ENC-2020-0682
NUMERICAL SIMULATION OF HOT DIP GALVANIZING FLOW

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Abstract. Zinc-coated steel sheets have high efficiency in corrosion resistance. The most common processes in the industry to obtain this coating are hot-dip galvanizing, thermal spraying, and electrodeposition. During this process, certain parameters can lead to the formation of intermetallics know as dross particles (Zn-Al-Fe), that have harmful effects on the final coated products. This work aims to study possible dross formation in steel sheets with coated surfaces in a hot-dip galvanizing continuous line through fluid dynamics analysis. A simulation using the OpenFOAM software is employed for the study of the fluid dynamic conditions of the process, addressing particularly the flow conditions and particle trajectories in the snout.

Keywords: hot-dip galvanizing, snout, zinc bath

1. INTRODUCTION

Hot-Dip Galvanization (HDG) is a process to coat steel sheets with a thin metallic layer for the protection of the sheet against corrosion damage. This process is characterized by the immersion of a metal part in molten zinc at temperatures between 440 - 470°C (Nasouri *et al.*, 2019; Wang *et al.*, 2018; Reiss *et al.*, 2019; Mahinroosta and Allahverdi, 2018).

The HDG process is of great importance for protection from corrosion, firstly with a barrier to protect the metal part against aggressive environment to which it is exposed. The zinc electrochemical potential is lower than that of other metals, thus serving as a sacrifice element and being corroded instead of the principal part, or substrate. The zinc is also capable of protecting the substrate from minor damages, as the electrochemical conditions allow it to generate a corrosion product that can act to repair a damaged local barrier. This is due to an increase in the volume of the corrosion products which fills the barrier failure. During galvanizing, the iron present in the steel reacts with the molten Zinc to form layers of intermetallic coating that acts like a physical barrier between the steel substrate and the corrosive environment (Bellini *et al.*, 2019b).

2. Aluminium Addition and Dross

There is an interaction between the iron atoms on the surface of the steel sheet, which are in the solid phase, with the molten zinc atoms present in the bath, that can, as a consequence, change places. Therefore, diffusion of these elements occurs, forming a solid mixed layer, called intermetallic compound. This Fe-Zn alloy has a very low ductility, causing fragility of the material. The aluminium addition works as an inhibitor of this reaction. This new alloy layer (Fe-Zn-Al) enhances the adhesion of the coating, and results in better conforming plates (Bellini *et al.*, 2019a; Reiss *et al.*, 2019). For continuous lines, the standard aluminium concentration in the bath is between 0.15 to 0.19 percent. However, based on recent studies of this type of metallurgic process, some manufacturers use between 0.20 and 0.25, while some special alloys, such as Galvanneal, require that the level is lowered to about 0.12 to 0.14.

According to Mahinroosta and Allahverdi (2018), with the addition of aluminium to the bath, Zn-Al-Fe intermetallic particles may appear. This material is called dross and its appearance is described schematically in Fig. 1. Initially, a surface layer of zinc oxides (ZnO) forms in the metal bath (Fig.1a). Then, this oxidized layer is suppressed by the movement of the bath (Fig.1b) where the zinc oxide (ZnO) particles sink or float according to their densities and sizes (Fig.1c). Over time, the aggregation of these oxide particles begins to occur (Fig.1d). These clusters are filled with Al (Fig.1e), which consequently results in the formation of aluminium oxide (Fig. 1f). The dross generated is removed from

the bath surface with a spoon (Fig.1g), however, with continued oxidation on the exposed surface of the bath and with denser particles, the dross formation may persist (Fig. 1h).
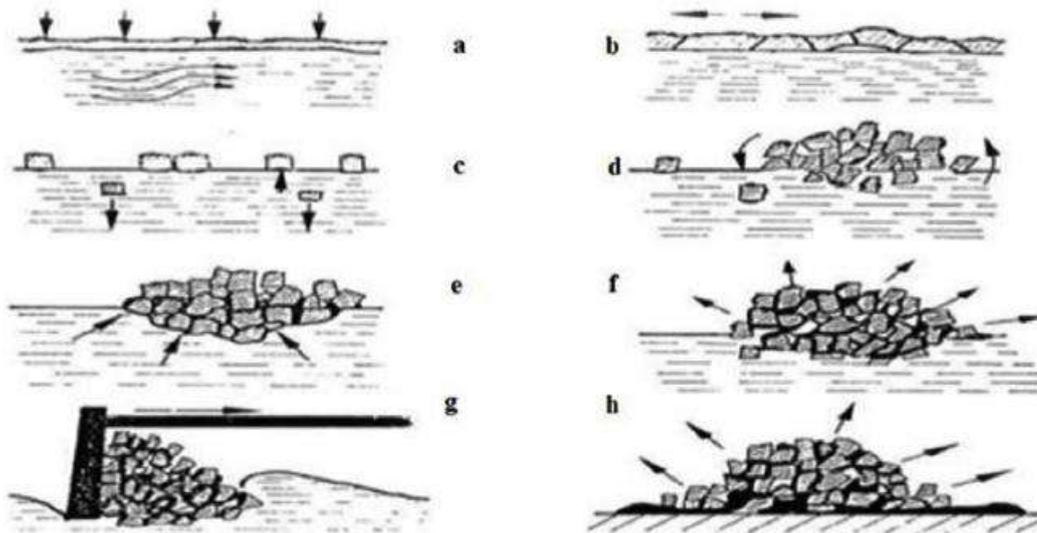

