Note

Modeling the Coating Iron Content as a Function of Small Changes of Processing Variables in Hot-dip Galvannealed Coatings on IF Steel Sheets

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Galvanneal coatings are normally obtained by annealing the hot-dip galvanized sheet as soon as it emerges from the zinc bath. During this heat treatment commonly called “galvannealing”, intermetallic Fe–Zn phases are formed and the iron content in the coating correspondingly increases. The final coating iron content is a critical control parameter. It is generally accepted that it must be kept between 10–11 mass% for optimum coating properties. Therefore it is of considerable interest to understand and to quantify the evolution of the coating iron content as a function of processing variables during the galvannealing process. In previous works^{1–10)} the kinetics of iron enrichment for the zinc coating of IF steel sheets has been quantitatively modeled taking into account two “chemical” processing variables, namely, coating mass and aluminum content. This modeling was combined with the time–temperature path followed by the moving sheet during the galvannealing cycle. This time–temperature path depends on two “mechanical” processing variables: the line velocity and the galvannealing furnace. An example of a time–temperature path is given in Fig. 1 obtained by passing the sheet through a galvannealing furnace with a velocity of 1 m/s. In what follows the soaking temperature indicated in Fig. 1 will be taken to represent the whole temperature cycle. This combination of the kinetic modeling with the time–temperature path produced “processing windows” such as those shown in Fig. 2, for details see Lopes *et al.*¹⁰⁾ The processing window is the area between two reference lines corresponding to the lower boundary coating iron content, 10 mass%, and to the upper boundary coating iron content, 11 mass%. Within these boundaries any values of line velocity and soaking temperature will produce a coating iron content within the desired limits. However in practice even if one accurately knew the best values of processing variables, small changes around these values are unavoidable. Consequently in a production plant it is not an easy task to keep the coating iron content within the desired 10–11 mass% range.

From industrial practice, the production engineer knows what are the parameters that require more strict control, as he has a “historical” experience derived from the considerable amount of material that is produced everyday in a large galvanizing plant. He usually has a control sheet in which

the optimum processing conditions for a given steel grade are specified based mainly on this “historical” experience. However, it is not uncommon that sometimes certain batches will be produced with lower quality in spite of the control sheet having been followed. So it is clear that the knowledge of the optimum production conditions is not enough, but it is also necessary to understand what effect small changes of the processing variables can have on the controlling parameter.¹¹⁾

This paper is a first attempt to propose a simple mathematical treatment to such a problem.

The control parameter, W_{Fe} , the final iron content of the zinc coating in mass%, is assumed to be a function of four processing variables: soaking temperature in °C, T_S ; line velocity in m/s, v ; zinc bath Al content in mass%, W_{Al} , and coating mass in g/m², M . Certainly, there are other important processing variables, for example, the zinc bath temperature, but they could be included if data were available. The desired value of the control parameter, W_{Fe} , say 10.5 mass%, is obtained for certain values of these processing variables so that one can write:

$$W_{Fe} = W_{Fe}(T_S, v, W_{Al}, M) \dots\dots\dots(1)$$

Any departure from the targeted values of the processing

Fig. 1. Temperature profile of a steel sheet in a galvannealing furnace as a function of furnace length. The sheet velocity is 1 m/s. The heating stage is 7.5 m, the soaking stage is 5 m and in the cooling stage the cooling rate is 10°C/s.

Fig. 2. Processing windows for IF steel sheets: coated in a zinc bath with 0.20 mass% Al and with a coating mass of 60 g/m²; coated in a zinc bath with 0.20 mass% Al and with a coating mass of 90 g/m², coated in a zinc bath with 0.14 mass% Al and with a coating mass of 60 g/m². The letters and arrows are explained in the text.

