A STUDY ON STRIP CROSSBOW CORRECTION FOR UNIFORM COATING WEIGHT CONTROL

By

Changwoon Jee
POSCO
SOUTH KOREA

ABSTRACT

In coating process of continuous galvanizing line, transverse crossbow is frequently found in the case of thick gage or high strength steel processing. This transverse crossbow arises due to the unbalanced residual stress distribution along the thickness, which is made by the elasto-plastic behavior that the steel sheet experiences during roll to roll transportation under continuous steel strip processing like surface cleaning and annealing.

Because this crossbow makes the air knife to strip gap distribution uneven, it is difficult to get the uniform coating weight distribution along the transverse direction. In order to correct the crossbow of steel strip at the zinc coating position, correction roll displacement is used. While the mathematical model that calculates the crossbow curvature with theoretical and experimental background is introduced for the proper crossbow correction roll displacement determination, it is very difficult to guarantee the accuracy of its calculation because of many uncertain parameters that govern the model.

In this study, a model adaptation method was developed to enhance the steel strip crossbow estimation accuracy using coating weight data and coating weight estimation model. This estimation method was applied to the classified operation results of many high strength steel and thick gage strip to verify the model estimation performance. The analysis of this application results shows the improved accuracy of the estimation model. Furthermore, future works for refining the developed model as well as the achievement with it will be discussed in this paper.

NOMENCLATURE

a	coating weight model coefficient for line speed
b	coating weight model coefficient for air knife gap
c	coating weight model coefficient for wiping pressure of air knife
C_W	coating weight

C_{WS}	strip work side coating weight
C_{CS}	strip center coating weight
ΔC	coating weight deviation between center and edge of strip
h	deviation of air knife to strip gap between center and edge of strip
G	air knife to strip gap
K_d	model constant for coating weight model
P	wiping pressure of air knife
R	radius of crossbow curvature
V	line speed
w	strip width

INTRODUCTION

In coating section of continuous galvanizing line(Figure 1), there are some disturbances in uniform coating weight control along the strip transverse direction. One of those disturbances is strip transverse crossbow which causes air knife to strip gap distribution uneven. The crossbow arises from the residual stress imbalance due to the elasto-plastic behavior that steel strip experiences during roll to roll transportation[1,2]. This residual stress due to the elasto-plastic behavior is inevitable because the strip experiences excessive strain by the repeated roll wrapping in continuous strip processing line. In order to remove the crossbow during coating process, many crossbow correction technologies were introduced as described hereafter.

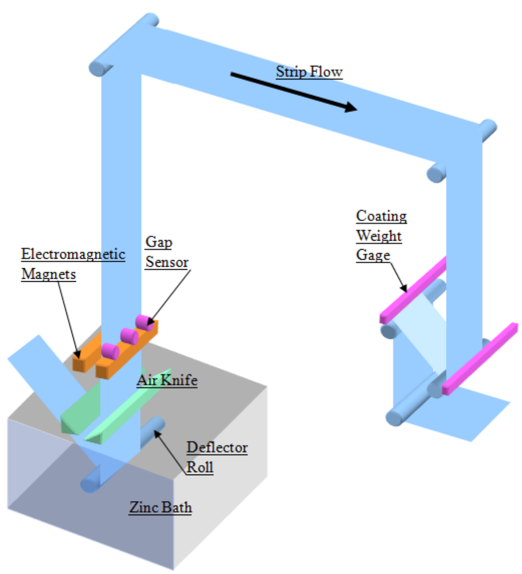

Figure 1 – Coating section of continuous galvanizing line

<u>Gap sensors and elecromagnetic magnets</u>

In this method, a set of gap sensors and electromagnetic magnets are installed in rear position of air knife which is used to remove the excessive zinc melts on the strip surface in order to control the coating weight as ordered by customer. Gap sensors are placed along the strip transverse direction so as to measure the air knife to strip gap at each sensor position. Referring to this measured gap information, electromagnetic magnets are controlled so that the steel strip cross bow should be corrected in flat shape. Even though direct gap measuring with sensor and reducing crossbow for correction seems to be the best way, the gap sensor with high accuracy is very expensive and installation of the sensors in the hot air and zinc fume environment causes some additional cost of maintenance in the aspect of device itself and measuring accuracy. So, efficiency to cost should be profoundly reviewed for this sensor installing method. Additionally, electromagnetic magnets are inclined to be effective only for thin gage and mild steel strip, and are not applicable to thick gage and high strength steel strip.

