Global process control of a cluster mill for rolling stainless steel strip

A new 64-inch cluster mill for rolling stainless steel strip, installed in the Tornio works of Finnish mill operator Outokumpu Polarit Oy, features an advanced mechanical design and new, powerful actuators from ABB for controlling the thickness, flatness and thermal evolution of the strip during rolling. To meet the productivity and quality requirements of the mill, a new global process control system was developed which supervises production and controls the plant automation functions. A consistently high quality is ensured by a combination of auto-adaptive mathematical models for optimizing the mill set-up and advanced on-line process control. Integration of the new system in the mill and production management network, local roll grinding area network and coil tracking system improves plant flexibility and productivity for a better overall efficiency.

Process control capability and production line flexibility are becoming an increasingly crucial factor in rolling mill efficiency. This industry trend, plus strong market demand for cold-rolled, flat stainless steel products of a consistently high quality (ie, with narrow tolerances), has led to investment in control equipment rising in proportion to total plant investment. In such a context, quality control and product quality certification clearly extend beyond the control of technological parameters to include the overall control and supervision of the production process [1].

To meet the above requirements, ABB Industria, steel producer Acciai Speciali Terni and research company Centro Sviluppo Materiali of Italy, jointly developed a new global process control system based on advanced mathematical models. The new system, which has been operating successfully in rolling mills in Italy and Taiwan, was more recently installed in the process computer of a new cluster mill producing stainless steel strip in Finland, where it helps to ensure high productivity and product quality through supervision of production and control of the automation functions.

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Advanced design of the cluster mill

The new 64-inch cold-rolling mill **1**, which was built by Mannesman Demag, began commercial operation at the Tornio, Finland, works of Outokumpu Polarit Oy in March 1996. It features an advanced mechanical design with 20 rolls **2** and an open mill housing which is similar to that of a conventional four-high mill stand. Besides the global process control system, ABB delivered the main drives and the drive systems for the tension reel and pay-off reel **3**, **4**. *Table 1* gives the main technical data of the installed mill.

Passline control of the upper roll cluster is by hydraulically actuated wedge adjustment. Thickness control and roll gap tilting are realized through screw up positioning, involving bottom hydraulic screws that act on the roll gap.

The mill has four different devices for adjusting the roll gap profile and thereby control the distribution of the tensile stress in the rolled strip. These are the top side and top central eccentric backing bearings with independent working gear rack drives for adjusting the width of the support saddles (crown adjustment), the devices for shifting the first intermediate tapered roll and the hydraulic screw cylinders for the screw up tilting **5**.

The strip temperature is controlled during rolling by an oil cooling system consisting of spray plates, each with several rows of nozzles. The rows are arranged in the direction of strip travel as well as in the counter-direction at the entry and exit sides of the mill. Servovalves regulate the oil flow **6**.

Process control

The main tasks of the new process control system go beyond presetting and data acquisition functions to cover mill management and production control **7**. To this end it has a relational database which not only receives data from the mill but is also linked to the plant network and the local roll grinding area network 8. The coil tracking system provides real-time information about the location of each coil in the plant, while the roll management system informs the maintenance staff of the on-line situation in the roll park. Information from the mill and from the grinding area is sent to the roll database to keep it up to date.

The data have been organized and structured for optimum utilization, ie for mill operation as well as for the production supervision and control functions.

The following process control functions are integrated in the system:

- Coil quality, technological and engineering reporting
- Production reporting
- Rolling schedule calculation
- Mill set-up
- Automatic gauge control (AGC) 9 and automatic flatness control (AFC) 5

Auto-adaptation algorithms based on physical laws are included in the mathematical models for calculating, in real time, rolling schedule and mill set-up parameters such as the number of passes and reduction distribution, rolling forces, strip tensions, rolling speeds, motor powers, flatness presetting, strip cooling oil flows, change in strip temperature.

On-line process control, including coil tracking, sequencing, automatic roll changing, automatic thickness control and automatic flatness control are performed by the first-level automation system.

Coil tracking

The coil tracking function provides real-time information about the location of each coil in the mill and initiates any further action that may be necessary. This function allows physical primary data to be assigned to each coil being tracked in the mill.

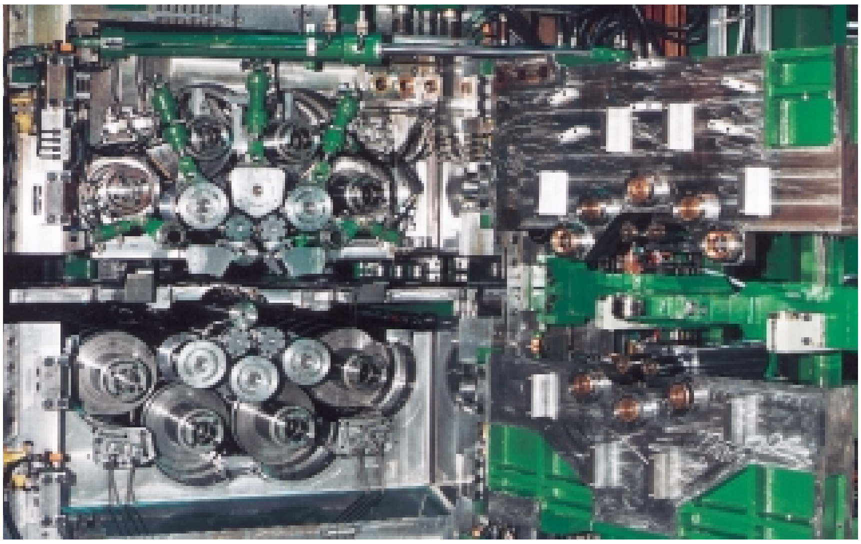
Coil identification

The coil identification function assists the operator in selecting the correct mill set-up data. It combines data from the coil

New cluster mill for cold-rolling stainless steel strip in the Tornio works of Outokumpu Polarit Oy, Finland. The mill is equipped with a global process control system that supervises production and controls the plant automation function. 1

