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Automatic Gauge Control of Plate Rolling Mill

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Abstract

The design and implementation of a steel plate mill is discussed together with the impact on the design of process models, available measurements, available control actuators and material properties. Rolling process is a high-speed system which requires high-speed control and communication capabilities. Meanwhile, it is also a typical complex electromechanical system and distributed control has become the mainstream of computer control system for rolling mill. A high-level software design approach provides the ability to make quick and accurate modifications to both control loops and tuning constants. Control loop strategies and theoretical concepts of steel plate rolling are discussed. Performance results achieved during the startup of a steel plate mill are included.

Keywords: *hydraulic position control, automatic gauge control, plate rolling mill, roll thermal expansion, mill modulus control*

1. Introduction

In the steel industry, the production of a hot-rolled plate calls for high accuracy in the product specification and high stability of the process. Because the control objects are electromechanical and hydraulic systems with small inertia and fast response, plate rolling is a fast process which requires high-speed control and communication capabilities. With the technological and industrial development, requirements for high-quality plates and high-level automation are becoming critical. Distributed control has become the mainstream of computer control system for rolling mill which is a typical complex electromechanical system [1, 2].

Automatic Gauge Control (AGC) system is installed in the four-high plate mill, and it is the most important mechanism for dynamic thickness control in conventional rolling mills. Since the AGC system is responsible for maintaining the dynamic performance of the predicted quality of thickness, it is designed to suppress the disturbances during the rolling process such as hardness and temperature fluctuation of the strip. The extremely sophisticated algorithms are developed to fulfill the task of dynamic thickness control, however, the philosophy and the principles for tuning AGC control gains become very complicated and difficult to the operators in the case of improving the quality for specific product and process [3].

The schematic diagram of a plate mill is shown in Figure 1. The mill stand consists of a mill housing containing two cylindrical work rolls, which perform the reduction, and a pair of larger backup rolls, which support them. Gap control includes the control for the top mounted variable speed synchronous motor driven no-load screw-downs and a bottom mounted servo controlled hydraulic cylinders [4]. These two actuators are controlled as required to support roll change, plate rolling and mill testing.

The thickness of the steel is controlled by dynamic roll positioning. Because the reduction of hot steel in the roll bite is sensitive to mill speed changes as well as temperature and hardness changes in strip entry, the gauge control must be able to

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control to the desired thickness of strip in the face of these disturbances. This control involves the careful coordination of a number of strategies. The rolls are placed prior to entry bar of the mill. It involves predictive models of the steel-rolling process, which will give accurate roll-position settings. To produce output strip of the desired thickness, the roll position is then altered during rolling of the bar. This dynamic roll positioning during rolling of the strip is referred to as automatic gauge control (AGC). The results of rolling each strip are further analyzed and used as adaptive corrections to the predictive models [5].

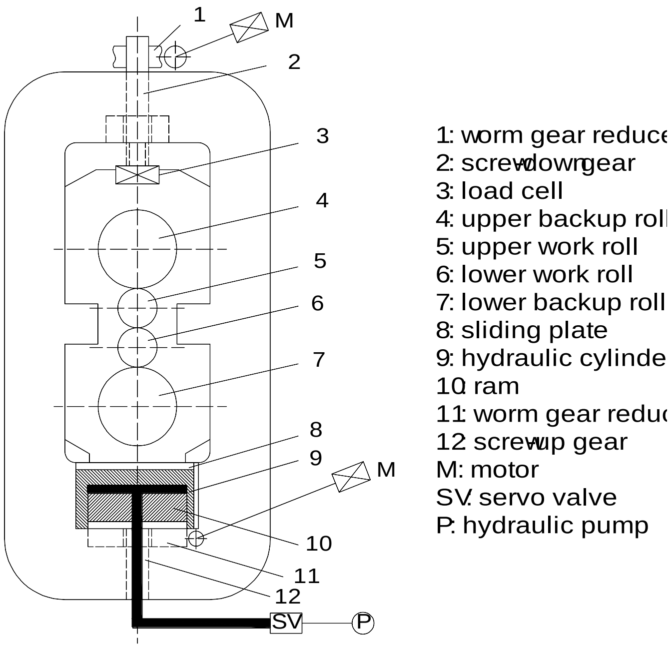

Figure 1. Schematic Diagram of a Plate Mill

The success of the thickness control depends on the ability of these various facets of the control to blend in a cohesive system. This blending is particularly evident in the successful development of the absolute, or predicted, mode of automatic gauge control. This mode of control involves an intimate connection between the traditional mill setup and AGC functions. Here it can be seen that a structured system design approach is necessary to ensure the proper integration of the various components of the thickness control [6].

