Kocks microstructure simulator (KMS) – New technical tool for process simulation of long products

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Since years temperature-controlled rolling is a known application in rolling mills to improve the technological properties of the material. More than ever the main focus of the operators today is directed to the continuous improvement of their products and to an optimized adjustment of the individual production route. Therefore the future success of rolling technologies in practical operation is more and more dependent on prior off-line simulation of the rolling process in the quality management.
As a leading supplier of long product rolling technology and process, FRIEDRICH KOCKS GMBH & CO KG has developed the KMS - KOCKS Microstructure Simulator. The KMS is a semi-empirical model that can be used as a stand-alone tool and can also be considered as a complement to KOCKS thermo-mechanical rolling equipment for bar, wire rod and tube rolling mills. The KMS incorporates for the first time the unique deformation characteristics of the KOCKS 3 roll technology and enables rolling mill operators to model temperature conditions of the rolled stock, to illustrate phase transformations and to predict grain size formations and mechanical properties throughout the cross-section of the finished product.
Furthermore the KOCKS Microstructure Simulator is a perfect tool to simulate and develop new rolling strategies without applying cost-intensive and time-consuming rolling trials.
The features and unique characteristics of the KMS in conjunction with KOCKS thermo-mechanical rolling equipment are the subject of this paper.

Keywords: 3-roll technology - 3-roll Reducing & Sizing Block (RSB) - Improvement of product quality - Improvement of operation and cost performance - Thermo-Mechanical Rolling (TMR) - Thermo-Mechanical Processing (TMP) - Reduction of post-processing costs

INTRODUCTION

For modern Special Bar Quality (SBQ) mills it is a prerequisite to supply an excellent, consistent and reproducible quality in order keep or extend its competitiveness in a permanent challenging market. Besides serving the market with tightest tolerances, superb metallurgical properties and surface qualities, economical requirements such as rolling with highest yield, ultimate mill availability, lowest conversion costs and unlimited flexibility are a must for SBQ rolling mills. It is obvious that the quality of the finished product as well as the economy of the rolling mill are mainly influenced by the performance of the finishing train for bars in coils and straight lengths and which acts in combination mills as the pre-finishing mill for the wire rod outlet, too. Thanks to the unique 3-roll deformation characteristics, the operating philosophy, the design of the machinery and its processes, the RSB as a key component in the finishing area of bar mills, ideally meets all the above mentioned requirements [1]. Fig. 1 shows a schematic layout of a 1-strand combination wire rod and bar mill with a 5-stand Reducing & Sizing Block (RSB).

Another important factor gaining more and more importance in SBQ mills is the application of the so called Thermo-Mechanical Processing (TMP). This process can shorten or completely eliminate downstream heat treatments with significant cost reductions and is, therefore, an important part of new and/or modernized rolling mills.

Planning and implementation of the TMP process in rolling mills can no longer be imagined without simulations in al-

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Paper presented at the Int. Conf. ROLLING 2013, Venice 10-12 June 2013, organized by AIM

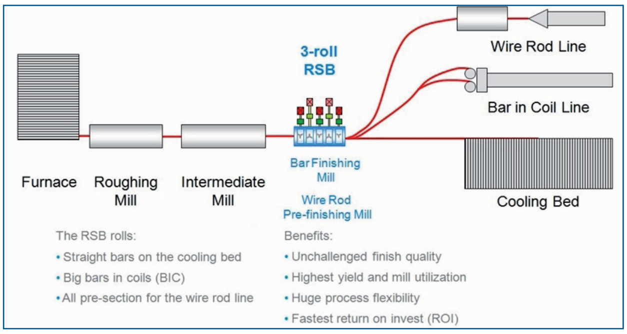


Fig. 1 - Application of the Reducing & Sizing Block (RSB) in a combined wire rod and bar mill

Fig. 1 - Applicazione del blocco calibratore/finitore RSB in un laminatoio combinato per barre e vergella

