Metallurgical Monitoring – Prediction of quality of hot rolled production as a component of the process control system.

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Abstract

Ability of process control systems (Level 2) to ensure mechanical properties of hot rolled products depends significantly on their capability to predict final mechanical properties from real process data calculated or measured for process control purposes. Theoretical background, algorithms and results of verifications of the Hot Rolling Metallurgical Monitoring model (HRMM) that predicts final mechanical properties (hardness, ultimate tensile strength and yield stress) of hot rolled products (coils, plates, long products) after final cooling are presented together with general data requirements of this model. The physically based HRMM model is technologically independent and various ways of its implementation for purposes of hot rolling technology design and control are discussed (off-line predictors, on-line monitoring systems, on-line control systems). Experiences with concrete HRMM software applications especially for off-line prediction of final mechanical properties of hot rolled wire rods and bars and for on-line metallurgical monitoring system in Hot Strip Mill Level 2 control system are presented at the conclusion.

Key words: Hot rolling, mechanical properties prediction, process control, computer simulation, metallurgical monitoring.

1. Introduction

Metallurgical models predicting mechanical properties of hot rolled products has to take into account influences of three subsequent cooling processes affecting final mechanical properties as it is shown in the Fig. 1:

- microstructure of deformed austenite resulting from the hot rolling process itself,
- quick accelerated cooling where transformation of austenite begins but does not have to finish,
- subsequent slow air cooling that can affect final mechanical properties significantly especially when improper accelerated cooling is applied or higher coiling or laying temperatures are reached. The austenite transformation continues in coils and other processes as precipitation, growth of the ferrite grain and tempering of the secondary structure can affect the final mechanical properties of rolled product.

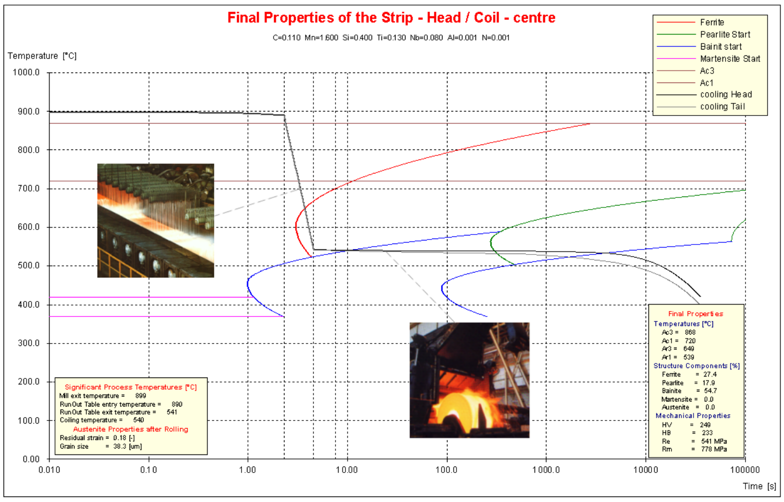

Fig. 1: Prediction of final mechanical properties of hot rolled strip

2. Hot Rolling Metallurgical Monitoring System – basic concept

Hot Rolling Metallurgical Monitoring (HRMM) means the off-line prediction of final mechanical properties of hot rolled steel products based on process data receiving on-line from the Level 2 of the rolling mill control system.

The HRMM system consists of three basic software modules as follows from the Fig. 2:

- **HRMM Predictor** – calculation of temperature curves not delivered by Level 2 and prediction of final mechanical properties of rolled product,
- **HRMM Corrector** – calculation of corrections of the HRMM Predictor based on results of quality control tests,
- **HRMM Database** – database contains records of process data created by the control system for each rolled piece necessary for the HRRM Predictor calculations.

