Research and application of computer control system for aluminium single-stand 4-high cold rolling mill

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Abstract: This study introduces the technical specifications and the technological process of the aluminium single-stand 4-high cold rolling mill, and analyses the mathematical model of the rolling process. The automation system adopts 3-level computer control, which actuators and sensors (Level 0), basic automation level (Level 1) and process automation level (Level 2), to realise the network data tracking, dynamic adaptive rolling procedure setting, self-learning model and automatic control of the whole rolling process. The computer control system described has been in full commercial operation after a large number of functional and performance tests. The effectiveness of 3-level control concept was verified to ensure the quality of the product, and to meet the expected goal of designing.

1 Introduction

Aluminium cold rolling is a rolling process to reduce the thickness with a further objective of improving the strength, surface finish and formability of the stock by conducting the process of rolling at the room temperature [1]. Aluminium alloys can be cold rolled down to thickness of around 0.05 mm. Pure (low-alloy) aluminium can be cold rolled into foil as thin as 0.0025 mm. Strip destined for cold rolling to thickness under about 1 mm is usually hot rolled to about 3-6 mm before cold rolling begins.

Quality in this industry means a material that has the same properties over all its length and width: identical thickness, lack of internal tensions (good flatness), surface quality [2] etc. During rolling, the mill is subject to the disturbances which affect product thickness, shape and tension. The first of these is the variation in entry strip thickness. The incoming strip has previously been hot rolled, and has some pattern of thickness variations characteristic of the hot mill. Second, the mill is threaded at low speed, and accelerated to its working speed after winding the head end of a coil on the coiler. A similar process of deceleration is followed on runout at the end of the coil. It is well known that roll-bite friction between the work rolls (WRs) and the strip changes as the rolling speed is increased from thread speed to run speed, causing changes in roll force and subsequent gauge and tension disturbances [3].

As the work hardening increases, it takes more power to roll the sheet thinner. Beyond a certain degree of hardness, the metal may crack if it is rolled again [4]. This imposes practical limits on the amount of cold rolled thickness reduction that can be achieved in an uninterrupted series of passes. When further thickness reduction is necessary, the sheet must be annealed as described above to soften the metal for further cold rolling.

In this paper, attention is focused on the control of gauge, or strip thickness, shape and tension, during cold rolling of flat rolled aluminium strip in the presence of disturbances that are repeatable from coil to coil. Fig. 1 illustrates the major components of an aluminium single-stand 4-high cold rolling mill, and introduces some of the terminologies used in the rest of this paper. The main specifications of the mill are demonstrated in Table 1.

2 Mathematical models

Thickness precision and shape precision are the two most important quality indexes in strip rolling process [5, 6]. In the rolling of metals, especially the final cold rolling of sheet materials, the variation of thickness along the length as well as flatness along the width of the strip must be controlled within very tight tolerances [7].

2.1 Force equation

The well-known Sims' model is presented widely in the literature as being useful for control development [8]. In Sims' model, the specific roll force is represented as

$$P = Wkk_{\mathrm{t}}Q_pL \tag{1}$$

where W is the strip width, k is the resistance to deformation, k_{t} is the effect of tensions, Q_p is the roll force function and L is the projected contact length.

Referring to Fig. 2, which approximately represents the strip in the roll-bite area, the incoming strip is of thickness H at its centreline and is moving toward the roll bite with speed v_{in}. The strip exits the roll bite with thickness h at its centreline and with speed v_{out} [9–11].

The projected contact length is expressed as

$$L = \sqrt{R'(H-h)} \tag{2}$$

The flattened but still circular roll radius is obtainable from Hitchcock's relation [12]

$$R' = R\left[1 + \frac{16(1-v)^2}{\pi E(H-h)}\right] \tag{3}$$

where R is the original radius of the WR, and v and E are the Poisson's ratio and the Young's modulus for the WR, respectively.

