SIMULATION OF ZINC FILM FORMATION DURING CONTINUOUS WITHDRAWAL OF STEEL STRIPS FROM GALVANIZING BATHS

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Abstract

Process stability is essential to produce high quality homogeneous zinc coatings at continuous galvanizing lines. In order to be able to predict the zinc film thickness after gas jet wiping, the adhered film thickness and its formation before the wiping process has to be known. For this reason, the Volume of Fluid (VOF) multiphase model considering surface tension effects together with the RNG *k-ε* and Large Eddy Simulation (LES) turbulence model were applied. For validation, the simulation results were compared with the theoretically predicted film thickness of Landau, Levich and Deryaguin (LLD) for static bath conditions. It was found out that up to a certain strip withdrawal speed, the RNG *k-ε* turbulence model shows good agreement with the theoretically predicted film thickness. For higher strip withdrawal speeds, as usually operated at continuous galvanizing lines, the theoretical film thickness can only be achieved by applying the LES turbulence model. Furthermore, it is demonstrated, that changing the flow conditions from a static bath to actual flow conditions inside a zinc bath, highly influences the local flow at the meniscus region. The flow near the meniscus and the meniscus movement itself affect the film thickness on the strip below the gas jet wiping nozzles. Therefore, controlling the flow near the meniscus region could lead to a better process stability for the gas-jet wiping process.

Keywords: Volume of Fluid (VOF), Large Eddy Simulation (LES), galvanizing, zinc bath, thin film, meniscus

1. INTRODUCTION

Continuous galvanizing lines produce zinc alloy coated steel strips in a sustainable and economical way. Advanced fields of applications require high surface quality coatings. In order to achieve this, process stability has to be ensured. The thickness of the coating after gas jet wiping is on the scale of few µm. It should be homogeneous to be a perfect basis for further applications.

Crucial parts of a galvanizing line - apart from annealing oven or skin-pass unit - are the galvanizing bath and the gas jet wiping process shown in **Fig. 1**. This is the actual galvanizing step where a zinc alloy is applied onto a steel sheet. At first, the steel strip is withdrawn from a zinc bath with an adhered fluid film of zinc on its surface. Following this, the excess of zinc is hydrodynamically reduced by gas jets to a desired film thickness. With the aid of Computational Fluid Dynamics (CFD) it is possible to gain a deeper understanding of the underlying processes and hence improve the production of high quality zinc coatings. Some researchers simulate the gas jet impinging on a blank moving strip [1, 2]. The resulting pressure and shear stress profiles along the strip are used to calculate analytically a dimensionless film thickness. It is defined as the relation of the film thickness before and after the gas jet wiping process.

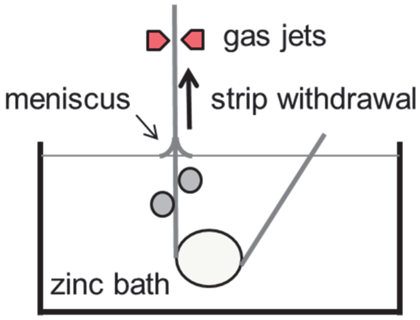

Fig.1 Steel strip withdrawal from a zinc bath in the continuous coating process

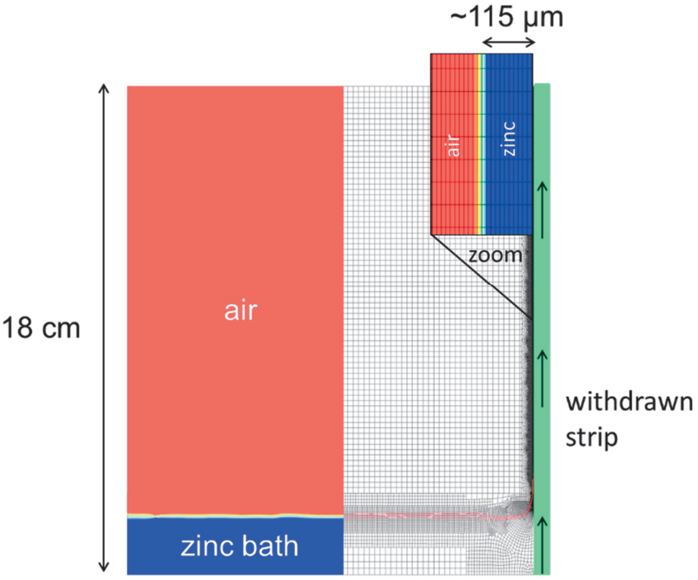

Fig. 2 Simulation domain and computational mesh. The zoom window shows the grid resolution in the zinc film

