Horizontal Single-Belt Casting (HSBC) of TRIP Steels
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ABSTRACT
Horizontal Single Belt Casting (HSBC) is one of the emerging Near-Net-Shape-Casting (NNSC) Processes for producing thin strips directly from liquid metal. It has been shown to have significant advantages compared to the Conventional Continuous Casting (CCC) methods in steel casting. Some process conditions need to be thoroughly controlled to obtain high-quality TRIP strips. Among them are the “back meniscus” and metal “backflow” behavior. In the present research, the effects of the gap distance between the back refractory and the belt, and the belt speed, are studied for the single belt casting of a TRIP Steel, using the commercial CFD software, ANSYS-Fluent 19.1. The optimal set of processing parameters was evaluated to promote “back meniscus” stability for the HSBC process employing a double impingement, liquid steel feeding system, adopted for TRIP Steel casting. The use of side-dams proved essential in preventing any outflows of liquid steel, and in obtaining good top surface quality strips.

Keywords: Horizontal Single Belt Casting (HSBC), Meniscus, Thin strips, TRIP Steel, CFD Modelling

1. INTRODUCTION
1.1 Horizontal Single Belt Casting
Horizontal Single Belt Casting (HSBC) is one of two emerging Near Net Shape Casting processes (NNSC). It has been under development for the last thirty-five years, as a viable alternative to conventional processes traditionally used for producing thin strips for a wide range of alloys, including light metal alloys1 and steels2,3. The HSBC process has significant economic and environmental advantages over traditional Continuous Casting (CC) technologies. Two advantages are the elimination of the slab reheating furnaces and Hot Mills, thanks to the fact that in the HSBC process, thin liquid metal “sheets” (3-15 mm) are poured directly onto a moving metal belt, on which they freeze to form a thin “transfer bar”. HSBC is one of two emerging NNSC technologies surviving from the last half of the past century, for steel casting, the other being Twin Roll Casting (TRC)4. TRC, or Bessemer Casting, in 2008, proved to be industrially successful for NUCOR, in producing NNSC steel sheet products5. On the HSBC side, this process was commercialized by Salzgitter GmbH in 2012, at their steel plant in Peine, Germany, under the name “Belt Cast Technology (BCT)”. In 2015, they reported having cast twenty-six iron-manganese heats among ninety heats altogether, producing a 2.5mm thick sheet. These would have been impossible to cast and reduce in thickness within a conventional seven-stand hot mill, owing to the strong work-hardening effects of these advanced high strength Hadfield-type steels6. More recently, the HSBC has also been used commercially for producing thin strips of copper alloys, by Materion Brush, USA, following successful parallel demonstrations in Canada, at the pilot-scale, by MMPC/MetSim Inc. There, we have cast crystalline metals and alloys such as aluminum, steel, and copper alloys, as well as the earlier casting of bulk amorphous sheet products. These commercial and pilot-scale successes prove that this HSBC technology is a technically feasible, viable process, that should replace conventional casting technologies.

Figure 1 presents a schematic diagram of the pilot-scale HSBC, where the molten metal from the tundish is distributed directly through a nozzle onto the water-cooled belt, moving horizontally. There, progressive solidification takes place. One drawback of HSBC sheets can be the upper surface variability or quality, but this can be eliminated with one or two rolling step(s), and careful flow control. Another problem with the HSBC process can be the potential formation of a “back” skull which could curtail further casting, caused by liquid metal backflows through the back gap of the metal delivery system. This has primarily been observed on aluminum alloys7,8.
To avoid excessive metal backflow and thereby compromise the process stability, two main types of feeding systems have been researched to date for various liquid metal and alloy systems; the single impingement or vertical back wall, and the double impingement or inclined back wall. Steel has been exclusively cast, using a double impingement system. The impingement refers to the number of times the flowing molten metal collides with a surface. The double impingement system is normally achieved using a 30-45° inclination of the back wall. Figure 3(a) presents the schematic of the double-impingement system used for casting AHSS alloy (17%Mn–4%Al–3%Si–0.45%C wt-%) strips. Figure 2 shows the risks of the generation of excessive backflow on the strip surface quality for an AA2024 aluminum alloy.
As previously noted, some Advanced High Strength Steels (AHSS), like the Transformed Induced Plasticity (TRIP) and the Twinning Induced Plasticity (TWIP) steels, require excessive hot rolling stages after the CC process due to the inherent work hardening of these types of steels. HSBC has proven to be a good alternative to cast said types of steel, as 10-15 mm thick strips can be obtained directly from the liquid metal, eliminating some of the hot rolling steps of its usual steel processing.

