Note

An Alternative Method to Calculate Processing Variables for the Galvannealing Process

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In order to produce galvanneal coatings¹⁾ the hot-dip galvanized sheet is heat treated in a galvannealing furnace. Such a heat treatment is expected to produce an alloyed iron-zinc coating with an iron content normally between 10–11 mass%.

Recently, the concept of “processing window”^{2–6)} for the galvannealing process has been introduced. A processing window is essentially an area in a soaking temperature vs. line velocity plot within which the galvannealing cycle of a certain zinc coated steel sheet will result in a coating iron content between 10 and 11 mass%.

A methodology to determine processing windows a methodology was devised in a previous works.^{2,4)} It is repeated below, in condensed form, for convenience:

(1) First, the isothermal iron enrichment kinetics of the coating is obtained. This is done by isothermally annealing samples of the zinc coated steel sheet 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 model:^{7–15)}

$$W = W_0 + (W_s - W_0)(1 - \exp(-kt)) \dots \dots \dots (1)$$

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 and W_s are obtained. Example of such data can be found in Table 1 of Ref. 4).

(3) The third step consists in defining, at least approximately, the temperature vs. time cycle undergone by the galvanized sheet within the galvannealing furnace. An example of the temperature profile experienced by a galvanized sheet inside a galvannealing furnace can be seen in Fig. 1. Figure 1 shows that this temperature profile consists of three distinct stages. In the heating stage, the temperature is increased from the galvanizing bath temperature up to the soaking temperature. In the soaking stage, the temperature is kept constant. Finally, during the cooling stage, the temperature is fairly quickly decreased. The temperature at which the sheet enters the galvannealing furnace can be taken to be 450°C. A cooling rate equal to 10°C/s, representative of forced air cooling, can be used.

(4) In the fourth step, one uses $k(T)$ and $W(T)$ obtained in the second step together with the temperature profile de-

finied in the third step to calculate the coating iron content after the galvannealing treatment. Seixas *et al.*¹⁰⁾ present both experimental evidence and theoretical discussion to show that the conversion of isothermal data to non-isothermal data is a good approximation in this system. For the conversion itself the method suggested by Faria *et al.*⁴⁾ can be used.

This method has the advantage that experimental data can be obtained by means of a simple equipment, for example, a salt bath. The disadvantage of this method is that it requires certain mathematical calculations to be performed on the isothermal data in order to generate the non-isothermal step of the galvannealing furnace.

In this work, an alternative method is proposed in which the mathematical calculations are very easy but more sophisticated experiments are need.

In a recent work, Faria and Rios⁶⁾ showed that the following equation is valid:

Table 1. Selected values of parameters $\tau_i(T, M\%)$ and $\tau_H(T, M\%)$ calculated from data acquired by isothermally annealing hot-dip galvanized steel sheets from Faria *et al.*⁴⁾

0.20 mass%Al bath coating on low carbon steel substrate(80 g/m ²)				
Temperature (°C)	$\tau_i(T, 10\text{mass}\%)$ (s)	$\tau_H(T, 10\text{mass}\%)$ (s)	$\tau_i(T, 11\text{mass}\%)$ (s)	$\tau_H(T, 11\text{mass}\%)$ (s)
475	82.2	172	109.4	327.4
500	64.4	81.8	80	105.6
525	83.6	75.6	110	97.8
550	9.8	45.2	12.8	60.2

0.20 mass%Al bath coating on IF steel substrate(80 g/m ²)				
Temperature (°C)	$\tau_i(T, 10\text{mass}\%)$ (s)	$\tau_H(T, 10\text{mass}\%)$ (s)	$\tau_i(T, 11\text{mass}\%)$ (s)	$\tau_H(T, 11\text{mass}\%)$ (s)
475	36.6	48.8	46	58.8
500	12	26.2	16	34.8
525	5.6	12	8	17.2
550	5.4	6.4	9	10.4

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 10 m and in the cooling stage the cooling rate is 10°C/s.

