Effect of process parameters on solidification of Al-33Cu strip in high speed twin roll strip casting- A numerical study

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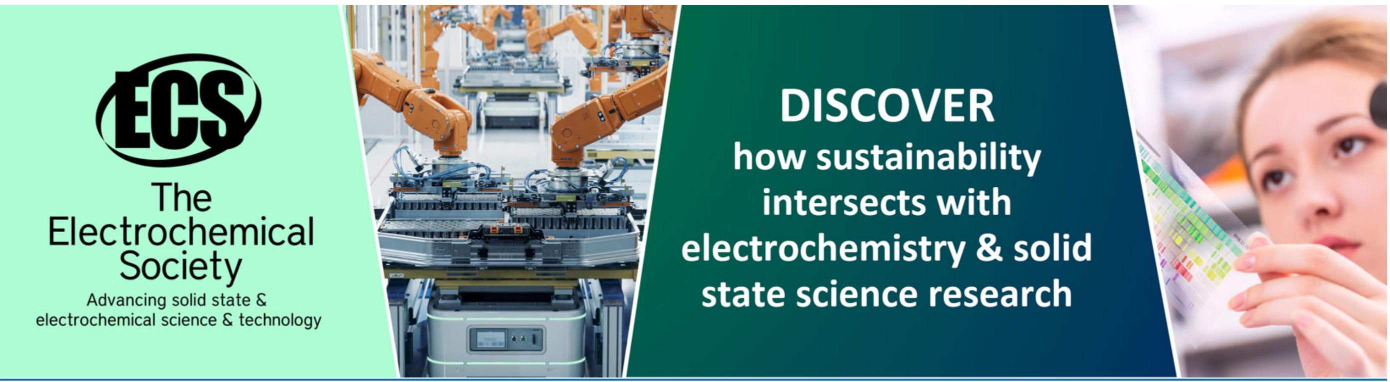


Effect of process parameters on solidification of Al-33Cu strip in high speed twin roll strip casting- A numerical study

Seshadev Sahoo
Department of Mechanical Engineering, Institute of Technical Education and Research, Siksha 'O' Anusandhan University, Khandagiri square, Bhubaneswar,OR, India

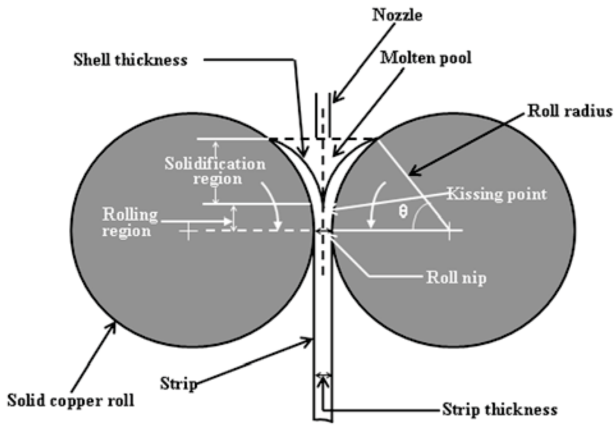
Email: seshadevsahoo@soauniversity.ac.in

Abstract. In twin roll strip casting process, the solidification behavior in the molten pool affects the process efficiency and the product quality which is influenced by the process parameters. Numerical simulations have been carried out to analyze the fluid flow, heat transfer and solidification in high speed twin roll strip caster at different pouring temperatures and roll gaps and the knowledge of heat flux distribution at the liquid metal-roll interface. In the present study a numerical simulation has been carried out for the solidification of Al-33wt% Cu in the twin-roll strip casting system at different pouring temperatures and roll gaps. FLUENT 6.3.16 was used to model fluid flow, heat transfer and solidification behavior during the casting of Al-33wt. % Cu alloy. From the simulation results, the initial pouring temperature of the liquid metal and the roll gap has been optimized for producing quality strips.

