DLPP® - Quality management software tool for Rolling and Heat Treatment Optimization

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Process simulators are used in the steel industry in order to reduce risks, time and cost when introducing new products and equipment. They allow to enhance the quality and performances of the final product, avoiding mistakes in layout definition and "trial-and-error" approach during normal production. The increasing demand of as-rolled products' quality (wire rods, smooth and ribbed bars, bars in coil, spoolers) is challenging the SBQ producers to implement new technologies by combining high plant productivity and efficiency of superior quality finished products thanks to the introduction of in-line heat treatment.

For this purpose, Danieli and ITA have developed a specific quality management software tool, DLPP® (Danieli Long Products Predictor), which allows the prediction of metallurgical and final mechanical properties of hot rolled wire rods and bars. Metallurgical module MetaCool® implemented in DLPP® is used for quick and efficient computer simulation of In-Line-Rolling heat treating processes as well as for Off-Line conventional heat treatment. This paper will focus on the following three real processes where the use of DLPP® significantly helped optimize the heat treatment technology:

- the best layout definition for a SBQ wire rod line;
- the definition of controlled rolling conditions for a spooler line (hot-rolled rebar in coil);
- the definition of the correct process parameters for an Induction Hardening line.

KEYWORDS: DLPP[®] - METALLURGICAL PREDICTOR METACOOL[®] - THERMOMECHANICAL TREATMENT - ROLLING AND HEAT TREATMENT OPTIMIZATION

INTRODUCTION

In the current industrial scenario proposed by "Industry 4.0" and "IOT" models, the so-called "smart factories" need to reduce costs and downtime without renouncing to improve product quality and productivity. On-field experiments are by their nature time and money consuming, while computer simulation can save resources and avoid mistakes both in the project definition phase and during real production itself.

For steel rolling mills, Danieli and ITA have developed DLPP, a simulation tool for in-line or off-line prediction of temperature and microstructure and final mechanical properties of hot rolled wire rods and bars. This software enables to calculate temperatures of long products during rolling and final cooling for various classes of steel grades and for several nickel, aluminum and titanium alloys, as well. For a wide range of carbon steels, microstructural evolution during and after rolling can be simulated, thus predicting the final mechanical properties.

In this paper an explanation of the main characteristics of DLPP are presented and three study cases where this simulation tool was used are reported.

METACOOL - BASIC CONCEPT OF THE METALLURGICAL PREDICTOR

Although steel processing technologies can differ, the physical background of ongoing metallurgical processes is similar. That was the reason why ITA company decided to develop technology independent metallurgical predictor MetaCool [1-2-3]. The MetaCool is the library of functions written in the C programming language with pure physical quantities on input (chemistry, temperatures, times, strains, cooling curve) and microstructure

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shares and final mechanical properties of steel (hardness, yield stress, ultimate tensile strength) on output. The MetaCool library is ready to be linked to various types of technology dependent process simulation or control software packages. One of such off-line process simulation software is DLPP.

MetaCool is divided internally into 3 steel groups and 17 steel subgroups. The "Ultra Low Carbon" steels group covers steels with carbon from 0.001% to 0.06%. The "Carbon&Alloyed" steels group covers steels with amount of carbon from 0.06% to 0.6% and with the total sum of alloying additions up to 10%. "Tool steels" group covers steels with amount of carbon from 0.6% to 1.15% with the total sum of alloying additions up to 5%.

The CCT diagram model

The model of the CCT diagram consists of the set of lines (significant temperatures Ac3, Ac1, Ms) and curves (unsymmetrical parabolas) specified by time and temperature coordinates in their significant points (nose, upper and lower branch). The position of lines and curves in the CCT diagram for specified chemistry was acquired from published diagrams processed separately for each steel group with the use of regression analysis [4-5]. The following functions were used for approximation of time and temperature coordinates of definition points of the CCT Diagram:

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

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

where

| S ^o _{struct} (PT), T ^o _{struct} (PT) | is time and temperature of the significant | |
|--|--|--|
| | point, | |
| struct | means particular start and finish lines | |
| | and curves, | |
| A_0, B_0, A_i, B_i | are regression coefficients, | |
| C, | is percentage of alloying addition (i). | |

The model takes into account the microstructure of initial austenite as well, especially its grain size and residual hardening if the transformation of deformed austenite is simulated. These quantities can shift curves of the diagram along time axis significantly.

