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Artificial Intelligence-Based Descriptive, Predictive, and Prescriptive Coating Weight Control Model for Continuous Galvanizing Line

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Zinc wiping is a phenomenon used to control zinc-coating thickness on steel substrate during hot dip galvanizing by equipment called air knife. Uniformity of zinc coating weight in length and width profile along with surface quality are most critical quality parameters of galvanized steel. Deviation from tolerance level of coating thickness causes issues like overcoating (excess consumption of costly zinc) or undercoating leading to rejections due to non-compliance of customer requirement. Main contributor of deviation from target coating weight is dynamic change in air knives equipment setup when thickness, width, and type of substrate changes. Additionally, cold coating measurement gauge measure coating weight after solidification but are installed down the line from air knife resulting in delayed feedback. This study presents a coating weight control model (Galvantage) predicting critical air knife parameters air pressure, knife distance from strip and line speed for coating control. A reverse engineering approach is adopted to design a predictive, prescriptive, and descriptive model recommending air knife setups that estimate air knife distance and expected coating weight in real time. Implementation of this model eliminates feedback lag experienced due to location of coating gauge and achieving setup without trial-error by operator.

Keywords: *Air knives, AI Coating weight Control*

1. Introduction

Galvanized steels like zero spangle Galvanized (GI) & Galvannealed (GA) flat products have widespread application in the field of white-good industry, automotive skin panels, fuel tanks, etc. The main objective of galvanizing is to protect the steel strip from corrosion by applying a coating of zinc-based alloy. Fig. 1 shows a schematic of the continuous hot-dip galvanizing line (CGL). In continuous hot-dip galvanizing, prior to the immersion in the zinc bath, the steel sheet is first prepared by using mechanical (brushing) and chemical methods (electrolytic cleaning) to remove cold rolling oils, grease, loose oxides and other surface contaminants. After cleaning, the steel sheet goes to an atmosphere controlled annealing furnace in which iron oxides at the surface are reduced and the desired mechanical properties and microstructure are obtained after passing through the cooling section.

Then, during hot-dip galvanization, the steel strip after leaving the annealing furnace is submerged in a bath of molten zinc. When the steel substrate is immersed in the Zn bath, there is iron dissolution from the steel. This is followed by nucleation and growth of the metastable $FeAl_3$ phase which forms a compact layer of fine crystals on the steel surface. Further dissolution of the steel substrate is prevented after formation of this layer. However, iron continues to migrate towards the Zn bath by diffusion through the inhibition layer. Also, Zn and Al diffuse towards the steel substrate. Then the metastable $FeAl_3$ begins to transform to $Fe_2Al_5Zn_x$ Marder, 2000 [1]:

$$FeAl_3 + 2Al_{bath} + Fe_{subs} + xZn_{bath} = Fe_2Al_5Zn_x$$

Where,
Al_{bath} – Aluminium atoms from molten bath
Fe_{subs} – Iron atoms from steel strip
Zn_{bath} – Zinc atoms from molten bath
$FeAl_3$ – Metastable phase
$Fe_2Al_5Zn_x$ – Intermetallic ternary alloy

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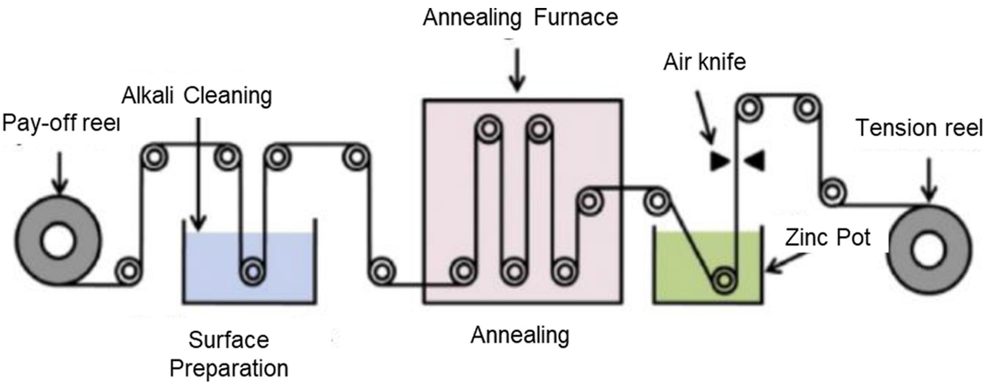