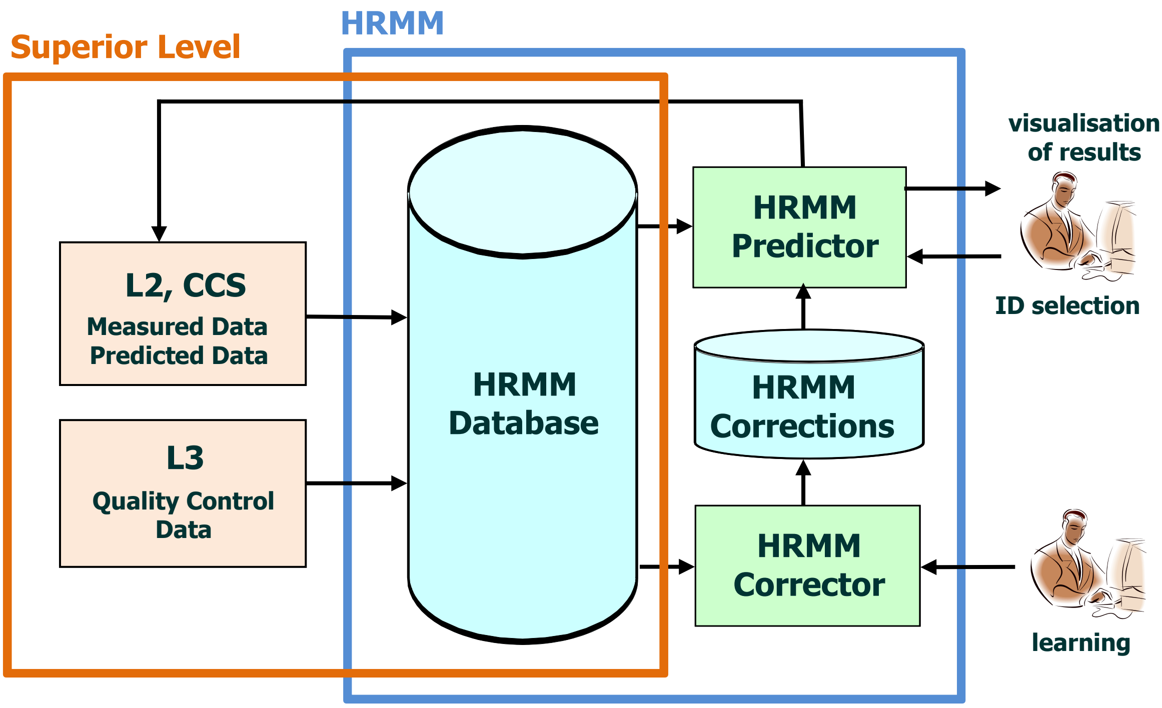

Fig. 2: Basic structure of the Hot Rolling Metallurgical Monitoring System

3. Hot Rolling Metallurgical Monitoring Predictor

The HRMM Predictor is the crucial part of the monitoring system. It consists of the following three basic software modules which calculate temperature, microstructure during rolling and final mechanical properties of rolled product after final cooling as it is shown in the Fig. 3:

- **MetaROLL Module** - calculation of the size and residual strain of deformed austenitic grains after the last reduction formed by gradual deformation and subsequent recrystallization before accelerated cooling. Influence of precipitation of micro-alloying additions is taken into account through its impact on the activation energy of recrystallization [5, 6],
- **MetaCOOL Module** - calculation of austenite transformation and final mechanical properties of steel after the final cooling,
- **TempC Module** - calculation of temperature curves which were not delivered by Level 2 of the control system (e.g. final cooling of strip in coil or bars lying on the cooling bed or subsequent heat treatment of rolled products after final cooling).

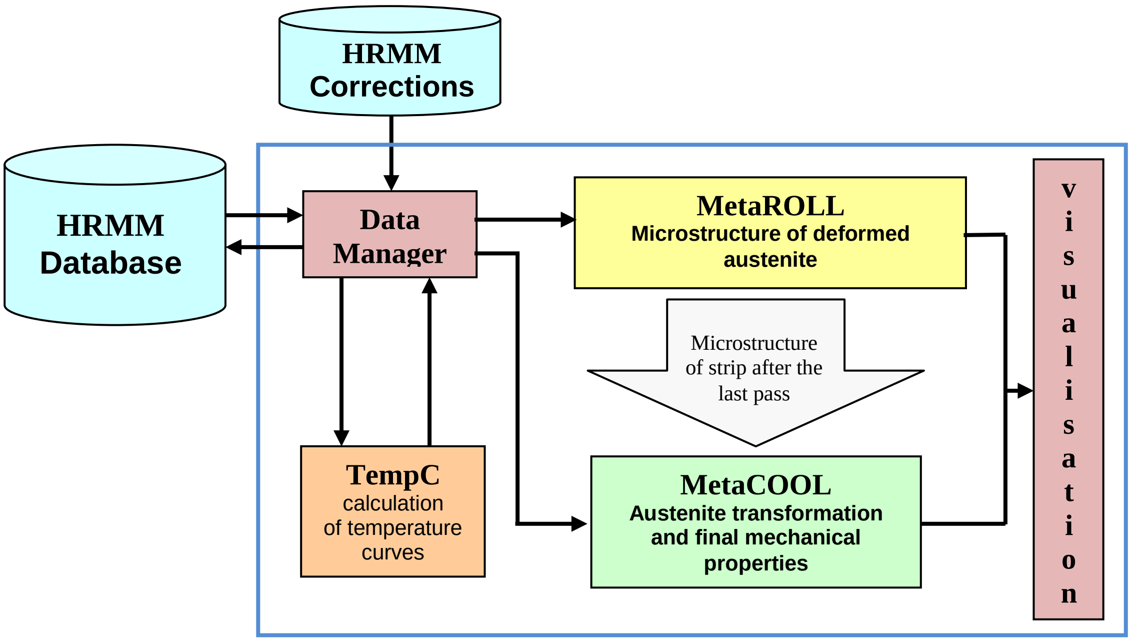

Fig. 3: Basic chart of the Hot Rolling Metallurgical Monitoring Predictor

3.1 Metallurgical Coupling of Rolling and Cooling Processes

Coupling of rolling and follow-up cooling metallurgical calculations in the HRRM Predictor is enabled by the help of two metallurgical parameters namely grain size and residual strain of austenitic grain after the last pass. Position of noses in the CCT-diagram is influenced by these parameters significantly and values of these parameters are influenced by the CCT diagram again. To solve this problem the iterative process was used as described in the Fig. 4.

