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Control, automation and the hot rolling of steel

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THE ROYAL SOCIETY

Control, automation and the hot rolling of steel

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The current state of automation and control for hot rolling mills, with a particular emphasis on flat products, is introduced. A typical modern control-system design is discussed together with the impact on the design of process models, available measurements, available control actuators and material properties. Both the piece-to-piece mill-control calculations and in-piece dynamic control are covered.

Currently, control of microstructure is achieved by imposing deformation and temperature time profiles on the process. The need for ever more stringent product quality will lead to the demand for a tighter control of microstructure. How might microstructure modelling and process control affect each other in achieving this? Some ideas are introduced and discussed.

Keywords: feedback control; feedforward control; model adaption; tandem rolling mills; rolling mill models

1. Introduction: aims of automation

The metal rolling industry continues to have a leading role in the practical application of innovative automation techniques. As always, technical performance is a prime motivation: the market demands improvements; new technology allows improvements, and it is the role of the automation engineer to convert possibilities into realities. Technical performance is considered in six interacting areas, as follows.

(i) *Throughput* in terms of tonnes per unit time is the most obvious performance metric.

(ii) *Quality* in terms of dimensional accuracy and mechanical properties is easy to define but, as will be shown, hard to measure and hard to achieve.

(iii) *Availability* is a measure of the percentage of time that a mill is available for production.

(iv) *Yield* is a measure of tonnes output versus tonnes input. Prime yield is a (slightly) lower figure indicating the proportion of saleable product.

(v) *Costs and efficiency* relate to energy and consumables, to inventory, to response to customers, and to adherence to the production plan.

(vi) *Market share* is enhanced by the capability of offering a wider range of products with high quality and short delivery.

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Introduction of an automation system needs very careful planning. The scope of work and delivery programme are selected on the basis of cost-effectiveness but, as the system is often being retrofitted to an operational mill, the installation plan is also of prime importance: production of good quality metal must be maintained throughout the project. For this reason, upgrades are staged, as far as possible, to make use of existing, or slightly extended, maintenance down time. A further issue to consider at the planning stage is the need not only to achieve good performance immediately after each upgrade, but also to achieve the expected improvement quickly. For this reason, such concepts as 'design for start-up' have been highlighted in recent years. A final aspect to consider in the planning stage is the expectation of future developments: a rolling mill is never static and the automation system should be able to provide justification and support for future developments.

Because of the sophistication of automation techniques and the vast amount of information available from modern systems, a growth area in recent years has been the support that can be given to personnel in carrying out important tasks.

(i) *Operators* are still required because in many cases they have the best sensors and are required to intervene where material is diverging from the planned path in a manner not detectable by the on-line system. Well laid-out screens and intelligent intervention tools are needed, as events can happen very quickly on rolling mills.

(ii) *Maintainers* benefit from the fact that the automation system knows what constitutes 'normal' mill behaviour and records current behaviour and behavioural trends. Many mills include features providing forewarning of potential problem areas so that repairs can be effected before the rolling operation suffers.

(iii) *Managers* are responsible for the overall operation of the mill and need to have a well-focused set of data available, ranging in detail from broad production figures to intricate fault analysis. They also need the facility for calling for new views of the data, so the automation system needs, as well as the usual gigabytes of storage, an intelligence capable of transforming raw data into meaningful information.

(iv) *Engineers* are responsible for diagnosing the difficult faults, for implementing changes (new products, sensors or practices), and for supporting the management in long-term development planning (including answering 'what if?' questions).

2. The process

Figure 1 shows the outline of a typical hot strip mill (HSM). Its purpose is to process cast steel slabs into steel strip. The first obvious effect is the large dimensional change of the processed piece; the slabs, of up to 35 t weight, are typically 250 mm thick and 10 m long, and the rolled pieces are typically 2 mm thick and 1250 m long. This reduction in thickness is achieved by passing the piece through a series of rolling mill stands. Typically, at the first stand, the roughing mill (RM), the thickness of the hot slab (1240 °C) is reduced by making several passes, forward and reverse, through the mill. At the end of this roughing process the piece will

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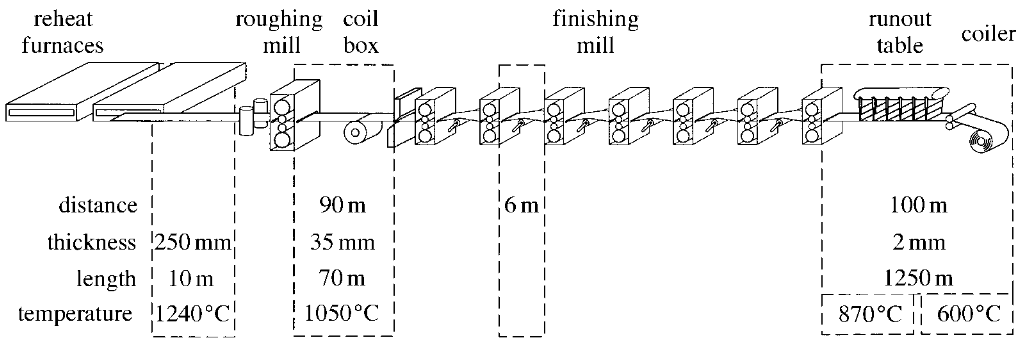

Figure 1. A typical HSM layout showing the piece thickness, length and temperature at key points through the process.

be 35 mm thick and 70 m long and its temperature will have dropped to 1050 °C. Further reduction in thickness takes place in the six or seven close-coupled rolling finishing stands. The strip elongation is so great that the piece can straddle a region from the finishing mill (FM) approach tables to the coiler. During this part of the process, piece temperatures are important and should be, typically, 870 °C after the last rolling stand and 600 °C at the coiler.

The width of pieces ranges from 500 to 2000 mm, but width changes in the process are limited to a few per cent. Most of the range is achieved by varying the width of the slabs entering the process.

The HSM changes, not only the work-piece dimensions, but also the microstructure of the steel, which is important in determining its final mechanical properties. Microstructure is primarily determined by the FM deformation, the exit temperature from the FM and the cooling of the strip on the run-out tables (ROTs).

The general parameters of a modern high-production rolling mill are impressive. Weekly throughputs exceed 60 000 t, and the hourly rate can peak significantly higher at more than 500 t h^{-1}. For narrow product, up to 60 pieces per hour may be rolled. Variability of throughput is consequent on the different processing times when rolling different products. Wide products are furnace limited; narrow, heavy-gauge products are RM limited; light-gauge products are FM limited. At gauges below *ca.* 2.5 mm, the FM threads at its maximum speed, so for light gauges, throughput is approximately inversely proportional to exit gauge. The rolling of the strip also involves high forces and powers on the mill stands: forces can reach 3000 t and the power to drive each stand 10 MW or more.

Strip rolling is a complex combination of batch and continuous processing. As each piece approaches the mill, the machinery must be individually set up for it. Even when rolling batches of the same product, significant changes to the set-up of the machines are necessary to maintain quality because of changes in the mill machinery (due to, for example, thermal expansion effects and wear) and variability in seemingly similar slabs (differences in dimension, chemical composition and thermal state). The control procedure for setting up the mill for the piece is termed the *mill set-up*.

When a particular piece is in a mill, it is continuously processed from nose to tail and is still subject to disturbances, again from changes in the machinery and from variability along the piece as it is rolled. Of particular significance is variation in piece temperature. To maintain product quality along the length of the piece in the face of this variability, the mill actuators are modulated to eliminate disturbances by feedforward and feedback control. This is the *dynamic control*.

