Effect of Pouring Pressure on Typical Structure of ZL114A Lube Oil Pump Casting

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Abstract. In this paper, a complex aluminum alloy lube oil pump casting with many interconnected oil pipes was produced by sand mould-type, low-pressure casting (LPC). The sand mould was designed as a monolithic structure and produced by selective laser sintering (SLS) technology. The impact of pouring pressure on casting defects was studied by the casting simulation software PROCAST. The optimal lifting pressure velocity was 0.65KPa/s and the filling pressure velocity was between 2.4KPa/s and 4.8KPa/s. Adopting optimal pouring pressure conditions, the casting with defect-free and high dimensional accuracy was successfully produced.

1. Introduction

Low-pressure casting (LPC) is used as the dominant technology for producing Al alloy casting, which has the advantages of stable filling and enhanced ability of feeding for realizing improved mechanical properties and casting quality in Al alloy [1-3]. This is a low-cost process, with the capability of near-net-shape component production. The Al alloy castings produced by LPC have been widely used in various industries, such as the automotive industry and aviation. The pressure parameter for low pressure casting (LPC) process is important for controlling the quality of castings [4]. Using a rational pressure parameter not only avoids turbulence of molten metal in the filling process, but also refines microstructure and improves the component compactness of casting in the solidification process[5]. Wang Y et al. used the Taguchi method to optimize the process parameters of LPC and investigate the effect of packing pressure and filling time on the shrinkage porosity ratios of ZL205A alloy casting. The results showed that the packing pressure had the most significant effect on shrinkage, and that filling time had less effect [6]. Liu S. G. et al. studied the effect of pressure speed of LPC on the molding filling and entrainment of oxide film of A356 alloy. The results showed that the reasons for oxide film entrainment were the falling velocity and relatively rotating vortex [7]. Jiang W. M. et al. showed that the influence of process parameters on filling ability of A356 alloy was in the following order, from strong to weak: pressure speed, pouring temperature and pressure value [8]. Fu P. H. et al. studied the influence of the process parameters on mechanical properties, microstructure and density of LPDC AM50 alloy casting; the optimized parameters were as follows: filling time 15-22s, casting temperature 705-710°C, pressure holding time 8-12s and holding pressure 0.08MPa[9]. A study of the
effect of pouring pressure on the filling and solidification process, therefore, is necessary to determine how to control the quality of the casting.

The Al alloy castings are usually produced by a permanent mould casting process. However, the mould for permanent mould casting requires long production cycles and high manufacturing cost, which cannot meet the marketing requirement of varieties, small batch production and short supply cycle. To solve these problems, the sand mold/core is produced by selective laser sintering (SLS). This method offers great benefits by shortening the production cycle of mould for sand casting [10]; in addition, it modifies and verifies the mould with the aid of a CAD model at any stage of the process. These technology improvements help perfect casting design and provide powerful technical support for the rapid development of casting products. Many studies report on making the coated sand mold (core) by SLS. However, they mainly focus on process parameters for strength and surface quality of a single mold (core); there are few reports on the production of casting by the integral sand mold manufactured by SLS [11-13]. The casting manufactured by combined mould cavity and core assembly usually has CT9 tolerance. Integral sand mold manufactured by SLS need not assemble sand mold and sand core; it can improve the dimensional tolerance of the casting. In this paper, we propose a new production process of the casting with a complex structure and strict precision requirement. In this process, the integral sand mold for the casting is manufactured by SLS, and we focus on the effects of casting pressure on casting defects and the optimization of pouring pressure, which sets up a basis for successful manufacture of this casting and other similar types of casting.

2. Material and Manufacturing Process

2.1 Model Building and Casting Material

LPC was adopted to produce the casting; its 3D model, with a size of 355mm×218.5mm×161mm, is shown in Figure 1(a); many pipelines intersect with each other with a wide variation in shape. The gating and feeding systems are shown in Figure 1(b). The gating complex consisted of a bottom gating system, supplementary gating system and basin. A supplementary gating system (red) was adopted to avoid turbulence which appeared from the rapid rise of melt under pressure; in addition, it also provided effective feeding of melt during the solidification process. With this gating system, we avoided the jetting of molten metal and eliminated air entrapment during the filling process, which facilitated control of gas defects and slag inclusions. As the chill cannot be set in integral sand mold manufactured by SLS, a large riser (pink) was designed instead to feed the top of the casting. Five air vents (green) were designed in a converging position with respect to the molten metal to eliminate the defects of misrun.

