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NUMERICAL SIMULATION OF FLOW, TEMPERATURE AND COMPOSITION VARIATIONS IN A GALVANIZING BATH

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Abstract — The modern hot dip galvanizing operation is a complex process subject to a number of configurational, physical, chemical and kinetic parameters. Small decreases in temperature can precipitate intermetallic dross particles, which can be entrained in the flow towards the strip leading to surface imperfections. The numerical simulations carried out in this study clearly define the spatial distribution of velocity, temperature and compositional variation in the bath. The modeling of the transient effects during ingot melting and non-melting periods have also identified the critical periods and zones within the bath where dross formation can occur within an operating cycle.

Résumé — L'opération moderne de galvanisation à chaud est un procédé complexe exposé à plusieurs paramètres configurationnels, physiques, chimiques et cinétiques. De petites diminutions de température peuvent précipiter des particules intermétalliques de scories, lesquelles peuvent être entraînées dans l'écoulement vers la bande, conduisant à des imperfections de surface. Les simulations numériques effectuées dans cette étude définissent clairement la distribution spatiale de la vitesse, de température et de la variation de composition dans le bain. La modélisation des effets transitoires lors des périodes de fonte et d'absence de fonte du lingot a également identifié les périodes critiques ainsi que les zones dans le bain où la formation de scorie peut se produire à l'intérieur d'un cycle d'opération.

INTRODUCTION

More than half the world's production of zinc is used for general and continuous galvanizing in the coating of steel products and the future outlook indicates that this trend will continue to increase with the development of new market applications [1]. By far the most important product is hot dip galvanized steel sheet used for automobile body manufacture. As a result of the ultralight steel automobile body (ULSAB) initiatives over the years, the steel makers have been able to supply automobile manufacturers with coated sheet having excellent corrosion resistance, ready-to-paint surface quality, good weldability and formability. This high quality coated steel is a very important and large volume product linking steel producers with zinc suppliers around the globe. New types of high strength steels such as dual phase and transformation induced plasticity (TRIP) steels are being introduced to further decrease the vehicle weight while maintaining the necessary impact resistance. Thinner, more adherent coatings for these new steels are a challenge to the galvanizers. Since

these products are a major factor in the profitability of all steel sheet producers, the technology and process control of the galvanizing operation is of primary concern [2]. Process simulation of the coating operation, by quantifying the influence of configurational and operational parameters on dross formation within the bath, has been found to be a very powerful tool for zinc bath management. The analysis of these simulations results in attaining more predictable coating characteristics as well as in increasing the productivity of the process.

DESCRIPTION OF THE PROCESS

The hot dip galvanizing process is a complex metallurgical process where a steel strip of various width and thickness is continuously coated by rapid immersion in a zinc alloy bath normally maintained between 450 and 480 °C. Contact times range between 2 and 6 seconds and depend on pot size, hardware arrangement and line speed which is limited by sheet thickness (thin strip can be processed at a higher speed than

thick strip). The interfacial reactions occur almost immediately after immersion by forming an inhibition layer. On exiting from the bath, the excess zinc is deflected back into the bath by means of air knives, leaving a thin coating on the steel sheet. Coatings for automobile products generally measure about 10 to 15 μm (70-100 g/m^2 on each side), whereas the construction materials have considerably thicker coatings. Beyond the air knives, the sheet rises vertically and is cooled to an ambient temperature for the galvanized product or it can pass through a temperature controlled galvannealing section where further reactions occur in the coating. Generally, both types of products can be produced on the same line where the galvannealing unit can be put into place as required. An illustration of a typical modern galvanizing bath is shown in Figure 1.

Role of Aluminum in the Coating Process

Aluminum additions to the galvanizing bath are essential in order to obtain an adherent coating with good formability. Concentration levels for the galvanneal product are in the range of 0.11 to 0.13% Al and up to 0.30% Al for the galva-