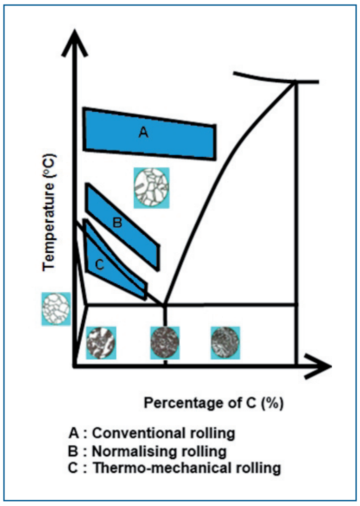


Fig. 2 - Temperature ranges for hot forming processes in den Fe-C diagram

Fig. 2 – Intervalli di temperature per i processi di formatura a caldo in un diagramma Fe-C

most all fields of long steel production.
As a supplier of mill technology mainly for the production of long product quality steel, FRIEDRICH KOCKS GMBH & CO KG has developed the microstructure simulation model. This simulation software is based on a semi-empirical approach. Special attention was paid to the 3-roll technology, which has successfully been used by KOCKS clients for many years to produce high-quality steel bar and wire rod products. The target was to develop an improved microstructure simulation model featuring an analytic model to calculate the strain distribution for different reduction configurations and for a variety of technological parameters, such as temperature, speed and pass geometry. The simulation is based on the distribution of strain modifications and of temperatures over the cross-section of the rolled product. With this information the microstructure simulation is carried out to get a realistic image of the micro-structural formation.

METALLURGICAL FUNDAMENTALS OF THE THERMO-MECHANICAL PROCESSING

In principle, hot rolling can be divided into three different hot forming processes named conventional rolling, normalising rolling (NR) and thermo-mechanical rolling (TMR). These three different processes vary in the temperature where the final deformation takes place (Fig. 2).
Conventional rolling is realised at high temperatures in the area of the stable austenite. This temperature region results in low rolling forces and large reductions can easily be achieved. However, the inevitable outcome is a coarse austenite grain with undesirable grain formation and mechanical properties at the finished product. An additional cost intensive heat treatment to improve the properties is often required.
To shorten or eliminate these downstream heat treatments of hot rolled material it is possible to make use of the normalising rolling or the thermo-mechanical rolling. Both methods are part of the thermo-mechanical processing.
For these two rolling strategies three different temperature ranges have to be taken into account:

- Temperature range, where the austenite recrystallises (TR > TNR)
- Temperature range, where the austenite no longer recrystallises (TNR > TR >A3)
- Temperature range of ferrite/austenite-forming (A3 > TR >A1)

The final rolling temperature (TR) for normalising rolling is slightly above the recrystallisation stop temperature (TNR) of the austenite. This leads to a fine and homogeneous microstructure equal to the results of the heat treatment process normalising. By choosing this rolling strategy the heat treatment process can completely be eliminated.
Unlike the normalising rolling the final forming of the thermo-mechanical rolling takes place below the recrystallisation stop temperature of the austenite (TNR > TR >A3). This treatment can lead to an even finer final grain size

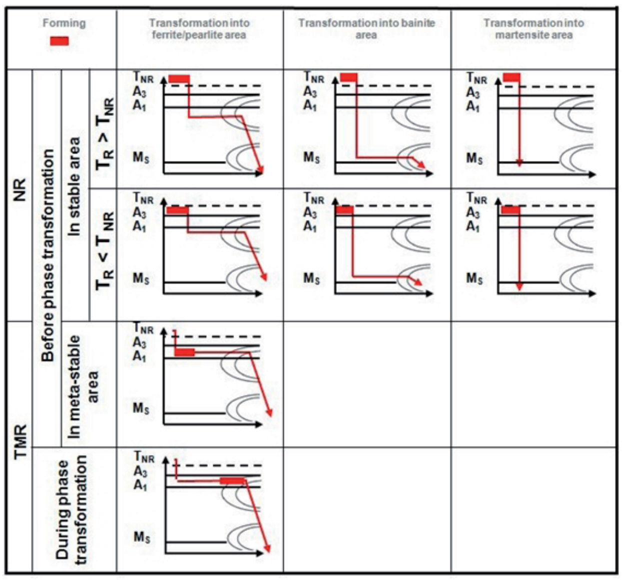


Fig. 3 - TMP map (isothermal time-transformation diagrams)