So far, two Fe-Mn alloys (TRIP and TWIP steels) have been successfully cast on the HSBC pilot-scale machine and simulator at MMPC/MetSim Inc; 17%Mn–4%Al–3%Si–0.45%C wt-%2 and Fe–21%Mn–2.5%Al–2.8%Si–0.08%C wt%3. After casting, the alloys were subjected to a variety of heat treatments to obtain the desired microstructures, resulting finally in specimens with the desired microstructure and matching mechanical properties with those expected.

For the 17%Mn–4%Al–3%Si–0.45%C wt-%2 alloy, an average yield strength of 654 MPa and a tensile strength of 880 MPa resulted from the corresponding mechanical test. The average surface roughness was in the range of 0.2 mm. Figure 4 shows the microstructures obtained, revealing annealing and deformation twins.

For the Fe–21%Mn–2.5%Al–2.8%Si–0.08%C wt%3 alloy, an average yield strength of 610 MPa and a tensile strength of 950 MPa were obtained. The average surface roughness was in the range 0.13-0.16 mm. Figure 4 shows the microstructures obtained, revealing annealing and deformation twins.
The Computational Fluid Dynamics (CFD) ANSYS Fluent has been used to complement the study of the HSBC process for casting Fe-Mn alloys. Previous mathematical studies concluded that an isokinetic system (slot inlet velocity equal to the belt speed) is necessary to promote an optimal strip surface quality. The angle inclination of the back wall for the double impingement feeding system was also studied, reaching the conclusion that a 45° inclination angle will render less surface disturbances on the process. However, air entrainment in the first impingement was predicted. Figure 6 shows the predicted phase contour and velocity field using an 45° inclined back wall, revealing the air entrainment due to the rotational motion on the first impingement. The mathematical predictions of both studies agreed well with experimental observations.

![Figure 6. Predicted air entrainment.](image)

More recently, mathematical modeling studies have been carried out to determine the optimal set of parameters to promote a stable back meniscus and to avoid backflow with the aluminum alloy AA2024 with both a single and double impingement feeding systems. For the double impingement system, the “free fall distance”, referring to the distance between the nozzle and the inclined back wall on the first impingement, was modified from 6 mm (used in the previous studies) to 3 mm. The comparison of both “free fall distance” is presented in Figure 7. The reduction of said distance has proven to promote a more stable process for aluminum casting, avoiding air entrainment in the first impingement and promoting a stable back meniscus. Therefore, the objective of the present study is to evaluate the effect of the change of “free fall distance” on the casting of a Fe-Mn alloy via CFD modeling, to obtain a more stable HSBC process and ultimately produce high quality TRIP steel sheets.