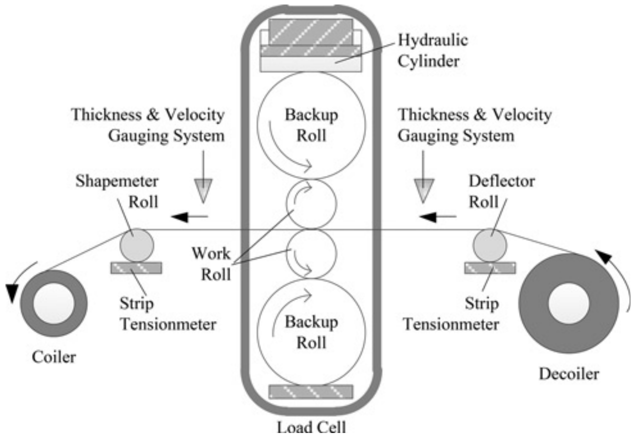

Fig. 1 *Structure of the aluminium cold rolling mill*

Table 1 Specifications of the aluminium cold rolling mill

Name	Content
mill type	single-stand 4-high cold rolling mill
coiler type	cantilever pyramid
maximum mill speed, m/min	1500
maximum roll force, kN	16,000
maximum weight of the coil, kg	20,000
maximum outer diameter of the coil, mm	2500
bending force range, kN	−350∼500
WR diameter, mm	370–400
BUR diameter, mm	1110–1150
incoming strip width, mm	830–1700
incoming strip thickness, mm	2–10
delivery thickness, mm	0.2–4.0

2.2 Gaugemeter equation

A typical and basic modelling task is that associated with setting up the roll gaps in a mill. Since the large deformation force P required to reduce the strip thickness from entry thickness H to exit thickness h causes the stand frame holding the rolls to stretch, and mill rolls to bend and flatten. The result is the exit thickness as a function of force P. In simplified form this can be expressed as [13]

$$h = S + f(P) \tag{4}$$

where S is the unloaded roll gap and the term $f(P)$ is the mill stretch.

As shown in Fig. 2, the normally used simplified thickness model of gaugemeter equation or spring equation has the following form [14]

$$h = S + \frac{P}{M} \tag{5}$$

where M is the mill modulus or stiffness coefficient and P/M is the approximate value of mill stretch.

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 (BUR) and WR. Stack deflection is typically linear with force but varies significantly as the strip width changes. Fig. 3 attempts to show the relationships between gap position, mill stretch and strip thickness [14].

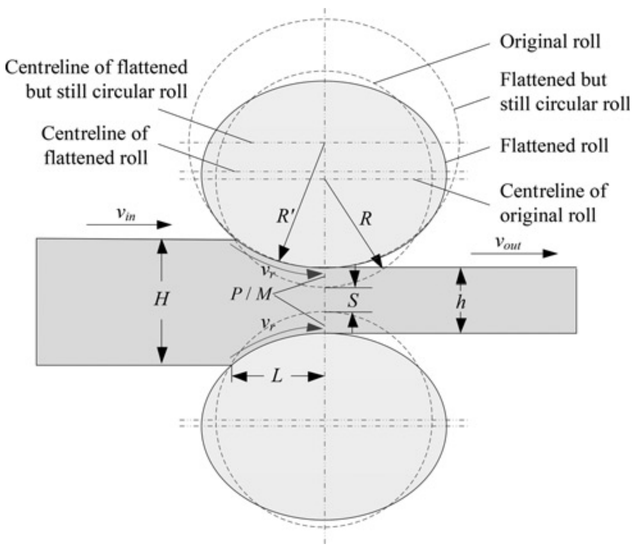

Fig. 2 *Roll-bite area*

2.3 Forward slip equation

The forward slip results from the difference between exit strip velocity and WR velocity [15] and is defined as

$$f = \frac{v_{\rm out} - v_{\rm r}}{v_{\rm r}} \tag{6}$$

where $v_{\rm out}$ is the exit strip velocity and $v_{\rm r}$ is the WR velocity.

When the exit strip velocity cannot be measured directly, the forward slip can be obtained by measuring strip tension and thickness [16].

A more useful model is that described by Ford *et al.* in [17]. In this model, which is often applied for cold mill applications and is used in the work described in this paper, the forward slip is expressed as

$$f = \frac{R'}{h}\beta_n^2 \tag{7}$$

where $\sigma_{\rm in}$ and $\sigma_{\rm out}$ are the strip tension stresses at the stand input and output, respectively; μ is the friction coefficient and

$$\beta_n = \frac{1}{2}\sqrt{\frac{H-h}{R'}} - \frac{(H-h)k + \sigma_{\rm in}H - \sigma_{\rm out}h}{4kR'\mu} \tag{8}$$

In the case of cold rolling, μ is taken as the coefficient for sliding friction. In the case of hot rolling, μ is taken as the coefficient for sticking friction which is approximated by the empirical relationship given in Roberts [18] as

$$\mu = 0.00027T_{\rm F} - 0.08 \tag{9}$$

where $T_{\rm F}$ is the temperature of the strip in degrees Fahrenheit.

