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Plate Thickness Control of Hot Rolling Mills

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November 1993

Plate Thickness Control of Hot Rolling Mills

Literature review

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Abstract

This report is a literature review of articles, and reports collected in connection with the research project "Improvement of roll gap control system". The articles should be seen as a broad collection of all the articles about thickness control of steel plates. The main purpose of the review is to give an impression of the state of the art of thickness control of rolling mills. This is done by giving a summary of the contents of each article. In the last part of the report interesting articles, authors and publications are described together with the state of the art of thickness control today. To give newcomers to the field a chance to get a grip of the contents of the summaries of the articles, a review of the main problems of thickness control of hot plate mills is also given.

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Preface

This literature review has been made during the fall of 1993 in connection with the research project "Improvement of Roll Gap Control System". It contains a review of about 80 articles relevant for the plate thickness control problem. The report is primarily directed towards control engineers with interest in the hot rolling process.

The work has been supported financially by The Danish Steelworks Inc., where I am employed, and the The Nordic Fund for Technology and Industrial Development in connection with my Industrial Research Education. The work has mainly been done at the Department of Automatic Control at Lund Institute of Technology, Sweden. I want to thank my colleagues in Lund, Karl Henrik Johansson and Johan Nilsson, and my advisor Björn Wittenmark for their valuable comments on this manuscript.

LARS MALCOLM PEDERSEN

1. Introduction

This report is a literature review of articles, and reports collected in connection with the research project "Improvement of roll gap control system". The subject of the project is improvement of the thickness tolerances of the plates rolled by the plate mill at The Danish Steelworks Ltd. (DDS) in Frederiksværk, Denmark. The improvement of the thickness accuracy shall be obtained by designing a better controller for the process.

There are many ways to roll flat products, and the articles collected are related to thickness control of many other kinds of mills than just plate mills. These articles are included in the review, since conversion of a method from one kind of rolling to another may be a way to obtain improved thickness tolerances.

The articles have been collected during the last few years, come from many different publications, and are written by many different authors. The articles should therefore be seen as a broad collection of all the articles about thickness control of steel plates. This review gives an overview over what has happened, and what is happening in the field. Thus it is not a detailed description of one narrow area.

The main purpose of the review is to give an impression of the state of the art of thickness control of rolling mills. Naturally this description is concentrating on methods which could be used in plate rolling. The emphasis is therefore put on the basic ideas, and how they are accomplished. Since the improvement of thickness control at DDS should be accomplished using control theory, and the author of this report is a control engineer, the main weight has been put on this subject. Therefore very complicated articles on other subjects have only been skimmed. It is also interesting to note what has not been considered in the articles. It is of course here new work should be done.

Other things of interest are what has been done by who, and which theory, and methods have been used for solving the thickness control problem. This is summerized together with the state of the art of thickness control today in the last part of this report.

To give newcomers to the field a chance to get a grip of the contents of the summaries of the articles, a brief review of the main problems of thickness control of hot plate mills is given.

With the above in mind, the contents of this report are:

- Description of thickness control problem
- Summaries of articles
- Interesting articles, authors, and publications
- State of the art in thickness control
- Applied theory
- Conclusion

The summaries of the articles are divided in modeling, design, and implementation.

2. Thickness control of hot rolling mills

To give some background to the thickness control problem a general introduction to hot rolling is given. In the following the rolling mill is described. First the hydraulic positioning equipment used for the thickness control is described. After this the various factors affecting the thickness of the plate are commented, and the problem of estimating the plate thickness is treated. The necessary signals for estimating the thickness are determined, and measurement problems are described. Hereafter the material behavior is treated, this is combined with the mill behavior, and the equilibrium conditions for the roll gap are determined. The equations obtained in this connection are used for determining the stability of the thickness control system.

2.1 The rolling mill

There are many specific types of rolling of flat products. The most common ones are:

- Hot plate rolling. The thickness of a preheated slab [1] is reduced in a reversing single stand rolling mill. Used for thick heavy plates (5 – 100 mm).
- Hot strip rolling. A preheated slab is first reduced to about 40 mm in a roughing mill with one or more stands, the plate is hereafter passed one time through the strip mill, which consists of 5 – 8 stands. Used for thinner products than the plate mill (1 mm – 10 mm).
- Cold rolling, single stand. Used for rolling of cold coiled plates. The thickness of the finished products is between 0.1 – 3 mm.
- Cold strip rolling. Used for cold coiled plates. Consists of several stands. Same thickness interval as above.

The basic problem, to reduce the thickness of a steel block or plate by passing it through two parallel rolls, is in all cases the same. Therefore the basic physics of all kinds of rolling of flat products are the same. Many of the measurement problems are also the same. In hot rolling the temperature variation is larger, and therefore has greater importance for the process than in cold rolling. The material behavior is also different. Furthermore, the stands in the strip mills interact with each other, the main problem being that there is a force acting on the plate in the longitudinal direction (tension). Since the project is considering thickness control in hot plate rolling the following description is concentrating on treating this problem in detail.

Most plate mills are a four high mills (four rolls) equipped with a hydraulic roll positioning systems, see figure 2.1. The main problem is to make the plate thinner, and longer by pulling it through the gap between the two parallel work rolls. The backup rolls are used to support the work rolls in order to reduce the roll bending due to the large forces obtained during the rolling. The rolling mill itself is used as a frame for placing the rolls in. Again, due to the large forces, it is a rather solid construction. Many of them have originally been constructed without the hydraulic equipment, which has been added during the seventies, and eighties.

1 Steel block.

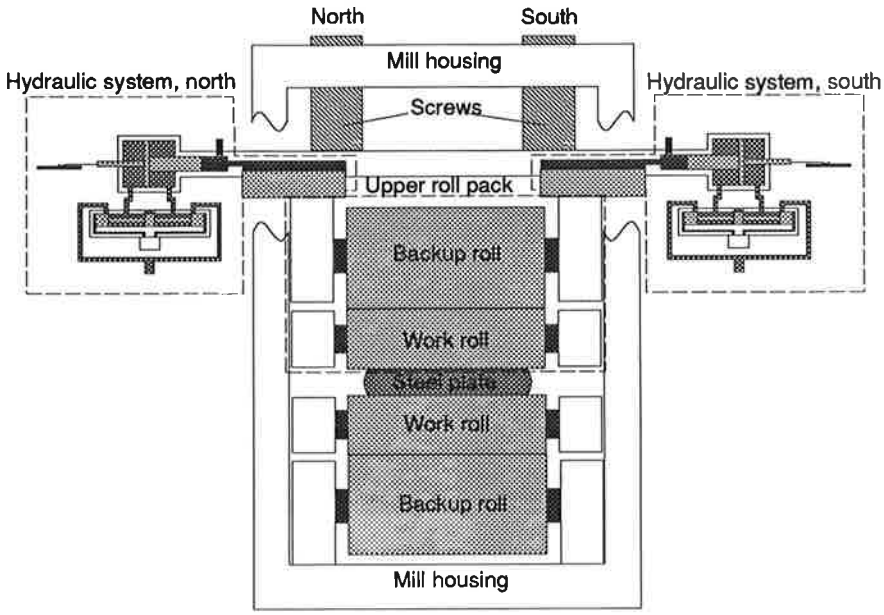

Figure 2.1 Sketch of hot plate mill

The main action in connection with the control of the plate thickness is the adjustment of the roll gap. This is done by varying the position of the upper roll pack. The screws are used to make the large adjustments, and can only be used for positioning when there is no plate in the mill. The hydraulic equipment can be used for adjusting the roll gap both with, and without a plate in the mill. The thickness control system is usually called the Automatic Gauge Control or simply AGC.

The thickness control is done by adjusting the roll gap during rolling. The hydraulic roll gap positioning equipment is therefore the actuator of the thickness controller. A close up view of the hydraulic system is shown in figure 2.2. As shown in this figure the hydraulic system constist of two sides: an oil side, and a grease side. These two sides are connected by a common piston with a large area on the oil side, and a small area on the grease side. Therefore it works as a mechanical amplifier increasing the pressure from the oil side to the grease side. The main measurements are the measurement of the position of the common piston and the measurement of the pressure on the grease side (which is used as a rolling force measurement). The specific configuration of the hydraulic system varies a bit, some systems has no increase of the pressure through the system. Also some uses load cells placed in the rolling mill to measure the rolling force.

The thickness control is done by determining the plate thickness in one way or another, and then change the vertical height of the roll gap to obtain the desired thickness. Thickness control of steel plates is a central problem in rolling. One important reason is that the thickness can not be changed after the rolling, the width, and length can at least be decreased. The rolling process might seem simple, but the process is very hard to describe and model analytically, and the behavior of the process is time-varying and nonlinear, especially for hot rolling where the temperature varies. Therefore The problem of mathematical modeling still gets much attention, since accurate models are not yet obtained . The finite element technique is often used in this connection.

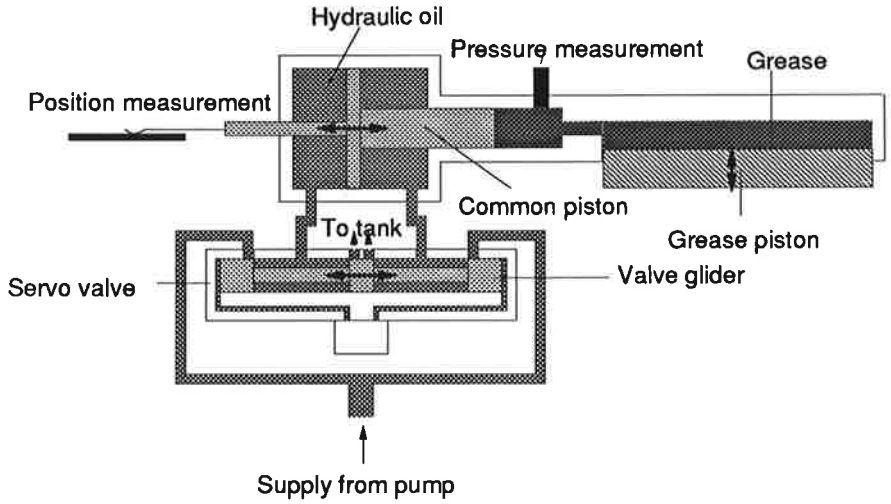

Figure 2.2 Close up of hydraulic system with sensors

Another basic problem of thickness control in hot rolling is that the thickness is hard to measure during the rolling. This is due to the hot, and wet environment (the oxidized surfaces of the plate are cleaned with water under high pressure), and the physical construction of the process. Instead it is often chosen to estimate the plate thickness during rolling. The estimator is corrected using thickness measurements made after the rolling. The estimation of the thickness is obstructed by mechanical imperfections of the rolling mill.

Generally the thickness estimation has received most attention in the literature about the thickness control of rolling mills. The estimation of the thickness, and the imperfections of the rolling mill are well investigated, and described.

