in earlier publications [2-5] and are repeated briefly below for a consistency of this paper. The constitutive model used in the Larstran software is described, as well.

2.1 Hot rolling

Larstran finite element code is based on the rigid-plastic Levy-Mises flow rule:

$$\boldsymbol{\sigma} = \frac{2\sigma_p}{3\dot{\varepsilon}_i}\dot{\boldsymbol{\varepsilon}} \tag{1}$$

where: $\boldsymbol{\sigma}$, $\dot{\boldsymbol{\varepsilon}}$ - stress and strain rate tensors; σ_p - flow stress; $\dot{\varepsilon}_i$ - effective strain rate.

The flow stress in the constitutive model is introduced by the equation:

$$\sigma_p = 5843.3\varepsilon^{0.237}\exp\left(-0.347\varepsilon_i\right)\dot{\varepsilon}^{0.132}\exp\left(-0.00342T\right) \tag{2}$$

where: T - temperature in °C; $\dot{\varepsilon}$ - effective strain rate; ε - effective strain.

Coefficients in equation (2) were determined on the basis of plastometric tests performed for the pearlitic steel containing 0.71%C, 1.1%Mn, 0.31%Si, and 0.13%Cr. Inverse algorithm proposed in [10] was applied to determine these coefficients and to avoid an influence of friction and deformation heating during the tests. **Fig. 1** shows plots of the flow stress of the investigated rail steel as a function of strain for different strain rates and temperatures. Modelling of rolling of another pearlitic steel with different chemical com[position would require performing similar plastometric tests and identification of the coefficients in equation (2).

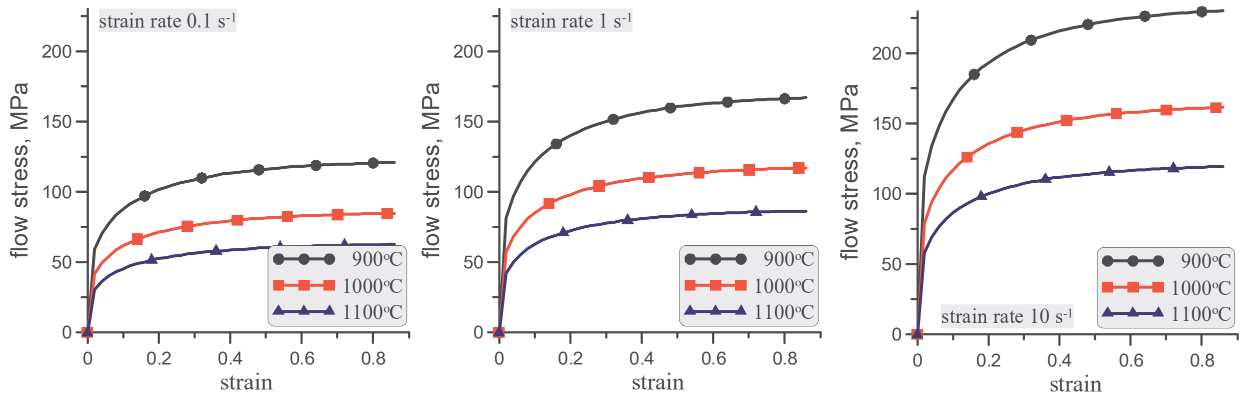


Fig. 1 Flow stress of the investigated rail steel as a function of strain for different strain rates and temperatures.

Microstructure evolution model developed in [11] was implemented in the FE code. This model is composed of the following equations:

$$X = 1 - \exp\left(\ln\left(0.5\right)\left[\frac{t}{t_{0.5}}\right]^{1.7}\right) \tag{3}$$

$$t_{0.5} = 2.403\times10^{-8}\varepsilon^{-s}\dot{\varepsilon}^{-0.288}D_0^{-0.2}\exp\left(\frac{160420}{R\hat{T}}\right) \qquad s = 1.006D_0^{-0.2} \tag{4}$$

$$D_{RX} = 9.91\varepsilon^{-0.65}\dot{\varepsilon}^{-0.1}D_0^{0.54}\exp\left(\frac{-17540}{R\hat{T}}\right) \tag{5}$$

$$D^2 = D_{RX}^2 + 10^A t \qquad A = 7.0 + \frac{5900}{T} \tag{6}$$

where: X - recrystallized volume fraction; t - time; D_0 - grain size prior to deformation; D_{RX} - recrystallized grain size; $\widehat{T}$ - absolute temperature in K; D - grain size during growth.

