A Study on Rolling Mill Dynamics Model and Automatic Gauge Control System

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Abstract: In the rolling of steel or non-steel metal the most important quality aspect are thickness and flatness. In thickness, there are two important factors. One of them is getting close with accurate goal, nominal gauge, the other is minimize gauge bandwidth, the variation in gauge. In this thesis, we proposed the fuzzy model AGC to minimize gauge variation along the length, developed the rolling mill dynamic model using the math mode of the rolling mill process and the rolling model related with the variety character of the rolling material. We compared the gauge control efficiency of fuzzy model AGC and PI mass flow AGC. We have got a simulation result, that the exit gauge variation of PI mass flow AGC was 2 micron and fuzzy model AGC was 1.2 micron at 1200mpm of rolling speed when each controller was rolling 5 micron of material that is the entry gauge variation.

Keywords: Automatic gauge control (AGC), fuzzy model AGC, rolling mill dynamics model, rolling model.

1. INTRODUCTION

In this article, we describe regarding gauge bandwidth improvement of the aluminum Can Body Stock (CBS). We proposed the fuzzy model AGC to minimize gauge variation along the length, developed the rolling mill dynamic model using the math mode of the rolling mill process and the rolling model related with the variety character of the rolling material. First, in the rolling mill process we developed it to understand action state, the development of the rolling mill control system, the best gain of the control system. Secondly, in the rolling model to make new rolling pass schedule for improvement in productivity, to change operation method for improvement in quality and to make initial pass schedule for the development of new manufactures.

PI mass flow automatic gauge control system has excellent performance among measuring control equipment up to now [1]. But in proportion to the increase of the rolling velocity, the system has an unstable defect. And to replenish these defects, fuzzy controller was designed to control stable thickness at high rolling speed.

The fuzzy rule is used to find the optimized cylinder target using estimated thickness through mill bite. The input variables are estimated thickness error at mill bite, rolling speed, and metal hardness.

We used rolling model and rolling mill dynamic model to modify control rules for the input variables. We found the rolling variations such as rolling passes, coolant, and material from upper computer. Also, using rolling model and mill data. We found the rolling variations, created by rolling material, such as rolling load. Additionally, we estimated mill stretching due to load, strip speed on entry and exit site, strip gauge change, roll load cylinder location by rolling mill dynamic model based on mathematical model of process. Based on these modeling, it produces the best-suited control rule, and the produced rules delivered to fuzzy rule transformer. The transformer delivers to fuzzy controller

The content of this paper is organized as follows. In section 2, the general subjects about the mass flow gauge control are described. In section 3, the rolling dynamics model is described. In section 4, we present a configuration of new fuzzy model AGC and a implementation of the control system. In section 5, the simulation result of fuzzy model AGC is described. Finally, section 6, the conclusion is described.

2. MASS FLOW GAUGE CONTROL

Mass flow gauge control is based on the continuity of material flow across the roll bite which in simple terms states that what goes in must come out. In other words, by assuming constant material width across the roll bite the product of entry gauge and entry speed must be equal to the product of exit gauge and exit speed. This means that by knowing the values of entry gauge, entry speed and exit speed, the exit gauge at the roll bite can be calculated. The advantage of calculating the exit gauge at the roll bite is that it removes the transport delay associated with a downstream exit gauge measurement.

The mass flow gauge controller is as shown in Fig. 1 and comprises an inner loop using measurements of entry speed, exit speed and entry gauge, and an outer loop using a measurement of exit gauge.