2. Gap Control

2.1 Screw-Down Control

Screw-down position can be adjusted manually by the operator by a fixed speed reference to the motor drive or in a closed loop position regulator configuration that automatically adjusts the speed reference to the drive. When the clutch is opened, each side can be adjusted independently to change the level of the top roll stack. Each screw has a brake that can be set to stop movement.

The operator and drive side screws are normally mechanically coupled by an electromagnetic clutch so that both sides move the same amount to maintain average position. For open or close movements, the clutch is closed to couple the sides. When coupled, the average position feedback is used and a speed reference is applied to one side while the other side operates as a current follower. For leveling movements the clutch is opened to allow individual move on each side. During leveling the screw on each side operate as individual position regulators.

2.2 Hydraulic Cylinder Control

Cylinder position is controlled by a closed loop position regulator that automatically adjusts the flow according to a hydraulic servo valve. There are regulators on both sides of Operator and Drive respectively. Both sides are coupled together by software control. The control maintains the level of two sides when they move together. Each side has blocking valves that can stop motion of the cylinder and a vent valve that can relieve cylinder pressure. The hydraulic cylinders set the pass line and change gap opening while rolling to maintain strip thickness.

The position regulator calculates the error between the reference and feedback position. The error is used by a speed balance control to keep either the operator or drive side from lagging behind during long movements of both sides. This will prevent excessive tilt of the roll stack during movements. The control acts by reducing the servo valve flow command for the side with the smaller error and increasing it for the side with the larger error. A deadband causes this control to only act when the difference exceeds a specific amount.

Hydraulic cylinder control also includes a total force regulator with a differential position loop to maintain the stand level. The force regulator is only used during special sequences like establishing light force and gap zeroing.

3. Architecture of Automatic Gauge Control System

Figure 1 shows two kinds of mechanisms for roll gap adjustment: one is to control the position of a screw-down by an electrical motor control unit, and the other is to regulate the cylinder position via a hydraulic servo control system. The former is the so-called Electrical AGC system (EAGC), which is popularly adopted in traditional plate mill; and the latter is the schema of Hydraulic AGC system (HAGC). The main consideration for selection between these two architectures is the cost and the performance of system's dynamic response. Generally speaking, the bandwidth of HAGC system is larger than EAGC system, so HAGC system produces more accurate control result.

Since the AGC system is responsible for maintaining the dynamic performance of the predicted quality of thickness, it is designed to be able to suppress the disturbances of the rolling process such as hardness and temperature fluctuation of the plate. Consequently, as shown in Figure 2, two kinds of algorithms are supplied to provide suitable gap correction for the AGC control system: (1) AGC Compensation function; and (2) AGC control function. In these two control loops, the sophisticated algorithms are automatically calculated to fulfill the task of dynamic thickness control, however, the philosophy and the principles for tuning AGC control gains become very complicated and difficult to the operators in seek of improving the quality for specific product and process. Roll-gap errors and strip-hardness errors are the major sources of disturbances. They must be eliminated in the control of strip thickness. The roll gap is modeled by a number of open-loop models, which are calibrated using mill tests. Residual roll gap errors are isolated using X-ray thickness measurements and the principle of mass flow and are used as adaptive feedback for the roll-gap models. These errors are usually small, also because the roll gap can be modeled accurately, the absolute mode of AGC can operate so successfully.