2.2 Controlled cooling

A cyclic immersion hardening of the rail head [4] was investigated. The objective of this process is to achieve as small as possible interlamellar spacing and to avoid occurrence of degenerated pearlite and bainite in the microstructure. The rail is inserted in the tank with the coolant directly after rolling but the solution level is kept below the running surface level (**Fig. 2a**). Accelerated cooling process starts when the temperature of rail head reaches about 820°C, then the solution is supplied to the tank and the rail head is gradually immersed (**Fig. 2b**). To avoid the appearance of degenerated pearlite and bainite, the head is immersed for a short period of time, after which the coolant is removed from the tank. Afterwards, the heat is transferred from the hotter rail head centre and the running surface temperature increases. It is critical for the surface temperature not to increase above 570°C, therefore, the solution level is raised again and cooling stage is repeated. The head is immersed cyclically until the pearlite transformation is completed in the entire head.

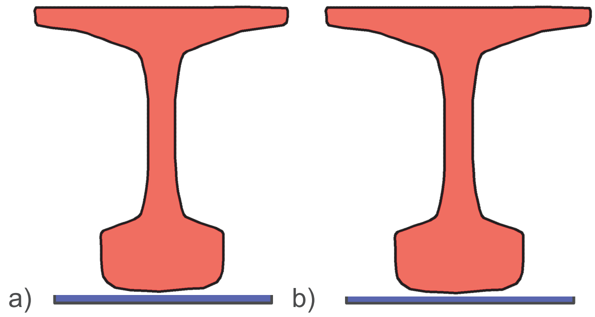


Fig 2 Schematic illustration of one stage of controlled cooling; a) head above the level of the solution; b) head immersed in the solution.

Proper selection of times of accelerated cooling and cooling in the air is necessary to maintain low temperature of pearlite transformation and to prevent cooling the running surface below the bainite transformation start temperature. In simulations of this cooling process the macro scale model was based on the FE solution of the heat transfer equation. Microstructure evolution equations [6,8,9] were implemented in the FE code and they were solved at each Gauss integration point.

3. FEM SOFTWARE

Larstran-PEP (Programmer's Environment for Pre-/Postprocessing) software allows easy access to the application of the finite element method for metal forming in 2D and 3D computational domains. Software supplies the material data base that is a universal open tool. New material models defined by temperature dependent flow stress relations can be added to the base. There is a possibility to use various forms of the material flow curve description, i.e. tabular form or mathematical function.

The exchange of data with external software is possible due to import and export modules in PEP. Shapes of the tools and the workpiece can be imported to Larstran software using various format systems (for example STL from SolidWorks) and added to the simulation FEM-model. Automatic mesh generation is available. Beyond this Larstran-PEP software allows for specific solver modifications to adapt the program to the users needs. The diagram of the user procedures implementation is presented in **Fig. 3**.

Larstran PEP software solvers are written in FORTRAN programing languagle. A control of the procedure or a manipulation of the data base is possible by writing subroutines with predefined parameters such as number of elements (NELU), current time increment (ISTP) or strain rate (EV), stress (EVP) and temp (TC) for Gaussian integration point. If the standard version of the defined subroutines are not sufficient for the control of an analysis, they may be replaced by the user. Subrutines beginning with the letter X are called in the algorithms. All subroutine beginnng with the letter Y are tools, which may be used in the X-subroutines to get informations or to manipulate the data base. The necessary processors are only linked together, the main program of Larstran is a collection of processors calls. User can take existing main program out of the unitility library or writes himself a FORTRAN program with calls of the required processors. Modyfication of the solvers source code file linked with the program allows to extrude necessary information to the Author's FE software. Added modification are represented by the green color in **Fig. 3**.

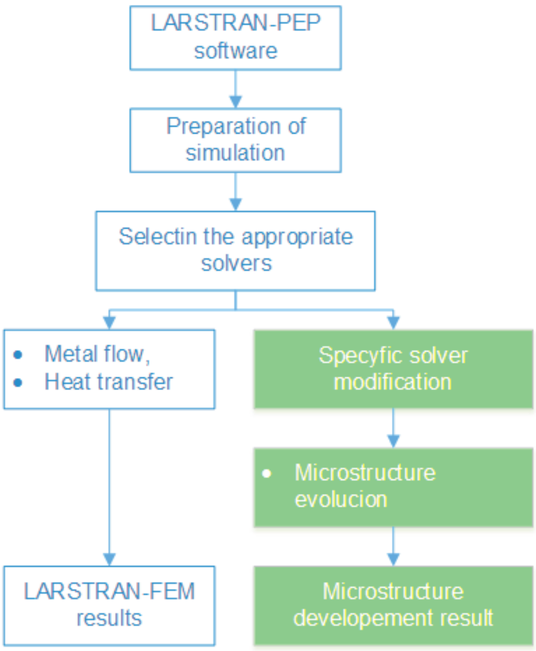


Fig. 3 Diagram of Larstran-PEP use and implementation of user procedures

Results obtained form the numerical simulation of the last pass of the rail rolling process were used as input data in the external Authors' software that allows to compute the microstruture parameters after the cooling and the mechanical properfies of the final product.