Three things affect the thickness of the steel plate during rolling. These are the roll position, the elastic deformation of the rolling mill, and variation of the shape of the rolls. These effects include:

- Changes in position of work rolls relative to the mill frame.
  - Roll gap setting (screws, and hydraulic equipment). The position of the upper work roll can be changed by the roll gap positioning equipment. The effects are illustrated in figure 2.3.
  - Backlash in positioning system. This introduces an upward movement of the upper roll pack when the rolling force is increased, that is when a plate enters the mill. A roll balancing system applies enough force in order for the upper roll pack to seem weightless for the positioning system. This tends to keep the backlash in the positioning system at a minimum.
  - Speed effect. This is the change of backup roll position when the speed of the rolls is changed. This is due to the changed thickness of the oil film in the bearings due to the variations in centripetal forces. If roller bearings are used the oil film thickness is not importance to the roll gap position. Note that the the work roll bearing house is not supported in the vertical direction. This implies that the work roll is hanging between the backup roll , and the plate, and therefore speed effect for the work rolls does not affect the plate thickness.
- Elastic deformation of rolling mill parts. Due to the large forces obtained during rolling the elastic deformation of the rolling mill is of the same

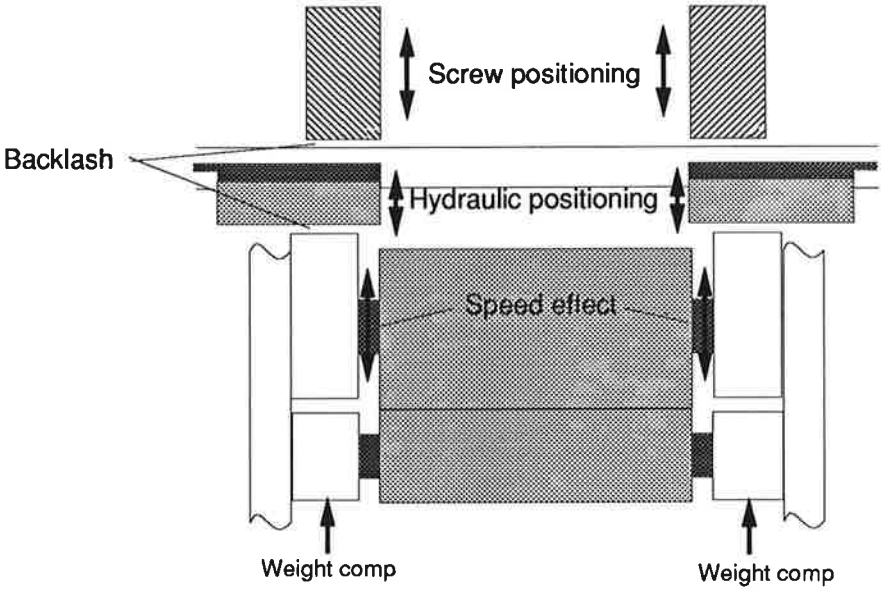

Figure 2.3 Illustration of position variations

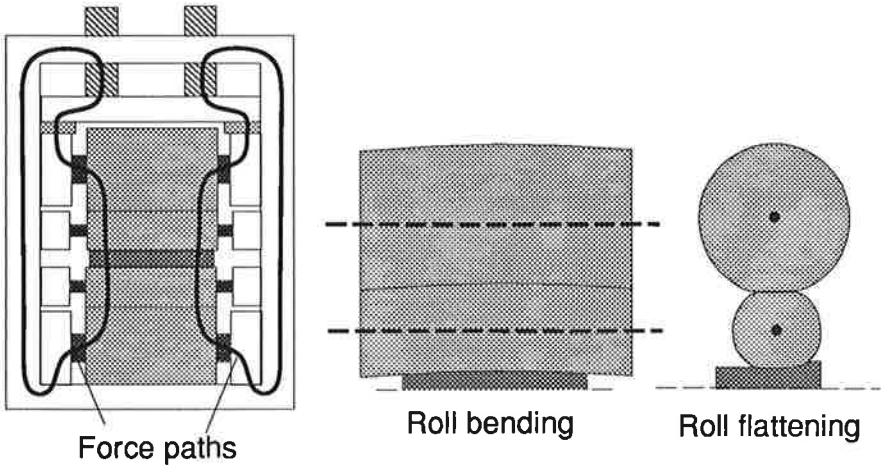

Figure 2.4 Illustration of behavior of rolling mill when exposed to rolling forces

order of magnitude as the plate thickness. The main effects in this connection are illustrated in figure 2.4.

- Elastic deformation of mill housing, and rolls. The mill housing or frame, the screws, and the bearings are stretched or compressed when exposed to the rolling force. The forces acting on the various components can be illustrated by the force paths shown in figure 2.4.
- Roll bending. Both the work, and backup rolls are bended around the plate.
- Roll flattening. The shapes of both the work, and backup rolls are changed. They are flattened at the contact areas.

- Changes, and imperfections in roll diameter, and shape. The shape and diameters of the rolls can vary due to other reasons than the rolling force. The effects are illustrated in figure 2.5.
  - The rolls are ground regularly, and due to the nature of this process the rolls are normal circular. The center of the circular shape of the

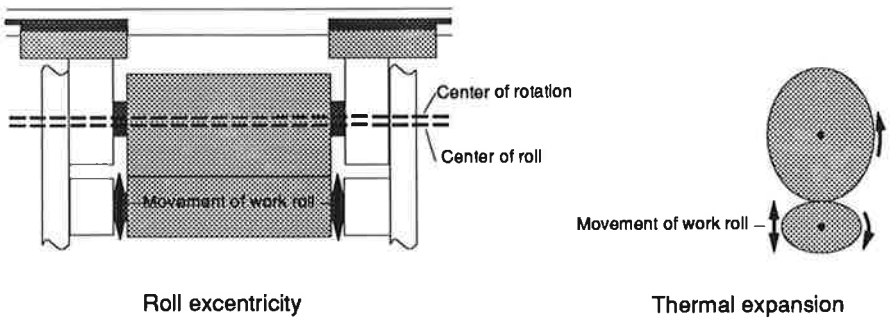

Figure 2.5 Effects of imperfections of the rolls

rolls need though not be the same as the center of rotation. Since the work roll is hanging between the plate, and the backup roll, only the backup roll eccentricity has importance.

- Thermal expansion. Due to the heat transfer from the hot slab to the rolls, the temperature of the rolls varies considerably with time. The rolls expand with increasing temperature. Since the heating need not to be uniform, the thermal expansion can affect both diameter, and shape.

The above effects can be divided in those varying much during a single pass, and those varying little. Typical short term effects are:

- Elastic deflection of mill due to the rolling force
- Roll gap changes due to imperfections in roll shape
- Roll gap changes due to speed effect

These things has to be handled during the pass, and are therefore taken care of by the thickness control system. The rest is handled by the computer planning the pass schedules. These effects will not be investigated further in this treatment of the thickness control problem.

2.2 The thickness control

Before servo valves which are able to handle high pressure were invented, the mill spring was reduced by prestressing the mill with a force from the top, and the bottom of the mill housing to counteract the elastic deformation due to the rolling force. This was also done using a hydraulic system. AGC control was also implemented using powerful electro-mechanical screws. The improvement of servo valves has made it possible to use hydraulic equipment for thickness control. The use of the hydraulic systems has decreased the response time of the roll positioning system considerably (about a factor 10).

The plate thickness is usually defined to be the average thickness of the plate about 10 cm from the edges. The thickness between this point, and the edge is not well defined due to material flow in the sidewise direction. Usually the material can be assumed to be rigid plastic, which results in that the plate thickness is equal to the roll gap. Assuming symmetry around the vertical center axis of the rolling mill, and neglecting dynamical effects makes it possible to reduce the mill deflection, and hereby the plate thickness to a scalar equation:

$$h(s, f, w) = s + d(f, w) \tag{2.1}$$

where h is the exit thickness, w the plate width, f is the rolling force, s the roll gap without a plate in the mill (unloaded roll gap), and d is the mill spring as a function of plate width, and rolling force. d is width dependent due to the dependence of the roll deflection of the width. The mill spring is a nonlinear increasing function of the rolling force. The nonlinear relation between force, and elastic deformation is dominating for low forces. This is due to badly fitted mill elements which first are pushed together until the force reaches a certain level. The limit between backlash, and mill spring is therefore somewhat floating, usually the backlash is included in the mill spring when it is modeled.

Without thickness control the mill spring cancels some of the effects of imperfect roll shape on the plate thickness. When the roll gap becomes smaller due to these imperfections the rolling force increases and the mill spring increases, and vice versa. The cancellation of the mill spring by using AGC control cause these imperfections to be imprinted directly in the plate thickness. Therefore the roll eccentricity has to be handled in order to obtain a proper thickness control. This can be done in four different ways:

- Using notch filters to cancel the critical frequencies in the rolling force used for the thickness control. This prevents the AGC to compensate for the mill spring at the frequencies excited by the roll eccentricity.
- Introduction of dead zones to prevent the thickness control to react to the force variations due to the roll eccentricity.
- To use force control where the the roll gap position is controlled to obtain a constant rolling force when the force is within specified bounds. This cancels the variations in the changes in roll gap due to roll eccentricity.
- Estimation of the real roll shape, and using this information in the thickness estimation.

The first three methods has been used for a long time while the last has been developed, and implemented recently.

The compensation for the speed effect is normally done using an empirically obtained curve for the change of the roll gap due to roll speed changes. This information is again used by the thickness estimator.

Another problem in the roll gap control is if the rolling force is different in the two sides of the rolling mill. This happens if the plate is not in the middle of the roll gap or if the temperature is inhomogeneous. The mill spring is then different in the two sides, and because of this the plate thicknesses in the two sides are also different. This implies that the thickness reductions of the two sides of the plate are not equal, and different elongation of the sides will therefore be obtained. Thus the plate will be curved in the longitudinal direction.

Interaction with pass scheduling computer

The rolling force of the next pass is predicted by the computer calculating the pass schedules. From this the mill spring, and the mill spring constant can be estimated. The AGC decreases the roll gap with the estimated mill spring, and uses the spring constant for the mill spring compensation. Generally the AGC can operate in two modes; relative, and absolute control. In relative mode the AGC locks on the thickness obtained when steady state is obtained, and holds this thickness constant. This implies that the plate will have constant

thickness. But if the working point deviates from the one calculated by the computer, the thickness of the plate will be wrong. In absolute mode the thickness control system tries to obtain the specified plate thickness. Generally absolute control is used in the last passes in order to obtain correct mean thickness.

The plate is only elongated in the length direction during rolling. Therefore the desired plate width is obtained by first rolling the plate in the direction perpendicular to the length direction. When the length of the plate is equal to the desired plate width the plate is turned 90°, and the length rolling is started. This is also handled by the pass scheduling computer.

Measurements

The thickness controller should be able to handle the above mentioned variations of the roll gap during rolling. By using the following variables as inputs to the thickness control system it is possible to handle these variations:

- Measured rolling force
- Measured position of upper roll pack relative to mill frame
- Speed of the backup rolls (this can be measured or estimated from the work roll speed)

Normally the measurement of the roll speed causes little trouble. The measurement of roll position, and rolling force are more critical, and have therefore gained more attention.

The main idea is of course that the force measured should be as close as possible to the rolling force applied to the work roll. The problem with the harsh environment makes it necessary to place the force measurement some distance away from the roll gap. This implies that there is some mechanical equipment between the place where the rolling force is applied, and where it is measured. By looking at the force paths in figure 2.4, the mechanical equivalent diagram shown in figure 2.6 can be constructed [2]. The roll pack is assumed to be massless, and the mill housing are assumed to be inflexible. In this figure F_r is the rolling force applied at the work roll, F_p is the measured force in the hydraulic system, x_r is the position of the work rolls, x_p is the position of the piston in the hydraulic system, d_c is the coulomb friction coefficient, d_v is the coefficient of the viscous friction, k_r is the spring coefficient of the equipment between the roll pack, and the force measurement, and k_s is the spring coefficient of the screws.

As shown in figure 2.6 the relationship between F_r, and F_p is dynamical, but this causes seldom trouble. The problem is the nonlinearity due to the static friction. It can be quite large, and results in a constant offset between the real, and the measured rolling force.

The position of the roll pack is measured in the hydraulic cylinder and therefore the deflection of the positioning system is included in the mill spring. One thing that can cause trouble is backlash in the positioning system, the problem can be handled in several different ways. One way is to always make the final adjustment of the screw position downwards in order to keep the positioning

2 Note that the diagram is turned upside down compared to the original system.

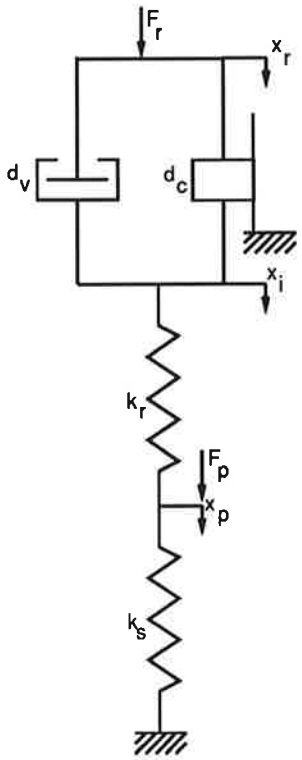

Figure 2.6 Mechanical equivalent of roll pack

system compressed. The backlash has only importance when the plate enters the mill, hereafter the positioning system is compressed by the rolling force. It has therefore little importance for the hydraulic control equipment during pass. The initial backlash is included in the mill spring curve, as mentioned above.