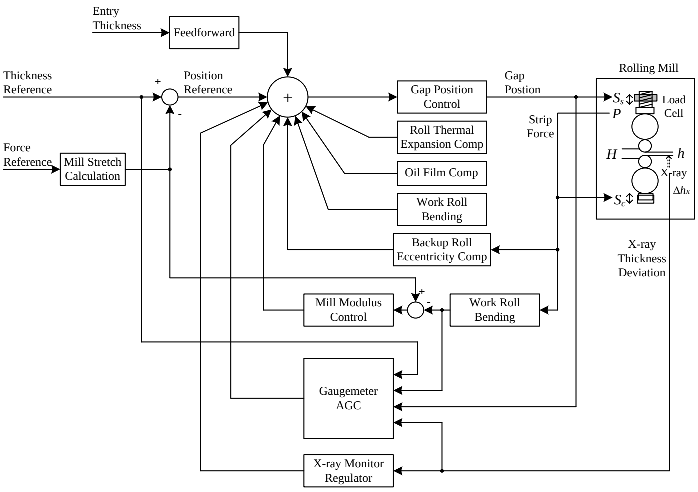

Figure 2. AGC Block Diagram

Strip hardness and deformation characteristics are also modeled for the numerous grades of steels and rolling conditions. Errors in these models are isolated using roll-force predictions during the adaptive feedback process. Any remaining steady-state error is removed by the mill vernier feedback, which compares the desired thickness with the actual thickness. These bar-to-bar control loops work in conjunction with the in-bar automatic gauge control.

Automatic gauge control uses two methods to measure the strip thickness. The first uses the roll position and force measurements at the rolling mill stand as the basic one. Strip thickness differs from roll position because of various mill housing deflections and roll deformations, which are compositely known as “mill stretch”. The total roll force of the stand reacts to this mill stretch but also reacts to changes in the mill stand. Therefore, while roll position and force measurements offer the potential of an immediate measure of strip thickness at each stand, certain prerequisites must be met. Because roll force is one indicator of mill stretch, it is necessary to know how to extract it and convert it to mill stretch by an accurate transfer function. The control of strip thickness using roll position and force measurements is known as Gaugemeter, or BISRA, AGC, named after the British Iron and Steel Research Association. In practice, different control goal requires different mill modulus in the manufacture process of hot rolling mill [7, 8]. AGC can compensate elastic deformation of the rolling mill to a certain extent when rolling force fluctuates. In other words, the mill modulus can be controlled. So, there is a concept of the mill modulus control (MMC) to be brought forward. According to different requirement of rolling technology, different equivalent mill modulus can be obtained while changing adjustment coefficients in the AGC system. MMC also uses the Gaugemeter equation to estimate stand exit strip thickness changes. The second measurement of strip thickness is provided by a thickness gauge at the exit of the plate mill. This device accurately measures the strip thickness in a distance from the mill and therefore gives a delayed measurement of the strip thickness. This means that the control that uses the thickness gauge must carefully account for this delay. The control of strip thickness using thickness gauge measurements is known as monitor control. By using the measured thickness, Feedforward AGC is provided to help compensation for known incoming product variations. Feedforward AGC assists MMC and Gaugemeter as they cannot completely correct gauge due to factors such as window friction and load cell hysteresis.

4. Model of Automatic Gauge Control System

In order to predict the dynamic variation of delivery thickness under the correction of roll gap from AGC system, an AGC control model is utilized to calculate the consequent effects of roll gap variation on the strip. In this section, firstly, a popular BISRA (British Iron and Steel Research Association) equation and its linearized model are introduced. And then, for the purpose to simplify the structure of the simulation system, two main control algorithms of the AGC control system are taken into account, and the corresponding mathematical models are also introduced.

4.1 Gaugemeter Thickness Calculation

The gaugemeter equation ($h = S_0 + P/M$, see Figure 3) uses gap position and rolling force to estimate exit strip thickness of the last stand. In Figure 3, before metal enters the roll bite the effective roll gap is equal to the setup gap position, S_0. When metal enters the roll bite, force builds up and the mill stretches causing the effective roll gap to open. In the gaugemeter equation P/M is the amount of the mill stretch when a roll separating force is applied. Exit thickness is therefore equal to the unloaded gap position plus the stretch.