Fig. 1. Schematic of the continuous hot-dip galvanizing line [CGL]

It is common to add small amounts of Al to the continuous galvanizing zinc bath to improve the reflectivity of the coating, reduce the oxidation of the zinc bath and suppressing the formation of Fe-Zn intermetallic ternary alloy layer with a composition of 45% Al, 35% Fe, and ~20% Zn (Fe_2Al_5-Zn_X). The extent of this ternary alloy reaction (and the amount of zinc incorporated into it) is very sensitive to the amount of Al in the bath, to the immersion time, and to the bath and strip temperatures. This ternary alloy is helpful to produce a ductile, more corrosion resistant and adhesive coating. This reaction is followed by the growth of an upper, coarser layer of iron. The final inhibition layer morphology has a two-layer structure with a layer of fine and compact $Fe_2Al_5Zn_x$ crystals which is preferentially oriented adjacent to the steel substrate and a layer of coarser randomly oriented $Fe_2Al_5Zn_x$ crystals on top of the fine layer Chen et al., 2008 [2].

Surface tension forces cause a layer of molten zinc to adhere to the sheet when it exits the bath leading to accumulation of excess zinc on the strip. Coating weight is regulated by the air knives (A.K.) which with the help of high pressure air subjected to the moving steel strip causes the excess zinc to move back into the bath. Fig. 2. Schematic of the wiping operation in continuous hot-dip galvanizing line.

To solidify the zinc coating, the strip is passed through a cooling tower. Finally, the zinc coating weight is determined with the help of an X-ray device commonly called cold coating gauge.

The optimized operation of zinc wiping equipment is critical for obtaining the perfect coating weight. Any deviation (both over and under coatings) from the customer specification may have consequences. For instance: Supplying over -coating of zinc leads to in-efficient alloying in GA which may be detrimental during forming process at customers' line, while undercoating will lead to inferior corrosion protection. Hence, customer specification has a minimum & maximum coating weight prescribed. To avoid any non-complaint material, as per design, there is an operating range with lower specification limit or LSL (minimum allowable coating weight as per customer specification), nominal (target coating weight as per customer specification) and upper specification limit or USL (maximum allowable coating weight as per customer specification) coating weights are prescribed to the operator. To avoid any undercoated material and remain in a safer region, usually some extra coating of ~2-4 gsm (grams per meter square) to the LSL is

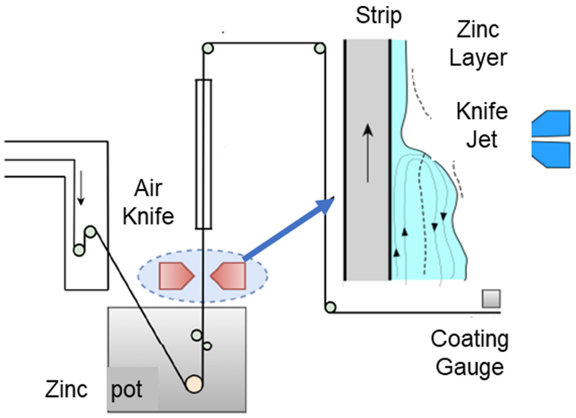

Fig. 2. Schematic of the wiping operation in continuous hot-dip galvanizing line [CGL]

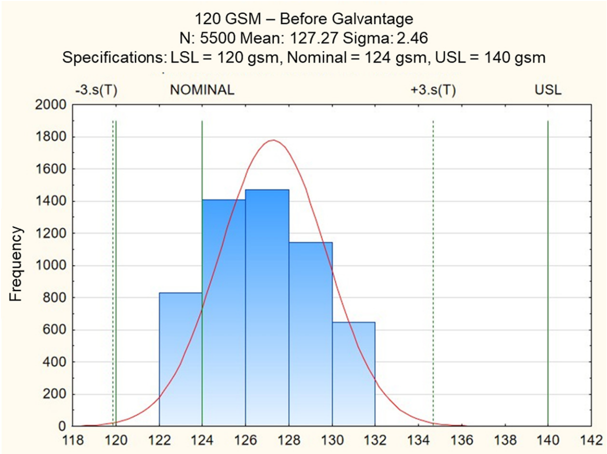

Fig. 3. Coating weight control at continuous galvanizing line or CGL #2 for 120 gsm coating

prescribed as target coating weight, for e.g., for LSL of 45 gsm → 47 gsm is the nominal setpoint. Fig. 3 illustrates coating weight control of Z120 (120 gsm coating). Although, the nominal/ target coating weight is 124 gsm, the histogram depicts are larger operating range with standard deviation of 2.46. The data indicates towards a scope for improved control of the process.