1. Introduction

The twin roll strip casting process has gained more attention due to its higher productivity and good surface quality of the as cast strips. This process is applied to produce thin strips whose thickness varies between 0.1-6 mm directly from the liquid metal by combining casting and rolling in a single step. During strip casting operation, the molten metal is introduced into the casting machine via the nozzle, which solidifies on the surface of the casting rolls by the removal of heat and the thin strip is obtained continuously [1-3]. A schematic diagram of a vertical twin roll strip caster is shown in Figure 1. The control of microstructure of the strip is of primary importance in twin-roll strip casting process because further significant modification of the microstructure, on which the properties of the strip depends, may not be possible. The microstructure of the strip depends on cooling rate and solidification front speed at various locations in the strand, which in turn depends upon the casting parameters like casting speed, roll gap, superheat of liquid metal, roll force, roll materials, etc. These casting parameters affect the fluid flow, heat transfer and solidification behavior in twin roll strip casting process. As the process looks very simple but in actual practice it is very difficult to control the process parameters experimentally during the casting operation because the solidification of liquid metal occurs within few seconds. For arriving at the right combination of design and process parameters to achieve high speed/productivity as well as right microstructure, mathematical modeling and optimization based on it are indispensible.

Corresponding author: S. Sahoo, Email: seshadevsahoo@soauniversity.ac.in



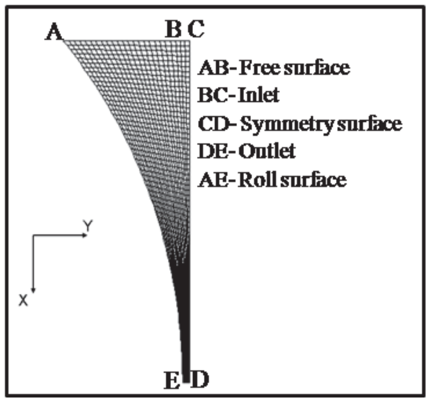


Figure 1. Schematic diagram of vertical twin roll caster. **Figure 2.** Computational domain

Santos et al. [4] presents a numerical model for the two-dimensional solidification process in twin roll continuous casting system by using finite difference technique and gives valuable information in to the thermal characteristics of solidification and processing for the strip casting. Kim et al. [5] numerically studied the fluid flow and heat transfer in wedge shaped pool during strip casting process and also investigated the effect of roll gap thickness and superheat of the melt on liquid metal velocity, variation in temperature distribution and solidification in the wedge shaped pool. But in their model the author considered temperature independent thermo-physical properties. The turbulent fluid flow, heat transfer, and solidification of a twin roll melt drag thin strip casting of steel simulated by Gupta and Sahai [6] and studied the effect of roll speed and melt superheat on thickness of the strip and found that by increasing the roll speed and melt superheat, thickness of the strip decreases. Zhao et al [7] developed a twin roll caster to cast aluminum alloys and investigated the process parameters including casting temperature, casting speed and thickness variation of the strip on microstructure and mechanical properties of the cast strip and found that twin roll caster has the ability to produce thin strips directly from the liquid metal with improved mechanical properties. The numerical investigation of turbulent fluid flow and solidification in twin roll caster was studied by Kim et al. [8] The authors studied the effect of roll gap thickness on the melt flow and temperature distribution in the melt pool and based on the results they estimated the patterns of the superheat removal. Zhang et al. [9] developed a FEM model to simulate twin roll strip casting process at 0.52 m/s casting speed and studied the influence of the process parameters, i.e., pouring temperature and height of liquid level to control the twin roll strip casting process and improve the quality of the strips. They also compared the variation of theoretically calculated and experimentally measured temperature of strip surface with the pouring temperature. A CFD model was developed by Zheng et al. [10] which provides better understanding of the melts flow characteristics and thermal exchange during rapid solidification of the Mg in twin roll casting process under different casting speed and gauge opening (roll gap) condition. They used constant thermo-physical properties like density, specific heat, latent heat, thermal conductivity and viscosity and measured the temperature of the casting strip both from the model and experiment and found that the calculated results for varying casting speeds are in good match with experimental determination. Fang et al. [11] simulated the temperature field of the strip in twin-roll casting method and studied the variation of temperature with different roll radii and roll gaps. In their model they simulated the model having casting speed of 0.5 m/s to 1.33 m/s and they did not consider the temperature dependency of thermo-physical properties. Miao et al. [12] developed a 3D model which describes the flow and temperature in molten pool and study the effect of process parameters on the flow and temperature field having casting speed 0.3-0.6 m/s. In their study they found the simulated results are in good agreement with the experimental results. Li et al. [13] developed a steady state finite element model to study the effect of processing parameters like casting speed and pouring temperature of liquid metal on the freezing point position of 304 stainless steel during twin-roll strip casting process. With the use of the model, the authors optimized the casting speed and pouring temperature for producing quality strips. But, in their model they also have considered temperature independent thermo-physical properties and casting speed of 0.5 m/s. Sahoo et al. [14, 15] developed a model for high speed twin roll caster having casting speed varies from 0.79 m/s to 3.98 m/s to produce layered structure material and compared with the experimental results.

