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Prediction of mechanical properties of hot rolled steel products

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Analysis and modelling

ABSTRACT

Purpose: Model for prediction of mechanical properties of rolled steel products after final cooling from exit rolling temperature is one of the basic component of any software for complex computer simulation of rolling technologies. Theoretical background and implementation of such software tool is described.
Design/methodology/approach: After calculation of cooling curves by any technology dependent Shell the software tool MECHP can be called to predict CCT Diagram from current chemical composition of steel and initial properties of deformed austenite first than structure shares (percentage of ferrite, pearlite, bainite and martensite) resulting from austenite decomposition process for given cooling curve and finally mechanical properties of final product after cooling (hardness, yield stress, tensile strength) are calculated. Implementation of MECHP tool into the software RollFEM3D for 3D Finite Elements Method simulation of rolling processes is presented.
Findings: Comparison of MECHP calculations with measured process data (water cooling and subsequent air cooling of hot rolled narrow plate and wire) shows correspondence that is satisfactory for using in control of process cooling technology.
Practical implications: Results of verification showed that the software tool MECHP is implementable as a postprocessor into off-line rolling process simulation software or can be used as a mechanical properties predictor in software for on-line control of cooling.
Originality/value: Developing of technology independent Library solving the problem of final mechanical properties prediction for various kinds of rolling technologies.
Keywords: Computational material science; 3D FEM simulation; Hot rolling; Mechanical properties

1. Introduction

For computer modelling of various kinds of steel hot rolling technologies the prediction of mechanical properties of final product is the question of great importance [1, 2, 3, 4, 5]. Even if rolling technologies differ each other significantly in details the metallurgical background of processes after rolling is very similar. That was the main reason for developing of technology independent tool MECHP that receiving general physical information on input (chemical composition of steel, grain size and hardening of austenite after rolling and set of cooling curves) calculates structure shares (percentage of ferrite, pearlite, bainite and martensite) and final mechanical properties (HV/HB hardness, yield stress, tensile strength) after cooling. The software tool MECHP is available as library of software modules that can be linked to various kinds of technology dependent software packages.

2. Description of the MECHP Model

The described software tool is based on the model that calculates mechanical properties of deformed steel product after cooling in the three steps showed in the fig. 1.

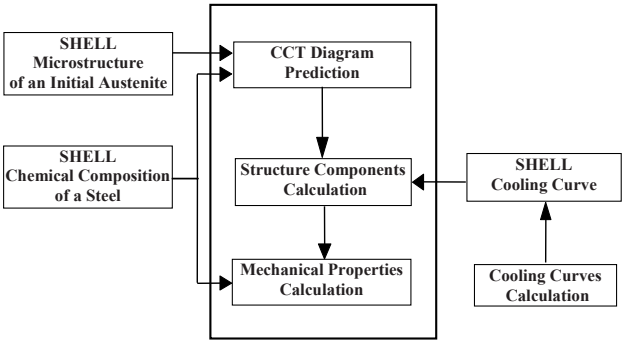

Fig. 1. Basic Flow chart of the MECHP Model

2.1. CCT diagram Prediction

CCT Diagram prediction is based on the concept of ***hybrid CCT diagram*** published by Elfmark [10, 11, 15]. The attribute "hybrid" means the model was constructed from time-temperature coordinates of significant points of various kinds of transformation diagrams. The large set of published TTT, CCT and $t_{8/5}$ Diagrams for various steel grades were collected and sorted into the following four steel groups:

- low-carbon and low-alloyed steels with maximum content of carbon = 0.08%,
- carbon and structural steels with amount of carbon from 0.08% to 0.5% and with the total sum of alloying additions up to 10%,
- tool steels with amount of carbon from 0.5% to 1.8% and with the total sum of alloying additions up to 5%,
- microalloyed Ti, Nb, V steels with amount of carbon from 0.05% to 0.4%.

The primary knowledge acquired from transformation diagrams was processed separately for every steel group and every transformation curve with the use of multiparametric linear regression analysis. The following functions were selected for approximation of time and temperature coordinates of definition points (noses, ...) of the CCT Diagram:

$$T^{0}_{struct}(PT) = A_0 + \sum_i A_i \cdot c_i \tag{1}$$

$$S^{0}_{struct}(PT) = \exp(B_0 + \sum_i B_i \cdot c_i) \tag{2}$$

where

$T^0_{struct}(PT)$ is temperature of the significant point *PT* of the CCT curve *struct*,
$S^0_{struct}(PT)$ is time of the significant point *PT* of the CCT curve *struct*,
struct=F, B, P, M F = Ferrite, B = Bainite, P = Pearlite, M = Martensite
A_0, B_0, Ai, Bi are regression coefficients,
c_i is percentage of alloying addition (i).

