Models for Level-2 Control of Cooling Processes during Hot Rolling

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ABSTRACT

Ability of process control systems (Level-2) to improve or ensure mechanical properties of hot rolled products depends significantly on the quality of its cooling control subsystems. Theoretical background and algorithms of two types of physical based models that can be implemented into cooling control subsystems are presented. The first model controls an Inter Stand Cooling at wide hot strip mill to provide a defined temperature drop in the last passes and ensure constant exit rolling temperature lengthwise respecting temperature oscillations of the transfer bar. The second model combines thermal and metallurgical aspects of cooling and can be used for monitoring of cooling process from the point of view of final mechanical properties of hot rolled product or for initial setup of cooling conditions to ensure required mechanical properties. Results of verification and practical experiences are discussed.

Keywords: Hot Rolling, Inter Stand Cooling, Accelerated Cooling, Control System, Mathematical Model, Mechanical Properties Prediction.

INTRODUCTION

Control of cooling during Hot Rolling process itself and after the last pass has a significant effect on mechanical properties of final product. The Inter Stand Cooling (ISC) at Hot Tandem Mills partakes fundamentally in reaching and maintaining the required exit rolling temperature (ERT). Thus it enables to reach better and more homogeneous microstructure along a rolled product. The subsequent accelerated cooling (ACC) controls transformation of deformed austenite and together with slow cooling in coil or on cooling beds creates final mechanical properties of a rolled product.

For correct function of all devices providing cooling during hot rolling process is necessary to fulfil two basic requirements – to keep at disposition a hardware with sufficient cooling power including the possibility of fast and fluent regulation of flow rate and an advanced process control software, both for cooling setup, feed forward and feedback control.

FEM TEMPERATURE MODELS

One of the most important ability of cooling control systems is reliable and quick prediction of temperatures in specified position of rolled product and in specified time. Demand on physical and dimensional complexity is not so important due to presence of adaption feedback algorithms. Presented cooling control systems use 1-D and 2-D models based on the Finite Element Method (FEM).

The model THERM1D enables to calculate the temperature profile through the rolled product cross-section. Linear 2-node element is used to calculate time evolution of temperature in mesh nodes non-uniformly distributed from the centre to the surface (Fig. 2). This model neglects heat conduction along length of rolled products and along width of flat products. However, understanding of the temperature along the length is very important and therefore it is necessary to calculate the temperature profile in several points lengthwise.

The axisymmetric temperature model COIL2D is used to calculate temperature evolution during cooling in a coil. The number of mesh elements is significantly limited in that case but supposed low cooling rates and lower sensitivity of final mechanical properties on small disturbances of temperature eliminates influence of possible numerical errors. Linear 4-node tetragonal element is used to calculate time changes of temperature in uniformly distributed mesh nodes which covers only symmetrical part of a coil (Fig. 1). Thermal properties of steel takes into account heterogeneity of a coil.

Boundary conditions based on prescribed heat flux through specified part of surface enables to describe heat transfer during all kinds of cooling process stages which can arise during hot rolling. There is necessary only to know proper heat transfer coefficient and gradient between surface and coolant temperature. Experimental verification of boundary conditions is of fundamental importance and there is necessary to organize such measurements case to case to affect specific heat transfer conditions of particular technological devices [1,2].