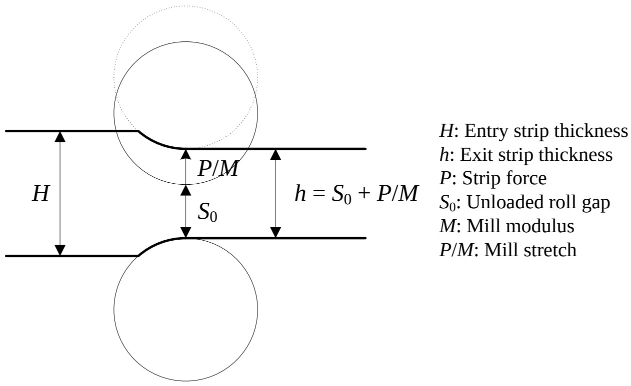

Figure 3. Gagemeter Equation

The amount that the mill stretches is not actually linear as suggested in the above gaugemeter equation. The amount of stretch is a combination of stretch in the mill housing and deflection in the roll stack. The mill housing stretch is typically non-linear at low forces and becomes nearly linear with force at high forces. Roll stack deflection includes bending of the roll necks and flattening of rolls at the point of contact with the strip and between backup roll and work roll. Stack deflection is typically linear with force but varies significantly as the strip width changes. Figure 4 attempts to show the relationships between gap position, mill stretch and strip thickness.

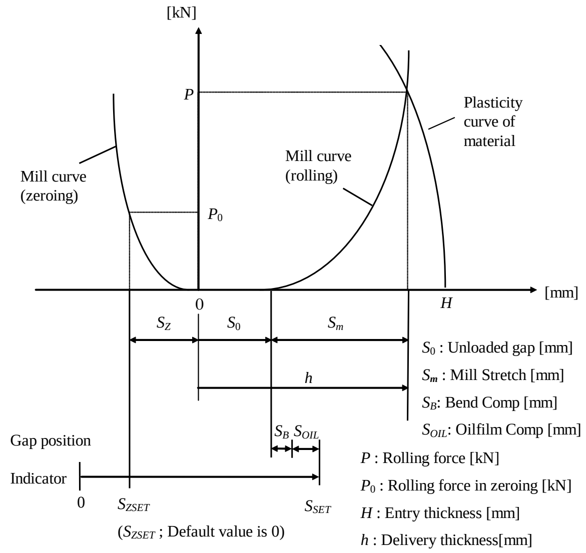

Figure 4. Mill Stretch Characteristics

Mill total stretch is measured by closing the roll gap with roll on roll while measuring force and gap position. The setup model fits a curve to the data and provides coefficients for an equation that approximates the measured stretch. The setup model provides the coefficients for each product to account for the effect of strip width on stretch.

The equation for mill stretch is of the following form.

$$S_m = \frac{1}{C_2}\left(\sqrt{C_1^{\,2} + 2C_2\frac{P}{K_B}} - C_1\right) \qquad (1)$$

where, C_1, C_2, K_B are coefficients provided by the setup model, P is rolling force.

Then, mill modulus can be derived as follows.

$$M = \frac{\partial P}{\partial S_m} = K_B\left(C_1 + C_2 S_M\right) \qquad (2)$$

4.2 The BISRA's Control Model

Figure 5 shows a popular AGC control model, the main methodology is to predict the strip's delivery thickness (h) and rolling force (P) by the entry thickness (H) of the slab and the gap correction (S_0) from the AGC system.

Nevertheless, as shown in Figure 5, the delivery thickness can be influenced by the process parameters of mill modulus and strip modulus. The former is the representation for the strength of mill's housing which can be estimated by an experiment of mill modulus test, consequently, it is the function of rolling force and roll gap; the latter presents the characteristics of the rolled strip, which is related to the rolling temperature, and strip's geometry and material. Moreover, the rolling results can also be varied by the thickness of entry strip in the case with the same roll gap; and dynamic variation of roll gap from AGC adjustment with the same entry thickness also give different effects to the delivery gauge.

Although the AGC model shown in Figure 5 is highly nonlinear, a linearized model can possibly be utilized to simplify the calculations, under the consideration of the general operation range, so that the characteristics of mill modulus and strip modulus can be assumed to present linear behaviors. And the expressions for the delivery thickness and the roll force can be presented as follows:

$$h = S_0 + \frac{P}{M} \tag{3}$$

$$F = Q(H - h) \tag{4}$$

where Q and M denote the strip modulus and mill modulus, respectively. And the equation (3) presents the so-called gagemeter equation or BISRA equation. Therefore, the deviation of thickness and the roll force under the influence from the variation of roll gap and entry thickness can be derived:

$$\Delta h = \frac{Q}{M+Q}\Delta H + \frac{M}{M+Q}\Delta S_0 \tag{5}$$

$$\Delta F = \frac{MQ}{M+Q}\Delta H - \frac{MQ}{M+Q}\Delta S_0 \tag{6}$$

Since the target of the AGC system is to regulate the deviation of the delivery thickness and the roll force of the strip to zero, this control task can be achieved by the adjustment of the roll gap from the computation of the equation (5) and (6).