A further complicating characteristic of the HSM is the large number of degrees of freedom in the process. For example, in principle, there are many possible strip reduction paths through the process from slab to finished coil. In practice, much of this redundancy is lost because of processing and machine constraints. In the practical control system, much of the functionality is devoted to guiding the piece safely through a multiplicity of constraints from slab to rolled coil.

3. Control objectives

The introduction listed six areas that need to be considered in defining the technical performance of a mill automation system. The automation system is not the sole determinant of performance in any of these areas. However, for any given configuration of mechanical and electrical equipment, the potential performance of the mill will only be achieved with high-performance control and automation. Attention will be focused on *throughput* and *quality*, where control is particularly important in achieving good performance. Note that *throughput* and *quality* interact in both positive and negative ways with the other four areas, and these interactions have to be considered in defining the control system.

(*a*) *Throughput*

The ultimate *throughput* that can be achieved in a mill is limited by the capabilities of the mechanical and electrical hardware. To achieve throughputs consistently close to this limit requires high-quality control and automation.

At high throughputs, three or more pieces may be in the rolling mill at different stages of processing at the same time. To avoid catastrophic collisions in the mill, accurate tracking is essential. The tracking system uses signals from mill instrumentation and process information (for example, as a piece is rolled, so its length increases) to maintain a dynamic map of the mill. It must, of course, be robust against the loss of individual mill instruments.

Throughput control looks ahead at the rolling schedule and determines which part of the installation, furnace, RM, FM or coiler, will limit *throughput*. The limiting process is then controlled to achieve maximum *throughput* and other parts of the process are controlled to match this *throughput*. This results in an improvement in energy *efficiency* and a reduction in wear and tear on the equipment, thus reducing *costs*.

Throughput and *quality* also interact. As *throughput* increases, control becomes more difficult, and to maintain the required level of *quality* and *yield* requires careful design of the control system.

Quality and *throughput* control also interact in positive ways. For example, to achieve a greater range and accuracy of temperature control out of the FM, interstand cooling sprays may be fitted. These must be controlled to maintain the strip temperature at the mill exit but, further, they can be used to increase the speed at which the piece is rolled in the FM, while maintaining the target exit temperature.

(*b*) *Quality*

A principal aim of the automation system is to control the mill equipment so that the rolled coils meet the dimensions (gauge, width, profile and flatness) and material properties required by the customer.

There are two aspects to controlling the *quality* parameters: control of the head end of the piece as it threads the mill; and control of the mill machinery to maintain the desired *quality* parameters through the rolling of the coil. These two control modes were introduced above: set-up and dynamic control. A fundamental difference in control strategy is imposed on the two modes by the availability of measurements. As the mill threads, there are no measurements of the final *quality* parameters, the strip simply has not reached the measuring instruments, and control is achieved by feedforward and model-based control. Once the mill is full, direct measurements of (some of) the final *quality* parameters are available, and dynamic feedback control comes into operation. Accuracy in both modes of control is important, and good head-end *quality* parameters lead to a high *yield*.

Width control in the HSM is also important. Coils are often sold by length rather than by weight; therefore, any excess width represents a *yield* loss.

The shape of the strip is defined by two parameters that interact: profile and flatness. Profile is the thickness variation across the width of the strip and, for downstream processing, is required to be controlled: there is a need for uniform thickness both along the strip length and across its width. Flatness is the ability of the strip to lie flat without applying any external forces and is also important to the downstream processes. Flatness defects are induced by poor control of proportional profile (profile divided by thickness) through the mills and, hence, there is an interaction between profile and flatness control. The flatness-control problem also differs from that for profile because flatness is important, not just at the mill exit, but in the interstand gaps between the FMs. Bad flatness defects between stands can lead to instability of the rolling process in the FM, resulting in a complete loss of control and the destruction of the coil, a cobble. This represents a *yield* loss and also affects mill *availability* by stopping the process while the mill is cleared.

In addition to the dimensional parameters, there are other *quality* parameters that are important. A particularly important objective is the control of the mechanical properties of the finished strip. Mechanical properties are determined, to a large extent, by microstructure, and the microstructure itself is determined, to some extent, by the strain, and to a large extent by the temperature history of the rolled coil. In current control and automation systems, control of microstructure is achieved indirectly by controlling the temperature evolution as the strip is cooled on the ROTs between the mill exit and coiler. The metallurgist defines the target cooling trajectory, and the control system adjusts the cooling sprays on the ROT and the FM speed to match the desired temperature trajectory as accurately as possible.

(*c*) *Control-system structure*

The control objectives for the HSM are expressed in terms of throughput and product quality parameters. However, the practical scope of control covers a very wide range of applications ranging from individual local high-speed position control loops with operational speeds at the ms or sub-ms level to the overall piece scheduling task that operates on an hourly or longer time-scale. All these controls contribute

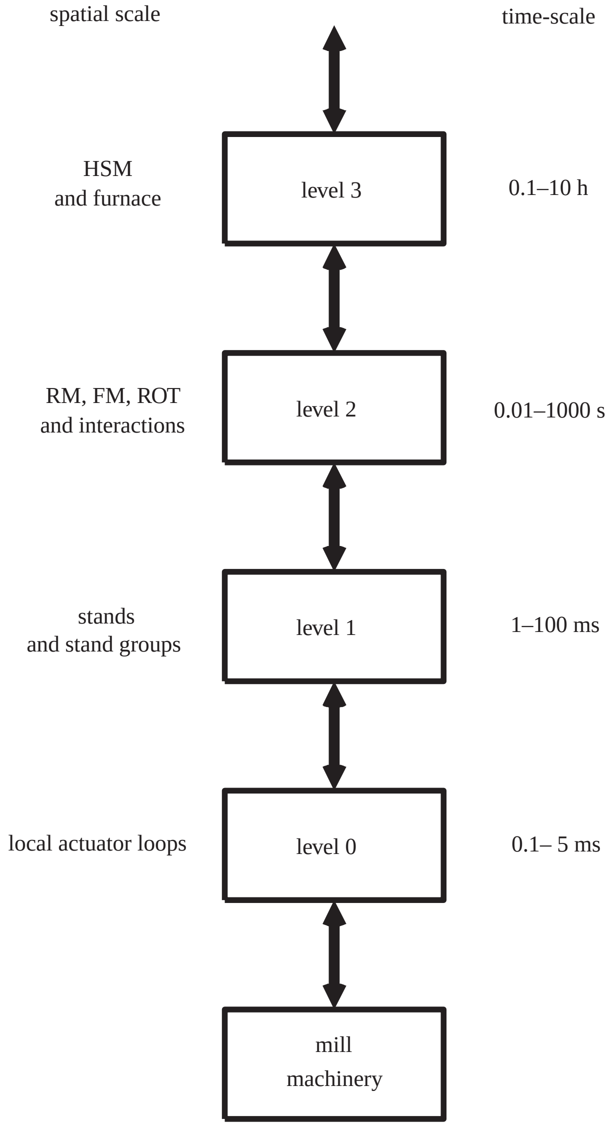

Figure 2. Extent and time-scales of automation levels.

to the overall performance required from the automation system but the objectives are often expressed in terms of sub-goals more appropriate to the time-scale of the particular controller. For example, a position loop's goal may be expressed in terms of the rate of change and overshoot in response to a demanded position change, while the overall scheduling of products through the mill may be expressed in terms of speed of satisfying customer orders.