Hence Mass Flow control is based on the principle that amount of material flowing into the roll bite must equal that living it, and that material in cold rolling mills only flows in direction of rolling. Mass flow equation is obtained as follows Eq. (1).

$$V \cdot H = v \cdot h \qquad (1)$$

Where V : Entry strip speed (m/min)
H : Entry thickness at the roll bite (mm)
v : Exit strip speed (m/min)
h : Exit thickness at the roll bite (mm)

Based on these assumptions it is possible by knowing the entry gauge, entry speed and exit speed to calculate the exit gauge at the work roll bite and hence the exit gauge error. Eq. (1) can be represented as estimated exit gauge h as Eq. (2).

$$h = \frac{V \cdot H}{v} \tag{2}$$

Therefore to find exit gauge error, Δh is described as Eq. (3)

$$\Delta h = \left(\frac{V \cdot H}{v} \right) - h_{tgt} = h_{bite} - h_{tgt} \tag{3}$$

Where h_{tgt} : Exit gauge target

h_{bite} : Calculated exit gauge at the roll bite

If all of the measurement instrument were correctly calibrated and sufficiently accurate then there would be no need to include the gauge controller. However, in practice there will always be calibration and measurement errors and it is necessary to use gauge error feedback with mass flow control. Eq. (3) can be represented as an exit gauge target h_{tgt} Eq. (4).

$$h_{tgt} = h_{ref} - h_{trim} \tag{4}$$

Where h_{tgt} : Exit gauge target

href :Operation nominal exit thickness target

htrim:Gauge error feedback trim

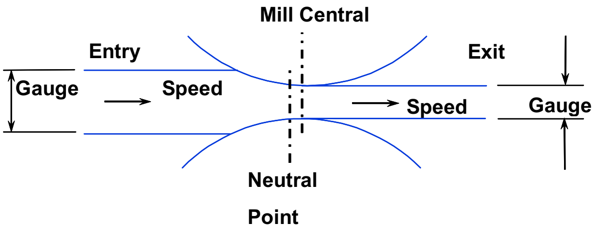


Fig. 1.Continuity Equation

As shown in Fig. 2, the inner loop is used to attenuate gauge errors whereas the outer loop is used to ensure nominal exit gauge during the coil. To this end the inner loop has a highly tuned speed dependant proportional and integral controller whereas the outer loop has a relatively detuned integral controller.

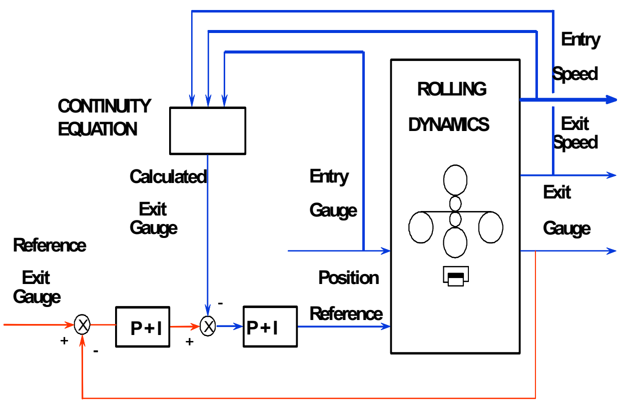


Fig. 2 Mass Flow Gauge Controller

3. ROLLING MILL DYNAMICS MODEL

A model has been developed for the cold mill as outline as Fig. 3. The roll load cylinders are in position control and provide force acting within the mill stack. Changes in entry gauge and entry tension also provide force acting within the mill stack with the former tending to push the rolls apart and the latter tending to pull the rolls together [2].