2.3 The steel plate

The material behavior during rolling is even more complex than the behavior of the rolling mill. In addition to this not only the thickness profile is affected by the thickness control. Also the flatness of the plate is affected when the roll gap is changed. If the shape of the roll gap is not appropriate the plate will get waves in the length direction. This also has to be considered in connection with the thickness control. One way of controlling the plate profile is to use backup roll bending. This is a hydraulic system which is able to bend the backup rolls. In this way the profile of the roll gap can be varied independently of rolling force, and plate width. Roll crossing, and roll shifting can also be used for this purpose.

Three things are of importance in connection with the thickness control. These are the plate shape in the width direction, the flatness of the plate and the plates reaction when rolled. This include:

- Shape. This is the cross profile in the width direction, also called the thickness profile. It is affected by the following factors
  - Width boarding. Due to the high pressure some of the material flow in the sidewise direction.

- Transversal shape of work rolls. The thickness profile is formed by the shape of the work rolls, see figure 2.4

- Flatness. In order to meet the costumers demands, waves in the length direction should be reduced to a minimum. The factors affecting the flatness are:
  - The profile of the plate, which is also called plate crown. In order to obtain a good shape of the plate the relative crown (the difference between the thickness at the center, and the edges divided by the thickness at the edges) of the plate should be kept constant.
  - The shape of the roll gap. This affects the crown of the plate , and therefore determines the plate shape.
- When the plate is rolled it applies a pressure profile to the work rolls, integrated over the area of contact this gives the rolling force. The magnitude, and shape of this profile is dependent on:
  - The thickness reduction (the ratio of the ingoing the outgoing thickness). The more the plate is reduced the higher rolling force is obtained.
  - The hardness of the material also affects the rolling force. The harder the material, and the lower the temperature the higher rolling force. The temperature varies with the plate length, and width. These temperature variations are due to nonhomogeneous cooling of the plate or cold areas from the furnaces, these cold zones of the plates are known as skid marks.
  - The rolling speed also affects the rolling force, the higher speed the higher rolling force.

Again, defining the thickness as the mean value of the thickness in two points with the same distance to the vertical axis of symmetry, and assuming symmetry around this axis the model can be reduced to a scalar equation. If the dynamics furthermore are neglects the model then is:

$$f = f(H, h, \rho, T, v) \tag{2.2}$$

where f is the rolling force, H is the ingoing thickness, h is the outgoing thickness, ρ is a constant defining the material hardness, T is the plate temperature, and v is the rolling speed.

The counter reaction of the plate when the reduction is increased is to increase the rolling force. A general problem in the thickness control is that when the force increases, the mill spring becomes larger making it necessary to decrease the roll gap which makes the force increase etc. This positive feedback has crucial influence on the closed loop stability of the thickness control.

2.4 Equilibrium between plate and mill

The plate thickness is the result of an equilibrium between the height of the roll gap, and the counterreacting force applied by the plate. An approximate analytical description of this can be found by linearizing the expressions for mill spring, and rolling force.

The nonlinear equations 2.1, and 2.2 for the force, and the plate thickness is linearized around the working points f_0, and h_0, assuming that all other

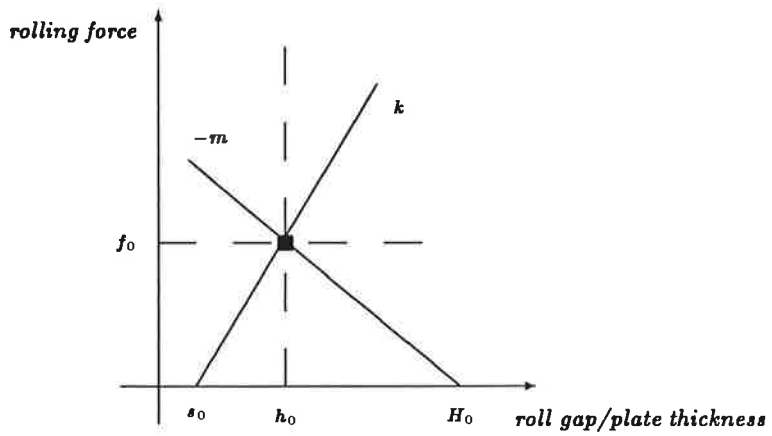

Figure 2.7 Illustration of equilibrium

factors except roll position, and ingoing thickness are constant. Assuming that the force is only dependent of the difference $(H - h)$ the following equations can then be derived using a first order Taylor expansion.

$$\begin{aligned} f(H-h) &\approx f_0 + \frac{\partial f}{\partial h}(H_0, h_0)(h - h_0) + \frac{\partial f}{\partial H}(H_0, h_0)(H - H_0) \\ &= f_0 - m(h - h_0) + m(H - H_0) \end{aligned}$$

$$\begin{aligned} h(s, f) &\approx h_0 + (s - s_0) + \frac{\partial d}{\partial f}(f_0)(f - f_0) \\ &= h_0 + (s - s_0) + \frac{1}{k}(f - f_0) \end{aligned}$$

where s_0, f_0, H_0, and h_0 are working points for the roll position, the rolling force, the ingoing plate thickness, and the outgoing plate thickness. k, and m are positive real constants. This can be rewritten as:

$$\Delta f = -m\Delta h + m\Delta H \tag{2.3}$$

$$\Delta h = \Delta s + \frac{1}{k}\Delta f \tag{2.4}$$

where $\Delta f = (f - f_0)$, $\Delta h = (h - h_0)$, $\Delta H = (H - H_0)$, and, $\Delta s = (s - s_0)$.

Assuming that the above functions are linear the above equations can be illustrated as shown in figure 2.7. The graph has the plate thickness, and roll position on the ordinate axis, and the rolling force on the abscissa axis. The change in outgoing thickness, and rolling force when the roll position is decreased is illustrated in figure 2.8. As shown in this figure the plate thickness is decreased, and that the rolling force increases. This results in a larger mill spring making the change in plate thickness smaller than the change in position. The effect of a change in ingoing thickness can be analyzed in a similar way.

2.5 Stability of the thickness control

The relationship between change in roll position, and change in rolling force,

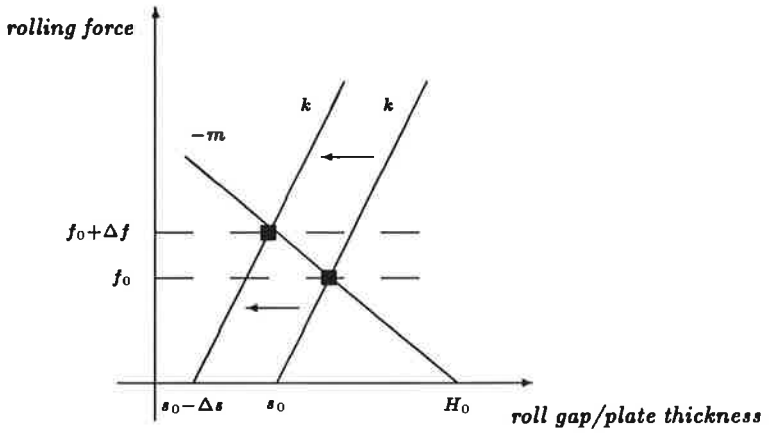

Figure 2.8 Result of a change in roll position

and can be derived from equations 2.4, and 2.3.

$$\Delta f = -\frac{km}{k+m}\Delta s + \frac{km}{k+m}\Delta H$$

If it is assumed that the thickness control only includes compensation for mill spring the control system can be represented as:

$$\Delta s = -\frac{1}{\tilde{k}}G(s)\Delta f$$

where $\tilde{k}$ is the estimated mill spring coefficient, and $G(s)$ is the dynamics of the positioning system with a dc-gain of 1, and a phase shift of 0° in order to ensure proper steady state operation of the system. Finding the closed loop transfer function from ΔH to Δs yields:

$$\Delta s = \frac{-\frac{k}{\tilde{k}}\frac{m}{m+k}G(s)}{1-\frac{k}{\tilde{k}}\frac{m}{m+k}G(s)}\Delta H$$

From the above it can be seen that changes in the hardness of the plate causes changes in the dynamics of the control loop, while variations in ingoing thickness introduce an additive disturbance. The minus sign in the denominator is due to the positive feedback. When the plate is hard, m will be large compared to k, and the term $m/(k+m)$ will be close to one. The characteristic equation for the closed loop hereby becomes:

$$1-\frac{k}{\tilde{k}}G(s) = 0$$

because of the positive feedback the critical phase shift is 0° which will be the case around dc. Since $G(s)$ has dc gain 1 it is important to ensure that the factor $k/\tilde{k}$ is below 1. Therefore the mill spring compensation for the thickness control is reduced, it is usually around of 80 %. This stability problem has obtained a lot of attention in the literature, and of course better thickness control can be obtained if the percentage of mill spring compensation is increased.

From the above it is seen that the better the mill spring constant is known the more accurate it is possible to do the thickness control. Therefore the plate thickness calculation is usually updated using a thickness measurement made after the rolling is finished. The principle of using the rolling mill as a measurement device is called the "gaugemeter principle".

The thickness control amplifies the variations in rolling force. A problem of this is that it changes the shape of the roll gap, and therefore the relative crown of the plate is changed. This affects the flatness of the plates, if the relative crown is changed too much. The thickness control should therefore be used with care if the rolling force is too far from the aimed value.

3. Summaries of articles

In this section the contents of the articles included in this literature review are summarized. The summaries of the articles are partitioned after main subject. The articles covering several areas are grouped after the main subject.

3.1 Modeling, and estimation

3.1.1 Mechanical behavior

General

A general treatment of the mechanical behavior of the rolling mill relevant for the thickness control is given in [Teoh *et al.*, 1984]. The topics covered are the roll eccentricity, hysteresis in the force measurement due to static friction, and how to cope with the variation of the material hardness. Furthermore a systematic design approach for the thickness control problem is stated. In this approach, the control action is based on the estimated roll eccentricity, the estimated mill spring, and the downstream measurements of the thickness measurement device. The controller used is of PI type where the gain is changed due to the material properties. The roll eccentricity is estimated from the variations in rolling force, and the thickness measurement. The estimates are stored in a ring buffer with each cell defining the eccentricity in a area of the periphery of the backup roll. The controller has been tested on the cold strip mill of Western Port in Australia.

Hydraulic systems

The main part of [Ginzburg, 1984] is dedicated to the construction of a linear model for the thickness control system of a single stand hot rolling mill. This includes controllers, hydraulic system, rolling mill, and plate. The rolling mill is modeled as a second order system and the plate is modeled as a spring. The effect of variations of parameters of the hydraulic system, the rolling mill, and the steel plate is analyzed. An adaptive control strategy based on the model is briefly described, and is evaluated using computer simulations. It is concluded that the material stiffness, and the spring coefficients has the most important influence on the stability of the control system.

In [Gou, 1991] the design of hydraulic systems for AGC is considered. This is done by an evaluation of the nonlinear dynamical model for the hydraulic system, the rolling mill, and the plate. In this case the rolling mill is modeled as a second order mechanical system. The plate is modeled as damping in the mechanical model for the rolling mill. Both single, and double acting hydraulic systems, and three different servo valve configurations are considered. The conclusion is that the bandwidth of the hydraulic system should be considerably lower than the natural frequencies of the mill. It is furthermore concluded that the double acting system is to prefer to the single acting system for position control, while the performance of both systems are fairly equal for pressure control.

The purpose of [Paul, 1975] is to develop a nonlinear model for hydraulic systems in cold rolling mills. The roll pack is modeled as a nonlinear second order system, and the plate is modeled as a nonlinear spring. A computer simulator is constructed, and the responses of the thickness control system using a proportional controller are evaluated. It is concluded that hydraulic thickness control systems are superior to electro-mechanical systems with respect to the response time.

Roll profile

[Kawanami *et al.*, 1990] gives a review of the shape, and crown control in strip rolling mills. First a theoretical analysis of the behavior of the rolling process with respect to crown, and shape is done. Then different kinds of mechanical equipment for controlling the crown such as roll bending, roll shift, and roll crossing is described, and analyzed. The conclusion is that the HC-method (which is a combination of roll shifting, and roll bending), and the PCM (which is crown control by varying the angle of crossing of the two roll packs), are the most efficient methods.

