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Coating deviation control in traverse direction in a Continuous Galvanizing Line

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Abstracts A new air knife system for coating thickness control in hot dip galvanizing process had been developed and installed on the CGL in Pohang Steel Works,POSCO. This new system consists of air knives with remotely adjustable nozzle slot and an automatic control system which can control both longitudinal and traverse coating deviations. Based on the optimal control algorithm, a traverse coating deviation control was designed. The controller controls the lip profile of the air knives with flexible structure according to the deviation of coating weight. From the measured values which are dependent on the strip width, the lip gaps are calculated with optimal algorithm and the model of the coating deviation. Time delay between knives and a coating thickness gauge is solved by the Smith Predictor.

Keywords Coating control,Optimal control,Air knife,Zinc coating,Galvanizing.

1 INTRODUCTION

In hot dip galvanizing process, the amount of zinc coated on the strip surface is controlled by air knives. The air knives wipe the excessive zinc by blowing out compressed air onto the strip surface. Final coating weight is a complex function of the strip speed,air jet pressure, lip geometry,material properties and etc.

Wiping force is generated by impact pressure and shear stress acting on the strip surface,which are function of chamber pressure,knife position and lip gap size. Air knife controls the coating weight by adjusting the wiping force. During the line running, line speed is virtually fixed by furnace capacity and other line constraints. Thus, in conventional air knives, there are two control variables, knife position and chamber pressure. Figure 1 shows coating weight control with air knives.

When a liquid zinc is wiped,it runs down the strip or tends to move toward the strip edges. That causes heavy coating at the edges and light in the middle. Therefore galvanizers have used either tapers slot or bow-tie slot for the nozzle lip gap profile in order to get greater wiping force at the strip edge. But large coating variation across the strip width inherent because the strip width changes coil by coil, strip pass line moves, and also the strip deformation occurs between the air knives.

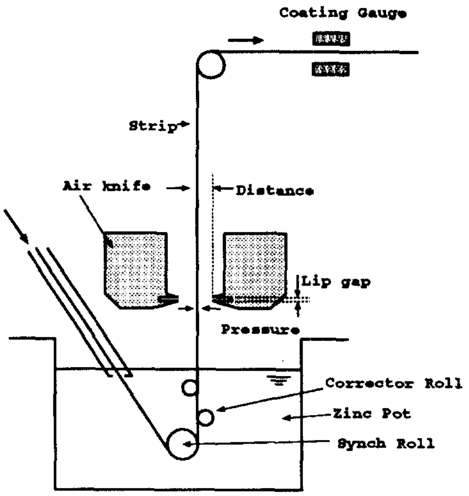

Figure 1: Coating control using air knife

New concept of dynamic air knife system(DAK) is remote control of lip slot profile during the line running. In DAK,the lip is composed of fixed lower lip and deformable upper lip with actuators. The upper lip can have any shape within the range of few millimeters. So, DAK can adapt itself to the various strip conditions, such as size change,flatness defects and shifting.

Coating control can be considered as two parts,that is,longitudinal direction and lateral direction coating weight. Longitudinal coating control is to control the mean value of coating to get the target reference by adjusting air pressure and horizontal distance. The traverse coating control manipulates the deviation by only changing lip gap profile.

2 MODELING OF COATING WEIGHT

In new air knife system, the coating weight is controlled by several lip gaps and one coating weight is affected by the two lip gaps because one lip gap can control a few coating weight. In order to control the coating weight, modeling of coating weight should be computed according to change of the lip gap. The lip consists of fixed lower lip , deformable upper lip and motors which move the upper lip.

The cross section is shown in figure 2. In figure 2, e_j means a gap of ith lip and x_j distance from the first lip to jth lip axis. Structure of the deformable lip can be considered as figure 3. p_i is a position of ith coating weight,d_j on the strip surface. Modeling needs assumptions as follows ;

- The lip profile is considered as linear between jth and $j-1$th lip.
- The correction on jth actuator affects only lip shape between $j-1$th and $j+1$th actuator and does not affect the lip shape between $j-2$th and $j-1$th actuator or $j+1$th and $j+2$th actuator.
- Only 2 dimension phenomena is taken into account.