Crossbow correction with touch roll behind air knife

Two sets of rolls, which are placed adjacent to air knife in rear flow of it, are used to correct the crossbow by contacting each roll with top and bottom surface of strip. The crossbow is corrected by adjusting the roll-strip contact angle. This method is also direct approach to correct the crossbow. However, the contact between rolls and strip surface can make surface defect which should be critically avoided for best surface quality coating product. This defects can be apparent because the roll sets are installed in product flow position that zinc solidification is incomplete. Furthermore, for maintaining high quality product surface, touch roll surface maintaining should be strictly managed. As a result, maintaining cost of equipment will soars unimaginably.

Coating weight gage feedback control

Using coating weight gage is classical approach to correct the crossbow shape. It is common that transverse coating weight is taken from coating weight gage that scans the coating weight along the strip transverse direction. After recognizing the shape of coating weight profile and coating weight difference between center and edge part of the strip, correction roll intermesh position can be controlled manually or automatically. However, scanning type coating weight gage is usually installed at distant position typically 100~200m behind the air knife position at which coating weight adjustment is practiced. So, there is dead time that we cannot know the coating weight information until coated position arrives at coating weight gage. For this matter, we have to wait for some time to know the coating weight profile so that inevitably the control is delayed with some waste of material. Specifically, this situation is aggravated in the case of thick gage strip processing because crossbow is much more serious and we have not enough feedback opportunity due to the relatively short strip length.

In order to obtain the uniform coating weight distribution along the transverse direction of strip while avoiding the problems described in previous part, a control method without control dead time was developed. For this method, crossbow estimation model without using gap sensors was developed to estimate and control the correction roll position without any response delay. The crossbow estimation method that uses both of physical equation and operation data was developed to calculate the crossbow of strip with good accuracy and this estimation is used for designing pot roll unit and dynamic control.

COATING WEIGHT DEVIATION ALONG STRIP TRANSVERSE POSITION

A set of coating weight data which was scanned transversely by scanning type coating weight gage in continuous galvanizing line is shown in Figure 2. As shown in this figure, much more zinc is coated in the strip center than strip edges due to the air knife to strip gap profile in which the center gap is bigger than that of edge.

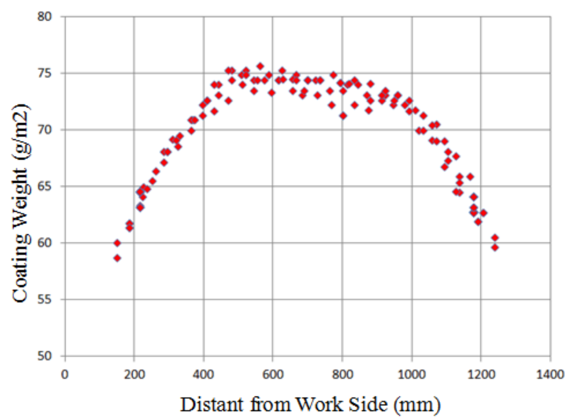

Figure 2 – Coating weight profile along the strip transverse direction

For the purpose of convenience of data processing, spot area coating weight can be defined for three parts of transverse strip position, i.e., C_{ws}, C_{cs} and C_{ds} for coating weight of work side, center and drive side, since the scanned coating weight is distributed transversely.