Temperature curve and transformation kinetics

The MetaCool predictor assumes that the cooling curve is a sequence of (time, temperature) couples that need not to be uniformly decreasing. Transformation kinetics of diffusion processes is described by the Avrami equation (3) that was modified for cases of cooling curves with non-uniform cooling rates:

$$X(t,T) = X_{\gamma} \cdot (1 - \exp(-k(T) \cdot t^{n(1)}))$$
(3)

where parameters k(T) and n(T) depend on the cooling rate, t is the time and X_{γ} is the rest of austenite. With the use of (3) the percentage of ferrite, pearlite and bainite is calculated in accordance with intersections of the cooling curve with particular CCT curves.

Process of martensitic transformation is not time dependent, so the standard Koistinen Marburger equation (4) is used:

$$Xm(T) = (1 - \exp(-b \cdot (TMs - T)^{n})) \cdot X_{\gamma}$$
⁽⁴⁾

where b, n are constants, TMs is the Martensite start temperature and $X_{\rm u}$ is the rest of austenite.

Mechanical properties prediction

Basic information for prediction of final mechanical properties

of steel after hardening and tempering is HV hardness. The HV hardness after hardening was determined by regression analysis for the shape function (5) with the percentage of alloying addition c_{μ} amount of particular structure shares Xstruct and constants C_{0} , D_{μ} , E_{μ} , F_{i} and G_{i} [6]:

$$HV = C_0 + X_F \cdot \sum_i D_i \cdot c_i + X_P \cdot \sum_i E_i \cdot c_i + X_B \cdot \sum_i F_i \cdot c_i + X_M \cdot \sum_i G_i \cdot c_i$$
(5)

Relationship between HV and ultimate tensile strength is well known [7-8]. The calculation of yield stress is more difficult. Apart from the values resulting from regression analyses, the calcula-

tion of yield stress reflects the ferritic grain size effect in Hall-Petch equation and influence of the cooling rate CR on the transformation of austenite and amount of fraction Xstruct:

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

As-tempered mechanical properties are calculated from the chemistry $c_{(i)}$ by the equation (7) based on the regression

analysis of HV hardness of particular structure shares for various tempering temperatures Ttemp but fixed tempering time 3hrs:

$$HVx_{3} = \left\{\sum_{i} R_{(i)} \cdot c_{(i)}\right\}_{Ttemp, 3 hrs}$$

(7)

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

$$H_{p} = (T_{temp} + 273.15) \cdot (C + \log t_{temp}) / 1000 \tag{8}$$

where C is a constant varying between 15 and 21.

DLPP – DANIELI LONG PRODUCTS PREDICTOR

The DLPP is a metallurgical predictor designed for computer simulation of hot rolling and heat treatment technologies, which are used for the production of bars and wire rods. The DLPP executive algorithm consists of the three basic software modules:

- Temp1D Module 1D FEM calculation of temperature curves during deformation and subsequent cooling of bars and wire-rods from surface to core. Temp1D works in two regimes:
 - Temp1D_DEF calculates temperature curve during the deformation process
 - Temp1D_COOL calculates temperature curve after the last deformation

- 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,
- MetaCool Module calculation of austenite transformation and final mechanical properties of steel after the final cooling. MetaCool works in two regimes:
 - MetaCool_SHARES calculates increments of structure shares for one time step increment of temperature curve
 - MetaCool_PROPS calculates mechanical properties for final structure shares after hardening and subsequent tempering



Fig.1 - Basic chart of the executive part of the DLPP Metallurgical Predictor

The scheme of the basic DLPP functionality is presented in Figure 1.

Backed by this theoretical background, on site-measurements have been taken in several rolling mills designed by Danieli; during the hot commissioning stage of these plants software predictions have been validated, and DLPP has become a reliable simulation tool.