3 System configuration

According to our previous engineering experience, the characteristics of aluminium cold rolling process and the development trend of computer control system should be considered in the design of computer system structure to make the system advanced, reliable, simple and reasonable. The control system design of cold rolling mill follows the principle of ‘high-speed control, high-speed

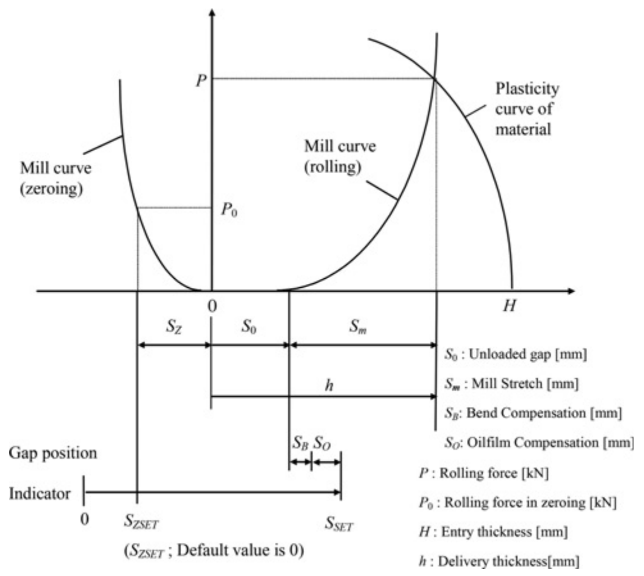

Fig. 3 *Mill stretch characteristics*

communication'. In recent years, thanks to the development of computer technology and hydraulic servo technology, control cycles of closed-loop hydraulic systems have reduced from 100 to 10 ms, and some of them are even <2 ms. Since of the interactions between the functions of the cold rolling, the data update rate of the communications between controllers is <1 ms.

On the basis of the equipment parameters and process layout, we designed the hardware and software configuration of the automation control system of the production line. Automation system adopts 3-level computer control, which includes actuators and sensors (Level 0), basic automation level (Level 1) and process automation level (Level 2), to realise the network data tracking, dynamic adaptive rolling procedure setting, self-learning model and automatic control of the whole rolling process. The structure of the aluminium cold rolling mill is shown in Fig. 4.

The automation architecture of the cold mill includes the following three levels [12]:

Level 2: From entry and exit coil data specifications, this level is responsible for finding the best mill set-up in order to ensure high quality and productivity. On the basis of static models, this level includes a set-up optimisation procedure and an adaptive loop which improves the set-up specification for every new coil.

Level 1: According to the reference signals from level 2 and measured process signals, suitable control signals are generated in this level for the actuators. This level includes the dynamic model and the mill master logic. In addition, it records the process variables necessary to the adaptive functions of level 2.

Level 0: This level includes sensors, motor drives and hydraulic actuators for gap control.

4 Process automation system

4.1 *Software structure*

Operating system and application software adopt sophisticated and generic commercial products. Middleware is the core software to support process automation system or the application software development platform and the running environment. Its main role is to shield the differences of hardware platform and operating system and the complexity of underlying operating system, make application developers face a simple and unified development environment, and reduce the complexity of development and maintenance of process automation application software.

This project uses our independently developed middleware process control develop platform (PCDP), whose system architecture is shown in Fig. 5, where open database connectivity (ODBC) is short for open database connectivity; realtime data file management (RDFM), inter-process communication (IPC), HubWare, Logger, DBLinker, TagCenter and TaskWatch indicate real-time data file management, inter-process communication management, external