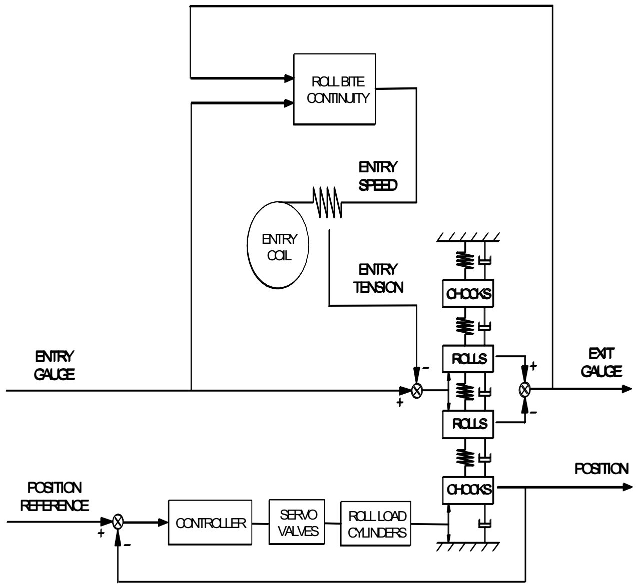


Fig. 3 Cold mill model

3.1 Mill stack model

Within the mill stack the rolling load passes from the roll load cylinders, through the bottom back-up roll assembly, through the bottom work roll, through the material, through the top work roll, through the top back-up roll assembly and finally through the housings. Under the rolling load each one of these mill components will offer some compliance as following:

- Roll contacts will flatten with a stiffness K_{CT}.
- Back-up roll necks will bend with a stiffness K_{NK}.
- Housings will stretch with a stiffness K_{HG}.
- Material will be squashed with a stiffness K_{SP}.

The stack dependent terms K_{CT}, K_{NK} and K_{HG} combine, as shown in Fig. 3, to give what is referred to mill stiffness K_{ML} as follow Eq. (5).

$$\frac{1}{K_{ML}} = \frac{3}{K_{CT}} + \frac{1}{K_{NK}} + \frac{1}{2K_{HG}} \tag{5}$$

The simplified mill stack is shown in Fig. 4.

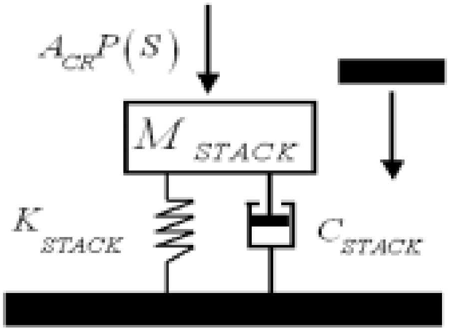


Fig. 4 Simplified Mill Stack and Housing Model

Fig 4 shows such a system where the roll load cylinder force which is lifting a mill stack of mass, moving against a mill housing of stiffness with an overall damping coefficient [3].
A simplified transfer function for mill is obtained as follows Eq. (6).

$$\frac{X(s)}{P(s)}=\frac{A_{CR}}{M_{STACK}\cdot s^2+C_{STACK}\cdot s+K_{STACK}} \tag{6}$$

Eq.(6) can be represented in mill stack model as block diagram Fig. 5

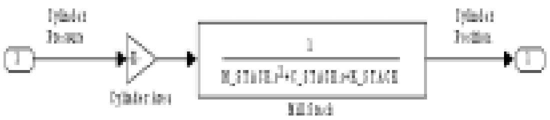


Fig.5 Mill Stack Block Diagram

By comparing Eq. (6) with the standard equation for second order system, as Eq. (7).

$$\frac{Output(s)}{Input(s)}=\frac{\omega_n^{\ 2}}{s^2+2\cdot\zeta\cdot\omega_n\cdot s+\omega_n^{\ 2}} \tag{7}$$

Where $\omega_n=\sqrt{\dfrac{K_{STACK}}{M}}$ $\qquad C=2M\zeta\omega_n$

3.2 Addition of Roll Load Cylinder Control Loop

The addition of the roll load cylinder control loop also requires consideration of the dynamics of the hydraulic system used. Thus the effect of the hydraulic stiffness of the roll load cylinders and some consideration of the control valve dynamics are needed. Also in this stage the entry interactions have been written in expanded from as shown in Eqs (8)~(12).