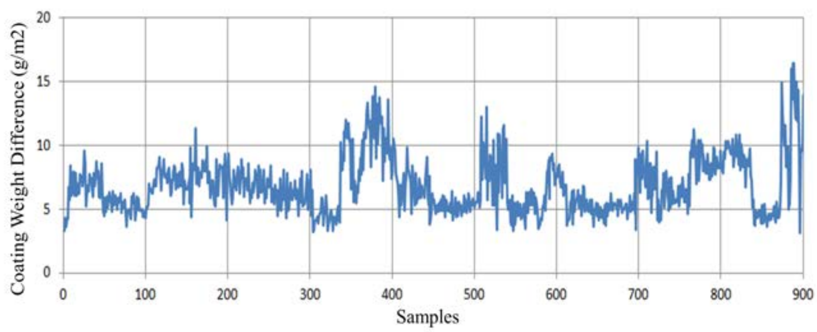

Figure 3 – Coating weight difference between center and edge of strip

And more comprehensively, coating weights of center and edge can be defined. From this two coating weights, coating weight difference between center and edge is calculated with below equation{1} to evaluate the coating weight distribution.

$$\Delta C = C_{cs} - (C_{ws} + C_{ds})/2 \qquad \{1\}$$

An example of center-edge coating weight difference plotted with time sequence is shown in Figure 3.

CROSSBOW FROM COATING OPERATION DATA

The crossbow of strip can be calculated using the spot area coating weights(C_{ws}, C_{cs}, C_{ds}), which are defined in previous section. For this crossbow calculation, the parameters of coating weight estimation model which are adapted during coating operation, are used. And the coating weight estimation model is defined as below,

$$C_w = K_d V^a G^b P^c \qquad \{2\}$$

By taking each side of above equation with logarithmic function, Equation {3} of linear combination can be gotten as below.

$$\ln C_w = \ln K_d + a \ln V + b \ln G + c \ln P \qquad \{3\}$$

Because the above equation is linear combination of parameters, the parameters a, b, c are adapted during on-line process with least square algorithm[4,5]. As the parameters of the above equation is adapted during on-line process, these parameters can reflect the process changes over long term time scale. And we can make many sets of parameters depending on the classified operation conditions(coating weight, line speed, steel grade) as a form of lookup tables. These are the lookup tables for the coating weight estimation model parameters. The stored parameters are reused for estimation of coating weight or wiping pressure.

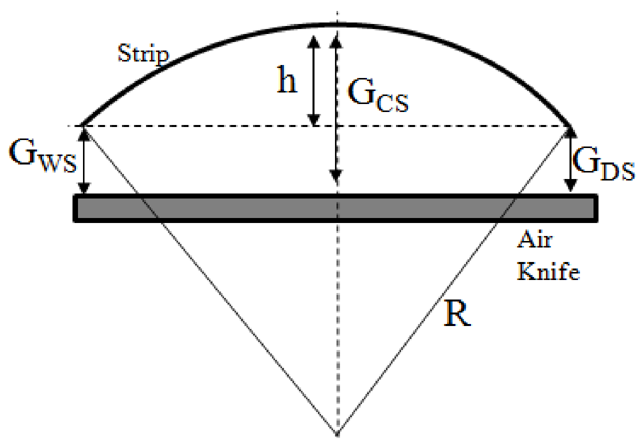

Figure 4 – The relationship between radius of strip crossbow and air knife gap

With the above parameters of coating weight estimation model, spot area coating weight(C_{ws}, C_{cs}, C_{ds}) and the relationship defined by equation{1}, the air knife to strip gap at each spot area(work side, center, drive side) is obtained. That is, the gap G is

$$G = \{C_w/(K_d V^a P^c)\}^{-b} \qquad \{4\}$$

Each air knife to strip gap for each spot area, G_{ws}, G_{cs}, G_{ds} is shown in Figure 4. And as shown in this figure, gap difference between center and edge due to the crossbow is defined as h, then radius of this crossbow is approximated as below,

$$R = \frac{h}{2} + \frac{w^2}{8h} \qquad \{5\}$$

Radius of curvature calculated from the equation{5} is shown in Fig.5. In this figure, measured correction roll intermesh is also shown. Since the intermesh affects the curvature, the inclination of increase or decrease of radius can be found depending on the intermesh change.