Fig. 3 – Mappa dei processi TMP (diagrammi isotermi tempo-trasformazione)

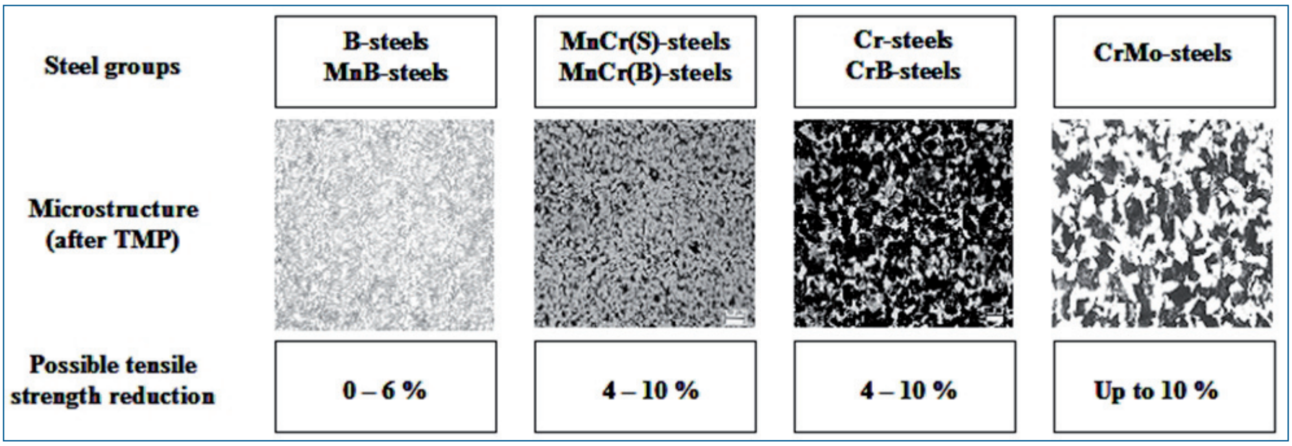


Fig. 4 - Possible tensile strength reduction for different cold heading steel grades produced by thermo-mechanical processing

Fig. 4 - Possibile riduzione della resistenza a trazione per diversi gradi di acciaio per bulloneria prodotti mediante processi termomeccanici

than the NR, due to a higher dislocation density in the deformed austenite.
By choosing the final forming temperature in the austenite- + ferrite-area (A3 > TR >A1), a higher yield strength at the final product can be achieved if necessary. [2]
A detailed classification of the various rolling processes that are part of the thermo-mechanical processing can be provided on the basis of time-transformation diagrams (Fig 3). These diagrams show the behaviour of the individual steel groups. The classification distinguishes between transformation into ferrite/pearlite, bainite or martensite. [3]
Thermo-mechanical processing is used for various applications and different steel groups. Some examples are:

- Higher tensile strength for carbon steel grades
- Lower tensile strength and higher formability for cold heading steel grades (Fig. 4) [4]
- Reduced carbide precipitations at the bar core of ball bearing steels and other high carbon steel grades
- Improved low temperature toughness due to better homogeneity and finer grain size

In addition:

- Improved shearability
- Improved straightness
- Better control of surface decarburization and scale formation

BASIC STRUCTURE OF THE KOCKS MICROSTRUCTURE SIMULATOR

The basic structure of the KMS model is shown in Fig. 5. The material characteristics required for the simulation are provided by the material database MATILDA® (Material Information Link and Database Service). Another module of the KMS is the technology editor, which maps the simulated rolling mill with its specific core components. The material data from the database and the technological data from the technology editor are linked together in the simulator. The simulation tool consists of sub-modules, such as the temperature model, the grain size calculation, the phase transformation model and the calculation of mechanical properties. In the simulator all the related calculations are carried out. [5]