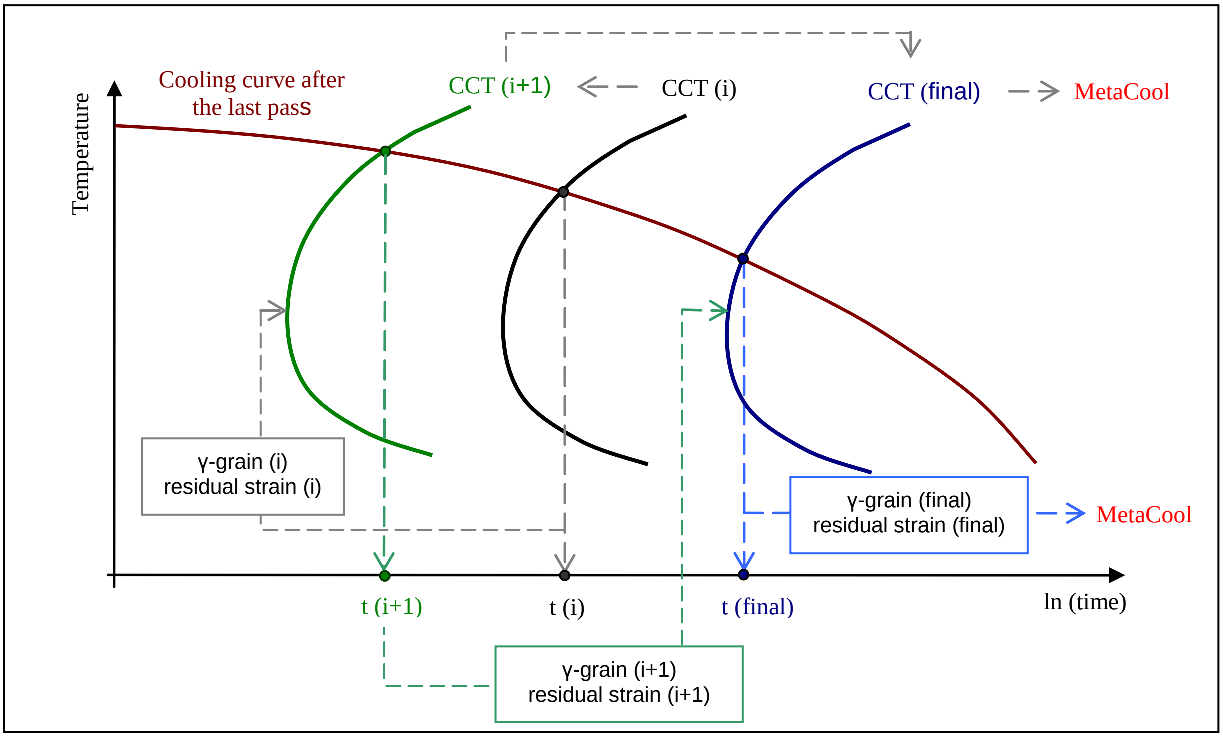

Fig. 4: Iterative metallurgical coupling of rolling and cooling calculations

The iterative process is finished when difference of times to the beginning of austenite transformation is small.

4. Hot Rolling Metallurgical Monitoring Predictor - Off-line Implementation

Off-line applications that can be used by technology designers for sensitivity analysis of various technological influences are one of possible implementations of the HRMM Predictor. Two such off-line applications are mentioned below.

4.1 Verification of the HRRM Predictor for wire rod rolling

The developed software DLPP (Danieli Long Products Properties Predictor) based on the HRMM Predictor is off-line tool for calculation of microstructure and final mechanical properties of hot rolled wire rods and bars. Wire rod mill installation according to the Fig. 5 was used for the HRMM verification.