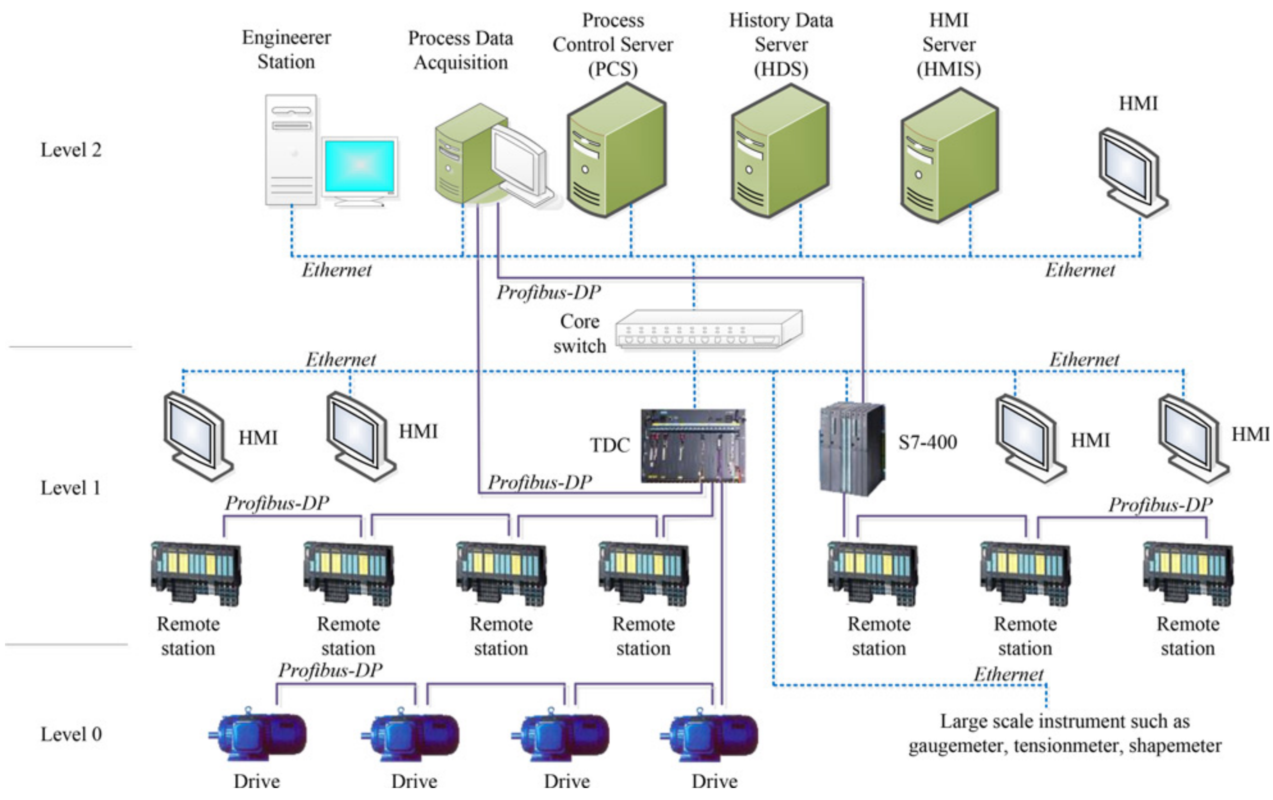

Fig. 4 *Structure of the aluminium cold rolling mill*

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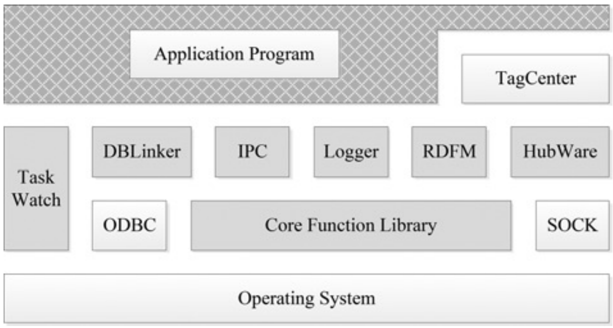

Fig. 5 *System architecture of PCDP*

communication management, alarm log management, database connection management, human–machine interface (HMI) tag management and system process management, respectively.

As a very complex software system, level 2 control system needs to be realised by different levels, different functions of multiple tasks. It is generally divided into middleware, application programme, operating system and system software, which are illustrated in Fig. 6. The application software can realise the free combination according to the configuration of production equipment and function, and can be separately upgraded and partially reformed, which provides a great convenience and space for further expansion and upgrade of the system.

4.2 Control functions

Process control system is a comprehensive software system including rolling strategy, set value calculation, raw data collection, set value output, self-adaption and self-learning of mathematical models. It is one of the most important parts of automatic control system. As shown in Fig. 7, the rolling process control can be organised in accordance with following functions:

(i) *Primary data and rolling schedule management:* According to production plan, the operator inputs and edits the primary data of aluminium coil in the HMI screen, and then saves the data to the appropriate database management system. The main primary data information (PDI) data includes current coil number, incoming coil number, incoming thickness, incoming width, incoming weight, incoming length, incoming coil diameter, material composition grade, delivery thickness etc.
(ii) *Rolled piece data tracking:* The purpose of tracking is to determine the actual position and the situation of the rolled piece in the production line, so as to start related programmes in the stipulated time to complete other functions of process control. The tracking function of Level 2 is based on the tracking results sent from Level 1.
(iii) *Rolling parameter setting calculation:* Rolling parameter setting calculation function is the basic function of the process control system, and it is the premise and foundation of computer control. The setting control model consists of two parts: namely, the rolling strategy model and the setting calculation model.
(iv) *Self-adaption and self-learning of mathematical models:* The setting value of process control is the starting point of automatic gauge control (AGC) and automatic shape control (ASC). The precision of the setting value directly influences the efficiency and effect of the thickness and shape control. To improve the accuracy of the set value, the mathematical model is modified by measured data to constantly adapt to the evolution of equipment and environment over time.

