A CFD Study of Alloy Dissolution and Homogenization in Ladle Metallurgy Furnace

The addition of microalloying elements in steel production is essential to improve steel properties, as they have a strengthening effect even in small amounts. The dissolution process of copper in the ladle metallurgy furnace was studied using parametric tests on the number of plugs and argon gas flowrates for stirring. To understand the particle movement in the molten bath, numerical simulations were performed using a three-dimensional computational fluid dynamics method. The results show that the mixing time is affected by the number of plugs and the gas flowrate, with the shortest mixing time achieved with a single-plug ladle with a flowrate of 0.85 m³/minute and a dual-plug ladle with a total flowrate of 1.13 m³/minute, both taking 5.6 minutes.

Ladle metallurgy furnaces (LMFs) are commonly used in secondary steelmaking processes to produce various steel grades. The process involves modifying the chemical composition of steel through alloy addition, electrical reheating, desulfurization and flotation of inclusions. The basic alloying process usually takes place during tapping, where the kinetic energy of the tapping stream is used to homogenize the alloys in the ladle. However, additions may still occur during ladle treatments with the use of new technologies for controlled alloying based on steel sample analysis. Argon blowing is the first stage in integrating these advanced methods in steel production.

Gas stirring or blowing is utilized during the metallurgical process to increase the speed of heat and mass transfer phenomena, such as heat distribution from the arc, dissolution and mixing of alloys and lime, slag-metal reaction, and inclusion flotation. The amount and size of the gas bubble injected affects the process outcome. The intensity of churning produced by gas stirring also enhances homogeneity by accelerating convective diffusion and heat transfer rates during mixing.

The steel quality is dependent on the even distribution of its alloying components, making dissolving of the alloy into the liquid steel a crucial step in secondary metallurgy. Various factors such as the size, physical and chemical properties, and hydrodynamics of the alloys in the ladle, as noted by D. Webber, impact their integration into the melt. Typically, the addition of the alloy results in a solidifying steel shell on the surface of the cold alloy, followed by melting of the shell and release of the alloy into the bath, meaning the dissolution process is influenced by both mass and heat transfer. Zhang and Oeters mathematical models address the duration of the shell’s existence and the heat transferred from the melt to the particle when the shell is still within the melt, and are based on the fundamental processes of melting, dissolution and mixing.

A study conducted by Aoki et al. used both single-fluid experiments and computational fluid dynamics (CFD) simulations to examine mixing in a ladle. The differences in alloy melting times are attributed to the short-term effects of superheat. Microalloying elements, which can significantly enhance steel properties with low concentrations, were investigated for their dissolving and mixing behaviors in the LMF, particularly in high-strength, low-alloy...
(HSLA) steels. These elements are used to improve grain hardening and refinement, making microalloyed steels suitable for high-strength applications. The dissolving properties of copper (Cu) were examined. Moderate amounts of Cu improve atmospheric corrosion resistance and add precipitation-hardening qualities, while excessive amounts are harmful.

The model developed for this multi-phase study determines alloys’ critical time of dissolution and regulates the release of particle mass into the bath, as well as their injection time. The amount of time it takes for the scattered components to reach a specific level of homogeneity is also taken into account. The recoveries of these alloys after a certain amount of time are compared to plant data. ANSYS Fluent 2020 R1 was used to solve the models representing the flow inside the ladle and the turbulence caused by the movement of gas bubbles.

Methodology

Governing Equations

Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

(Eq. 1)

where

\( \rho \) = the density of the mixture,
\( t \) = time and
\( \vec{u} \) = the local velocity.

Momentum:

$$\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \left[ \mu \left( \nabla \vec{u} + \left( \nabla \vec{u} \right)^T \right) \right] + \rho \vec{g} + \vec{F}_b$$

(Eq. 2)

where

\( p \) = local pressure,
\( \mu \) = viscosity,
\( \vec{g} \) = acceleration due to gravity and
\( \vec{F}_b \) = force from bubbles.

Turbulence model:

$$\frac{\partial}{\partial t} \left( \rho k \right) + \nabla \cdot (\rho k \vec{u}) = \nabla \cdot \left[ \left( \mu + \frac{\mu_k}{\sigma_k} \right) \nabla k \right] + G_k + G_b - \rho \epsilon$$

(Eq. 3)

Standard k-epsilon model is used to model the turbulence flow in the multi-phase system. The transportation equation of turbulence kinetic energy and turbulence dissipation rate are shown below:

$$\frac{\partial}{\partial t} \left( \rho \epsilon \right) + \nabla \cdot (\rho \epsilon \vec{u}) = \nabla \cdot \left[ \left( \mu + \frac{\mu_k}{\sigma_k} \right) \nabla \epsilon \right] + C_{\epsilon_1} \frac{\epsilon}{k} \left( G_k + C_{\epsilon_2} G_2 \right) - C_{\epsilon_2} \rho \frac{\epsilon^2}{k}$$

(Eq. 4)

where

\( G_k \) and \( G_b \) are mean velocity gradient and buoyancy effect in the flow causing the kinetic energy generation,
\( \sigma_k \) and \( \sigma_b \) represent turbulence Prandtl numbers and
\( C_{\epsilon_1}, C_{\epsilon_2} \) and \( C_{\epsilon_3} \) are constant.