This difference in time-scale and scope of the individual controls is reflected in the multilevel structure of the control systems now widely used on rolling mills. In figure 2, the block diagram of such a multilevel system is shown. The separation of functions between the various levels is not sharp, and whether specific functions are

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implemented in, say, level 1 or level 2 may vary from installation to installation and in response to the development of better control methods and equipment.

Level 0 is the lowest level of control and includes, for example, the control loops for hydraulic capsules used to position the rolls in the rolling mills and for the main electric motors powering the mill.

Level 1 is primarily concerned with in-piece control. At this level, the quality parameters such as strip thickness and temperature start to appear. However, the objectives for the level 1 loops are often sub-goals supplied by level 2. For example, level 1 control loops function to control the exit thickness out of intermediate stands in the FM, and this exit gauge pattern through the mill is set by level 2 to achieve the required mill exit gauge within machine and process constraints.

Level 2 directly addresses the control of the *quality* and *throughput* parameters discussed above. Its domain of operation is much wider than level 1, and, in a well-developed system, will cover the integrated control of the reheat furnace, RM, FM and ROTs. It is very much concerned with the set-up control of the mill from piece to piece, but often includes part of the dynamic in-piece control too. Usually the dynamic control at level 2 is concerned with the overall coordinated control of, say, the FM. Local control loops are more appropriate to level 1. Much of the control at level 2 is feedforward in nature and model based. Most of the process models necessary for state of the art control of rolling mills reside here.

Level 3 functions mainly as a scheduler of the hot RM. It takes the order book for the mill and organizes it into rounds of, typically, 100–200 pieces that comply with the scheduling rules developed for the mill. As well as the HSM itself, level 3 takes account of upstream and downstream processes and stock areas. The scheduling rules used are, essentially, a global model of the mill that enables the scheduler to organize the round so that the required quality parameters can be achieved within the constraints imposed by the mill equipment. Traditionally, the most important factor is the evolution of the profiles of the rolls in the mills caused by their wear and thermal expansion. From this derives the 'coffin' schedule: start narrow; quickly build up to wider material as the thermal crowns increase on the rolls; and gradually fade back to narrow as the rolls wear.

4. Models

Good control performance requires predictive models of the process (e.g. deformation and temperature models) and dynamic models of the mill machines and sensors. Some aspects of these models are reviewed here.

(*a*) *Process models*

A typical and basic modelling task is that associated with setting up the roll gaps in a mill. Figure 3 illustrates the problem: given entry gauge H, where should the roll gap, S, be set to give an exit gauge h? The difficulty arises because the large deformation forces required to reduce the strip thickness from H to h cause the stand frame holding the rolls to stretch, and mill rolls to bend and flatten. The result is the exit thickness as a function of force, P. In simplified form this can be expressed as

$$h = S + f(P). \tag{4.1}$$

The term $f(P)$ is the mill stretch.

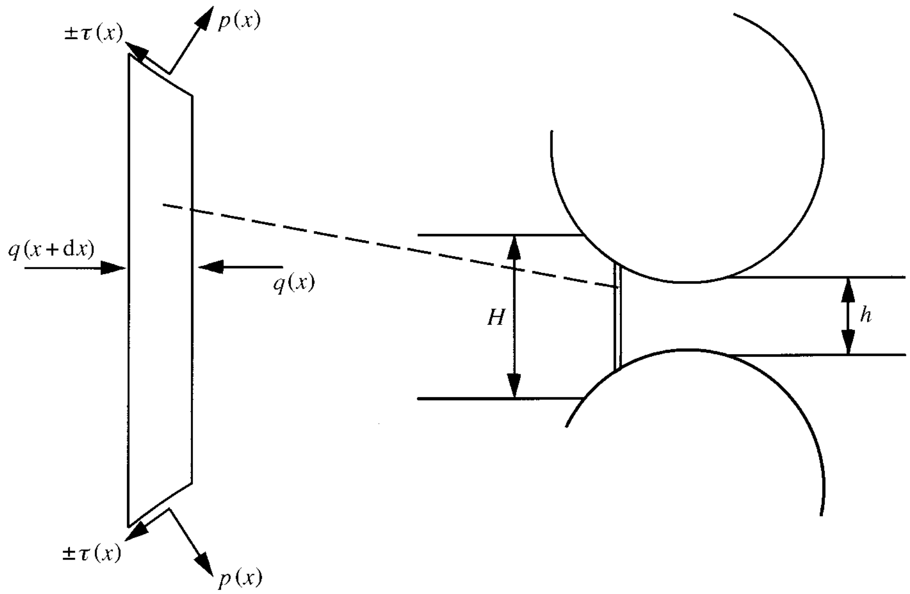

Figure 3. Roll force modelling principles: H is the roll gap entry gauge; h is the roll gap exit gauge; q is the horizontal force on the strip element; τ is the tangential friction force on the strip element; P is the radial roll pressure force of the strip element; x is the distance from the gap exit.

Given the deformation force, the required gap setting can be calculated. Of course, during the set-up calculation, no measured force is available so, to pre-set the gap correctly, a model is also required to predict the deformation force:

$$P = P(H, h, W, T, \dots). \tag{4.2}$$

For a particular strip, thicknesses, width (W) and temperature (T) are the main factors determining the force. There are other significant factors but, for simplicity, these are omitted.

Given the temperature T and width W (further modelling problems!), the two simultaneous equations can now be solved for the required roll gap setting S.

The modelling of roll force has a long history, and the classical plane strain model theory probably began with Siebel (1924, 1925) and von Karman (1925). Many workers have subsequently developed and refined their theory. The physical system that the theory models is shown in figure 3. The development of the model is based on two principles: a plasticity criterion relating horizontal and vertical stresses on an element to the yield stress of the material; and the equilibrium of the internal forces and the boundary frictional (tangential) and roll pressure (normal) forces on the element, as shown in figure 3. To obtain a solution, some fairly gross simplifying assumptions about the strain that occurs in the material as it is rolled are necessary.

Given the yield stress of the material and the friction coefficient between the strip and roll, the roll separating force can be calculated, at least to the accuracy implied by the assumptions. However, obtaining material yield stresses and friction coefficients for realistic rolling conditions is not a trivial task. It is possible to measure yield stress under laboratory conditions, but direct evaluation of a friction coefficient in the roll gap has not yet been done. The friction coefficient is usually adjusted in the model to make predictions fit measurements obtained from laboratory mills or production plants. The resulting friction coefficient tries to account for all the errors in the model irrespective of source: yield stress, strain assumptions, etc. There are other factors that affect the roll separating force. The material yield stress is highly temperature sensitive and, hence, the strip temperature is a significant factor. Also, the strip is held under tension between the finishing mill stands to maintain the stability of the rolling process. The resulting tension stresses at the rolling gap entry and exit reduce the roll separating force and must be specified. Usually, temperature is calculated from a surface temperature measurement made earlier in the process by a model. The interstand tension stress is usually specified and, as the strip is rolled, it is maintained at this reference value by the tension control loop. Thus, as has already been intimated, the accuracy of the force model predictions depends, in turn, on the accuracy of the temperature model predictions and also, to some extent, on how well the tension control loop maintains its reference.

All these factors mean that, to achieve an accuracy sufficient for the performance requirements, the classical force model must be supported by on-line adaption as discussed below.

The force model illustrates the major factors that affect the accuracy of all rolling process models. They are

(i) the simplifying physical assumptions made;

(ii) the accuracy and availability of material properties in the rolling range; and

(iii) the accuracy with which boundary conditions are known in the rolling range.