If ith lip move unit distance,U and let the lip gap at the p_i position be m_{ij}, the each unitary lip gap,m_{ij} is as follows with a triangle relationship;

$$m_{ij} = \begin{cases} 0 & if\,|p_i - x_j| > LA \\ \frac{1-\frac{|p_i - x_j|}{LA}}{\sum_{i=1}^{n} m_{ij}} & else \end{cases} \qquad (1)$$

where LA is the distance between two lip axes. Thus, according to the lip gap(e_j)at the position, p_i the coating weight(d_i) is sum of amount of the each unitary action multiplied by the coating weight model,$\frac{\delta W}{\delta e}$ as

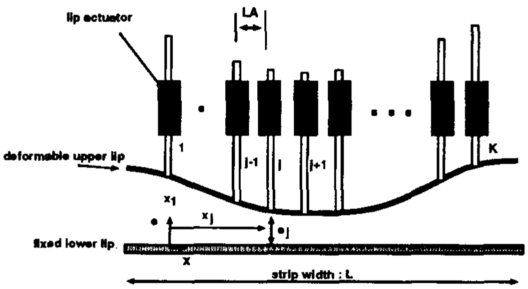

Figure 2: Structure of deformable lip

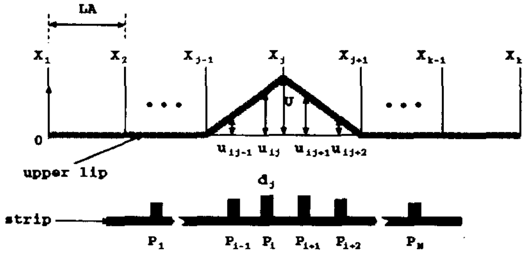

Figure 3: coating weight model according to the lip gap change

$$d_i = \sum_{j=1}^{k} m_{ij} \frac{\delta W}{\delta e_j} \Delta e_j \qquad (2)$$

From the above equation(2) the coating model can be expressed as

$$\frac{\delta W}{\delta e_j} = -\frac{\mu_n \mu_a H \overline{W}}{e_j^2} \qquad (3)$$

where μ_n is value extracted from a table depending on the line speed and μ_a is value extracted from a table depending on the air pressure. H is distance between air knife and strip. $\overline{W}$ is the coating weight average in traverse direction. Equation(2) can be expressed as matrix formula

$$\mathbf{D} = \mathbf{M}\ \mathbf{G}\ \mathbf{\Delta E} \qquad (4)$$

where $\mathbf{M}$ is the $n \times k$ matrix which is called mapping matrix, $\mathbf{G}$ is $\frac{\delta W}{\delta E_i}$,$k \times k$ diagonal matrix.

3 ALGORITHM FOR COMPUTING THE OPTIMAL CONTROL

The main problem in this paper is to find the optimal lip gap profile for the current coating deviation. The n measured coating deviations are controlled by

k actuators and each coating deviation is affected by two actuators at least. Each lip has a gap limitation between itself and near lips. That is, the maximum of difference gap of two lips is limited. The limitation depends on the power of the motor which moves the upper lip up and down. When one of the actuators is faced by the movement limitation ,it cat not move which is called saturated. So,there are two cases for the cost function. The first one is the case with saturated lip the other one the case without saturated lip.

No saturation case :

Let us consider the following cost function.

$$J = \sum_{i=1}^{n}(Ce_i - \sum_{j=1}^{k} m_{ij} g_{jj} \Delta e_j + \gamma)^2 \qquad (5)$$

where Ce is the coating error and γ is constant. This function can be minimized by

$$\frac{\partial J}{\partial e_h} = 0 \quad \forall h = 1, \ldots, K \qquad (6)$$

Here we have one constraint,

$$\sum_{j=1}^{k} \Delta e_j = 0 \qquad (7)$$

This constraint is for the change of the impact pressure onto the strip. If sum of the lip correction is not zero, the total cross section area will change and finally the average of coating will be changed.

Then the differential equation(6) becomes

$$\begin{aligned} \frac{\partial J}{\partial e_h} &= \sum_{i=1}^{n} m_{ij} g_{jj} \sum_{j=1}^{k} m_{ij} g_{jj} \Delta e_j \\ &- \sum_{i=1}^{n} m_{ij} g_{hh} C - \sum_{i=1}^{n} m_{ih} g_{hh} Ce_i \qquad (8) \end{aligned}$$

where g_{jj} is (j,j) element of $\mathbf{G}$ matrix. From the two equation(7), (8),we have the following relation

$$\begin{pmatrix} (\mathbf{MG})^{\mathbf{T}}(\mathbf{MG}) & \begin{matrix} g_{11} \\ g_{22} \\ \vdots \\ g_{kk} \end{matrix} \\ 1 \ldots 1 & 0 \end{pmatrix} \begin{pmatrix} \Delta e_1 \\ \Delta e_2 \\ \ldots \\ \Delta e_k \\ -\gamma \end{pmatrix} = \begin{pmatrix} (\mathbf{MG})^{\mathbf{T}}\mathbf{Ce} \\ 0 \end{pmatrix} \qquad (9)$$

where $\mathbf{M}$ is a mapping and $\mathbf{G}$ a coating model matrix. We can solve the equation(9) with many matrix inverse algorithm. In (9) matrix $\mathbf{M}$ and $\mathbf{G}$ should be adjusted because these matrices may have zero column. It means that the solution of the equation (9) may have the singularity. Therefore,all zero columns of the mapping matrix should be eliminated.