The purpose of [Fujii and Saito, 1975] is to introduce a shape controlling algorithm in the pass scheduling algorithm for a single stand rolling mill. This is done by developing a model, and estimating the roll profile. The estimate is based on the measurements collected during rolling, and is updated from a thickness measurement after the rolling. The estimation is done using a Kalman filter. The estimated profile is used in the pass schedule calculations for maintaining a constant relative crown on the plates. The plate temperature is also estimated using a Kalman filter. The algorithm is implemented at Nippon Kokan Fukuyama Iron Works in Japan.

[Davies and Shuman, 1992] considers eccentricity of the rolls. It is concluded that this phenomenon is due to imperfect roll grinding. The effects of roll eccentricity in connection with the plate thickness are analyzed. It is concluded that in order to prevent roll eccentricity, the rolls should be ground in their bearing houses, and that the tolerances of the grinding machine should be appropriate for the task.

Models for key variables

[Cumming, 1972] describes the identification of parameters in models for rolling force, rolling torque, and forward slip of a strip mill. The input parameters to the models are in-, and outgoing thickness, and tension for the stands, and exit velocity from the last stand. The tension is the horizontal force applied to

the strip by the coiler, and the other rolling stands. The process characteristics are analyzed, and linear SISO models are derived. The parameters in the models are estimated using a correlator. This is done by using a white noise signal as input to the process, and finding the cross correlation with the system output. System identification using a computer is also tried. The author concludes that the correlator is the superior tool for the system identification.

Vibrations

[Nieb and Nicolas, 1991] analyzes the vibrational effects in rolling mills. These effects are split in three, vibration due to an oscillating forcing function, excitation of a resonant frequency, and instable dynamics due to internal force loops in the rolling mill. The vibrations affect the roll gap, the rolling speed, and interstand tension, and are typically in the frequency areas of 150 Hz, and 1500 Hz. The article furthermore suggests a monitoring system to detect the vibrations. This system is not implemented

3.1.2 Material behavior

Reviews

[Montmitonnet and Buessler, 1991] is a review article covering the development of the theoretical analysis of hot rolling in Europe in the late eighties. The article covers analysis of both hot, and cold rolling. The modeling mainly covers product geometry, thermal effects, metallurgical aspects, and friction between work rolls, and plate. It also describes the work of several important authors. The main conclusions are that there is a general lack of verification and use of the models in connection with practical applications.

Material deformation

[Kim and Kobayashi, 1990] investigates the effect of preshaping the plate in the last pass of the width rolling. The purpose of this is to make the shape of the finished plate as rectangular as possible. This is done by forming the thickness in what will be the width direction of the finished plate. Three different profiles using parallel rolling as well as diagonal rolling are investigated using a three dimensional rigid plastic Finite Element Method (FEM). It is concluded that FEM is a powerful tool for analyzing the hot rolling process.

Shape, and crown phenomena are analyzed in [Matsumoto, 1991]. This is done by analyzing a two dimensional mathematical model derived from three dimensional theory. The model considers width broading, and the thickness profile. The predictions of the model are in good agreement with experimental results.

In [Kumar *et al.*, 1992] material deformation, and heat transfer of steel plates during rolling are investigated using a two dimensional FEM model. The article analyzes the inhomogeneous deformation of the plate due to inhomogeneous temperature, and the way the plate is deformed in the roll gap. The simulation results are compared to experimental rolling of stainless steel samples. The model will be used for prediction of rolling force, and microstructural characteristics of the rolled material.

The subject of [Shohet and Townsend, 1971] is modeling of crown, and flatness of hot rolled products. The developed theory implies that the change in relative crown should be within certain limits related to the final plate crown

in order to obtain good flatness. These limits are parametrized by making experiments with aluminum rolling using a laboratory mill.

Force model

In [Shevtsov *et al.*, 1988] a force model for plate rolling is developed. This is done by a systematic investigation of the deformation resistance of the rolled steel types, and the pressure distribution across the roll gap. The model was developed using experimental laboratory data. The method is used in the pass schedule calculation in several Russian plate mills, and is found superior to other models used for on line calculation of the rolling force.

Temperature distribution

The temperature distribution in the thickness direction of hot rolled steel plates or strips is investigated in [Laasraoui and Jonas, 1991]. This is done using a finite difference simulation. The factors investigated are the heat transfer to the rolls, and heat produced by the mechanical working of the plates. The temperature model is used for predicting rolling force, and microstructural characteristics of the plates. The results of the temperature simulations are in good agreement with experimental results.

3.2 Design

3.2.1 Control systems

Reviews

[Jonsson, 1991] gives a literature review of thickness control for hot rolling. This includes a basic description of the process characteristics, and the basic algorithms for thickness control. Furthermore plate crown using backup roll bending, and its interaction with AGC control are described.

[Heidepriem, 1990] gives a review of the development of the control of the hot rolling process in the late eighties. Main innovations are new sensors, actuators, and control algorithms in various kinds of rolling. The main development has been in the area of flatness, and shape control. In plate rolling, thermo mechanical rolling [3], and water cooling have gained increased interest. In roughing mills Automatic Width Control, preshaping of the slab, and Progressive Width Control, which compensates for varying strip temperature, have been developed, and implemented. In the strip mill itself width, and flatness control have gained most attention. Furthermore Artificial Intelligence such as fuzzy control, and expert systems have gained much interest.

[Young, 1983] gives a review of the development in the thickness control in strip mills. The development of AGC control is briefly described as well as feedforward control, and mass flow control. The latter is based on thickness, and velocity measurements of the steel strip, and ensures that the mass flow through the mill is constant. Using this control principle a constant strip speed is obtained, and therefore large variations in strip tension are prevented. The

3 This technique implies that the rolling is finished with the plate temperature below a certain level. It increases the strength of the product.

author concludes that this is the best way to solve the thickness, and tension control problem in strip mills.

General

In [Katori *et al.*, 1992] a two degree of freedom thickness controller for hot rolling is designed. The main purpose of the controller is to cancel the disturbances due to skid marks, and roll eccentricity. First the performance of conventionally designed AGC is analyzed, and it is concluded that it can not handle both disturbance types. After this the two degree of freedom controller is designed, each degree taking care of g one disturbance type. The performance of the controller is evaluated by simulations.

[Kitamura *et al.*, 1987] describes the design of a control system compensating for roll eccentricity, and thermal expansion of the rolls in a four high rolling mill. The eccentricity is modeled as a sine wave for each roll, and the amplitude, and phase angle of this are estimated using the recursive least square method with exponential forgetting. Initially the eccentricity is estimated using a roll kiss test [4]. During rolling the thermal expansion of the rolls is estimated using the rolling force, and roll position measurements. The compensation for the roll eccentricity is done by feeding the estimated eccentricity signal forward to the hydraulic positioning system. The performance of the controller is verified by simulations.

[Kokai *et al.*, 1985] analyzes a general gaugemeter thickness control system of a plate rolling mill. First the factors affecting the accuracy of the thickness control system are investigated. They are divided into entry thickness, rolling load, and gaugemeter estimation error. It is in connection concluded that it is important to estimate the mill spring constant correctly. Errors in the rolling force measurement can also be severe. The total error of the thickness estimation can in worst case be 0.1 mm. Another factor analyzed is the AGCs impact on plate flatness due to the amplification of the rolling force. Large deviations are obtained when the preset value from the pass scheduling computer is wrong. The conclusion is that maintenance of the measuring devices for the thickness control is crucial for the thickness control.

In [Papapanagiotou and Koivo, 1983] the design of an adaptive controller for the thickness, and tension control of a single stand mill is described. First a linear model is derived, and the parameters of this are estimated using the recursive least squares algorithm. Using the estimated parameters an optimal controller is designed. The performance of the adaptive controller is evaluated using simulations.

[Shabaro-Hofer *et al.*, 1993] describes the application of neural nets to the thickness control of the rolling process. The neural nets are trained to perform an inverse modeling of the rolling process, and the training is based on simulated data. The inverse model is used for testing several control algorithms including open loop control, PI control, Internal Model Control (IMC), and Model Predictive Control (MPC). The performances of these controllers are compared to traditional control by simulations, and it is found that the PI controller with the inverse model has the best performance.

[Yeh *et al.*, 1991] describes the design of a control system for compensation for roll eccentricity of the back up rolls in a rolling mill. The roll eccentricity

4 The rolls are pressed together with a large force and no plate in the mill

is estimated from the variations in rolling forces during a roll kiss test. The eccentricities in a number of points can be found by solving a linear matrix equation. The positions of the backup rolls are measured by pulse encoders. The estimated values are stored in variables representing the eccentricity of a number of equidistant points on the backup roll periphery. The system is then supposed to work in parallel with a conventional AGC. Results from a rolling test are presented.

In [Foda and Agathoklis, 1992] a stability analysis of the rolling process is done. This is done using a theory for linear repetitive processes which covers processes involving repetitive working of an item. The thickness profile of a plate is a function of the actions of thickness control in the actual pass, but is also a function of the thickness profiles in the previous pass. This can be modeled as a delay differential system using both the Laplace, and z-transforms. The stability of this 2D system can be analyzed using 2D Lyapunov functions. Several stability definitions exist. The strongest is stability along the pass which assures that original variations in plate thickness are attenuated. In the article, asymptotic stability is proven for a system with a PD thickness controller. The result is bounds on the controller coefficients. Application of this theory for design of a discrete tracking controller is also reported.

Single stand mills

[Ettler and Jirkovsky, 1991] describes the SKODA control groups work on controlling cold strip rolling in Eastern Europe. The use of adaptive control of strip thickness, and flatness is reported. The controllers have been implemented, and is working well. This group has also worked with digital position control, and is starting to get into roll eccentricity control.

The group mentioned above has also published [Ettler, 1986]. The subject is adaptive control of a single stand cold rolling mill. Available measurements are in-, and outgoing thickness, and speed. The implementation is based on a simplified linear model. The sampling rate is dependent on the rolling speed in order to eliminate the speed dependence of the time delays in the thickness measurements. The estimation algorithm is recursive least squares with directional forgetting. The controller is of PI type. The controller has been implemented in KZ Beroun, Czechoslovakia, and Bad Salzungen, East Germany, and the thickness accuracy is on the level of measurement accuracy of the measurement devices.

In [Hishikawa *et al.*, 1990] a digital thickness, and shape control algorithm for a single stand aluminum cold rolling mill is developed. The algorithm includes compensation for the delay of the thickness measurement, analog eccentricity control, shape control by roll coolant, and decoupling of thickness, and tension control. The time delay in the thickness controller is handled by a conventional controller with a Smith predictor. The signal for the eccentricity control is found by filtering the rolling force through band pass filters with center frequency, and gain fitted after the eccentricity frequencies. The shape control by roll cooling is implemented using fuzzy control, which controls the roll diameter in different zones which affects the thickness profile of the strip. The method has been implemented on a rolling mill in Fukuri Works, Japan, with good results.

The purpose of [Kondo *et al.*, 1988] is to improve the response of the thickness control system for a single stand cold rolling mill. The mill is equipped with

measurements of in-, and outgoing thickness. The problem is that when the thickness control makes a change in position the tension also has to be adjusted before the right thickness is obtained. The idea of the paper is to make minor adjustments in the thickness by the tension control, and larger changes by the position control. In this way the reaction time due to the position control is removed for small thickness changes. The controllers are implemented using a minicomputer. The algorithm works well, and is implemented on the mill in Naoetsu Works, Japan.

[Nose *et al.*, 1993] describes the tuning of the gain of the thickness control of a single stand cold rolling mill. This is done using fuzzy control which uses a kind of gradient algorithm. The rules for the controller are found using operator experiences. The performance is evaluated using simulations, and a test rolling.

Multi stand mills

The subject of [Asada *et al.*, 1986] is thickness control of cold strip mills. Two disturbances are treated: hardness variations of the steel strip, and roll eccentricity. These facilities are combined with an AGC control using the gaugemeter principle, and a feedforward from a thickness measurement before the first stand. The hardness variations are estimated in the first stand from variations in the rolling force, ingoing thickness, and roll gap position. The hardness variations are then fed forward to the thickness control in the next stand. The roll eccentricity for each roll is approximated with a sine wave. The amplitude, and phase of this are estimated using a Kalman filter. The estimator is initialized by pressing the rolls together with a large force. The roll eccentricity is also estimated during rolling. The performance of the system is verified using simulations which suggest improvements of the thickness tolerance by 40 %.

