Investigation on Liquid Segregation during Rheo-Casting Process Based on Eulerian-Granular Multiphase Model

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Abstract: A crucial problem concerned with the semi-solid forming process is the liquid segregation phenomena during shape formation, especially for rheo-casting process. Liquid segregation occurs due to the separation phenomena of the solid grain and the liquid phase. In this work, using commercial finite element software, the liquid segregation during rheo-casting process was numerically investigated by Eulerian-granular multiphase model based on the comparable results of single phase model, Eulerian-granular two-phase and three-phase model, along with Eulerian-granular DDPM three-phase model. In the study, solid grains and liquid phases were regarded as rigid material and non-Newtonian fluid at microscale, separately. This validation was experimentally proved and also compared to the proposed relationship of power law, Herschel-Bulkley model with yield stress at macroscale.

1. Introduction

Semi-solid Rheo-casting is a forming process between solidus and liquidus temperature, near-spherical solid grains suspended in liquid matrix make it is remarkably different from the dendritic structure of traditional forming process [1-6]. Power law and Herschel-Bulkley model as the most class of non-Newtonian fluids have been successfully applied for one-phase modelling for semi-solid alloy [7]. Compare to the Power law, the effect of yield stress has been considered in Herschel-Bulkley model. However, there are still much disparities existing in many constitutive modelling developed to describe the rheological behaviour of semi-solid slurry during casting, such as whether existing yield stress in semi-solid mushy zone, these disparities in quantitative literature results contribute to the difficulty to modelling, especially for multiple-phase modelling. As we know, there are four mechanical phases within a real semi-solid material: the solid globules, the solid bonds, the entrapped liquid and the free liquid. It has been proved that the free liquid at boundaries primarily contribute to the semi-solid forming process [8]. Therefore, liquid segregation occurs between primary phases of solid grains and free liquid will be investigated in this work.

The prediction of characteristics of semi-solid alloy is extremely complex due to the rheological behaviour of semi-solid slurry, depending on its solid fraction, solid-phase morphology and thermal mechanical history. Numerical simulation based on Eulerian multiphase model is a cost-effective tool in the optimization of process parameters for investigating the mould filling process visibly[9-14], the use of which to obtain liquid segregation is clearly of great interest. Broadly speaking, there are three types of CFD models for multiphase models, namely, volume of fluid, and mixture and Eulerian model [15], which are widely applied for gas-solid or gas-liquid flow simulations at present, rather than solid-liquid for semi-solid flow. All phases in Eulerian model are treated as fully interpenetrating continua. In addition, Dense Discrete Phase Model (DDPM), belong to one type of Eulerian multiphase model, is used for the secondary phase that has a particle size distribution. The liquid segregation can result in non-uniform mechanical properties and undesirable final quality of semi-solid products [16]. Based on the current research work, a granular flow of Eulerian multiphase model was used to investigate the liquid segregation during Rheo-casting process for 357.0 aluminium alloy. In order to find out a more appropriate viscosity law to capture the rheological...
behaviour of primary liquid phase in Eulerian multiphase model, and then further investigate liquid segregation during Rheo-casting process, the single phase model of Power law and Herschel-Bulkley, along with Eulerian-granular two-phase and three-phase model, Eulerian-granular DDPM three-phase model, have been adopted by comparing their velocity field in this work. After appropriate selection of viscosity law, the phenomenon of liquid segregation during Rheo-casting process has been finally addressed by Eulerian-granular DDPM multiphase model, which is in line with the general observations in experimental results.

2. Experimental procedures

The commercial 357.0 aluminium alloy was used to investigate the liquid segregation during rheo-casting process. Thermal analysis of differential scanning calorimetry (DSC) was performed to determine that the solidus and liquidus temperatures are 820K and 888K respectively. The rheo-casting process at the temperature of 848 K, corresponding to the liquid fraction of 0.5, was studied in this work. The semi-solid 357.0 slurry was prepared by enthalpy equilibration method, with its near-spherical solid grains shown in Fig. 1(a), and then transferred to die casting machine for rheo-casting process, the final obtained semi-solid casting part is shown in Fig. 1(b).

![Fig.1 Semi-solid optical microstructure (a) and semi-solid casting part (b)](image)

Image analysis was performed by the software Image Pro Plus based on the semi-solid microstructure shown in Fig. 1(a), the maximum, minimum and mean diameters are 31, 18.5 and 23.6 respectively. It should be noted that the representative semi-solid microstructure shown in Fig. 1(a) is relatively small in order to guarantee convergence during simulation. These measurement results are the input parameters for Eulerian multiphase modelling.