variables will result in a change of the desired value of the control parameter. This can be mathematically expressed by the total differential:

$$dW_{Fe} = \left(\frac{\partial W_{Fe}}{\partial T_s} \right)_{v, W_{Al}, M} dT_s + \left(\frac{\partial W_{Fe}}{\partial v} \right)_{T_s, W_{Al}, M} dv + \left(\frac{\partial W_{Fe}}{\partial W_{Al}} \right)_{T_s, v, M} dW_{Al} + \left(\frac{\partial W_{Fe}}{\partial M} \right)_{T_s, v, W_{Al}} dM \quad (2)$$

or, using Δ for d and omitting the subscripts of the partial derivatives:

$$\Delta W_{Fe} = \left(\frac{\partial W_{Fe}}{\partial T_s} \right) \Delta T_s + \left(\frac{\partial W_{Fe}}{\partial v} \right) \Delta v + \left(\frac{\partial W_{Fe}}{\partial W_{Al}} \right) \Delta W_{Al} + \left(\frac{\partial W_{Fe}}{\partial M} \right) \Delta M \quad (3)$$

Figure 2 can be used to estimate the values of the partial derivatives for IF zinc coated steel sheet. Figure 2 shows the processing windows of temperature and line velocity for IF steel sheets coated in three different conditions: a) zinc bath with 0.20 mass%Al and with a coating mass of 60 g/m²; b) zinc bath with 0.20 mass%Al and with a coating mass of 90 g/m²; c) zinc bath with 0.14 mass%Al and with a coating mass of 60 g/m².

The processing windows shown in Fig. 2 were calculated using the methodology described in detail in Ref. 10) where one can also find detailed information on the materials and methods used to obtain the relevant experimental data. As said above, the processing windows shown in Fig. 2 are related to the specific time-temperature path followed by the galvanized sheet within the galvannealing furnace. The galvannealing furnace used here, see Fig. 1, had three stages: a) inductive heating stage, 7.5 m in length, in which the sheet temperature increased approximately linearly with furnace length; b) A 5 m long soaking stage in which the temperature was maintained constant; c) A cooling stage with a constant cooling rate of 10°C/s that corresponds to forced air cooling.

In order to find the partial derivatives of Eq. (3) one initially fixes the soaking temperature in 490°C, a reasonable temperature for galvannealing and also convenient for the present analysis since one has data for this temperature. Next one locates the points within the processing windows that are equidistant from the two reference boundaries, 10 and 11 mass%, these are the points labeled “A”, “D” and “E” in Fig. 2. For the present purposes it is reasonable to assume that these points correspond to a coating iron content of 10.5 mass%. One can then proceed to find the partial derivatives for the 0.20mass%Al–60 g/m² coating as follows.

In order to find $\partial W_{Fe}/\partial T$ one starts from point “A” in Fig. 1. Increasing the temperature by $\Delta T_s = 5^\circ\text{C}$ one reaches point “B” located at the 11 mass% reference line. Writing the corresponding changes:

$$\Delta T_s = T(B) - T(A) = 5 \quad (4a)$$

$$\Delta W_{Fe} = W_{Fe}(B) - W_{Fe}(A) = 0.5 \quad (4b)$$

$$\Delta v = v(B) - v(A) = 0 \quad (4c)$$

Moreover within the same processing window one can assume:

$$\Delta W_{Al} = 0 \quad (4d)$$

$$\Delta M = 0 \quad (4e)$$

Substituting Eqs. (4a)–(4e) into Eq. (3) and rearranging one finally obtains:

$$\frac{\partial W_{Fe}}{\partial T_s} \equiv \frac{\Delta W_{Fe}}{\Delta T_s} = \frac{1}{10} \quad (5)$$

Similarly one can find $\partial W_{Fe}/\partial v$ by increasing the line velocity from “A” to “C” and following an entirely analogous procedure as above:

$$\frac{\partial W_{Fe}}{\partial v} \equiv \frac{\Delta W_{Fe}}{\Delta v} = -4 \quad (6)$$

Putting together the information obtained so far one obtains:

$$\Delta W_{Fe} = 0.1 \Delta T_s - 4 \Delta v + \left(\frac{\partial W_{Fe}}{\partial W_{Al}} \right) \Delta W_{Al} + \left(\frac{\partial W_{Fe}}{\partial M} \right) \Delta M \quad (7)$$