To get better performance and predictive ability from a model, it is necessary to improve in all three areas. Currently, there is much interest in 'finite-element' (FE) models of the rolling processes. While these models remove many of the physical assumptions made in deriving the classical rolling model described above, the material properties and boundary conditions they require are significantly more complex. Despite their raw predictive power, FE deformation models give results in terms of predicted strip force that are only slightly (if at all) better than those of the classical models. For use in an on-line control system, adaption will still be required. Fulfilling the potential of FE models will require the acquisition of appropriate material constitutive equations and corresponding improvements in the accuracy with which the boundary conditions are defined, be they measured, modelled or controlled.

The control system requires a range of process models to predict the evolution of strip attributes that are of interest. They include

(i) dimensional models;

(ii) deformation/hardness models;

(iii) temperature evolution models;

(iv) strip-profile models;

(v) strip-flatness models;

(vi) material phase models; and

(vii) material microstructure models.

Not all the attributes need to be modelled in all parts of the mill but all are used, at least implicitly, somewhere in the mill.

There is one important process that crucially affects the strip dynamics in the mill: the transport times of the rolled material between different positions. The transport delays between control actuator movements and measured responses at physically removed sensors are important in determining the characteristics of the control-system structure and requirements. Feedforward control is critical to high performance and the limiting factor on feedforward control performance is model accuracy.

(*b*) *Machine models*

Models of the behaviour of the stands, drives, capsules, etc., are also required. Drive and capsule models are dynamic and usually defined accurately. But, for example, the model of stand deflection under load needed to predict the elastic deformation of a complex structure (as shown in the previous section, this model is essential to setting the stand gap for a piece) is partly derived from experiments done on the mill, and, therefore, is subject to uncertainties of the same nature as for the process models.

(*c*) *Model accuracy*

Historically, models have never been accurate enough. Any improvement in model accuracy has been rapidly overtaken by the need for better performance to meet more stringent quality targets. To satisfy performance requirements, model errors must be reduced to the absolute minimum that the technology will allow.

Experience shows that there is a significant time structure in the resulting modelling errors. Very significant improvements in model accuracy are possible by adapting them on-line, and it is by this means that high performance is sustained.

The source of model prediction errors, and some of the techniques used to attack them, are outlined in § 9.

5. Measurements

There are certain key process variables (typically, mill exit gauge, width, profile and flatness, mill exit and coiler temperatures) that must be measured for quality control purposes. However, for control and for safe operation of the mill, many other measurements are used. Strip-surface-temperature measurements are made at several key points in the mill, the temperature measurements between the RM and the FM being particularly important. Other measurements include stand forces, drive currents and voltages, and actuator positions.

Generally, the more measurements that are available to the control system the better the control that is possible. For example, set-up and dynamic control need estimates of the stand exit gauges. Direct measurements would simplify the control system and improve performance but very few mills have installed any interstand thickness-measuring gauges because they are expensive to install and maintain and

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are vulnerable to damage. In practice, the stand exit gauge can be estimated sufficiently well indirectly from stand force and roll gap.

The justification for each additional instrument is always scrutinized carefully, and only if there is compelling evidence of improved product quality or mill safety will it be installed.

6. Materials

The range of mechanical properties required for hot-rolled steels dictates a large number of grades, each grade having its own chemical composition. Unfortunately, properties within the process are also affected by composition, so the control system must hold a database of those properties (yield stress, specific heat, etc.) that are needed by the process models. For some steels, these properties are highly sensitive to composition, which can vary from batch to batch and over time. By adapting the properties on-line in response to measurements, the control system is able to maintain the required performance despite the disturbance.

Another operational factor affecting the control-system performance is the drive by producers to reduce the number of steels with different chemical compositions that need to be manufactured and held in stock. In order to achieve the required range of final mechanical properties of the strip, tighter control of the strip processing in the mill is necessary. This requirement imposes an additional set of constraints on the control system to achieve the process conditions (particularly the temperature trajectory on the ROTs) to meet the quality requirements.

7. Actuators

The characteristics of the control actuators significantly constrain the operation of the control system. Usually, the small signal dynamic response of the actuators is accurately modelled by linear methods and can be handled analytically in the control loop design. However, the actuators are subject to hard limits on the effective range, and also, importantly, maximum rate of change limits apply. The control system has to be sufficiently robust, not just to remain stable but also to operate efficiently when these constraints apply.

The drive for better quality, throughput and wider product ranges has fuelled the development of new actuators. In the past decade, many old mills have been upgraded by replacing or augmenting actuators. Examples are high-speed hydraulic capsule control of roll gaps; roll bending force jacks for flatness and profile control; and FM interstand cooling sprays for greater strip-temperature control. Actuator development continues. Each actuator brings its own set of benefits but also brings design challenges to the control system.

8. Mill set-up

The mill set-up control function has already been introduced in § 2. It is at the heart of the automation system and its prime task is to calculate for each piece, before it is rolled, the mill machinery setpoints required to transform it from slab to rolled coil. The overall objective of the set-up is to ensure that the maximum length of coil satisfies the final product quality targets, but a major sub-objective

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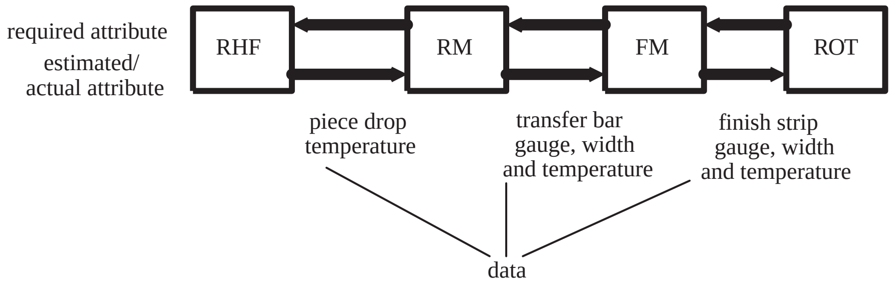

Figure 4. Key data exchanges between the level 2 mill set-up functions.

is the establishment of a stable mill thread with high-quality performance on the strip head end. The set-up is essentially feedforward control, and it relies heavily on accurate predictions from the process models.

The set-up function requires a complex supporting environment. It sits at the centre of, and communicates with, a set of processes responsible for piece tracking in the mill; prime data input (from level 3); communication with level 1; human–machine interfaces; and data concentrators.

In the HSM, the set-up functions cover the whole area from the reheat furnace to the coilers. There are separate calculations for the reheat furnace, RM, FM and ROTs with a small but vital exchange of data between the individual set-up calculations. This interaction of data is critical in defining the goals of each subsystem. Figure 4 shows the main data exchanges. There are two paths: one working back up the mill to the furnace; and one working forward through the mill. The backward path defines the 'ideal' processing route through the mill and is done in advance of the piece entering the process (usually at furnace charge). The forward path is followed as the piece is rolled and allows the set-up calculations to refine the set-up at each downstream stage using the latest estimates of piece and mill attributes and adaptors.

The FM set-up calculation is the most complex. It is this calculation that is directly concerned with most of the quality parameters of the final strip: gauge, profile, flatness and exit temperature. The last parameter defines the entry boundary condition for the ROTs, where the strip cooling is critical to attaining the required strip-mechanical parameters. The control of the other key dimensional parameter, width, is achieved mainly in the RM, although a small but valuable amount of control is possible in the FM.