Figure 1. Scheme with the process of appearance of the dross. Mahinroosta and Allahverdi (2018)

Mondal *et al.* (2020) studied in depth the effects of the inclusion of Al in the formation of galvanized steel phases with a primary nickel coating (Prior-Ni). High and ultra strength steels (AHSS and UHSS) were used, which have higher amounts of alloying elements such as Mn, Si, and Al. In the process of hot-dip galvanizing, these elements can form oxides on the surface of the substrate, which causes the wettability of zinc in the steel substrate to be impaired. For this process to occur satisfactorily, a primary nickel layer is included before the process begins, forming a barrier that protects it, as it retains the alloying elements in the coating layer, also affecting the formation of phases. With a higher concentration of Al, an intermediate layer of Ni-Al-Zn formed in the coating preventing further diffusion, such as the formation of NiZn8 and gamma phases in the coating microstructure, as shown in Fig. 2.
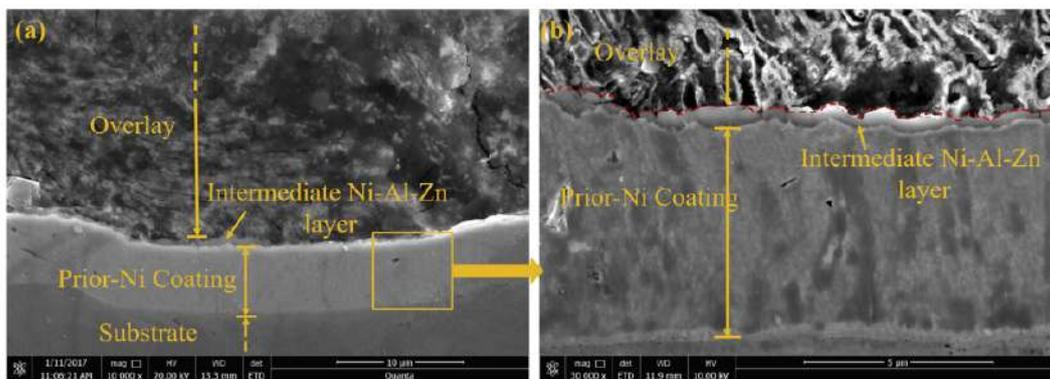

Figure 2. Microstructure with a primary Ni layer (Prior-Ni) in a bath zinc with Al. Adapted from (Mondal *et al.*, 2020)

3. Snout

The steel sheet manufacturing process goes through several stages. On the step before the zinc bath, the material comes from an oven. To avoid loss of temperature in this process, there is a snout. The snout is a metallic structure, which serves to isolate the material from the exit of the oven to the bath, therefore, preventing the contact of the steel sheet with the outside environment. It is also responsible for removing lees that are formed on the surface of the bath, thus preventing surface imperfections (Felix *et al.*, 2017). The snout is shown in Fig. 3. Its positioning is regulated manually, and, under certain conditions, it can accumulate a large amount of dross.