Recently, numerical simulation has been developed rapidly, which can replace some experiments for the research of the twin roll strip casting process. However most of the above mentioned models have not taken into account the variation of thermo-physical properties with temperature and having low casting speed. The present research work is a numerical investigation of the characteristics of fluid flow, heat transfer and solidification in a wedge shaped pool during the high speed twin roll strip casting process and to study the effect of initial pouring temperature of liquid metal and roll gaps on solidification of Al-33wt. % Cu alloy in the molten pool.

2. Mathematical model

Liquid metal which is poured between the two counter rotating rolls is solidified as the rolls rotate and is machined to strips at the exit. Considering the practical process of casting operation the following assumptions are made in the development of the mathematical model: (1) The process is steady state, (2) Liquid metal is incompressible and Newtonian fluid, (3) There is no slip condition between the roll and the solidified strip, (4) Process is symmetric around the center line of roll gap, (5) The heat transfer is dominated by convection and conduction modes, (6) The value of heat transfer coefficient is constant along the strip/roll interface.

2.1 Governing equations

Numerical simulations of fluid flow and heat transfer in twin roll strip casting processes has been conducted by solving the two dimensional turbulent form of the Navier-Stokes equation which is fully coupled with a differential energy balance equation, which takes solidification into account.

The continuity equation is given by

$$\frac{\partial \mathrm{u}}{\partial x}+\frac{\partial \mathrm{v}}{\partial y}=0 \qquad (1)$$

The momentum equation in x-direction is given by

$$\frac{\partial \mathrm{p}}{\partial x}+\frac{\partial(\rho \mathrm{uv})}{\partial x}=\frac{\partial}{\partial x}\left(\mu\frac{\partial \mathrm{u}}{\partial x}\right)+\mathrm{S}_x \qquad (2)$$

and that in y-direction is given by

$$\frac{\partial \mathrm{p}}{\partial y}+\frac{\partial(\rho \mathrm{uv})}{\partial y}=\frac{\partial}{\partial y}\left(\mu\frac{\partial \mathrm{v}}{\partial y}\right)+\mathrm{S}_y \qquad (3)$$

The two-equation k-ε model of turbulence was used for the turbulence considerations.

Turbulent kinetic energy equation:

$$\left(u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}\right)\rho=\frac{\partial}{\partial x}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial y}\right)+\mu_t\phi-\rho\varepsilon \qquad (4)$$

Dissipation rate of turbulence equation:

$$\left(u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}\right)\rho=\frac{\partial}{\partial x}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)+C_1\mu_t\phi\frac{\varepsilon}{k}-C_2\rho\frac{\varepsilon^2}{k} \qquad (5)$$

where ,

$$\mu_{eff}=\mu_0+\mu_t \qquad (6)$$

$$\mu_t = C_\mu \rho k^2 / \varepsilon \quad (7)$$

$$K_{eff} = K_0 + K_t \quad (8)$$

$$K_t = c_p \, \mu_t / \mathrm{Pr} \quad (9)$$

where , Pr is the turbulent Prandtl number.

According to Laundar and Spalding [16], the constants in the standard k-ε equation takes the following values: C_1=1.44, C_2=1.92, C_μ=0.09, σ_k=1.0, σ_ε=1.3.