Species transport model:

After alloy dissolved into steel, species transport model will be used:

$$\frac{\partial}{\partial t} \left( \rho Y_i \right) + \nabla \cdot (\rho \vec{u} Y_i) = \nabla \left( \frac{\mu}{\sigma_{i,m}} + \rho D_{i,m} \right) \nabla Y_i + S_i$$

(Eq. 5)

where

\( Y_i \) = the local mass fraction of species in the continuous liquids,
\( D_{i,m} \) = the mass diffusion coefficient for species i in the mixture and
\( S_i \) = the source term of species i due to the species addition from alloy.

Discrete phase model:

Argon bubble and alloy before dissolution are modeled using discrete phase model (DPM). The force balance is shown below:

$$\frac{d\vec{x}_b}{dt} = \vec{F}_b \left( \vec{v} - \vec{v}_b \right) + \frac{\vec{g} \left( \rho_p - \rho \right)}{\rho_p} + \vec{F}_{VM} + \vec{F}_{pressure}$$

(Eq. 6)

From Eq. 6, Re is the particle Reynolds number. \( C_D \) is the drag coefficient referring from Aoki et al. The alloy injection process is performed as a two-stage simulation. Once the flow reaches a near-steady state, the alloy presented by the DPM particle will be released from the top of the ladle. As the alloy dissolves into the steel, the mass carried by the DPM will be transferred to the continuous phase, and the tracking of the DPM particle will end.

Shell dissolution time is called “critical time \( t_c \).” When critical time is achieved, the source of particle mass will be adding to continuous phase. Based on Zhang and Oeters, the critical time can be written as:
\[ t_i = \frac{C_p \rho R T_S - T_0}{\pi h T_m - T_S} \]  
(Eq. 7)

where

- \( C_p \) = the specific heat,
- \( R \) = the radius of the ferroalloy particle and
- \( \rho \) = the density of the ferroalloy.

The time it takes for the mixture to completely homogenize is known as the “mixing time.” In this work, the mixing percentage is defined as follows:

\[ C_m = 1 - \frac{C_{i, \text{max}} - C_{i, \text{min}}}{d_A} \]  
(Eq. 8)

where \( C_{i, \text{max}} \) represents maximum alloy concentration at all monitoring points. The time when \( t_m \) reaches 95% will be recorded as mixing time.

**Simulation Procedures**

The whole process can be considered in two parts: flow field simulation and alloy dissolution simulation. In the flow field simulation, all the transportation equations will be solved except species transport equations. When flow reaches quasi-steady state, the flow field will be maintained. Flow and turbulence equations will be deactivitated. Alloy is then injected from top, and the species transportation equation will be enabled.

The alloy injection location is at the slag-steel interface above one of the plugs. Fourteen points throughout the ladle are used to monitor species mass fraction change. Then the mass fraction evolution history will be used on mixing time analysis.

**Computational Details**

Fig. 1 shows the computational domains — air, slag and steel — with two porous plugs of diameter 0.104 m at the bottom. The steel height and slag thicknesses are 3.23 m and 0.147 m, respectively. Ladle walls are set to a no-slip boundary condition. The top surface is set as a pressure outlet. The mesh can also be found from the figure. The plug region and initial fluid-fluid interfaces are refined.

The base mesh has a cell count of 1.2 million cells. A mesh sensitivity study has been done by refining or coarsening the cell counts of 1.6 million and 0.7 million. The average velocity from difference mesh on the parallel plane (1.2 m above ladle bottom) is shown in Fig. 2. From the figure, base mesh has similar accuracy compared to finer mesh but has less run time. The base mesh is selected for further study.

**Material Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Viscosity of liquid steel</td>
<td>0.0062 Pa.s</td>
</tr>
<tr>
<td>Surface tension of liquid steel</td>
<td>1.4 N/m</td>
</tr>
<tr>
<td>Melt density</td>
<td>6,795 kg/m³</td>
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<tr>
<td>Argon density</td>
<td>1.6 kg/m³</td>
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<tr>
<td>Slag density</td>
<td>2,785.96 kg/m³</td>
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<tr>
<td>Specific heat of liquid steel</td>
<td>820 J/kg.K</td>
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<tr>
<td>Specific heat of copper</td>
<td>390 J/kg.K</td>
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<tr>
<td>Thermal conductivity of liquid steel</td>
<td>40.3 J/m.s.K</td>
</tr>
<tr>
<td>Density of copper</td>
<td>8,960 kg/m³</td>
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<tr>
<td>Temperature of liquid steel</td>
<td>1,805 K</td>
</tr>
<tr>
<td>Diffusion coefficient of alloy in liquid steel</td>
<td>m²/s</td>
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</tbody>
</table>
Model Validation With Plant Data
The alloy injection process has been validated with plant measured data provided by Nucor Corp. The sample point is located at the midpoint of the line connecting the two porous plugs 7 inches below the ladle top.

