Note

Modeling the Processing Window for Iron Enrichment in Hot-dip Galvannealed Coatings on IF Steel Sheets

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For optimum properties desirable galvannealed coating iron content is normally between 10–11 mass%. In a series of works^{1–13)} the iron enrichment of the zinc coating of IF steel sheets has been quantitatively modeled taking into account factors such as coating mass and aluminum content.

Based on those previous works^{1–13)} a methodology is proposed to generate “processing windows” that might be useful to understand the influence of fundamental metallurgical and processing variables in industrial galvannealing practice.

In order to apply the methodology proposed below two interstitial free (IF) Ti steel sheets with the same nominal compositions were used. One was hot-dip galvanized in a zinc bath with 0.14 mass% Al and had a nominal coating weight of 60 g/m² on both sides. Another was hot-dip galvanized in a zinc bath with 0.20 mass% Al and had a nominal coating weight of 60 g/m² on one side and 90 g/m² on the other side. In what follows the expressions: 0.14 mass% Al bath coating or 0.20 mass% Al bath coating will be used meaning the zinc coatings that were produced in zinc baths containing 0.14 or 0.20 mass% Al. Specimens measuring 100 × 100 × 0.85 mm were galvannealed in salt bath at temperatures ranging from 450 to 550°C for holding times up to 90 s and water quenched (average cooling rate about 90°C/s). The average heating rate from room temperature to the annealing temperature was about 40°C/s and the annealing times were measured from the instant the specimen reached the required temperature. From the center of the specimens, disks with 60 mm in diameter were taken for the determination of iron content. This was done separately on each side of the disk using a sulfuric acid solution to dissolve the coating. The iron contents reported in this work for the 0.14 mass% Al coating always refer to the same side of the sheet.

The proposed methodology consists of five steps:

1. First, the isothermal iron enrichment kinetics for a certain hot-dip galvanized sheet obtained under well-defined practical conditions is determined. This is

usually done by isothermal annealing of the samples within the temperature interval of 450–550°C for times ranging from 0–120 s and analyzing the resulting iron content in each case.

2. The data obtained in step 1 are fitted by a simple isothermal model¹⁾:

$$W = W_0 + (W_s - W_0)(1 - \exp(-kt)) \quad \text{.....(1)}$$

where W is the coating iron content, W_s is a saturation coating iron content and W_0 is the initial coating iron content; all in mass%. From such a fitting $k(T)$ and $W_s(T)$ are obtained. The values of $k(T)$ and $W_s(T)$ fitted to the experimental data are shown in **Table 1**. These values were used in the subsequent calculations. Notice that although the values of W_0 shown in Table 1 were used for the purpose of obtaining the fitted values of k and W_s they were not used in the subsequent calculations.

3. The third step consists in defining at least approximately the temperature vs. time cycle undergone by the galvanized sheet within the galvannealing furnace. Of course such a profile is highly dependent on the furnace available on the plant. An example is given in **Fig. 1**. The profile shown in Fig. 1 is obtained by passing the sheet through a furnace with a velocity of 1 m/s. The furnace has three stages: a) Low frequency inductive heating stage, 7.5 m in length, in which the sheet temperature increases approximately linearly with furnace length; b) A soaking stage in which the temperature is maintained constant, in what follows soaking stages of 0, 5 and 10 m in length were used; c) A cooling stage with a cooling rate of 10°C/s that corresponds to forced air cooling. It is assumed that galvannealing starts at 450°C and ends also at 450°C. Although the furnace shown in Fig. 1 does not represent a furnace of a particular steel plant it is believed that it is fairly representative and is used here to illustrate the

Table 1. Summary of parameters k and W_s obtained by fitting Eq. (1) to data acquired by isothermally annealing hot-dip galvanized IF steel sheets.

T (°C)	$k(s^{-1})$	$W_s(\text{mass}\%)$	$W_0(\text{mass}\%)$
450	0.0565	13.4	0.8
475	0.122	14.2	0.8
500	0.262	14.2	0.8
525	0.104	14.8	0.8
0.20 mass%Al bath coating(60 g/m²)			
T (°C)	$k(s^{-1})$	$W_s(\text{mass}\%)$	$W_0(\text{mass}\%)$
450	0.0398	12.5	0
475	0.0937	13.0	0
500	0.105	15.6	0
525	0.126	14.9	0
0.20 mass%Al bath coating(90 g/m²)			
T (°C)	$k(s^{-1})$	$W_s(\text{mass}\%)$	$W_0(\text{mass}\%)$
450	0.0185	10.6	0
475	0.0564	11.9	0
500	0.0735	12.5	0
525	0.0707	13.2	0

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. Effect of zinc bath Al content on the processing window, coating mass equal to 60 g/m² and soaking stage length equal to 5 m.

proposed methodology. Of course the present method can be applied to any furnace. In fact other simulations with different furnace profiles were also carried out but are not reported here. The trends obtained with other furnace profiles were similar to those shown in the present work.