The energy equation is given by

$$\left(\frac{\partial(\rho H)}{\partial t}\right) + \nabla.(\rho u H) = \nabla.(k \nabla T) + S_h \quad (10)$$

where ρ is the density, H is the enthalpy and S_h is the source term.

2.2 Boundary conditions

Because of the symmetry, the computational model adopted in this work is half of the real domain as shown in Fig. 2. The boundary conditions are as follows (refer to Figure 2):

(1) At the entrance of the liquid metal on the surface of the melting pool (BC), $V_x=V_{in}$, $V_y=0$, $k=0.05(V_x^2+V_y^2)$, $\varepsilon=C_\mu k^{1.5}/0.03D_{in}$, T_{in}=851 K,
where V_x is the speed in x-direction, Vy the speed in y direction, V_{in} is the speed of the entrance, K the turbulence kinetic energy, ε the dissipation rate of the turbulent kinetic energy, and D_{in} the size of the inlet.

(2) On the free surface(AB), $\frac{\partial V_y}{\partial X} = \frac{\partial k}{\partial X} = \frac{\partial \varepsilon}{\partial X} = 0$, V_x=0

(3) At the symmetry interface (CD), $\frac{\partial V_x}{\partial Y} = \frac{\partial k}{\partial Y} = \frac{\partial \varepsilon}{\partial Y} = 0$, V_y=0

(4) On the outer surface of the roll, the tangential velocity of the roll is equal to the casting speed. So velocity components V_x and V_y on the roll boundary have the following values, $V_x = V_{roll} \cos\theta$, $V_y = V_{roll} \sin\theta$
where V_{roll} is the casting speed and θ is the angular position of the node on the roll surface. At the contact interface of liquid Al-33 wt.% Cu and the roll, a constant value of heat transfer coefficient was utilized in the model. The value of heat transfer coefficient was calculated based on the correlation given by Wang and Matthys [17]. The correlation is given by the following equation:

$$\overline{h_s} = 17.3 V_{roll}^{0.65} \quad (11)$$

where, $\overline{h_s}$ is the average heat transfer coefficient and V_{roll} is the casting speed. This correlation was validated by Guthrie et al. [18] experimentally.

(5) At the exit or nip of the roll (ED), fully developed boundary condition was used. The outflow conditions at the exit or nip of the roll are $V_x = -V_{roll}$, V_y=0.

3. Results and discussion

In the present work simulations were carried out for casting of Al-33 wt.% Cu strips having different initial pouring temperatures and roll gaps. The level of liquid metal pool was kept fixed at 0.0489 m. The liquid metal was fed through a nozzle of diameter 4 mm and the temperature drop during feeding was assumed to be negligible. Thus the temperature at the inlet was taken as the feeding temperature of the liquid metal. To know the effect of initial pouring temperature and roll gap on the solidification phenomena of Al-33wt. % Cu alloy during high speed twin roll strip casting, the thermal as well as the solidification behavior during twin roll strip casting process at high casting speed has been simulated on

FLUENT 6.3.16 platform. The parameters of the casting used for simulation are given in Table 1 and the detail procedure of the simulation are described elsewhere [14].

Table 1: Process parameters used in the simulation

Parameters	*Value*
Roll diameter (m)	0.1524
Roll width (m)	0.0254
Casting speed (m/s)	0.79
Roll gap (mm)	0.8 - 3
Pouring temperature of liquid metal, T_{in} (K)	831 - 941
Inlet diameter, D_{in} (m)	0.004

3.1 Initial pouring temperature of the liquid metal

Numerical simulations are carried out to study the effect of initial pouring temperature on solidification of Al-33wt. % Cu alloy during high speed twin roll casting. The simulations are carried out for casting of Al-33wt. % Cu strips having thickness of 2 mm in a twin roll caster at casting speed 0.7979 m/s (100 rpm). The initial pouring temperature of liquid metal varied from 831 K - 941 K and all other parameters is kept constant.