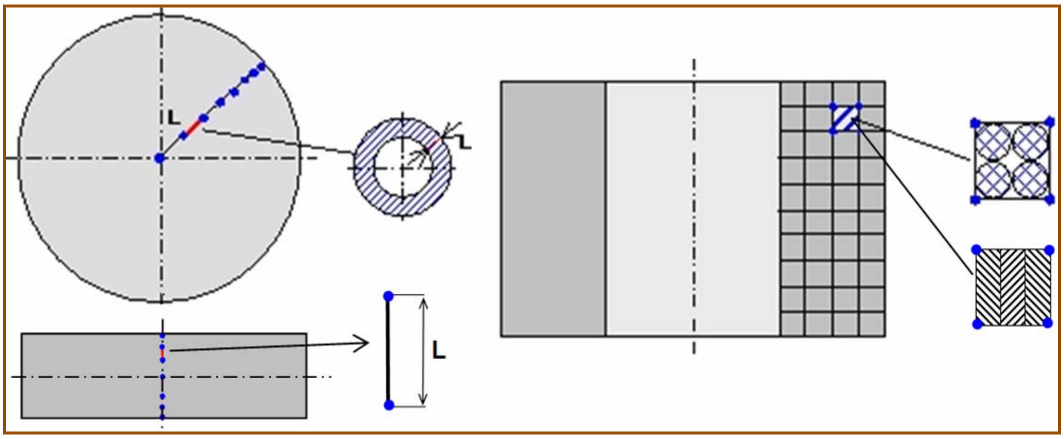


Fig. 1: Chart of FEM models of geometry (a) single strip/plate, single circular bar, (b) bar/strip in a coil

CONTROL SYSTEM OF INTERSTAND COOLING

Presented ISC control system has been designed to work either within existing Level-2 of the hot strip mill or to work rather independently of it. It consists of three basic parts: the Setup (working within existing Level-2 or on separate computer), the V-Controller and the T-Controller (Level-1). Basic scheme of the system is in Fig. 2. The main task of the Setup is to calculate the number and power of cooling headers for reaching the temperature in the whole strip length. The V-Controller is feed forward regulator respecting the influence of the strip speed changes. The T-Controller is feed back temperature regulator.

The measured strip surface temperature is mostly available only at limited number of spots (the roughing mill exit, the finishing mill entry and exit). Nevertheless, the temperature measuring before the finishing mill entry is usually very unreliable because it is influenced by a thick scale layer, emissivity of which strongly depend also on the steel chemical composition. Temperature obtained from pyrometer at the outlet from roller table can be used to get more complex information but the control system can work without this information quite accurately.

As the transfer bar temperature oscillates, the number and cooling power of the headers must be calculated in several spots lengthwise (35 to 50 points). The points are situated in the local extremes of the temperature curve in the transfer bar. Special filter is used to get rid of incorrect measurements, to smooth the temperature curve and to find local extremes of the temperature behind the roughing mill.

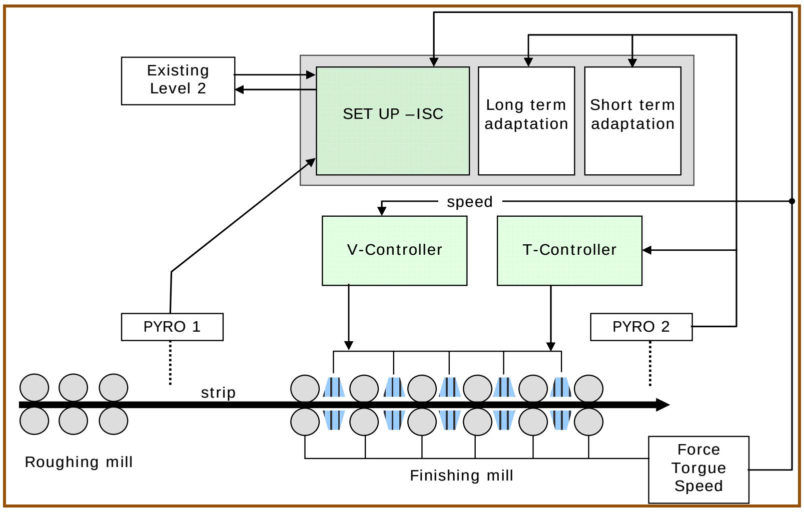


Fig. 2: Basic scheme of the ISC control system

Inverse ISC Module for the Headers Setup

The task of the module is a fast calculation of the cooling power and number of suitable headers so that the required exit rolling temperature is reached (for one examined point along the strip). For the calculation, the optimization method Merortha predictor corrector is applied. The next constraints were used for the optimization calculation:

- Specific power of each of headers must vary in between 0 (off) up to 1 (max. power).
- Cooling power of headers must not decrease along the rolling course.
- Cooling power of headers is distributed to cool most at the largest thicknesses.
- Priority to set off or to set on the full power is given.