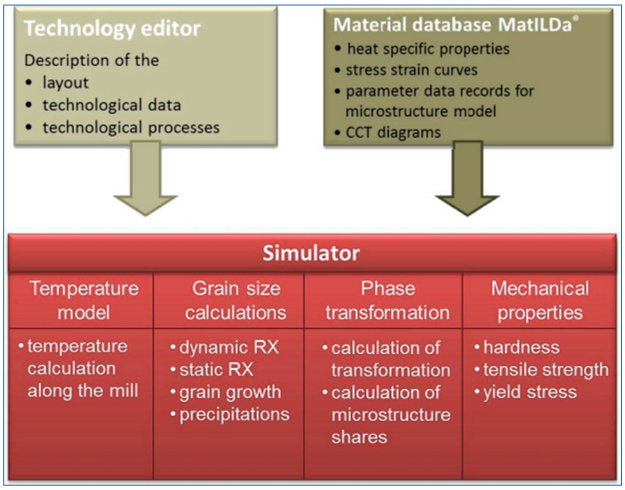


Fig. 5 - Structure of the KMS model

Fig. 5 – Struttura del modello KMS

MATERIAL DATABASE MATILDA

Today, the main demands of customers on simulation models are to predict microstructure development depending on the transformation process and the individual process parameters, rolling technologies and the possibility to influence thermal aspects. This requires regarding the plasto-mechanical processes and microstructure changes during transformation as a whole.
Therefore, the material database MATILDA® developed by GMT was taken as basis and core of the KMS model to simulate crystalline structure. [6][7] On one hand it contains

all material data required for simulation and on the other hand it is a flexible database, which is customized and can be extended. Within the cooperation scope the database was supplemented by further general material information as well as by basics of phase transformation.
Besides the archive modules for heat specific data, flow curves and transformation diagrams, the archive of the material model data is the core component and basis for the microstructure simulation (Fig. 6).
Heat specific characteristics and flow curves for approx. 500 different materials of different material groups are saved in the material data base MATILDA®, Fig. 7. Nevertheless, it is quite self-evident that situations may occur in the daily use of simulations – within the framework of material-technological developments and the implementation of new or optimized rolling technologies under practical conditions – for which the corresponding necessary material data are not available. In this case, it is possible to create a “virtual material” by combining parameter sets of different materials and adapting flow curves based on one’s own experience. By intention, the function of the material database is flexible to offer the user the possibility to enter his own material specific data.

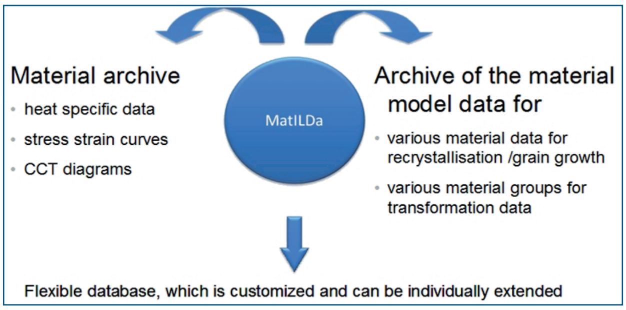


Fig. 6 - Structure of the material database

Fig. 6 - Struttura del database del materiale

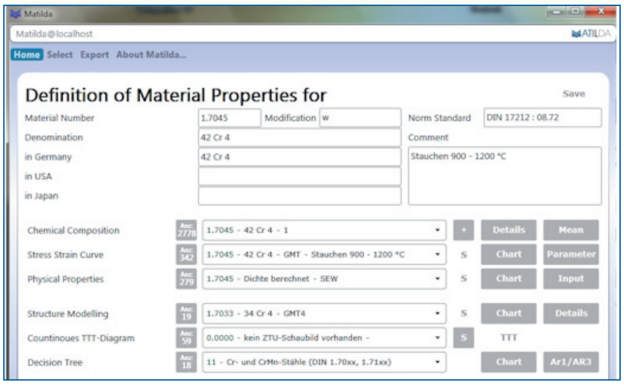


Fig. 7 - MATILDA main screen

Fig. 7 – Schermata del database MATILDA

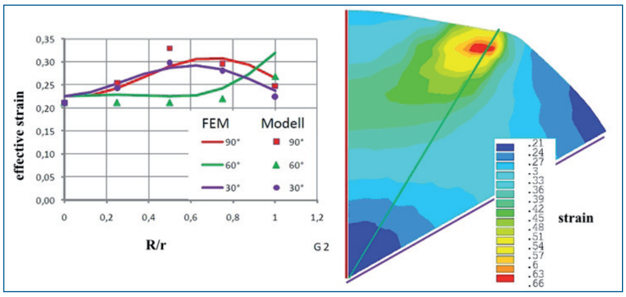


Fig. 8 - Comparison of the FE calculation results with those of the modulus of elasticity of the analytic approach