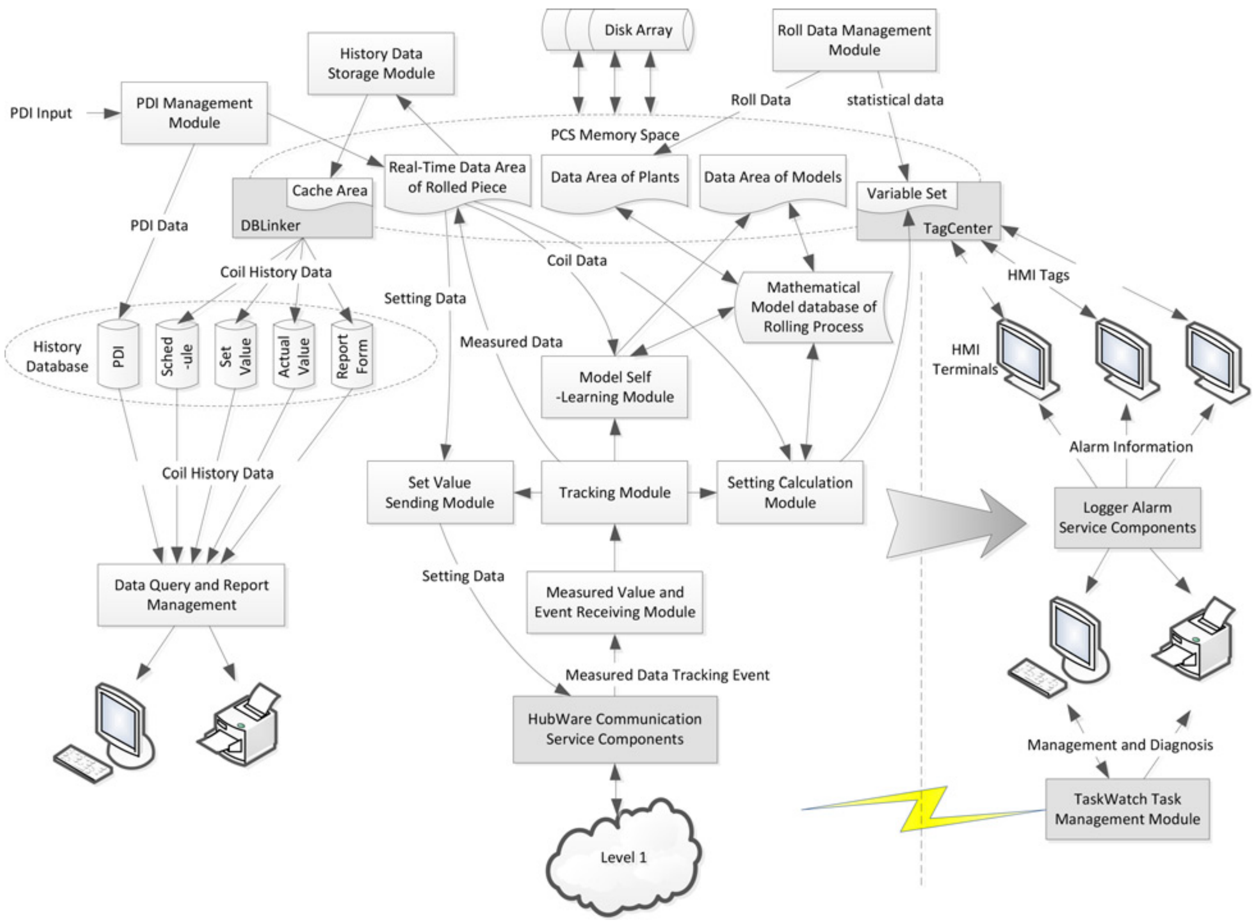

Fig. 6 *Structure chart of application software*

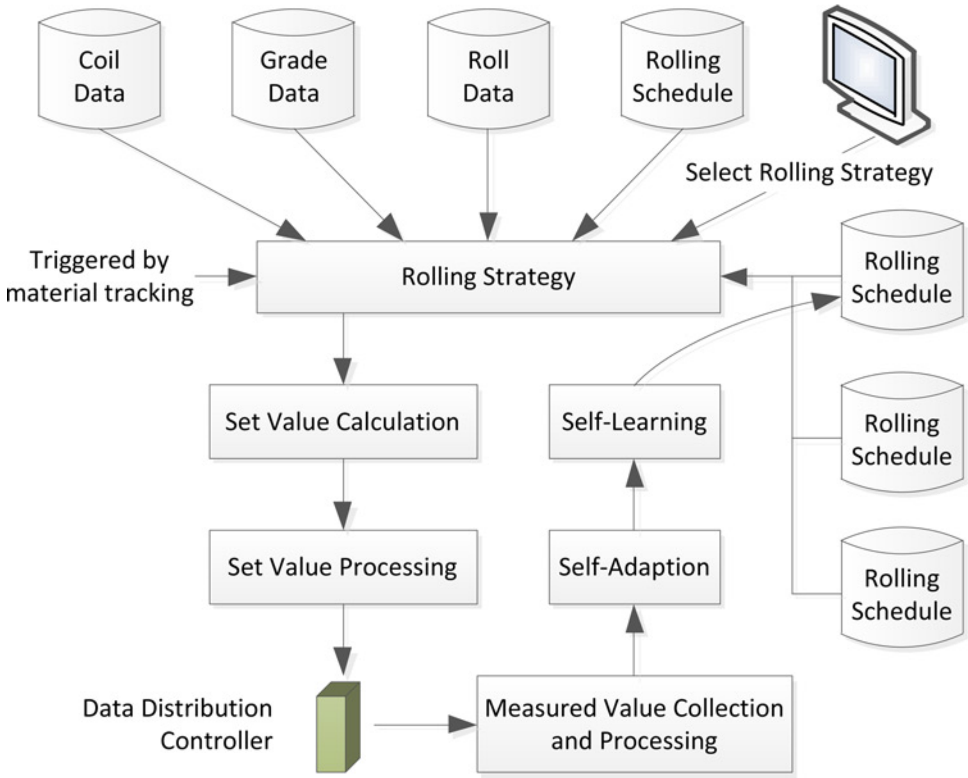

Fig. 7 *Control system function chart*

(v) *External communication management:* The data communication module is mainly to collect and process the measured value from Level 1, and to send the set value to Level 1 when the calculation is finished. The process control server directly exchanges data with technology and drive control (TDC) and S7-400 of Level 1 through HubWare component of the middleware PCDP.

(vi) *HMI management:* HMI screen is divided into two types of display screen and input screen. The process control information is available through display screen. The necessary data and commands are input to the computer through input screen or keyboard. HMI management module calls the HubWare components of the middleware PCDP to programme interface function after the completion of the setting calculation, and displays the set value to HMI terminals. In addition, it monitors HMI action to trigger corresponding application in response to the various operator control command.

5 Basic automation system

5.1 Controllers and communications

The Siemens SIMATIC programmable logic controller (PLC) family consists of several types of scalable central processing unit (CPU) lines. Depending on the type and speed of the control loop, the user can choose the optimum PLC required for his application. As shown in Fig. 8, SIMATIC TDC and S7-400 are adopted as controllers of the basic automation system.

SIMATIC TDC solves even complex drive, control and technology tasks with maximum quantity frameworks and shortest cycle times on one single platform. The system is used particularly for large plants in the process, energy and drive technology. The powerful processor modules of SIMATIC TDC allow the processing of maximum quantity frameworks in short cycle times down to 100 µs. The engineering of even complex control structures is carried out efficiently with the SIMATIC standard languages continuous function chart (CFC) and sequential function chart (SFC) and an extensive function block library. The user gets a maximum flexibility by creating own user libraries based on ANSIC code.