One of the biggest reasons to deviation from target coating weight is because of dynamic changes required from operator in the zinc-wiping equipment because of change in type of substrate (steel grade), large range of processing speeds, wide range of thickness, width and coating weight requirements. This implies that the air knives wiping system experiences multiple line speed and coating weights transients. Due to these reasons, there always arrives a scenario where there is a need to achieve a precise set-up of zinc wiping equipment for effective functioning. In many CGLs [continuous galvanizing lines], this exercise is done manually based on experience of the operator, making it difficult for the operator to hit the precise setup in first attempt. Additionally, the parameters affecting the zinc-wiping equipment are very sensitive to minor change and estimation of such parameters follow a non-linear complex relationship. Such difficult calculations are difficult to arrive at the setup when done manually. Additionally, due to cold coating measurement gauge systems being installed away from air knife to allow the zinc coatings to solidify, feedback of any changes made in the zinc-wiping equipment set-point is delayed by 1-2 mins.

With the intention of controlling the coating weight with a modeling framework, several efforts have been made to model the wiping phenomena. Thorton and graff 1976 [3] developed a coating control model based on first principle rules considering maximum flux principle with pressure gradient and gravity forces. Further improvements were proposed by Ellen and Tu, 1984 [4] and Tu and Wood, 1996 [5] to consider shear stresses during wiping. Elsaadawy et al., 2007 [6] further developed the coating weight model as a function of operating parameters by combining experimental and computational methods to improve the pressure and shear stress correlation using the k-ε turbulence model. They developed the pressure and shear stress correlation based on the earlier work of Ellen and Tu, 1984 [4].

Although first principle models have been efficient, researchers have also inclined towards data driven modeling solutions intrinsic to their process plant. These data driven approach covers the otherwise missed deviations due to sensor calibrations or unreliable data. Myrillas et al., 2010 [7] considered the impact of surface tension for modeling the coating weight. Taking pointers from Tu and Wood 1996 [5], they considered maximum pressure gradient and maximum shear stress to calculate the coating thickness using an analytical model. Additionally, Zhang 2012 [8] also did 3D numerical simulation in Fluent of turbulent flow to determine the impact of key parameters like pressure, nozzle to strip distance, slot opening, edge baffle plate, angle of knife. Then based on production data of CGL – effect of parameters is analyzed to develop a regression-based model and results are tallied with metallographic methods. Although, data-based approaches have been adopted, the concern of unavailability of one parameter makes it difficult to develop a data based real time model. The un-availability can be attributed to obsolete air knife equipment.

This work presents a model-based approach presents a reverse engineering approach for developing the coating weight model for air knives without accurate positional control.

1. This model enables to select the optimum parameters in a prescriptive mode to avoid over & under coating, eliminating hit & trials, also reducing operator fatigue.
2. It also addresses the issue of lag in feedback due to position of the coating gauge by predictive control.

2. Development of Model

The zinc coating thickness depends on parameters like distance [air knife to strip center], air knife angle, pressure, speed, distance of air knife to zinc bath top surface, temperature of the zinc bath etc.