Table 1:
Specification of the new Outokumpu 64-inch cluster mill

Product data		
Strip material	Austenitic/ferritic	stainless steel
Strip width	800 – 1625	mm
Strip thickness, entry	0.8 – 8.0	mm
Strip thickness, exit	0.3 – 6.5	mm
Coil weight	max 28	t
Roll data		
Work roll diameter	75 – 130	mm
1st intermediate roll dia	127 – 146	mm
2nd intermediate roll dia	228 – 240	mm
Backing bearing dia	406.4	mm
Rolling force	max 16,000	kN
Rolling speed	max 800	m/min
Motor ratings		
Main drives	6,000	kW; 188/600 rev/min
Tension reel	5,400	kW; 107/386 rev/min
Pay-off reel	900	kW; 440/1500 rev/min



2 ***Detail of the 64-inch, 20-roll cluster mill. New, powerful actuators from ABB control the thickness, flatness and thermal evolution of the strip during rolling.***

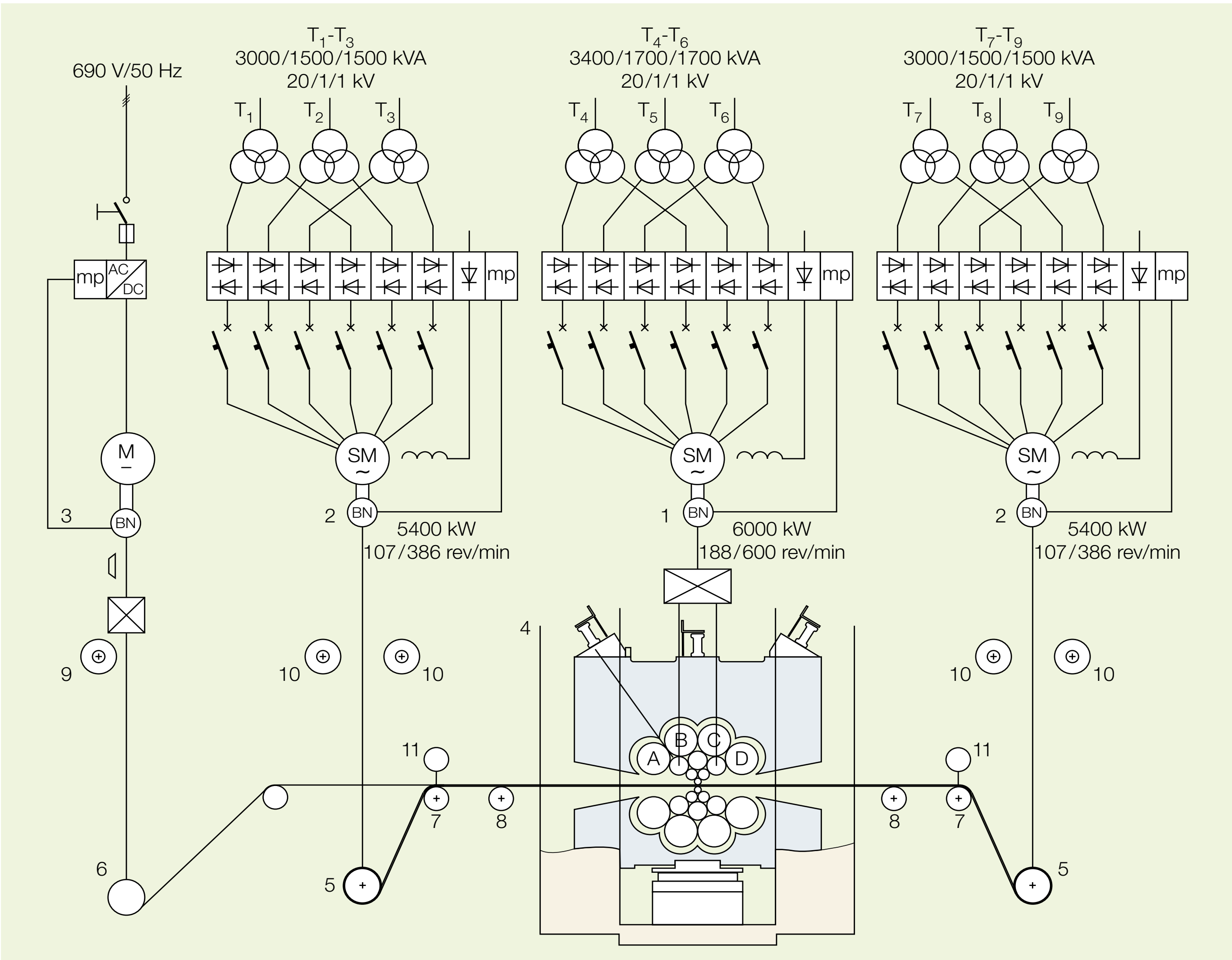
tracking function and from the mathematical model, and also checks the validity of the technological parameters calculated for the mill set-up on the basis of the relevant algorithms.

Roll management

This function manages the data relating to the rolls actually stored in the mill. The roll database is updated with information

Main drives of the Outokumpu cluster mill in Tornio **3**

1 *Main drive for roll stand*
2 *Drives for winders*
3 *Pay-off drive*
4 *Mill stand*
5 *Winders*
6 *Pay-off reel*
7 *Deflector roll*
8 *Stressometer roll*
9 *Pay-off paper winder*
10 *Paper winders*
11 *Encoder*
$T_1 - T_9$ *Supply transformers*