3. Viscosity law and Eulerian multiphase simulation setting

3.1 Power law

\[ \eta = K \gamma^{n-1} \]  

Where \( \eta \) denotes the viscosity of semi-solid slurry, \( K \) is the consistency index, which represents the initial value of viscosity, and \( n \) is power-law index. If \( n < 1 \), the slurry behaves as a shear-thinning fluid, otherwise flows as a shear-thickening fluid \( (n > 1) \).

The value of power-law index, \( n \), is determined as 0.2 from the experimental result in literature [17].

3.2 Herschel-bulkley model

The Herschel-bulkley model is shown as follows, which is constructed using a combination of the ideal Bingham model and a power-law [18].

\[ \tau = \tau_0 + K \gamma^n \]  

(2)
In this yielded viscosity law, \( \tau \) is the shear stress, which is dependent on the solid fraction, and \( \gamma \) is the shear rate.

The Herschel-bulkley fluid behave as a rigid solids when the local shear is below the yield stress \( \tau_0 \) and flow as a fluid in yield region \( (\tau > \tau_0) \) followed by Equation (3). The initial value of shear stress \( \tau_0 \) is found to be 121.5 Pa at the solid fraction of 0.5 [19].

\[
\eta = \eta_0 + K \gamma^{n-1}
\]

### 3.3 Input parameters for Eulerian multiphase model

The Numerical analysis parameters applied for Eulerian multiphase model (see Table 1) were strictly kept consistent with actual casting process as described in experimental procedures. The densities of solid and liquid were calculated by Rule of Mixture based on the compositions of solid (Al-1.6%Si) and liquid (Al-12.6%Si) in Al-Si phase diagram, the results and other physical properties of 357.0 are listed in Table 1. The mould material is H13, the thermal conductivity and specific heat of mould are 32.2 W/m·k and 460 J/kg·K. The geometry of casting part was simplified as 2D modelling to better understand the filling pattern during Rheo-casting process. Furthermore, different type of viscosity laws were investigated to finally determine the most suitable viscosity evolution law which could use for liquid segregation characterization.

<table>
<thead>
<tr>
<th>Casting temperature</th>
<th>Mold temperature</th>
<th>Filling speed</th>
<th>Filling time</th>
<th>Total flow rate</th>
<th>Interface heat transfer coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>848K</td>
<td>473K</td>
<td>0.75 m/s</td>
<td>2.1s</td>
<td>1.12kg/s</td>
<td>3000W/m²K</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of 357.0 aluminium alloy used in Eulerian multiphase model

<table>
<thead>
<tr>
<th>Solid density</th>
<th>Liquid density</th>
<th>Specific heat</th>
<th>Thermal conductivity</th>
<th>Latent heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>2694kg/m³</td>
<td>2378kg/m³</td>
<td>963J/kg·K</td>
<td>152 W/m·k</td>
<td>389kJ/kg</td>
</tr>
</tbody>
</table>

### 4. Results and discussions

In order to find out an appropriate constitutive law for viscosity that can accurately describe the liquid segregation during Rheo-casting process, different phases of modelling were carried out as shown below. The heat transfer was taken into account for all the cases of numerical simulation. For Eulerian multiphase model, solid grains and liquid phases were regarded as rigid material and non-Newtonian fluid at microscale, respectively. The apparent viscosity of liquid fellow different viscosity laws, while that of solid was assumed as \( 2 \times 10^4 \) Pa·s.

#### 4.1 Single-phase model

The simulation results of single-phase model (see Fig.2) were compared with constant viscosity, variation of magnitude order of initial viscosity, namely the value of the consistency index \( K \), in power law and Herschel–Bulkley model. It is seen that two branch of casting part with constant viscosity appears asymmetric filling pattern, as shown in Fig.2 (a). The different order of magnitude of \( K \) as listed in Equation (1)-(3) \( (10, 1 \times 10^5 \text{ and } 1 \times 10^8 \text{ Pa·s}) \) in power law were also analysed, as shown in Fig.2 (b) (c) and (d), which is clearly shown that the simulation of power low at \( 1 \times 10^8 \text{ Pa·s} \) of \( K \) (see Fig.2 (d)) is most unreliable case. For single-phase model with yield stress, Herschel–Bulkley model at \( 1 \times 10^5 \text{ Pa·s} \) of \( K \) (see Fig.2 (e)) is unlikely suitable for semi-solid modelling. The most possible cases of Fig.2 (b), (c) and (e) will be further validated in next step.
4.2 Eulerian-granular two-phase model