Based on the literature, the three most important parameters are taken into consideration and the relationship between them can be expressed in terms of power law as follows:

$$\text{Coating Weight} = \text{constant} * \text{pressure}^{a} * \text{speed}^{b} * \text{knife to strip distance}^{c} \quad (1)$$

Where a, b, c and constant are coefficients

Table 1. Sample data set of various parameters during the trials

Pressure, mbar	Speed, mpm	AK distance [mm]	Actual coating for one side, gsm
564	79	16	31
595	97	16	35
367	90	16	52
598	90	16	38
598	105	16	37
222	70	20	145
308	110	20	152
348	130	20	152
200	58	20	160
200	75	20	175

Although other parameters are important but have moderate effect on the coating weight. To find the coefficients in equation (1), data approximation methods can be applied to find the best fit, which can capture the relationship between the variables. As the online measurement of air knife distance was not available, various experiments were conducted in the galvanizing line where the variables like speed, pressure and distance were varied and the corresponding coating weight over the steel strip was recorded. The air knife to knife distance was physically set for each trial. The parameters like speed, pressure and coating weight are measured along the length of the coil and stored in Level -2 system [L2] in industrial automation system. Conventionally, in industrial automation systems, the first level which comprises of sensors, actuators, instruments, motors, valves, actuators, switches, and other equipment is known as L0 or level 0. These L0 systems are controlled by a manipulation and control layer know as Level 1 which comprises programmable logic controllers or PLCs and proportional-integral-derivative controller. These are used by control engineers to regulate temperature, flow, pressure, speed, and other process variables in industrial control systems. L2 or level 2 systems are know to be supervisor control systems which encompasses several of L1 systems controlled by network and communications among the PLCs.

Experiments were carried out at the minimum and maximum air-knife distance varying the other variables at both the levels. The sample trial data with coating weight results are shown in Table 1.

The approximation method was applied over the trial data with the python library scipy (curve_fit) and coefficients were estimated. The assumption during the trial was that the air knives (front and rear) were at equal distance from the center of the strip along the entire width. In actual condition, there will be vibrations and skewness in the steel strip which leads to coating variation across the width of the steel strip.

Since online measuring systems are not available and physical measurement has safety risks associated, the novelty of this model is the capability of estimation of the air knife distance and then prediction of the setup for coating weight.

2.1 Feed forward model

In the continuous galvanizing line, different coating thickness is given over the steel depending on the customer requirements. If the subsequent coil has different dimension or coating weight, necessary adjustment is done by the operator accordingly. To achieve the desired coating, the operator adjusts the air knife system and waits for the coating gauge which is after 180 m from the air knife. This induces delay in the feedback. To overcome this delay, a feedforward model is used to prescribe the pressure if there is change in the line speed or coating thickness or air knife distance. This can reduce the amount of zinc overcoating which goes in the 180 m length of coil. This will assist in maintaining the uniformity of coating along the length of the coil.

Huge volume of data is generated in the CGL line, and it is not possible to store the data at milliseconds interval and hence the raw data is averaged over 1 meter length of coil and stored in the database. The model takes the data from this database and provides the required setting for the operator for target coating thickness. This model operates almost real time as it is very close to the CGL network and decision is taken in real time by the operator. The above-mentioned coating weight thickness model implemented at Level-2 systems are prescriptive and this can be integrated with Level-1 systems to make it close loop control. This would enable the elimination of operator dependency.

2.2 Automatic adaptive model approach

In absense of online measuremnt of air knife distance, the experience of operators plays a major factor to get the desired coating over the steel strip. The above developed model can be used to assist the operators by feed forward approach and the distance can be predicted based on reverse engineering method. Since the coefficients will remain same for the equation, the distance can be back calculated from the coating weight, pressure, and speed as shown in equation (2).

$$\text{knife to strip distance} = \left(\frac{\text{Coating Weight}}{\text{constant} * \text{pressure}^{a} * \text{speed}^{b}}\right)^{1/c} \quad (2)$$

This calculated distance will not match the exact physical distance as this also takes care of other variables like height of air knife distance from zinc bath, angle air knife angle, temperature and so on. Any change in the air knife system will be reflected in the coating gauge which is situated 180 m from the air knife system. The coil needs to be tracked from the air knife system to the coating gauge based on the speed of the coil and time of change in the system. This is to ensure the correct coating weight are measured for the corresponding speed, pressure, and distance.

Whenever there is change in the air knife system, the distance will be recalculated based on reverse engineering approach and the feed forward model will be able to prescribe pressure after the affected portion goes beyond the coating gauge. The coating gauge measures the coating thickness along the width of the coil and to get a representative input for the model, average of coating weight, pressure, and speed for 100 m length of coil is calculated. These average values are used to calculate the air knife distance based on air knife pressure set-up and line speed data as explained in the flowchart Fig. 4.