At the core of the FM calculation are the process models. There are stand-force and power models, strip-temperature models, roll thermal and wear models, strip-profile and shape models, etc. These models have strong and complex interactions both across a stand and from stand to stand (see, for example, figure 5).

The task of the calculation is to set up the FM machines (roll gaps, roll speeds, spray flows, etc.) to satisfy the boundary conditions at mill entry (the measured/estimated exit conditions from the RM) and exit (the required final strip quality parameters). The set-up must take account of the highly interactive nature of the rolling process (which is reflected in the overall model of the mill), and avoid all the process and actuator constraints. Situations also occur where a conflict arises between the various strip quality parameters, and the calculation has to make a trade-off to resolve it. The resulting calculation is complex and is, essentially, a constrained optimization problem (see, for example, Bilkhu *et al*. 1994).

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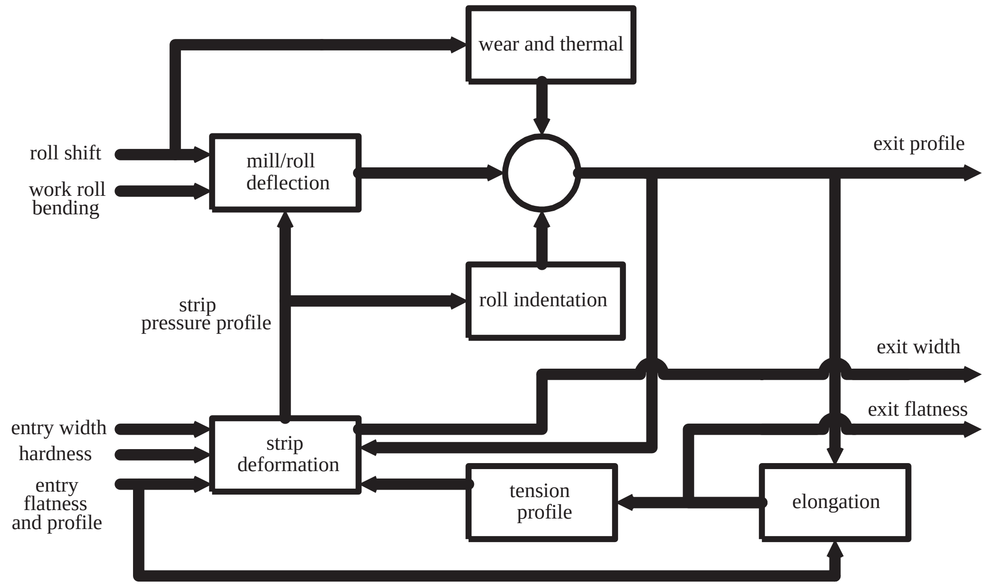

Figure 5. Stand models and their interactions, shape and profile.

The set-up calculation is continually responding to changes in the process. These can be known in advance (e.g. slab composition); measured (e.g. piece temperature); estimated indirectly (e.g. roll thermal profile); or 'random' interference (e.g. unmodelled wear in mill components). All the sources of uncertainty affect the predictive ability of the process models on which the accuracy of the set-up relies. To minimize their effect, the set-up must be supported by an efficient adaption system.

9. Adaption

Adaption is a key component of the control system and, without it, the high performance obtained on mills could not be achieved. It is a learning process: it takes the measured data gathered as each piece is rolled in the mill and uses them to improve the on-line process models, reducing their prediction errors. Figure 6 shows a generalized schematic of the adaption process; note that it is a closed-loop system.

The sources of possible error are numerous but can be grouped into the following categories.

(i) Material properties: dimensions and composition of feed stock are not precisely known.

(ii) Measurements: instruments are subject to error (offset, scale, random noise, drift).

(iii) Models: no model is 100% accurate.

(iv) Mill behaviour: the mill is a complex electromechanical system subject to concealed failures as well as semi-predictable changes (wear and warm-up).

There are two aspects to adaption: adaption within each piece and from piece to piece.

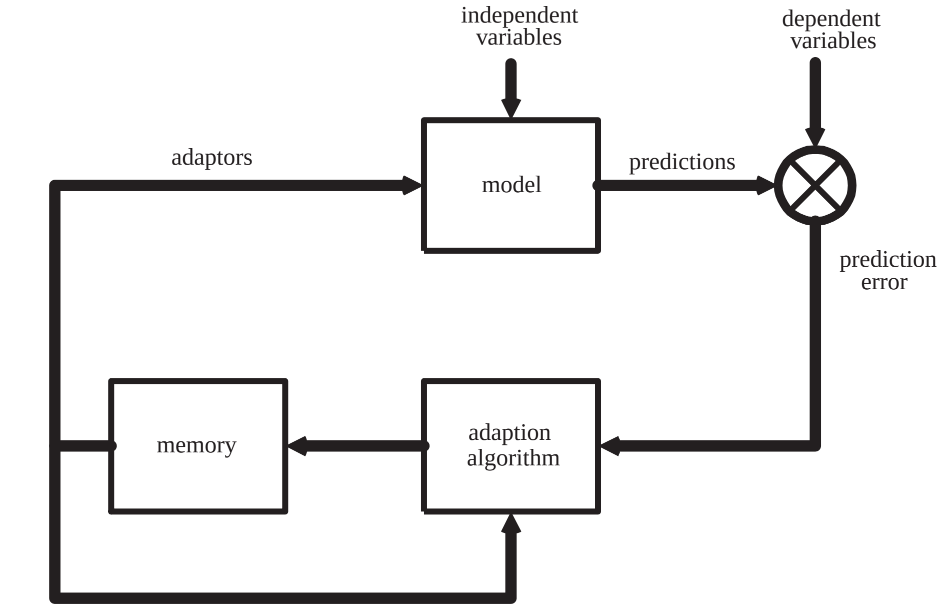

Figure 6. Adaption system schematic.

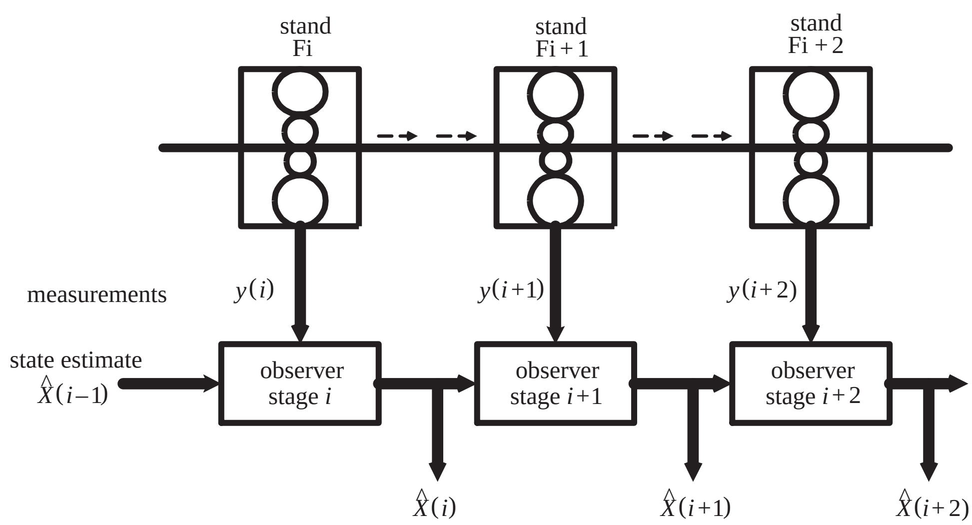

Figure 7. Finishing mill adaptive thread: multistage state estimation. y measurements at each stand; $\hat{\boldsymbol{x}}$ strip state estimate at each stand.