4. Computational Fluid Dynamics (CFD) and Hot-Dip Galvanization (HDG)

Computational Fluid Dynamics (CFD) is very useful to study the intermetallics phases that occur in hot-dip galvanization. Reiss *et al.* (2019) used a computational framework with CFD thermodynamic model to calculate the turbulent flow
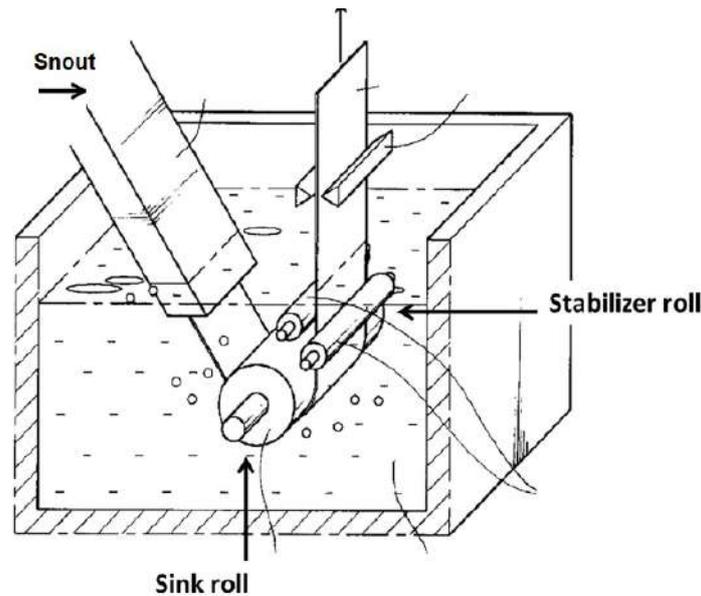
Figure 3. Scheme with the position of the snout in a zinc bath process. Adapted from (Mondal *et al.*, 2018)

conditions within the liquid melt and investigated the driving force for the formation of intermetallic dross particles in the zinc bath. A mathematical model computed the flow, temperature, and species concentrations in the zinc bath. The correct modeling of the interface influences the temperature and dissolution of iron and aluminum uptake. These parameters have a significant influence on the thermodynamic conditions of the bath, as seen in Fig. 4
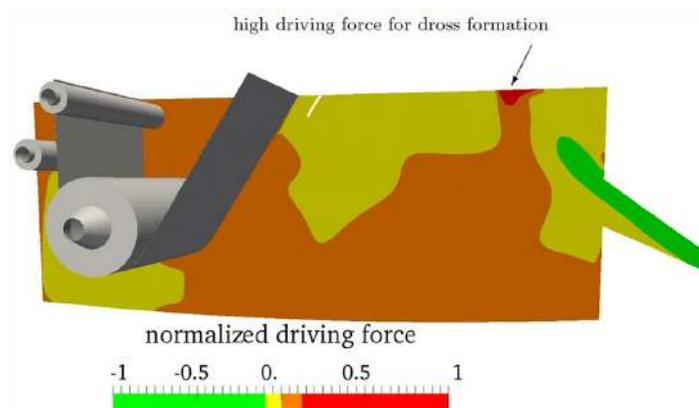

Figure 4. Driving force in the zinc bath, deduced from the distance to the thermodynamic solubility. Adapted from (Reiss *et al.*, 2019)

5. OpenFOAM Simulations

OpenFOAM is a software that can perform Computational Fluid Dynamic (CFD) as well as multi-physics simulations. It is an open source library, written in C++ language (Guimarães Dias Siqueira and Barbosa de Souza, 2019), and it was employed to model and simulate the fluid flow in the zinc bath.

The goal of the current work is to elucidate the basic physical phenomena involved in this process. Therefore, several assumptions were made to simplify the model in order to obtain a preliminary understanding. The results of the OpenFOAM simulations performed using *icoFoam* solver are presented in Fig. 5 and Fig. 6. They show the simulation of a tank with a zinc bath and a snout that is on top of the tank, and limited by a cylinder on the bottom, which in the present geometric model is simplified to a flat surface. They represent the particle trajectories of an idealized zinc bath, which considers a Newtonian fluid laminar flow in steady-state. These initial results were performed using a simplified two-dimensional geometric model, and neglecting the relative velocity between the particles and the fluid. A detailed study of the particle trajectories considering a more realistic geometry, buoyancy effects, turbulence models and inertia of the particles will be presented in future works.

Figure 5 shows the evolution in time of particles initially uniformly distributed in the domain. As can be seen,