Figure 1(c) and (d) show the surface grid and the volume mesh divided by Hypermesh and MeshCAST software respectively. According to the software calculation result, the total number of finite elements of volume mesh of the whole casting containing the gating and feeding systems was 521890 and the number of nodes was 107442.
Figure 1. 3D model and finite element mesh. (a) the view of production (b) the view of casting (c) surface grid (d) volume mesh

ZL114A was used as casting material in accordance with the technical requirements of the casting and its chemical composition is as follows: Mg(0.58%), Si(6.92%), Ti(0.12%), Fe(0.26%), Mn(0.078%) and Cu(0.014%).

2.2 The Parameter Setting
The parameter settings were as follows in the casting process simulation. The casting material was ZL114A, and sand mould material was Baozhu sand coated with resin. The interfacial heat transfer coefficient was 500W/m²·K between Al melt and the sand mould. The sand mould was preheated to 50°C. The pouring temperature of 720°C was used and good mold-filling ability was obtained at this temperature.

The relation between filling velocity and pressure value is expressed by the Bernoulli equation, as follows [14]:

\[
H + \frac{P_f}{\gamma_m} + \frac{v_f^2}{2g} + h_f = \frac{P_l}{\gamma_m} + \frac{v_l^2}{2g}
\]  

(1)
where \( H \) is the height of liquid metal rising to the top of lift tube, \( h_f \) resistance loss of pressure, 
\( \gamma_m = \rho g \), \( P_V \) cavity pressure, \( P_f \) filling pressure, \( v_r \) filling velocity of the liquid metal, and \( v_d \) the descending velocity of the liquid metal in the crucible.

The volume of the liquid metal was constant during the casting process and so the flow rates of liquid metal in crucible (\( Q_2 \)) and lift tube (\( Q_1 \)) are equal. \( Q_1 = \pi r^2 v_r \), \( Q_2 = \pi (R^2 - r^2) v_d \), where \( R \) and \( r \) are the radii of the crucible and riser tube, respectively.

Supposing \( \frac{r^2}{R^2 - r^2} = N \), \( v_d = N v_r \), \( v = v_d + v_r \),

\[
H = \int_0^t v dt = \int_0^t (1 + N) v_r dt
\]  
(3)

Based on formulas 2 and 3, formula 1 can be expressed as:

\[
(1 + N) \int_0^t v_r dt + \frac{P_V}{\gamma_m} + \frac{v_r^2}{2g} = \frac{P_f}{\gamma_m} + \frac{(v_r N)^2}{2g}
\]  
(4)

Through the derivation to formula 4 and supposing \( \frac{dP_r}{dt} = 0 \), \( \frac{dv_r}{dt} = 0 \) formula 4 is further expressed in the following:

\[
v_r = \frac{1}{(1 + N)\gamma_m} \frac{dP_f}{dt} - \frac{(R^2 - r^2) \frac{dP_f}{dt}}{R^2 \gamma_m}
\]  
(5)

It can be seen that the filling velocity is regulated through pressure velocity \( \frac{dP_f}{dt} \) from formula 5.

The allowed max filling velocity was 150mm/s for the complex casting according to the casting manual. From using this value in formula 5, the max filling pressure velocity was set to 7.2KPa/s. The lifting pressure velocity was set to 1KPa/s to ensure the smooth rising in the basin according to the casting manual. The filling pressure velocity of 7.2KPa/s and lifting pressure velocity of 1KPa/s needed to be optimized by computer simulation (see section below).

2.3 The Fabrication of the Integral Sand Mould

The integral sand mould was fabricated by SLS, and Baozhu resin coated sand was used as raw material. The 3D model of integral sand mould and the bottom support of integral sand mould are shown in Figure. 2(a) and Figure. 2(b) respectively. The bottom support containing the supporting plate and supporting pillars was designed to prevent the deformation of integral sand mould during sintering and post cure. The thickness of the supporting plate and the height of supporting pillar were both 20mm, and the diameter of supporting pillars and the adjacent spacing between them were 30mm. The sand exclusion holes (A, B, C, D, E, F and G) were set in the non-critical parts of the casting to ensure its dimensional accuracy. Figure. 2(c) shows the morphology of spherical Baozhu sand with particle size between 35\( \mu m \) and 140\( \mu m \). The fabricating process of integral sand mould by SLS included such sections as sintering process, loose sand cleaning, post cure and glass beads cleaning. SLS process parameters are as follows: layer thickness 0.2mm, laser power 21.5W, scan speed 3000mm/s, main body sintering temperature 58°C, support sintering temperature 70°C, post cure temperature 190°C, post cure time 32h. The sintering temperature of the support was higher than the temperature of other parts. The sintering temperature of 70°C provided enough strength support to prevent the deformation of the sand mould. The main sand mold and the insert blocks (Figure. 2(d) and Figure. 2(e)) matched up to form an integral sand mold.
Figure 2. The fabrication of integral sand mould. (a) 3D model of integral sand mould (b) the support (c) morphology of Baozhu sand (d) main body mould (e) insert blocks
3. Results and Discussion