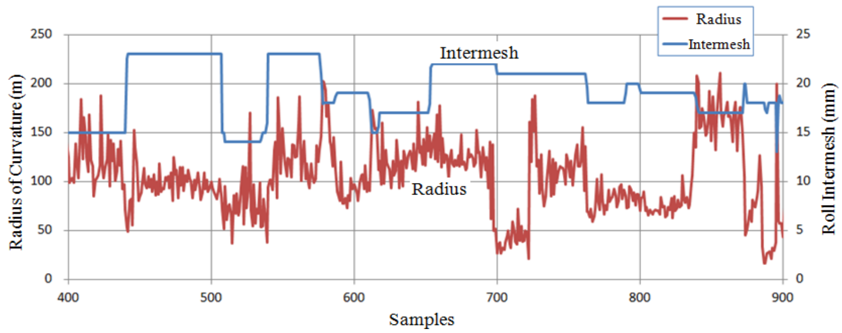

Figure 5 – A calculation result of radius of curvature from coating weight

CORRECTION OF THEORETICAL CROSSBOW CURVATURE

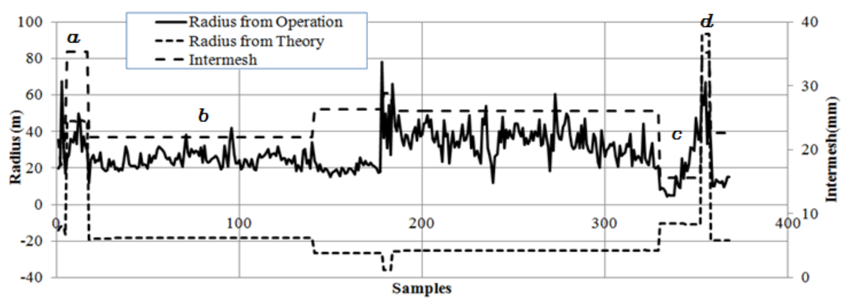

Figure 6 – The calculation of radius of curvature from operation and theory

There are some previous studies that dealt with the calculation of radius of transverse strip crossbow curvature arising from the repeated roll wrapping experienced by the transported strip. This calculation model is based on the elasto-plastic behavior of strip and was used for the design of strip shape correction device (ex: tension leveler) or sink roll unit of continuous galvanizing line. This calculation model is based on 1) the experimental equation that calculates the longitudinal curvature which happens as the strip is involved with roll wrapping and moving during transportation of strip, 2) the elasto-plastic behavior of the strip that experiences repeated bending and unbending when the strip passes through many deflector rolls and 3) theoretical calculation of strain hardening by repeated plastic strain[3]. A result of this calculation model is shown in Figure 6. The result of Figure 6 is governed by factors that influence the shaping of strip transverse curvature such as strip mechanical properties (Young's modulus, yield strength, strain hardening coefficient) and process variables (strip tension, strip size, correction roll intermesh).

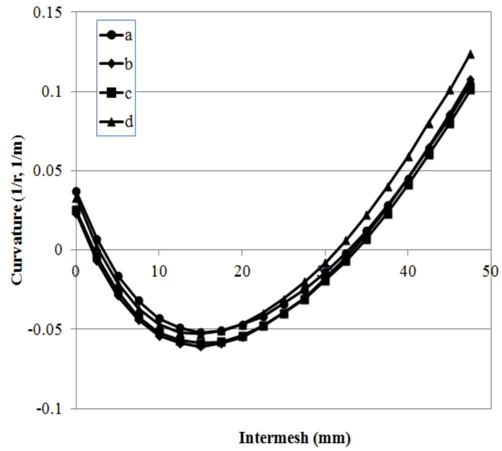

Figure 7 – Theoretical strip curvature at position a, b, c, d depending on roll intermesh

When the result of Figure 6 is compared with the curvature calculation result from coating weight data which was chosen from real operation, not just the big contradiction is shown but no approximate matching is shown. While both of positive(+) and negative(-) curvature are estimated as the correction roll intermesh changes according to the theoretical model calculation, only the positive(+) curvatures are shown in the calculation results based on the operation log data. For the same strip thickness and tension at the points *a*, *b*, *c*, *d* of Figure 6, the theoretical curvature calculation results for some correction roll intermeshes are shown in Figure 7. In Figure 7, while both of the point at which curvature changes from positive(+) to negative(-) and the point at which curvature changes from negative(-) to positive(+) exist, that is, the curvatures at points *a* and *d* are positive and those at points *b* and *c* are negative, curvatures at all the points are positive in the results of operation data (Figure 6). In the results of curvature calculation based on the real operation log data as shown in Figure 6, as curvatures at points *b* and *c* are all positive, it is supposed that all the points on the curvature graph be above the 0 line. And it is estimated that the mismatch between model and real machine is one of the causes of discrepancies between the two curvature calculations. One of the methods to fine the discrepancy is to find the matching case by changing the model elements with repeating tries. Another method to overcome discrepancy between model and actual case is to use parameter adaptation with least square approach for narrowing the contradiction between model and real case.

