Research on pressure loss and filling ability of semi-solid rheological behavior in squeeze casting

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Received: 10 September 2021 / Accepted: 14 April 2022 / Published online: 20 April 2022
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Abstract
The filling ability of semi-solid melt under pressure is significant for improving the dimensional integrity of thin-walled and thin-rod parts with complex structures via squeeze casting. The semi-solid rheological behavior involves many physical characteristics, e.g., heat conduction, phase change, apparent viscosity, pressure loss, and rheological shear, and has a crucial effect on the filling ability. In this study, Archimedes spiral samples of A356 alloy were used to investigate the filling length variation with the squeeze pressure and filling speed during squeeze casting. According to the calculation of the characteristic temperature distribution during the alloy melt filling process, the melt state was determined, and the spiral filling was confirmed to be a semi-solid rheological behavior. The stop filling of the semi-solid melt directly contributed to the pressure loss, which was mainly affected by the apparent viscosity determined by the alloy melt’s temperature distribution and filling speed in the channel. Prediction models of the pressure loss and filling length were established based on steady-state heat-fluid coupling rheological behavior to determine the minimum critical squeeze pressure and avoid insufficient filling. The agreement between the results of the theoretical calculations and experimental measurements demonstrated that the models could be used to quantitatively characterize the filling ability of alloy melt during the squeeze casting.

Keywords Pressure loss · Filling ability · Semi-solid · Rheological behavior · Squeeze casting

1 Introduction

The filling ability of alloy melt highly influences the integrity and surface roughness of precision castings, especially complex thin-walled and thin-rod parts [1–3]. Applying pressure to the alloy melt poured into the mold cavity, i.e., squeeze casting, could significantly improve the castings’ filling ability and mechanical properties, as demonstrated in solidification manufacturing [4, 5]. An alloy melt flowing in a channel with a small radius has a high cooling rate and easily transforms into a high-viscosity semi-solid melt, which is confirmed to be complex semi-solid rheological behavior [6, 7]. The squeeze pressure is continuously lost along the filling length until the melt cannot be driven, stopping the filling. Therefore, understanding the rheological mechanism of semi-solid melt and predicting the pressure loss and filling ability of squeeze casting could effectively improve the formation of thin-walled and thin-bar castings [8, 9].

Many experimental and theoretical studies have been conducted to quantitatively improve the filling ability and predict the filling length of squeeze casting by optimizing the process parameters [10–12]. Increasing the squeeze casting pressure can continuously improve the filling ability; however, this significantly reduces the mold life and increases the equipment cost. Thus, a variety of other measures have been adopted to enhance the filling ability. For instance, Bai et al. have studied the influence of the pouring temperature, applied pressure, and filling speed on the rheological filling ability of semi-solid A356 alloys to determine the optimal ranges of these parameters [13]. Moreover, Zhang et al. [14] have developed a theoretical evaluation model to predict the maximum filling length based on the flow theory of incompressible viscous fluid. They believe that the squeeze pressure and filling speed prominently influence the mold filling ability of an alloy melt. Obviously, increasing the pouring temperature would also improve the filling ability, but too
high a temperature would cause entrainment defects during rheological squeeze casting [15, 16]. Many studies have also shown that the chemical composition, rare addition, and fine-grained structure are beneficial to the filling ability of aluminum alloys [17–21]. However, the method of calculating the pressure loss and filling ability of semi-solid rheological behavior in squeeze casting is still imprecise and cannot guide the formation of high-precision thin-walled parts.

In fact, the squeeze pressure applied to semi-solid melt decreases along the filling length and the pressure loss rate is critically determined by the apparent viscosity of semi-solid melt. The greater the apparent viscosity of semi-solid melt, the faster the pressure loss. Thus, the apparent viscosity of semi-solid melt is an essential factor that resists the melt filling ability and is mainly affected by the shear rate and temperature [22]. Li et al. [23] have found that the apparent viscosity of semi-solid 7075 aluminum alloy decreases as the shear rate increases; they believe a shear thinning phenomenon occurs due to less liquid being entrapped in the solid particles. Blanco et al. [24] have studied the rheological behavior of a semi-solid Al-5Cu melt using a high-temperature Searle rheometer and shown that the higher the shear rate, the lower the melt’s apparent viscosity. Many researchers agree that the relationship between the apparent viscosity and shear rate conforms to the power law [25–27]. However, regarding semi-solid filling, it is impossible to directly calculate the apparent viscosity with an immeasurable shear rate, making it challenging to predict the filling length. In addition, the pressure loss variation during the semi-solid melt filling process is unclear, so it is difficult to quantitatively optimize the process parameters according to the casting integrity and mechanical property requirements. Therefore, determining the mechanism of the pressure loss and filling ability of semi-solid rheological behavior in squeeze casting requires further research.