S7-400 is a programmable logic controller. Almost any automation task can be implemented with a suitable choice of S7-400 components. S7-400 modules have a block design for swing-mounting in a rack. Expansion racks are available to extend the system.

The network topology structure adopts the hierarchical design, which fully considers the characteristics of information flow and data flow in cold rolling production. Communications between controllers, servers, HMIs, large-scale instruments and other computers rely on industrial Ethernet. The optical cable is used for long-distance communication network while twisted pair cable for short distance.

Profibus is a messaging format specifically designed for high-speed serial input/output (I/O) in factory and building automation applications. It is an open standard and is recognised as the fastest fieldbus in operation today. By introducing a network bus between the main controller (master) and its I/O channels (slaves), we have decentralised the I/O, which can be seen in Fig. 4, where TDC and S7-400 serve as the profibus masters, remote I/O stations and drive controllers serve as the profibus slaves. Each slave processes information and sends output to its master.

5.2 Control functions

The basic automation system realises logical control, sequence control and important technological control functions, and also monitors the running status of the equipment. It ensures highly automated operation and control of the process and affects the quality and yield of the whole line directly [19].

(i) *Hydraulic gap control (HGC):* Cylinder position is controlled by a closed-loop position regulator that automatically adjusts the flow reference to a hydraulic servo valve. There are separate operator and drive side position regulators. The operator and drive sides are coupled by software control that maintains the level between the

Fig. 8 *Controllers of the basic automation system*
a SIMATIC TDC
b SIMATIC S7-400

two sides as the two sides are moved 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.

