ABSTRACT

During production of galvanized products, the Hot Dip Galvanizing bath is managed with additions of ingots allowing to guaranty the stability of the bath level and composition. Hot Dip Galvanizing pot productivity (in kg/h) is then defined as the amount of materials melted in the pot during a given time. The pot productivity is generally monitored to maintain the HDG bath at a stable level and varies depending on the production conditions (coating weight, line speed and strip width). In case of extreme process conditions (high coating weight, high line speed and wide strip), the pot productivity may become bottleneck, resulting on the necessity to limit the line speed to maintain the stability of the bath level, and thus affecting the HDG line productivity.

In the present paper, the different parameters affecting the pot productivity are highlighted and discussed considering the constraints induced by the ingot’s immersion technology, but also by the ingots melting kinetic itself. Different ways to improve the pot productivity are then proposed and were investigated based on laboratory ingots melting trials and on-line industrial trials with instrumented ingots.

KEYWORDS

Bath, pot productivity, ingots, melting kinetic, ingots immersion technologies

INTRODUCTION

During production of hot-dip-galvanized products, steel product is immersed in a pot containing liquid metal. The objective is to produce a corrosion resistant coating on the surface of the steel product. Molten metal is continuously removed from the pot dragged out by steel surface during the coating elaboration. To guaranty the stability of the bath level and its composition, material input is required in the pot. Hot Dip Galvanizing pot productivity is then defined as the amount of materials melted in the pot during a given time:

$$PP = \frac{m}{t} \quad \text{Equation (1)}$$

PP: Pot Productivity (in kg/h)
m: mass melted in the pot (in kg)
t: duration (in h)

In the case of flat product continuous hot dip galvanizing, ingots addition is monitored from a bath level measurement system to compensate the material output from the pot. The two main sources of the material output are the coating and the products extracted during the bath skimming operation. The pot productivity can then be evaluated by considering in equation (1) m as the ingot weight (in kg) and t as the duration between two ingots immersion (in h).
In case of production of wide strips, high coating weight at high line speed, the required pot productivity increases due to the higher materiel output from the pot. For extreme process conditions, the pot productivity may even become bottleneck if the ingots loading system or the ingot melting kinetic are not adapted to this required pot productivity. This results on the necessity to decrease the line speed, and thus affecting the HDG line productivity.

1. PARAMETERS AFFECTING THE POT PRODUCTIVITY

POT HEATING CAPACITY

The most common HDG pot heating technologies are channel inductors pot, coreless pot and metallic pot with resistance heating. Whatever the selected heating technology, the pot heating capacity (in kW) must be adapted to guaranty that the energy outputs from the pot can be compensated to maintain the targeted bath temperature. Main parameters to be considered for the estimation of required pot heating capacity are:

1. Amount of heat required for ingots melting:
   The ingots are inserted in the pot at room temperature and heated up to the melting temperature by the surrounding bath, then melts absorbing the latent heat of fusion and, finally, the recently melted material continues heating until reaching the bath temperature. The maximum required pot productivity must firstly be estimated from the production conditions (coating weight, line speed, strip width, skimming formation ratio). Then the required heating capacity for complete ingot melting can be estimated considering the specific heat and the latent heat of the material.

2. Amount of heat coming from the strip:
   Depending on the difference between of the strip immersion temperature and the bath temperature, the strip will consume or release heat in the melt after immersion.

3. Thermal losses of the pot: through the pot walls and at the top surface

4. Efficiency ratio of the heating system

5. Safety coefficient in case of degraded production conditions (low strip immersion temperature for example)

In case of low pot heating capacity, the amount of heat supplied by the heating system will not allow to compensate the heat consumption in the pot. The bath temperature will decrease, increasing the risk of melt freezing. The line productivity must then be decreased to adapt the pot productivity to a level in adequation with the pot heating capacity.

In the rest of the paper, assumption is made that pot heating capacity is adapted to regulate the bath temperature at the targeted level, whatever the quantity of immersed ingots.