The algorithm for achievement of Exit Rolling Temperature in one point is plotted at Fig. 3.

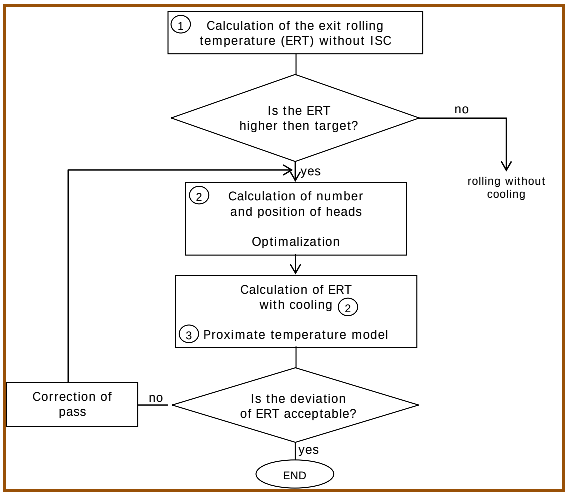


Fig. 3: Headers setup algorithm for one point

Cooling Efficiency of Inter Stand Cooling

The ISC capacity was determined by computer simulations and measurements at the hot strip mill 2000 mm [1,2]. The scheme of finishing mill with headers is shown in Fig. 4.

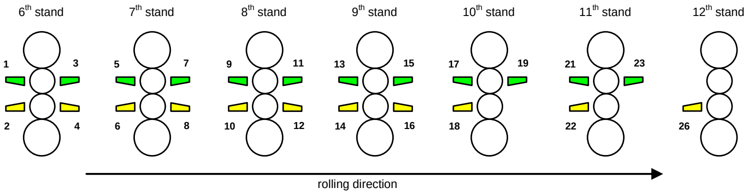


Fig. 4: ISC headers position in finishing mill 2000mm

The ultimate possible temperature drop varies from 80 °C for the thick strip (thickness > 8 mm) up to 140 °C for the thin strip (thickness < 2,7 mm) as can be observed at Fig. 5.

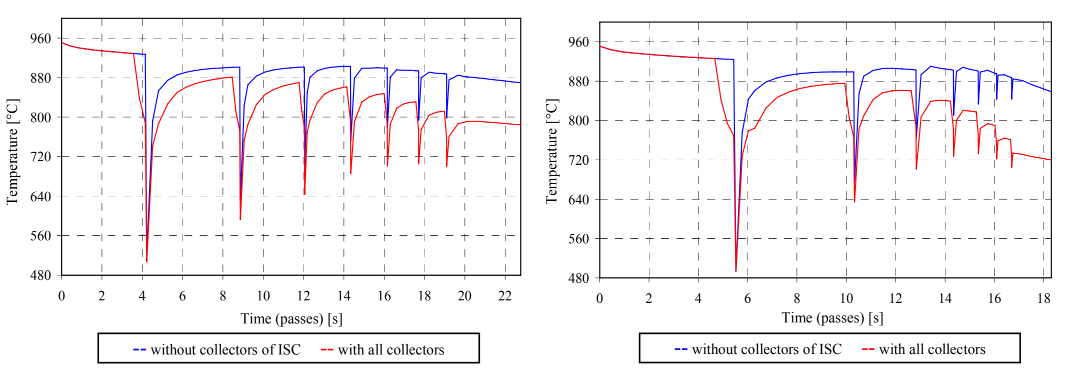


Fig. 5: Efficiency of ISC in cooling of thin and thick strip

Target Exit Rolling Temperature

Exit rolling temperature can be kept lengthwise within a tolerance of ±10 °C from the target temperature. In thin strips (<5 mm), the observed deviations are less than ±5 °C. In thick strips (>10 mm) the tolerance ±10 °C can be reached only if the temperature oscillation in transfer bar is less than 15 °C. Higher deviations can be observed in strip head and tail due to unreliable temperature measurements at these parts.