$$\delta Q=\delta Q_{SLEW}+\delta Q_{COM} \tag{8}$$

$$\delta Q_{SLEW}=2A_{CR}Z2 \tag{9}$$

$$\delta Q_{COM}=\delta\dot{P}\frac{2V_{CR}}{\beta_E} \tag{10}$$

$$K_{CR}=\frac{2\beta_E A_{CR}^{\ 2}}{V_{CR}} \tag{11}$$

$$\dot{Z}9=\frac{\beta_E}{2V_{CR}}(Z10-2A_{CR}Z2) \tag{12}$$

where δQ : flow of hydraulic oil

δQ_{SLEW} : cylinder movement

δQ_{COM} : compressibility of the hydraulic oil

A_{CR}: the cylinder area

β_E : effective bulk modulus

$\delta\dot{P}$: rate of change of cylinder pressure

4. FUZZY MODEL AGC

Fig. 6 shows a simplified block diagram of the Fuzzy model AGC scheme. As with the feed forward controller it is necessary to compensate for the entry transport delay such that the exit gauge error is correctly calculated for the section of the strip which is actually in the roll bite. Having delayed the entry gauge measurements, Fuzzy Mass flow controller then reflects the Mass Flow equation. It can produce the exit gauge error (Δh) by comparing the actual Mass flow calculated exit gauge at the mill bite (h_{bite}),with the GEFB modified target exit gauge(h_{tgt}).this error is then passed through the Fuzzy Mass Flow controller witch outputs a required change in roll gap The require change in roll gap (Δgap)is passed through a hardness compensation block witch predicts the amount of mill stretch that will result from the gap correction and hence determines the change in cylinder position target (Δtgt)required to achieve the desired change in roll gap Finally the cylinder position controller adjusts the flow of oil in to or out of the roll load cylinder to ensure that the actual cylinder position matches the target cylinder position.

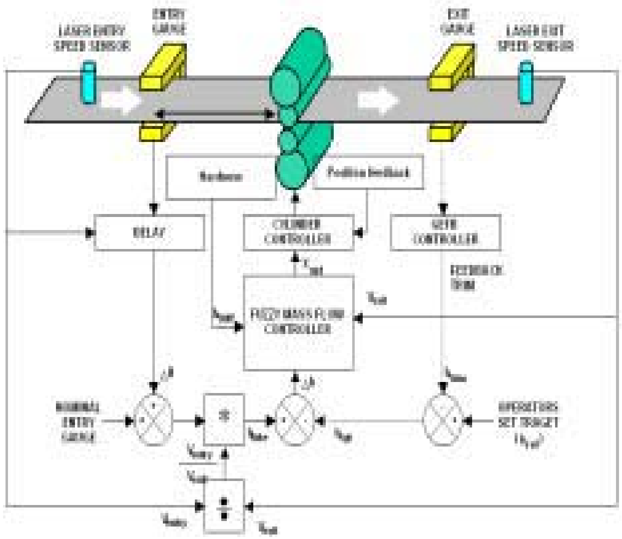


Fig. 6 Block diagram of fuzzy model AGC

4.1 Fuzzy model controller

Fig. 7 shows a simplified block diagram of the fuzzy model AGC for automatic gauge control system. This level 2 computing system transports the coiling schedule from upper system to low system. Moreover, Using the process data collector can get the quality information of strip, the motion status of process, the alarm of process, which is able to inform to operator the fail report, the quality report by HMI. And then transports the quality information of a rolled coil to level 3 system [4].

Rolling model calculates the rolling variables and presuppose for rolling information, such that receive the width of strip, the material composition of strip, the coefficient of friction, the temperature of strip, the processing pass, the pressure rate, the forward tension, back tension, and the rolling speed, from upper computer. Rolling mill dynamics model, which is composed the rolling mill with mechanical physical volume and control system, used mathematical model and then obtained input, output relation. Online supervisor make decision for each variable of rolling material, starting of the Rolling mill dynamics model as well as the fuzzy rule transducer generates and modifies the rule of fuzzy controller for the rolling information which is got to the rolling model.