INGOTS IMMERSION SYSTEM

Material input in the HDG bath is required during production to guaranty the stability of the bath level and its composition. This material input is done by melting of ingots. The ingots immersion system must be adapted to the ingot shape and weight. The most common ingot designs used for HDG bath feeding being Jumbos, Blocks and Slabs [1]. Other shapes and sizes as may be agreed upon between the producer and the customer can be produced. The ingots are generally melted:

- either in a dedicated pot called “premelt furnace”; the melted material will then be transferred to the HDG pot with the use of launders.
- or directly in the HDG pot by using an ingot immersion system. Different technologies have been developed to allow ingot immersion directly in the HDG pot: tilting tables, vertical immersion with crane, forks, immersion baskets,…

The Pot Productivity defined in Equation (1) can then be adapted to take into account the ingots immersion system specificities:

$$PP = n \times m_i / t_i$$  \hspace{1cm} \text{Equation (2)}

- $PP$: Pot Productivity (in kg/h)
- $n$: number of ingots that can be immersed simultaneously
- $m_i$: mass of one ingot (in kg)
- $t_i$: duration of the full immersion sequence of one ingot (in h)

Increasing the number of ingots immersed in the pot is a simple way to increase pot productivity but is often limited by the available place for implementation of other ingots immersion systems.

The full immersion sequence of the ingot must be considered to evaluate the pot productivity, beginning at the start of immersion of the ingot in the bath, and ending at the start of immersion of the following ingot. This full immersion sequence can be generally divided in 3 steps:

- Step 1: immersion of the ingot in the bath: the immersion speed of the ingot is generally monitored from a bath level measurement system.
- Step 2: holding period after complete immersion of the ingot in the bath. This holding period is mandatory to ensure complete melting of the ingots and avoid removing of non-melted ingots parts after immersion. The holding time is generally based on local experience with adapted safety margin.
- Step 3: after complete melting of the ingot, a new ingot must be installed on the ingot immersion system. This operation generally requires translation of the ingot immersion system to the ingot loading area, ingots loading and then translation to the immersion zone. Depending on specificities of the ingot immersion system, this step can be more or less time consuming and may affect the pot productivity. Ingot conveyor with automatized ingot loading can be considered, allowing optimization of the required time for the operation and safety improvements.

The time $t_i$ required for the full immersion sequence of the ingot in the bath can then be divided in the three parts:

$$t_i = t_1 + t_2 + t_3$$  \hspace{1cm} \text{Equation (3)}

- $t_1$: duration of the immersion of the ingot (in h)
- $t_2$: duration of the holding time after complete immersion of the ingot (in h)
- $t_3$: duration of the new ingot installation on the bath feeding system (in h)

To evaluate the performance of an immersion system, the time required for each step must be evaluated, including the sequencing of the ingots immersion in case of many ingots immersion.
Even with adapted pot heating capacity and ingots loading system, the pot productivity can be limited by the ingots melting kinetic. Figure 1 illustrates the shape of an aluminizing jumbo ingot after partial immersion with a tilting table and removal from the bath. It can be clearly seen that the immersed part of the ingot is not completely melted and present a conical shape. The shape of the non-melted part after immersion will mainly depend on the ingot design, the ingot immersion rate, the material thermophysical properties and the process conditions.

![Fig. 1: illustration of aluminizing jumbo ingot removed from the pot after partial immersion during production](image)

Thermal simulations model can be used to evaluate the shape of the non-melted part during immersion and the required time for ingots melting. Figure 2 shows an illustration of Jumbo ingot melting simulation during vertical immersion performed with the Finite-Elements software Abaqus®. The cooling of the melt surrounding the ingots is not simulated in the presented configuration. After adaptation of boundaries conditions, the entire ingot immersion with the classical immersion and holding steps can be simulated, allowing to study the influence of ingots design or immersion conditions on the ingots melting.

![Fig. 2: illustration of numerical simulation of Jumbo ingot melting (vertical immersion)](image)
4 main parameters will affect the ingots melting kinetic after its immersion in a metallic melt:

1. Ingot design [2]: as heat exchanges between the ingot and the melt occurs through the ingot surface, modification of the ingot design to increase the surface/volume ratio allows to minimize the time required to melt a given mass. Numerical simulations as illustrated on Figure 2 can be used to estimate total ingot melting time and validate ingot design modification. Ingots design modification remain however reliant on ingot supplier capability and adaptation on the ingots loading system available on the industrial line.