More information about algorithm and verification of this model is available in [6].

2.2. Structure components calculation

Calculation of structure components is based on standard Avrami equation describing kinetics of austenite transformation on condition that amount of rising secondary fraction X_{struct} is time dependent for uniform temperature

$$X_{struct}(t,T) = 1 - \exp\left(-k \cdot t^{n}\right) \tag{3}$$

where

$X_{struct}(t,T)$ is amount of fraction *struct* rising in time *t* for given temperature *T*
k, *n* are parameters calculated from CCT diagram for given temperature T

The algorithm was modified for anisotermic case when cooling rate varies with time. The standard Avrami equation (3) can be used but parameter $k_{(t)}$ and exponent $n_{(t)}$ are time dependent in that case and their values differ on intervals with different cooling rates (see Fig. 2)

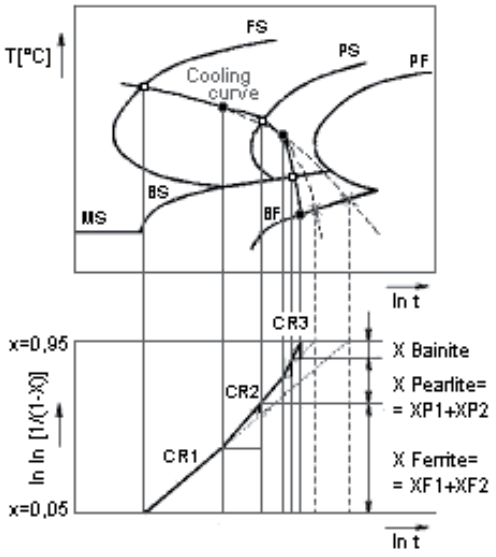

Fig. 2. Kinetics of austenite decomposition into secondary fraction X for cooling curve with nonuniform cooling rates CR_x

2.3. Mechanical properties calculation

Basic step for prediction of final mechanical properties is calculation of HV Hardness. The HV Hardness has been determined by multiparametric linear regression analysis for the shape function (4) with percentage of alloying addition c_i, amount of fraction X_{struc} and constants C_0, D_i, E_i, F_i and G_i :

$$HV = C_0 + X_F \cdot \sum_i D_i \cdot c_i + X_P \cdot \sum_i E_i \cdot c_i + X_B \cdot \sum_i F_i \cdot c_i + X_M \cdot \sum_i G_i \cdot c_i \tag{4}$$

The ultimate tensile strength can be determined from the HV Hardness by the standard linear equation with constants a, b:

$$R_m = f(HV) = -a + b \cdot HV \quad [MPa] \tag{5}$$

Yield stress calculation is based on the basic physical equation taking into account size of the secondary grain d_α (Hall-Petch), influence of the cooling rate CR on the transformation of austenite [8, 9] and amount of fraction X_{struct}:

$$R_e = f(d_\alpha, CR, X_F, \sum(X_P + X_B + X_M)) \quad [MPa] \tag{6}$$

3. Software implementation

The MECHP Tool was implemented into the software RollFEM3D [14] developed for 3D FEM simulation of rolling processes. Process of water cooling (3s) of flat narrow plate with cross-section 240x20mm and exit rolling temperature 850°C with subsequent free air cooling (1800s) was calculated. Resulting cooling curves in all mesh nodes were used in the MECHP Module for calculation of final mechanical properties of plate. Examples of computer simulation are plotted on Fig. 3, 4 and 7.