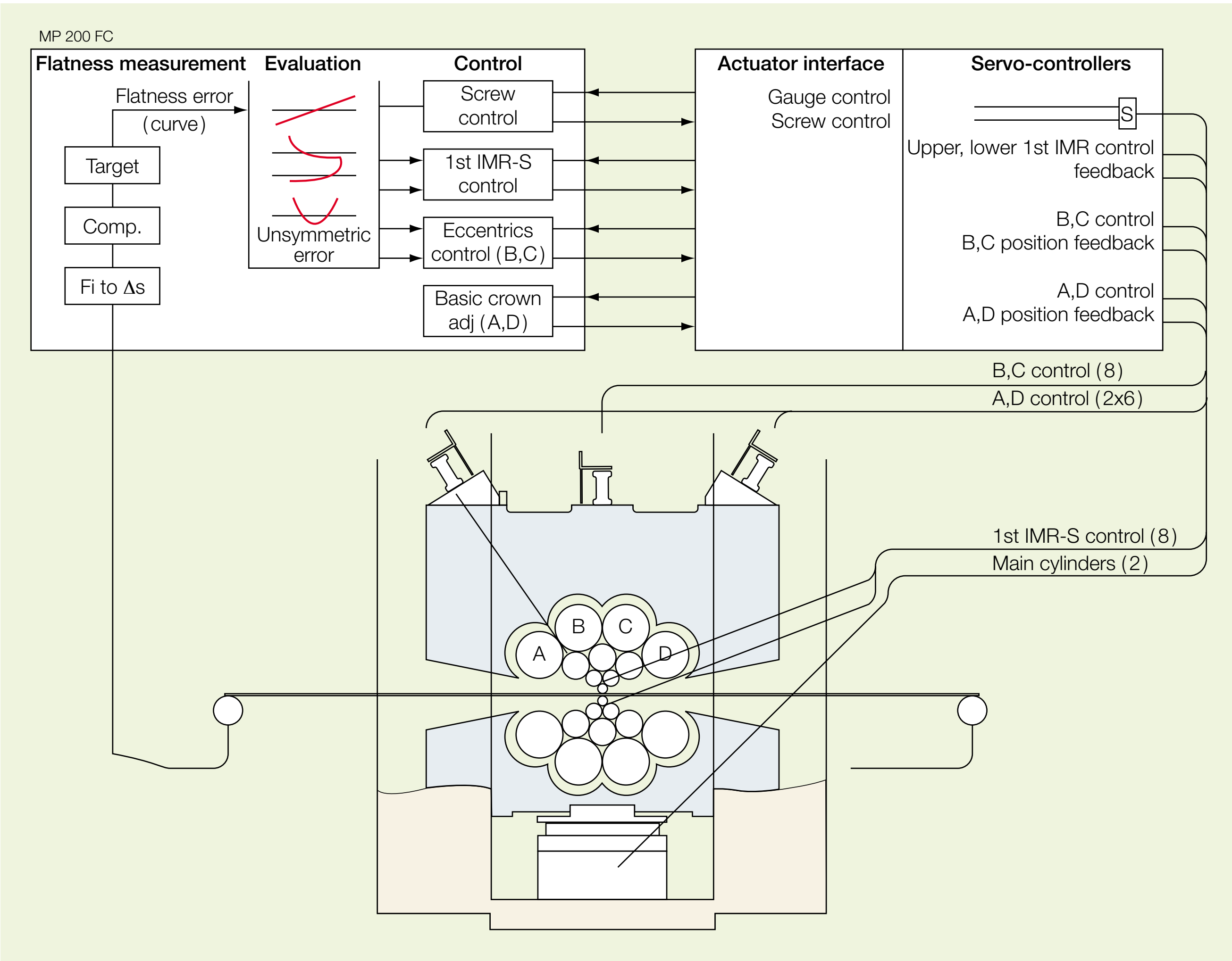
from the mill and from the grinding area. Rolls are identified by a serial number. The data received from the roll grinding area (eg, diameter, camber, taper geometry) is combined with information from the mill (operating hours, kilometers of rolled material, calculated surface wear, etc) **10**.

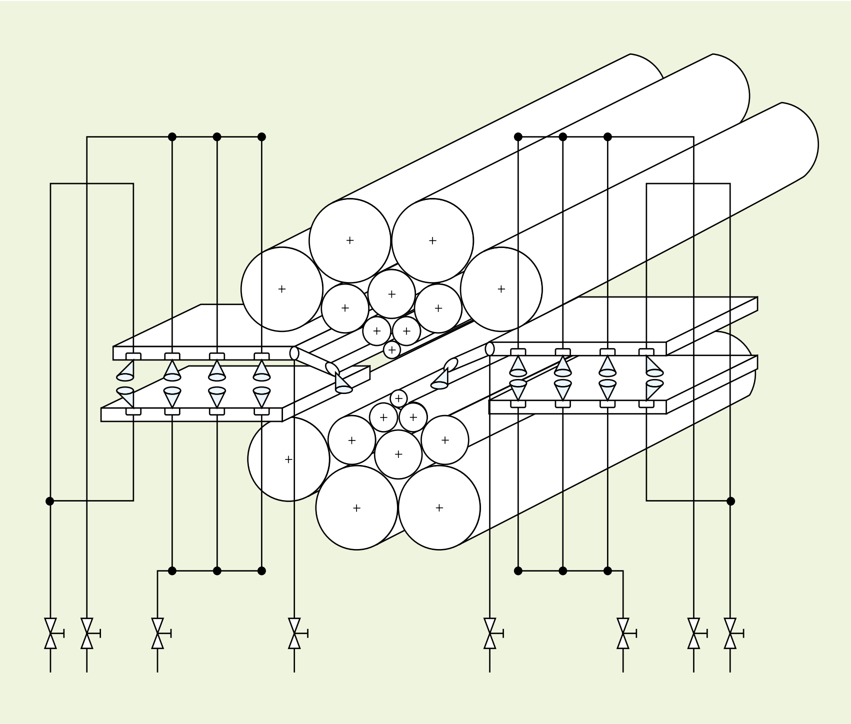
Reporting

Quality, technological and engineering reports can be generated by the system. Each report contains information on the production of each single coil, and compares coil processing data with the guaranteed mill performance. Production reports organized on a daily or monthly basis and containing information about the mill productivity can also be generated.