3.1 Filling Process Simulation and Analysis

According to the formula $P = \rho gh$, a lifting pressure of 5.3KPa and a filling pressure of 17KPa were used. The other process parameters were determined as follows: filling pressure velocity 7.2KPa/s, lifting pressure velocity 1KPa/s, skull pressure 22KPa, and crystallization pressure 27KPa. Using the above values, pressure curve 1 is plotted, as shown in Figure. 3(a). The simulation results for the 30% filling process are shown in Figure. 3(b) under pressure curve 1. From Figure. 3(b) we see that the molten metal rises fast and enters the cavity before the basin fills to capacity, which results in fluid flow disorder with no-horizontal rising of the liquid surface. The simulation result for the 50% filling process under pressure curve 1 (Figure. 3c) shows that the fluid confluence appears in parts of the pipeline of the casting, which will result in the gas and oxide filming involving and defects of the gas holes and bifilm. Otherwise, from Figure. 3(d) we note that the air vents are covered with the molten metal prematurely, resulting in blockages of the exhaust passage so that gas will not discharge effectively, thus causing a misrun. It is obvious that lifting pressure and filling pressure rise fast. The molten metal cannot fill smoothly under pressure curve 1, so that there is a tendency to form defects of gas holes, bifilm and a misrun. So pressure curve 1 needs to be optimized to improve the filling process of the casting.
As shown in Figure 4(a), lifting pressure and lifting pressure velocity are adjusted to 3.6KPa and 0.65KPa/s in pressure curve 2 to ensure stability of the liquid surface during the lifting process; other parameters remain unchanged. Figure 4(b) shows that the lifting process clearly improves during the process of 30% filling under pressure curve 2, compared with pressure curve 1, and the basin almost fills with molten metal smoothly before it enters the casting cavity. From Figure 4(c) the liquid level of the metal rises fast and turbulence occurs during the process of 50% filling, which results in the gas and oxide filming involving and forming the casting defects of gas holes and bifilm. As shown in Figure 4(d), the liquid level is still unsteady. Based on analysis of the above, a desirable lifting process does not necessarily result in smooth filling. We suggest that high pressure velocity is the main reason for turbulence in the filling process. To improve the stability of filling, therefore, the filling pressure velocity needs to be adjusted.

The filling pressure velocity decreases from 7.2KPa/s to 4.8KPa/s (see Figure 5(a)) which is calculated from formula 5 using a filling velocity of 100mm/s. From the results of the 30% and 50% filling process simulation (Figure 5(b) and (c)), we observe that the filling process markedly improves. The liquid level of the 50% filling process is not very smooth but does not result in the liquid converging in the cavity during the filling process. As shown in Figure 5(d), the liquid level becomes

![Figure 4](image-url)
smooth in the 70% filling process. The tendency of defects forming is reduced under pressure curve 3. Although the filling process appears satisfactory, the whole filling process is not entirely smooth. We need to continue lowering the filling pressure velocity.

![Pressure curves](image)

**Figure 5.** The filling simulation results under pressure 3. (a) Pressure curve 1, 2 and 3 (b) 30% filling process (c) 50% filling process (d) 70% filling process

Combined with the data of pressure curves 1, 2 and 3, the filling pressure velocity decreases from 4.8KPa/s to 2.4KPa/s (see Figure. 6 (a)). The filling pressure velocity of 2.4KPa/s is calculated by using a minimum filling velocity of 50mm/s in formula 5. From Figure. 6(b) and (c) we observe that the liquid level of the metal rises smoothly and fluid flow disorder and turbulence do not appear during the process of filling, which favours the non-occurrence of casting defects of gas holes, bifilm and misrun. A comparison of simulation results, obtained under pressure curves 1, 2, 3 and 4 show that the filling process is most stable under pressure curve 4 and casting without defects is likely to be obtained.
3.2 Solidification Process Simulation and Analysis