4.3 Philosophy of Gagemeter AGC and Monitor AGC

Figure 5 and 6 present the control philosophy of Gagemeter AGC and Monitor AGC, respectively. In Figure 5, the feedback of roll force from load cell is utilized to compensate the effect of mill stretch, and the gain of the Gagemeter AGC control loop is used to adjust the correction of roll gap as follows:

$$\Delta S_{GM} = -G_{GM}\frac{\Delta F}{M} \tag{7}$$

Where ΔS_{GM} denotes the roll gap correction of Gagemeter AGC, and G_{GM} presents the control gain of Gagemeter AGC system. ΔF is the difference between target and actual roll force.

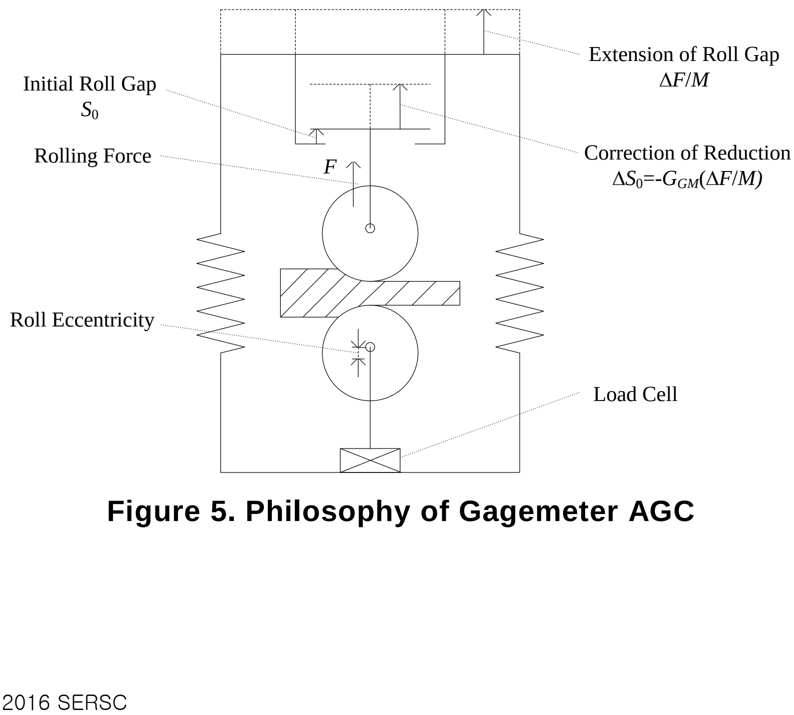

Figure 5. Philosophy of Gagemeter AGC

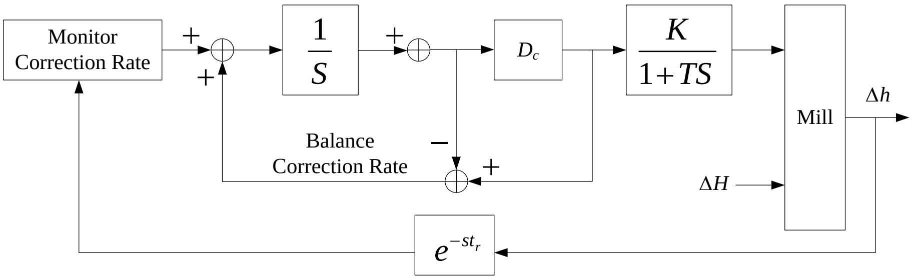

Figure 6. Philosophy of Monitor AGC

In addition, the control philosophy of Monitor-AGC is shown in Figure 6, the measuring result of delivery thickness is feedback to regulate the roll gap. In the control loop, the time delay (t_r) of the measurement is considered to reflect the actual sensing situation, and an integrator is used as the main controller to compensate the deviation of the delivery thickness. Moreover, the total correction rate of Monitor AGC is the summation of balance and monitor correction parts, and the loop gain is defined in equation (8):

$$K = G_{GM} + (1 - G_{GM})\frac{M+Q}{M} \tag{8}$$

and a time constant ($\boldsymbol{T}$) to present the dynamic behavior of the actuator.