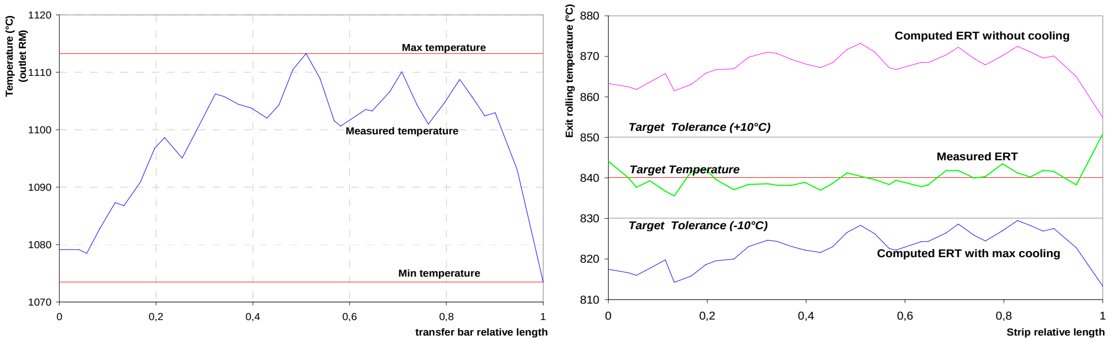


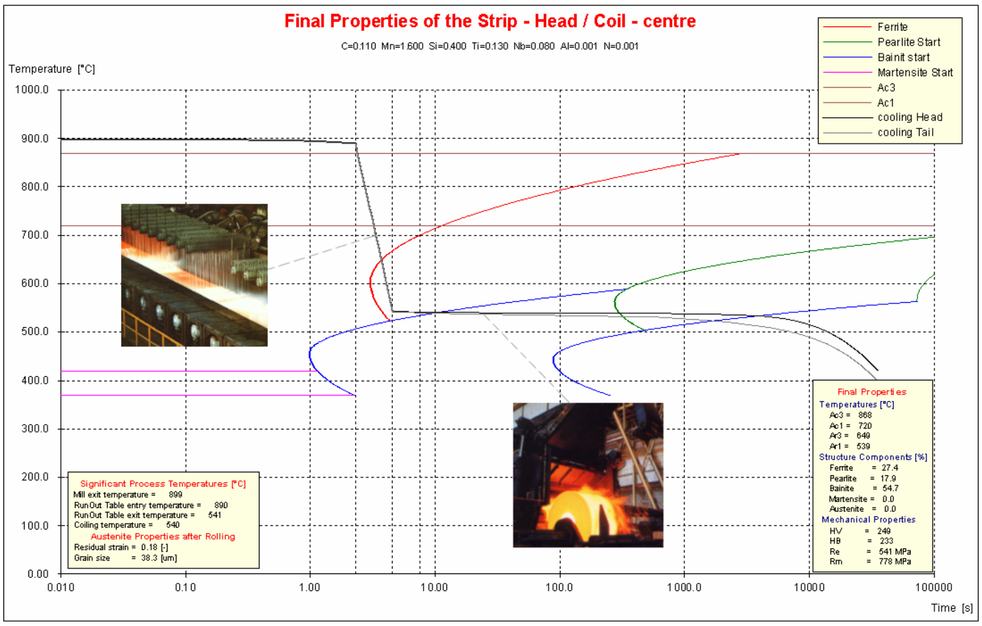
Fig. 6: Measured deviations of the transfer bar and exit rolling temperature

Enhancement of Speed/ Speed up

Reaching of required exit rolling temperature is one of the limiting parameters for setting of rolling speed and speed up of the strip. Providing that ISC has enough cooling power and can be effectively controlled, limits of speed and speedup can be significantly raised. There are several metallurgical and technological aspects prohibiting extensive cooling in special steels nevertheless practical experience proved an increase of production productivity due to ISC is realistic.