When other processing parameters are constant, the pouring temperature of liquid metal has a direct effect on the heat transfer between the casting roll and molten pool, which affects the flow and heat transfer in the molten pool. Figure 3 shows the solidification profile of liquid Al-33wt. % Cu in the molten pool for different pouring temperatures. From the solidification profile it is observed that, when the pouring temperature of the liquid metal is 831 K, the thickness of the solidified shell is 0.29 mm and the thickness of the solidified shell is 0.08 mm at pouring temperature of 941 K. Beyond 941 K the presence of solidified shell is not observed.

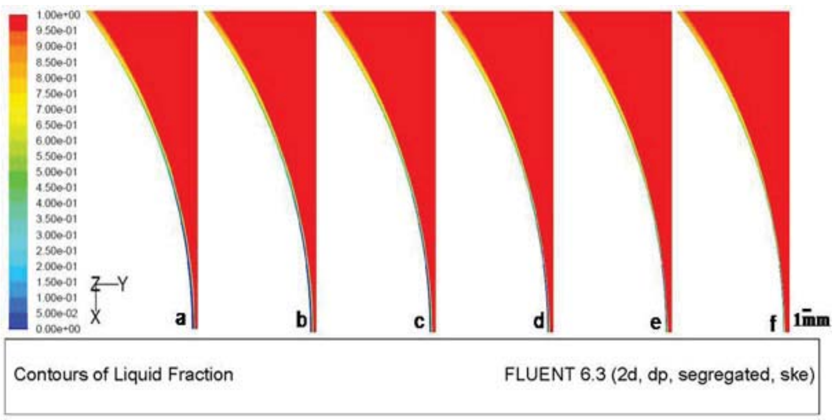


Figure 3: Solidification profile of Al-33Cu at different pouring temperatures (a) 831 K (b) 851 K (c) 871 K (d) 891K (e) 921 K (f) 941 K (casting speed 0.79 m/s).

The temperature of the strip at the outlet increases with increase in pouring temperature. Figure 4 shows that the variation of surface temperature of the cast strips at the exit section. It can be seen that the temperature of the strip at the exit section increases with increase in pouring temperature. However, at the surface of the strip the increase in the temperature as a result of 110 K increase in pouring temperature is not significant, i.e., ~5 K. At the plane of symmetry the increase is ~15 K. The higher pouring temperature results in higher temperature at the exit of the casting strip, which leads not only severe oxidation but also cracks of the casting strip. So considering the factors affecting the cast strip quality, the superheat should be as low as possible.

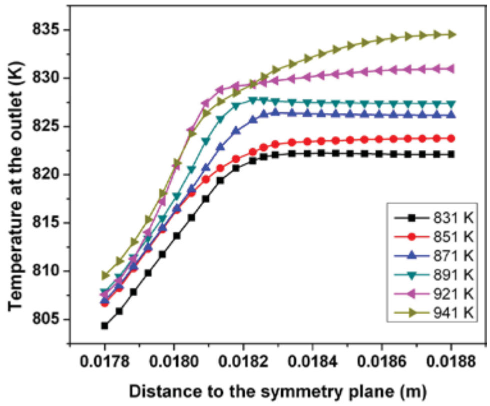


Figure 4: Temperature of the Al-33Cu strip at the nip position at different pouring temperatures

Figure 5 shows the effect of pouring temperature of melt on the solidification front speed. The solidification front speed decreases significantly with increase in pouring temperature of the melt. Similar trends can be observed for the variation of shell thickness at nip with the pouring temperature as shown in Figure 6. With increase in the pouring temperature, the superheat increases resulting in delay in the initiation of solidification and thus the shell thickness and front speed decreases.