In the following paragraphs some examples of how DLPP simulation actually supported the decision making process are presented.

CASE STUDIES

Case study #1 - The best layout for a SBQ wire rod line

In recent years, the steel market has become extremely competitive and steel producers constantly aim at achieving a better quality in order to sell products with HAV. Being mainly focused on automotive industry, where it is fundamental to ensure products with excellent performances, the SBQ is the most demanding market. For this reason, SBQ rolling mills must enhance product quality in terms of dimensional tolerances, internal structure and uniformity of mechanical properties, shape and packaging of the produced stock. Specific thermomechanical treatments performed by rolling practice can lead to a decrease in downstream process time (e.g. annealing times), thus reducing the transformation costs for the final user.

These needs were kept in consideration for the real case of a new SBQ wire rod line, hereunder described. DLPP was used to define the best rolling mill configuration, so as to design a layout of a wire rod line with the maximum flexibility in terms of heat treatment capability. The final solution had a significant impact on space optimization and, consequently, on project cost reduction. Firstly, input data were identified: steel grades and sizes, starting billets to roll, reheating temperature pattern to set, roll pass design and rolling speeds. After the definition of these data, the study for the layout optimization could start.

In modern rolling mills, a sequence of waterboxes can be installed along the line in order to cool the bar down to specific rolling temperature at the Fast Finishing Block (FFB) and Twin Module Block (TMB) entry, thus performing a Controlled Cooling Rolling or a Thermo-Mechanical Rolling (TMR) strategy. There are several benefits related to the application of TMR process on the final product [9-10-11], such as grain size refinement leading to better mechanical properties and resilience, reduction of scale formation, and toughness increase.

In spite of these aspects, the additional cooling equipment increases the rolling mill overall length, if compared with a traditional hot rolling route. Therefore, it is important to minimize the overall length still considering that the feedstock entering the rolling block must be properly equalized in terms of core-to-surface temperature difference. As a matter of fact, if the difference in temperature is too high between the center of the bar cross section and its surface, different recrystallization and metallurgical properties could result.

Another issue to consider is the fact that the cooling stage cannot be too drastic (surface overcooling), otherwise the surface temperature could lead to an uneven, hard and fragile microstructure. To avoid these undesired phenomena, cooling stage must be fractioned and several "shorter" waterboxes need to be placed on the line with adequate space between them, which allows the hot bar core to temper the cooled surface and to equalize the temperature across the bar section.

In order to apply TMR in the reference temperature range of 820-840°C at the Fast Finishing Block or TMB entry, a maximum coreto-surface difference of 50°C should be ensured and the correct cooling lengths and equalization distances should be defined for the whole product mix.



Fig.2 - A two-strands wire rod line

An example of this process dimensioning approach is shown in Figure 3 and Figure 4, where a specific product is simulated with the same starting conditions (billet dimension, steel grade, rolling speed) but different layout and cooling strategies.

In Figure 3 it can be noticed that the chosen configuration for TMR would lead to a high core-to-surface ΔT at the eight-pass block entry. Meanwhile, in Figure 4 it can be seen that, with the same temperature of the bar surface (which would be read by on-field measuring device), the additional waterboxes and the increased length before the eight-pass block would lead to a nearly fully equalized temperature.

This additional length can be obtained through a loop configura-

tion, as sketched in Figure 5. With this arrangement, there are several advantages: while maintaining the overall rolling mill plant length unchanged, the loop can be used in case of products requiring high temperature drop and self-tempering time to perform TMR. On the other side, if some steel grades do not require such intense cooling, the main straight line can be used, thus reducing equipment wearing.



Fig.3 - Simulation of Line 1: no loop



Fig.4 - Simulation of Line 2: loop



Fig.5 - Different possible routes for bar entering FFB and TMB

An additional advantage deriving from the loop configuration is related to changing time minimization: in case the eight-pass block is bypassed (bigger products), the loop route can be used and the bypassed portion can be accessed for maintenance or preparation for the next rolling campaign, thus reducing overall stop time. Furthermore, the loop grants the correct equalization distance (see Figure 6 and Figure 7 for a comparison), which in the straight line could be possible only by increasing the building length.