Saturation case :

This case is that some lips can't move up or down because differences between nearby lips exceed their limitations. In this case, the other lip gap can be calculated by making the saturated lips fixed with allowable gap. If one sth lip is limited, let us consider the following cost function

$$J = \sum_{i=1}^{n}(Ce_i - \sum_{j=1}^{k} m_{ij} g_{ij} \Delta e_j - m_{is} g_{ss} \Delta e_s + \gamma)^2 \quad (10)$$

where Δe_s is the allowable lip gap of saturated lip. The constraint can be written as

$$\sum_{j=1}^{k-1} \Delta e_j + \Delta e_s = 0 \qquad (11)$$

By solving the above cost function with the two conditions, (6) and (11), we get

$$\begin{pmatrix} (\mathbf{M^S G^S})^{\mathbf{T}}(\mathbf{M^S G^S}) & \begin{matrix} g^s_{11} \\ g^s_{22} \\ \vdots \\ g^s_{k-1k-1} \end{matrix} \\ 1 \ldots 1 & 0 \end{pmatrix} \begin{pmatrix} \Delta e^s_1 \\ \Delta e^s_2 \\ \ldots \\ \Delta e^s_{k-1} \\ -\gamma \end{pmatrix} = \begin{pmatrix} (\mathbf{M^S G^S})^{\mathbf{T}}(\mathbf{Ce} - \mathbf{M^S g_{ss} \Delta e_s}) \\ -\Delta e_s \end{pmatrix} \qquad (12)$$

where matrix $\mathbf{M^S}$ is $\mathbf{M}$ matrix of which zero colmuns and saturated lip's columns are excluded, matrix $\mathbf{G^S}$ is $\mathbf{G}$ matrix of which saturated lip's columns are excluded and Δe_s is allowable lip gap correction of the saturated lip. In two equations, (9) and (12), we can solve the optimal gap correction by taking several matrix inverse solution.

4 DEVIATION CONTROL EXPERIMENTS

In galvanizing precess, one of problems is time delay generated between air knife and coating gauge. The time delay depends upon the line speed with which the strip goes through from air knife to gauge. So, Smith Predictor is applied to this deviation controller in order to minimize the time delay affect.

Control block diagram for coating control is shown in figure 4. The reference for coating weight deviation is zero. The deviation(Co_i) of the measured values(W_i) by coating gauge is computed as follows

$$Co_i = W_i - \frac{\sum_{i=1}^{n} W_i}{2} \quad (13)$$

The process model for Smith Predictor is expressed as

$$\mathbf{Cm} = \mathbf{M\ G\ \Delta E} \quad (14)$$

The calculated process model(Cm) is imitated by the model delay block with measured line speed. There are two modes in scanning coating weights. one is dwell mode and the other scan mode which is traverse scanning. The scan mode is used for deviation coating control. Another delay factor exists in scanning process. So,this factor is also considered in model delay block.

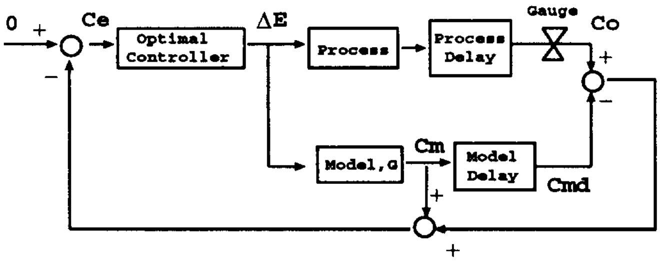

Figure 4: Control Diagram

Algorithm presented above is applied to CGL(continuous galvanizing line). The controller is embedded within a Multibus I system which consists of iSBC boards and I/O boards. The information of first test coil is

- Coil number : A45844
- Coil size : 0.68 X 828
- Line speed : 56 mpm
- Pressure : 14.5 KPa
- Horizontal distance : 34.0 (mm)
- Vertical distance : 93.4 (mm)
- Target coating : 90 g/m^2 (one side)

The result of first test coil is shown in figure 5 and 6. The initial status is marked by dot line and final status by solid line. At initial status, standard deviations of front and rear side are 8.0 and 5.2 g/m^2 ,respectively. Finally, the standard deviations of coating weight are reduced to 1.8 and 2.0 g/m^2. As shown in figures,the lip gaps are changed according to the deviation of coating weight.