The simulations of solidification process under pressure curve 4 (Figure. 7) shows that the process of solidification begins on the air vent, and then the casting and, lastly, the joint of the casting and the risers (top riser and runners of the supplementary gating system). Figure. 7(a), (b), (c) and (d) show the solidification stage at different times and each riser responsible for an area providing molten metal. We observe that each riser provides molten metal and the feeding channels still exist before the lube oil pump casting solidifies completely. The red frame shows the joints which are the feeding channels. Progressive solidification from top to down occurs and shrinkage and porosity are eliminated, which is due to crucial feeding of the top riser and the runners of the supplementary gating system during the solidification process.
Figure 7. Solidification simulation and casting defects simulation results. (a) t=30s (b) t=120s (c) t=180s (d) t=260s (e) shrinkage simulation result (f) void simulation result

Figure 7(e) shows shrinkage porosity defects (purple) of the casting simulation results which are predicted by the Niyama criterion and a boundary value of void fraction of 0.01%. From Figure 7(e) a few small shrinkage cavities exist in the top riser of the casting. Figure 7(f) shows the defect of void (blue) in a red wire frame which exists in the air vent. The shrinkage porosity and simulation results of void defects indicate that the casting is free of defects, and can be manufactured under pressure curve 4.
3.3 Trial Production and Casting Inner Detection
The casting with T6 heat-treatment must have excellent comprehensive mechanical properties, high dimensional accuracy and good sealing property. The comprehensive mechanical performance and dimensional precision requirements are as follows: dimensional tolerance is CT7, tensile strength is higher than 300MPa, elongation is higher than 4%, Brinell hardness is higher than 80HBS.

3.3.1 Casting quality verifying and microstructure observation. As shown in Figure. 8(a), the casting is of good surface quality without cold shut and crack casting defects. The dimension of the casting is measured by cutting it and its dimensional tolerance is CT7 which conforms to blueprint tolerance. The surface roughness of no-machining place of the casting is 12.5, which conforms to the technical requirement of the casting.

The images of X-ray detection are shown in Figure. 8(b). The X-ray detection is a good method to detect inner quality of the casting. From Figure. 8(b) we see that there is no shrinkage, blowhole and inclusion in the casting and its structure is complete. It is obvious that the lube oil pump casting with defects-free can be manufactured by optimizing pressure parameters to ensure the sequence solidification and effective feeding of melt according to HB963, HB5395, HB5396 and HB5397 aviation standards of the People's Republic of China.

The microstructure of ZL114A alloy casting after T6 heat treatment (Figure. 8(c) and (d)) shows that the grains are fine and relatively homogenous, which significantly enhances mechanical properties of the casting. Figure.8 (d) shows that the eutectic Si exists in long rod or spheroid on grain boundaries and no dendrites are found.
3.3.2 Leakage Examination. The internal tightness of the lube oil pump casting is an essential functionality that must be tested and verified before use. The leakage examination condition requires that the casting is full of the kerosene under the 0.4MPa for 5 minutes. The result shows that there is no exudation of the kerosene according to HB963-2005 aviation standards of the People's Republic of China. And the lube oil pump casting can meet the operating requirement.

**Figure 8.** Production detection and metallographic images. (a) trial production (b) X-ray detection (c) metallographic
3.3.3 The Mechanical Property Testing. The 1000kgf pressure value and the 10mm steel head were adopted in the Brinell hardness test. The loading time was 30s. The Brinell hardness of the casting is $105\pm 2\text{HBS}$ which is higher than that of the technical requirement. Six tensile test bars were machined and the test was controlled by a computer with a constant cross-head speed of 1mm/min at room temperature. The tensile strength is $330.71\pm 2.43\text{MPa}$ which is higher than 300MPa. The elongation is $6.5\pm 0.38\%$ which is higher than 4%. The results show that the mechanical properties meet People's Republic of China HB962-2001 aviation standard.

4. Conclusion
In the paper, using integral sand mould, the lube oil pump casting was successfully produced by LPC technology and the influence of pressure parameters on filling and solidification process was investigated. We conclude the following from this study:

(a) The integral sand mould with high dimensional accuracy and no deformation was fabricated by SLS method. The adding of support and using a higher support sintering temperature (70°C) prevent its deformation.

