Research Article

Simulation Study on the Investment Casting Process of a Low-Cost Titanium Alloy Gearbox based on ProCAST

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A model of investment casting of a titanium alloy gearbox based on the ProCAST software was established in this work, and the simulated result was used to optimize the casting process. The flow and temperature field of casting were simulated based on an actual pouring process. Casting defects and the solidification process were analyzed. The results show that the defects can be predicted by the simulation result exactly, and the simulated temperature field is in accordance with the actual process. Shrinkage and porosity are observably alleviated by remodelling the casting mould. The casting temperature field and solidification simulation results show that the casting defects arise from hot spots and heat accumulation. The temperature-time curve of different representative location nodes of casting further confirms the defect simulation results. In addition, the use of low-cost alloy elements reduces raw material costs. Compared with TC4 alloy, the mechanical properties of the casting remain unchanged.

1. Introduction

Titanium alloys are ideal materials for aerospace and military applications due to their advantages of low density, high-temperature resistance, high specific strength, and corrosion resistance [1–6]. The successes of applying titanium alloys have largely been the result of pragmatic engineering as opposed to bottom-up scientific discovery and application [7]. Thin-walled, complicated, integrated, and precision casting technology has become the main tendency of manufacturing titanium alloy components [8, 9]. Compared to other manufacturing techniques, investment casting requires low costs and provides high efficiency for industrial production [10–12]. Besides, it is also a possible manufacturing route to producing near net shape titanium components [10, 13].

In order to achieve weight reduction requirements for complex structure and thin-walled military vehicle components and equipment, titanium alloy investment castings are taken into account. However, high cost of Ti alloys is a handicap for the application. Low-cost titanium alloy is one of the key directions of titanium alloy development and application, which has attracted more and more attention all over the world [14–18]. The success of the development of low-cost titanium alloys seems to be related to a good choice of alloying elements. Elements such as Al, Fe, Cr, and Mn in titanium alloys are used to replace expensive elements like V, Zr, Nb, and Mo [14]. Major low-cost titanium alloys developed by various countries are shown in Table 1.

TIMETAL LCB was designed to be used for automotive spring applications to reduce manufacturing cost by TIMET Corporation [15]. Low-cost TFC alloys, developed by Ikeda et al., have an attractive balance of tensile strength and ductility applied in the medical field [16, 17]. Low-cost Ti8LC and Ti12LC titanium alloys were designed and developed by using cheap Fe-Mo master alloys. Tensile properties at room temperature of both Ti8LC and Ti12LC are better than those of TC4, and Ti12LC alloy has even lower hot processing temperature [18].
As product realization cycles become shorter, it becomes increasingly important to use modelling and simulation to reduce time and cost of qualifying materials for a given application [1, 19]. For this reason, computer simulations are performed to predict the behavior of investment casting processes. Simulation technology is widely used to simulate the temperature field, solidification, stress distribution, defects formation, and distribution characteristics during the casting process. To reduce the defects, a model of centrifugal casting, a wet-type cylinder liner based on the ProCAST software was constructed by Lu et al. [20], and the simulated result was used to optimize the casting process. Tao et al. [21] simulated the investment casting process of a titanium alloy thin-walled casing under different process conditions using self-developed software. The results show that the centrifugal casting process with respect to gravity casting had no obvious improvements in concentrated shrinkage defects, and the gravity casting process can be more reasonable from the engineering point of view. Most of the literature [4, 6, 8, 11, 20–25] focused on the influence of processing and simulation technology. The formation mechanism of casting defects was rarely discussed.

The aim of the present work is to cast a thin-walled and structurally complex titanium alloy gearbox with low-cost titanium alloys in a ceramic mould using an investment casting technique. In this paper, low-cost alloy elements such as aluminum, chromium, and iron are added into the cast billet to replace vanadium and other expensive elements. Molybdenum is added to the ingot with relatively cheap ferromolybdenum alloy. Compared with Ti-6Al-4V titanium alloys, the cost of raw materials is reduced by 20%, while the mechanical properties remain unchanged. Before actual experiments, three-dimensional (3D) models of the casting were established by Unigraphics software. Then, the simulation analysis of filling and solidification processes was conducted using ProCAST software. The factors affecting the temperature field and the solidification process were investigated by combining the results of the defect analysis of the gearbox. Based on these analyses, the processes of investment casting were optimized, and the defects of the cast were reduced. It is expected that the results will help save experimental expenses and provide guidance for industrial production.

### 2. Materials and Methods

In this study, maximum dimension of length, width, and height of the gearbox are 360 mm, 270 mm, and 312 mm, respectively. Refractory zirconia is used as the mould material, which can be found in the database of ProCAST2016 software. According to the chemical composition (Table 2) of the gearbox, the material performances, such as the enthalpy curve, the fraction of the solid curve versus temperature, density, viscosity, and thermal conductivity were computed automatically by the software. The initial temperature of the ceramic mould was set to 200°C in the software. The liquidus temperature and solidus temperature utilized in the simulation were calculated to be 1680°C and 1585°C, respectively.