Also measurements of pressure and shear stress profiles at experimental conditions were preformed [3, 4]. In contrast to measurements, CFD simulations can capture the pressure and shear stress profiles at industrial galvanizing line conditions with high speed gas jets of around 230 m/s.

To simulate quantitatively the aim film thickness after gas jet wiping, it is essential to know the zinc film thickness below the gas jets. Krechetnikov and Homsy discover the dynamics of the meniscus region for the hot-dip galvanizing process. The dynamic meniscus region is defined where the forces of drag, gravity and surface tension are in balance [5]. Due to flow dynamics, the position of the balanced forces changes as well which makes the meniscus moving in time. In hot-dip galvanizing processes the physical parameters, immersion time, withdrawal speed and bath temperature affect the zinc coating thickness [6]. Continuous galvanizing lines are operated with constant bath temperatures and short immersion times. Here, the zinc growth during the bath immersion time is small compared to the withdrawn fluid zinc film.

The purpose of the present work is to predict the zinc film thickness and its evolution on a withdrawn steel strip below the gas jets during industrial operation. Furthermore, a validation of several turbulence models was performed and the influence of the fluid flow inside the zinc bath on the film thickness was studied.

2. SIMULATION DETAILS

Mass and momentum conservation in the computational domain were achieved by solving the continuity equation and the Navier Stokes equations for incompressible Newtonian fluids. The solution yields the pressure and velocity components at every point in the domain. For Simulation, the commercial computational fluid dynamics software ANSYS Fluent was used. In order to calculate the multiphase flow, the volume of Fluid (VOF) Model was applied. This model tracks the liquid fraction of the immiscible phases air and zinc. The compressive scheme method is applied to interpolate the interphase [7].

2.1 Turbulence Models

The turbulent flow field was modeled with the RNG k-ε and the algebraic Wall Modeled Large Eddy Simulation (LES) model. The RNG k-ε model was chosen, due to its analytically derived formula for effective viscosity for low Reynolds number effects in regions with low turbulence [8]. The advantages of the RNG k-ε turbulence model are the low computational costs.

The LES model solves the large scale eddies directly. Eddies, which are smaller than the grid scale, are modelled by a sub-grid-scale model. The algebraic Wall Modeled LES approach reduces the Reynolds number dependent grid resolution requirements compared to a classical wall resolved LES model [9]. LES can be applied for laminar and turbulent flow regions. The disadvantages of the LES model are the high computational costs. It is known that the assumption of LES is based on the 3D motion of turbulent flow. However, in this paper the LES turbulence model is applied in 2D. Myrillas et al. could show an analytical validation of 2D applied LES simulation to simulate a gas jet wiping process at experimental conditions [4].

2.2 Landau, Levich and Deryaguin (LLD) Theory

To validate the VOF model together with turbulence models for simulating the adhered zinc film during strip withdrawal, a comparison with the LLD Theory for several withdrawal speed was performed. The flow in the zinc bath, which is normally induced by the rotation of the upper roll, was neglected. Assuming constant material data, the adhered film thickness h_0 depends only on the strip withdrawal speed. With material properties for zinc alloy, as used in continuous galvanizing baths, the capillary number Ca is, up to a strip withdrawal speed of U = 2.6 m/s, lower than 0.01 and is defined as,

$$\mathrm{Ca} = \frac{\mu U}{\sigma}. \tag{1}$$

Here, μ is the viscosity, U is the strip withdrawal speed and σ is the surface tension. Larger values of the capillary number lead to faster growth of the film thickness h_0 as a function of the strip withdrawal speed [Landau]. The theoretical film thickness h_0 for Ca < 0.01 is defined as [10, 11],

$$h_0 = 0{,}945\sqrt{\frac{\sigma}{\rho g}}\left(\frac{\mu U}{\sigma}\right)^{2/3}, \tag{2}$$

where, g is the acceleration of gravity. The root expression represents the capillary length which determines the meniscus size.