(b) The lifting pressure and filling pressure velocity were optimized: the optimal lifting pressure velocity was $0.65\text{KPa/s}$ and the filling pressure velocity was between $2.4\text{KPa/s}$ and $4.8\text{KPa/s}$. The optimal pressure parameters ensured the smooth filling and the progressive solidification of the casting and eliminated shrinkage and porosity.

(c) Mechanical performance testing results showed that the strength and hardness values meet the technical requirements of the lube oil pump casting.

(d) The lube oil pump castings had CT7 tolerance which is smaller than that of the casting manufactured by sand casting mould.

(e) The X-ray detection results showed that no shrinkage, blowhole and inclusion existed in the casting and its quality satisfied HB963, HB5395, HB5396 and HB5397 aviation standards of the People's Republic of China.

(f) No leakage inside the casting occurred in the test, which was due to no defects in the casting, such as coarse grain, shrinkage cavity, and shrinkage porosity.

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6. Reference
[1] Yong B.C, Kazuhiro M, Gen S, Kazushi A; Analysis of manufacturing processes for metal fiber reinforced aluminum alloy composite fabricated by low pressure casting. Materials transactions, 2006, 47(4): 1227-1231.
[2] Zhang L.Q, Wang R.J; An intelligent system for low pressure die cast process parameters optimization. Int J Adv Manuf Technol, 2013, 65: 517-524.
[3] Yan QS, Yu H, Xu ZF, Cai CH et al; Effects of Pouring Process on Mechanical Properties of Permanent Mold Casting ZL114 Alloy. Foundry Technology, 2009, 30(2): 265-268.
[4] Yan Q.S, Wang F, Lu G, Xiong B.W, Xu S, Effect of solidification pressure on Si distribution in vacuum counter pressure casting ZL114A alloy. Special Casting & Nonferrous Alloys. 2013, 4: 989-991.
[5] Jiang W.M, Fan Z.T, Liu D.J, Wu H.B; Influence of gas flow rate on filling ability and internal quality of A356 aluminum alloy castings fabricated using the expendable pattern shell casting with vacuum and low pressure. Int J Adv Manuf Technol, 2013, 67:2459-2469.
[6] Wang Y, Wu S.P, Niu L.J, Xue X, Zhang J.B, Xiao W.F; Optimization of low pressure die casting process parameters for reduction of shrinkage porosity inZL205A alloy casting using Taguchi method. P I Mech Eng B-J Eng, 2014, 228(11): 1508-1514
[7] Liu S.H, Cao F.Y, Zhao X.Y, Sun J.F; Characteristics of mold filling and entrainment of oxide film in low pressure casting of A356 alloy. Materials Science & Engineering A. 2015, 626: 159-164.

[8] Jiang W.M, Fan Z.T, Liu D.J, Lian D.F, Zhao Z. Dong X.P; Influence of process parameters on filling ability of A356 aluminium alloy in expendable pattern shell casting with vacuum and low pressure. International Journal of Cast Metals Research 2012, 25(1): 47-52

[9] Fu PH, Luo A.A, Jiang H.Y, Peng L.M; Low-pressure die casting of magnesium alloy AM50: response to process parameters. J Mater Process Technol. 2008, 205:224–234

[10] Joy A.H; Determination of Interfacial Heat-Transfer Boundary Conditions in an Aluminum Low-Pressure Permanent Mold Test Casting. Metallurgical and materials transaction B. 2004, 35B: 299-310

[11] Tang Y, Fuh J.Y.H, Loh H.T, Wong Y.S, Lu L; Direct laser sintering of a silica sand. Materials and Design. 2003, 24: 623-629.

[12] Wang X.H, Fuh J.Y. H, Wong Y.S, Tang Y.H; Laser Sintering of Silica Sand Mechanism and Application to Sand Casting Mould. Int J Adv Manuf Technol. 2003, 21: 1015-1020

[13] Xu Z.F, Liang P, Yang W, Li S.S, Cai C.C; Effects of laser energy density on forming accuracy and tensile strength of selective laser sintering resin coated sands. China Foundry. 2014, 11(3): 151-156

[14] Jiang W.M, Fan Z.T, Liu D.J, Wu H.B; Influence of gas flow rate on filling ability and internal quality of A356 aluminum alloy castings fabricated using the expendable pattern shell casting with vacuum and low pressure. Int J Adv Manuf Technol. 2013, 67: 2459-2468