In this paper, an Archimedes spiral experiment on squeeze casting A356 aluminum alloy at different pressures and filling speeds is conducted. The alloy melt’s temperature distribution along the spiral channel during the filling process is calculated, and the fluid state is analyzed. Prediction models of the pressure loss and filling length are established based on the steady-state heat-fluid coupling rheological behavior, and their influencing factors are quantitatively discussed. Finally, the rheological mechanism of the semi-solid alloy filling is discussed, providing an important basis for forming precision castings and optimizing the process parameters.

### 2 Experimental procedure

To gain insight into the squeeze pressure loss mechanism during the semi-solid alloy rheological filling process, a spiral squeeze casting experiment was conducted using a commercial A356 aluminum alloy (Table 1) and a self-designed spiral mold divided into four main parts, i.e., the upper die, lower die, punch, and chamber (Fig. 1). The upper die contained an Archimedes spiral channel with a length of 1,350 mm and radius of 4 mm. The lower die was a cylindrical chamber connected to the Archimedes spiral cavity by a channel on the side wall.

The alloy was melted in an electrical furnace at 5 kW, and the temperature was measured using TES-1310 contact thermometric instruments and K-type thermocouples. When the melt temperature reached 990 ± 5 K, CCl₄ (2 wt%) was added to refine the alloy melt before being slagged off 10 min later. The liquid alloy was allowed to stand; once the

#### Table 1 Chemical composition of A356 alloy (wt%)

|  | Si | Mg | Fe | Cu | Ti | Sr | Zn | Ni | Al |
|---|---|----|----|----|----|----|----|----|----|
|  | 7.153 | 0.394 | 0.127 | 0.085 | 0.007 | 0.007 | 0.008 | 0.004 | Bal |

![Fig. 1](image-url)  
**Fig. 1** a Self-designed spiral mold structure diagram and b spiral specimen
temperature was adjusted to 990 K, it was directly poured into the lower die which was preheated to 440 K. Then, driven by the filling cylinder, the punch moved down to squeeze the alloy melt back into the upper die. The punch was reset after a holding time of 20 s. The pressure was removed from the movable beam, driving the upper die to reset. Finally, the samples were ejected out of the mold by ejectors. The spiral specimens were prepared under squeeze pressures of 20, 50, and 80 MPa and filling speeds of 0.01, 0.02, and 0.05 m/s.

3 Results

Figure 2 demonstrates that both the squeeze pressure and filling speed could be considered to have a linear influence on the filling length. The influence of the squeeze pressure was not obvious at low filling speeds, but as the speed increased, the pressure’s promoting influence became more significant. However, the filling speed had a more obvious effect on the filling length (Fig. 2b). In fact, the volume fraction and morphology of the α-Al phase were important factors affecting the semi-solid melt’s apparent viscosity. When the filling speed increased, the semi-solid melt had a smaller volume fraction because the higher shear rate broke the large dendrites into fine equiaxed crystals [28], which helped to reduce the melt’s apparent viscosity and improve the filling ability.

Figure 3 shows that as the filling speed increased, the α-Al changed from dendritic to equiaxed, indicating that the high shear rate had a good shearing effect on the primary dendrites. Samat et al. believed that α-Al particles transform from dendritic in gravity casting to near spheroidal in rheocasting [29, 30]. In this study, the filling process of the alloy melt in the channel could be regarded as a transition from gravity solidification at a low filling speed to rheological solidification at a higher filling speed. Table 2 shows the grain size (GS) and shape factor (SF) of the α-Al particles as measured using Image-Pro Plus 6.0 and the following equations:

\[ GS = \left[ \frac{\sum_{i=1}^{N} 2 \left( \frac{A_i}{\pi} \right)^{1/2} }{N} \right] \]

\[ SF = 4 \pi A / P^2 , \]

where \( A \) and \( P \) are the area and perimeter of α-Al, respectively. And, \( N \) is the total number of α-Al particles measured in each image. As the squeeze pressure and filling speed increased, the grain size decreased from 62.1 to 43.5 μm, and the shape factor increased from 0.814 to 0.927. The filling speed had a greater influence than the squeeze pressure.