Fig. 8 – Confronto fra i risultati dei calcoli a elementi finiti e quelli del modulo di elasticità dell’approccio analitico

SIMULATION TECHNOLOGY

The knowledge of the local deformation is important to determine the heat input and metallurgical processes (e.g. dynamic re-crystallization) during rolling. These information are essential for a temperature and microstructure simulation.
Since no commercially available system for microstructure simulation had been able to realistically image the particularities of deformation distribution in a KOCKS 3-roll block the KMS was developed. On the basis of time-consuming Finite Elements (FE) calculations, an analytical approach was derived with the intention to reach short simulation times (Fig. 8). This formula approach mainly consists of a module to calculate the external geometry of the rolled product (spread module) and of a module to calculate radial, circumferential and effective strains (modulus of elasticity). In order to reduce the calculative effort the symmetrical conditions in a 3-roll block are taken into account. Thus, only 3 defined directions (90°, 60°, 30°) over the whole radius have to be calculated.
Another important part of the simulation software is the prediction of the constituents of the final microstructure. The phase transformation is mainly based on the deformation history, the chemical composition and the cooling speed. Due to the complexity of the interaction between input and output parameters progressive calculation methods have to be used. For this purpose the neural network technology [8] was chosen (Fig. 9). An extensive data archive of continuous time-temperature-transformation diagrams (CTT) allows the description of the transformation behaviour of a steel grade or of steel groups.
For a variety of steel groups – reaching from unalloyed carbon steels to case-hardening and tempering steels as well as spring and ball bearing steels – neural networks for the CTT diagrams were worked out.
Last but not least the simulation of the microstructure evolution is also very important for such a simulation tool. This part is based on the semi-empiric model of Sellars and Whiteman [9] with the modifications of Lehnert and Cuong [10].
The microstructure model consists of the following algorithms:

- Dynamically recrystallized fractions
- Statically recrystallized fractions
- Grain growth
- Delay of re-crystallization processes due to precipitation (precipitation hardening)

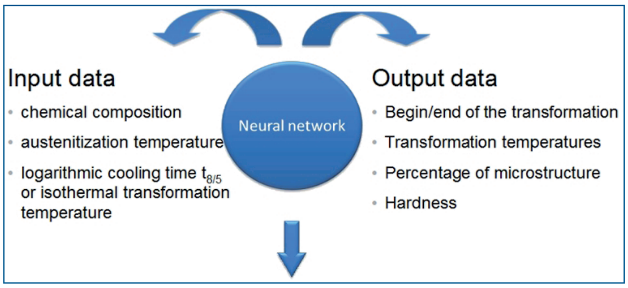
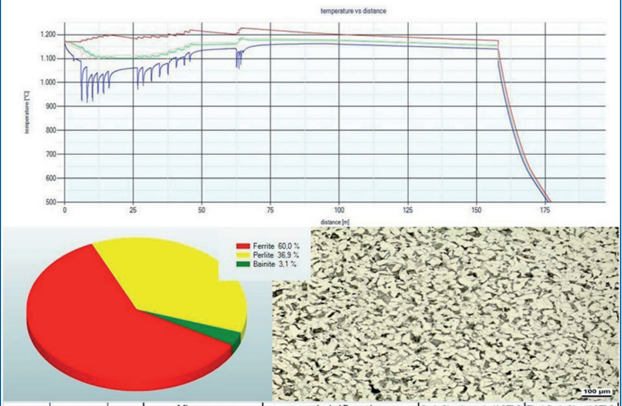


Fig. 9 - Calculation of phase transformation based on a neural network

Fig. 9 - Calcoli delle trasformazioni di fase basate sulla rete neurale



	Material Grade	Diameter	Microstructure				mechanical Properties			Grain Size Austenite(ASTM)		Final Grain Size (ASTM)	
			Ferrite	Perlite	Bainite	Martensit	Yield Point	Tensile Strength	Hardness HV	Behind RSB	Cooling Bed	Ferrite	Perlite
measured	26Mn5	25	58	42	0	0	425	611	-	8	7	10	11
calculated			60	36,9	3,1	0	430	660	217	7,5	7,5	10	10,5

Fig. 10 - Results of the KMS model

Fig. 10 - Risultati del modello KMS

KOCKS MICROSTRUCTURE SIMULATOR – EXAMPLE AND RESULTS

After this description of the theoretical structure of the simulation model, an example of a combined bar and wire rod line will be presented and explained.