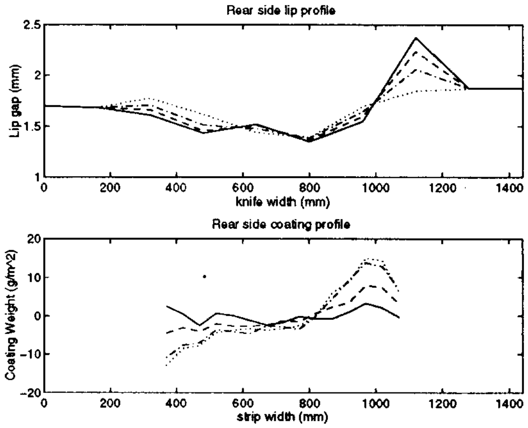

Figure 5: Rear lip profile and coating weight of first test coil

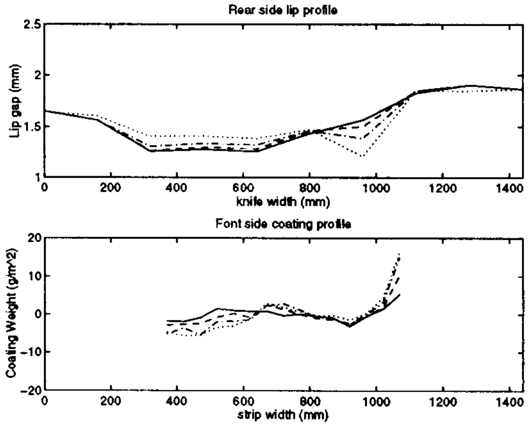

Figure 6: Front lip profile and coating weight of first test coil

The information of second test coil is

- Coil number : A5592A
- Coil size : 0.5 X 1224
- Line speed : 50 mpm

- Pressure : 12.0 KPa
- Horizontal distance : 31.7 (mm)
- Vertical distance : 95.5 (mm)
- Target coating : 90 g/m^2 (one side)

The result of second test coil is shown in figure 7 and 8. At initial status, standard deviations of front and rear side are 11.0 and 7.0 g/m^2 ,respectively. Finally the standard deviations of coating weight are reduced to 2.5 and 1.5 g/m^2.

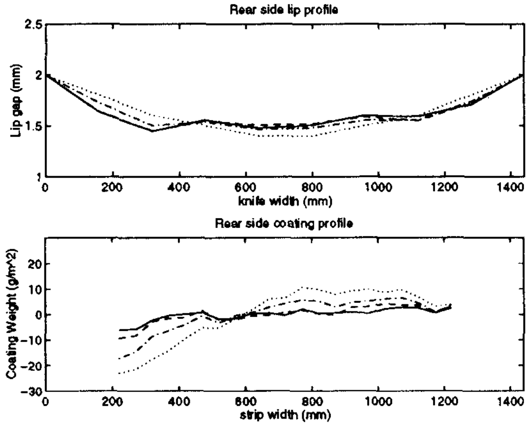

Figure 7: Rear lip profile and coating weight of second test coil

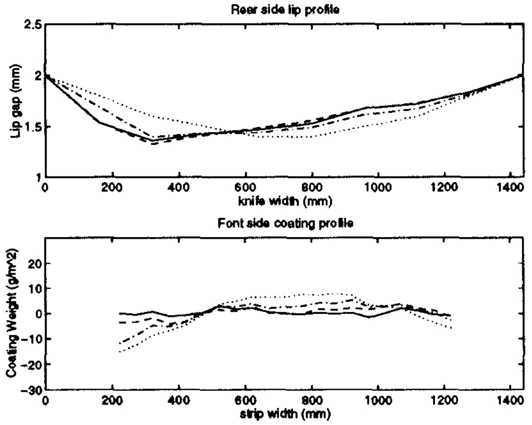

Figure 8: Front lip profile and coating weight of second test coil

5 CONCLUSIONS

We have proposed a new method for controlling coating weight with flexible lip. This method is used in DAK system which reduces the coating deviation in traverse direction as well as in longitudinal direction at POSCO CGL line. As the zinc consistency is improved,the operator is able to lower the the operating target for the same customer's requirement. In conventional air knife,the operating target was usually 202 g/m^2 for the 180 g/m^2 of customer's requirement. The developed controller has ability to deal with the cases as follows

- change of the strip shape
- change of strip center line
- shifting from side to side
- non-uniform pressure distribution through lip

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