4 Discussion

The semi-solid rheological filling process in the spiral experiment was divided into two stages: increasing the pressure and maintaining the pressure. As the pressure gradually increased to set maximum value \( P_{set} \), the filling speed was constant and equal to set value \( v_{set} \). As the heterogeneous nucleation undercooling was small and the melt temperature near the channel wall was lower than that in the center of the channel, the solid phase first precipitated on the channel’s inner wall. Then, under the scouring action of the subsequent overheated melt, the solid phase was partially remelted and mixed into the alloy melt to form a semi-solid melt. The fluid state also transformed from a Newtonian to a non-Newtonian fluid. Therefore, the spiral filling process could be regarded as having semi-solid solidification behavior. When the squeeze pressure reached \( P_{set} \), the pressure maintenance stage began. Due to the decrease of the melt temperature and continuous increase of the filling length, the alloy melt’s viscous resistance was greater than applied.
squeeze pressure $P_{\text{set}}$, so filling speed $v$ decreased until the melt stopped filling.

According to the melt state and filling characteristics, the pressure loss $P_{\text{loss}}$ could be divided into three parts (Fig. 4). Initially, during the pressure increase stage, when the melt was being filled at constant speed $v_{\text{set}}$, $P_{\text{loss}}$ comprised $P_1$, caused by liquid melt length $L_1$, and $P_2$, caused by semi-solid melt length $L_2$. Meanwhile, $P_3$ was caused by semi-solid melt length $L_3$ during the pressure maintenance stage. In the pressure increase stage, there was a relationship between applied squeeze pressure $P_a$ and the $P_{\text{loss}}$ caused by the filling melt: $P_a = P_1 + P_2 - P_0$, where $P_0$ is the atmospheric pressure. Compared with the squeeze casting pressure, the atmospheric pressure could be ignored. Thus, the $P_{\text{loss}}$ during the rheological filling process was considered to be equal to the applied squeeze pressure. During the pressure maintenance stage, the relationship between the maximum $P_{\text{set}}$ and the $P_{\text{loss}}$ caused by the filling melt was $P_{\text{set}} < P_{\text{loss}}$.

### 4.1 Temperature characteristic

During the alloy melt filling process, the melt temperature was one of the main factors affecting the filling resistance, which ultimately determined the interaction relationship between the filling length and squeeze pressure. When the melt flowed into a spiral channel, the heat was transferred to the mold via heat conduction. The melt temperature distribution during the filling process was calculated based on the following assumptions: The temperature of the mold remained constant, the heat convection and radiation were neglected, and the heat convection of the alloy melt along the spiral channel was ignored.

According to the heat balance principle and $dx = vdt$, the heat balance relationship at $x$ from the beginning of the spiral channel could be expressed as follows:

$$\frac{h(T - T_0)}{
u}dSdx = -\rho C dVdT,$$

(3)

where $h = 0.0011P^3 - 0.112P^2 + 6.605P + 2924.57$ (i.e., the heat transfer coefficient between the melt and the mold [31]),
$T$ is the melt temperature at $x$, $T_0$ is the mold temperature, and $dS$ and $dV$ are the unit heat conduction area and unit melt volume at $x$, respectively. The relationship between $dS$ and $dV$ is $dV/dS = R/2$, where $R$ is the spiral channel radius, $\rho$ is the alloy melt density, and $C$ is the equivalent specific heat capacity for the melt and semi-solid melt. The latter could be expressed as follows:

\[ C = C_0 \text{ (for the melt)}, \]
\[ C = C_0 - \frac{df_s(T)}{dT} \Delta H \text{ (for the semi-solid melt)}, \]

where $C_0$ is the specific heat capacity, $\Delta H$ is the enthalpy change of the alloy melt, and $f_s$ is the solid fraction. The variation of $f_s$ with the temperature obtained through a DSC analysis could be expressed as follows [32]:

\[ f_s(T) = 94.63 \left[ \frac{0.00478}{1 + 10^{-0.397(T - 832.44)}} + \frac{0.99522}{1 + 10^{-0.0184(T - 1004.84)}} \right] - 93.61. \]

Integrating Eq. (3) with a constant filling speed, the relationship between the melt temperature and filling length could be calculated as follows:

\[ T = (T_c - T_0) \exp \left( -\frac{2hL}{v_{set}R\rho C_0} \right) + T_0 - \Delta f_s(T) \Delta H/C_0, \]

where $T_c$ is the pouring temperature, and $\Delta f_s$ is the solid fraction difference.

To understand the melt’s temperature variation along the spiral channel at a constant filling speed and determine whether it was in a liquid or semi-solid state, its temperature distribution and filling length were calculated and analyzed. When the melt’s temperature dropped to the eutectic temperature, its solid fraction increased rapidly, and it was reasonable to assume that the melt had to stop filling at this temperature point. The thermophysical properties of the A356 alloy are shown as in Table 3.