View of the three main drives delivered by ABB for the roll stand and coilers **4**

Flatness control is implemented through four different devices for adjusting the roll gap profile, and hence the distribution of tensile stress in the rolled strip. **5**



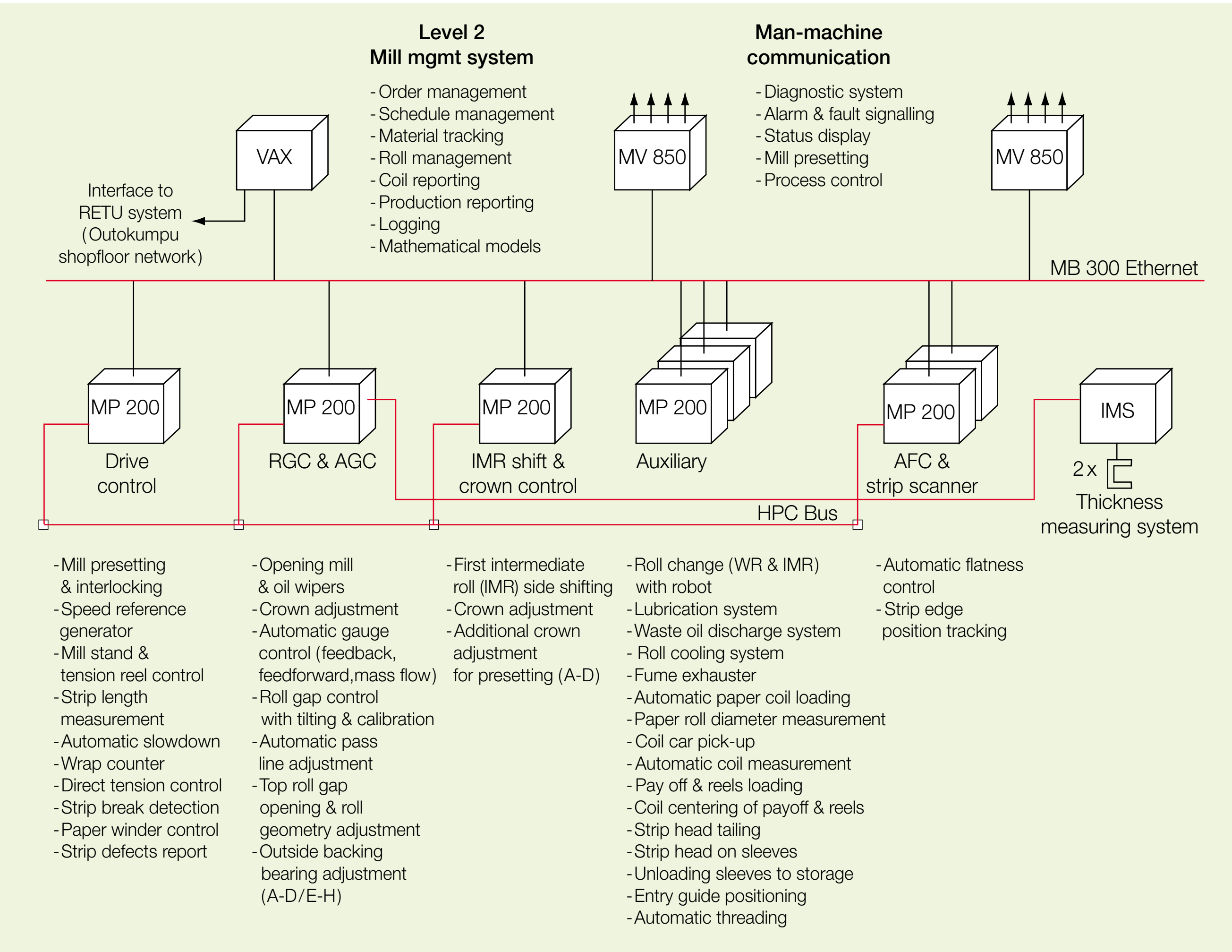


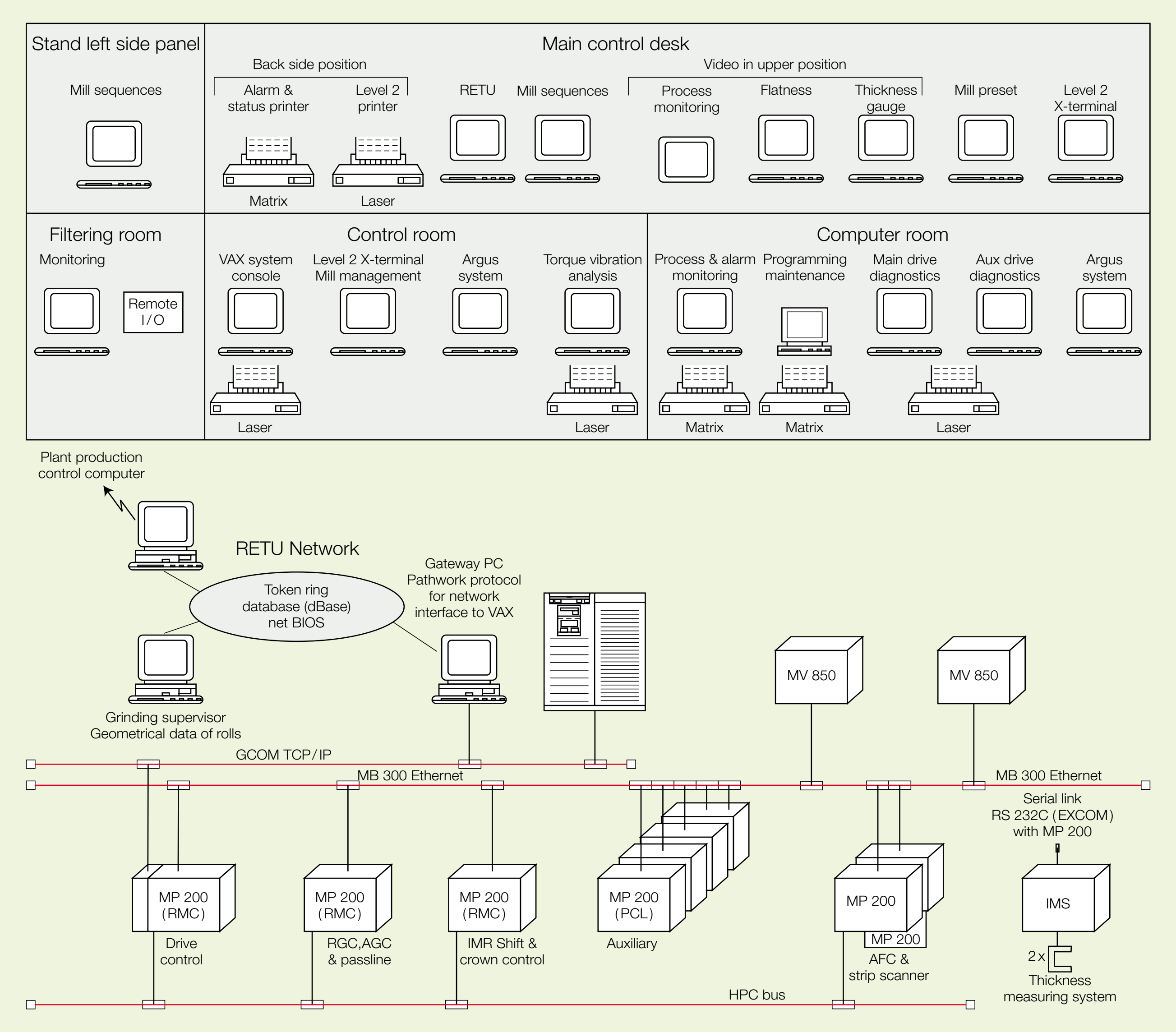
Mill set-up

The set-up control is based on mathematical models **11a**, **11b** that perform three main functions: a pass schedule calculation, a shape calculation and a strip temperature evolution calculation. These tasks run in real time and either generate or modify the rolling schedules on the basis of the coil data, the roll data and the