5. Gap Compensations

Gap compensations are open loop corrections to the gap position regulator for known effects that change the effective roll gap opening but are not directly measured by the gap position transducers. Gap position transducers measure the amount of cylinder (and/or screw) extension. Although the measurements are very accurate, between position measurements and the actual gap opening are the backup roll chock and bearings, the backup roll diameter and the work roll diameter. When force is applied, the mill housing stretches, the backup roll necks bend, the roll surfaces flatten at the points of contact, the oil in the cylinder compresses and the backup roll moves off center in its bearing. As the mill stand speed increases the backup roll will become more centered in its bearing. As the rolls heat up they expand and their diameters increase. As the rolls wear their diameters decrease. The amount the rolls bend changes as roll bending force changes. The centerline gap changes as the side shift position changes. Force measurements (load cells) drift. In addition, the strip thickness changes when strip tension changes.

Some of these effects are predictable and so an open loop estimate of the effect on the actual roll gap opening is calculated and used to establish the roll gap position. The mill zeroing procedure accounts for all the factors under the specific zeroing conditions of speed and force. The open loop calculations attempt to take care of the changes from the zeroing conditions. In general, factors that change slowly like roll wear and long term roll heating can be calculated by the setup models. Factors that change quickly are calculated by AGC functions [9-11].

The stretch of the mill housing and the stack deflection (roll chock dimension changes with force and roll flattening) are corrected by the MMC AGC function. The Backup Roll Eccentricity function compensates for Backup roll diameter variations during a revolution. Compensation for oil compression in the gap cylinders and manual load cell zeroing are provided by the Gap Control function.

All other effects that can be predicted by open loop calculations are grouped into the Gap Compensations AGC function.

5.1. Oil Film Compensation

The backup rolls settle to the outer side of their bearings at low speeds, but as the rotation of the Backup Roll increases, the bearing oil is pulled evenly around the roll, causing the roll moving to center itself. The speed effect on roll gap is to decrease roll opening as mill speed increases. The magnitude of this effect decreases as roll force increases as shown in Figure 7. The gap position sensors do not detect the change in roll gap opening. This change can be significant in oil type bearings and can cause large errors in gage control if not properly compensated. Roller bearings may not require compensation.

This compensation provides an offset to the gap position regulator to maintain a constant effective gap as mill speed changes. The effect on the roll gap is separated into a speed effect and a force effect. The speed effect determines the correction to roll gap position with the roll separating force equal to zeroing force. The speed effect is zero at zero speed. As speed increases the gap will be opened. The force effect determines a per unit modifier which relates the correction at other forces to the correction required for zeroing force. The per unit effect is 1.0 at zeroing force. As force increases the amount of correction must be reduced.

Curves of the speed effect and force effect are stored as arrays. Linear interpolation between data points is used to determine the speed effect and force effect for operating speed and force. The final correction is calculated by multiplying the interpolated speed effect value times the interpolated per unit force effect.

5.2. Roll Thermal Expansion

The work and backup rolls heat up when metal is in the stand and cool down when the stand is empty. As roll temperature increases the diameter expands causing the actual roll gap to decrease.

This effect cannot be measured while rolling so it is modeled by the setup model using the roll material characteristics, metal temperatures, rolling time and length, cooling spray flows, etc. The effect is separated into a long term effect and a short term effect. The long term (pass to pass, product to product) effect is included a gap position reference offset. The short term effect is modeled as a simple exponential time constant. The setup model provides the final value of gap change and the time constant for each product.

5.3. Roll Bending Compensation

Roll Bending is used to help control strip profile and flatness. Depending on the mechanical configuration, the force produced by positive (crown in) roll bending cylinders can be measured by the stand force sensors even though the positive bending forces do not help to reduce the strip. Therefore the Strip Force is calculated by subtracting the positive roll bending force from the load cell force. Note that the load cells are calibrated to produce zero tons with Backup Roll balance on, Roll Bending and balance off, and the stand roll gap open that determines a Tare Force that must also be subtracted from load cell force.