4. In the fourth step one uses $k(T)$ and $W(T)$ obtained in the second step together with the temperature profile defined in step 3 to calculate the coating iron content after the annealing treatment. In order to do this one can use the additivity principle as suggested in previous work^{1,6)}:

$$\int_{t=0}^{t=t_f} \frac{k(T(t))dt}{\ln\left(\frac{W_s(T(t)) - W_0}{W_s(T(t)) - W_x}\right)} = 1 \quad \dots\dots\dots(2)$$

Equation (2) means that in order to reach a certain iron content W_x the integration must be carried out from $t=0$ to a final time $t=t_f$ until the integral is equal to one. Conversely if the final integration time $t=t_f$ is known then the coating iron content W_x obtained in the end of the integration time $t=t_f$ can be determined by solving Eq. (2) for W_x . Details of the calculations are

fully given in Seixas and Rios.⁶⁾

5. Finally one can plot the calculated results as a “processing window” such as those shown in Fig. 2. In order to construct such a processing window one plots the soaking stage temperature on the vertical axis and the line velocity on the horizontal axis.

One then chooses a given soaking temperature say 500°C and calculates the line velocity that will result in a coating weight of 11 mass% Fe. This will be the minimum line velocity since line velocities lower than this will result in coating iron contents higher than 11 mass% Fe. One also calculates the line velocity that will result in a coating weight of 10 mass% Fe. This will be the maximum line velocity since line velocities higher than this will result in coating iron contents lower than 10 mass% Fe. As one repeats this calculation for several soaking temperatures two lines are generated. Within these two lines is the “processing window” and any combination of line velocity and soaking temperature will produce a coating iron content within the desired limits of 10–11 mass% Fe.

In what follows some selected results from the simulations are presented to illustrate the methodology.

Figure 2 shows the effect of the zinc bath Al content on the processing window. One can see in Fig. 2 that an increase in zinc bath Al content from 0.14 to 0.20 mass% has a significant effect on the processing window. The soaking temperature interval is narrower for the processing window of the 0.14 mass% Al coating, about 5°C, than for the processing window of the 0.20 mass% Al coating, about 10°C. Another noticeable difference is the slope of the window, the processing window of the 0.14 mass% Al coating is much more “horizontal” than the processing window of the 0.20 mass% Al coating. One can see that galvanneal process control for the 0.14 mass% Al zinc bath will be in principle more difficult than for the 0.20 mass% Al coating as the window is narrower. On the other hand a 0.20 mass% Al zinc bath has the disadvantage of needing lower line velocities and/or higher soaking temperatures. In summary zinc bath Al content has a strong effect upon the processing window. This is reasonable as it is well known that Al bath content has a strong inhibiting effect upon the kinetics of formation of iron–zinc intermetallic phases.^{8,12,14–21)} The novel point of the present approach is to show how this effect is translated in terms of processing conditions.

In Fig. 3 one compares a coating with the same zinc bath Al content, 0.14 mass%, and same coating weight, 60 g/m² processed in the same way except that the furnace has a soaking stage length of 0 m in one case and 5 m in the other. Figure 3 shows that a longer furnace soaking stage shifts the processing window to lower temperatures and higher line velocities but has not a significant effect upon the shape of the processing window.

Figure 4 shows the effect of the coating weight on the processing window for a zinc bath Al content of 0.20 mass%. One can see that the coating weight has a significant effect on the position of the processing window. It is immediately obvious from the processing windows that it would be impossible to obtain the

Fig. 3. Effect of furnace soaking stage length on the processing windows, zinc bath Al content is equal to 0.14 mass% and coating weight equal to 60 g/m².

Fig. 4. Effect of coating weight on the processing window, zinc bath Al content is equal to 0.20 mass% and furnace soaking stage length is 10 m.

desirable coating iron content on both sides of the coating. So close control of the coating weight is important if one wishes to obtain optimum properties on both sides of the galvanized sheet.

In summary, the above results show that the proposed methodology of constructing processing windows can be useful. These processing windows are helpful to understand the effect of metallurgical and processing variables such as: zinc bath Al content, coating weight,

line velocity and furnace characteristics in the production conditions of galvanized coatings with optimum coating iron contents.

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