Schematic showing the selective cooling of the strip surface. Variable-speed pumps with controlled valves allow the coolant flow to be varied from the entry to the exit end and with different flows on the upper and lower strip sides. **6**

Overview of the control layout and monitoring functions for a cluster mill **7**





The relational database of the new global process control system receives data from the mill and is also linked to the plant network and the local grinding area network. **8**

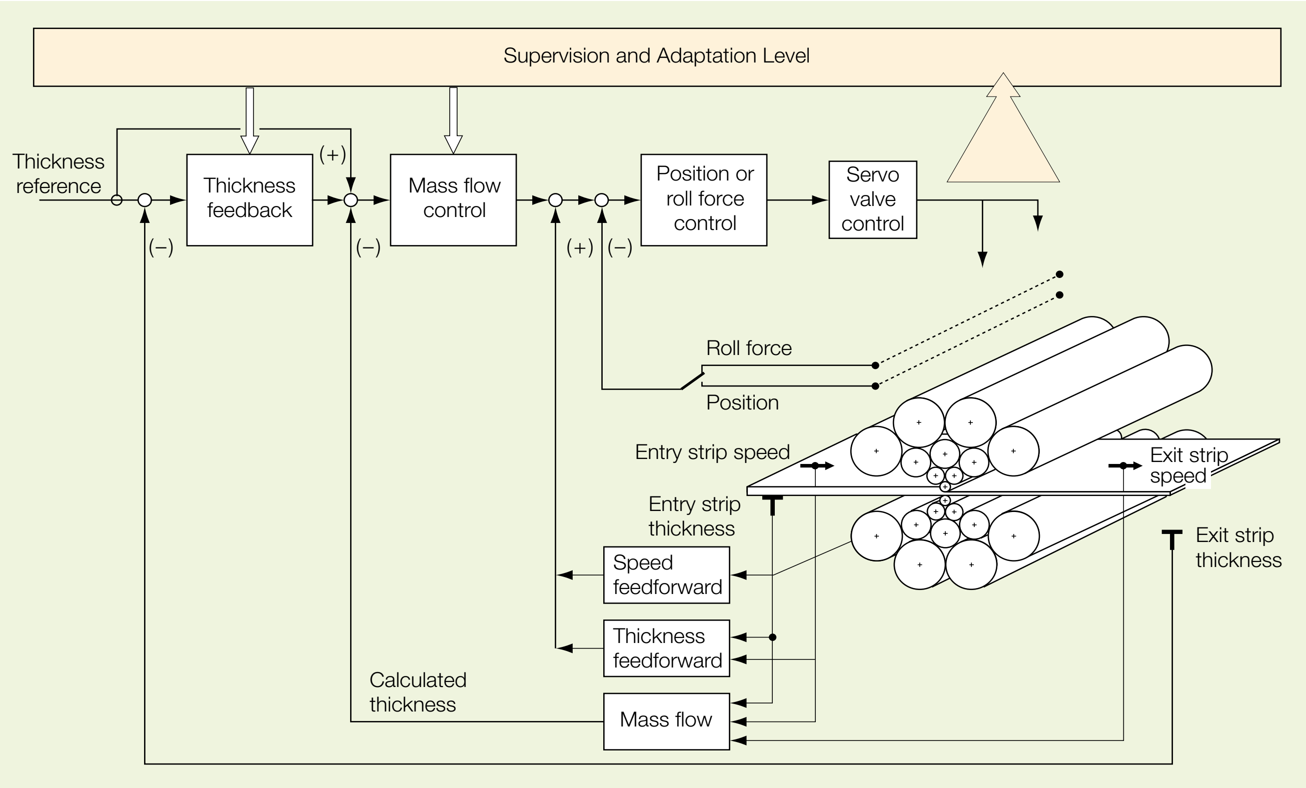
restrictions imposed by actual plant conditions. Auto-adaptation algorithms are implemented for updating the mill and material characteristics on the model database as a function of the measured rolling parameters. Automatic mill set-up is made possible by an interface module that links the mathematical models to the automation system (level 1).