Figure 5 shows the relationship between the melt temperature along the spiral channel and the filling length at different pouring temperatures. When the alloy melt flowed into the spiral channel, its temperature quickly dropped to the liquidus with a short filling length, indicating that the pouring temperature had little influence on the filling length. Then, due to the release of enthalpy during the solidification process, the melt temperature decreased slowly; the filling length increased linearly and significantly with the melt temperature, and the solid fraction increased to improve the filling resistance. When the alloy melt reached the eutectic temperature, its rapid solidification led to a large filling resistance, preventing continued filling. Based on Fig. 5b, when the pouring temperature was lower than the alloy’s liquidus temperature, it had a greater influence on the filling length of the spiral channel. However, when the pouring temperature was higher than the alloy’s liquidus temperature, the filling length increased slowly as the pouring temperature increased. These phenomena indicated that the alloy melt in the spiral channel was primarily a semi-solid melt.

### 4.2 Apparent viscosity characteristics

It is generally believed that a semi-solid melt is a non-Newtonian fluid whose apparent viscosity is related to both the melt temperature and shear rate. A power law model has been formulated to describe the apparent viscosity model for a semi-solid A356 alloy melt when the melt temperature decreases to below the liquidus [34]:

\[ \eta(T, \gamma) = Ky^{n-1}, \]

\[ \gamma = \frac{6n + 2}{2n + 1} \frac{v}{R}. \]

Coefficients $n$ and $K$ have been obtained by Ma et al. as follows [35]:

\[ n = -0.00866(T - 273) + 5.225. \]
\[ K = 10^{4.344(T - 298.15)/1.899 + 3.594}. \]

Thus, Eq. (8) can be transformed as follows:

**Table 3** Thermophysical properties of the A356 alloy [33]

| Property and symbol | Value |
|---------------------|-------|
| Spiral channel radius $R$ (m) | 0.004 |
| Initial mold temperature $T_0$ (K) | 443 |
| Specific heat capacity $C_0$ (J·K$^{-1}$·kg$^{-1}$) | 963 |
| Enthalpy change $\Delta H$ (J·kg$^{-1}$) | 398000 |
| Density $\rho$ (kg·m$^{-3}$) | 2650 |
| Liquidus temperature $T_l$ (K) | 888 |
The solid fraction and morphology of primary α-Al directly affected the apparent viscosity of the semi-solid A356 alloy melt. Figure 6 shows that as the temperature decreased, the precipitation of primary α-Al increased, which reduced the alloy melt’s fluidity. In particular, when the melt temperature was reduced to the eutectic temperature, the solid phase fraction increased rapidly. Due to the difficulty of experimental measurement, it was assumed that the apparent viscosity at the eutectic temperature became so large that the alloy melt could no longer flow. In addition, it was found that increasing the filling speed was beneficial to reducing the melt’s apparent viscosity and improving its filling ability.

4.3 Pressure loss and filling length

According to Poiseuille’s law, the $P_{\text{loss}}$ with the filling length of the alloy melt $L$ could be calculated as follows:

$$P_{\text{loss}} = 8\eta v L / R^2.$$  \hspace{1cm} (13)

where $\eta$ is the melt viscosity, $v$ is the filling speed, and $R$ is the channel radius. As the melt viscosity and flow speed varied at different temperatures and locations, the $P_{\text{loss}}$ calculation was transformed as follows:

$$\int_0^{T_{\text{loss}}} dP = \int_0^L 8\eta v dx / R^2.$$  \hspace{1cm} (14)

When the melt temperature was greater than the liquidus, the melt could be considered a Newtonian fluid, and the viscosity was only related to its temperature. Therefore, combining Eqs. (7) and (14), $L_1$ and $P_1$ were calculated as follows:

$$L_1 = -\frac{v_{\text{set}} R \rho C_0}{2h} \ln \frac{T - T_0}{T_c - T_0}, \ T_l \leq T < T_c, \hspace{1cm} (15)$$

$$P_1 = \frac{4\rho C_0 v_{\text{set}}^2}{hR} \int_T^{T_c} \left( \frac{T - T_0}{T_c - T_0} \right) \eta(T) dT, \ T_l \leq T < T_c. \hspace{1cm} (16)$$

Combining Eqs. (3), (5), and (14), $L_2$ and $P_2$ could be expressed as follows:

$$L_2 = -\frac{v_{\text{set}} R \rho C_0}{2h} \ln \frac{T_c - T_0 + \Delta H(T) / C_0}{T - T_0}, \ T_w \leq T < T_f, \hspace{1cm} (17)$$

$$P_2 = \frac{4\rho C_0 v_{\text{set}}^2}{hR} \int_T^{T_f} \left( \frac{T - T_0}{T_c - T_0} \right) \eta(T) v_{\text{set}} \left( C_0 - \frac{dH}{dT} \right) dT, \ T_w \leq T < T_f. \hspace{1cm} (18)$$

where $\gamma$ is the shear rate and $T_w$ is the temperature of the filling fluid’s “head” when the applied squeeze pressure reached the maximum $P_{\text{set}}$, i.e., $P_a = P_{\text{set}} = P_1 + P_2$. Moreover, $T_w \geq T_c$. $T_e$ is the eutectic temperature of A356 alloy. If $T_w = T_e$, $P_3 = 0$ and the filling behavior stopped.

