Rolling models

Adaptive setup models for cold rolling mills

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Cold rolling mills are an important part of the production of metal sheet. In these plants, the metal is incrementally deformed by rolls in a number of passes to obtain the required surface and material properties and thickness.

To remain competitive, producers of flat rolled products are continually seeking to maintain and improve product quality, mill flexibility and productivity. Such steps require a deeper understanding of, and greater control over what happens inside the process.

ABB has developed a portfolio of models that help customers optimize their mills. In this article, *ABB Review* looks at the company's solutions for adaptive setup models.

Maintenance for productivity

Improvements in product quality mainly focus on finding ways to decrease tolerances in thickness and flatness and improve surface quality. Furthermore, mill flexibility must be increased to satisfy the growing demand for product variety, while high productivity (in both throughput and yield) is a prerequisite for remaining competitive in the global economy.

From the automation point of view, these demands translate into, among others, the following requirements:

- Reliable and modern automation control system
- Reliable sensors and actors
- Adaptive setup model for pass schedule[1)] and preset calculation
- Advanced technology control solutions
- Intuitive visualization, operation and diagnosis system and concept

Factbox 1 lists some of the applications that the models designed by ABB provide for.

To reach these goals, a mathematical model is used to calculate the pass-schedule and the mill preset 1. Based on the coil- and roll-data, scheduling uses reduction and tension tables that are derived from both practical experience and mathematical submodels, and predicts the behavior of the process on the basis of these. The model essentially consists of four parts: the work-hardening curve of the material (the flow-stress model), a roll-gap friction model, the roll-gap model (providing rolling load, drive torque, forward slip and strip temperature), and the mill model (providing the references for the strip-flatness actuators and the roll-gap positions).

Measured values are collected and filtered during each pass, and then compared with the corresponding predicted values. Adaptive parameters are calculated to bring the predictions into agreement with the measured values.

The rolling model consists of a package of various sub-models that are closely connected to each other and mainly based on physical principles.

The main sub-models are:

- Pass scheduling (Calculates the number of passes and related strip thickness distribution)
- Preset (Calculates all necessary preset values)
- Adaption model (Adapts the model by measurements)

Setup- and adaption-reports are generated for every coil and are stored to the database for further analysis and offline tuning of the model.

Pass-scheduling calculation

The task of the pass schedule calculation is to identify a suitable distribution of the reductions over several passes for given coil data (material grade, strip width, start and finish gauges). First, the boundary within which the optimal path must lie is defined by calculating the maximum reductions, pass by pass from the initial gauge forwards, and then again from the final gauge backwards 2. Then, taking into account the boundary conditions set by the mill and standard practice limits, a reduction path is sought that comes closest to meeting the chosen criterion. This can, for example, be a simple minimization of rolling time, or the achieve-

Footnote

[1)] A pass is one deformation step consisting of the different phases threading, rolling at constant speed, deceleration and tailout of the strip through the mill. A pass schedule is a series of values for the pass, such as thickness, speeds and forces presets.

Factbox 1 ABB and rolling mills

Rolling mill applications covered by ABB include:

- Single and multistand Mills
- Cluster and Sendzimir*) Mills
- Inline and continuous rolling mills
- Reversing and non-reversing
- Reduction, skin-pass, double cold reduction (DCR) and foil rolling
- Steel, stainless, aluminium, copper and brass for a wide range of end products