$$\frac{x}{l_s(v)} + \frac{y}{l_h(v)} = 1 \dots\dots\dots(2)$$

where x and y are the furnace soaking and heating length, respectively, as indicated in Fig. 1. In Eq. (2), $l_s(v)$ is the length of the soaking stage of an isothermal furnace, in which the sheet is heated instantaneously to the soaking temperature, allowed to remain at the soaking temperature for a time equal to $l_s(v)/v$ and cooled with the desired cooling rate, 10°C/s, in the present case. On the other hand, $l_h(v)$ represents the length of a non-isothermal furnace, a “ramp” furnace. In this furnace the specimen is heated to the soaking temperature and immediately cooled with 10°C/s. The heating time is $l_h(v)/v$. If the lengths of the isothermal furnace, $l_s(v)$, and of the ramp furnace, $l_h(v)$, are such that the resulting coating iron content in each case is 10 mass% then the resulting coating iron content of a galvannealing cycle will also be 10 mass%. This will take place provided that the galvannealing cycle is carried out in a furnace with suitable x and y so that Eq. (2) will be satisfied. For fuller details of this see Faria and Rios.⁶⁾ Notice that the values of $l_s(v)$ and $l_h(v)$ are a function of the iron enrichment kinetics so that they have unique values for each coated sheet.

Faria and Rios⁶⁾ showed that Eq. (2) can be generalized as follows. The time at a certain isothermal temperature necessary to reach a coating mass content of M mass% for a certain isothermal furnace operating at a temperature T must be equal to:

$$\tau_i(T, M\%) = \frac{l_{s1}(v_1)}{v_1} = \frac{l_{s2}(v_2)}{v_2} = \text{isothermal time} \dots\dots(3)$$

where $l_{s1}(v_2)$, v_1 and $l_{s2}(v_2)$, v_2 are arbitrary isothermal furnace lengths and line velocities, respectively; $\tau_i(T, M\%)$ is the time that it takes for the sheet to travel the isothermal portion of the isothermal furnace, $M\%$ corresponds to a given coating iron content in mass%. The temperature against time profile of an isothermal furnace is shown schematically in Fig. 2.

Moreover, the non-isothermal or heating time necessary to reach a coating mass content of $M\%$ must be equal to:

$$\tau_h(T, M\%) = \frac{l_h(v_1)}{v_1} = \frac{l_h(v_2)}{v_2} = \text{heating time} \dots\dots\dots(4)$$

where $l_{h1}(v_2)$, v_1 and $l_{h2}(v_2)$, v_2 are arbitrary non-isothermal or ramp furnace lengths and line velocities, respectively; $\tau_h(T, M\%)$ is the time that it takes for the sheet to travel the heating portion of the ramp furnace. The temperature against time profile of a ramp furnace is shown schematically in Fig. 3.

Using Eqs. (2)–(4) one obtains a generalized form of Eq. (2):

$$\frac{x/v}{\tau_i(T, M\%)} + \frac{y/v}{\tau_h(T, M\%)} = 1 \dots\dots\dots(5)$$

The interesting consequence of Eq. (5) is that, if $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ are experimentally determined then, for a given furnace configuration, with known values of x and y , a line velocity can be found that will result in a coating iron

Fig. 2. The temperature against time profile of an isothermal furnace.

Fig. 3. The temperature against time profile of a ramp furnace.

content equal to $M\%$ for a soaking temperature equal to T .

For the purpose of calculating the processing windows, the most important values of $M\%$ are 10 and 11 mass%. Taking this and Eq. (5) into account following methodology can be proposed:

(1) Obtain the values of $\tau_i(T, 10\%)$, $\tau_h(T, 10\%)$, $\tau_i(T, 11\%)$ and $\tau_h(T, 11\%)$ for the temperature range of interest. $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ can be obtained directly from experiment. A suitable equipment capable of reproducing the temperature cycle of the isothermal and the ramp furnace is needed.