nized product. Adherence of the coating is generally measured using "powdering" tests according to a specific bending mode where the amount of non-adhering particles of the coating are quantified. The rapid reaction of the Al in the bath with the steel forms an inhibition layer of Fe_2Al_5 generally less than 1 μm thick which is both adherent and deformable as opposed to the iron zinc intermetallic phases which are much more fragile. On exiting the bath, this solid layer is covered with an entrained liquid layer of the alloy at the bath composition. The air knives control the coating thickness by a variation of air pressure and gap width from the strip. The amount of Al in the inhibition layer increases with the Al content in the bath up to 0.20% as was shown by Hertveldt *et al.* [3] as well as with steel composition and temperatures of the steel strip and the zinc bath [4]. Galvanized products for exposed applications are frequently produced in baths containing 0.25% and higher aluminum contents. Addition of zinc ingots with Al contents higher than the bath composition are therefore necessary to maintain a steady state operation. The layer of Fe_2Al_5 needs to be sufficiently thick to ensure coverage of the entire surface. Excessive thickness is undesirable since it was clearly shown by Bilello *et al.* [5] that the coating ductility decreases with the increasing thickness of the Fe_2Al_5 layer. The galvanizing bath therefore can be considered to be a reactor where a product layer Fe_2Al_5 intermetallic and Fe-Zn-Al alloy are continuously removed from the bath. Linares *et al.* [6] have described the reactor where zinc and aluminum are transported from the ingot to the steel by the induced flow of the bath from the movement of the strip and immersed equipment. It can generally be stated that the bath is iron saturated due to the continuous contact with the steel. Make up ingots of zinc alloy are in the range of 0.50 to 1.0 wt% Al depending on the type of product or operation. Local decreases in the temperature near the melting ingot surface reduce the solubility of both iron and aluminum and are considered to be one of the primary sources of dross particles which can nucleate and grow. Control of bath temperature is therefore of primary importance in order to prevent this precipitation phenomenon during the production of high quality coatings.

The thermodynamics have been investigated in a number of studies [7-9]. A review of the thermodynamic data and solution models has also recently been presented by Costa e Silva *et al.* [10]. Tang [8] measured the aluminum and iron solubility in molten zinc as a function of temperature at 450, 460 and 470 $^{\circ}\text{C}$ by atomic absorption spectroscopy. Solid intermetallic compounds zeta (ζ), delta (δ) and eta (η) phases were identified and characterized using electron microscopy and the data was analyzed using solution models. McDermid and Thompson [11] have also studied the relationship of temperature on iron solubility using available experimental data and rigorous thermodynamic analysis and have found slightly different phase boundaries. The comparison of the solubility equations for the galvanized region (Al contents above the 'knee' point) agrees to within 95% with the data of Tang [8], whereas the invariant point in the galvanneal region (liquid- δ) was found to be at a much lower Al content. A comprehensive

Fig. 1. Configuration of a typical galvanizing bath.

model for this region of the phase diagram, shown in Figure 2 for liquidus temperatures from 450 to 480 °C, was found to be very useful for galvanizers. Tang's version of the diagram [8,12] is well established in the industry and is used by a large number of galvanizers in their daily operations [13]. This representation of the Fe and Al solubility is used to calculate the effective (dissolved) Al content in the bath for each isotherm. Assuming Fe saturation, the total Al content of a bath therefore corresponds to the dissolved amount plus any excess amount associated with the formation of either δ or η phases.

PROCESS SIMULATION

Previous simulations progressed from laminar to turbulent flow models where the effect of line speed, strip width and induction mixing has all been quantified for isothermal bath conditions operating at a steady state. It has become clear that the flow is three-dimensional due to the complex geometry of the immersed hardware. This still only simulates the condition for periods of the process when no make up ingots are added to the bath. However, when ingots are added to replenish the liquid metal taken out by the strip, the bath can no longer be considered to be isothermal. During this period, the induction heating rate is increased to adjust to the heat demand of the melting ingot thereby increasing temperature variations in the bath. The temperature at the inductor exit is higher and the region at the melting surface of the ingot is lower than the average bath temperature. Since the liquid zinc alloy densities are very sensitive to the temperature variations, it is anticipated that temperature variations in the bath would affect the overall flow due to natural convection, especially in regions where forced convection is small. This occurs in regions away from the moving strip and immersion rollers which are significantly affected by the temperature variations. The simulations show the importance of these temperature variations on the flow within the bath resulting from the melting of an ingot as compared to the isothermal case. The bath configuration used in the study is the same as that used for the previously reported isothermal calculations [14]. Heat losses through the pot sidewalls, bottom and bath sur-

face are taken into account in the heat balance so that the overall average bath temperature remains relatively constant at 460 °C.