The roll gap position is calibrated with Roll Bending at a roll balance force. When bending force changes from balance force there will be a change to the effective roll gap. The predominant effect on the roll gap is that an increase in positive bending will stretch the mill housing causing the effective gap to open. MMC AGC will not correct for this stretch because the positive bending force is not included in strip force. The gap correction necessary to compensate for this stretch must close the gap by an amount equal to the bending force (above bending force at gap calibration) divided by the mill housing modulus.

6. Applications

6.1. Design Approach

This thickness control could only be achieved through proper system design. The most important design objectives were high availability, efficient installation, optimum delivery, and ease of maintenance. A flexible modular approach was chosen to enhance these design objectives. This approach was further enhanced with the extensive use of structured design techniques.

Structured design techniques were used throughout both the hardware and software parts. The essential nature of structured design involves breaking down the complex requirements into small modules which are then easily managed. The main design effort is involved in the process of building each module and assembling them together to form the complex set of automation functions. Good structured design promotes the flexible modular approach which is significant both during the design phase and for the long-term maintenance of the system.

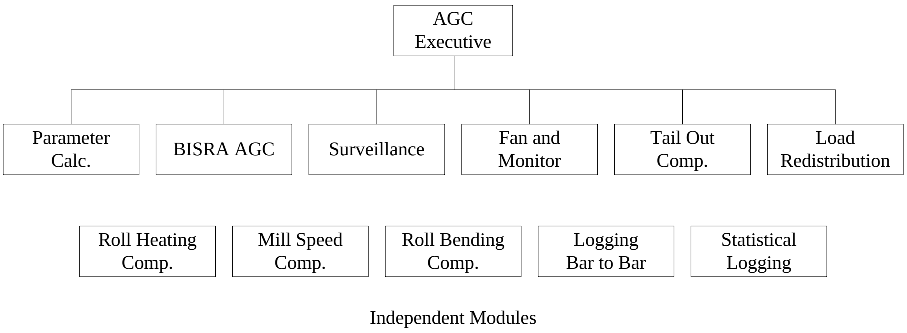

Figure 7. Software Structure of Automatic Gauge Control

The AGC software was divided into a number of individual control units, actions, and communication modules. Many of them were managed as a coordinated group of AGC functions while other functions were performed as more individual modules separate from this group. The division of the AGC functions is shown in Figure 7.

6.2. Software Planning

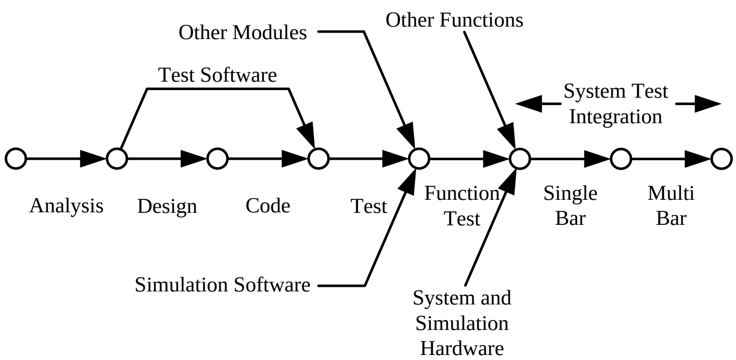

Figure 8. Software Design Planning Chart

Each of the individual software modules has a similar life history. Figure 8 contains a generalized view of that history. There is an analysis phase, a design phase, a coding phase, and an individual testing phase. Groups of modules were brought together to provide functional tests. Then many functions were combined together for a total simulation involving both hardware and software integration. Individual module test software was designed. In addition a very flexible and comprehensive software simulation package was developed and used prior to, and during, the hardware and software integration phase.

In the initial analysis phase fully 80-90 percent of the final system documentation was produced. This documentation was subject to a rigorous design inspection and review procedure. This procedure was very successful and ensured at an early stage in the project that all the individual parts would eventually fit together correctly. Both customer and factory personnel worked together during the design phase. Work activities were allocated based on skill and experience among all team members.