Fig.6 - Simulation of Line 1: no loop



Fig.7 - Simulation of Line 3: loop used + Finishing Block bypassed

During the start-up of this new plant, DLPP was used to select the best line according to the selected rolled size, steel grade and rolling process, thus voiding trial-and-error approach and saving time and resources.

With its metallurgical algorithm, DLPP can predict microstructure

share and final mechanical properties, once the technological temperatures along the line are defined. In Table 1 a comparison between real data measured and DLPP simulation results for a wire rod sample are reported. In Figure 8 the output for mechanical properties calculation of DLPP is also presented.

| VARIABLE | [-] | REAL VALUE (AVERAGE) | SIMULATED VALUE |
|---------------------------------|-------|----------------------|-----------------|
| Mill Exit Temperature | [°C] | 1010 | 1008 |
| FFB Entry Temperature | [°C] | 840 | 831 |
| TMB Entry Temperature | [°C] | 840 | 834 |
| Laying Head Exit Temperature | [°C] | 775 | 768 |
| Reforming Pit Entry Temperature | [°C] | 640 | 630 |
| Ferrite Share | [%] | 87 | 90 |
| Pearlite Share | [%] | 13 | 10 |
| Bainite Share | [%] | 0 | 0 |
| Martensite Share | [%] | 0 | 0 |
| Ultimate Tensile Stress | [MPa] | 492 | 486 |

Tab. 1 - Real and simulated data of Ø6.0mm 23MnB4 wire rod



Fig.8 - Simulation of a wire rod cooling and prediction of microstructure and mechanical properties

Case study #2 - Controlled rolling conditions for a spooler line (hot-rolled rebar in coil)

Spooling process consists in twist-free coil formation by regular distribution of the hot-rolled and on-line control-cooled bar into subsequent homogeneous layers on spooler rotating drum. The result is an extremely compact and regularly-shaped coil.

The bar coming from rolling stands passes through the water cooling line in order to undergo in-line treatment, so that the temperature of the bar during spooling is suitable to maintain its mechanical and structural characteristics constant, before going to the spooling machines. The coiling temperature on the spooler for cooled ribbed rounds is typically in the 500-650°C range,

depending on size and grade. Optimized bar cooling throughout the bar section makes it possible to obtain a homogeneous product, fully complying with ductility requirements. Furthermore, it provides consistent quality with very small deviations in material characteristics amongst the various billets that form a production lot of the same steel grade.

After the water cooling line, the bar is conveyed to the drum by means of a distributor that consists of a conveying tube hinged at the end where the rolled stock is fed in. After hooking, turns are formed on the spooler drum until the entire billet is made into a coil, layer after layer.



Fig.9 - Bar during spooling and spooled coils on conveyor

Several in-line heat treatments are possible before the spooling, depending on chemical composition and desired technological properties: QTS (Quenching & Self-Tempering in Spooler), SQ (Soft Quenching), CC (controlled Cooling).

In the SQ process, the material is spooled splitting the quenching stage. The target of the process is to optimize the microstructure of the different steel grades avoiding undesirable grain growth and drastic cooling that would lead to a thick martensite layer. The difference of mechanical properties between the internal and external part of the spool is reduced compared to QTS, because the transformations take place at about the same temperature across the section of the bar.

The SQ process involves 3 stages:

- Pre-cooling stage: In this cooling stage there are no microstructural modifications. All the bar remains in the austenitic temperature range.
- Fast Cooling Stage: After an equalization sector, the bar is cooled down to the desired coiling temperature. The final microstructure is different if compared to the one obtained by QTS treatment (Quenching & self-Tempering Spooler) with a thinner martensite layer and a more uniform microstructure (see Figure 10).
- Final cooling Stage: Coil is cooled down to room temperature in free air.



Fig.10 - A: bar surface QTS treated, B: bar core QTS treated, C: bar surface SQ treated, D bar core SQ treated

A simulation tool can be used to identify the correct number of waterboxes needed to achieve the correct technological temperatures, as well as the distance between the waterboxes in order to assure the SQ process treatment.