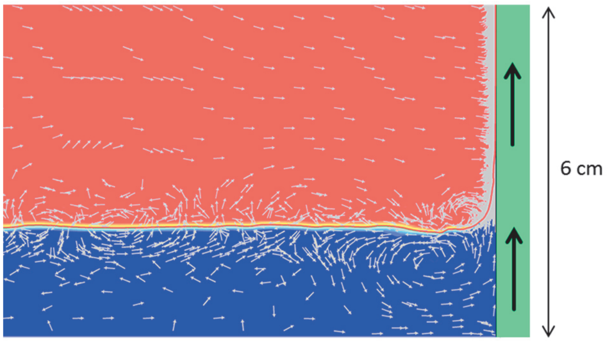

Fig. 3a Vectors of velocity and phase field near the meniscus region with static bath conditions for a withdrawal speed of U = 1.63 m/s

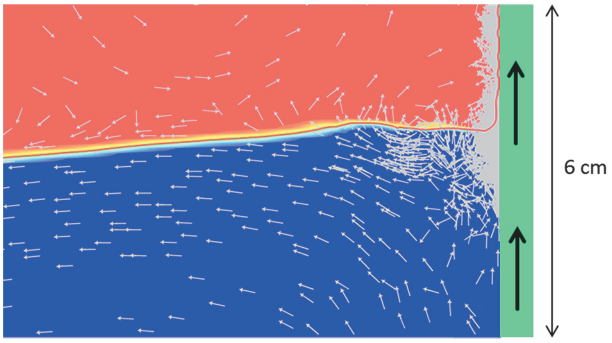

Fig. 3b Vectors of velocity and phase field near the meniscus region with industrial bath conditions for a withdrawal speed of U = 1.63 m/s

2.3 Boundary Conditions

The simulation domain and the computational mesh are shown in **Fig. 2**. The continuously withdrawn steel strip is modeled as a moving wall with constant velocity and no slip condition. To resolve the thin zinc film on the strip, mesh refinement near the strip and near the phase boundary is essential. The phase boundary is illustrated by the red line in **Fig. 2**. The mesh resolution near the strip surface is shown in the zoom window in **Fig. 2**. There, the horizontal cell size is 10 µm with an aspect ratio of 1:5. Pressure outlet assuming atmospheric pressure is used as outlet boundary for the air and zinc flow. For the comparison with the analytical LLD theory the zinc bath is assumed to be static and the simulation domain is surrounded by walls. For the industrial bath condition simulation, the walls were changed to velocity inlets with predicted velocity and turbulence profiles from a 3D zinc bath simulation done before.

3. RESULTS AND DISCUSSIONS

3.1 Model Validation

For the model validation static bath conditions were applied. **Fig. 3a** shows an instantaneous phase and flow field at a certain time. The phase boundary between air and zinc is colored as phase fractions from blue equal to zinc to red equal to air. Vectors with a fixed length are colored in light grey indicating the direction of the flow. Mesh density was increased near the strip to capture the film flow motion near the meniscus. The upwards moving strip at the right boundary induces the zinc moving upwards near the strip.

Due to the continuously withdrawn strip and surface tension between the phases air and zinc, a round shaped moving meniscus is formed. Excess zinc is flowing down again along the meniscus surface till it is dragged downwards by the flow in the bath. The meniscus always tries to keep its round shape constant. The arising movement of the meniscus results in a wavy film thickness along the strip which is illustrated in **Fig. 4a**. At static bath conditions the meniscus height is a function of strip withdrawal speed. In the case of a withdrawal speed of U = 1.6 m/s, the meniscus reaches a height of 8 cm compared to the bath surface.