7. Conclusion

The plate mill thickness control system described herein was successfully installed at the No. 2 Plate Mill of Handan Hongri Metallurgy Co. Ltd., China. The system has surpassed its original performance targets. This success was not the result of a single factor, but of the thorough coordination of the total thickness control system. This included well-developed control strategies, structured design implementation, accurate simulation and calibration of the mill prior to rolling, as well as the availability of fully tested engineering analysis tools for the first day of rolling. The system was quickly brought on-line and has continued to enjoy very stable high performance as a result of these efforts.

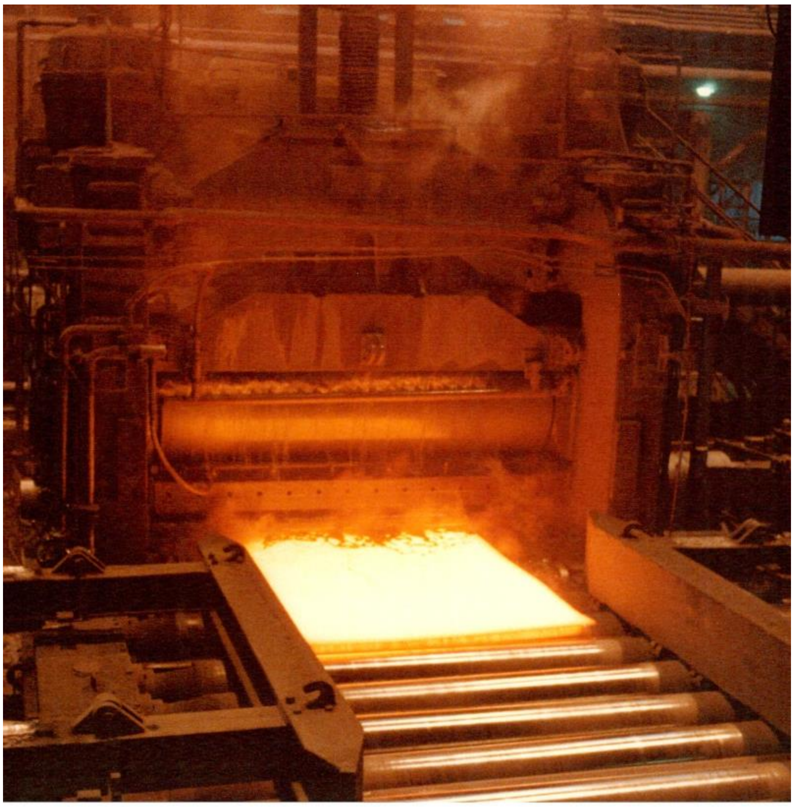

Figure 9. Plate Rolling Process

The thickness accuracy guaranteed value of the automation system is shown in Table 1. With AGC function in basic automation system, the plate thickness accuracy can be guaranteed.

Table 1. Plate Thickness Accuracy Guaranteed Value

	Target thickness range (mm)	Thickness tolerance (2σ) (mm)
Thickness accuracy along one plate length	$6 \le h \le 10$	≤0.08
	$10 < h \le 20$	≤0.10
	$20 < h \le 30$	≤0.12
	$30 < h \le 50$	≤0.16
	$50 < h$	≤0.24
Thickness accuracy for different plates	$6 \le h \le 10$	≤0.10
	$10 < h \le 20$	≤0.12
	$20 < h \le 30$	≤0.15
	$30 < h \le 50$	≤0.20
	$50 < h$	≤0.30

We have collected statistics data for 7 months, and conclude from the data analysis that the average thickness qualified rate of the No. 2 plate mill is 1.4 percent higher than the No. 1 Plate Mill which was built two years ago.

Although there are fruitful research achievements in the field of thickness control, AGC technique still has a great space to improve. To design more accurate gauge models and compensations is a direction for the development of AGC, and under the complex mode condition, the elastic curve model is still worth further study. In high-precision rolling, tiny fluctuations of thickness due to roll eccentricity, wear and bearing oil film can never be ignored. That means how to realize the measurement and compensation of these tiny signals is an important task. In addition, thickness control technology based on artificial intelligent is another direction for the development of AGC. Nowadays, AGC based on the artificial intelligent control strategies is mostly in the stage of theoretical simulation, and how to apply in the actual project needs further study.

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

Acknowledgements

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