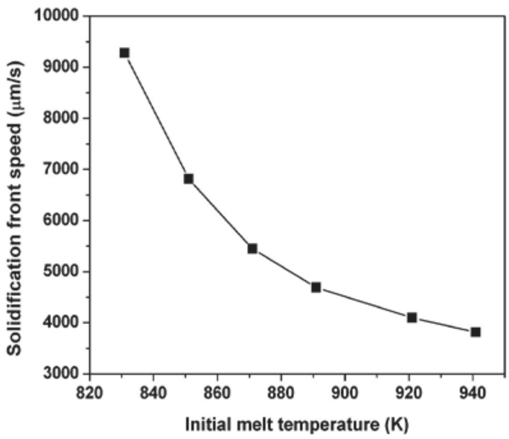


Figure 5: Effect of initial pouring temperature on solidification front speed

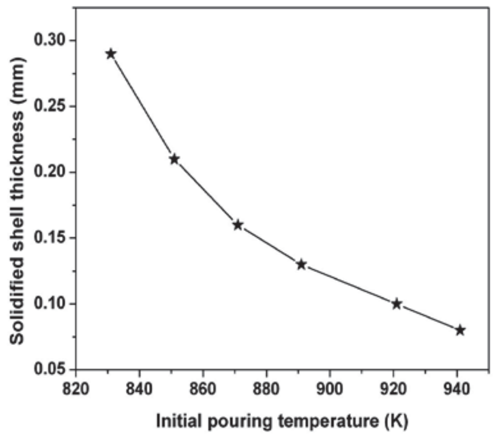


Figure 6: Effect of initial pouring temperature of the melt on solidified shell thickness

3.2 Effect of roll gap

The distance between the two rolls (roll gap) at the roll nip limits the maximum strip thickness and may affect transport phenomena in the molten pool. The simulations are carried out for casting of Al-33wt. % Cu strips at different roll gap, i.e., 0.8 mm, 1 mm, 2mm and 3 mm. The simulation results show the solidification pattern, temperature and velocity vector profile of Al-33wt. % Cu in the pool region respectively for the case when the roll speed is 0.79 m/s, pouring temperature of liquid metal is 851 K.

Figure 7 shows the solidification profile of the Al-33wt. % Cu alloy strip in the strand at different roll gaps. At roll gap thickness of 0.8 mm. the end point of solidification is above the roll nip position. When the roll gap thickness is 1 mm, the solidification end point is close to the exit. With increases in thickness of the roll gap from 2 mm to 3 mm, the solidification end point is below the roll nip position. As the roll gap thickness varies, the rate of heat transfer from the liquid metal to the roll surface remains constant because all other parameter like casting speed remains constant. However the mass of the liquid Al-33Cu enclosed between the rolls and thus the total heat to be removed increases with the roll gap. Therefore the solidification front speed and the shell thickness at nip decreases with increase in the roll gap as shown in Figure 8 and Figure 9. With decrease in roll gap, the solidification end point is close to the exit. This is because the quantity of liquid metal passing in and out of the molten pool is less than that with larger thickness and the heat brought into the melting pool is small. If the roll gap is too large and the end point of the solidification is lower than the exit, the strip may break off because of the incomplete solidification at the roll nip. If the roll gap is too small, then the roll pressure is too high which may break the strip.

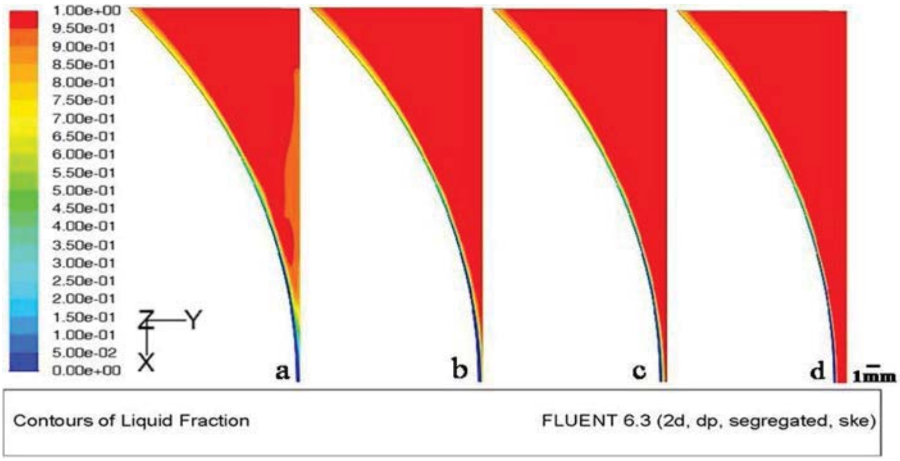


Figure 7: Solidification profile of liquid Al-33Cu at different roll gaps (a) 0.8 mm (b) 1 mm (c) 2 mm and (d) 3 mm