METALLURGICAL MONITORING AND SETUP IN THE ACCELERATED COOLING CONTROL SYSTEM

Metallurgical models predicting mechanical properties of rolled products has to taken into account influences of three subsequent cooling processes affecting final mechanical properties. The first effect is microstructure of deformed austenite resulting from the hot rolling process itself, the second one is quick accelerated cooling where transformation of austenite begins but may not finish and the third one is 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. Example of such complex prediction for a hot rolled strip is shown in Fig. 7.



Significant Process Temperatures [°C]
Mill exit temperature = 899
RunOut Table entry temperature = 890
RunOut Table exit temperature = 541
Coiling temperature = 540
Austenite Properties after Rolling
Residual strain = 0.18 [-]
Grain size = 38.3 [um]

Final Properties
Temperatures [°C]
Ac3 = 868
Ac1 = 720
Ar3 = 649
Ar1 = 539
Structure Components [%]
Ferrite = 27.4
Pearlite = 17.9
Bainite = 54.7
Martensite = 0.0
Austenite = 0.0
Mechanical Properties
HV = 249
HB = 233
Re = 541 MPa
Rm = 778 MPa

Fig.7: Prediction of final mechanical properties of hot rolled strip

Metallurgical Monitoring in the Accelerated Coling Control System

Presented Metallurgical Monitoring has been designed to work within existing Level-2 of the mill. It consists of three basic software modules as follows from Fig. 8.

- MetaROLL Module – calculation of the size and residual strain of austenitic grains after the last reduction formed by gradual deformation and subsequent re-crystallization before accelerated cooling. Influence of precipitation of micro-alloying additions is taken into account through its impact on the activation energy of re-crystallization [5, 6].
- MetaCOOL Module – calculation of austenite transformation and final mechanical properties of steel after final cooling.
- MetaLEARN Module – calculation of MetaCOOL corrections based on process and quality control data.

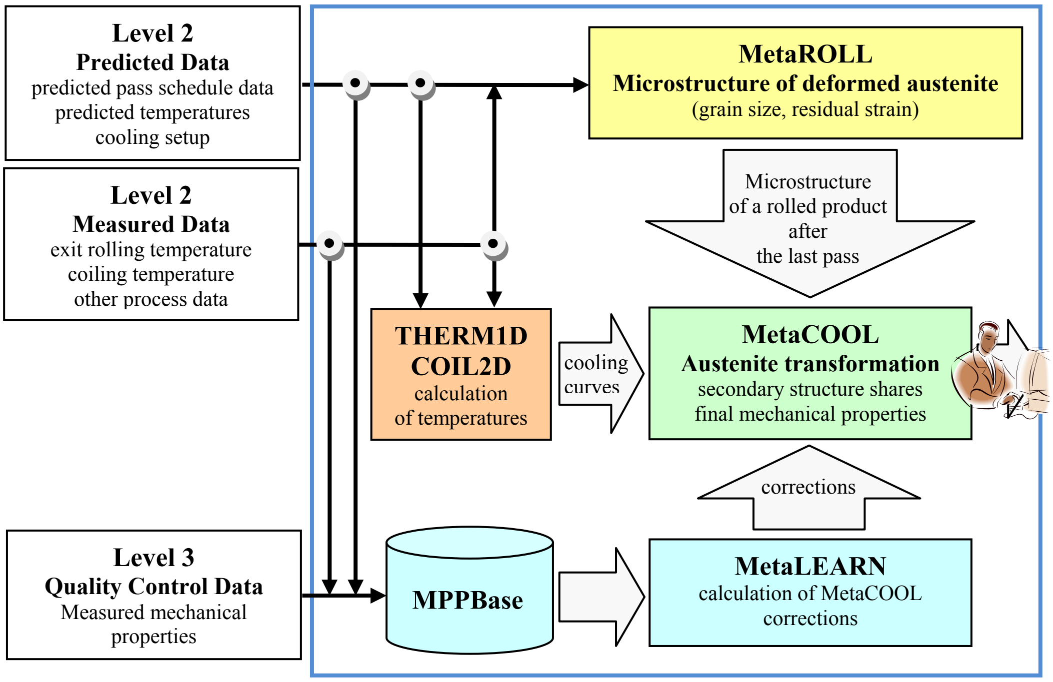


Fig. 8: Basic scheme of the Metallurgical Monitoring Module

The concept of hybrid cooling decomposition diagram (HCT Diagram) [3,4] and standard Avrami equation (1) that was modified for cases with non-uniform cooling rates were used to describe kinetics of austenite transformation for various cooling conditions