[Bryant *et al.*, 1975] is considering the interaction between the thickness and tension control of strip mills. The purpose of the article is to decouple the multivariable system in order to obtain single input single output systems. The decoupling is done by building a matrix array for the strip mill, and eliminating the influence between tension and thickness by using Cramers rule. This yields the structure, and coefficients of a decoupling network for the process. After the decoupling the controllers can be designed independently for thickness and tension.

In [Edwards, 1978] a historical review over the development of thickness control in strip mills is given. Various controller structures have been proposed to solve the multivariable problem. An improved solution of the thickness control problem is given including both feedforward, and feedback algorithms. The feedforward control gives the necessary changes to the stands proceeding the thickness measurement. The method employs compensation for the time delay between thickness measurement, and the rolling stands. The feedback control includes eccentricity compensation by a force loop, compensation for material properties, and PI-control of the thickness with varying gain due to the varying delay time dependent on rolling speed. Force control is used to keep the rolling force constant when it is within some limits, this is used for rejecting the effects due to roll eccentricity. Both the force, and gaugemeter loop are compensated for material variations. The new control strategy is evaluated by simulations, and a test implementation at Port Kembla, Australia, has been done.

In [Edwards *et al.*, 1987] a complete thickness control system for a strip mill is described. The main subject is roll eccentricity compensation, but the ar-

ticle also treats mill spring compensation, and compensation for variations in material hardness. Furthermore the hysteresis effects in the rolling force due to static friction is analyzed. The description of the eccentricity compensation system considers the estimation of the roll eccentricity, control algorithm, and various filters. The eccentricity is estimated for a number of equidistant points on the roll peripheries using the screw position, the rolling force, and the thickness measurement after the mill. The estimator is a multi period averaging filter. It is shown that this is equivalent to using a Kalman filer or a Fourier analysis. The system is implemented in the strip mill of BHP Steel International, Australia and the thickness control error is within ± 1 %.

In [Hoshino *et al.*, 1987] geometrical theory for linear systems is used for designing a combined thickness, and tension control system for an aluminum cold strip mill. The main purposes of the control are to decouple the thickness, and tension control, and to handle the disturbances on the process appropriately. The algorithm is implemented on the mill in Sumitomo Light Metal Industries, Japan, and is reported to work well.

In [Kuznetsov *et al.*, 1989] the transfer functions from various disturbances to strip thickness in a hot strip mill are investigated. The input variables to the transfer functions are chosen as strip temperature, rolling force, and prestressing pressure. The transfer functions are estimated by introducing known disturbances, and then using correlation analysis.

The subject of [Mizuno *et al.*,] is thickness, and tension control of a multistand rolling mill. The linear differential equations governing the process are derived. They are then decoupled, using a method proposed by Wonham, parting the system equations into block diagonal state equations. This is done by using a state feedback controller. After the decoupling, thickness, and tension controllers are introduced. The performance of the control algorithm is evaluated by computer simulations.

[Nakagawa *et al.*, 1990] describes the design of a thickness control system for a hot strip mill using optimal control theory. The objective of the controller is to minimize the thickness deviations of the finished strip due to temperature variations, and other disturbances. First a linear model of the strip mill is derived, and hereafter an optimal controller is designed. The stability of the optimal control loop is compared to a conventionally designed controller, and it is found that the stability margin for the optimal controller, is considerably better. The two control algorithms are compared using simulations, which shows that it is possible to use full mill spring compensation with the optimal controller without stability problems. The optimal control strategy has been tested on the Wakayama strip mill in Japan. The results shows that the optimal controller reduces the thickness deviations with 45 %.

[Nishikawa *et al.*, 1986] considers the control of strip thickness, and width in a hot strip mill. A high order linear model for the strip mill, including time delays between stands, is derived. Then the validity of the linear model is compared to the original nonlinear model using simulations. Good agreement is obtained. The linear model is simplified, and a feedforward control is designed to cancel disturbances in the thickness due to variations in the strip temperature. After this the model is simplified in another way, and an optimal controller is designed for the system. This controller makes it possible to control thickness, and width at the same time. The performance of the controllers is evaluated by comparing it to the performance of conventionally designed controllers. This is done using computer simulations.

The subject of [Saito *et al.*, 1988] is optimal control of thickness, and tension of the steel strip in a cold strip mill. First the structure of the linear model is described, and the interaction between the different stands is removed by introducing a state feedback (blocked non-interacting control). After this, optimal controllers are designed for the control of each stand. This approach makes it possible to use parallel processing for the control of each stand. The performance of the optimal control is compared to the performance of conventional control by simulations, and it is found that the thickness deviations can be reduced by 50 %.

In [Zhao, 1987] the control of thickness, and tension in a strip mill is investigated. Due to the time delays the model of the process is infinite dimensional. A controller is designed on the basis of the infinite dimensional equations. The controller is evaluated using simulations.

[Takahsahi, 1977] constructs a digital simulator for a hot strip mill. The simulator is based on the nonlinear differential equations governing the process. Using the simulator the response to roll eccentricity, skid marks, and variations in ingoing thickness is evaluated. Mills with electro-mechanical, and hydraulic roll gap positioning are simulated. It is investigated in which stands it is important to use hydraulic systems in order to improve the response of the thickness control. Hydraulic loopers [5] for controlling the tension are also introduced. It is concluded that these are necessary to obtain optimal performance for the hydraulic roll positioning systems. A proposal for a thickness, and tension control strategy is also given.

In [Yamashita *et al.*, 1976] an optimal controller for the strip thickness in a hot strip mill is designed. First a simple model of the rolling mill is presented. On the basis of this a feedforward control, where the roll force disturbances are fed down stream in the strip mill, is proposed. Furthermore an optimal feedback controller is designed for each stand. The method has been implemented at the Kashima Steel Works, Japan, and considerable improvements in strip thickness are reported.

Production planning

[Rademacher, 1987] considers the design of a computer control system for the pass schedule calculation for a single stand cold rolling mill. The main objective is to minimize the rolling time subject to the physical constraints of the rolling mill. This is done by varying the thickness reduction, and rolling speed. The basis of the algorithm is mathematical models relating thickness reduction to rolling force and torque. Furthermore models for forward slip, and plate temperature are necessary. The rolling time can be estimated on the basis of the above model. The optimization problem is solved using dynamic programming. By utilizing the structure of the problem, the number of calculations is reduced considerably. The computer system is implemented in a cold rolling plant resulting in time saving of approximatively 10 %.

In [Lu *et al.*, 1989] a neural net for the production scheduling in a hot strip mill is developed. The production control system handles the material flow through the reheating furnaces, and rolling mills. The plant is modeled using mass, and energy equations. The purpose of the production schedule is to

5 Device for controlling the interstand tension.

maximize the production, and minimize the energy consumption considering the physical constraints of the processes. This is accomplished using the models for the system, and a neural network. Furthermore hardware, and software configurations for the production control system are proposed. The system is neither simulated or implemented.

3.2.2 Mechanical systems

Review

[Stone, 19XX] gives a review of the development of the modern automatic gauge control systems. It starting with the hydraulic prestressed mill and ends with the hydraulic position control. Characteristics such as force paths, and achievable performance are analyzed for the different thickness control configurations. References to the inventors of the various principles are given as well.

Hydraulic

[Huzyak and Gerber, 1984] describes the mechanical design of hydraulic gauge control systems. The design includes the cylinder, servo valve, measurement devices, and control system. The operation of the thickness control system is analyzed, and demands on the equipment is derived from this. The external disturbances to the control system are analyzed as well. Furthermore simple dynamical models for the AGC system are derived.

Roll bending

In [Stone, 1969] the design of the BackUp Roll Bending (BURB) is described. The purpose of this equipment is to change the profile of the roll gap, and thereby the thickness profile of the plates. This is done by applying bending forces to the backup rolls of the four high mill. This makes it possible to vary the thickness profile independent of rolling force, and plate width. A mathematical model for the dependence of the thickness profile of, the width, rolling force, and backup bending force is given. Several different configurations are given. Experimental results for aluminum rollings are given, and they show good agreement with the mathematical model. In the last part of the paper the interaction between AGC, and BURB is described. This interaction is due to the influence of BURB on the rolling force, and thickness profile.

3.3 Applications

3.3.1 Control systems

General

A basic review of the different kinds of roll gap control systems is given in [Wright and Young, 1979]. Typical values for the performance of electro-mechanical, and hydro-mechanical systems are also given.

[Miller, 1989] gives general descriptions of rolling mill automation systems, and adds guidelines for the design, and implementation of these systems. Rational choice of process to automate, deliverer, and implementation of the system is emphasized. Hardware configurations of the control systems are considered, and an overview over state of the art of control systems for hot, and cold strip

mills is given. For the thickness control system this includes head, and end thickness control and suppressing the interaction between the thickness, and tension controls. Good performance is when thickness errors are within ± 1 % of the strip thickness. It is predicted that the improvements in the nineties will come through invention of new types of sensors, and application of artificial intelligence systems.

[Greenspan, 1992] describes some hardware, and software developed by Tippins Inc., which can be used for implementing thickness, and tension control in strip mills. Normal PLCs are usually to slow for handling this kind of control [6]. The hardware is programmed using an IBM PC, and the software is constructed as a block programming language. The system is used for thickness, and tension control on a tree stand aluminum cold strip mill using a scan time of 1 ms, and 10 ms, and for speed, and tension control of a three stand bar mill using a scan time of 10 ms.

In the three short papers [Omohri *et al.*, 1986a], [Omohri *et al.*, 1986b], and [Omohri *et al.*, 1986c] the design, and application of a plate crown control system is described. First a mathematical model for calculation of the plate crown is described, and verified by experiments. After this a method for measuring the plate crown is described. It consists of three measurements devices in order to be able to handle non-perfect alingment of the plate when it is comming out of the mill. Finally a control system using the model, and crown measurement for controlling the plate crown is described. The plate crown is controlled by varying the force applied by the roll bending system. The thickness controller is compensated for the roll force, and change of thickness profile due to this. The system has been implemented in the Mizushima Works, Japan.

Single stand mills

In [Morel *et al.*, 1984] design, and implementation of a computer control system on the plate mill at Unisor, France, are described. The control system handles pass schedule handling, automatic gauge control, and MAS control. The mill is equipped with a hydraulic positioning system, and the thickness control performs mill spring compensation where the thickness estimation is updated by micrometer measurements of the cold plates (!). Width control is done by measuring the slab dimensions before, and after width rolling with the side guides. The MAS control implies that the plate shape is preshaped using the hydraulic position equipment in the last pass of the width rolling. This redistributes the material of the plate in order to obtain a more rectangular shape of the finished plate. This has resulted in a yield improvement of about 1 %. The standard deviation of the thickness error is 0.19 mm.

[Saito *et al.*, 1981] describes the development, and implementation of an absolute mode AGC for a plate mill. The thickness controller locks on the preset values given by the rolling mill computer, and therefore controls the deviations from the desired thickness of the plate. The thickness control includes mill spring compensation, compensation of effects from BURB, roll expansion, and wear. The compensation for the changes in roll profile is done using thickness measurements in the center, and the edges of the rolled plates. Furthermore the speed effect is compensated dynamicly during pass, and the roll

6 The rise time of the positioning system of the valve glider of the servo valve at DDS is around 4 ms

eccentricity is estimated, and used for compensation. The control gain is varied dependent on material hardness. The standard deviation of the thickness errors is 0.075 mm.

The short paper [Takeuchi *et al.*, 1986] describes the development of a new dynamic model for roll profile for the hot plate mill in Mizushima Works, Japan. The model includes the variation of roll profile, and roll flattening as a function of plate dimensions, and rolling force. The model is used for estimating the roll gap in connection with the thickness control. The use of the model has resulted in an improvement of the thickness accuracy of 20 % .

Multi stand mills

[Naitoh *et al.*, 1989] describes the implementation of a digital control system for strip thickness, and tension at Kakogawa Works, Japan. The motor speeds are controlled by digital controllers, and have a steady state accuracy of 0.01 %. The thickness control includes mill spring compensation, feedforward of variations in strip hardness, and roll eccentricity control. When a new strip comes into the mill the initial set up of the mill is corrected using feedforward from the first, and second stand. When major thickness errors have to be corrected the thickness reductions in the mill are redistributed, this prevents strip breaking, and overload of the mills. No standard deviation for thickness deviations is given.