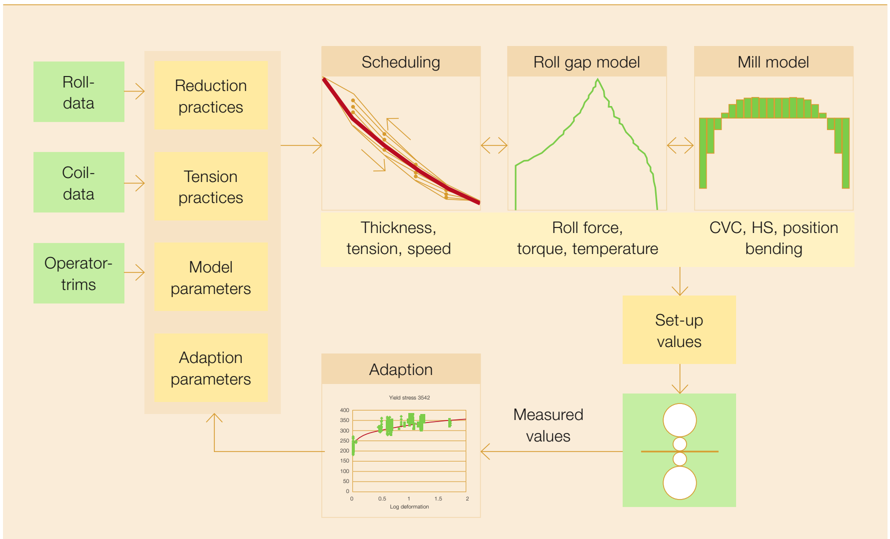
The task of the rolling model is to supply the appropriate setup-values to the level 1 open control system (OCS). The most important goals of the preset model are:

- Optimization of strip quality regarding off-gauge length, surface and flatness
- Optimization of throughput by faster threading, acceleration and maximum speed
- Ensuring that preset values remain within material and mill limitations
- Avoiding strip breaks, roll marking and threading stops
- Provision of stable rolling conditions
- Minimization of operator interventions

Footnote

*) A Sendzimir mill is a mill with small diameter work rolls, each backed up by two rolls of larger diameter which are in turn jointly backed up by a cluster of three rolls. This mill configuration is often used for height-strength- and stainless steel.

1 Interaction of data and functions in the rolling-mill process



ment of the same rolling loads for all passes.

The standard practice limits referred to above are process-boundary conditions that are defined in tables according to the product group, and may specify, for example, maximum reductions, coiling tensions in the first and last passes and so on.

The distribution of reduction per pass can be optimized according to several criteria. Criteria relating to high throughput or strip quality (eg, flatness and strip surface) may sometimes be contradictory. Schedules can be generated to fulfill demands for reduction and force limits as well as reduction and force trends (eg, constant reduction per pass or declining specific roll force per pass). Schedules can be optimized to gain the maximum rolling speed by equalizing the required motor power of all passes or stands. This can be achieved by changing the reduction or the tension distribution.

To meet operational requirements such as, for example, the charging and discharging of the coil on a certain side of the mill, an odd or even number of passes can be enforced. A fixed reduction in the final pass can be also configured. During the rolling of a pass, a recalculation correcting the subsequent passes can be performed when, eg, an intermediate thickness was not reached or the material appeared to be harder than estimated.

An essential element of the pass-schedule calculation is a roll-gap model based on physical laws. Besides entry and exit gauges and tensions, such a model also requires as entry data the resistance to deformation of the material, and the characteristics of the friction between rolls and strip. The resistance to deformation is described in the form of a flow-stress curve, which is in turn based on the results of tensile tests on samples of strip at each stage of rolling. The major influences on the roll-bite friction conditions are considered to be the roll roughness and the rolling speed. The effect of friction variations on the rolling load can be most clearly seen with mild steel and light gauges 3.

Preset model

After a pass schedule has been determined, the preset calculates the remaining set-up values. Sometimes the schedule data (eg thicknesses, tensions) are taken from a pass-schedule table or delivered by an external system (PPS, ERP, Level 3).

Required strip related input data for the preset calculation are:

- Entry thickness, width, entry temperature
- Hot rolling thickness or last annealing thickness
- Material grade, annealing type
- Strip profile, outer coil diameter
- Exit target thickness (for reduction mills) or exit target elongation (for skin pass mills)

The actual roll data such as roll diameter, crown, taper, length and texture are also important for a precise calculation.