2. Bath temperature: Toussaint [2] already validated in industrial condition that an increase of the bath temperature allows to significantly improve the melting kinetic of GI-ingots immersed in HDG pot. Increasing bath temperature to improve pot productivity must however be considered with care and require a dedicated Process & Product risk assessment to ensure that production conditions and quality will not be affected. Main topics to be investigated being: pot heating capacity, immersed material lifetime, dust formation in snout, dross precipitation, cooling tower capacity, …

3. Ingots temperature [3]: The ingots are generally immersed in the pot at room temperature. Energy is firstly transfer to the ingot to heat it up until the melting temperature. Immersion of preheated ingots allow to decrease the time required to heat the ingots before melting. It has also a positive effect on the thermal homogeneity of the bath by limiting the formation of cold zones in the ingot immersion area.

4. Melt flow: immersion in a dynamic melt will allow to avoid the formation of a cold area around the ingots that will slow down the ingot melting kinetic. Melt flow can also have a mechanical effect by eroding the solidification front of the ingots.

2. LABORATORY INGOTS MELTING TRIALS

Immersion of instrumented aluminizing ingots have been performed in laboratory with the objectives of:
- Estimating the impact of bath temperature on aluminizing ingot melting rate
- Estimating the impact of pre-heating on aluminizing ingot melting rate
- Collecting experimental data for tuning of the numerical simulation parameters

As illustrated on Figure 3, ~10kg aluminizing ingots (Al-10wt%Si) with a square section of 88x88mm² and 500mm length were instrumented with 3 thermocouples at 125, 250 and 375mm height in the core of the ingots. The ingots were installed in a basket before immersion to allow safe displacement and preheating in a dedicated resistance heating furnace before immersion in a static ~600kg aluminizing bath (Al ~10wt%Si - saturated in Fe).

4 different trial conditions have been tested:
- Immersion at room temperature in a bath at 650°C
- Immersion at room temperature in a bath at 680°C
- Immersion after preheating at 500°C in a bath at 650°C
- Immersion after preheating at 500°C in a bath at 680°C
Figure 4 illustrates the temperature evolution in the ingots immersed at room temperature in the bath at $650^\circ$C and $680^\circ$C. The graph shows the temperature profile measured by the thermocouples situated in the center of the ingots. A plateau close to $580^\circ$C is visible on both curves, corresponding to the Al-Si eutectic melting. The end of the ingots melting can be estimated when the thermocouple indicates the bath temperature. The melting time was estimated at 6 min 40 sec for the ingot immersed in the bath at $650^\circ$C and 1 min 54 sec for the ingot immersed in the bath at $680^\circ$C. This trial validates the significant effect of the bath temperature on the ingot melting kinetic.
Figure 5 illustrate the temperature evolution in the ingots (thermocouples situated in the center) immersed in the bath at 650°C without preheating and after preheating at 500°C. The melting time was estimated at 6 min 40 sec for the ingot without preheating, and 2 min 10 sec for the preheated ingot. This trial validates the significant effect of the ingot preheating on the ingot melting kinetic.

![Temperature Evolution Graph](image)

Table 1: estimated times for complete ingot melting during laboratory trials

<table>
<thead>
<tr>
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<th>Bath T°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without preheating</td>
<td>650°C</td>
</tr>
<tr>
<td>With preheating (500°C)</td>
<td>650°C</td>
</tr>
</tbody>
</table>

Table 1 summarizes the estimated times for complete ingot melting during the 4 laboratory trials. The trial performed with ingot preheating and immersion in a bath at 680°C indicate ingot melting in 45 sec. This result indicates that the effects of the bath temperature and of the ingots preheating are cumulated.

A thermocouple situated in the melt at 680°C close to the ingot immersion zone indicate a melt temperature decrease of 16°C during the melting of the ingot immersed at room temperature. A melt temperature decrease of 8°C was measured at the same location during the melting of the preheated ingot, validating that preheating of the ingot also minimize the thermal impact of ingots immersion on the bath.

These laboratory trials validated the significant influence of bath temperature and ingot preheating on the ingot melting time. However, the melting times measured during these laboratory trials can not be directly transposed to ingots melting time in industrial conditions due to the different shape of the ingots, and the immersion in a static bath (in comparison to dynamic industrial bath).
3. ON-LINE INDUSTRIAL TRIALS WITH INSTRUMENTED INGOTS

On line industrial trials have been performed with instrumented aluminizing ingots with objectives to estimate the melting time of the jumbo ingot in industrial immersion conditions.