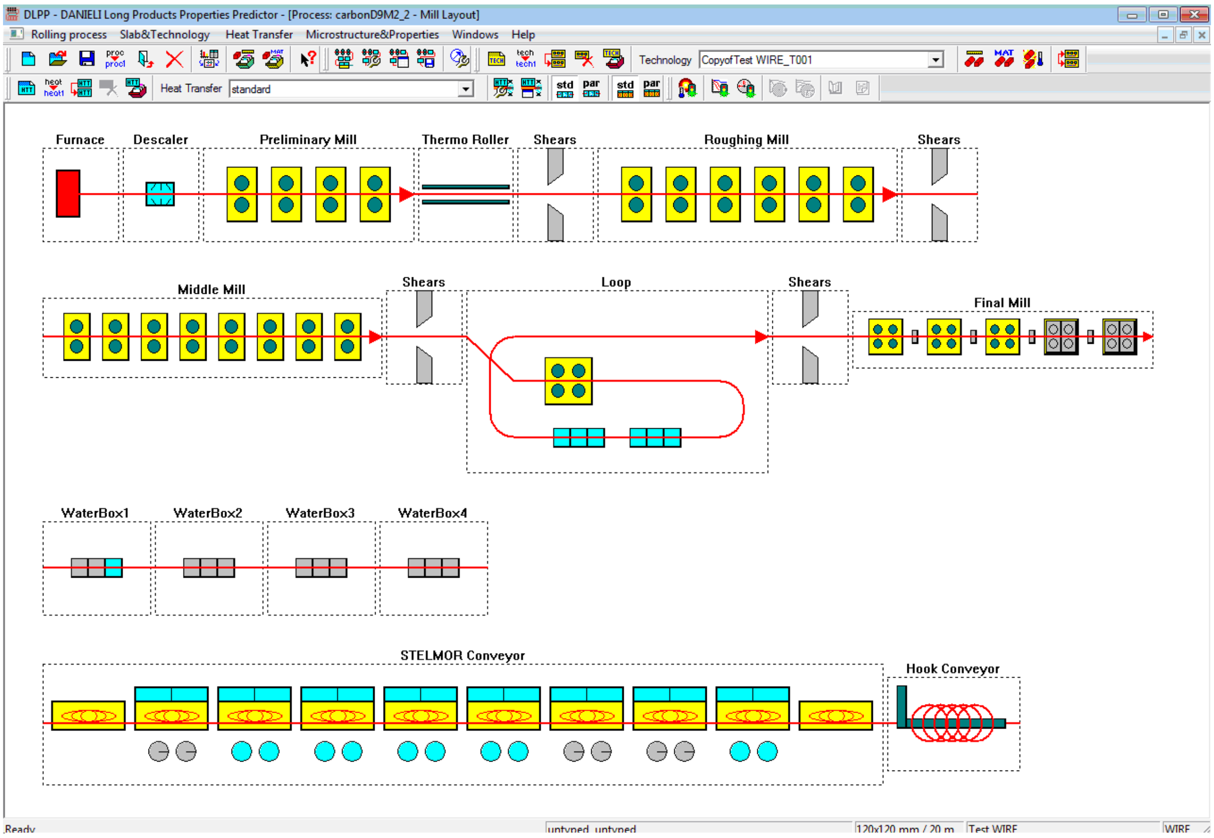

Fig. 5: Wire rod mill layout used for the verification

Verification for the micro-alloyed 23MnB4 steel

Values for over 350 continuous casting slabs made of titanium and boron micro-alloyed steel were available for this verification. The following table shows chemical composition of steel from one selected heat:

Tab. 1: Chemical composition of analysed steel (in mass %)

	C	Mn	Si	Cr	Ni	Ti	B
23MnB4	0.219	0.91	0.053	0.27	0.03	0.0267	0.0027

The following graphs provide the comparison of measured and calculated mechanical properties:

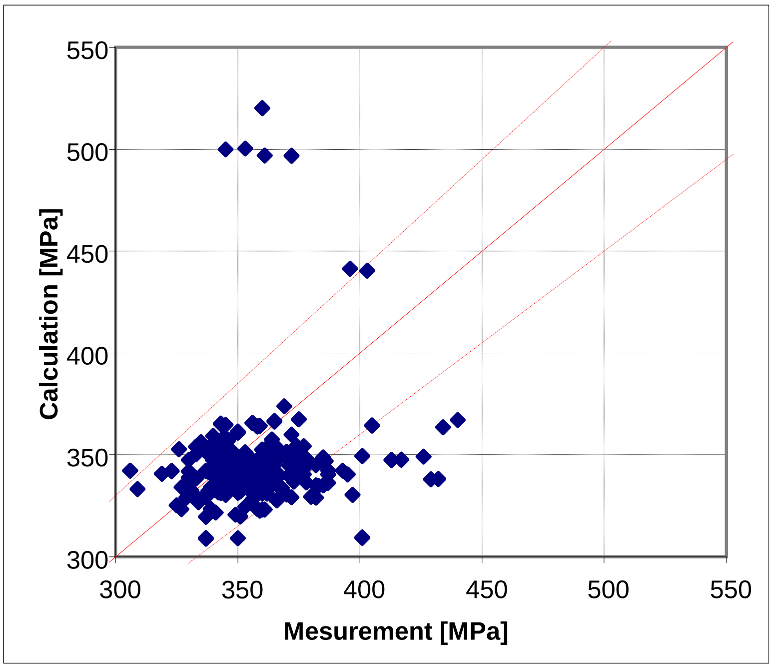

Fig. 6: Comparison of calculated and measured yield stresses for 23MnB4 steel

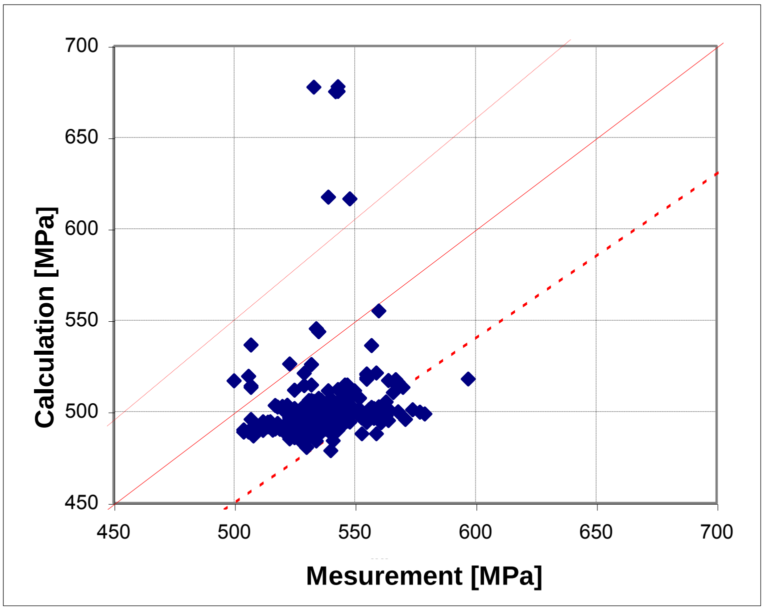

Fig. 7: Comparison of calculated and measured tensile strengths for 23MnB4 steel

Verification for the C40D2 Steel

There were 64 continuous casting slabs rolled to produce wire of 5.5 to 20 mm diameter available for the verification. The following table shows chemical composition of steel from one selected heat:

Tab. 2: Chemical composition of analysed steel (in mass %)

	C	Mn	Si	Cr	Ni	Ti	B
C40D2	0.403	0.64	0.26	0.06	0.02	0.002	0.0002

Microstructure containing mixture of ferrite and pearlite was calculated for the most of heats. The following graph displays predicted CCT diagram together with calculated cooling curve for one selected heat:

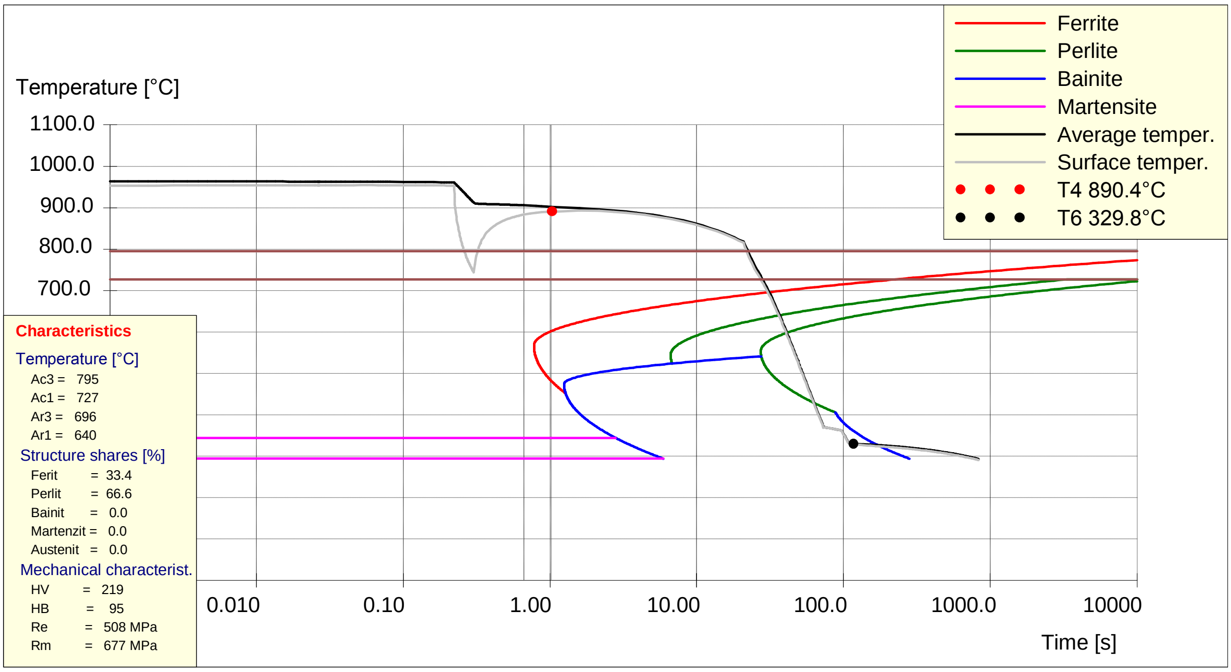

Fig. 8: Predicted CCT diagram and cooling curves for one selected heat C40D2

The following graphs displays provide the comparison between measured and calculated mechanical properties:

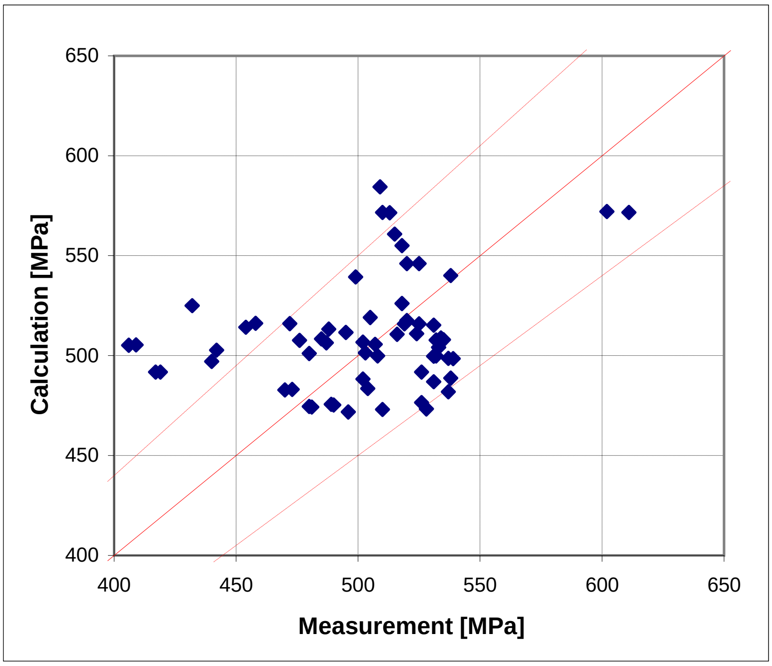

Fig. 9: Comparison of calculated and measured yield points for C40D2 steel

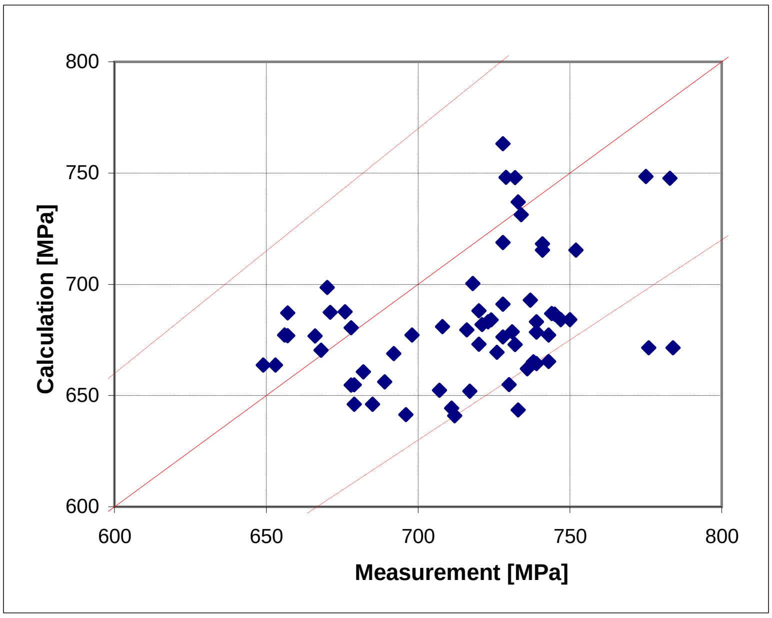

Fig. 10: Comparison of calculated and measured tensile strengths for C40D2 steel

Verification of the HRRM Predictor for heat treatment of reinforcing bar

The software QTSteel (Quenching and Tempering of Steels) based on the HRMM Predictor is off-line tool for calculation of mechanical properties of steels after hardening and subsequent tempering. Process of heat treatment of hot rolled reinforcing bar diameter 32 mm and chemistry described in the Table 3 was used for the HRMM verification [11].

Tab. 3: Chemical composition of analysed steel (in mass %)