As is known in the curvature diagram (Figure 6) which was derived from coating operation log data, there is no correction position so that it is estimated that the theoretical calculation shown in Figure 7 is not the real case as installed machine. So, in this case, it is possible to correct the theoretical model with some model parameter perturbation after reviewing the influence of model parameters. As shown in Figure 8, the crossbow curvature diagram moves upward direction as the sink roll offset decreases under the same condition of the other parameters. From this crossbow curvature diagram moving tendency, previously reviewed curvature log data(Figure 6) is estimated to be the uppermost case of three curves (Figure 8) because there is no curvature direction changes. The newly calculated theoretical curvature based on the corrected sink roll offset is shown in Figure 9. As shown in this Figure 9, while the estimation of curvature is better than before in some parts, the estimation error was worsen in some parts. So, it is thought that any other parameters are needed to be corrected for much more accurate estimation in this case. Another corrected theoretical curvature calculation for different steel grade is shown in Figure 10. With the same correction method, much better curvature estimation result was obtained. According to the results of Figure 9 and 10, it is difficult to correct the cross bow with the control of correction roll intermesh under present sink roll offset condition so that the adjustment of sink roll offset is needed in order to obtain the curvature decrease up to negative direction.

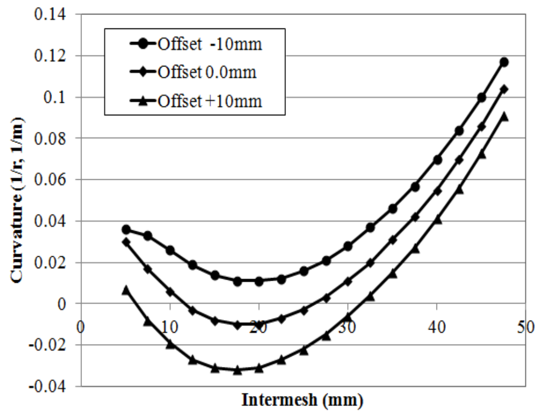

Figure 8 – Theoretical crossbow calculation with sink roll offset changes

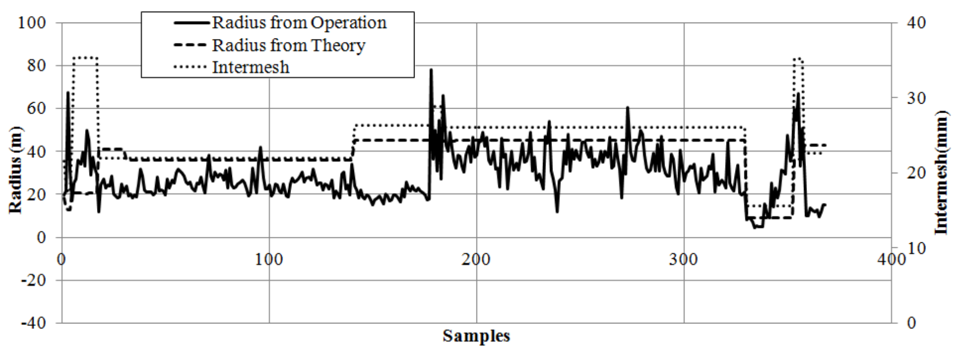

Figure 9 – Radius of curvature from theoretical model after correcting sink roll offset

CORRECTION ROLL INTERMESH MODEL FOR ON-LINE CONTROL

The corrected crossbow estimation model calculates the crossbow radius of curvature with enhanced accuracy under various operation conditions such as the roll intermesh, strip size and material properties. However, in order to apply the result of this estimation model to on-line control, we need to have the roll intermesh model for any operation condition. Actually it is impossible to calculate the roll intermesh position with which the crossbow is eliminated with this estimation model arithmetically. Therefore, it is necessary to prepare the intermesh table or model curve that is made from the calculation results of curvature estimation model from which the intermesh for eliminating strip crossbow can be selected and applied to on-line control loop.