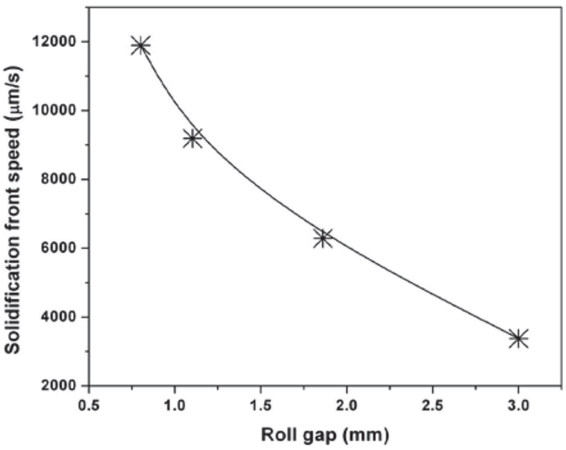


Figure 8: Effect of roll gap on solidification front speed at roll nip

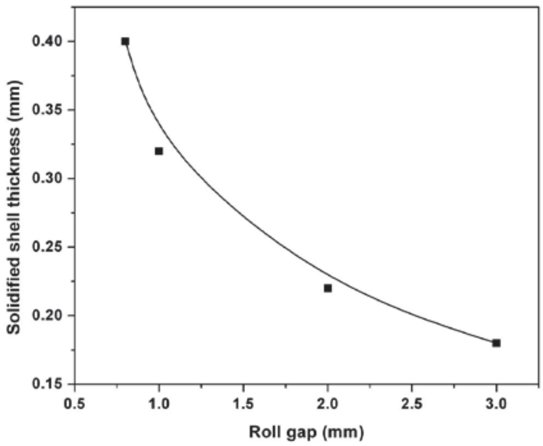


Figure 9: Effect of roll gap on solidified shell thickness at roll nip

Figure 10 shows the variation of the strip temperature from strip center to surface at the exit section with change of the roll gap. By varying the roll gap from 0.8 mm to 3 mm the surface temperature at the exit increases by ~9 K where as the temperature at the centre increases by ~15 K. The sensitivity of the temperature at surface and plane of symmetry (Figure 10) to roll gap is much higher when the roll gap is below 1 mm. It can be observed that the rise in temperature at surface when the gap is increased from 0.8 mm to 1.0 mm is approximately equal to that when the gap is increased from 1 mm to 2 mm.

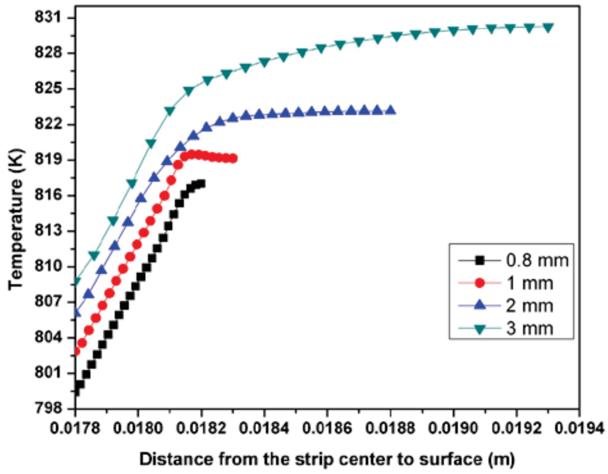


Figure 10: Temperature of the strip at the nip position from strip center to roll surface at different roll gaps.