(ii) *Mill zeroing:* For zeroing, the roll gap is closed using the hydraulic capsules. The gap actual value is set to a defined value at a given roll force. During the mill zeroing procedure, the HGC is operated in roll force control mode in order to level the roll gap. The calibration programme is a step controller that creates the process environment for the zeroing and for calibrating the position and tilt counters. The basic calibration sequence is always necessary when no relationship exists between the counter and the stand position. This can occur when the count is lost (screwdown control restart, power failure, position encoder fault and counter fault) or when the operating conditions have changed (roll change, pass line position adjusted).

(iii) *AGC:* During rolling process, thickness deviation or hardness transformation in the material of an incoming strip causes transformation in the roll force, which for its part cause transformation in the stand elongation and thus deviation from the strip target thickness. This transformation is used in a roll force control system by comparing the transformation with a roll force target value. These roll force deviation is corrected on the basis of the gaugemeter principle. This results in keeping the roll gap and thereby the thickness of the material constant. As shown in Fig. 9, the AGC correction is considered by the HGC as an additional position reference.

(iv) *ASC:* With a 4-high mill, the rolling reaction force results in deflection of the BUR and WR, flattening of the WR and other

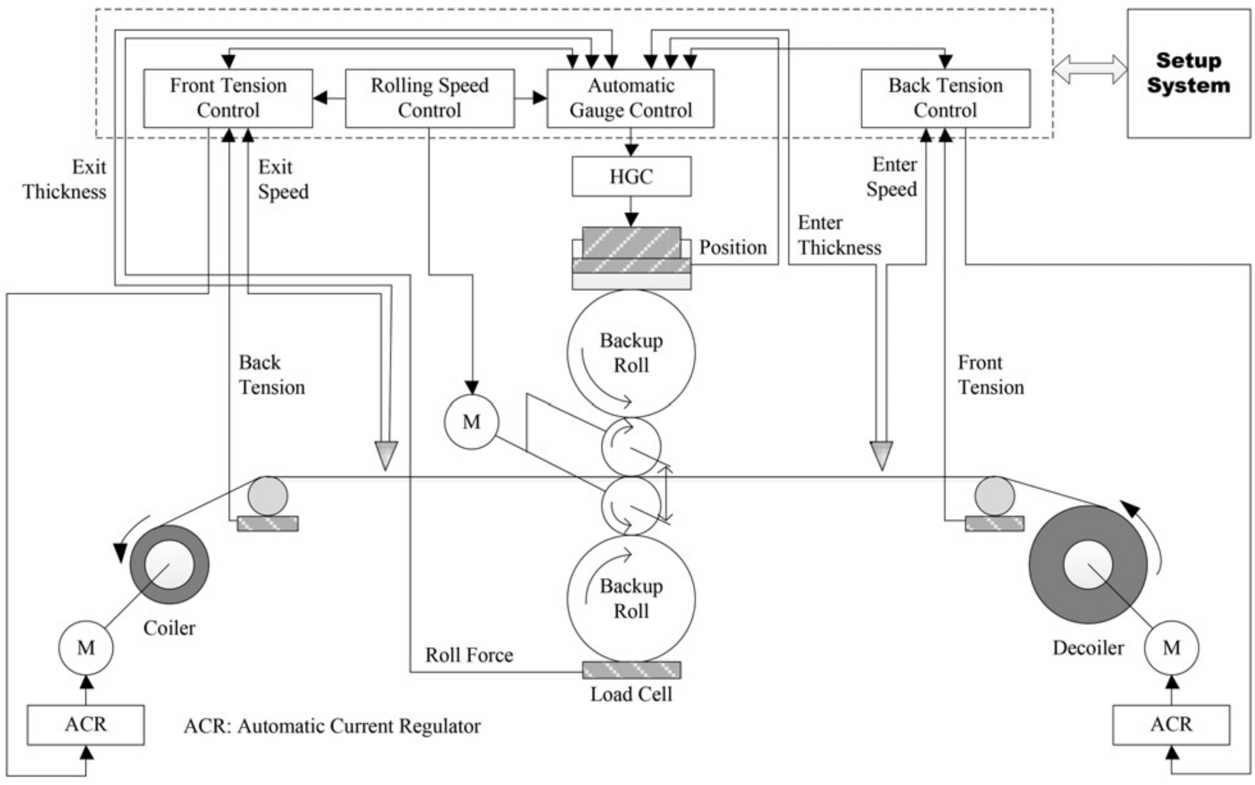

Fig. 9 *Outline of AGC*

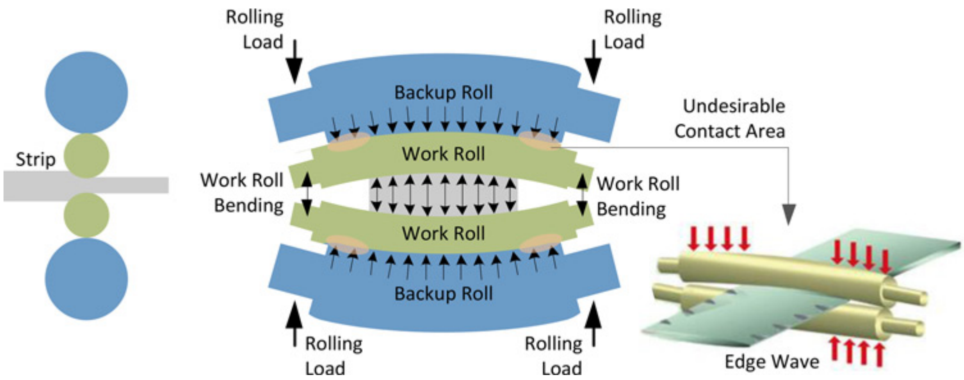

Fig. 10 *Roll gap profile during rolling process*

Fig. 11 *Cold rolling aluminium coils*

problems during rolling. This leads to unevenness in the rolled material strip thickness and to shape problems, as shown in Fig. 10. Especially at the strip head and the strip tail end, high gradients of the roll force changes are occurring. For the improvement of the control result at roll force changes, the process model considers this disturbance variable and the shape actuators are pilot controlled. The operating model calculates the manipulated variables for the shape actuators in consideration of the regulations filed in the process model and the existing disturbance variables. The calculation of the manipulated variables is effected by minimisation of the shape fault by means of the error square method. Here, the different dynamic behaviours of the individual actuators are considered in such a way that dangerous strip tension distributions are avoided during control. After the calculation, actuating commands are output to the shape actuators of the mill stand. The actuating commands are roll bending, roll tilting and roll cooling.

Table 2 Thickness accuracy guaranteed value

	Product thickness range, mm	Thickness tolerance (2σ), µm
thickness accuracy	$0.1 \le h \le 0.2$	±2
	$0.2 < h \le 0.4$	±3
	$0.4 < h \le 0.6$	±5
	$0.6 < h \le 1.0$	±6
	$1.0 < h \le 2.0$	±8
	$2.0 < h$	±12