4. RESULTS

Developed model was used to simulate rolling-cooling sequence for rails. Implementation of the user procedures into the Larstran-PEP software solvers enabled calculation not only distributions of temperature and strains but also the microstructure development. These results were the input data in the model describing cooling process.

4.1 Hot rolling

Fig. 4 shows view of the roll-workpiece setup generated in the Solid Works program and implemented into the Larstran-PEP software. Calculated shape of the rail and strain distribution in the roll gap is shown in **Fig. 5**. Finally, distributions of temperatures, strains and grains size at the cross section of the rail after hot rolling are presented in **Fig. 6**.These latter results were used as input parameters for modelling of controlled cooling using external software that allows to calculate the microstructure parameters and properties of final product.

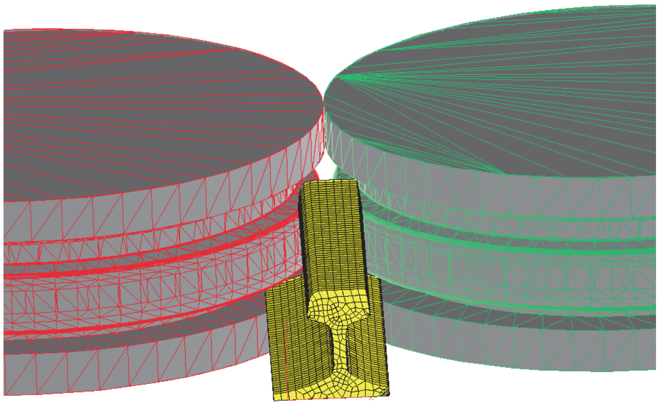
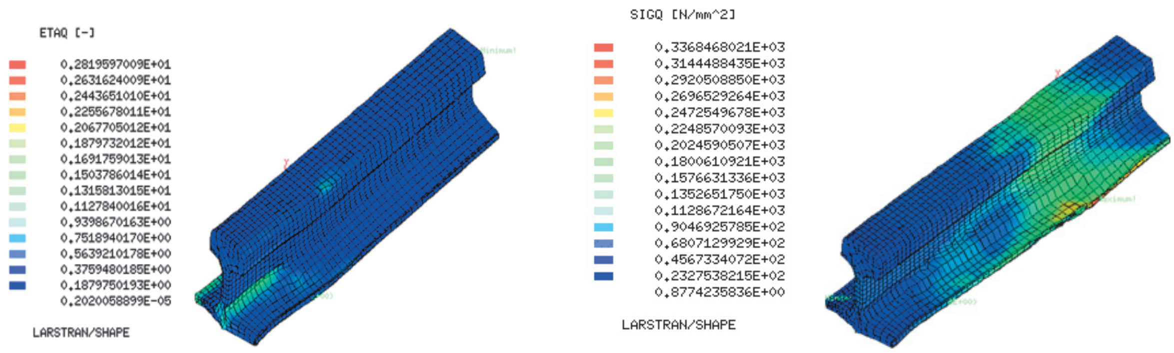
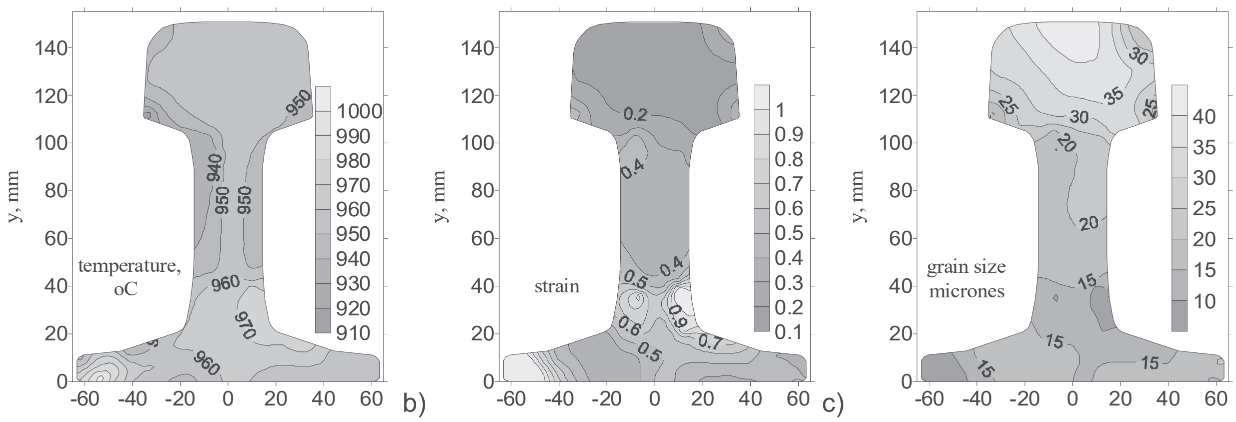