The implementation of a process control for the hot strip mill at Hoogoven, The Netherlands, is described in [Heesen and Burggraaf, 1991]. The control system is used for set up, and control of the thickness, shape, speed, tension, and temperature. The core of the mill set up system is an improved rolling force model. To improve the accuracy the model is adapted from the measured values. By using the force model the roll gap positions, roll bending systems, and the tension controllers are set up. The strip temperature is measured after the roughing stands, and the finishing stands. These measurements are used for the strip temperature control, which is predicting the strip temperature all the way through the mill. The temperature is controlled by water sprays, and water curtains placed between the stands. The temperature accuracy is within $\pm 15°$ K for 96.2 % of the strips while the thickness error of the strip, including head, and tail is within ± 0.1 mm for 95 % of the rolled strips.

[Harpster, 1983] describes the development, and implementation of a digital thickness controller for a hot strip mill. The controller is a discrete time PID controller with a sampling time of 50 ms. The actuators for the thickness control are electromechanical screws. The controller performs mill spring compensation using the gaugemeter principle.

In [Ferguson and de Tina, 1986] the functions of the thickness control of the no. 2 hot strip mill at Dofasco Inc. in Canada are described. The roll gap positioning in connection with the thickness control is done by electro-mechanical screws. The functions of the thickness control are compensating for mill spring, thermal crown, speed effect, roll bending, backlash in the positioning system, and roll eccentricity. The compensation for the mill spring is done using the gaugemeter principle while the compensation for the thermal crown is done by a simple estimation of the effect on the average thickness. The compensation for the influence of the roll bending on the thickness control is done by compensating for its effect on rolling force, and thickness estimation. The backlash is measured, and incorporated in the thickness estimator while the

component due to roll eccentricity is removed from the rolling force using a band stop filter. Furthermore absolute control has been implemented. When the strip rolling is started the hardness of the material is estimated, and fed forward to the proceeding stands to improve the head end thickness tolerances. The thickness of the strip is measured after the mill, and used for corrections of the thickness estimation. The standard deviation of the thickness error of the strips is around 0.017 mm.

[Fischer *et al.*, 1991] describes a revamp of the cold strip mill at Hoogovens, The Netherlands. The revamp includes replacement of the control systems for AGC, tension, and flatness control, and installation of BURB, and CVC work roll shifting. Also the electrical power supply for the electro-mechanical screws used for the thickness control is replaced. The control principle for the new AGC system is the mass flow principle. The flatness of the strips is measured using a stressometer, the measurement is used for controlling the BURB system, the CVC rolls, and roll gap positioning system. The thickness error for 98 % of the strips is within 1 %. The flatness control has reduced the number of coils with flatness problems by 40 %.

[Readal *et al.*, 1991] describes a revamp of the computer control systems for the hot strip mill at the USS Gary Works, USA. The revamp includes replacement of the original AGC, position, and speed control systems by digital ones. The production control system for the strip mill is also replaced. The hardware configurations of the new systems are described, and the start up of the new system is summarized.

[Tsuji, 1987] describes the development, and implementation of an absolute mode AGC on the hot strip mill at Hirohata Works, Japan. The thickness control compensates for mill spring, speed effect, thermal roll expansion, and roll eccentricity. In the model for mill spring, roll bending, and flattening are modeled explicitly. The thickness estimation is updated using a thickness measurement after the mill. Furthermore the interaction between the AGC, and BURB systems is cancelled. The strip tension is controlled using an optimal controller. The standard deviation of the thickness error is 0.028 mm.

In [van Ditzhuijzen, 1986] a flatness control system for a hot strip mill is described. The systems controls the strip crown during pass using a BURB system, with a sampling time of 1 s. The strip flatness is measured using a laser measurement, and this is used as feedback for the flatness control. The initial set up of the mill is found using physical models for the roll gap. No concrete performance results are given.

[Yabuuchi *et al.*, 1982] describes an almost total automation of the hot strip mill at the Nippon Kokan plant, Japan. The primary goals of the automation are increase of productivity, and reduction of the number of employees. The areas automized are the slab yard, and coil storage. In order to accomplish this an automatic labeling system is also developed. Furthermore all cranes are automized. The reheating furnaces, and strip temperatures are also controlled by process computers. The result of the automation is that productivity per man-month has been increased by 250 %.

[Zeigman *et al.*, 1991] describes the implementation, and start up of a computer control system for the hot strip mill at LTV Cleveland, USA. The main goal is to improve the thickness tolerances of the finished strips. The modernization includes new AGC, installation of work roll bending, and new thickness measurement devices. The functions of the AGC systems are compensation for

speed effect, mill spring, thermal crown, head end control, compensation from effects of roll bending, and feedforward control form the preceding mills stands. The specifications for the control system is that 98 % of the strips should have less than ± 1 % thickness error.

Production planning

[Davies and Mantyla, 1983] describes the implementation of a computer control system for pass schedule calculation for the plate mill at Rautaruukis, Finland. The pass schedules are found using look up tables with plate thickness, and plate width as input parameters. The predictions of rolling force, thickness reduction, and rolling torque are stored in the tables. The thickness control, and backup roll bending systems are also described in the article. The thickness control system is compensating for the mill spring using the gaugemeter principle. The two sides of the rolling mill are controlled independently. It can operate in both relative, and absolute mode. The flatness of the plates is also controlled by the computer control system. The is done by determining the rolling forces so a constant relative crown of the plates is obtained.

3.3.2 Mechanical systems

Hydraulic

[Clarke *et al.*, 1983] describes the construction, and performance of several Sermes hydraulic thickness control systems in reversing single stand plate mills. The actuators of the hydraulic systems are divided into a grease, and an oil side connected by a common piston. They are placed between screws, and backup rolls. The oil flow is controlled using two parallel servo valves. Furthermore the configuration of the hydraulic system is described. The system is controlled using more or less the standard controller configuration described in the introduction. The standard deviation of the thickness error is within 0.1 mm.

[Davies, 1989] describes the design, and application of a hydraulic width, and thickness control device for a hot strip mill. The width control is done by a pair of vertical rolls placed after the roughing mill. The width is measured after the third, and fourth roughing stand the first signal is used for feedforward, and the last for feedback for the width control action. The last four stands of the finishing mill are equipped with short stroke hydraulic cylinders. The article describes the functions of the mechanical systems, and the control system. The hardware configuration of computer control system is also described. The thickness control systems of the two sides of the mill are independent which ensures a parallel roll gap despite different mill spring of the two sides due to a different roll forces. The systems are implemented in the no. 2 strip mill at Pohang Iron & Steel, South Korea. The performance of the equipment is a width tolerance of ± 2 mm, and a thickness tolerance of ± 0.045 mm.

3.4 Measurements

Rolling force measurement

[Wood and Ivacheff, 1977] describes the rolling force measurement in connection with thickness control of strip mills. Hysteresis appears to the AGC control system as variations in the mill spring, and can therefore cause problems

in connection with the accuracy of the thickness control. The rolling force is measured using load cells placed between the upper roll pack, and the screws. The hysteresis effects in the force due to static friction, and backlash in the positioning system is investigated. The hysteresis curves are obtained by a roll kiss test. The hysteresis effects are systematicly reduced, and it is found that load cell alingment is crucial to obtain a precise force measurement.

Also [Zeltkalns and Riccatti, 1977] analyzes the rolling force measurements in quarto mills. First the factors affecting the mill modulus are found and analyzed, and the force paths for the rolling forces in the rolling mill are described. Hereafter the friction effects along the force paths are investigated. The deformation of the rolling mill, and its temperature dependence is then analyzed. The force measurement characteristics for different placements of the load cell are analyzed. It is concluded that maintenance of the rolling mill, and measurement devices is important in order to obtain optimal precision of the measurements.

Position measurement

[Morel and Houdion, 1983] describes a method for measuring the position of the upper roll pack in connection with digital control of the roll position. The main advantage of the digital position sensor is that it measures the position of the piston in contact with the roll pack. Furthermore the center position of the piston is measured to cancel effects from tilting of the piston. In the thickness control system the rolling force is measured as the pressure of the hydraulic oil. It is noted that it is important to measure the pressure where the oil velocity is zero. A conventional thickness control system for mill spring, speed effect, and roll eccentricity is also described.

Thickness measurement

In [Mangan *et al.*, 1974] the design, and construction of a isotope thickness measurement device is described. The purpose of the device is to measure the thickness of the plates rolled in the reversing single stand rolling mill during rolling. To protect the device from the harsh environment it is placed on a carriage that moves it over the plate when a thickness measurement is requested. The design, and construction of the electrical, and mechanical parts of the device is described. The device has been available to the production 99 % of the production time, and the measurement accuracy is within 0.5%.

Speed measurement

[Yanai *et al.*, 1986] is a short paper describing a new non-contact method for measuring cold strip speed. The measurement is done using a laser Doppler velocity meter. The measurement is used in connection with mass flow control. The new system has reduced the errors in velocity measurement by 75 %.

3.5 Education

[Masten and King, 1991] describes the investigation of the necessary knowledge for control engineers working in rolling mills. The work is a part of The

Engineering Skills Assessment Program sponsored by IEEE. The article review a typical process control system for a strip mill and describes the main characteristics of the process. The main tasks of the control engineer include implementation, documentation, and to be used by various departments as a consultant. The necessary knowledge of the control engineer concerns analysis, and design, user support, and evaluation of the performance of the control systems. As sources of information of new technology Transactions of ISIJ, Iron and Steel Engineer, and Journal of Metals are mentioned. It is concluded that control engineers have a pivotal role for improvements of product quality in the steel industry (!).

3.6 Interesting articles, authors, and publications

In this section the best articles, authors, and publications are pointed out. A short description is also given.

Articles

The best articles have been chosen from the quality of the technical solution, that they are clearly written, and that at least some details are given in the paper.

- [**Edwards *et al.*, 1987**] gives a detailed description of the function of a thickness controller including a roll eccentricity compensator. The description is not very well organized but contains many good tricks for the implementation of a thickness controller. Furthermore the equations governing the rolling process are described and the simplified equations are derived.
- [**Ferguson and de Tina, 1986**] gives a clear, and systematic description of the thickness control problem. This leads to the functions of the thickness controller which includes what was state of the art some years ago.
- [**Foda and Agathoklis, 1992**] analyzes the stability of a thickness control system. Even though a simple model is used, and the analysis is done for a fixed controller structure the article gives a good description of the application of the theory for linear repetitive processes. The future aspects for the use of this theory is described elsewhere in this report.
- [**Gou, 1991**] gives a good, and general description of the hydraulic positioning systems used for thickness control. The nonlinear differential equations governing the system, and rules of thumb for what is neglectable are given. Special phenomena in connection with the thickness control action are also analyzed.
- [**Kokai *et al.*, 1985**] gives a good fundamental analysis of the accuracy of the thickness control. The article is rather hard to understand but gives some important results. The analysis is general but the error is also evaluated using typical data for plate rolling mills. Also the effect on flatness is analyzed.
- [**Saito *et al.*, 1981**] gives a good description of an early solution to the thickness control problem. An interesting point is that the on line model gives the thickness profile of the plate. This model is updated using a

thickness measurement device. The other factors affecting the roll gap, and the solutions in connection with these are also shortly described.

- [**Stone, 19XX**] gives a good description of the ideas behind the development of the thickness control equipment. The description starts with the earliest thickness controllers developed in the thirties, and ends with the hydraulic position controllers. The characteristics of the technical solutions are also analyzed.
- [**Wood and Ivacheff, 1977**] gives a detailed analysis of the force measuring problem. The hysteresis in the force measurement is analyzed and the improvement of the measurement accuracy is described step by step.

The articles in this review are generally not very detailed, this is probably a result of secrecy restrictions given by the involved companies. Furthermore the scope of most of the articles is rather practical; they do not normally use advanced theory of any kind. This should be seen in the light of that many of the authors are research engineers employed in the steel industry.

Authors

The authors mentioned below are the ones who have written good articles or have appeared on two or more occasions during the reading of the articles.