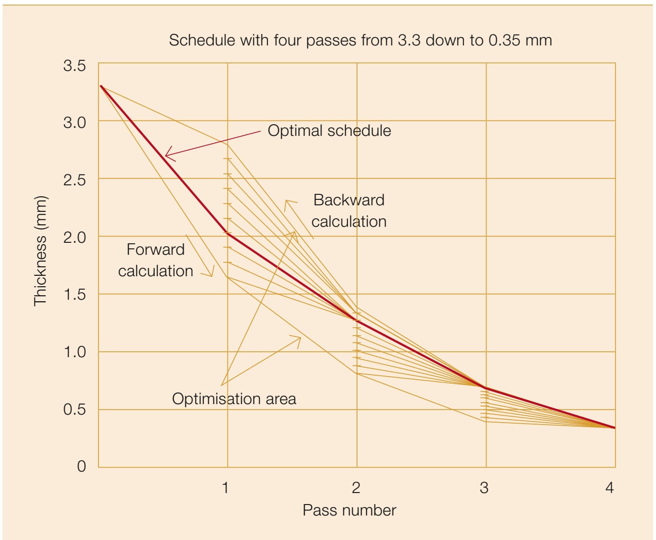
General parameters such as mill and drive limits, standard practices, adaption coefficients, yield stress and friction values are stored locally on the Level 2 (MES) system. The different sub-models are closely connected to each other 4, with the outputs of one model being available for use as inputs for other models.

The preset calculation function produces set-up values for threading-, rolling- and unthreading conditions, of all required passes. The calculated values are fed to the different control functions on Level 1 (OCS). The main

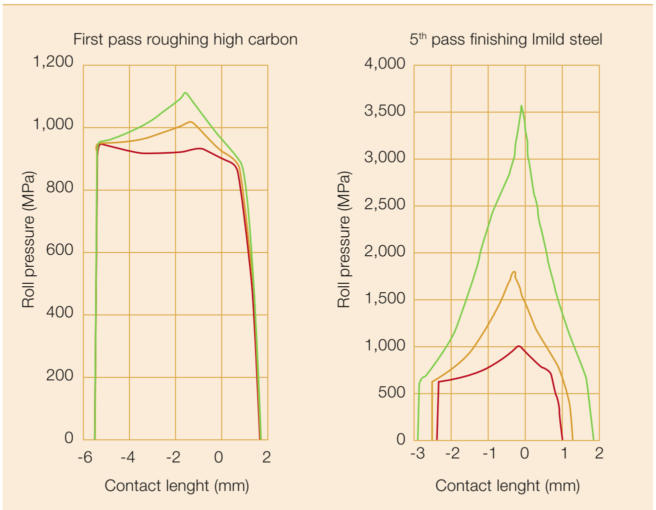
Factbox 2 Main values transferred from preset calculation to OCS Level 1

- Entry, intermediate and exit thickness
- Rolling speed
- Entry, intermediate and exit tensions
- Rolling force
- Roll gap position
- Rolling torque
- Flatness actuators (bending and shifting)
- Cooling quantity

2 The procedure used for calculating the pass schedule



3 Influence of different friction coefficients (μ=0.03, 0.05, 0.07) on the rolling load



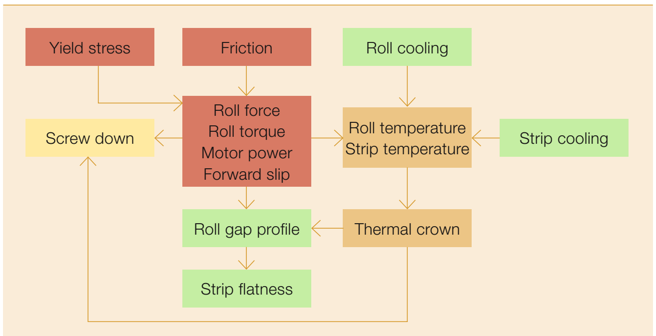
Maintenance for productivity

preset values transferred are listed in Factbox 2.

The scheduling and preset calculation is activated automatically when:
- The coil data was available the first time (plausibility check)
- The coil gets the state “next coil” or when the next coil is mounted to the pay-off reel
- The adaption of the previous coil is finished
- By manual request of the operator

The calculated preset values can be viewed by the operator. After possible modifications via the operator trim values and final check, the operator transfers the preset values to the level 1 and threading of the coil can be initiated. The state of the coil changes from “next coil” to “current coil”. Preset values for that coil can only be changed when the mill is stopped. The operator can view the set points of the current coil and can prepare the set points for the next coil.

4 Interaction of sub-models in the rolling mill model



The different sub-models are closely connected to each other, with the outputs of one model being available for use as inputs for other models.