When the squeeze pressure increased to the maximum $P_{\text{set}}$ and $T_w > T_e$, it remained constant. As the $L$ increased and the melt temperature decreased continuously, the filling speed decreased. Since the $P_{\text{loss}}$ was larger than the $P_{\text{set}}$, the filling speed was calculated as follows:
Since \( (P_{\text{loss}} - P_{\text{set}}) / \rho L \) was much greater than the \( v_{\text{set}} \), the filling time at this stage was extremely short; thus, \( L_3 \approx 0 \), and \( P_3 \approx 0 \).

The variation of \( P_{\text{loss}} \) with the decreasing melt temperature and along the \( L \) at different filling speeds was calculated by Eqs. (15)–(19) (Fig. 7). As the melt temperature decreased, the \( P_{\text{loss}} \) increased rapidly. When the melt temperature dropped to 860 K, an actual squeeze pressure of more than 100 MPa was required to drive the filling, indicating that the filling stopped before the melt temperature dropped to the eutectic temperature. The greater the filling speed, the greater the \( P_{\text{loss}} \). Thus, the alloy melt with a higher filling speed stopped filling at a higher temperature because it could be filled for a longer distance, which led to a larger \( P_{\text{loss}} \).

Similarly, the \( P_{\text{loss}} \) variation with the decreasing melt temperature and along the \( L \) at different channel radii was calculated (Fig. 8); the influence of these factors on the \( P_{\text{loss}} \) was the same as that shown in Fig. 7. As the melt temperature decreased and the \( L \) increased, the \( P_{\text{loss}} \) increased rapidly. It was found that decreasing the channel radius had little effect on the relationship between the \( P_{\text{loss}} \) and melt temperature but significantly reduced the filling ability. When the channel radius was less than 1 mm, it was difficult to significantly improve the filling ability by increasing the squeeze pressure. This quantitative influence of the channel radius on the filling ability provided a method to calculate the critical dimensions required for squeeze casting thin-walled and thin-rod parts (Fig. 8b).

4.4 Verification

Figure 9 compares the filling length results of the theoretical calculations and experimental measurements of the spiral squeeze casting. The experimental results were basically in agreement with the theoretical calculation results but were all lower since the partial \( P_{\text{loss}} \) of the spiral was ignored in the calculations. The greater the squeeze pressure, the more accurate the predicted filling length. However, based on the experimental results in Fig. 2 and theoretical results in Fig. 7, increasing the filling speed could significantly improve the filling ability, but increasing the squeeze pressure could not. The latter method was mainly used to strengthen the mechanical properties through refining the microstructure in the squeeze casting [36–38].
The filling behavior of the squeeze casting mainly occurred during the rheological filling process, prediction models of the pressure loss and filling length were established. The prediction results were in agreement with the experimental measurements. Increasing the filling speed significantly improved the filling ability, but the pouring temperature and squeeze pressure had little influence on the filling length. The filling behavior of the squeeze casting mainly occurred in the pressure increase stage, and the filling ability in the pressure maintenance stage was very low. Therefore, the dimensional integrity of thin-walled and thin-rod parts with complex structures in the squeeze casting was primarily determined by the filling speed.

**Author contribution** XA: writes original manuscript, revises the paper, data processing, and verifies the results; YW: experiment, data collection.

**Funding** This work was supported by the National Natural Science Foundation of China (Nos. 52105504 and 51935003), Beijing Natural Science Foundation (No. 3204054), the National Key Research and Development Program of China (No. 2018YFB1105304), and the Youth Academic Launch Program of Beijing Institute of Technology.

**Data availability** The data in this paper are all obtained from experiments. All data generated during this study are included in this manuscript.

**Declarations**

**Ethics approval** My research does not involve ethical issues.

**Consent to participate** All authors have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript. The authors guarantee that the contribution to the work has not been previously published elsewhere.

**Consent for publication** All authors agreed to publish this paper.

**Competing interests** The authors declare no competing interests.

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