The example deals with a 16-stand rolling mill in horizontal-vertical arrangement with an integrated 5-stand KOCKS Reducing & Sizing Block for the production of steel bars without using TMP. A carbon steel 26Mn5 with a final diameter of 25.0 mm is calculated. All input parameters, such as the furnace temperature and the rolling speed, are inquired in the input editor of the simulator in advance. In addition, the points to be simulated along and over the cross section of the rolling stock have to be determined. A definition of the points along the rolled product is also common in other models. The new aspect of the KMS model is the inclusion of the cross section area with the objective of a precise calculation of microstructure differences between the core and the surface as well as the visualization of microstructure inhomogeneities.

Fig. 10 shows the calculated temperature curves of the rolled product for the surface, half of the radius and the core of the bar over the length of the mill line. Fig 10 also shows the corresponding microstructure constituents and the grain sizes obtained by the KMS compared with the microstructure and grain sizes of a real product rolled with the same parameters as simulated. The calculated microstructure consist of 60% ferrite, 36,9% pearlite and 3,1% bainite, the measured one of 58% ferrite and 42% pearlite. The calculated final ferrite grain size is ASTM 10 and the final pearlite colony size is ASTM 10,5, the measured ones are ASTM 10 for ferrite and ASTM 11 for pearlite.

CONCLUSION

Steel is an innovative material and it continues to be in the future. The theory of the thermo-mechanical processing is mainly well understood, improved rolling technologies are implemented in practical operation.

The core know-how of the rolling mill users is mainly founded on the automation degree, the individual process and material-technological development in view of their implementation in the production of high-quality products and the individual formation of their Human Recourses. Keeping this in mind KOCKS developed the user friendly KMS model, open for implementation of individual knowledge of material data, for temperature, process and microstructure calculations. With this model the mill operator is able to quite precisely simulate and optimize rolling processes in combination with material related aspects regarding transformation processes as well as resulting microstructure and mechanical properties before they are applied under practical conditions.

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SIMULATORE DI MICROSTRUTTURA KOCKS (KMS) - NUOVO STRUMENTO PER SIMULAZIONE DI PROCESSO DEI PRODOTTI LUNGHI

Parole chiave: Laminazione - Simulazione - Processi termomeccanici

La laminazione a temperatura controllata è un'applicazione impiegata da anni nei laminatoi per migliorare le proprietà tecnologiche del materiale. Oggi più che mai gli obiettivi principali degli operatori sono il miglioramento del prodotto finale e l'ottimizzazione del percorso di produzione.
Quindi il successo delle tecnologie di laminazione è sempre più legato, nella gestione della qualità, alla simulazione off -line prima del processo di laminazione e alla qualità.
Il simulatore di microstruttura Kocks-KMS è un modello semi-empirico che può essere utilizzato sia come strumento autonomo che come complemento agli impianti di laminazione termomeccanica Kocks nei laminatoi per barre, vergella e tubi.
Il KMS per la prima volta incorpora le caratteristiche uniche di deformazione della tecnologia di laminazione Kocks-3 e consente agli operatori degli impianti di laminazione di modellare le condizioni di temperatura del laminato, per determinare le trasformazioni di fase nonché per prevedere la granulometria e le proprietà meccaniche lungo l'intera sezione trasversale del prodotto finito.
Inoltre il simulatore Kocks è uno strumento in grado di simulare e sviluppare nuove strategie di laminazione evitando costose e laboriose prove di laminazione.
Le funzioni e le caratteristiche uniche di questo sistema abbinato alle macchine di laminazione termomeccanica Kocks sono l'oggetto di questo studio.