The numerical model assumes that the melt behaves as a Newtonian fluid and that the flow is turbulent. Turbulence is modelled by the $k - \varepsilon$ model of turbulence and buoyancy effects are considered through the Boussinesq approximation. Time dependent effects are included and solutions were obtained at different time intervals. The momentum and continuity equations are as follows:

$$\rho_0 \frac{D\mathbf{u}}{Dt} = -\nabla p + \nabla \cdot [2(\mu + \mu_T)\dot{\gamma}(\mathbf{u})] \quad (1)$$

$$-\rho_0 \mathbf{g} \beta_T (T - T_0) - \rho_0 \mathbf{g} \beta_{Al} (c_{Al} - c_{Al_0})$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$ is the particular derivative, $\dot{\gamma}(\mathbf{u}) = (\nabla \mathbf{u} + \nabla \mathbf{u}^T)/2$ is the strain rate tensor, ρ is the density, and μ is the fluid viscosity. In the last two terms of the momentum equations, which describe the buoyancy effects, $\mathbf{g}$ is the gravity, T is the temperature, c_{Al} is the aluminum concentration, ρ_0 is the density at the reference temperature T_0 and reference aluminum concentration c_{Al_0} , while β_T and β_{Al} are the thermal and aluminum concentration expansion coefficients defined as

$$\beta_T = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_{p, c_{Al}} \quad (3)$$

$$\beta_{Al} = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial c_{Al}} \right)_{p, T} \quad (4)$$

The turbulent viscosity μ_T is computed using the standard $k - \varepsilon$ model of turbulence [15]

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

For this model, the turbulence quantities are the turbulence kinetic energy k and its dissipation rate ε . The transport equations for k and ε are

$$\rho \frac{Dk}{Dt} = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P + G - \rho \varepsilon \quad (6)$$

$$\rho \frac{D\varepsilon}{Dt} = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} (P + G) - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \quad (7)$$

where P is the shear production term defined as

$$P(\mathbf{u}) = \mu_T \left[\nabla \mathbf{u} : (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \right] \quad (8)$$

and G accounts for the effect of the buoyancy on the produc-

Fig. 2. Zn-Fe-Al phase diagram in the zinc rich corner [12].

tion of turbulence.

$$G = \frac{\mu_T}{Pr_T} \beta g \cdot \nabla T \quad (9)$$

The constants σ_k , σ_ε , $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ and C_μ are as follow [15] $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$ and $C_\mu = 0.09$

Increased robustness of the solution algorithm is obtained by solving the turbulence equations for the logarithms of turbulence variables [16]. In such a way, the positivity of turbulence variables is enforced resulting in increased accuracy and a faster solution approach. For more details on the solution algorithm, see Ilinca *et al.* [17].

Temperature T is obtained by solving the energy equation

$$\rho c_p \frac{DT}{Dt} = \nabla \cdot [(\lambda + \lambda_T) \nabla T] \quad (10)$$

where c_p is the specific heat and λ is the thermal conductivity. The turbulent thermal conductivity λ_T is computed from

$$\lambda_T = \frac{\mu_T c_p}{Pr_T} \quad (11)$$

where Pr_T is the turbulent Prandtl number considered equal to unity.

Aluminum and iron concentrations c_i , (c_{Al} for the aluminum concentration and c_{Fe} for the iron concentration), are obtained by solving the mass transport equations

$$\frac{Dc_i}{Dt} = \nabla \cdot [(D + D_T) \nabla c_i] \quad (12)$$

where D is the molecular diffusion coefficient. For this work, we consider that the Schmidt number $Sc = \mu / \rho D$ is equal to unity. The turbulent diffusion D_T is computed from

$$D_T = \frac{\mu_T}{\rho Sc_T} \quad (13)$$

where Sc_T is the turbulent Schmidt number considered equal to unity.

Velocity wall functions were used to model all solid surfaces including the pot walls, the moving strip and the rotating sink and stabilizer rolls. Heat transfer through all surfaces was modelled using convection boundary conditions and a temperature wall function. The initial steady state temperature in the bath is considered to be 460 °C. For the aluminum and iron transport in the bath, the boundary and initial conditions must also be imposed for the aluminum and iron concentrations. The initial aluminum concentration in the bath is considered to be 0.14% in weight and the bath is considered to be saturated in Fe at the initial temperature of 460 °C [8]. Boundary conditions are specified on the strip and the inlet section (inductor inlet) as well as on the solid boundaries (walls) and top surface of the bath. Simulations were done for the cases with and without the presence of an ingot. When the