$$X(t,T) = X_{\gamma} \cdot (1 - \exp(-k(T) \cdot t^{n(T)})) \qquad \text{…. (1)}$$

where parameters k(T) and n(T) depend on the cooling rate and X□ is rest of austenite.

With the use of (1) the percentage of ferrite, pearlite and bainite is calculated in accordance with intersections of calculated cooling curve with particular HCT curves. An advantage of the HCT diagram is the fact the cooling curve does not involve constant cooling rate. Process of martensitic transformation is not time dependent so instead of (1) the standard Koistinen Marburger equation (2) is used

$$Xm(T) = (1 - \exp(-b \cdot (TMs - T)^{n}) \cdot X_{\gamma} \qquad \text{…. (2)}$$

where b, n are constants, TMs is Martensite start temperature and X□ is rest of austenite.

The calculation of mechanical properties is based on additional regression analyses reflecting the effect of chemical composition of steel and microstructure shares on the HV hardness. Relationship between HV and tensile strength Rm is well known. The calculation of yield stress Re is more difficult. Except values from regression analyses the calculation of yield stress reflects the ferritic grain size effect and austenite transformation rate in v Hall-Petsch equation as well.

Mechanical properties after tempering in a coil are calculated from chemical composition of steel $C_{(i)}$ by the equation (3) based on regression analysis of HV hardness of particular structure shares for various tempering temperatures T_{temp} but fixed tempering time 3 hrs.

$$HVx3 = \left\{ \sum_i R(i) \cdot C(i) \right\}_{Ttemp,3hrs} \quad \text{…. (3)}$$

The standard Hollomon-Jaffe parameter Hp (4) is used for calculation of equivalent tempering regime with various tempering times and temperatures

$$H_P = (T_{temp} + 273.15) \cdot (C + \log t_{temp})/1000 \quad \text{…. (4)}$$

where C is a constant varying between 15 and 21.

Metallurgical Setup in the Accelerated Cooling Control System

The first testing version of the Metallurgical setup, it means prediction of cooling conditions resp. cooling curve that ensure requested mechanical properties was developed with the following limitations:

- Cooling curve consists of two parts with different cooling rates (accelerated cooling and subsequent slow air cooling either on a cooling bed or in a coil).
- Cooling with variable intensity is allowed only in accelerated cooling section.
- Accelerated cooling doesn’t finish transformation of austenite in a significant volume.
- One average temperature is used to describe cooling of a rolled product.
- HV hardness only is used as a quantity representing final mechanical properties.

Inverse algorithm of the Metallurgical Setup uses above mentioned MetaCOOL Module and consists of the following steps:

- HV Sensitivity Determination – evaluation how final HV hardness depends on the Transformation_FINISH time for cooling curves with constant cooling rate and fixing of critical cooling rate that leads to achieving required HV (see Fig. 9).
- Critical Point Fixing - evaluation of time and temperature coordinates of crossing of cooling curve having critical cooling rate with Transformation_FINISH curve.
- Cooling Curve Searching – cooling curve having two parts with different cooling rates is looked for by varying the first cooling rate only (accelerated cooling) to fit cross-section

with Transformation_FINISH curve as precise as possible (see Fig. 10).

First computer tests showed this algorithm can work with deviation between requested and predicted HV hardness around ±10 %. But there is necessary to speed up this algorithm to be able to be implemented into real control system.