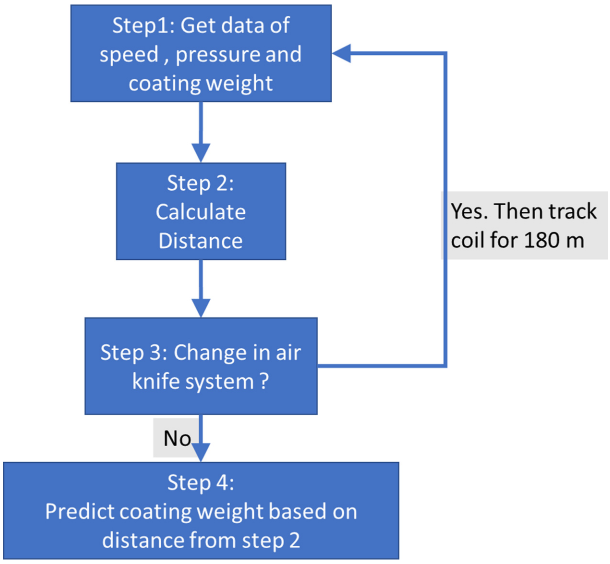

Fig 4. Flow chat for adaptive model approach for calculating the air knife distance

With this methodology, the unknown air knife distance can be predicted with manual measurement, and the predicted distance can be used to predict the coating weight for any change in speed and pressure. In CGL line of Tata Steel, the most preferred way for controlling the coating weight is air knife pressure, followed by distance and air knife angle.

2.3 Model validation

Before the feed forward model used for prescription, validation of the equation developed above was performed to ensure coating thickness is achieving the customer specification. A cold trial was taken where the pressure prescribed for various coating thickness change or speed change or distance change was noted. Also, the actual pressure set points and coating thickness achieved against those set points were noted. The model assumed coating thickness and the actual coating thickness was plotted as shown in Fig. 5. To find the goodness of curve fitting, RMSE (root mean square error) statistic is calculated. The RMSE value for the above trial is 1.76 gsm with R-square

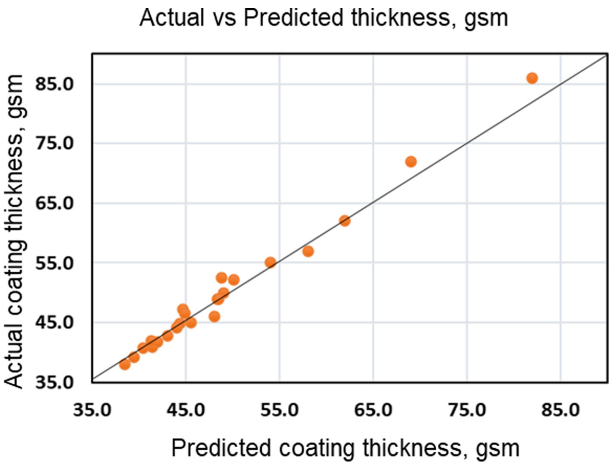

Fig. 5. Actual and predicted coating thickness for various conditions

–0.9835. This has given a good confidence to the operators where the model prescribed pressure are in close with their actual pressure set.

3. Results

A user interface was developed in Level-2 system where the data flows to the feedforward model. The coil information which will be processed next are available in level-2 database are also used as input to suggest the pressure set points for the next coils. Based on the recommendations in the UI, the operator decides the set points and the results are shown in Fig. 6, 7. To meet the customer specifications, the target coating weight is relatively on the higher side and due to the distance between the air knife and coating gauge, there are chances of more over coating for few meters. and this results in over coating of the zinc. After the implementation of this feedforward model, this delayed feedback was compensated