C	Mn	Si	P	S	Ti
0,19	0,89	0,434	0,019	0,016	0,03

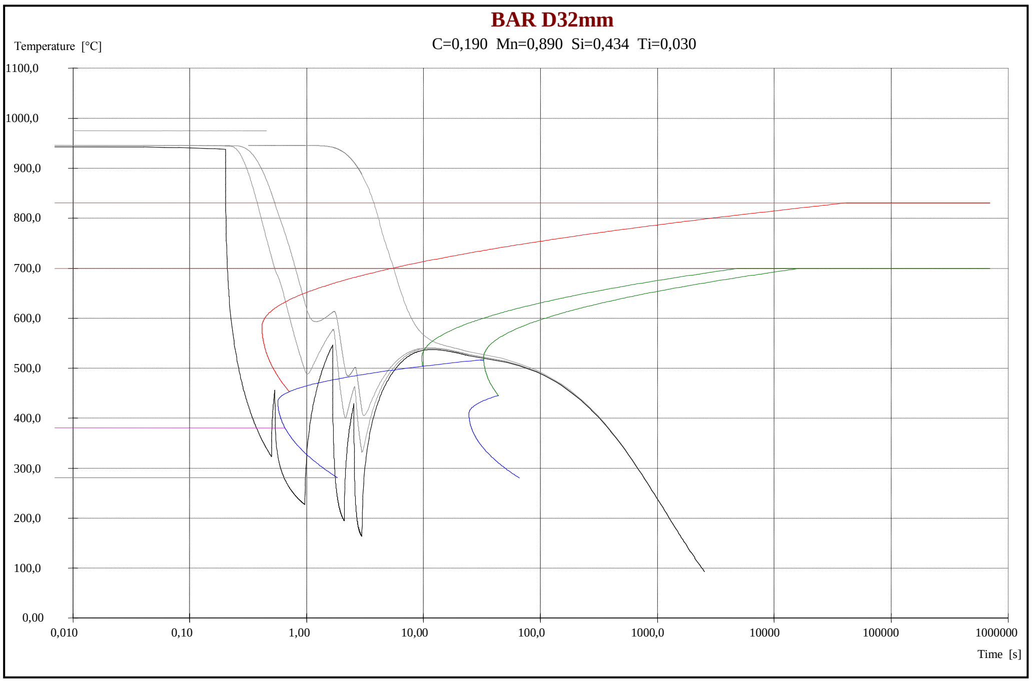

Fig. 11: Surface quenching and self-tempering of heat treated hot rolled bar D32mm

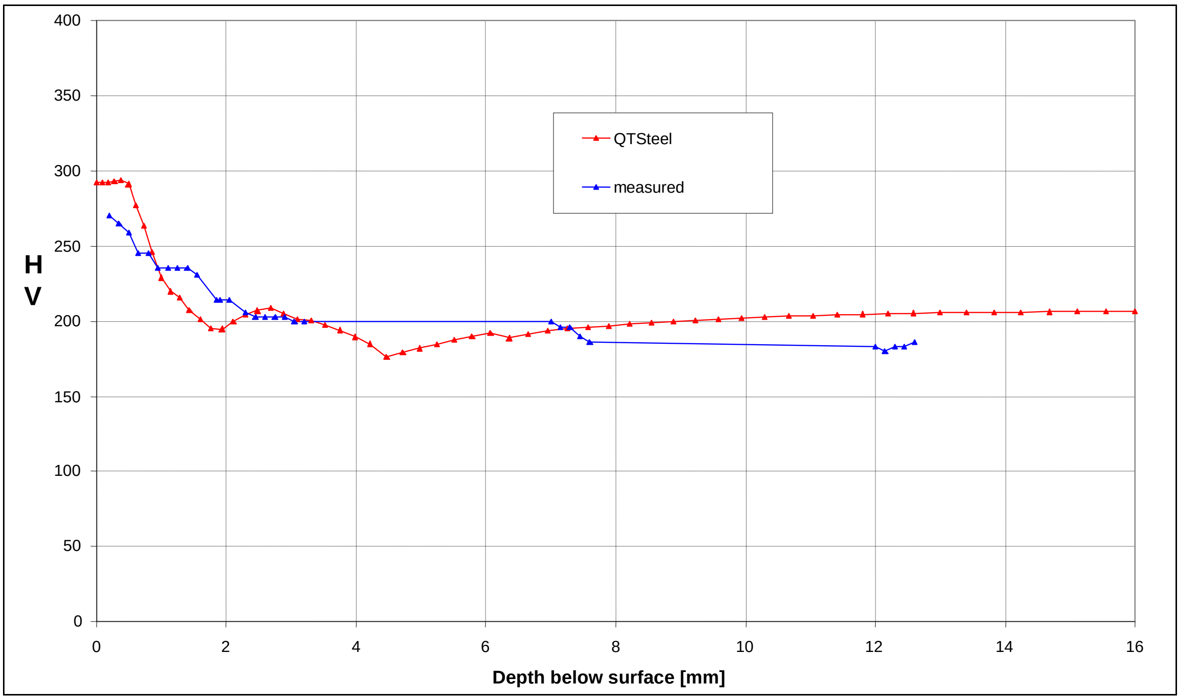

Figure 12: Comparison of measured and calculated HV hardness below surface

5. Hot Rolling Metallurgical Monitoring - Process Control Implementation

There are the following possible implementations of the HRMM directly into the process control system of the rolling mill:

- **Predictor of the start of austenite transformation** – exported function for quick calculation of the possible cross-section of temperature curve delivered by Level2 with CCT curves. The function returns time, temperature and transformed shares. This information is used for on-line control of rolling process itself especially for prediction of rolling forces.
- **Automatic predictor of final mechanical properties** – automatic on-line calculation of mechanical properties of each rolled piece based on the data delivered by Level2. This information is, together with corresponding technological input data, saved in the database and can be reported and off-line recalculated.
- **Setup of final cooling control** – inverse calculation of cooling device technology parameters necessary for achieving of required mechanical properties of final product.

5.1 SpOb - Strip Observer

The software SpOb for prediction of microstructure and final mechanical properties of hot rolled strip was developed according to concept described on the Fig. 2.

The SpOb requests as input complete temperature curve in specified point on the surface or inside the strip including temperature evolution during cooling of the strip in coil. It is supposed the temperature curve is delivered by the Level2 only till the moment when the strip enters the coiler. The remaining part of the cooling curve has to be calculated inside the SpOb.