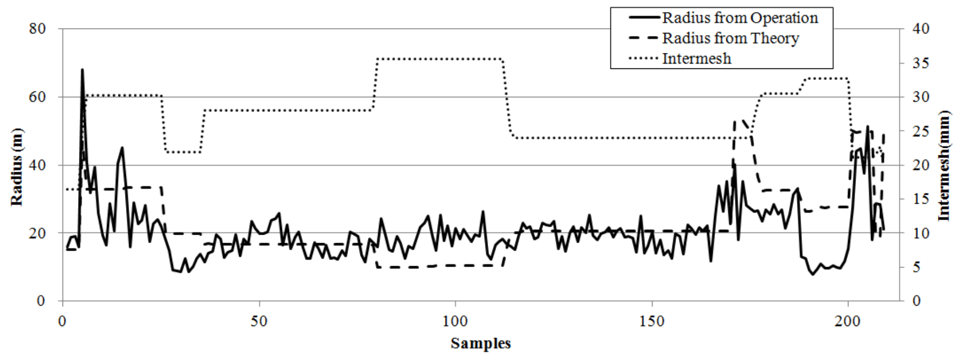

Figure 10 – Another radius of curvature from corrected theoretical model

APPLICATION OF INTERMESH MODEL

If there exists any roll intermesh position at which correction roll can eliminate the strip crossbow, there is no problem in eliminating crossbow. However, in some case, there can be no intermesh position that eliminates the crossbow with present sink roll structure. In this case, we have to redesign the sink roll layout so that with this sink roll, we can control crossbow under any operation condition. After adjusting the roll layout, we can derive the roll intermesh model for application to on-line control. In the previous example of a CGL, the present sink roll offset is identified as -10mm according to the model matching procedure. In order for the sink roll of this case to have the roll intermesh position that eliminating crossbow, sink roll offset have to be set to 15mm.

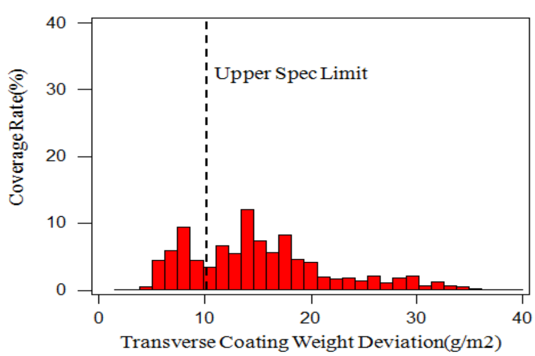

Figure 11 – Evaluation of transverse coating weight deviation for present sink roll

The performance change due to the adjustment of sink roll offset is discussed hereafter. The transverse coating weight deviation data from present sink roll unit was obtained and each coverage rate distribution over total operation log data of each deviation area was analyzed as shown in Figure 11. As shown in Figure 11, the coverage rate of the data under upper specification limit (10g/m2) is about 30%. So, there was much room to be improved. As the coating weight deviation along the transverse direction arises from the lack of capability to eliminate the crossbow due to the sink roll offset defect, sink roll offset is set to 15mm instead of -10mm which was identified as the present offset condition and coating simulation is done to evaluate the effect of sink roll offset change. The classified deviation coverage rate distribution for this case is shown in Figure 12. From this result, deviation coverage rate under upper specification limit (10g/m2) is 93%, which is much better than the previous case.