Key preset model components

The rolling model uses several sub models as components:

Tension model

The tension model is based on the determination of the specific tensions. These are calculated on the basis of strip thickness and yield stress of the material and the tension practice. Particularly, the first pay-off reel and last coiling tension depend on the pre-treatment and the post-treatment of the cold rolled coil. Rolling with inadequate tensions cause eg, coil slipping, unstable rolling and sticking during batch annealing.

When tensions can exceed the maximum values of the coiler or pay-off reel, they must be limited. When bridles are used, the ratio between pay-off reel/entry tension and exit/coiler tension is also limited.

Speed model

The maximum rolling speed is limited by the following restrictions:
- Maximum power of drives (mill drive, pay off reel/coiler drive)
- Maximum drive speed considering gear box ratio
- Maximum exit strip temperature
- Quality related speed limitation

The speed model reduces the speed until all of these limitations are satisfied.

Roll-gap model

The roll-gap model is further differentiated into a model for reduction mills and for skin pass / temper mills / foil mills.

For reductions of more than about five percent and a larger ratio between the mean gauge und contact length, a roll-gap model based on the classical circular arc theory of Ford, Ellis and Bland is used. This approach considers the plastic and elastic deformation of the strip in the roll gap. The deformed roll radius is calculated by the Hitchcock equation.

For skin-pass and foil rolling configurations (smaller reduction and ratio between the mean gauge und contact length), an online model is used that is tuned using a non-circular arc model based on the theory of Fleck and Johnson. The model calculates the roll force and torque, forward slip, deformation and friction energy. It uses the yield stress and friction model. Process disturbances are compensated by adaption coefficients.

The yield stress of a defined product is calculated on the basis of deformation, deformation rate and strip temperature. A product can be defined by a combination of properties such as material group, material grade or pretreatment (eg, type of annealing). The material-grade specific parameters need to be determined in close cooperation with the customer.

The friction coefficient is calculated on the basis of work-roll roughness/texture, speed and pass number.

Rolling with inadequate tensions cause eg, coil slipping, unstable rolling and sticking during batch annealing.

Strip temperature model

The purpose of the strip temperature model is to predict the temperature of the strip at all stages of the rolling process. The strip temperature is used for the yield-stress model and for the pass-schedule calculation. Factors affecting the strip temperature are the strip temperature at entrance, air cooling, heat extraction by the coolant pool, heat generation in the roll gap and heat exchange with the work roll.

If there is a separate strip cooling, the strip coolant flow needs to be calculated in such a way that the exit strip temperature stays below a defined maximum in order to avoid the occurrence of paper mark defects on the strip surface (stainless steel) or fire ignition (aluminum) due to an excessive temperature of the strip during coiling. If the calculated coiling temperature in one pass exceeds the safety limit with the maximum allowable oil flow, the rolling speed distribution over all passes is decreased accordingly.

Roll temperature and thermal expansion model

This two-dimensional transient model, which runs continuously, calculates the thermal state of the work during and after rolling. The finite-difference technique is used to calculate the temperature distribution in the work roll, balancing the heat flows into and out of the roll. The external heat flows from the strip to the roll and from the roll to the coolant, the backup roll and the air are represented by suitable heat-transfer coefficients. The spatial thermal expansion of the roll is then calculated from the resulting temperature distribution. The heat-input rate and the distribution of cooling effect across the roll are taken from the strip temperature and the roll cooling model.

Flatness model

The flatness model calculates the preset values of the flatness actuators to achieve the desired roll gap profile and flatness. A finite difference model takes into account the profile of incoming strip, roll force, strip width, roll diameter, grinding, deflection flattening and thermal expansion of rolls.

This thermal aspect is especially important when using a work roll of large diameter and small cooling efficiency combined with high heat input form the roll gap (eg, in aluminum mills). Depending on the type of mill, the profile model calculates the preset value for bending force of work and intermediate roll and axial shifting positioning of rolls.

This two-dimensional transient model, which runs continuously, calculates the thermal state of the work during and after rolling.

Roll gap position model

To permit a mill to be threaded in a stable manner, the roll-gap position of the loaded roll gap for a desired strip gauge has to be known. This model calculates the roll-gap position taking into account the stand modulus as a nonlinear function of the roll-force, strip-width and backup-roll-diameter. The thermal expansion of the work- and backup-roll and adaptation coefficients also influence the roll gap position.