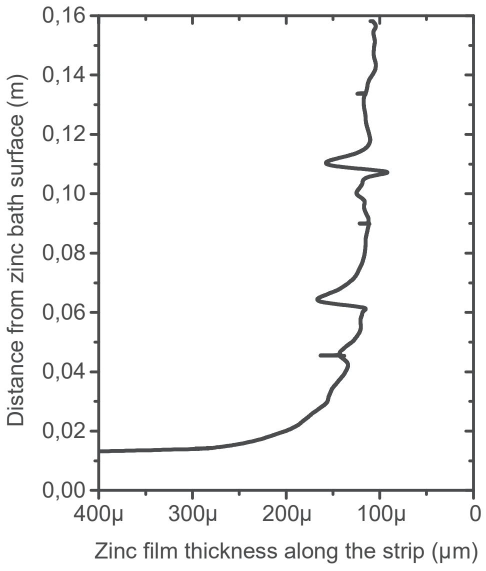

Fig. 4a Variation of the film thickness along the strip defined as volume fraction of f = 0.5 with static

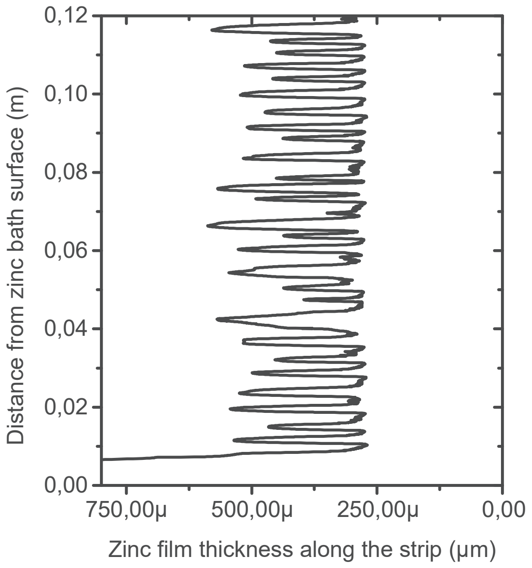

Fig. 4b Variation of the film thickness along the strip defined as volume fraction of f = 0.5 with

bath conditions for a withdrawal speed of U = 1.63 m/s.

industrial bath conditions for a withdrawal speed of U = 1.63 m/s.

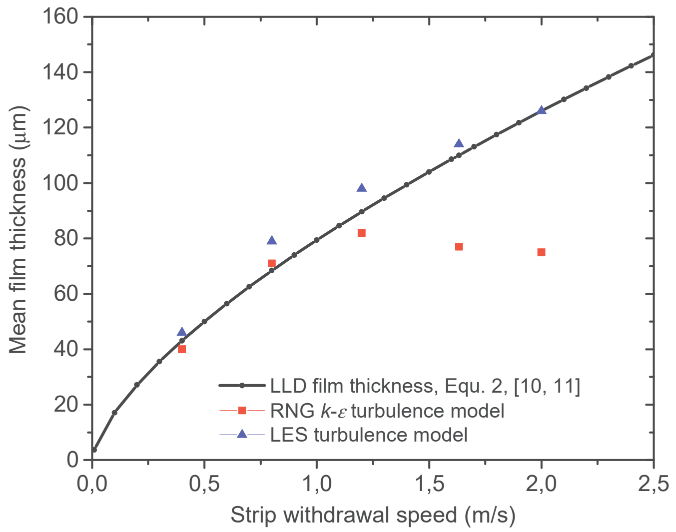

Fig. 5 Comparison between the LLD film thickness and the simulation results

Above the meniscus height, mean values of the adhered film thickness along the strip are plotted in **Fig. 5**. The film thickness increases with increasing strip withdrawal speed. The RNG k-ε and the LES turbulence models were compared to the theoretical LLD film thickness at various strip withdrawal speeds. The LES model predicts very well the theoretical film thickness for all investigated strip withdrawal speeds. The RNG k-ε model predicts the theoretical film thickness up to a strip withdrawal speed of around U = 1 m/s. Above this withdrawal speed an increase of speed does not result in an increase of film thickness. Therefore, only the LES turbulence model is able to predict correctly the film thickness for strip withdrawal speeds higher than U = 1 m/s. In industrial continuous strip galvanizing lines the withdrawal speed is usually between U = 0.83 m/s (50 m/min) and U = 2.5 m/s (150 m/min).