some particles get trapped inside the snout due to the movement that they perform in their preferred streamlines. The accumulation of particles in this region may be the reason for a major dross formation. Moreover, the particles get dragged and stuck with the steel strip and sucked by the cylinder, indicating that the dross formed in the snout neighborhood can get attached to the strip and pressed against it when passing through the cylinder.
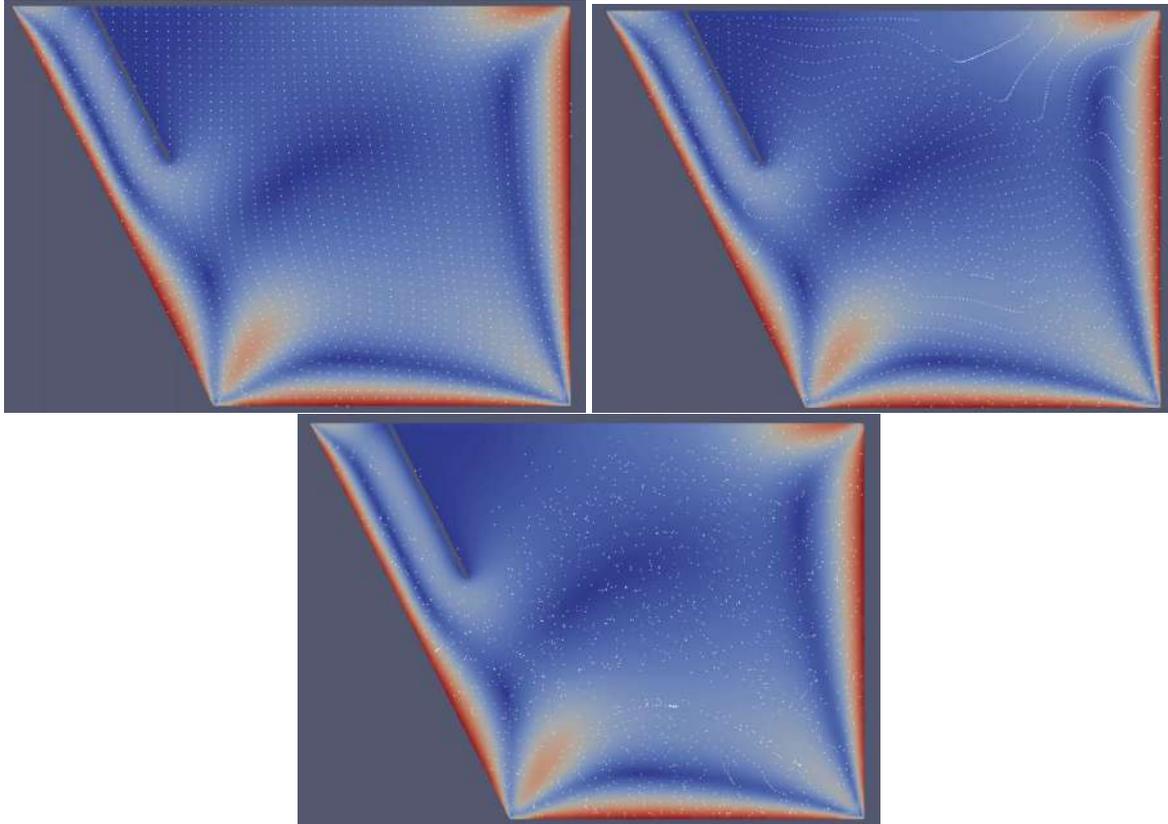

Figure 5. Evolution in time of ideal particles in zinc bath. Simulation using OpenFOAM
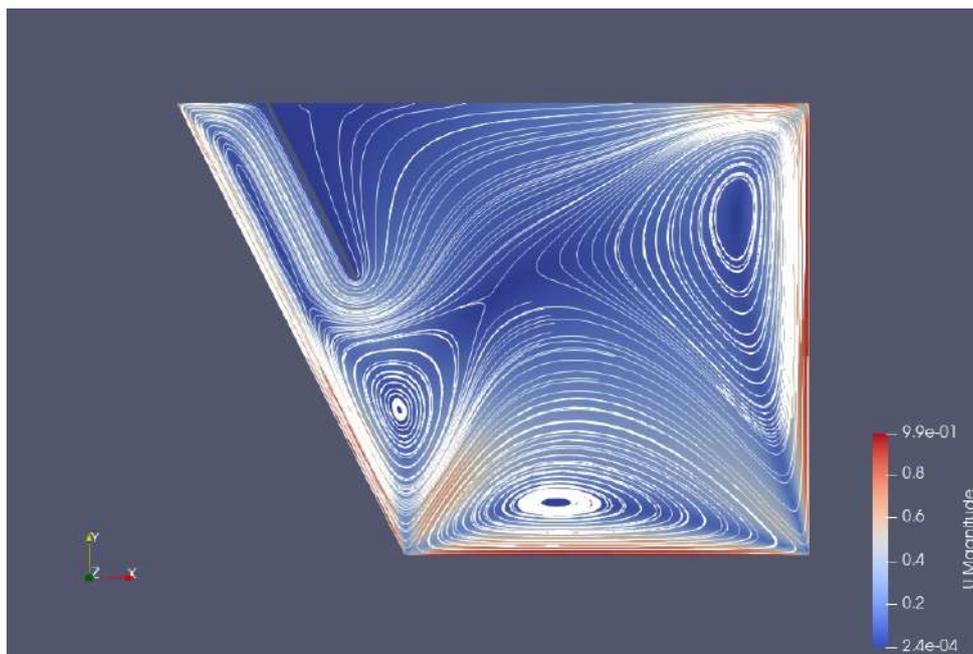

Figure 6. Numerical simulation of the zinc bath of a HDG process, showing the streamlines.