The FEM based temperature model TempC is used for temperature calculations when strip is cooled in coil. This model uses 2D-axisymmetric linear quadrilateral elements and divides the process of cooling of the strip into coiling itself and subsequent cooling of a final coil.

The model of coiling supposes the final strip is divided lengthwise into uniform segments (see Fig. 13) and the following information is available for every strip segment:

- time of coiling,
- average temperatures at left and right sides and at the centre of strip

Plane lengthwise strip segments are coiled step by step and create axisymmetric coil layers. Average strip segment temperatures are interpolated into the 2D coil mesh. Coil temperatures are calculated after each updating of coil layers (coiling).

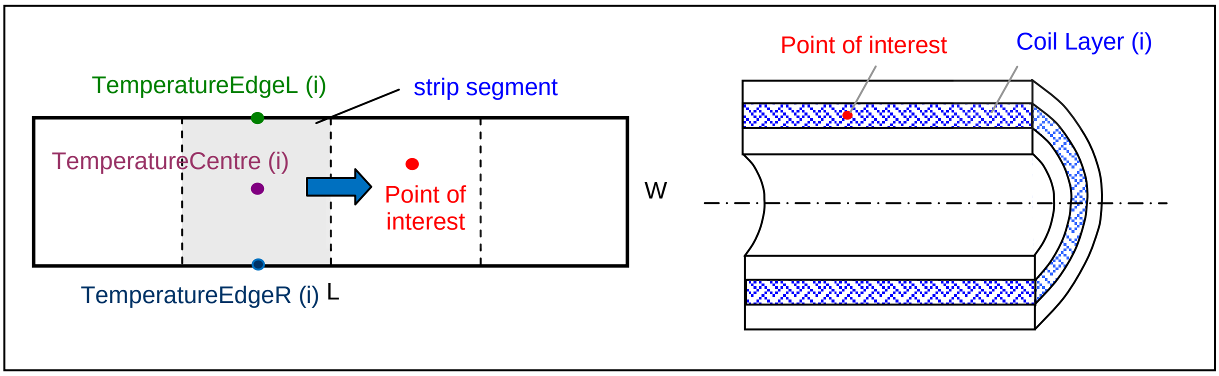

Fig. 13: Definition of layer structure of a coil

Cooling of the final coil after coiling is calculated by the same temperature module but for fixed coil dimensions. Temperature profile across the coil in specified time during coiling and final cooling curve in specified point on the strip are shown on the Fig. 14:

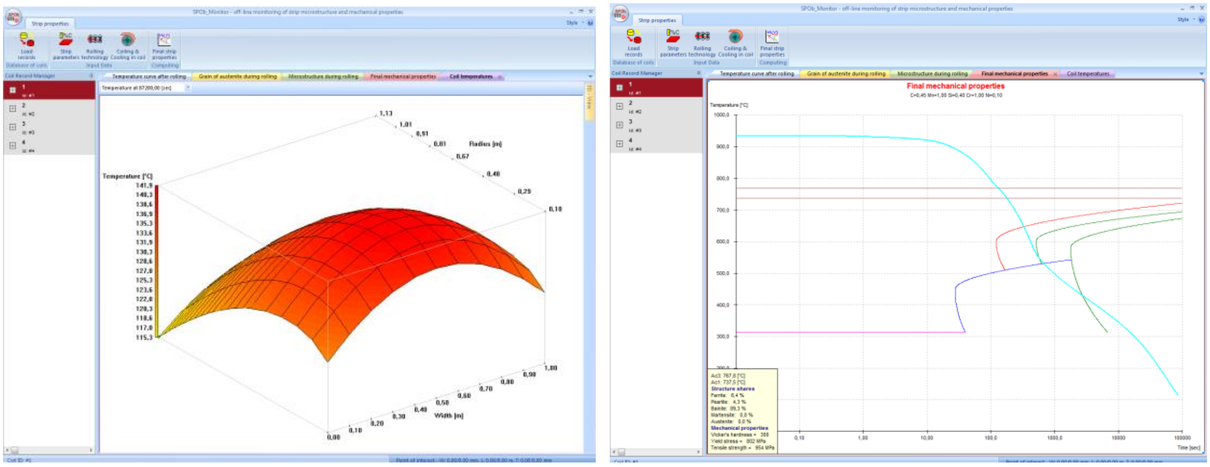

Fig. 14: Temperature in specified time profile across the coil and final cooling curve

6. Conclusion

Various implementations of the HRMM Predictor was presented. Off-line applications as for example DLPP or QTSteel can be instrumental to answer questions how microstructure and final mechanical properties of hot rolled product are sensitive to changes of rolling technology parameters. Metallurgical Monitoring applications as for example SpOb can serve as predictors of mechanical properties of final product based on data collected from the Level2 and Level3 control system of a mill. Mechanical properties predicted off-line by the HRMM Predictor were compared with measured properties to estimate possible precise.

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