3.2 Strip Removal Simulation at Industrial Conditions

In industrial continuous galvanizing lines the steel strip is drawn through a zinc bath. For the movement and stabilization of the strip, rolls are installed in the zinc bath. These rolls rotate as the strip moves through the bath. At the lower side of the steel strip in the bath, the rotation of the upper roll induces a flow which is directed upwards with high velocity to the meniscus, as it is shown in **Fig. 3**b. In the simulation industrial bath boundary profiles were applied. Flow boundary conditions were set at the bottom of the simulation domain to account for the flow given in an industrial zinc bath. **Fig. 4**b shows the uneven zinc film along the strip with the meniscus moving in time. The mean film thickness above the meniscus is predicted to be 373 µm, which is 3 times higher than the one predicted with static bath conditions at the same strip withdrawal speed. The reason is the upwards directed flow induced by the upper roll of the zinc bath.

CONCLUSIONS

Validation and application of the multiphase VOF model together with the RNG k-ε and the LES turbulence model to predict the zinc film thickness adhered on a steel strip withdrawn from a galvanizing bath were perfomed.

In the scale of µm, the simulated zinc film thickness shows to be very sensitve to the applied turbulence model. The RNG k-ε tubulence model fails to predict the film thickness above a withdrawal speed of 1 m/s. In this work the LES turbulence model was able to predict the film thickness even in 2D, which makes it as the only choice for qualitative good results and acceptable computational costs.

The results provide important information and serve as boundary condition for a quantitative prediction of the aim film thickness after the gas jet wiping process. The gas jet wiping of excess zinc on the strip surface was not yet taken into account in this paper. It is planned as a further step in the authors work.

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REFERENCES

[1] NAPHADE, P., MUKHOPADHYAY, A., CHAKRABARTI, S. Jet Wiping in Hot-DipGalvanization. *ISIJ Int.*, 2005, Vol. 45, No. 2, pp. 209-213.

[2] ZHANG, Y., CUI, Q.-p., SHAO, F.-q., WANG, J.-s., ZHAO, H.-y. Influence of Air-Knife Wiping on Coating Thickness in Hot-Dip Galvanizing. *Journal of Iron and Steel Research Int.*, 2012, Vol. 19, No. 6, pp. 70-78.

[3] GOSSET, A., BUCHLIN, J.-M. Jet Wiping in Hot-Dip Galvanization. *Transaction of the ASME*, 2007, Vol. 129, pp. 466-475.

[4] MYRILLAS, K., RAMBAUD, P., MATAIGNE, J.-M.,GARDIN, P., VINCENT, S., BUCHLIN, J.-M. Numerical Modeling of Gas-Jet Wiping Process. *Chemical Engineering and Processing: Process Intensification*, 2013, Vol. 68, pp. 26-31.

[5] KRECHETNIKOV, R. J., HOMSY, G. M. Surfactants Effects in the Landau-Levich Problem. *J. Fluid Mech.*, 2006, Vol. 559, pp. 429-450.

[6] BEN, J., SNOUSSI, A., BRADAI, C., HALOUANI, F. Optimization of Hot-Dip Galvanizing Process of Reactive Steels: Minimizing Zinc Consumption Without Alloy Additions. *Materials Letters*, 2008, Vol. 62, pp 3328-3330.

[7] ANSYS®FLUENT, 14.5, User‘s Guide, 2013.

[8] ORSZAG, S. A., YAKHOT, V., FLANNERY, W. S., BOYSAN, F., CHOUDHURY, D., MARUZEWSKI, J., PATEL, B. Renormalization Group Modeling and Turbulence Simulations. From Conference Proceedings *International Conference on Near-Wall Turbulent Flows*. TEMPE: Arizona,1993.

[9] SHUR, M. L., SPALART, P. R., STRELETS, M. K., TRAVIN, A. K. A Hybrid RANS-LES Approach with Delayed-DES and Wall-Modelled LES Capabilities. *Int. Journal of Heat and Fluid Flow*, 2008, Vol. 29, No. 6, pp. 1638-1649.

[10] LANDAU, L., LEVICH, B. Dragging of a Liquid by a Moving Plate. *Acta Physicochim. URSS*, 1942, Vol. 17, pp. 42-54.

[11] DERYAGUIN, B.V. On the Thickness of the Liquid Film Adhering to the Walls of a Vessel after Emptying. *Acta Physicochim. URSS*, 1943, Vol. 20, pp. 349-352.