The streamlines are summarized in Fig. 6 and show the formation of three large re-circulation regions. At the left, the steel strip enters the bath and imparts a downward velocity to the flow. The bottom cylinder surface, approximated

by a flat lower boundary, pushes flow against the descending strip on the left, thus causing the ejection of a liquid jet at approximately the direction of the bisector angle. Most importantly, the downward movement of the strip induced the suction of liquid from the top of the bath down to the snout entrance and up to the snout internal meniscus. The accurate positioning of the snout can lead to an improved flow in the snout region, preventing the trapping of particles in the strip boundary layer.

6. CONCLUSIONS

This article presented a study of the continuous process of zinc bath hot-dip galvanization of steel sheets. The aim was to study possible dross formation in steel sheets with coated surfaces through fluid dynamics analysis. A simulation using the OpenFOAM software was employed for the study of the fluid dynamic conditions of the process, addressing particularly the flow conditions and particle trajectories in the bath.

The behavior of ideal particles was achieved and could be observed using time evolution of particles and streamlines plot. Furthermore, initial results indicate that the region inside the snout is likely to be one of the main issues leading to dross formation, due to possible accumulation of particles which get dragged and sucked by the cylinder. Hence, improving the positioning of the snout could potentially offer substantial opportunities for improvement in the quality of the final product. Although the implemented model was simplified, an interesting physical behavior could be observed leading to useful conclusions. Lastly, this is a preliminary work and future studies must be performed to confirm the results and obtain further conclusions.

7. ACKNOWLEDGEMENTS

8. REFERENCES

Bellini, C., Carlino, F. and Natali, E., 2019a. "Analysis of the al and ti additions influences on phases generation and damage in a hot dip galvanizing process." *Procedia Structural Integrity*, Vol. 18, pp. 688–693.

Bellini, C., Iacoviello, F., Carlino, F. and Di Cocco, V., 2019b. "The influence of hot dip galvanizing process on inter-metallic phases formation." *Material Design & Processing Communications*, Vol. 39.

Felix, G., Sellin, N. and Marangoni, C., 2017. "Reduction of dross in galvanized sheets through automatic control of snout positioning in continuous operation". *The International Journal of Advanced Manufacturing Technology*, Vol. 89, p. 2345–2353.

Guimarães Dias Siqueira, G. and Barbosa de Souza, V., 2019. "Estudo computacional do escoamento de ar na câmara de testes de um túnel de vento subsônico utilizando cfd". *Revista Interdisciplinar Pensamento Científico*, Vol. 5.

Mahinroosta, M. and Allahverdi, M., 2018. "Hazardous aluminum dross characterization and recycling strategies: A critical review." *Journal of Environmental Management*, Vol. 223, p. 452–468.

Mondal, A., Halder, A. and Dutta, M., 2020. "Effect of al on phase evolution in prior-ni coated galvanized steel: Thermodynamic and kinetic assessment". *Journal of Alloys and Compounds*, Vol. 830.

Mondal, A., Halder, A., Nayak, S., Kumar, A., Chakraborty, A., Shukla, S., Sahoo, S., Pais, R. and Dutta, M., 2018. "Root cause analysis of an uncommon surface defect on galvannealed steel sheet". *Engineering Failure Analysis*, Vol. 93, p. 64–75.

Nasouri, R., Nguyen, K., Montoya, A., Matamoros, A., Bennett, C. and Li, J., 2019. "Thermally-induced demands due to hot dip galvanization of high mast illumination poles. part i: Finite element model development." *Journal of Constructional Steel Research*, Vol. 162.

Reiss, G., Ishmurzin, A., Mugrauer, C., Eßl, W., Ecker, W., Strutzenberger, J., Unger, H. and Angeli, G., 2019. "Thermo-chemical fluid flow simulation in hot-dip galvanizing: The evaluation of dross build-up formation". *Metallurgical and Materials Transactions B*, Vol. 50, p. 834–845.

Wang, Z., Shi, J., Gao, A., Meng, L. and Guo, Z., 2018. "Recovery of zinc from galvanizing dross by a method of super-gravity separation." *Journal of Alloys and Compounds*, Vol. 735.

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