As illustrated on Figure 6, a jumbo aluminizing ingot (Al-10wt%Si) was instrumented with 9 thermocouples:
- thermocouples 1, 4, 6 and 8 at different length, mid-height, and 12cm from the right side (opposite to inductor flow)
- thermocouples 2, 5, 7 and 9 at respectively the same length, mid-height, and 12cm of the left side (on the side of the ingot receiving the inductor flow)
- thermocouple 3 centered, mid-height.

![Fig. 6: jumbo ingot instrumented with 9 thermocouples on the tilting table before immersion](image)

The instrumented ingot was installed on a tilting table and immersed at room temperature with an imposed immersion sequence to simulate a high pot productivity. It can be highlighted on figure 7 that 78% of the ingot have been immersed in 14 minutes. As the signal obtained from thermocouples 1 & 2 indicated that ingot was not melted at this location after 14 minutes, decision was taken to stop immersion sequence for 10 minutes to avoid having non-melted ingot part too deep in the bath. The immersion sequence has then been completed.

![Fig. 7: immersion sequence of the instrumented ingot](image)
Figures 8, 9 and 10 show the thermal profiles measured by thermocouples situated on the same ingot height, but on the different size. The time required to melt the ingot at the position 1 and 5 can be estimated to be about 33 minutes after the immersion of these zones. It can be highlighted that all thermocouples situated on the right side of the ingot (opposite to the flow coming from the inductors) present longer melting time (up to 10 minutes more) than thermocouples situated on the same height but on the side receiving the inductor flow.

Fig. 8: thermal evolution in the ingot during the immersion (position 1 = opposite to inductor & position 2 = in front of the flow coming from the inductor)

Fig. 9: thermal evolution in the ingot during the immersion (position 4 = opposite to inductor & position 5 = in front of the flow coming from the inductor)
This industrial trial highlighted that:

- in the studied industrial immersion conditions, the pot productivity can be limited by the ingots melting kinetic. In case of required high pot productivity, the tested ingots immersion sequence is too fast to obtain continuous ingot melting.

- the flows coming from the inductor allow to decrease the ingot melting time. The flows induced two different contribution on the ingot melting:

  1. thermal contribution: as melt coming from the inductor have a higher temperature than the average bath temperature, the heating and melting of the ingot will be faster. It can be observed on Figures 8, 9 and 10 that thermocouples situated on the inductor side present a slightly higher heating after immersion than the thermocouples situated on the opposite side. The flow also contributes to the renewal of the liquid in the ingot immersion area, avoiding the formation of a cold zone around the ingots.

  2. hydrodynamic contribution: The flow coming from the inductor limits the formation of a cold melt area around the immersed ingot. The melt in contact with the ingot on the side receiving the inductor flow is probably renewed faster than on the opposite side. The flow is also suspected to impact the solidification front and to erode the melting structure. During melting of the eutectic structure, the solid fraction in this area decreases and the structure became more brittle; small solid particles may be removed from the interface with the flow, what strongly decreases the time of melting at this location.

4. CONCLUSIONS

Hot Dip Galvanizing pot productivity is defined as the amount of materials melted in the pot during a given time. The different parameters affecting the pot productivity are:

- pot heating capacity
- ingots loading technology
- the ingots melting kinetic (dependent of ingot design, bath temperature, ingot temperature before immersion, and flows in melt)
The ingot melting kinetic has been more deeply investigated with instrumented ingots immersion trial in laboratory and in industrial conditions:

- The significant influence of the bath temperature on ingots melting kinetic has been validated.
- Ingots preheating before immersion also allow to decrease the ingot melting time.
- Both effects (bath temperature and ingot preheating) can be cumulated.
- The flow induced by the inductor in the industrial pot impact the ingot melting kinetic thanks to a cumulated thermal and hydrodynamic contribution.

REFERENCES

1) ASTM B897 – 18: Standard Specification for Configuration of Zinc and Zinc Alloy Jumbo, Block, Half Block, and Slab Ingot