![Figure 7. Change in the “free fall distance” from 6 to 3 mm, on double impingement metal delivery system.](image)

### 2. MATHEMATICAL MODELLING OF THE HSBC PROCESS

#### 2.1 Mathematical modelling development

A similar mathematical model approach to the previous research performed at the McGill Metal Processing Centre was applied in the present work, where a 2-D transient state, isothermal model of the HSBC system for a double impingement feeding system, was developed. Two air gap sizes and three belt speeds were used in the present simulations, giving a total of 6 cases. A summary of the variables studied, is presented in Table 1. The geometry of the systems was generated with the ANSYS SpaceClaim Software, part of the ANSYS Workbench software package. The geometry generated is presented in Figure 8, indicating the relevant dimensions, for the case of a 0.8 mm back gap. The mesh for the system was generated using...
ANSYS Meshing, with cells refinement in the impingements zones for better interphase accuracy. The generated meshes were mostly quadratic, with an average cell size of $2 \times 10^{-3} \text{m}^2$. Figure 9 shows the refinement done in the back meniscus zone, to accurately capture its predicted behavior. The average number of cells for the geometries created, was 120,000 cells, with an average orthogonality of 0.99. The boundary conditions are presented in Figure 8. Similarly, the melt inlet (3mm long) was defined with a liquid steel (Phase 2) volume fraction of 1 and an inlet velocity of 0.8 m/s for all the cases. The moving belt conditions were defined as a moving wall with only an X positive velocity component. All other walls were specified as stationary and with a no-slip boundary condition. The properties of the materials, liquid steel, and air were considered constant, and are presented in Table 2.

Table 1. Modified Operating Conditions on the HSBC Mathematical Modeling

<table>
<thead>
<tr>
<th>Feeding system type</th>
<th>Double impingement/Inclined slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap size (mm)</td>
<td>0.4 and 0.8</td>
</tr>
<tr>
<td>Belt speed (m/s)</td>
<td>0.4, 0.8, and 1.2</td>
</tr>
</tbody>
</table>

Figure 8. Geometry generated in ANSYS SpaceClaim with the specified boundary conditions.

Figure 9. Mesh detail generated in ANSYS Meshing for the double impingement, 0.8 mm back gap case.

Table 2. Materials Properties and Casting Operating Conditions

<table>
<thead>
<tr>
<th>Material</th>
<th>Liquid steel</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, $\rho$ (Kg/m$^3$)</strong></td>
<td>6950</td>
<td>1.225</td>
</tr>
<tr>
<td><strong>Viscosity, $\mu$ (Kg/m s)</strong></td>
<td>0.0063</td>
<td>1.7894x10^-5</td>
</tr>
<tr>
<td><strong>Surface Tension (N/m)</strong></td>
<td>0.914</td>
<td>-</td>
</tr>
<tr>
<td><strong>Contact angle along the moving belt (degrees)</strong></td>
<td>105 (with moving belt), 135 (with refractory walls)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Inlet velocity (m/s)</strong></td>
<td>0.8</td>
<td>-</td>
</tr>
</tbody>
</table>

The mathematical model was developed for a transient state, with a variable time step, maintaining a Courant number of 2.0, and an initial time step of $1 \times 10^{-6}$ seconds. The Volume of Fluid (VOF) multiphase model was used to solve the Liquid Steel-Air-Wall’s interactions and the $k-\omega$ Shear-Stress Transport (SST) Turbulence model, to describe the fluid flow. The selection of both models was based on the good results from previous 2D mathematical modeling HSBC research$^2, 3, 8, 11$. The VOF
continuity equation is shown in Eq. (1) and the transient modeling for the Volume fraction was solved according to Eq. (2) with explicit time discretization. Eq. (3) presents the single momentum transport equation solved for the two phases, where the \( F_{\sigma} \) term is added to consider the surface tension forces in the momentum calculations.