The two remaining partial derivatives in Eq. (7) can be estimated using the other two processing windows. For $\partial W_{Fe}/\partial W_{Al}$ one can go from “A” to “D” and, as above, write the resulting changes:

$$\Delta T_s = T(D) - T(A) = 0 \quad (8a)$$

$$\Delta W_{Fe} = W_{Fe}(D) - W_{Fe}(A) = 0 \quad (8b)$$

$$\Delta v = v(D) - v(A) = 1 \quad (8c)$$

$$\Delta W_{Al} = W_{Al}(D) - W_{Al}(A) = -0.06 \quad (8d)$$

$$\Delta M = 0 \quad (8e)$$

as a result:

$$\frac{\partial W_{Fe}}{\partial W_{Al}} = -67 \quad (9)$$

Finally to determine the last partial derivative, $\partial W_{Fe}/\partial M$, one can go from “A” to “E” and proceed in the same way as above, obtaining:

$$\frac{\partial W_{Fe}}{\partial M} = -0.075 \quad (10)$$

Having all partial derivatives one can write:

$$\Delta W_{Fe} = 0.1 \Delta T_s - 4 \Delta v - 67 \Delta W_{Al} - 0.075 \Delta M \quad (11)$$

It is noteworthy that Eq. (11) has terms with positive and negative sign. So in certain cases fluctuations in one variable can be compensated by a simultaneous fluctuation in another. For example if the temperature rises above the targeted value by $\Delta T = 5^\circ\text{C}$ it would be almost fully compensated by a simultaneous increase of $\Delta W_{Al} = 0.007$ mass%. Physically this corresponds to the observation that increasing the temperature the kinetics of iron enrichment is increased whereas it is decreased by increasing the Al content in the zinc bath.

In general however the fluctuations are at random and in

the most severe case the total change in W_{Fe} , ΔW_{Fe} , will be:

$$\Delta W_{Fe} = 0.1|\Delta T_S| + 4|\Delta v| + 67|\Delta W_{Al}| + 0.075|\Delta M| \dots\dots(12)$$

In Eq. (12) one is assuming that a target variable, for example: a temperature with a control error of $\pm \Delta T_S$. Based on Eq. (12) one can estimate how realistic will be an aimed target range for the coating iron content, by substituting errors in the target values that would be allowed under strict controlling conditions, namely, $\Delta T_S = \pm 3^\circ\text{C}$, $\Delta v = \pm 0.01$ m/s, $\Delta W_{Al} = \pm 0.01$ mass%, $\Delta M = \pm 3$ g/m², resulting:

$$\Delta W_{Fe} \approx \pm 1.2 \text{ mass\%}$$

Such a result suggests that to keep the coating iron content within the processing window 10.5 ± 0.5 mass% in Fig. 2 is perhaps too optimistic. Since these fluctuations around the target value have a statistical nature, even if a large amount of material is being successfully produced, occasionally one may obtain a certain amount of coated steel sheet outside the specifications. It is important to mention that the fundamental characteristic of the present analysis is that it is carried out around a definite point so if different values of processing variables were used one would of course have different values for the coefficients in Eq. (11).

In a more general way the above mathematical treatment suggests that in order to improve the process control and minimize ΔW_{Fe} one has to consider two factors:

a) The uncertainties in the process variables: ΔT_S , Δv , ΔW_{Al} , ΔM and perhaps other variables that were not included in the present simplified treatment. In order to improve this one might resort to an ever stricter process control and measurement methods of the variables involved. Equation (11) could be useful to show which variables are more critical. These are fairly straightforward and intuitive considerations.

b) One must also consider the absolute values of the processing variables themselves: T_S , v , W_{Al} , M for which $W_{Fe}(T_S, v, W_{Al}, M)$ is equal to a certain desired value. The present work suggests that the behavior of the function $W_{Fe}(T_S, v, W_{Al}, M)$ in the vicinity of (T_S, v, W_{Al}, M) is also

important and determines the values of the partial derivatives that are the coefficients of Eq. (11). So one should consider that a certain set of values of the processing variables must be found not only that results in the optimum value of $W_{Fe}(T_S, v, W_{Al}, M)$ but also that results in an optimum value of $\Delta W_{Fe}(T_S, v, W_{Al}, M)$. This point is somewhat less straightforward and intuitive than the previous one.

In summary the simple mathematical treatment presented here can be useful to assist in the process control of galvannealing. Actually the method presented here is quite general and a similar formulation could be in principle applied to other production processes.

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