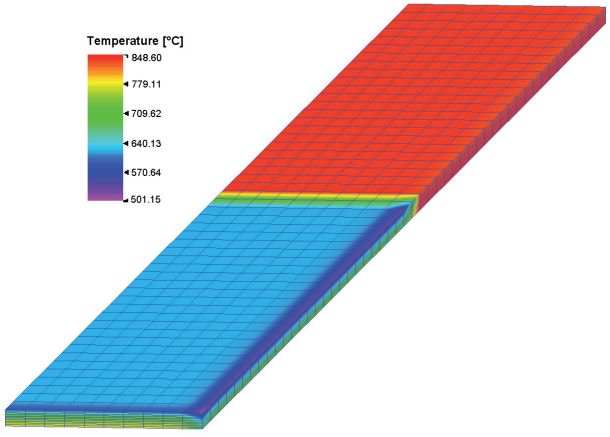

Fig. 3. Calculated Temperature of plate after 3s of water cooling

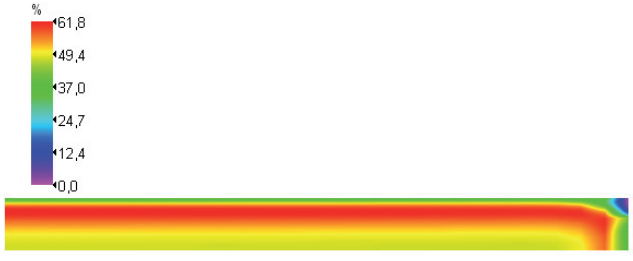

Fig. 4. Ferrite distribution calculated across the plate cross-section

4. Verification

Verification of the software tool MECHP was performed by comparing calculated [13] and predicted values of yield stress and ultimate tensile strength for large scale set of slabs (1287 pcs) rolled on continuous wire mill in Trinec Steel, Czech Republic. Process data for wire of diameter from 5.5 to 20 mm were available. Results of verification for one group of steel with chemical composition presented in the Table 1 was selected as example:

Table. 1.
Chemical composition of steel used for verification

% of C	% of Mn	% of Si	% of Cr	% of Ni	% of Ti	% of B
0.403	0.64	0.26	0.06	0.02	0.002	0.0002

Final microstructure containing approx. 30 % of ferrite and 70 % of pearlite was calculated (see Fig. 7). The following graphs on Fig. 5 and Fig. 6 provide the comparison between the measured and calculated values of mechanical properties:

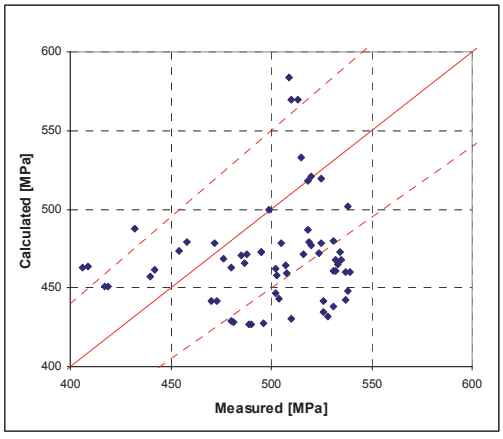

Fig. 5. Comparison of calculated and measured yield stresses

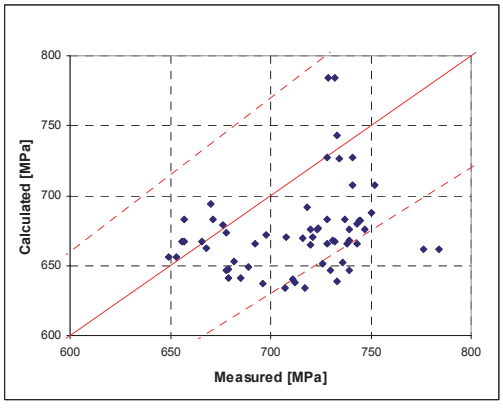

Fig. 6. Comparison of calculated and measured ultimate tensile strengths

More information about MECHP verification is available in [7], [12].

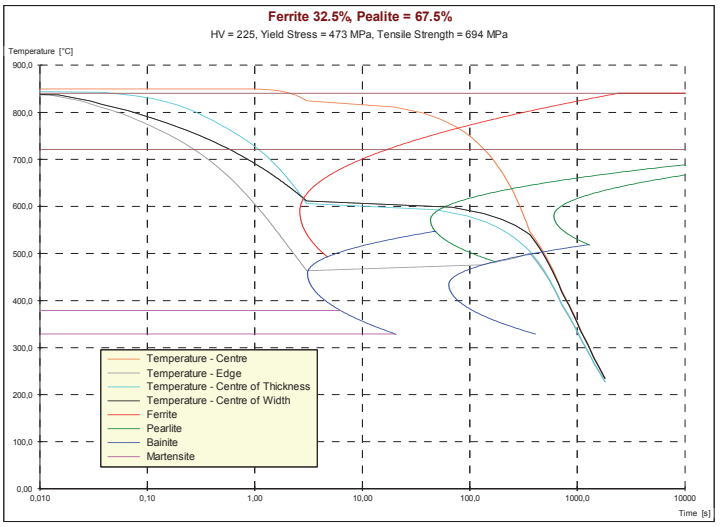

Fig. 7. CCT Diagram and cooling curves in significant points of plate cross-section

5. Conclusions

The technology independent software tool MECHP applicable for calculation of final mechanical properties of hot rolled steel product after final cooling has been presented. Implementation of this tool into the 3D FEM software RollFEM3D and results of verification of the tool for real hot wire rolling process has been discussed. The software tool MECHP can be linked into various technology dependent off-line and on-line (Level 2) software and used for heat treatment simulation and control.

Acknowledgements

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