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_p \rho_p \vec{v}_q) \right] = \sum_{p=1}^{n} \left( \bar{m}_{pq} - \bar{m}_{qp} \right) 
\]

(1)

\[
\frac{\alpha_q^{n+1} \rho_q^{n+1} - \alpha_q^n \rho_q^n}{\Delta t} V + \sum_{f} (\rho_q U_{q,f} \alpha_q^n) = \sum_{p=1}^{n} \left( \bar{m}_{pq} - \bar{m}_{qp} \right) V
\]

(2)

\[
\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla \vec{v}) = -\nabla p + \mu_{eff} \cdot \nabla^2 \vec{v} + \rho \vec{g} + F_{\sigma}
\]

(3)

The \( k-\omega \) SST Turbulence model was solved through the transport equations for the turbulent kinetic energy (\( k \)), Eq. (4) and the specific turbulence dissipation rate (\( \omega \)), Eq. (5). \( \Gamma \) terms represent the effective diffusivities of \( k \) and \( \omega \), which depend on the turbulent viscosity \( \mu_t \). Details of \( \Gamma \), \( \mu_t \) and the source terms \( G, Y, D, S \) and other details of the mathematical model can be found in previous work\(^2,3,8,11\)

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k
\]

(4)

\[
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega
\]

(5)

3. DISCUSSION OF RESULTS

3.1 Inclined slope, 0.8 mm back gap

The results for the 0.8 mm gap, predicted considerable backflow with the three different belt speeds (0.4, 0.8 and 1.2 m/s). Therefore, for brevity, only the results for the highest belt speed, 1.2 m/s, are presented and discussed. Figure 10 presents the predicted Liquid Steel (Phase2) volume fraction contours at different time frames after initial liquid metal pouring. At 0.019 seconds, it can be observed how the following metal stream is about to impinge the inclined back refractory plane, the first impingement zone. And then, at 0.029 seconds, it is appreciated how the Liquid Steel is about to reach the second impingement onto the moving belt. At 0.045 seconds, the simulation predicts a considerable backflow penetrating through the 0.8 mm back gap as the mainstream continues to be dragged forward by the moving belt. At 0.148 seconds, the backflow penetration increases to remain relatively stable at 0.482 seconds, when the mainstream reaches the end of the domain on the positive x direction and quasi-steady state operation is achieved. With the same results, the evolution of the oscillation of the first impingement zone, to be called “oscillation neck” henceforward, is appreciated. Firstly, at 0.029 and 0.045 seconds, the oscillation neck changes shape as it is dragged forward by the moving belt motion and then it remains stable at 0.148 and 0.482 seconds.

Figure 11 presents the predicted contours for velocity, pressure, and turbulence kinetic energy at 0.482 seconds, at stable HSBC operation. Figure 11(a) shows the velocity contour and vector map, where initially at the backflow penetration zone, low velocities of around 0-0.2 m/s are predicted, meaning a stagnation of the backflow, which will most likely solidify due to the inherent high heat extraction rates of the HSBC process. The mentioned flow stagnation is caused by the encounter between the positive x belt motion and the negative x motion of the backflow. The corresponding pressure contour is show in Figure 11(b), where the impingement zones correspond to high pressure areas. The backflow part shows pressure values of around 500 Pa, as the incoming flow exhorts such pressure that overcomes the tension force between the phases at the 0.8 mm gap, generating the observed backflow. Regarding the turbulence kinetic energy contour, presented in Figure 11(c), it can be said that a high turbulence zone is generated in the penetrating back flow due to the interaction of the moving motion of the belt on the positive x direction and the backflow motion on the negative x direction, generating a chaotic flow. Additionally, high turbulence zones are observed around the oscillation neck, generated possibly due to the backflow stagnation affecting all the flow in the system making it more turbulent in certain zones.

Similar results were observed for lower belt speeds (0.4 and 0.8 m/s), but with a more dramatic backflow. The previous discussion makes it clear that a 0.8 mm back size will promote important instabilities and risks in the casting of a Fe-Mn alloy.
via the HSBC process, regardless of the belt speed. As such, the use of a 0.8 mm back gap is to be discarded in casting this steel.