- **M. D. Stone** has been the Vice President of the Research, and Developments section at United Engineering & Foundation Co in Pittsburgh, USA. He has written two of the fundamental articles covered by this review, the quality of these is high.
- **M. Saito** employed at the Computer Systems Development Department, Kehim Works in Japan. He has also written two fundamental articles of high quality about the thickness control problem.
- **G. F. Bryant** who is a project director of the Industrial Automation Group at Imperial College, Great Britain. His article included in this review is not exceptional, but he is well known among engineers working with the rolling process. He has also written a book about thickness control of the rolling process.
- **P. D. Spooner** who is a senior research engineer at the Industrial Automation Group at Imperial College, Great Britain. He has worked together with Bryant.
- **W. J. Edwards** is the president of Industrial Automation Services Ltd in Toronto, Australia. He is involved in three of the articles, one of them together with Goodwin. His articles are good, and contain many good tricks for implementing thickness controllers in practice. He has worked with computer control in other areas than thickness control.
- **D. A. Davies** is a project sales manager at the Engineering, and Construction Division at Davy McKee in Sheffield, Great Britain. He is the author of three of the articles about implementation of thickness controllers.
- **R. M. Guo** is a senior staff engineer at Armco Inc in Ohio, USA. He has written a good article about nonlinear dynamic modeling of the hydraulic positioning system. He has also worked with the modeling of the work roll temperature profile.

- **S. Foda** who is working at the Department of Electrical Engineering at the Tyerson Polytechnical Institute in Toronto, Canada. He has written an article about the application of the theory about linear repetitive process.

An interesting fact about the authors covered by this review is that there are so many different. Only a few authors have written more that one article. This implies that many different people have been working with the rolling process.

Publications

The publications which has caught my interest are the following:

- **ISIJ International** is published by the International Steel Institute of Japan. The articles usually starts with a short literature review, holds a high technical level, and are generally well written.
- **Iron, and Steel Engineer** published by the Association of Iron, and Steel Engineers. This is the publication from which most of the articles included in this review are taken. The articles are in most cases describing implementations, and are usually easy to understand. The technical level is not always high.
- **Proceedings of the IFAC World Congresses** is also a source for many articles of this review. The articles are naturally mostly concentrating on control theory, and are well written. The technical level of these articles are generally high.

There are many other publications about hot rolling. They are published in many different languages including German, French, Russian, and Japanese.

4. State of the art

The state of the art of thickness control of rolling mills is given below. Even if the object of the project is the plate mill, some of the ideas from the control of strip mills which are directly applicable are mentioned as well.

4.1 Functions of thickness control systems

The state of the art consider the functionality of the control system. Implementation of the controller is not considered here except that new control systems should be implemented using computers.

The state of the art thickness controller includes following functions:

- Mill spring compensation
- Proper handling of disturbances from
  - Variations in ingoing thickness
  - Variations in plate temperature
- Variations in dynamics due to different material properties
- Compensation for eccentricity, and thermal expansion of the rolls

- Parallel control of roll gap despite different forces in each side
- Compensation for hysteresis effects in rolling force.
- Update of the thickness estimate from a measurement made after the rolling is finished

The design of the controller can be done by treating the rolling mill as a SISO system, and using traditional control theory. The only exception of this is roll eccentricity control where some recursive estimation methods have been used.

The compensation for the mill spring is still done as described in the section "Basic description of thickness control", the main idea of this technique is unchanged.

The systems should be designed to have a proper rejection of the most important disturbances. This is done based on a basic model of the system, and using traditional control theory. The same is the case with the compensation for variation in material properties. The controller should be designed to have constant dynamics despite the varying gain caused by the material variations.

The roll eccentricity, and thermal expansion can be modeled by choosing one of the given representations for the eccentricity of the rolls. The eccentricity can initially be identified using a roll kiss test, and the thermal expansion by using the estimator during normal rolling. To obtain a proper estimate of the roll eccentricity, it is necessary to measure the speed of the backup rolls. This can be done using pulse encoders. Using this measurement, and the rolling force, the eccentricity can be estimated using a suitable estimation method.

The article describing the parallel control does not describe the transfer function for this part of the mill. It is though possible to estimate this using a physical model, and some rolling tests. The problem of keeping the roll gap parallel can then be solved by using a heuristical design or treating the thickness control as a multivariable process.

The hysteresis effect due to the static friction between the bearing houses, and the mill frame should be compensated. One possibility is to estimate the hysteresis in the force measurement by performing a roll kiss test. The obtained curve can then be used for correcting the rolling force measurement. It is likely that the hysteresis effects are time varying, and an automatic procedure repeated a couple of times a day would be preferable.

The update of the thickness estimation from a thickness measurement is usually done by changing the mill spring curve. This procedure should be considered as a feedback with a considerable time delay, and one should recognize that there is also dynamics in this process. Neglecting these can lead to rather unfortunate stability problems.

Ideas from strip mill control

One idea is to use the feedforward principle used in the control of strip mills. This implies feedforward of hardness, and force variations from the first to the last stands of the strip mill. The same could be done in plate rolling, if the hardness of the material was estimated and recorded during the pass. This could be used for feedforward control in the proceeding passes. This would result in an improvement of the disturbance rejection of the thickness controller.

Today the start up of the thickness control is delayed until the rolling force has reaced a stationary level. This implies that thickness control is not performed on the plate head, and the first meters of the plates are therefore often of gauge. If the thickness controller is designed to follow the rolling force on its way up, and also keeping constant gauge. This problem could be solved. It could for example be done by changing the working point of the system using a prediction of the rolling force already recorded using the above idea.

General comments

The theoretical level of the articles concerning the thickness is more or less the same as in the above introduction to the thickness control. It is surprising that no applications of advanced control methods has been reported for plate mills. In fact no one is treating it as the multivariable control problem it actually is. If the rolling forces are not equal in the two sides, serious problems with bended plates can appear.

Another surprising thing is that a lot of effort has been spent on the thickness estimation problem, but the rolling mill, and plate are normally treated as a time varying constant. It seems that the fact that it is not possible to measure the plate thickness has affected that all the attention has been directed towards the thickness estimation problem. Due to this the modeling of the dynamics of the process has been forgotten. A fundamental fact is though that the dynamics are needed in order to be able to design a proper controller for the process. The built-in stability problem of the process makes this even more crucial.

Some authors have suggested the use of more advanced control techniques like adaptive control, and neural nets, but the complexities of the models are the same as described above. Usually these suggestions are only simulated. The exception from this is the strip mills where more advanced control has been applied in practice. Still only linear models are used for controller design, and the isolated mill stands are treated as SISO systems.

4.2 Applied theory

The control theory used for the design of thickness controllers is, as mentioned above, traditional control theory. Modern control theory is used for estimating the roll eccentricity, and the plate crown, where recursive least squares, and Kalman filters have been used. Another exception from this is the use of the theory for linear repetitive processes used for analyzing the stability of thickness controllers for the rolling process.

For controlling the thickness, and tension of strip mills modern control theory for linear multivariable systems has been used. The methods are optimal control, geometrical theory, and decoupling of the interaction between the rolling stands using a specially designed multivariable feedback. This is only reported implemented in strip mills in Japan.

For the analysis, and design of the rolling mill, and rolling processes both classical mechanics, and more advanced methods have been used. The advanced methods include the Finite Element, and the Finite Difference Methods.

5. Conclusion

The purpose of this paper is to give a review of the articles collected in connection with the research project "Improvement of Roll Gap Control System". The literature review include 77 articles related to the thickness control problem for rolling mills. The articles contain description of modeling, design, and implementation of mechanical, and control systems.

First a general introduction to the area is given. This includes a general description of the rolling mill, and the rolling process. Also the dynamics of the thickness control system is considered. After this a short review is given of each article. The summaries concentrate on the contents relevant to the thickness control problem. After this a survey of the state of the art of thickness control systems in plate mills, and interesting articles, authors, and publications are given.

Generally the articles either describes implementation of systems designed using conventional methods or development of control systems using advanced methods. Usually the advanced methods are not implemented and no real data are used. An exception is the use of multivariable control methods in the control of strip mills. No advanced theory is used for controller design for plate mills.

The state of the art for thickness controllers of plate mills of today includes compensation for mill spring, handling of disturbances in ingoing thickness, and compensation for imperfections of the rolling mill. The controllers are designed using simple linear SISO models, and traditional control theory. The methods for estimating the plate thickness are well developed, but the modeling in connection with the controller design is not satisfactory. No articles about the thickness control consider the rolling mill as the multivariable system it really is. The model therefore should be multivariable, and the structure should, if possible, be found by physical modeling. This would make it possible to exploit the structure of the model in the controller design. The development of two dimensional lateral flow models looks interesting, and will be considered in the future work.

The use of more accurate models would probably result in better performance of the thickness control systems. These models should contain a more accurate description of the dynamics of the rolling process, and should consider the multivariable nature of it. This kind of models would make it possible to obtain a better control of the plate form, and would ensure the stability of the thickness control system. Also the use of the theory concerning linear repetitive processes would ensure better performance. Using this theory it is possible to optimize the whole pass schedule, which will lead to improvements in the overall performance of the thickness control system.

The future work of the literature search will be directed towards finding relevant literature for the modeling problem. This will be done in order to obtain a proper model for the rolling mill. The theory for linear repetitive process will also be considered in connection with the literature search.

6. Bibliography

ASADA, Y., A. KITAMURA, K. NOSE, M. KONISHI, T. NAKADA, and K. TANI (1986): "New feed forward gauge control method for cold tandem mills." *Proceedings of the IFAC conference on automation in mining mineral and metal processing*, pp. 279 – 284.

BRYANT, G. F., P. D. SPOONER, and J. M. CALEY (1975): "Design of tandem mill dynamic control schemes." *Proceedings of the 5th IFAC World Congress*, pp. 53.3: 1 – 11.

CLARKE, J. F., J. D. SHINABARGAR, G. LAFFERTY, and G. E. MUELLER (1983): "Automatic gage control of a 110-in. plate mill." *Iron and Steel Engineer*, December, pp. 17 – 20.

CUMMING, I. G. (1972): "On-line identification of a steel mill." *Automatica*, **8**, pp. 531 – 541.

DAVIES, D. A. (1989): "Application of hydraulic AGC and width control to a hot strip mill." *Iron and Steel Engineer*, August, pp. 35 – 39.

DAVIES, D. A. and P. MANTYLA (1983): "Control of gage, width, profile and shape on Rautatuukki's 3.6-meter plate mill." *Iron and Steel Engineer*, December, pp. 39 – 44.

DAVIES, W. J. and T. SHUMAN (1992): ""Roll Camming" an analytical approximation for roll eccentricity studies." *Proceedings of the 33rd MWSP Conference*, **29**, pp. 129 – 136.

EDWARDS, W. J. (1978): "Design of entry strip thickness controls for tandem cold mills." *Automatica*, **14**, pp. 429–441.

EDWARDS, W. J., P. J. THOMAS, and G. C. GOODWIN (1987): "Roll eccentricity control for strip rolling mills." *Proceedings of the 10th IFAC World Congress*, pp. 187 – 198.

ETTLER, P. (1986): "An adaptive controller for SKODA twenty-rolls cold rolling mills." *Proccedings of the 2nd IFAC Workshop on Adaptive Systems in Control and Signal Processing*, pp. 277 – 280.

ETTLER, P. and F. JIRKOVSKY (1991): "Digital controllers for SKODA rolling mills." *Lecture notes in Control and Informations Sciences*, **158**, pp. 31 – 35.

FERGUSON, J. J. and R. F. DE TINA (1986): "Modern hot-strip mill thickness control." *IEEE Transactions on industry applications*, September/October, pp. 934 – 940.

FISCHER, H., R. MOL, L. MJORNING, and C. KALIN III (1991): "Revamp of electrical control system improves performance of 5-stand tandem mill at Hoogovens." *Iron and Steel Engineer*, October, pp. 21 – 27.

FODA, S. and P. AGATHOKLIS (1992): "Control of the metal rolling process. A multidimensional system approach." *Journal of the Franklin Institute*, **329:2**, pp. 317–332.

FUJII, S. and M. SAITO (1975): "A new mathematical model for plate mill control." *Proceedings of the 5th IFAC World Congress*, pp. 46.5: 1 – 7.

GINZBURG, V. B. (1984): "Dynamic characteristics of automatic control system with hydraulic actuators." *Iron and Steel Engineer*, pp. 57–65.

GOU, R. (1991): "Evaluation of dynamic characteristics of HAGC system." *Iron and Steel Engineer*, July, pp. 52–61.