The titanium alloy for casting the gearbox was melted in the vacuum self-consumption skull furnace. Before skull melting, sponge titanium and intermediate alloys were melted two times in the vacuum consumable electrode arc furnace.

The investment casting process was carried out by practical operation and process simulation. The mould core prepared by using a 3D printer was repeatedly dipped into the refractory zirconia slurry to form a layered and seamless mould. The ceramic cavity was sintered in a baking furnace. Before pouring, the cavity was preheated to 300°C in an electric heating furnace. After transfer, fixation, and other operations, the mould shell temperature is about 200°C at the time of pouring. Finally, the molten metal was poured and started to solidify. The HIP temperature is 920°C, pressure is 120 MPa, and time is 2 hours.

Casting samples were machined to the required size and annealed at 750°C for an hour and then cooled in air. The
tensile test and the impact test were performed by using a
tensile tester. The samples before and after annealing were all
subjected to tensile and impact tests. The properties of the
casting sample were compared with those of Ti-6Al-4V
alloys.

3. Description of the Models

The liquid metal is supposed to be an incompressible
Newton fluid. The equations employed for the filling process
are as follows.

The continuity of the melt is defined as follows:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0,
\]

(1)

where \(u\), \(v\) and \(w\) are the velocity vectors in \(x\), \(y\), and \(z\)
direction of the coordinate system, respectively.

The motion of fluid momentum conservation can be calculated by the Navier–Stokes equation:

\[
\rho \left( \frac{\partial v}{\partial t} + (v \cdot \nabla)v \right) = F - \nabla p + \mu \cdot \Delta v,
\]

(2)

where \(\rho\) is fluid density, \(v\) is the velocity vector, \(\Delta v\) is the
Laplace operator of \(v\), \((v \cdot \nabla)\) is a scalar product of the
velocity vector and the Laplace operator, \(t\) is time, \(p\) is
pressure, and \(\nabla p\) is the gradient of \(p\). \(\nabla p\), \((v \cdot \nabla)\), and \(\Delta v\) are
calculated by the following equations:

\[
\nabla p = \begin{bmatrix} \frac{\partial p}{\partial x} & \frac{\partial p}{\partial y} & \frac{\partial p}{\partial z} \end{bmatrix}^T,
\]

(3)

\[
v \cdot \nabla = u \cdot \frac{\partial}{\partial x} + v \cdot \frac{\partial}{\partial y} + w \cdot \frac{\partial}{\partial z},
\]

(4)

\[
\Delta v = \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}.
\]

(5)

The energy conservation equation can be expressed as follows:

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \frac{\lambda}{\rho \cdot C_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q}{\rho \cdot C_p},
\]

(6)

where \(T\) is temperature, \(\lambda\) is the fluid thermal conductivity,
\(C_p\) is the specific heat capacity, and \(Q\) is the internal power
source.

The volume function equation can be expressed as follows:
where \( F \) is a volume fraction of the fluid.

The boundary heat transfer equation can be expressed as follows:

\[
- K \cdot \Delta T_{\text{m}} = h \cdot f(t) \cdot g(T) \cdot (T - T_{a}),
\]

where \( h \) is the convective exchange coefficient, \( T_{a} \) is the boundary temperature, and \( G(T) \) is the temperature function.

Two models were employed to simulate the investment casting process. As shown in Figure 1, the first model (Model 1) was prepared in a traditional way. Two risers and one sprue that were used for overflow and feeding, respectively, were located at the top of the gearbox. The dimension of the risers was 50 mm diameter and 100 mm length. According to the meshing rule of ProCAST, the 3D model was divided into 427523 elements for the casting and 186174 elements for the mould.

The second model (Model 2) was established based on the first model. As shown in Figure 2, the location of the sprue and the number of risers were all changed. The cylindrical sprue and one of the risers were put directly above the square hole on the side of the gearbox. A nearly ladder-shaped riser was set above the round hole on the other side. Two flat fan-shaped risers were located at the bottom of the gearbox. This 3D model was divided into 709767 elements for the casting and 191070 elements for the mould.

The actual moulds of the gearbox shown in Figure 3 were in accordance with the 3D models.

4. Boundary and Initial Conditions

An interface heat transfer coefficient between the casting and the mould was set at 500 W·m⁻²·K⁻¹. According to the actual cooling process, the mould was cooled in the air, and the surrounding temperature was approximately 20°C.
An initial temperature of 1700°C was applied to the casting, representing the pouring temperature in investment casting of the gearbox. The sectional area of the sprue was about 2600 mm². An average mass flow rate of 2.5 kg/s calculated by the following equation was applied to the fluid flow part.

\[
\text{Mass flow rate} = \frac{\text{Volume} \times \text{Density}}{\text{Fill time}},
\]

where the fill time was 10 s in accord with the actual pouring time, and the volume and density were calculated by the software.