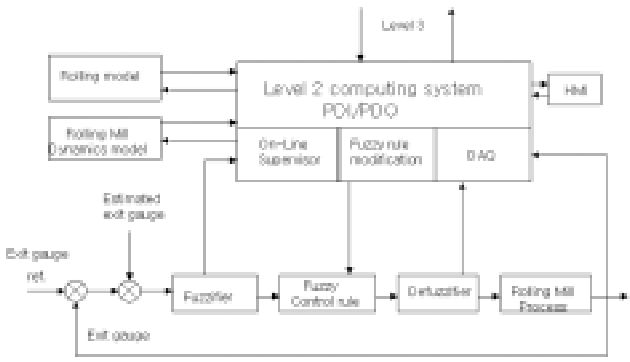


Fig. 7 Block diagram of fuzzy model

4.2 Fuzzy input and output

First input variable is the predictive gauge error, which can be measured entry strip speed, the entry gauge and exit speed. As using this variable, it can be calculated the entry delay time from the entry gauge measuring point to the mill bite. If system know measured gauge of the strip, it can calculate the predictive gauge error after pass the entry delay time.

Second input variable is the rolling speed, the volume of exit gauge variety rate have a great effect. A cylinder response need to fast things when not only rolling speed is too high but also entry strip has much gauge variety rate. But the roll load cylinder has generally big load, great the coefficient of damping, which means it can be limited the fast response. A fuzzy variable use exit rolling speed of strip among entry speed by the pressure rate, exit speed, mill motor speed.

Third input variable is the stiffness of strip, which can calculate two way, one is measured rolling load by load cell, the other one is calculated the stiffness of strip by measured the pressure of roll load cylinder.

The stiffness of strip is generally divided soft alloy, medium alloy, and hard alloy by hardness of strip

The output variable is the cylinder target position, as a basic condition, top work rolls are generally fixed statue, bottom work rolls are installed on the roll load cylinders, which means that the moving range of cylinder is a distance between top work roll and bottom work roll. Although the cylinder has regular moving range, roll gap size can be a different result because of work roll diameter, back up roll diameter.

Fuzzy input and output show in table 1. Input variable "the estimate exit thickness error" and output variable the" cylinder target position " divided 7 step like negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB). The rolling speed divided 5 step like high(H), medium high(MH), medium(M), medium low(ML) , low(L) and the stiffness of material divided 3 step like soft(S), medium(M)and (H)hard.

Table 1 Input and output of fuzzy model AGC

Input	Output
Estimate exit thickness error	Cylinder target position
Rolling speed	
Stiffness of material	

4.2 Fuzzy membership function

The exit gauge error is a difference value between a measured value exit gauge measuring system and a target value of exit gauge. Besides, the exit gauge error is a difference value between a calculated gauge value by mass flow and a error value of exit gauge.

The Predictive Gauge Error has a value between –10μm and +10μm,and Fig. 8 can show a simplified 7 grade of membership function of estimated thickness error.

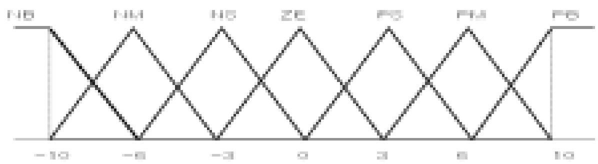


Fig.8 Membership function of estimated thickness error

The stiffness of strip is a original roll load value dividing reduction value, and then multiply the result by a compensation value and then conversion the value 0 to 1, Fig. 9 shows 3 member which is divided soft, medium and hard.

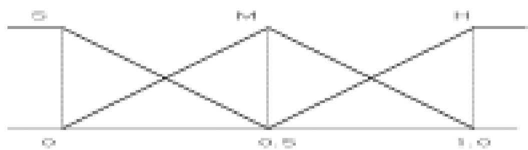


Fig.9.Membership function of hardness

Maximum rolling speed is 1800mpm, the same range as 5 grade of member as Fig. 10.

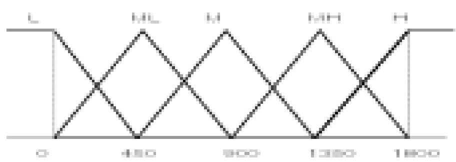


Fig.10 Membership function of rolling speed

The membership function has a range -15μm to +15μm value for a cylinder target position, as Fig. 11 composed

7membership grade.