(v) *Automatic tension control (ATC):* Tension mainly plays the following roles in aluminium cold rolling: (a) preventing lateral movement; (b) improving strip flatness; (c) reducing rolling force; and (d) properly adjusting strip thickness [20, 21]. Tension directly affects thickness accuracy, shape accuracy and surface quality of the product, further affects the rolling speed, and must be controlled effectively for faster and better rolling. ATC uses the combined tension control mode which is the combination of direct and indirect tension loops. Direct tension loop uses measured tension as the feedback and avoids the influence of coil diameter change, rolling speed change, no-load torque but its control effect is poor at low speed. Indirect tension loop uses tension calculated by torque and coil diameter. Its control effect is higher than direct tension loop at low speed. This combined method has the advantages of fast response, good stability of indirect tension control, high accuracy and no steady error of direct tension control.

6 Practical application results

The computer control system described in this paper has been in full commercial operation after a large number of functional and performance tests. The effectiveness of 3-level control concept was verified to ensure the quality of the product, and to meet the expected goal of designing. This success was not the result of a single factor but of the thorough coordination of the total computer control system. This included precise setting control model, well-developed control strategies, structured design implementation, simple and practical operation screen, accurate simulation 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 online and has continued to enjoy very stable high performance as a result of these effort. Fig. 11 shows the cold rolled aluminium coils produced by the production line which is controlled by the computer control system.

The thickness accuracy guaranteed value of the automation system is shown in Table 2, and the flatness accuracy guaranteed tolerance (2σ) is 10I. On the basis of set-up calculation in level 2, and with AGC, ASC and ATC in level 1, the thickness accuracy and flatness accuracy of the cold aluminium strip can be guaranteed.

7 Conclusions

This paper has presented a computer control system for aluminium single-stand 4-high cold rolling mill. The 3-level automation system can significantly improve the dimensional accuracy of the aluminium strip, quickly adapt to the changes in rolling specification, and significantly improve the mechanical properties of the steel plate. At the same time, it can also reduce the number of wrong rolling, streamline operations and improve rolling rhythm. According to the performance of the system after running, it is easy to operate, stable and reliable. The thickness accuracy and flatness accuracy have reached the domestic advanced level, which improved the competitiveness of aluminium products, and created good economic benefits for enterprises.

8 Acknowledgments

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