ingot is present in the bath, the inductor power is considered to be at 100%. The inductor power is decreased to 20% when no ingot is present in the bath. The inductor flow rate and temperature increase for these settings are taken from the data of the previous validation study [14]. The liquid zinc from the inductors enters the bath at 0.75 m/s and is heated to 20 °C above the temperature of the melt entering the inductor when 100% of the power is considered and at 0.4 m/s and 8 °C temperature increase when only 20% of the inductor power is used [18,19]. A heat balance calculation was carried out to assure that the average bath temperature returned to the initial condition after the ingot addition and melting cycle followed by a period of no ingot addition. This is illustrated in Figure 3 and in Figure 4 covering a two-hour period of simulation. The heat lost by the bath is higher during the period of melting ingot as shown in Figure 3, but also the heat input from

Fig.3. Heat lost by the bath.

Fig.4. Total heat balance in the bath.

inductors is higher during this period. Figure 4 indicates that during the ingot melting period, the bath has a positive total heat balance, while during the period at lower inductor power, the bath loses heat.

Since ingots are added to the bath at ambient temperature, no aluminum is transferred to the bath until the ingot reaches the melting point. This was found to take six minutes [20]. The melting time is therefore 14 minutes during which all the aluminum and zinc in the ingot is transferred in the bath. Hence, the effective ingot mass flux is

$$(q_{Al})_{ingot} = \begin{cases} 0 & , t < t_1 \\ q_{Al}^* \left[1 - \frac{(t - t_1)^2}{(t_2 - t_1)^2} \right] & , t_1 < t < t_2 \end{cases} \quad (14)$$

with $t_1=6$ min and $t_2=20$ min (see Figure 5) and q_{Al}^* is the initial flux of Al at $t=6$ min which is 2.143 times the average Al flux calculated for a total melting time of 20 minutes. The mass flux on the ingot surface for the iron concentration equation takes into account the fact that the ingot has no iron in its composition.

Aluminum consumption on the strip surface is assumed to take place on the first 0.35 m of the strip from its entry in to the bath (corresponding to 0.2 seconds at a strip velocity of 1.75 m/s). The overall aluminum concentration of the coating is considered to be 0.4% by weight for a coating weight of 60 g/m² (0.06 kg/m²) per side. The mean aluminum consumption flux is given by

$$(q_{Al})_{strip} = -\frac{0.06 \text{ kg/m}^2}{0.35 \text{ m}} V_{strip} c_{Al} \quad (15)$$

The mass flux is $(q_{Al})_{strip} = -0.3 c_{Al}$ kg/(m²s) for a strip velocity of 1.75 m/s with $c_{Al} = 0.4$. Similarly, an iron mass flux is imposed on the strip surface to take into account the iron dissolution. The iron dissolution rate was considered to be

Fig. 5. Al mass flux on the ingot surface during the ingot melting period.

constant at 120 mg/m² of coil [21] throughout the coating process.

Since the aluminum and iron solubility in the bath varies with temperature, any excess aluminum will be present in the form of precipitates of Fe₂Al₅ (top dross). Both dissolved aluminum and precipitated aluminum were calculated.

NUMERICAL RESULTS

The computational domain is illustrated in Figure 6. All computations were carried out using the IMI CFD solver. The computational domain was discretized using 4-node tetrahedral finite elements. The mesh has 64,522 nodes and 366,949 elements. Figure 7 illustrates the finite element discretization. Since the bath geometry is symmetrical, only half of the domain was considered. Constant material properties have been used to perform the analysis. The material properties for a Zn+0.15% Al at a temperature of 460 °C are: density $\rho=6600$ kg/m³, laminar viscosity $\mu=0.004$ Pa·s, specific heat $c_p=512$ J/ Kg·K, thermal conductivity $\lambda=60$ W/m·K, thermal expansion coefficient $\beta=1.666 \cdot 10^{-4} \text{K}^{-1}$ and aluminum concentration expansion coefficient $\beta_{Al}=1.44 \cdot 10^{-2}$.

Fig. 6. Computational domain.

Fig. 7. Finite element discretization.

Velocity vectors in a plane parallel to the symmetry plane are shown in Figure 8. When no ingot is present (Figure 8a), the natural convection term makes little difference in this plane since only the liquid zinc cooled on the left wall moves downward because of the higher density. In both cases, thermal effects are localized near the inductors and the ingot and are very small near the sheet and roller region. Comparing these solutions, we can conclude that the flow near the ingot is dominated by thermal effects, whereas close to the sheet and rolls, the flow is determined by the movement of the steel sheet. When the ingot is present in the bath, the temperature also has a major influence on the flow as can be observed from Figure 9 illustrating the low velocity regions (zinc velocity lower than 0.01 m/s) with thermal effects.