GREENSPAN, M. (1992): "Multiprocessor controller for gauge and tension control." *Iron and Steel Engineer*, March, pp. 30 – 36.

HARPSTER, R. A. (1983): "Programmable controller-based hot strip mill automatic gage control systems." *Iron and Steel Engineer*, February, pp. 29 – 32.

HEESEN, G. J. and D. H. BURGGRAAF (1991): "New process control system of Hoogovens hot strip mill. Key to improved product quality." *Ironmaking and Steelmaking*, **18**, pp. 190 – 195.

HEIDEPRIEM, J. (1990): "Trends in process control of metal rolling mills." *Proceedings of the 11th IFAC World Congress*, pp. 138 – 147.

HISHIKAWA, S., H. MEADA, H. NAKAKURA, S. HATTORI, M. NAKAJIMA, and Y. KATAYAMA (1990): "New control techniques for cold rolling mills. Applications to aluminum rolling." *Hitachi Review*, **39**, August, pp. 221 – 230.

HOSHINO, I., Y. MAEKAWA, T. FUJIMOTO, H. KIMURA, and H. KIMURA (1987): "Observer-based multivariable control of the aluminum cold tandem mill." *Proceedings of the 10th IFAC World Congress.*

HUZYAK, P. and T. L. GERBER (1984): "Design and application of hydraulic gap control systems." *Iron and Steel Engineer*, August, pp. 13–20.

JONSSON, N. G. (1991): "AGC vid varmvalsning – litteraturstudie." Technical Report, MEFOS.

KATORI, H., N. YOSHITANI, T. UEYAMA, and S. NYU (1992): "Application of two-degree-of-freedom control system to automatic gauge control." *Proceedings of the American Control Conference*, pp. 806 – 810.

KAWANAMI, T., T. ASAMURA, and H. MATSUMOTO (1990): "Development of high-precision shape and crown control technology for strip rolling." *Journal of Materials Processing Technology*, **22:3**, pp. 257–275.

KIM, N. and S. KOBAYASHI (1990): "Three-dimensional simulation of gap-controlled plate rolling by the finite element method." *International Journal of Machine Tools & Manufacture*, **30:2**, pp. 269 – 281.

KITAMURA, A., T. TAKAHASHI, K. NOSE, M. KONISHI, K. TANI, and T. NAKADA (1987): "Recursive identification technique for roll eccentricity control." *Proceedings of the 10th IFAC World Congress*, pp. 113 – 118.

KOKAI, K., Y. KAKO, and K. NAKAJIMA (1985): "Factors affecting the accuracy of plate tickness and their influences on plate flatness." *ISIJ Transactions*, **25**, pp. 482 – 488.

KONDO, K., Y. MISAKA, M. OKAMOTO, Y. MATSUMORI, and T. MIYAGI (1988): "A new automatic gauge control system for a reversing cold mill." *ISIJ International*, pp. 507 – 513.

KUMAR, A., I. V. SAMARAAEKERA, and E. B. HAWBOLT (1992): "Roll-bite deformation during the hot rolling of steel strip." *Journal of Materials Processing Technology*, **30**, February, pp. 91–115.

KUZNETSOV, B. I., V. I. KOVALEV, A. P. GOLUB, and V. P. GALAGAN (1989): "Statistical investigations of longitudinal thickness variation on hot rolling narrow strip mill." *Steel in the USSR*, **19**, pp. 166 – 168.

LAASRAOUI, A. and J. J. JONAS (1991): "Prediction of temperature distribution, flow stress and micro structure during the multipass hot rolling of steel plate and strip." *ISIJ International*, **31**, pp. 95–105.

LU, Y., L. BAO, Y. YANG, and B. LI (1989): "An integrated computer control system for steel plate mill." *Proceedings of the IFAC conference on automation in mining mineral and metal processing*, pp. 293 – 297.

MANGAN, E. L., W. G. BARLETT, and A. B. BROWN (1974): "Thickness gaging at Betlehems 160-in. plate mill at Burns Harbor." *Iron and Steel Engineer*, pp. 226 – 230.

MASTEN, M. K. and E. O. KING (1991): "Knowledge element identified for metal rolling control engineers." *IEEE Control Systems Magazine*, **11**, January, pp. 108 – 110.

MATSUMOTO, H. (1991): "2-dimensional lateral-material-flow model reduced from 3-dimensional theory for flat rolling." *ISIJ International*, **31:6**, pp. 550–558.

MILLER, W. E. (1989): "Applying distributed computer control to modernize steel strip rolling mills." *Proceedings of the IFAC conference on automation in mining mineral and metal processing*, pp. 11 – 19.

MIZUNO, K., Y. MOROOKA, and Y. KATAYAMA "Multivariable nonlinear control system design for multistand rolling mill." *Hitachi Review*, pp. PS2: 22 – 27.

MONTMITONNET, P. and P. BUESSLER (1991): "A review on theoretical analyses of rolling in europe." *ISIJ International*, **31:6**, pp. 525 – 538.

MOREL, M. and P. HOUDION (1983): "Digital measurement and control of mill roll position." *Conference Record of the Industry Applications Society IEEE-IAS-1983 Annual Meeting*, pp. 77–82.

MOREL, M., J. G. MONTASTIER, M. A. BERNOT, and M. F. CHABOUD (1984): "Quality control and production optimization in plate mills using the HYDROPLATE system." *Iron and Steel Engineer*, pp. 48 – 53.

NAITOH, Y., K. KIKUCHI, T. WASHIDA, T. NAKADA, E. SUZUKI, K. TANI, and A. KITAMURA (1989): "Advanced thickness gauge control system for tandem cold mill." *Proceedings of the IFAC conference on automation in mining mineral and metal processing*, pp. 241 – 246.

NAKAGAWA, S., H. MITURA, S. FUKUSHIMA, and J. AMASAKI (1990): "Gauge control system for hot strip finishing mill." *Proceedings of the IEEE Conference on Decision and Control*, **3**, pp. 1573 – 1578.

NIEB, J. R. and V. T. NICOLAS (1991): "Automated monitoring and control of vibrations and chatter in rolling processes." *Iron and Steel Engineer*, July, pp. 33 – 42.

NISHIKAWA, Y., M. ARAKI, T. FUJINAKA, M. AMANO, J. YAMASAKI, A. URANO, and H. YOSHIDA (1986): "Advanced control in hot strip finishing mill." *Proceedings of the IFAC conference on automation in mining mineral and metal processing*, pp. 259 – 264.

NOSE, K., A. WATATANI, and H. KATAYAMA (1993): "Application of fuzzy interference to gain tuning in thickness control of multi-high rolling mills." *Preprints of the 12th IFAC World Congress*, **6**, pp. 135 – 138.

OMOHRI, K., S. ISOYAMA, M. INQUE, T. MIYAKE, Y. TANAKA, and M. KITAHAMA (1986a): "An analysis of camber mechanism in plate rolling, I." *ISIJ Transactions*, **61**, pp. B–61.

OMOHRI, K., S. ISOYAMA, M. INQUE, T. MIYAKE, Y. TANAKA, and M. KITAHAMA (1986b): "An analysis of camber mechanism in plate rolling, II." *ISIJ Transactions*, **61**, pp. B–62.

OMOHRI, K., S. ISOYAMA, M. INQUE, T. MIYAKE, Y. TANAKA, and M. KITAHAMA (1986c): "An analysis of camber mechanism in plate rolling, III." *ISIJ Transactions*, **61**, pp. B–63.

PAPAPANAGIOTOU, I. and A. J. KOIVO (1983): "An application of self-tuning controller in the steel industry." *Proceedings of the American Control Conference*, **1**, pp. 14 – 17.

PAUL, F. W. (1975): "A mathematical model for evaluation of hydraulic controlled cold rolling mills." *Proceedings of the 5th IFAC World Congress*, pp. 53.4:1–10.

RADEMACHER, W. (1987): "Development and practical application of a procedure for computation time-optimal pass schedules for reversing rolling mills." *Proceedings of the 10th IFAC World Congress*, pp. 119 – 124.

READAL, G. J., J. L. DAVIS, and D. L. KELLEN (1991): "Computer control modernization at USS Gary works' 84-in. hot strip mill." *Iron and Steel Engineer*, October, pp. 15 – 20.

SAITO, M., S. TANIMOTO, H. TSUKAMOTO, and Y. NABA (1981): "High-accuracy plate thickness control." *Proceedings of the 8th IFAC World Congress*, pp. 2507 – 2514.

SAITO, Y., S. HATTORI, and Y. KATAYAMA (1988): "Application of blocked non-interacting optimal control to rolling mill." *Hitachi Review*, **37:4**, pp. 221 – 228.

SHABARO-HOFER, D., D. NEUMERKEL, and K. HUNT (1993): "Neural control of a steel rolling mill." *IEEE Control Systems*, June, pp. 69 – 75.

SHEVTSOV, V. K., V. KONOVALOV, E. A. RUDENKO, V. P. FILIPPOV, and V. S. RASSOLOV (1988): "Force model for plate rolling." *Steel in the USSR*, **18**, pp. 550–552.

SHOHET, K. N. and N. A. TOWNSEND (1971): "Flatness control in plate rolling." *Journal of The Iron and Steel Institute*, October, pp. 769 – 775.

STONE, M. D. (1969): "Backup roll bending – for crown and gauge control." *Iron and Steel Engineer*, December, pp. 69 – 87.

STONE, M. D. (19XX): "Hydraulic automatic gage control mills." Technical Report, Published by Association of Iron and Steel Engineers.

TAKAHSAHI, N. (1977): "Digital simulation of hot strip mill AGC system." *IHI Engineering Review*, July, pp. 76 – 83.

TAKEUCHI, T., K. OMORI, T. OGAWA, M. INQUE, and I. OKAMURA (1986): "Development of new gage-meter model for Micuhima plate mill." *ISIJ Transactions*, **26**, pp. B–60.

TEOH, E. K., G. C. GOODWIN, M. J. EDWARDS, and R. G. DAVIES (1984): "An improved strip thickness controller for a rolling mill." *Proceedings of the 9th IFAC World Congress*, **4**, pp. 144 – 149.

TSUJI, Y. (1987): "High quality control in hot strip mill." *Proceedings of the 10th IFAC World Congress*, pp. 107 – 125.

VAN DITZHUIJZEN, G. (1986): "Hot strip flatness control." Technical Report.

WOOD, G. E. and D. P. IVACHEFF (1977): "Mill modulus variation and hysteresis – their effect on hot strip mill AGC." *Iron and Steel Engineer*, January, pp. 65 – 71.

WRIGHT, H. and J. A. YOUNG (1979): "The hydraulic position controlled mill & automatic gauge control." *Steel Times International*, March, pp. 62 – 67.

YABUUCHI, K., Y. NOMA, R. SHIMIZU, and S. TANIMOTO (1982): "Unmanned operation technology for a hot strip mill." *Iron and Steel Engineer*, November, pp. 31 – 36.

YAMASHITA, A., Y. MISAKA, N. HASE, and R. TAKAHASHI (1976): "Development of feed forward AGC for 70" hot strip mill at Kashima Steel Works." *The Sumitomo Search*, **No 16**, pp. 34–39.

YANAI, K., K. KATAYAMA, I. SHONO, H. YANO, and H. UEKI (1986): "Automatic gauge control system for Sendzimir mill at Hikari Works, Nippon Steel Corporation." *Transactions ISIJ*, pp. B–342.

YEH, T., T. HWANG, S. TSAI, C. LIN, and L. LIAO (1991): "The development of new backup roll eccentricity compensation system for the plate mill." *China Steel; Technical Report*, **No 5**, pp. 92 – 99.

YOUNG, J. A. (1983): "Tandem mill gauge control." *Conference Record of the Industry Applications Society IEEE-IAS-1983 Annual Meeting*, pp. 83–90.

ZEIGMAN, R. A., R. D. COOK, W. M. REMLEY, and J. A. KASAWICH (1991): "Modernization of LTV's Cleveland 84-in. hot strip mill automation systems." *Iron and Steel Engineer*, October.

ZELTKALNS, A. and R. L. RICCATTI (1977): "Force sensing in rolling mills." *Iron and Steel Engineer*, January, pp. 72 – 78.

ZHAO, S. (1987): "Preliminary approach of continuous rolling process control described by distributed-parameter model." *Proceedings of the IFAC 10th World Congress*, pp. 181 – 186.