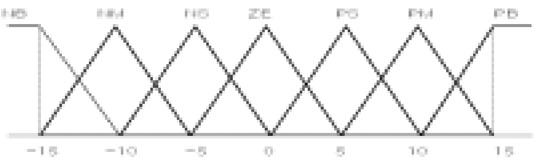


Fig.11 Membership function of gap position

The Fuzzy model of automatic gauge control system generated rules by 105 item like below item.

(1) If (estimated thickness error is NB) AND (speed is L) AND (hardness is S) then (position is PM)

.
.
.

(105) If (estimated thickness error is PB) AND (speed is H) AND (hardness is H) then (position is NB)

The defuzzified output using the center of mass of sum of weighted output membership functions [5] is as Eq. 13

$$z_0 = \frac{\int \mu_c(z) \cdot z \, dz}{\int \mu_c(z)} \quad (13)$$

5. SIMULATION RESULTS

For simulation a rolling mill, designed rolling mill dynamics model as Fig. 12.

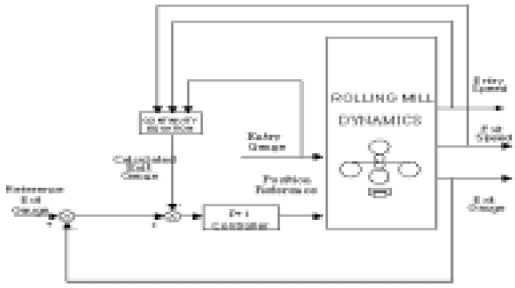
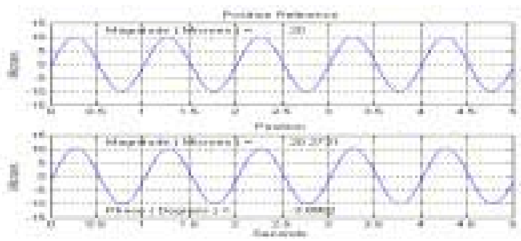
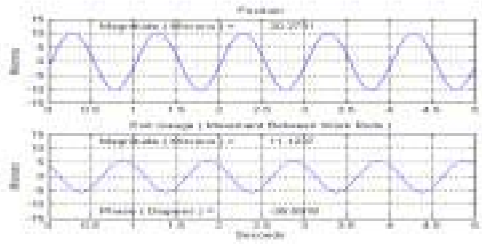


Fig. 12 Rolling mill dynamics model

The rolling mill dynamics model input was selected the amplitude of 20㎛, the frequency of 1hz sine wave to test exit gauge change according to the stiffness of strip. When rolling speed is 600mpm, stiffness of strip is 0.1 Fig. 13 shows a test result, which shows cylinder position orders, cylinder position feedback and exit gauge change.



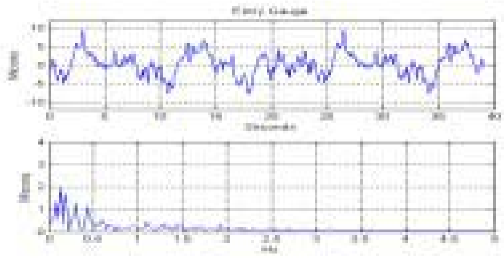
(a) Position reference and feedback



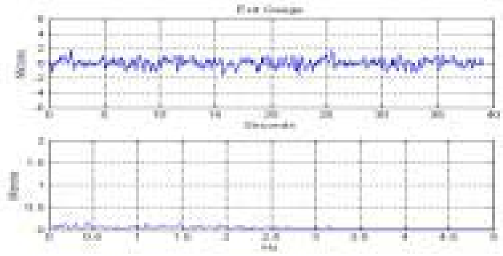
(b) Exit thickness.