Sensitivity model

The sensitivity model calculates the finite differences of the process inputs

to the outputs. These can then be used for the calculation of the feed forward and feed back controller parameters of gauge, tension and flatness control. This enables a constant quality for different products at all rolling phases.

The speed feed forward parameter, eg, describes the interdependency of speed and force. The bending feed forward parameter describes the dependency of force on bending. Both feed forward controls attenuate disturbances during acceleration and deceleration and are an important support of the gauge and flatness feedback control.

ABB's Preset model solutions for cold rolling mills play an important part in the improvement of product quality and productivity.

Adaption model

One problem encountered in mathematical modeling is that although the physical correlations within the process may be known, parameters are frequently unknown and may even be subject to change. The parameters of the cold-rolling process, for instance, yield stress, friction, heat transfer coefficients, etc, which are not all known and vary with time. This often leads to inaccurate predictions.

In order to improve the prediction capability of the preset model, an online model adaption for updating coefficients and parameters is performed which considers variations of material and mill behavior.

During rolling, measured data (if sensors are available: eg, entry and exit strip thickness, entry and exit strip tensions, entry and exit speed, rolling speed, rolling force, bending force, shifting and roll gap position) is acquired in a time-based cycle ("Input variables" in 5). After a plausibility check and filtering and estimation of unmeasured values, the recalculation ("Rolling model" in 5) and adaption for different rolling phases is started for the current coil to provide the adaption coefficients and parameters so that set-up calculation of the next pass can be calculated with an improved accuracy.

The adaption procedure learns from the differences between calculated and measured variables. The learning speed is configurable with a learning gain.

Short term adaption (fast learning speed) is performed from pass to pass and long term adaption (slow learning speed) from coil to coil and for a series of similar coils. Changes of product-classification (material class, width, gauge, etc), roll changes and long downtimes are taken into account 6.

An advanced roll model for mills

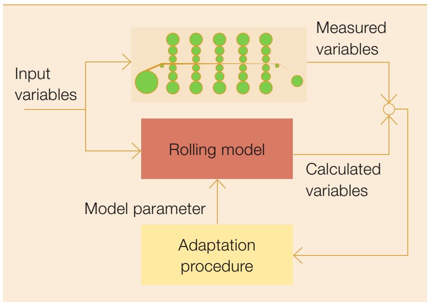
ABB's Preset model solutions for cold rolling mills play an important part in the improvement of product quality and productivity.

Main customer advantages are summarized in Factbox 3.

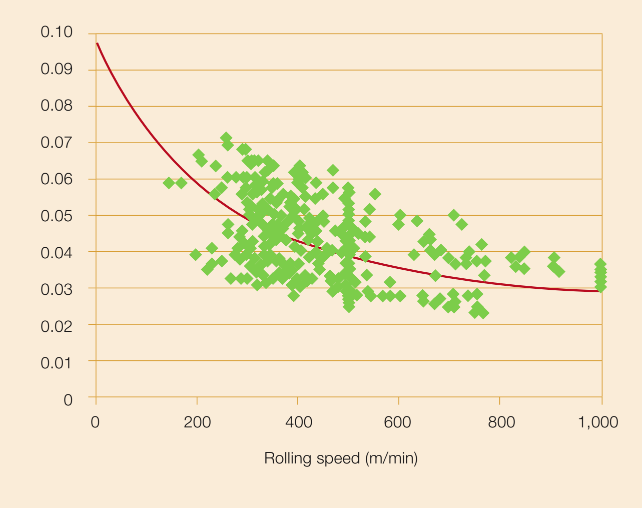
Factbox 3 Customer advantages

- Supports operator and production planer with automated set-point references
- Stabilizes rolling conditions with respect to the mill and process limitations
- Minimizes threading, tail-out and reversing times
- Reduces off gauge length at strip head and tail (in a recent revamped tandem cold rolling mill in average over the complete product range by 60 percent)
- Minimizes strip breaks, downtimes and roll damages
- Indirect improvement of strip surface quality
- Optimizes through-put rates (up to 4–6 percent, depending on mill and level of optimization)

5 Adaptation in a rolling model (the example is of a tandem cold mill)



6 Friction adaption with multiple passes



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