Figure 10 shows the distribution of temperature on the symmetry plane. With the ingot present, the cold zinc melting from the ingot flows to the bottom of the bath and the solution presents higher temperature gradients than for the case without the ingot. Figure 11 illustrates the distribution of total aluminum concentration on the symmetry plane with and without the ingot. With the ingot present, we observe a higher level of aluminum near the ingot and a lower level of aluminum near the strip entry where aluminum consumption takes place. Without the ingot, the aluminum concentration becomes very uniform except for a

Fig. 8. Velocity vectors on a plane parallel to the symmetry plane.

Fig. 9. Iso-velocity surface (smaller than 0.01 m/s) for the case with ingot present.

region near the strip entry point where most of the aluminum is deposited. These results are in agreement with the global mass exchange that is driven by the aluminum addition from the ingot and aluminum consumption during the formation of the inhibition layer in the region near the entry of the strip. Similar results are shown in Figure 12 for the iron concentration. Here, the region below the melting ingot has a lower iron concentration because the ingot has no iron, whereas at the strip entry point, the iron concentration is higher because of the iron dissolution

Fig. 10. Temperature distribution on the symmetry plane: a) with ingot ($t=10$ min) and b) no ingot ($t=60$ min) (increment between iso-values is 1 °C).

that occurs before the formation of the inhibition layer. At the end of the cycle (60 minutes), the iron concentration is relatively uniform with a slightly higher concentration close to the strip near its entry point due to iron dissolution from the strip.

In order to illustrate the evolution of different variables during two complete cycles of 20 minutes with ingot melting and 40 minutes without the ingot, graphs were plotted for 4 specific locations in the bath on the ingot side and for 4 locations on the strip exit side. These locations are illustrated in Figure 13.

Figure 14 illustrates the evolution in time of the temperature over two complete cycles. The initial temperature is uniform at 460 °C. As soon as the ingot is introduced into the bath ($t=0$), the temperature drops at the inductor/ingot side at the low centre and low side locations. The temperature rises at the up side location because inductors are running at a higher power projecting heated zinc towards the top surface of the bath. We can also observe that the temperature gradients are higher on the ingot side and during the ingot melting period ($t=0-20$ minutes). Without the ingot, the temperature becomes more uniform with an initial correction between $t=20$ minutes and $t=30$ minutes. The stratification of temperature in the bath is due to buoyancy. On the strip exit side, the temperature at the four locations is more uniform and varies as the mean temperature. During the period at 100% inductor power, the temperature increases by 3 to 4 degrees and

Fig. 11. Total aluminum concentration on the symmetry plane: a) with ingot ($t=20$ min) and b) no ingot ($t=60$ min) (increment between iso-values is 0.0005).

Fig. 12. Total iron concentration on the symmetry plane: a) with ingot ($t=20$ min) and b) no ingot ($t=60$ min) (increment between iso-values is 0.0001).

decreases back to a temperature close to the initial temperature at the end of each cycle.

Figure 15 shows the evolution in time of the total aluminum concentration. The total aluminum represents the amount that is in solution as well as the amount that is in precipitated form. Subsequent calculations to differentiate

Fig. 13. Location of points for plots in time (dimensions are in metres).

Fig. 14. Temperature history during two complete cycles.

between the dissolved and precipitated form of aluminum assume that the rate of dissolution and precipitation are instantaneous. During the first 6 minutes, the ingot is brought up to the melting point. During this period, the aluminum concentration decreases, especially near the strip, as aluminum consumption takes place on the strip without any supply from the ingot. When the ingot begins to melt ($t=6$ minutes), a sharp increase of aluminum concentration is observed on the ingot side. On the strip exit side, the increase is delayed by about 3 minutes corresponding to the time it takes for the zinc on the ingot side to reach the front (strip section) of the bath as a result of the overall bath flow. Validation tests using aluminum sensors to measure the variations in aluminum level after the addition of brightener bars [14] gave nearly the same value of the time increment. During ingot melting, the total aluminum concentration in the bath is higher with a maximum value near the ingot surface at about $t=14$ minutes. On the ingot side, the differences between different locations are more apparent resulting in higher values