Figure 10. Volume fraction of liquid steel contours (red) at different times, for a 1.2 m/s belt speed and 0.8 mm gap.
3.2 Inclined slope, 0.4 mm back gap

For the 0.4 mm back gap, the results of the three cases with the three different belt speeds are presented and compared. Figure 12 shows the predicted liquid steel volume fraction contour for a 0.4 m/s belt speed at different times after the start of pouring of the HSBC process. Initially, at 0.011s and 0.032s, the falling molten steel stream reaches the inclined back wall to then reach the second impingement zone. Then, at 0.048 seconds, no backflow is predicted, and the back meniscus remains stable at 0.062 seconds, where some shape change in the oscillation neck is also observed. At quasi-steady state operation, 0.261 seconds from “start pour”, the back meniscus remains stable and oscillation neck presents shape changes compared to the 0.062 seconds’ contour. Additionally, at 0.261 seconds, a relative stable top interface between the liquid steel and the air can be observed all along the melt stream, with some interfacial waves near the second impingement zone but with a flat interface closer to the end of the domain in the x positive axis. Moreover, no air entrainment was observed in the first impingement and nor in the back meniscus zone, contrary to the initial results. A continuous liquid steel strip with a mostly flat interface is predicted under a 0.4 mm back gap and a 0.4 m/s belt speed.
Figure 12. Volume fraction of liquid steel contours (red) at different times, for a 0.4 m/s belt speed and 0.4 mm gap.

Figure 13 depicts the predicted volume fraction contours with a 0.8 m/s belt speed (isokinetic case), where like in the 0.4 m/s case, no backflow is observed, and stable back meniscus is promoted throughout the different timesteps presented. As well, changes in shape in the oscillation neck are evident throughout the process and at 0.261 seconds, quasi-steady state operation, a top interface with more waves and a less flat in general than the 0.4 m/s belt speed case is observed. Similarly, to the previous case, no air entrainment is predicted, and a continuous molten stream is observed, without any backflow, which as previously discussed can be highly detrimental for the HSBC process.
Figure 13. Volume fraction of liquid steel contours (red) at different times, for a 0.8 m/s belt speed and 0.4 mm gap.

Figure 14 presents the volume fraction contours for the 1.2 m/s belt speed case. The predicted liquid steel contours do not differ considerably from the results already presented for the 0.4 mm back gap and 0.4 and 0.8 belt speed configurations. However, the interface at 0.261 seconds, presents more waves compared to the two previous cases, hence it can be said that by increasing the belt speed a less stable top interface might be obtained. As well, the oscillation neck changes in shape throughout the process, in what seems to be an inherent characteristic of a double impingement feeding system. In general, a stable back meniscus and no air entrainment are predicted, making it possible to conclude that the change in the “free fall height” from 6 to 3 mm has promoted a more stable HSBC casting process for a Fe-Mn alloy, using an inclined slope feeding system, compared to the previous mathematical studies. 

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Figure 14. Volume fraction of liquid steel contours (red) at different times, for a 1.2 m/s belt speed and 0.4 mm gap.