Fig. 4 View of the roll-workpiece implemented into the Larstran-PEP software



a) b)

Fig. 5 View of the rail with distribution of strains (a) and stresses (b) in the roll gap in the last pass

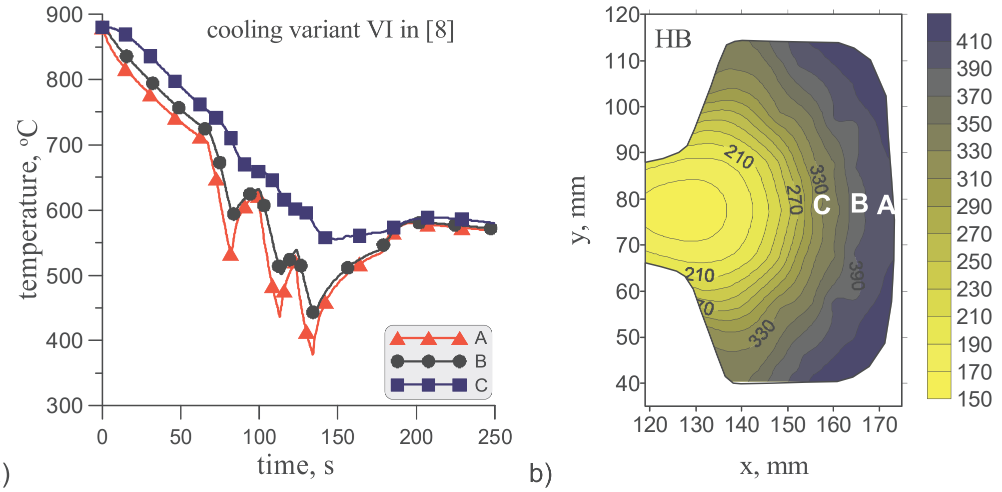


a) b) c)

Fig. 6 Distribution of the temperature (a); effective strain (b) and the austenite grain size (c) at the cross section of the rail after exit from the last pass

4.2 Controlled cooling

Controlled cooling of rails was simulated. After performed earlier investigation the value of the heat transfer coefficient during immersion in the polymer solution was selected as 1000 W/m^{2}K at the surface temperatures exceeding 700 ^{o}C. When temperature was decreasing below 700 ^{o}C the heat transfer coefficient was increasing and reached the maximum value of 3000 W/m²K at 300 °C. Further decrease of the temperature resulted in the decrease of this coefficient to the value of 800 W/m²K at the room temperature. Results of simulations of the controlled cooling process for rails S60 are show in **Fig. 7**.



a) b)

Fig. 7 Time-temperature profiles at 3 location at the rail head (a) and hardness distribution at the cross section of the rail head (b)

The cooling variant VI proposed in publication [8] was considered. This variant was composed of three immersions successively for 15s(S), 17s(A), 14s(S), 10s(A) and 11s(S), where (S) stands for solution cooling and (A) stands for air cooling. This cycle gave the most uniform distribution of the hardness at the cross section of the rail head. Selected result of calculated time-temperature profile at the three locations (respectively 2 mm (A), 6 mm (B) and 18 mm (C) below the running surface) are presented in **Fig. 7a**. Distribution of the hardness at the cross section of the head is shown in **Fig. 7b**. It can be seen in Fig. 7a that during cooling in the air the temperature at the head surface is increasing due to the heat transfer from the hotter centre of head.

CONCLUSION

Used model allow to predict metal flow, temperature field and microstructure evolution after the rolling process. These result were used as input parameters for simulation of cooling performed by using external software with implemented model of phase transformation for pearlitic steel.

Implemented user procedures into Larstran PEP specific solver allows to extract information from each Gaussian integration point during every single iteration of simulation, not only from the last past. Developed model will allow to formulate optimization task to select the best parameters for the rails manufacturing as it is possible. There parameters are suppose to give uniform hardness distribution and as low as possible interlamellar spacing in pearlite in the rails head and free of bainite microstructure in the whole volume of rail.

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