Due to the modularity of the models, the system for calculating the mill set-up can be adapted for different mill configurations. A benefit of using a standard interface module and modern programming languages is that they are independent of the installed hardware.

Pass schedule calculation

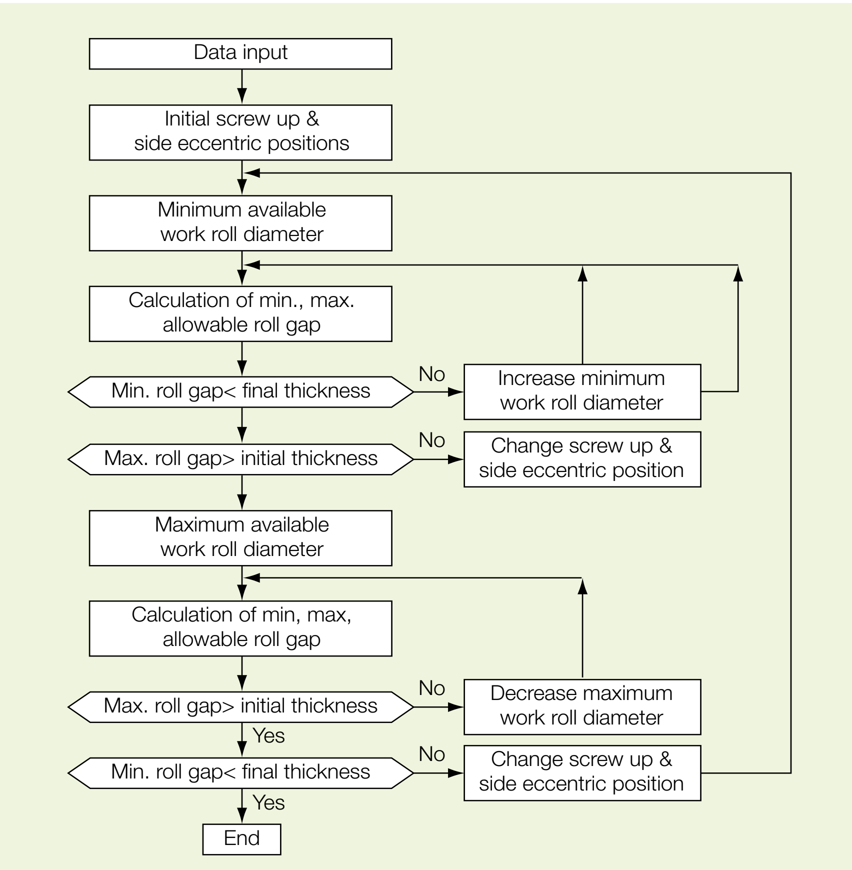
The main task of the pass schedule calculation is to define the reduction strategy and the rolling parameters for each pass (rolling force, entry and exit strip tensions, rolling speed and main motor power) which are necessary to obtain the final strip thickness. Intermediate strip thicknesses that might be required are also catered for by this function. Convergence calculations are run in such a way that the minimum number of passes can be determined taking into account all the restrictions imposed by the mill (maximum rolling force and motor power, maximum entry and exit strip tensions, range of shape control, and maximum allowable strip temperature). Pass by pass schedule calculation allows further improvements, for example correction of a pass schedule on the basis of rolling data collected during the preceding pass.