Based on the results of one-phase modelling, two magnitude order of $10$ and $1\times10^5 \text{ Pa}\cdot\text{s}$ of $K$ for both power low and Herschel–Bulkley model are compared in Fig.3. From the simulation results, Herschel–Bulkley model at $1\times10^5$ and $10 \text{ Pa}\cdot\text{s}$ of $K$, as indicated in Fig.3 (b) and (d), which should be presented as laminar filling pattern instead of turbulence, namely the same velocity gradient, during Rheo-casting process. It shows that the Herschel–Bulkley model can predict the flow behaviour of the material for one-phase model, but the model deviates from the experimental data for multi-phase simulation. Therefore, it turn out that the Herschel–Bulkley model with yield stress is not suitable for Rheo-casting process in the case of our work. Meanwhile, power low at $1\times10^5$ and $10 \text{ Pa}\cdot\text{s}$ of $K$ (see Fig. 3(a) and (c)) will be further verified in Eulerian-granular three-phase model.

4.3 Eulerian-granular three-phase model

According to the simulation results of Eulerian-granular two-phase modelling in Fig.3, the numerical simulation of power low at $1\times10^5$ and $10 \text{ Pa}\cdot\text{s}$ of $K$ by using Eulerian-granular three-phase modelling are compared in Fig.4. Besides considering solid and liquid phases in the semi-solid slurry, the effect of possible entrapped air at the volume fraction of 0.001 was investigated as well. It is of course possible to predict the velocity filed of semi-solid slurry for higher magnitude order of $K$, in which case, lower magnitude order of $K$ is proved to be more suitable for multiphase modelling, as shown in Fig.4.
4.4 Eulerian-granular DDPM three-phase model

Base on all above mentioned different phases for Rheo-casting process, with preferred 10 Pa·s of $K$ in power law, three phases with liquid (50%), solid and air (0.1%) were analysed by using Eulerian-granular DDPM multi-phase model. It is shown in Fig.5 (a), the semi-solid slurries was gradually filling into cavity characterized by the uniform gradient of velocity pattern. The diameter distribution of discrete phase for solid grains is depicted in Fig.5 (b), the maximum, minimum, and mean value of diameter for initial solid grains were calculated based on the quenched semi-solid microstructures after slurry preparation.

![Fig.5 Velocity pattern (a), diameter distribution (b) and liquid volume fraction (c) obtained by Eulerian-granular DDPM three-phase modelling by using power low at 10 Pa·s of $K$](image)

After Rheo-casting, the semi-solid part was cut into three cross-section (I,II,III) to investigate the liquid segregation at different locations, as shown in Fig.6. The optical micrographs show that liquid segregation phenomenon was clearly observed in cross-section I, the semi-solid microstructures at the centre ① and the margin ② of near in-gate part demonstrated that there is more of the liquid phase appearing at the margin ② of near in-gate cross-section I. As shown in Fig. 5 (c), the liquid fraction of near in-gate on the margin is quite higher than that of centre, which represent the occurrence of liquid segregation. This comparable results have proved that the numerical simulation result of liquid fraction obtained by Eulerian-granular DDPM three-phase modelling is reliable, which keep in line with the general observations in experimental results observed in Fig.6. The results show a good agreement between the proposed model and the experiments.

5. Conclusions

It is obvious that the final Eulerian-granular multiphase simulation results of liquid segregation keep consistent with the experimental results, and the proposed Eulerian-granular DDPM three-phase model combined with low magnitude order of $K$ in power law for primary liquid phase can predict the velocity pattern, diameter distribution over time as well as occurrence location of liquid segregation. The proposed model can further be used in numerical analysis for other semi-solid parts during Rheo-casting process. This crucial problem concerned with liquid segregation is required accurate predictions in engineering processes for industrial applications. The refinement and improvement of Eulerian-granular DDPM multiphase modelling for semi-solid alloys can be further explored and investigated in the future studies by combining the numerical analysis techniques and experimental tests.
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7. References