Fig. 13 Experiment on mill dynamics with 600mpm and stiffness by 0.1

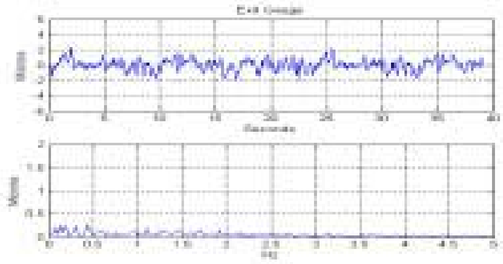
We applied the PI mass flow of automatic gauge control system to compare a entry strip (before rolling) with a exit strip (after rolled) according to rolling speed as Fig. 14.



(a) Entry gauge thickness.



(b) Exit gauge thickness with 600mpm.



(c) Exit gauge thickness with 1200mpm

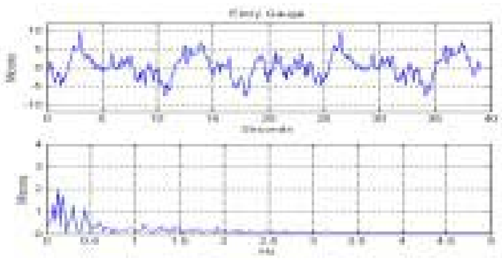
Fig. 14 Experiment on PI mass flow AGC

After the test, Exit gauge variation was about 1.5㎛ in 600mpm(rolling speed), when the strip of 5㎛gauge variation was supplied this rolling mill. But exit gauge variation was high as a table 2, when the rolling sped up at 1200mpm
As the result, it can know that the exit gauge variation is too stable, as well as exit gauge variation is not to high in the low rolling speed.
Therefore, another control method needs to control the exit gauge variation stably for advance Production and improve quality.

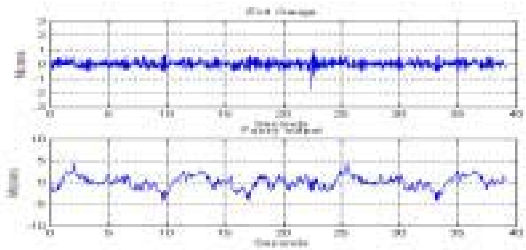
Table 2 Exit gauge bandwidth 3 sigma of PI mass flow AGC

AGC mode	Rolling speed	
	600mpm	1200mpm
PI mass Flow AGC	1.2 ㎛	2.0 ㎛

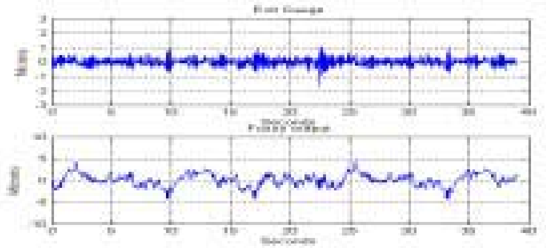
As Fig.15, a gauge improvement statue of exit strip is shown to compare a entry strip gauge with a exit strip gauge according to rolling speed.



(a) Entry gauge thickness



(b) Exit gauge thickness with 600mpm



(c) Exit gauge thickness with 1200mpm

Fig. 15 Experiment on fuzzy model AGC with 1200mpm

As shown in Fig. 15, exit gauge variation is improved in 1.2㎛ like a table 3, although the rolling speed up 600mpm to 1200mpm. Consequently, this improved gauge performance applied the fuzzy controller, which is to minimize the gauge variation to be decided the rolling speed, the predictive gauge error in mill bite, as well as the best cylinder position used the stiffness of strip.

Table 3 Exit gauge bandwidth 3 sigma of fuzzy model AGC

AGC mode	Rolling speed	
	600mpm	1200mpm
Fuzzy model AGC	1.0 ㎛	1.2 ㎛

6. CONCLUSION

We have got a simulation result, that the exit gauge variation of PI mass flow AGC was 2 micron and fuzzy model AGC was 1.2 micron at 1200mpm of rolling speed when each controller was rolling 5 micron of material that is the entry gauge variation. In conclusion We fully understand that PI mass flow AGC has an excellent variance of thickness variation at 600mpm but also increase the thickness variation according to increasing rolling speed. Fuzzy model AGC, which we proposed from this thesis, has small thickness variation at high rolling speed generally.

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