Figure 11 shows the flow field in the molten pool at different roll gaps. This figure makes it possible to gain an insight into the effects of different roll gap on the flow pattern in the pool. As the roll gap increases, there is an increase in the intensity of the recirculation flow in the pool region. This is due to the fact that for a fixed inlet, with an increase in roll gap the vortex area in the pool becomes larger, which leads to an increase in mass flow within the pool. With increase in roll gap, the recirculation flow in the pool region becomes weaker due to the decrease in resistance at the nip. For roll gap of 0.8 mm recirculation is observed adjacent to the nozzle. With the increase in gap to 1 mm, significant shift in flow pattern can be observed. The recirculation in the top has shifted towards middle region and increased in size. The lower recirculation zone has also shifted to a lower position. As the gap increases to 2 mm the lower recirculation zone disappears and the size of the upper recirculation zone increases. With further increase in the gap no significant change is observed. These changes are observed because the recirculation zones are formed due to resistance to flow through the nip, which increases with decrease in the gap.

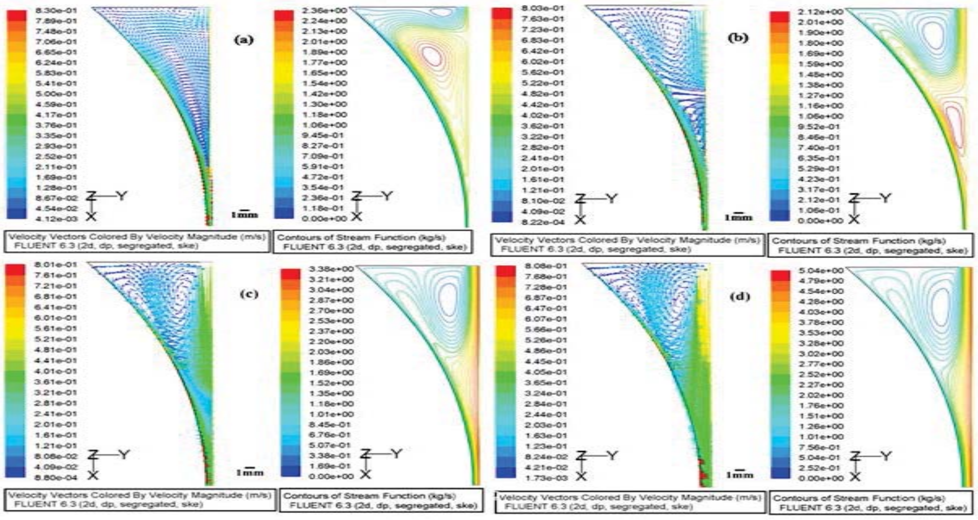


Figure 11: Contours of velocity vector and corresponding stream function of Al-33Cu in the molten pool at different roll gaps (a) 0.8 mm (b) 1 mm (c) 2 mm (d) 3 mm

4. Conclusions

When other processing parameters are constant, the pouring temperature and roll gap have a direct effect on the heat transfer between the casting roll and molten pool, which in turn influences the solidification of liquid metal in the molten pool. Simulations are carried out by varying the initial melt temperature from 831 K to 941 K (superheat 10 K to 120 K) and roll gap from 0.8 mm to 3 mm by keeping all other parameters constant. From the analysis of results it is found that

(i) The solidification front speed decreases from 9277.90 μm/s to 3815.42 μm/s and thickness of the solidified shell decreases from 0.29 mm to 0.08 mm with increase of initial pouring temperature of the melt from 831 K to 941 K.

(ii) The temperature of the strip at the exit section increases with increase in pouring temperature. However, at the surface of the strip the increase in the temperature as a result of 110 K increase in pouring temperature is not significant, i.e., ~5 K. At the plane of symmetry the increase is ~15 K.

(iii) With increase in roll gap, the recirculation flow in the pool region becomes weaker. The recirculation pattern significantly changes as the roll gap increases from 0.8 mm to 2 mm. Beyond a roll gap of 2 mm the change is not significant.

(iv) By varying the roll gap from 0.8 mm to 3 mm the surface temperature at the exit increases by ~9 K whereas the temperature at the centre increases by ~15 K. The sensitivity of temperature to roll gap is much higher for low values of roll gap.

(v) The solidification front speed and the shell thickness at nip decreases with increase in the roll gap.

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