(*a*) *Adaption within each piece*

As each piece progresses through the plant, measurements are received that enable the knowledge of the current state of the piece to be updated, and predictions of its subsequent behaviour to be amended. The errors in the model predictions may come from any of the four sources listed above and the problem is how to use the measurements to best effect in the subsequent processing of the piece. Consider the

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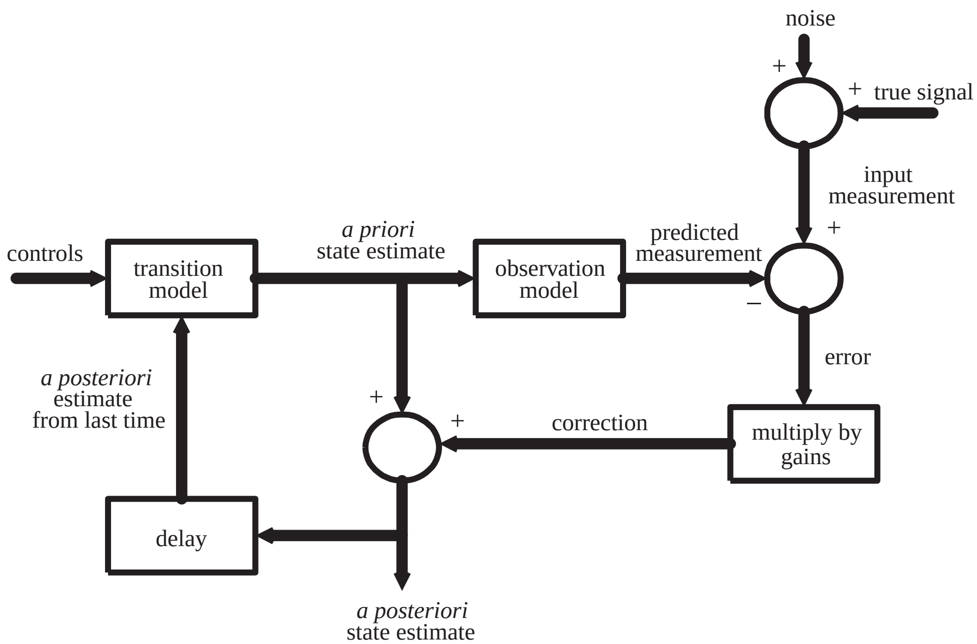

Figure 8. State observer.

case of adaptively threading the FM (Stephens & Randall 1997). As the strip threads the first stand, the errors between the expected and measured strip forces on a stand could arise due to inaccuracies in the force/gap measurements, in the assumed entry gauge/temperature, or in the force model. However, when the second stand threads, the added information allows the probable sources of error to be narrowed down, at least on a statistical basis. Mill threading is a multistage process (figure 7), where, as each stand threads, more information on the state of strip is gathered.

A sequential estimation task such as this is best handled by using a state observer. The well-known Kalman filter is a particular case that gives an optimal (in a least-squares sense) estimate of the current state of the piece (Kalman 1960; Kalman & Bucy 1961).

The 'state' of the observer is a vector of strip variables (thickness, temperature, etc.) and, usually, additional variables that are used to adapt the downstream models. The structure of the observer is illustrated in figure 8. The *a priori* knowledge of the behaviour of the state is held in the *transition model*, which describes how it evolves from stage to stage, and the *observation model*, which describes the way in which the measurement relates to the state. On each entry to the filter, the state is updated by the transition model to give an *a priori* state estimate. As in many least-squares applications, the error between the measurement (measured stand force) and its prediction from the *a priori* state estimate is constructed. This error is then multiplied by a gain vector, and the result added to the state to give the *a posteriori* estimate. The critical component of the observer is the gain vector, which apportions the error among the various elements of the state. The subtlety in the design of the observer is the calculation of this gain vector.

The Kalman filter calculates the optimal gains using an *a priori* assessment of the statistics of expected disturbances in the state and noise in the measurement. The disturbances are assumed Gaussian and, thus, they are completely specified by their mean values and covariance matrices. Using this information and the state transition and observation models, the Kalman filter calculates the evolution of the state covariance from stage to stage. This covariance matrix is then used to calculate the optimal gains.

In the case of FM adaptive thread, as each stand is threaded, the estimate of the strip state is updated using the force measurement. The updated strip state is then used to recalculate the downstream plant settings.

(*b*) *Adaption from piece to piece*

After a coil is rolled and a full set of measurements has been collected, it is important to make the fullest use of them to improve performance on subsequent coils.

Again, the errors in the predictions come from the four sources: material, measurements, models and the mill. Piece-to-piece adaption has to compensate for all these factors, which, again, combine so as to obscure the true position. The most difficult problem in piece-to-piece adaption lies in making the best use of limited measurements so as to apportion observed errors between various possible sources. The problem is clearly stochastic and eased by the fact that the adaptive system is, to a certain extent, working outside real time, in that scanning logic can select and average data over many readings and over several stands prior to carrying out any calculations.

The mill set-up calculation operates so as to predict nominal self-consistent mill variables. For adaption, on the other hand, the system is presented with a collection of measurements that are corrupted with complex noise sources and concealed correlations, so the first task is always that of data reduction: scanning, averaging, filtering, extrapolation, etc. Just as the fundamental physical characteristic of the mill leads to a suitable structure for the mill set-up calculations, so it also dictates the best approach to adaption, particularly for the all-important finishing train.

The first step is to estimate the strip gauges out of the finishing stands. This is done by integrating estimated mass flow through each stand and at the exit thickness gauge. Conservation of mass allows construction of adapted estimates of true roll gaps. From these, the gauge pattern down the mill can be calculated using the mill-spring equation. This gauge pattern is essential to subsequent adaptive operations. The most important adapted models are temperature, force, torque, width, crown and flatness. A great deal of attention has been given to methods of extracting as much information as possible out of the data obtained for each coil.

The key concepts of an approach that has been used with much success (MacAlister & Reeve 1987) are summarized here.

Rather than using simple multipliers and adders, adaption uses linearized recursive regression to identify model coefficients. To avoid the need to hold all previous measurements, and because of the useful properties of the technique, the data-set propagated from coil to coil comprises the *total information matrix*: a set of basic statistics of the observations of dependent and independent variables. In practice, for numerical stability, the 'square root' of the total information matrix is used (Bierman 1977). The operations from coil to coil are well proven and usually abbreviated to SRIF (square root information filtering).

Because regression operates on all previous coils, there is a need for some form of compensation recognizing that, in general, the more recent the observation the more relevant it is to the next coil. This is achieved by means of exponential weighting: a technique that damps down the effect of older observations by multiplying them by a forgetting factor depending on how old they are.

Adaption has to compromise between accuracy and response, the former being concerned with successful attribution of errors to their origins and the latter with the need to attenuate product-quality errors (as opposed to model errors) quickly. For this reason, adaption of any model tends to be layered into short-, medium- and long-term components with forgetting factors being used to set the update rates.

A further factor is safety: where we have a highly parametrized model with many internal correlations, there is a danger that the least-squares fit will move the adaptors into an area which, while plausible for the current product, would cause serious errors on other products. The solution here is to add in to the orthodox least-squares cost function extra terms penalizing movement of adaptors from their safe values (the latter corresponding to operation of the model with pre-set coefficients). This technique is known as *caution*.