(2) Choose the desired furnace configuration, that is, the values of x and y . The flexibility of this method is that once $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ are available they can be used to determine the processing window for any desired furnace configuration.

(3) Use Eq. (5) to determine the line velocity. In this way a set of values of line velocities and soaking temperatures can be found and the processing window can be generated.

In order to illustrate the method, the processing window of two coated steel sheets will be calculated and compared with the processing window calculated by the “old” method presented at the beginning of this paper.

In the present work, $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ were not measured experimentally. They are determined from the available experimental isothermal data. This was done by applying the “old” method to the isothermal and ramp furnace schematically shown in Figs. 2 and 3.

The two hot-dip galvanized steel sheets used in this work were the same used in a previous work.⁴⁾ Both were produced in zinc baths with similar Al content, 0.20 mass%

(nominal) and similar coating weight, 80 g/m² (nominal). On one sheet the substrate was a Ti-IF steel and on the other a low carbon steel. In what follows the former will be referred to as the IF steels sheet whereas the latter will be referred to as the low carbon steel sheet. The substrate chemical analysis were (in mass%): C - 0.0035; Mn - 0.14; P - 0.01; S - 0.007; Si - 0.006; Ti - 0.07; N - 0.003; Al - 0.05; Fe - balance and C - 0.04; Mn - 0.15; P - 0.01; S - 0.01; Si - 0.003; N - 0.004; Al - 0.04; Fe - balance, respectively. Specimens measuring 100×100×0.85 mm were taken from the same side of each sheet and isothermally annealed in salt bath at 450, 475, 500, 525 and 550°C for holding times ranging from 5–120 s and water quenched (cooling rate about 90°C/s). The heating rate 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 values of k and W_s used in the present calculations are summarized in Table 1 of Ref. 4).

Selected calculated values of $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ are shown in Table 1. The furnace dimensions were chosen to be equal to $x=10$ m and $y=7.5$ m and the cooling rate was 10°C/s.

The processing windows calculated by the “new” method are shown in Fig. 4. Figure 4 also shows the same processing windows calculated by the “old” method from the work of Faria *et al.*⁴⁾ The agreement between the two methods is very good.

The main advantage of the new method is probably the possibility of determining $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ directly. So, if one is mainly interested in the galvannealing behavior at 500°C, only experiments at this temperature have to be done. In the old method, the whole series of isothermal experiments from 450 to 500°C had to be made. In addition, the values of $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ are representative of the iron alloying kinetics of a given coated steel

sheet. As a consequence, direct correlation is expected between $\tau_i(T, M\%)$, $\tau_h(T, M\%)$ and important galvannealing variables such as aluminum content of the zinc bath, coating weight, composition of steel substrate and other relevant parameters. The disadvantage is the need for a more sophisticated experimental apparatus, capable of a controlled heating cycle, instead of a simple salt bath used for obtaining data for the old method. Of course, if isothermal data is already available, as in the present case, it can be readily converted into $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ whereas the opposite cannot be done.

It is important to recognize that the present methodology suffers from limitations imposed by its own simplicity: it uses an equation for total coating iron content that does not explicitly takes into account the detailed phase evolution. Obviously, detailed knowledge of alloy phase evolution in the coating is very important. So, a natural and desirable evolution of the simple model presented here would be a more detailed quantitative model describing the phase evolution in the coating. Such a model is not available yet. More fundamental studies concerning the influence of processing and material variables on the formation of the alloy phases in the coating are certainly necessary before such desirable goal is achieved.

In conclusion, a new method has been developed to calculate the processing window that presents certain advantages with regard to the old method. The parameters $\tau_i(T, M\%)$ and $\tau_h(T, M\%)$ can be useful for investigating the effect of certain important processing variables in the galvannealing kinetics.

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Fig. 4. Processing windows for low carbon and IF steel sheets coated in a zinc bath with 0.20 mass% Al and with a coating mass of 80 g/m² galvannealed with the furnace profile showed in Fig. 1. The lines correspond to the results from Faria *et al.*⁴⁾ and the points represent the results of the present work.