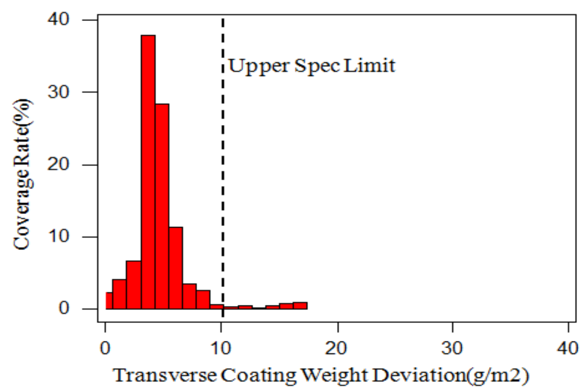

Figure 12 – Evaluation of transverse coating weight deviation for adjusted offset case

Corrected intermesh model was established in previous steps of model correction. This intermesh model is used in feedforward and feedback control. The on-line crossbow control scheme is shown in Figure 13 for these control loop. Just before new strip arriving, intermesh setup value is determined based on the intermesh model which refers to tension, size and mechanical properties of the strip that will be processed. For the feedback control, crossbow curvature is extracted from the scaning type coating weight gage output, correction roll intermesh is determined with intermesh –curvature model based on the curvature, and the difference between present and desired intermesh is fed back to the setup value of intermesh.

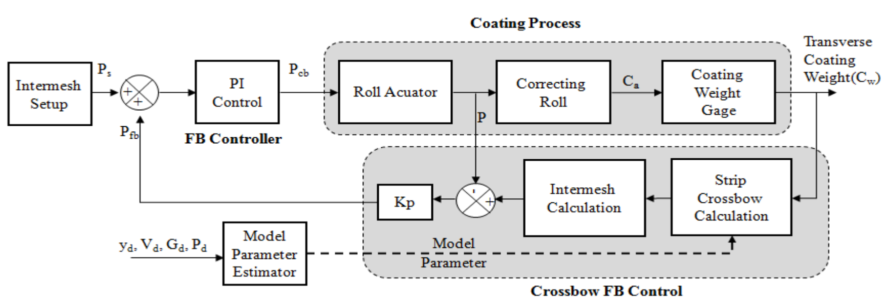

Figure 13 – Control schematics for transverse coating weight of steel strip

CONCLUSION AND FUTURE WORK

The conventional technologies to control the transverse coating weight in continuous galvanizing line were reviewed and analyzed in the aspects of improvement of coating weight control performance. For the purpose of evaluating the transverse coating weight distribution, coating weight deviation was defined. A steel strip crossbow estimation method based on the online coating weight estimation model and coating operation log data was suggested. In addition to this crossbow estimation method based on the operation data, the crossbow prediction model based on the elasto-palstic theory and experimental equation was discussed. This prediction model is used widely in on-line control as well as design of sink roll unit. Since theoretical crossbow prediction model has some errors in prediction, the correction of it which is based on the estimation with the real operation data was suggested and its performance was reviewed. The review of the performance of corrected theoretical crossbow estimation model showed much more improved results in the case that it is applied to simulated coating operation. The dynamic transverse coating weight control schematic was also suggested, in which feedforward and feedback control is available by using the crossbow prediction model.

Though linear estimation method was used for estimation of the coating weight, the non-linear estimation model that reflects the non-linear process much more easily and accurately can be developed and it can also used for the estimation of crossbow. And the correction of theoretical crossbow prediction model can be formed as the calculation procedure such as some equation set that includes calculation flow with further studies. Additionally, theoretical crossbow prediction model is thought to be improved in the aspect of accuracy with the introduction of FEM analysis for prediction of longitudinal curl that is now derived from experimental equation.

REFERENCES

1. Misaka, M., and Masui, T., “Shape Correction of Steel Strip by Tension Leveler,” Transactions ISIJ, Vol. 18, 1978, p.475
2. Masui, T., Kaseda, Y., and Ando, K., “Warp Control in Strip Processing Plant,” ISIJ International, Vol. 31, No. 3, 1991, p.262.
3. Park, K. C., and Hwang, S. M., “Development of Finite Element Program for Analyzing Strip Processing Lines and its Verification and Application,” POSCO Research Review, Vol. 6, No. 6, 2001, p.80.
4. Ljung, L., System Identification, Prentice-Hall, 1987.
5. Jee, C., “Air Knife Gap Estimation by Hybrid Modeling,” Proceedings of Galvatech 2011.