A final necessary feature for a modern adaptive system is the retention of data related to specific products or mill regimes over a longer period than is imposed by the forgetting factors. This is especially important where there is any dependency in the model on steel grade. The method adopted requires information matrices to be held on a *category* basis, where a category may be defined, for example, on the basis of grade or product thickness or stand, etc. It is possible to update the information matrices that apply to those categories relevant to the product under current consideration, while combining several information matrices into an overall matrix to be used in update of the adaptors. In this way, separation of mill and strip effects moving at different rates is facilitated.

10. Dynamic control

The HSM contains many dynamic control loops whose purpose is to maintain the correct material properties from head to tail. General concerns are

(i) limitations in instrumentation;

(ii) requirement for thorough modelling, integrated with the set-up calculation; and

(iii) requirement to handle interactions between controlled variables.

To illustrate these points, consider the control of gauge out of the FM (Hicks & MacAlister 1990). Here, we have a good measurement of the controlled variable and a short (*ca.* 0.5 s) transport delay between the last stand and the exit thickness gauge. However, correcting all the errors in the last stand would quickly result in stand limits being reached and serious flatness errors. So the correction must be distributed to several stands. This task immediately gives rise to two problems: the transport delay becomes significant (typically 11 s from the first stand to the gauge), and the system needs to know the sensitivity of gap to gauge (inaccurate modelling of which may have given rise to the measured error in the first place).

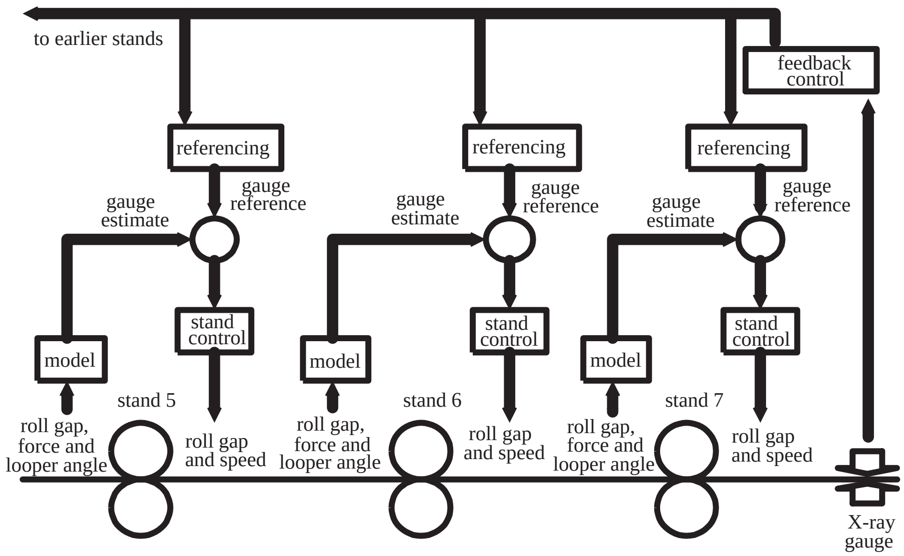

Figure 9. Dynamic stand controllers with exit gauge feedback.

It is, therefore, desirable to make use of any available intermediate information, as this reduces the effects of both transport delay and model error. Fortunately, at each stand there is usually an accurate measurement of force and, by means of the mill-stretch model introduced above, it is possible to form a reasonable estimate of exit gauge from each stand and to control exit gauge by adjustments to the roll gaps. Such an arrangement is shown in figure 9, which also shows the additional information given by looper angle changes and the additional control given by stand speeds. The loopers are mechanisms to maintain the tension in the strip between stands during rolling and, at the same time, to provide a small amount of strip length storage. A looper is a pivoted arm that is held against the strip by electric or hydraulic power. The motor torque applied is controlled to maintain the required tension stress in the strip. The angle of the looper arm is a measure of the length of strip between the stands and is used to control the roll speeds of the stands to maintain a constant length of strip between the stands. The stand controllers operate so as to hold gauge at reference values that are set by the exit thickness gauge feedback, taking into account the need for dynamic load redistribution for maintenance of crown and flatness.

Control of gauge via the mill-spring model has complications. Consider a cold section and consequent thick material passing through the stand. This is detected by the increased force and corrected by a downward (i.e. negative) movement in the roll gap, which causes a further increase in force: a positive feedback effect. A good dynamic controller will give a zero gauge error where the total downward roll gap movement is balanced by the total additional mill stretch arising from the roll force. Depending on its polarity, a significant error in the mill-stretch model could cause inadequate attenuation of gauge errors or a disastrous runaway effect in the roll gaps. The mill-stretch model is therefore very complex, taking into account not just the basic elastic deformation of the mill components in the vertical direction, but also the tendency of the rolls to bend round the strip.

The basic stand controllers described above are totally feedback. Even with fast hydraulic roll gap actuators, the bandwidth is limited and there is a need to add feedforward components. The basic feedforward controller takes the estimated gauge error out of each stand and stores it in a delay line ready to be used for control at the next stand. This requires sensitivity of stand exit gauge to stand entry gauge and, as the sensitivities have inaccuracies of their own, there is a typical control-system trade-off of precision versus response. Feedforward control is usually enhanced to become adaptive: model outputs for segments of strip are cascaded from stand to stand via the delay lines and used to estimate strip gauge and hardness for use in downstream stand controllers. Similarly, the feedback loop from the exit thickness gauge becomes an adaptive feedback loop, in which the final measurement for each segment is used to estimate stand model errors.

Despite this sophistication, the rolling process can always provide further intricacies. Most problematical is the phase change from austenitic to ferritic, which can occur in the FM when rolling steel of certain compositions or temperatures. In a dual phase region, the sensitivity of roll force to temperature may change sign so that colder material softens. The basic stand controllers, which rely more on the mill-stretch model than the roll-force model, operate correctly within their own limitations but can have difficulty in tracking quickly changing entry disturbances and can, by affecting the crystalline structure, create additional difficulties for the downstream stand. The feedforward controllers can become very confused, as a force ramp in the early part of the mill might change polarity in a later part. Although on-line models of dynamic recrystallization have had some success, it is in the area of material structure that current metallurgical models are most deficient. The ability to take theoretical and laboratory results and apply them to real mills is a prospect that must be approached methodically and in verifiable stages.

This discussion has taken gauge control as a typical example. To give some idea of the additional complexity involved, it should be mentioned that, typically, an FM contains additional dynamic controllers adjusting roll-bending jacks to maintain crown and flatness, adjusting tension to maintain width, and adjusting interstand water sprays to control temperature (e.g. MacAlister *et al*. 1998). Temperature affects the roll force, which affects gauge. Gauge affects the tension through mass flow, and tension feeds back into roll force. Width is affected by both temperature and tension. Control of such multivariable interactive systems is a continual development area within the discipline of control engineering.

11. Control and internal states

The internal state of the strip encompasses such attributes as material phase and crystalline structure that combine, on a microscale, to yield the macro thermomechanical properties desired for the finished coil or necessary for the processing of the coil in the mill.

The direct on-line control of the internal state of the steel strip is in its infancy. However, implicit and indirect control of internal state is a part of current control practice. The empirical form of yield stress models can now take into account the effects of strain history and recrystallization times, etc. Their application to control was mentioned above.