To make flatness control easier, the reduction distribution is defined in such a



Principle of automatic gauge control **9**

Work roll diameter calculation: flow chart **10**

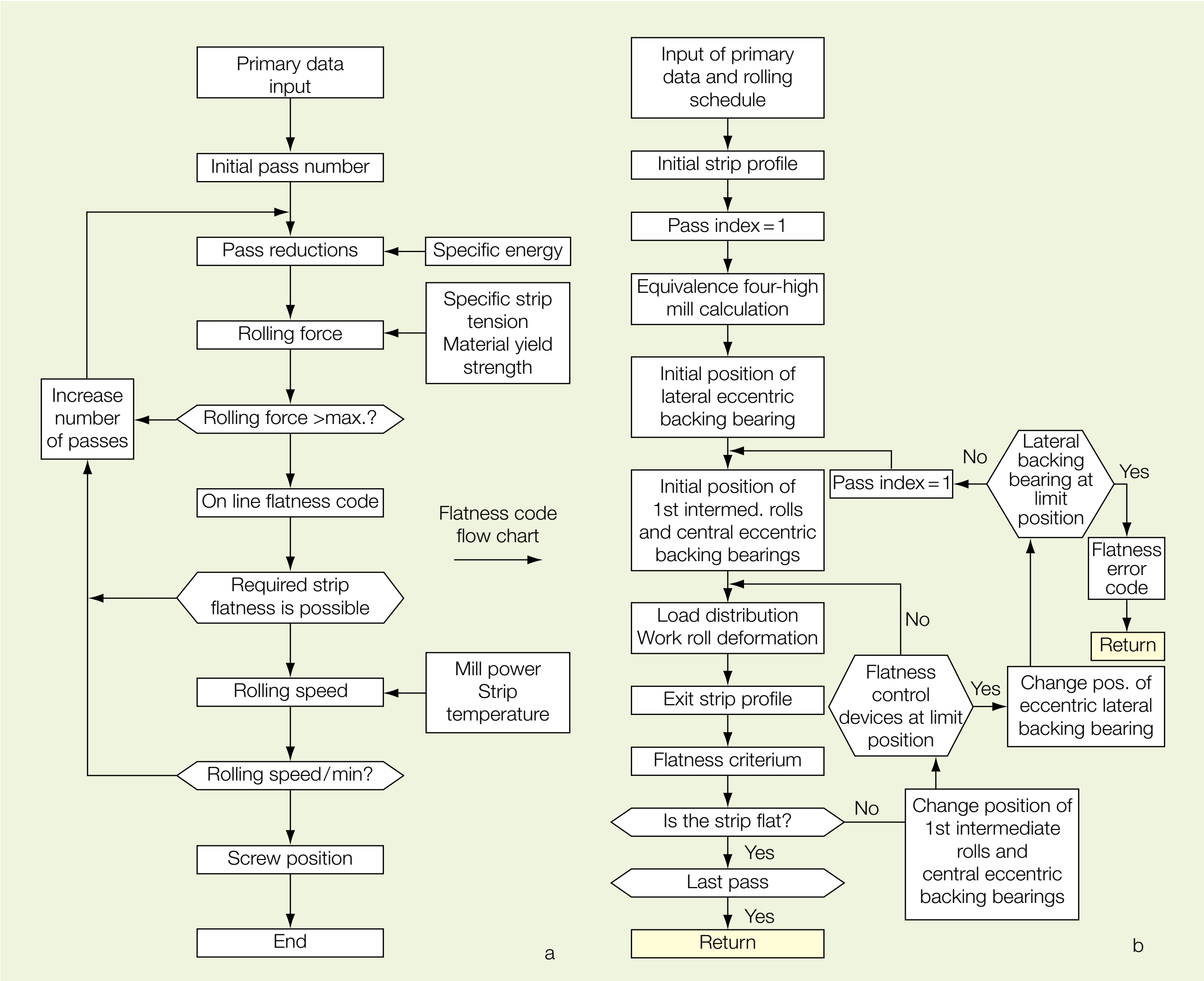


way that the rolling forces decrease from the first to the last pass. This strategy is adapted to the hardening properties of the material involved.

Flatness model

A new auto-adaptive flatness model was developed to take full advantage of the high degree of freedom offered by the mill control capabilities. The purpose of the model is to optimize, through an iterative/convergence procedure, the mill flatness presetting configuration in terms of the calculated pass schedule and the ingoing strip geometry (thickness, width and measured transverse profile).

The flatness model predicts the deformed roll gap profile and the strip flatness based on the assumption of a negligible lateral spread of the material. It is also assumed that the profile of the strip at the roll bite exit conforms to the roll gap profile. The tensile stress distribution across the width is calculated by solving the equilibrium equation, taking into ac-



Flow charts showing how the mill is set up with the help of mathematical models **11**

a *Set-up code* b *Flatness code*

count the differential strip elongation due to strip profile variations:

$$\int_0^{w/2} \left(\sigma_0 - E\varepsilon_1\right) dz = 0 \qquad (1)$$

where

w Strip width, in mm

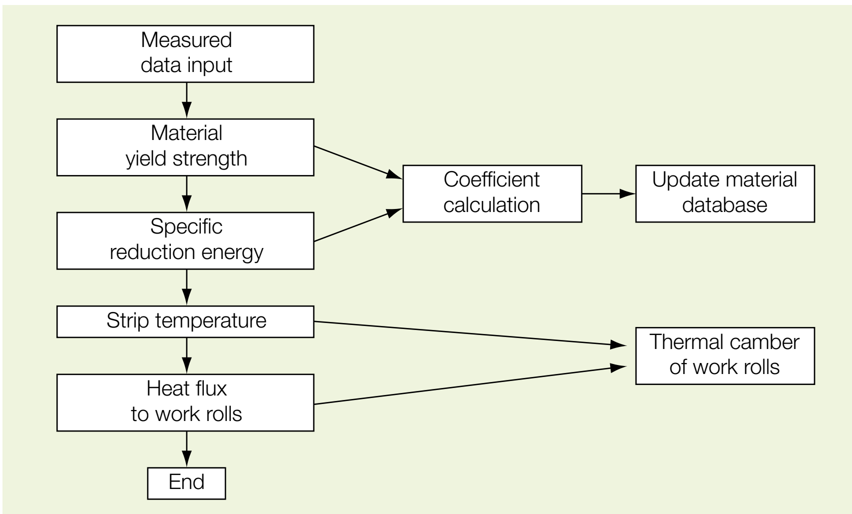
σ_0 Exit specific strip tension, in N/mm^2

E Young's modulus, in N/mm^2

ε_1 Differential strip elongation

To save computing time, the on-line flatness presetting model is based on the simplified hypothesis of equivalence between the elastic deformation of the 20-roll cluster and that of an equivalent two-high mill stand. Since mill symmetry is assumed, only half the work rolls and strip

Feedback code: flow chart **12**



are considered. Bending and shear deformation of the work rolls is evaluated with the help of equivalent work roll stiffness coefficients in order to simulate the influence of the deformation behaviour of the roll cluster on the roll gap profile formation under actual load (ie, rolling) conditions **12**.

The roll gap geometry C_j is determined as a linear function of the rolling factors:

$$C_j = \Sigma_i \eta_{ij} F_i \qquad (2)$$

In eqn (2), the rolling factors F_i are the components of the deformed roll gap geometry across the width: namely, the work roll bending and shear deflection, strip/work roll flattening, influence of the position of the first intermediate tapered roll, lateral and central back-up roll crown, and the work roll crown. n_{ij} represents the coefficients that influence the ith rolling factor in the jth position across the strip width.

The calculated tensile stress distribution is then compared with the reference flatness profile, and an iterative procedure is used to calculate the optimum mill flatness preset values that will ensure a strip flatness deviation which is smaller than the acceptable flatness error.

The calculation of the lateral back-up roll crown aims at the largest possible working ranges for the central back-up roll crown adjustment and shifting of the first intermediate roll.