The flowrate for each plug is 0.85 m³/minute during and after alloy injection. The alloy injection process will last for 30 seconds. The mass concentrations of dissolved alloys will be measured six times. Table 2 compares CFD model data against plant homogeneity test measurements.

A single alloy injection point is defined in a discrete phase at a downward velocity of 6 m/second on the y-axis above one of the plugs. The residence time of copper is calculated based on Eq. 8, and the initial steel temperature at the start of the homogeneity test is 1,892 K. The data shown in Table 2 is normalized. The normalization method can be described as:

$$ C_{\text{normalize}} = \frac{C_{\text{CFD}} - C_{\text{init}}}{\max(C_{\text{CFD},\text{plant}} - C_{\text{init},\text{plant}})} \times 100\% $$  
(Eq. 9)

The difference between CFD prediction and plant measurements is calculated as follows:

$$ \Delta = \frac{C_{\text{CFD},\text{plant}} - C_{\text{CFD}}}{C_{\text{init},\text{CFD}}} \times 100\% $$  
(Eq. 10)

The result shows the average difference between CFD and plant measurement is 13.58%. As it can be seen from Fig. 3, the difference at the early stage is smaller compared to the later stage. It may be caused by numerical error. More measured data and simulations will be compared in the future to improve the model accuracy.

Results and Discussion
To study the effect of plug arrangement and flowrate, three cases are compared.

Flow Field
The velocity vectors of Case 1 and Case 2 on a cross-sectional plane is shown in Fig. 4. It is important to note that the recirculation of two cases are similar, but not the same. The flow at the upper part of ladle shows stronger circulation toward a higher-flowrate plume, which can make alloy distribution more uneven throughout the domain.
Particle Dissolution Behavior
Alloy is injected below the slag-steel interface above one of the plugs as shown in Fig. 5. Once alloy particles are injected, they will follow the flow patterns to move. After critical time passed, alloy particles will dissolve into the steel. The trajectory of the particles will be terminated.

Fig. 6 and Fig. 7 show normalized alloy mass fraction for each case at 15 seconds and 60 seconds, respectively.

For case 1 (dual-plug symmetric flow), the discrete phase velocity magnitude of the particles entering the liquid steel decreases significantly, with copper particles sinking directly to the center of the bath due to their higher density than steel. Although the initial speed is reduced, it stays constant at around 0.8 m/second for the first 15 seconds of addition, with more fluctuations recorded. The particles accumulate between the plumes and form a mass shell around the perimeter, melting at the critical time of 1.14 seconds and gradually dissolving and diffusing across the steel bulk.

In Case 2 (dual-plug asymmetric flow), the flow-rate of each plug is not the same. The majority of the recirculation is pushed toward the higher flowrate, unlike the baseline flow which has centered recirculation regions between the plumes. The recirculation leads to faster mixing. When the same copper mass is injected into the flow field, the velocity magnitude of the DPM particles fluctuates significantly, as seen in the particle track color bar. The behavior of the copper particles from the baseline case is still observed, but the cluster of mass formed in the melt is closer to the higher flowrate plume, where the region of recirculation was previously noticed. The time for the steel shell to melt and allow the copper particles to dissolve is 1.13 seconds.

As for Case 3 (single-plug case), a process of injecting the same amount of copper at one point is carried out and observed. The results

<table>
<thead>
<tr>
<th>Case Matrix</th>
<th>Flowrates (per plug - m³/minute)</th>
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</thead>
<tbody>
<tr>
<td>Case 1 (Base)</td>
<td>2</td>
</tr>
<tr>
<td>Case 2</td>
<td>2</td>
</tr>
<tr>
<td>Case 3</td>
<td>1</td>
</tr>
</tbody>
</table>
show that the copper mass moves toward the center after injection, even though it occurs within one plume. When the steel shell melts, there is a slow diffusion of the particles as they are gradually distributed downward. As seen in the contour plots, high concentrations of the copper mass fraction are closer to the plume region, even during the dissolution process.

Mixing Time

The mixing time was determined by finding the variance of the concentrations at various monitoring points and reaching 95–100% homogeneity. The same process was applied to all other cases, and the results are listed in Table 4. The mixing time is influenced by several factors including liquid depth, mean ladle radius, gravity, and gas flowrate, and there may be time over-prediction if some points are located in dead zones or if superheat affects the time. Aoki et al.\textsuperscript{5} explains the dependence of mixing time on the flow field in detail.

Conclusion

Alloy addition was modeled through a two-stage process using a 3D multi-phase flow model. The first stage involved gas stirring, which resulted in a zone of recirculation between the plume pulses and an intensity close to the slag-metal interface. The high flowrate used in a dual-plug ladle for gas stirring was analyzed and compared with a lower flowrate in a single-plug ladle to determine the need for an extremely high flowrate. The mixing behavior of copper particles showed that the process was heavily influenced by the recirculation generated around the plume during argon gas blowing, as it slows down the velocity of particle dispersion from the injection point. An unconventional, asymmetrical flowrate resulted in a shorter mixing time compared to the standard, same flowrate. The dual- and single-plug cases, with flowrates of 1.13 m\textsuperscript{3}/minute and 0.85 m\textsuperscript{3}/minute, respectively, showed a close mixing time.

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References