Figure 15(a) presents the predicted velocity contour for the 0.4 m/s belt speed case at quasi-steady state operation (0.261 seconds), where a recirculation zone is to be observed on the left-hand side of the first impingement. This is the same recirculation zone which was observed previously with the results for the 6 mm “free fall height”, but it does not generate air entrainment with a 3 mm “free fall height”. However, this recirculation zone may be responsible for the behavior of the oscillating neck. On the second impingement and back meniscus zone, a low velocity magnitude is predicted, which can promote melt stagnation. In the zone posterior to the second impingement, it can be observed that the velocity of the melt adjacent to the moving wall, shows values between 0.4-0.8 m/s, whereas the predicted velocity increases with distance along the melt from the moving belt along the y axis. The previous velocity difference, between the bottom and the top parts of the melt, decreases as the melt moves towards the x positive axis, generating a more homogenous velocity along the melt thickness. Figure 15(b) shows the corresponding pressure contour and two distinctive high-pressure zones corresponding to both impingements are readily appreciated. The lower high-pressure zone corresponds to the penetration of the back meniscus into the back wall gap, where an equilibrium is maintained as the surface tension force in the 0.4 mm gap is enough to withstand the pressure of the second impingement. The corresponding turbulence kinetic energy contour is depicted in Figure 15(c) and the high turbulence areas correspond to zones adjacent to the impingement zone, near the first one due to the already discussed recirculation, and in the second one, due to the change of direction of the flow after the second impingement.
The predicted velocity contour for the 0.8 m/s belt speed case at quasi-steady state operation (0.261 seconds) is shown in Figure 16. Again, a recirculation zone is to be observed on the left-hand side of the first impingement but is located higher in the y axis and with higher velocity values compared to the 0.4 m/s belt speed case. As with the previous case, a low velocity magnitude zone is predicted at the second impingement and within the back meniscus zone. In the present case, it can be observed that the velocity of the melt adjacent to the moving wall, shows values between 0.8-0.9 m/s and again the predicted velocity of the metal increases by getting closer to the top of the liquid metal stream. The commented velocity difference is less dramatic than in the previous case. Figure 16(b) shows the corresponding pressure contour and the already discussed two distinctive high-pressure zones are visible, but with lower predicted pressure values compared to the 0.4 m/s belt speed case. The turbulence kinetic energy contour for the same case is depicted in Figure 16(c) and a high turbulence zone is to be observed within the recirculation zone on the left-hand side of the falling stream. Like in the previously discussed case, the second impingement zone corresponds to a relatively high area of turbulence. This promotes back meniscus stability since this leads to an increase in the local effective viscosity.
The corresponding results for the 1.2 m/s belt speed case are depicted in Figure 17, showing the predicted contours for (a) velocity, (b) pressure and (c) turbulence kinetic energy. In general, the results do not significantly differ to the previously discussed 0.4 and 0.8 m/s belt speed cases. For the velocity contours, a higher velocity magnitude recirculation zone near the oscillation neck is predicted, which can induce more oscillations on the falling stream and might explain the interface waves observed and discussed in Figure 14. The melt stream and a smaller velocity difference along melt thickness on the y axis is also predicted. Regarding the pressure contours, presented in Figure 17(b), no important changes are observed compared to the previous cases. For the turbulence kinetic energy contour, presented in Figure 17(c), a higher turbulence zone is promoted on the second impingement. This can promote a higher back meniscus stability due to the contribution of the turbulence in the effective viscosity of the liquid steel. Based on the mathematical modelling results for a 0.4 mm back gap with the three different studied belt speeds, a stable HSBC process with no backflow, compared to the 0.8 mm gap cases, and no air entrainment was predicted. An increase in the belt speed will lead to an increase in oscillations in the neck at the first impingement. This will also lead to an increase in the interface instability of the melt forward in the process due to relative low velocity difference within the melt strip, and also due to a marginal increase in the back meniscus stability because of the turbulence. The previous results are to be confirmed with its corresponding experiments in the HSBC simulator and pilot-scale machine.
CONCLUSIONS

Based on the present work, the following conclusions can be drawn:

- The HSBC Near Net Shape Casting Process (NSSC) has proven to be a viable option for the casting of Fe-Mn alloys for the emerging TRIP and TWIP steels, both industrially, with the “Belt Cast Technology ©”, and at pilot-scale, with the generic “Horizontal Single Belt Casting” process.
- The presented mathematical model, predicts an important improvement in the HSBC process with a double impingement feeding system by reducing the “free fall height”, since a more stable process is predicted compared to previous studies.
- By having a back gap of 0.4 mm, a stable back meniscus is promoted, and backflow is avoided. A correlation between the belt speed and the process behavior was obtained. By increasing the belt speed, an increase in activity of the oscillating neck and on the interface’s, instability was observed.
- Experimental work will follow to confirm the mathematical predictions of the impact of, and the influence of, the variables studied on the HSBC process for casting TRIP and TWIP steels.

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