Screw tilting preset values are calculated to avoid asymmetrical flatness faults due to the crown asymmetrical component of the strip being rolled. The strip profile information received from the profile meter at the exit of the hot rolling mill is fitted with a polynomial function of the 4th order. After evaluation of the strip crown asymmetrical component (strip wedge), the corresponding screw tilting preset value is calculated.

To improve the accuracy of the flatness presetting function, a learning (auto-adaptive) procedure runs every 20 seconds with the latest data from the mill. The coefficients of a 6th order polynomial function are evaluated via data measured by the Stressometer flatness controller. The symmetrical component of the measured flatness profile is calculated and compared with the tensile stress distribution calculated by the ‘learning’ model as a function of the measured rolling data. Afterwards, the equivalent roll stiffness coefficients are re-calculated and updated on the flatness model database.

Thermal pre-setting model

This model predicts the strip coiling temperature evolution for the purpose of establishing the oil flow setpoint for each strip cooling section and for all the passes as a function of the calculated rolling schedule **13**. The purpose of this is to avoid the occurrence of paper mark defects due to the strip coiling temperature being too high. If the calculated strip temperature in one pass exceeds the safety limit despite the total oil flow being a maximum, the rolling speed setpoint is reduced accordingly **14**.

The oil flow reference values are then sent to level 1, where they are used to preset the opening of the servo-valves during each pass.

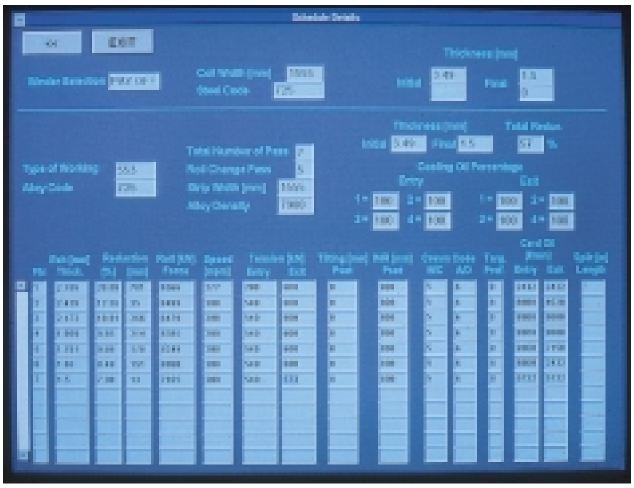
The strip temperature is measured online by optical pyrometers installed on the coilers, allowing the operator to monitor the change in coiling temperature during all of the rolling passes.

The heating due to the plastic deformation, taking into account the effect of oil cooling on the strip and neglecting air convection, is given by:

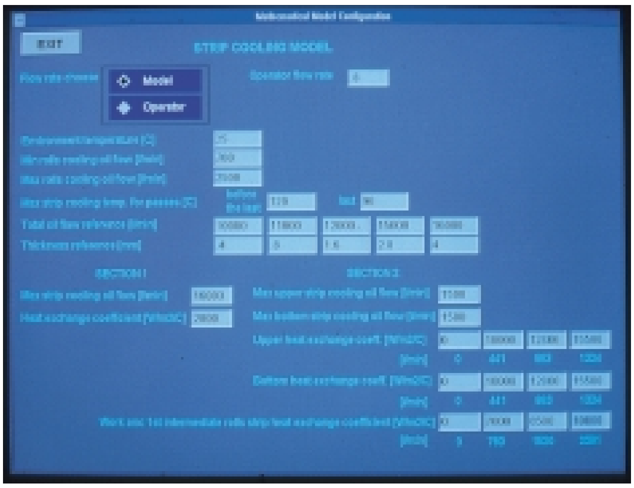
$$\Delta T = \frac{k}{\rho c_p} \ln\left(\frac{h}{H}\right) \qquad (3)$$

where

Example of a presetting schedule calculated with a mathematical model **13**



Strip cooling model: Screenshot showing the calculated parameters for optimum cooling of the surface of the steel strip **14**



Main operator's desk **15**

ΔT Strip temperature rise, in ˚C
k Material yield strength, in N/m²
ρ Material density, in kg/m³
c_p Specific heat of material, in J/kg/˚C
h, H Entry and exit strip thickness, in mm

The following equation is used to calculate the cooling of flat plate:

$$\Delta T_c = \left(T_{in} - T_{oil}\right)\left[1 - \exp\left(-\frac{\Delta t\, h_c\, S}{c_p\, Q}\right)\right] \qquad (4)$$

where

ΔT_c Strip temperature drop, in ˚C
T_{in}, T_{oil} Initial strip temperature and oil temperature, in ˚C
Δt Cooling time, in s
S Exchange surface, in m²
c_p Specific heat of material, in J/kg/˚C
Q Strip mass under the cooling oil flow, in kg

h_c is the strip/oil heat-exchange coefficient of the ith cooling section. It is determined as a function of the oil flow and the strip speed during rolling trials.

On-line flatness control

Closed-loop flatness control takes place during rolling as a function of strip shape measurements carried out by the ABB Stressometer. The central back-up roll crown, shifting of the first intermediate roll and the screw tilting function are adjusted during rolling to correct flatness defects. In cases where the CBUR crown control system has reached its working limit, the LBUR crown adjustment changes automatically when rolling stops at the end of the pass in progress in order to restore the CBUR crown control capability for the next pass.

Excellent results with the new control system

Field experience with the global control system has been excellent. Since being installed, it has demonstrated good reliability and has functioned to the full satisfaction of the customers.

The new system allows overall supervision of mill automation functions **15** and guarantees complete quality control of the production process. It also allows full advantage to be taken of the new and more powerful devices for controlling the strip thickness, strip flatness and final surface quality over the full coil diameter. Optimized mill presetting allows the industry's demand for improved plant productivity and product quality to be met, while the reporting procedures provide the maintenance and production staff with all the information they need to monitor the on-line production status.

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[1] M. Marcolini: ABB Master in control of Sendzimir mills. ABB Review 6/7–93, 17–28.

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