on the low centre location and the lower values for the up centre location. Flow from the ingot (rich in aluminum) reaches the low centre location first, followed by the low side, up side and finally up centre locations. This is in good agreement with the buoyancy driven movement of zinc [17]. On the strip exit side, the aluminum concentration is more uniform, since this area is mixed at a much higher intensity due to the roll and strip movement. Without the ingot, the aluminum concentration becomes more uniform but still remains higher on the ingot side. During this period, the aluminum concentration decreases constantly because of the aluminum consumption on the strip. Inside the snout, uniform aluminum concentration is observed except for the region near the centre of the inner side of the strip. This is indicative of a zone that does not readily mix with the zone in contact with the external side of the strip. In industrial practice, however, very little difference is observed in the total aluminum content of the coatings on either side of the strip. The small differences of aluminum content in the regions of the bath in contact with the inner and outer surface of the strip do not seem to affect the total amount of aluminum to the overall coating.

Fig. 15. History of the total Al concentration during two complete cycles.

Figure 16 shows the evolution in time of the total iron concentration. Iron concentration increases throughout the operation due to iron dissolution from the strip, except for a small period during ingot melting when material with no iron content is introduced in the bath [22]. The initial iron concentration corresponds to the limit of solubility product of aluminum and iron for 0.14 wt% Al content at the initial temperature of 460 °C and the total increase in the iron content is of only about 0.0005 wt% over two cycles.

Figure 17 illustrates the concentration of aluminum precipitated as Fe_2Al_3 dross. This value is determined as the mass of aluminum and iron above the temperature dependent limit of solubility product. Due to the sensitivity of the solubility of aluminum and iron in the bath as a function of temperature, moving particles of Fe_2Al_3 can either grow by continued precipitation or dissolve in different temperature zones of the bath. When the ingot is immersed, we observe a sharp increase in dross formation on the ingot side. This is caused by the decrease in temperature which is highest at the low centre location. During ingot melting, dross is also formed as the aluminum rich

Fig. 16. History of the total Fe concentration during two complete cycles.

Fig. 17. History of the precipitated Al concentration during two complete cycles.

ingot dissolves in the bath. The ingot melting determines the formation of dross only in the region around the ingot. Finally, dross is also formed at the end of the cycle because of the overall decrease in temperature. The numerical model clearly indicates that larger variations are observed on the ingot side. For an initial concentration of 0.14 wt% Al, dross is formed mostly at the bottom of the bath where the temperature is lower. The calculations also show that small quantities of dross are formed inside the snout representing only a very small fraction of the total dross formed.

CONCLUSIONS

The computed results for the specific cases illustrated show that forced convection flow is controlled principally by the movement of the immersed hardware and moving strip in the region of the

bath where the temperature gradients are the smallest assuming that the entering strip and average bath temperatures are the same. Large temperature variations were observed for the condition during ingot melting as a result of the large difference in temperature between the bath and the melting point of the ingot and because of the additional heat introduced by the inductors that is required for melting and maintaining the bath temperature at an average level of 460 °C. Flow in this region is dominated by a very significant contribution from natural convection.

It can be concluded that the calculated aluminum concentration gradients are much more pronounced at the ingot side during ingot melting, whereas a more uniform distribution occurs during the period when no ingot is present. A more uniform distribution can be observed on the strip side compared to the ingot side due to the high degree of mixing caused by the rotating equipment in this region. The aluminum concentration as precipitated Fe_2Al_5 also increases in the ingot melting zone due to the decrease of temperature near the ingot surface and also because of the higher aluminum concentration of the ingot. The slight decrease of the iron content in this region has an opposite effect reducing the formation of dross. It is clearly shown that the heat input needs to be closely controlled during ingot melting to maintain a stable temperature in the bath. However, the inherent temperature gradients caused by ingot melting result in the precipitation of aluminum as Fe_2Al_5 in the cold regions of the bath. Entrainment of intermetallic particles is almost inevitable and good bath management requires a minimization of dross formation.

Validations of numerical simulations have been carried out on an industrial bath as well as in a water model using laser Doppler velocimetry and particle image velocimetry (PIV) [23] showing good agreement with the experimental results. The advantage of the simulation lies in the possibility to cover a wide range of flow, composition and temperature variations within the bath and to be able to predict the localized formation of dross particles for the various conditions.

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