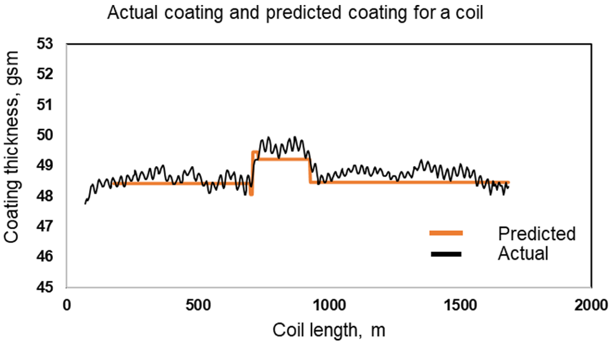

Fig. 6. Actual and predicted coating thickness within a coil

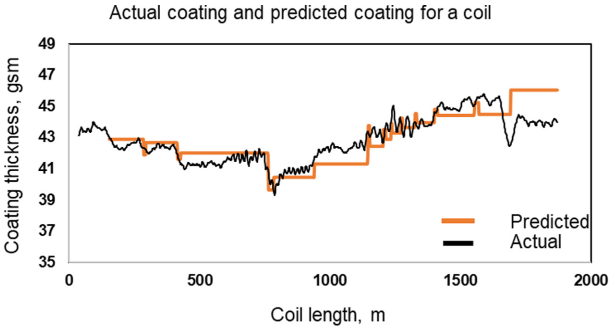

Fig. 7. Actual and predicted coating thickness within a coil

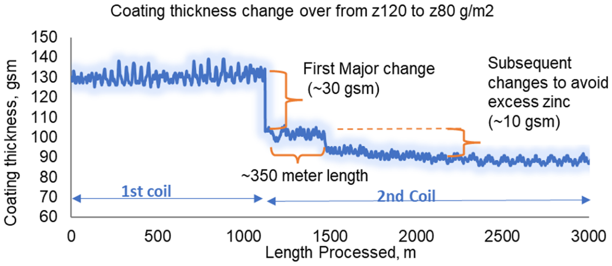

Fig. 8. Coating thickness changeover before implementation of model

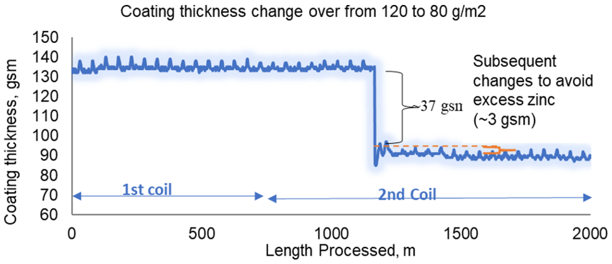

Fig. 9. Coating thickness changeover after implementation of model

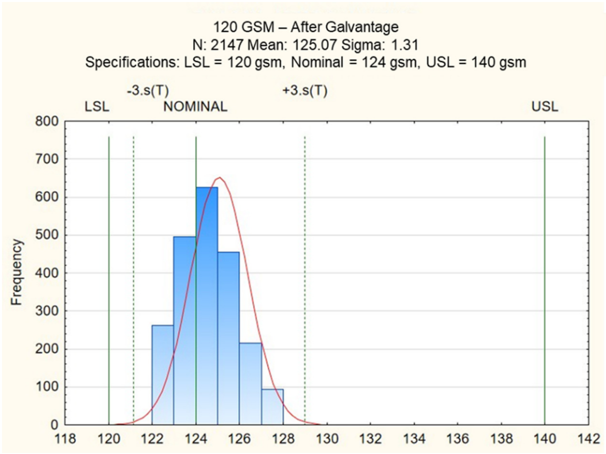

Fig. 10. Coating weight control for 120 gsm coating [after Galvantage implementation]

and resulted in zinc savings. The Fig.s 8, 9 explains the coating changeover from Z120 to Z80 gsm. Before the implementation, the coating thickness was achieved in steps based on the skill level of the operator. Fig. 10 shows the coating weight control for 120 gsm coil production with improved standard deviation of 1.31.

4. Conclusion

A mathematical model was developed to predict the coating thickness as a function of process parameters like coil speed, air knife pressure and distance with RMSE 1.76 gsm and R-square of 0.9835. The feedforward-based approach based on automatic air knife distance calculation can be utilized for prescription of air knife pressure during coating thickness change or thickness change. This type of approach has given satisfactory results and the ease of implementation has been straight forward. The model is validated over different coating ranges and the prediction showed good agreement with the actual coating weight data. Further it can be integrated with the Level-2 control systems in real time tool to provide set points for air knife pressure during coating changeovers.

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