In a recent revamping of a plant, DLPP was used to define the correct distances in order to perform Soft Quenching. Due to the nature of the project, the distances between last rolling passes

and the spooling device was fixed and an optimization of the available space was necessary in order to know where to install the waterbox. With the help of simulations, proper distance after the pre-cooling stage was defined to have a homogeneous temperature at the FFB entry. Moreover, after this first stage it was possible to estimate the best cooling strategy necessary to reach the final desired temperature.

In Figure 11, the correct configuration of the SQ line is simulated; whereas in Figure 12 QTS process is represented.







Fig.12 - Example of correct QTS setting

Case study #3 - Process parameters for an Induction Hardening line

In order to increase the added value of rolled bar products, some SBQ producers adopt verticalized strategies for their manufactur-

ing process. One possibility is represented by the induction hardening process (Figure 13), where the quenching and tempering process is realized on bar of heat treatable steel grades, involving multiple stages:

- Induction Heating: according to steel grade, bar temperature is uniformly enhanced up to austenitic range by an induction heating equipment;
- Direct Quenching System (DQS): from the fully austenitic range, the bar is immediately quenched by a sequence of independently controlled water cooling sectors;
- Tempering Stage: when exiting the water cooling area, the bar enters another induction heating equipment, to temper the crude martensitic structure;
- Final cooling stage: the bar is cooled down in a cooling bed (additional water cooling stage can be required immediately after tempering process for steel grades sensitive to tempering brittleness).

With the same equipment it is also possible to apply the normalizing process: the bar is heated up to austenitic range, typically around 950°C, then air cooled.



Fig.13 - Overview of an Induction Hardening Line

This process line usually presents productivities of few tons per hours, so bar speeds are very low if compared to rolling mill ones.

In order to obtain proper quenching on the whole bar section, a minimum cooling rate must be granted to ensure the occurrence of the martensitic transformation. After the quenching stage, the final temperature can be lower than 100°C to obtain the correct microstructure before the following tempering stage.

Taking these aspects into account, it is apparent that the proper dimensioning of the quenching module and of the water treatment facilities is crucial to adequately ensure process control. The length of a cooling module is determined by the pitch between the rolls of the conveying table, which depends on the minimum bar length and bar size to be treated, in order to avoid slipping of the bar on the rolls and excessive bar bending between rolls.

Once the starting parameters have been defined (sizes, speeds, steel grades, required technological properties), DLPP can be used to set the required cooling length and the process parameters to be used during line start-up in order to avoid any downtime due to "trial-and-error" approach.

In Figure 14, a real scenario for a bar of Ø105mm subjected to induction hardening process is presented. The bar is heated through a series of induction heating modules until the final temperature of 880°C is reached almost uniformly across the bar section. The bar then undergoes the quenching stage; from the simulation it is clear that to guarantee a target temperature of 100°C, at least 3 cooling modules of the defined length must be used.

The bar then leaves the quenching part and it is reheated through another series of inductors up to the desired tempering temperature. The bar is then maintained within this temperature range for adequate time to ensure proper martensite tempering. Finally, the bar leaves the inductors and it is naturally cooled by air in a cooling bed.



Fig.14 - Simulation of product in IH line

CONCLUSION

In modern steel rolling mills, assuring the best possible material quality is an absolute priority. As explained in this paper, the simulation software DLPP can be effectively adopted to define process targets in terms of plant dimensioning and production optimization.

In the dimensioning stage of a new rolling mill as well as in the revamping of an existing one, the simulation tool can be used to define the proper layout configuration. The implementation of inline thermo-mechanical treatments during and after the rolling process is crucial to obtain a product with higher added value. By using this simulation tool, the correct number of water cooling zones and equalization distances can be defined, hence assuring a proper heat treatment of the bar.

During the project execution stage itself, this simulation tool can be used for the correct setup of the heat treatment line during the startup period. Time losses due to trial-and-error procedure can be avoided and a consequent productivity increase will be gained.

DLPP has been largely used for these purposes over the last years, proving itself reliable and accurate in prediction of metallurgical and final mechanical properties of hot rolled wire rods and bars.

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