An area where the control of the internal state of the steel is paramount is the ROTs (Lawrence *et al*. 1996). The cooling regime that the strip is subject to determines the final microstructure and, hence, the macromechanical properties. However, this control is currently achieved indirectly by specifying the temperature trajectories that the strips must follow, and these are, in turn, determined by off-line test and calculation. Steel producers are demanding more of their strip cooling so as to get better control over the final strip properties. The requirements are now so strict that it is desirable to explicitly model the phase transformations and their effect on temperature in the ROT cooling model. It is of interest to look at this model in a little more detail.

For simplicity, only the single dimension of the strip from top to bottom and the one phase transition from, say, austenite to ferrite will be considered. The temperature distribution through the strip can be modelled by the one-dimensional diffusion equation,

$$\rho \cdot C(T(t,x))\frac{\partial T(t,x)}{\partial t} = \frac{\partial}{\partial x}\left(K(T(t,x))\frac{\partial T(t,x)}{\partial x}\right) + q_{\text{phase}}\frac{\partial P(t,x)}{\partial t},$$

where ρ, C and K are the density, specific heat and conductivity of the strip; $T(t,x)$ is the strip temperature at time t and position x; P is the proportion of material which has transformed from austenite, and q_{phase} is the heat per unit volume released as the material transforms.

So the temperature evolution of the strip, in addition to being determined by the boundary conditions at the top and bottom of the strip, is affected by the liberation of heat by the phase transition. To complete the model, the evolution of the material phase in the strip must be described. The following model can be used,

$$\frac{\partial P(t,x)}{\partial t} = \lambda\left(\frac{\partial T(t,x)}{\partial t}, T(t,x)\right)(1 - P(t,x)),$$

where λ is a rate parameter depending on the temperature and rate of change of temperature of the strip.

The added detail in the cooling model on the ROT comes at a cost. The additional model parameters q_{phase} and λ have to be determined. The heat released during the phase transition can be derived from the steady-state specific heat curves where they are available, but the rate parameter is more problematic. One method is to derive it empirically from dilatometry tests (Too 1993).

Even this relatively small change to the ROT cooling model has brought with it a need to determine additional material parameters that in the past could be ignored. As internal state models are developed further, so the need for more and more detailed material parameters will grow.

Developments in phase and microstructure modelling, such as the example above, are undoubtedly going to affect on-line control. The most immediate applications are likely to be their off-line use to refine the current and to produce new production rules that the on-line control system will have to apply. An interesting aside is to ask the question: can the models be used off-line to generate rules that make attaining the strip quality less sensitive to its processing? This could allow advanced on-line models and control to reduce the need for ever more expensive control equipment and measuring instruments.

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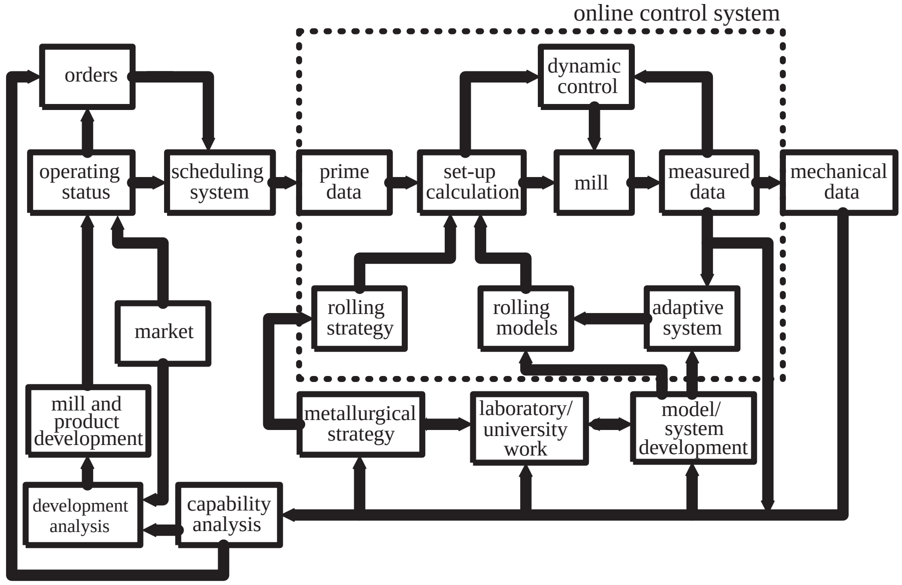

Figure 10. Rolling mill operations.

When will explicit non-simplistic internal state/microstructure models be widely used on-line? History suggests that their successful use on-line will await the development of instruments that measure directly or indirectly some of the desired states. Meanwhile, most of the internal state 'control' loops are likely to be closed via laboratory measurement and off-line refinement of the processing rules that the on-line control system must adhere to.

12. The control system in context

As we have seen, the control system uses rolling models to control the process with model/state refinement using a limited set of instrumentation over a limited time period. This arrangement is shown in the central block of figure 10. However, modelling and control of rolling mills have deeper associations which must address:

(i) ultimate material properties (not measured on-line);

(ii) laboratory experiments;

(iii) university research;

(iv) changing market requirements;

(v) enhancement of the mill;

(vi) extension of the product range; and

(vii) improvement of product quality.

Figure 10 gives an overview of key factors. Firstly, it should be noted that samples of rolled material are frequently collected and subjected to testing for mechanical properties (tensile strength, hardness, surface finish, etc.). The tests may result in direct intervention into the rolling process, but are more generally used as a longer-term check on product quality. A typical example is cold tensile stress, which is primarily controlled by the rate of cooling along the run-out tables. Since the transport time is different for different segments of strip, identical rates are not possible from head to tail, and a metallurgical strategy capable of compromise is required. The compromise is introduced into the on-line system by means of sacrifice rules embedded in the rolling strategy.

The set of historical logged data, typically 1.2 Mb per coil, is used for developing the basic models, set-up strategies and adaptive techniques. Data-sets of the order of 100 000 coils are used to regress nonlinear models based on current physical knowledge. Black-box techniques, such as neuro-fuzzy modelling, are used over a smaller data-set (say 10 000 coils) to refine the coefficients of the physical models.

In laboratories, it is possible to set up experiments in which metal is precisely deformed by defined amounts and at defined rates and temperatures. Such experiments on uniform material with well-instrumented test rigs can give insight into on-line control problems but must be used with care: real mill operations are less well instrumented, the material is inhomogenous and the plant subject to mechanical and thermal inaccuracies. Historical logged data are used as part of the definition, and verification procedures for laboratory work and the partnership between automation engineers, metal rollers and universities is, to a reasonable degree, mutually beneficial.

A final aspect of modelling and control to consider is the link with current and potential capabilities. At any given time, the mill has a certain operational status that sets the range (specification and tolerance) of orders that can be accepted and the constraints on scheduling the mill required to satisfy the order intake. Knowledge of the mill allows an analysis of mill capability with some degree of extrapolation beyond historical rolling practice. Because capabilities are accurately known, safety factors can be reduced and the mill becomes a more powerful production tool. The possibilities are even greater in that analysis based on theory, laboratory results and measured mill data allows future developments to be evaluated. Such developments can range in complexity from the decision to roll a new grade of material to the decision to build a new mill. At all times, the market exerts pressure on rollers to use the current process to its maximum capability and to develop the process in line with advancing technology and aggressive competition.

13. Conclusion

Automation of rolling mills is an important and vibrant activity that reaches into every aspect of mill operation and links together a number of academic and commercial disciplines. The role of automation has been well established for a number of years and is likely to expand for many years to come.

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