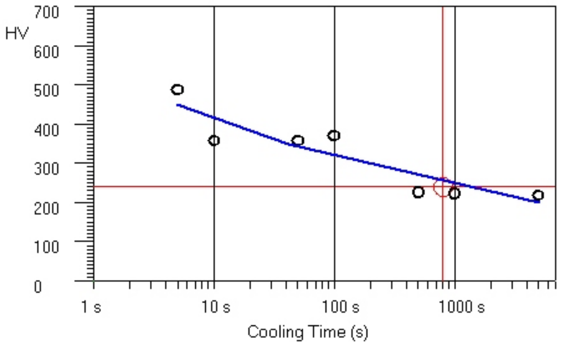


Fig. 9: Example of Metallurgical Setup – evaluation of HV sensitivity for cooling curves with constant cooling rate

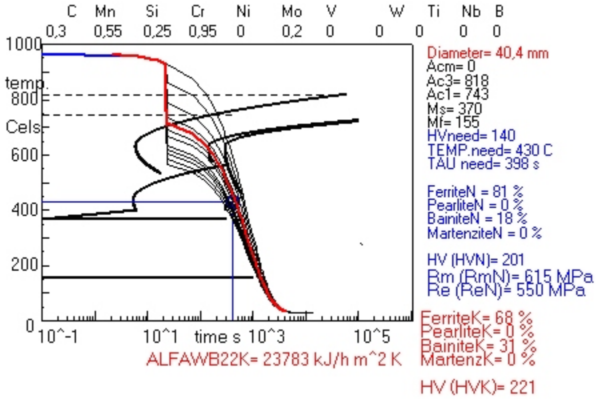


Fig. 10: Example of Metallurgical Setup – prediction of cooling curve with two different cooling rates (thick cooling curve was found)

Verification of Metallurgical Modules

The MetaROLLl and MetaCOOL modules were verified in cooperation with the steelmaking plant in Trinec (Czech Republic). Process data and corresponding final mechanical properties for over 1200 continuous casted slabs hot rolled to produce 5.5 to 40 mm diameter wire resp. bar were available [3,7]. Selected examples of verification are available.

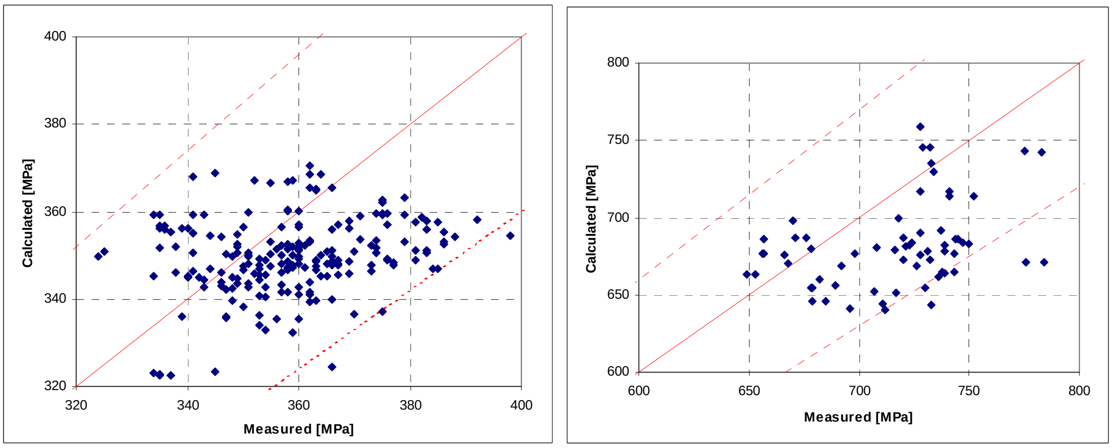


Fig. 11: Measured and predicted Tensile Strength Rm for the low carbon steel C4C (0.05%C, left) and the middle carbon steel C40D2 (0.4%C, right)

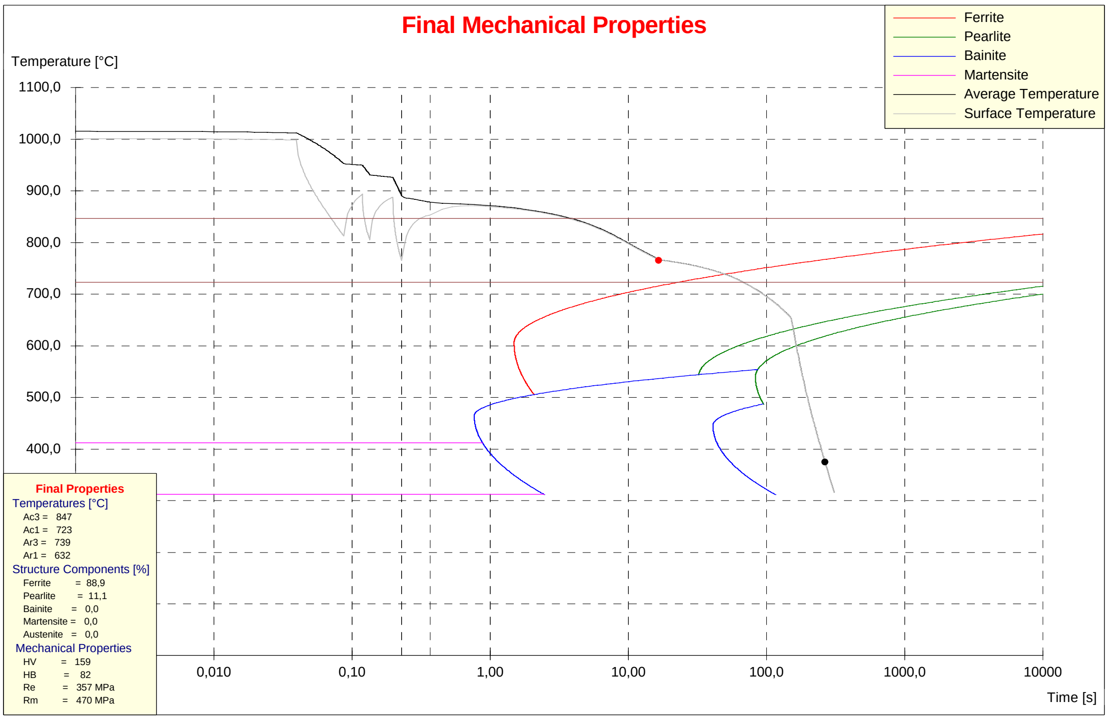


Fig. 12: Predicted HCT Diagram and cooling curves for microalloyed steel 17MnB4 Yield Stress Re: predicted 357 MPa, measured 341 MPa Tensile Strength Rm: predicted 470 MPa, measured 493 MPa

The comparison of measured and computed mechanical properties confirmed the fact that the prediction accuracy was satisfactory and deviations of at least 90 % of results from the measured values did not exceed ± 10 % for all analysed steels.

CONCLUSIONS

The complex approach to the Inter Stand Cooling problems solution together with some practical experience on wide strip finishing mill 2000 mm is briefly presented in the first part of this paper. The ISC helps to reach target exit rolling temperature and to ensure temperature homogeneity along the strip length. Exit rolling temperature can be kept lengthwise within a tolerance of ±10 °C from the target temperature for most of production. Temperature oscillations due to skid marks can be eliminated or considerably reduced. Constant exit rolling temperature helps to reach target coiling temperature in laminar cooling section. The productivity of the mill can be increased due to increasing of speed and speed up of the strip.

The implementation of the Metallurgical Monitoring and basic principles of the Metallurgical Setup in Accelerated Cooling Control System are briefly presented in the second part of the paper. The Monitoring module serves as a predictor of mechanical properties of final product based on data collected from the Level-2 and Level-3 control system of a mill. The Setup module calculates cooling curve necessary for achieving of required mechanical properties of final product. Mechanical properties predicted off-line by metallurgical modules used in Monitoring and Setup are compared with measured properties to estimate possible precise. Deviations between calculated and measured values were observed in the range ±10 % for all analysed steels.

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