5. Results and Discussion

5.1. Comparison and Analysis of Casting Defects. The simulation results of the total shrinkage porosity of Model 1 are shown in Figure 4. Macroscopic defects were mainly located around the square hole and round hole on the side as well as at the bottom of the casting. After the pouring process, the gearbox was then treated by HIP technology and then ground as shown in Figure 5. There were two obvious pits at the top of the square hole, as shown by the highlighted red circle. The position of the defects was consistent with the simulation result shown in Figure 4. Simultaneously, the position of the green oval in Figure 4 was in excellent agreement with that of Figure 5. It indicated that the defects in the round hole on the side of the gearbox were also predicted by the simulation result successfully.

Model 2 was an optimization model based on Model 1. The simulation results of the total shrinkage porosity of Model 2 are shown in Figure 6. Compared with Model 1, the total shrinkage porosity of Model 2 decreased significantly. The defects on the edge of the round hole transferred onto the ladder-shaped riser, and the defects at the top of the square hole disappeared. Concurrently, shrinkages at the bottom of the casting were reduced significantly due to the contribution of the flat fan-shaped risers. The gearbox (Model 2) treated by HIP and then ground is shown in Figure 7. The previous visible pits disappeared. Consequently, the defects of Model 2 after the modification were greatly reduced compared with those of Model 1, and the actual pouring results were in good agreement with the simulation results.

5.2. Casting Temperature Field Simulation Results. The gearbox was poured by gravity flow. It took 10 seconds to fully fill the whole casting. Figure 8 shows the simulation results of the temperature field at 1 s. The metal liquid passed the sprue and then was redistributed to each gap runner into the mould cavity. The fluid flow of Model 1 was obstructed by the mould and split into several branches, and the shape of which seemed like an inverted triangle as displayed in...
Figure 8(a). Compared with Model 1, the liquid metal flow of Model 2 is smoother. As shown in Figure 8(b), the flow shape appeared like an isosceles triangle. Accordingly, the instantaneous heat was mainly distributed at the upper part of Model 1 and at the lower part of Model 2. Due to gravity filling, the lower part of the casting solidified first, and then, the amount of heat was less than that of the upper part. Thus, the instantaneous heat accumulation in the upper solidification part of Model 1 led to hot spots and the increase in porosity of the casting.

The simulated temperature field at 55 s is displayed in Figure 9. It can be seen that the temperature difference of Model 1 is greater than that of Model 2. For Model 1, there are several island hot spots, which are mainly distributed in the sprue, around the round hole and square hole on the side. The hot spots would develop into solidification defects...
Figure 9: The temperature field and sectional view of (a) Model 1 and (b) Model 2 distributed at 55 s.
As can be seen from Figure 9, the temperature of the hot spot of Model 1 almost reached the liquidus temperature, and the temperature range was 1588–1700°C, whereas the temperature range of the corresponding area of Model 2 was 1476–1588°C. Finally, larger temperature difference of the hot spots of Model 1 led to more local heat discrepancy and more defects. The conclusion conforms to the result of the casting defect simulation.

The simulation result of time to solidus at 55 s is displayed in Figure 10. Compared with Model 2, the time to solidus of Model 1 was longer in most parts. The longer time to solidus was mainly distributed at the positions of hot spots. The temperature gradient resulted in inconsistency of the solidification time, while nonsimultaneous solidification led to bending deformation and hot tearing of the casting [22]. Hence, casting defects would grow around hot spots.

The temperature-time curves of different representative location nodes in Model 1 and Model 2 are shown in Figures 11 and 12, respectively. Five points were selected from the defective positions of the casting. The temperature gradient resulted in inconsistency of the solidification time, while nonsimultaneous solidification led to bending deformation and hot tearing of the casting.

Figure 10: Time to solidus and the sectional view of (a) Model 1 and (b) Model 2 at 55 s.

Figure 11: The temperature-time curve of different locations nodes in Model 1.
decreased gradually with time. The temperature curve of Point 5 of Model 1 is similar to that of Model 2. In addition, the temperature curve of Point 2 of Model 2 is higher than that of Model 1 because of the effect of heat accumulation of the ladder-shaped riser. The defect at Point 2 of Model 2 is moved up to the riser where heat was accumulating. The temperatures of Point 1, Point 3, and Point 4 at different solidification stages are shown in Table 3. At the same solidification time, the temperature of Model 2 is slightly lower, and the temperature range is considerably lower than the corresponding point of Model 1. The maximum temperature difference of Model 2 is 50°C, while that of Model 1 is 151.8°C. Therefore, the temperature differences between Model 1 and Model 2 at different solidification stages demonstrate the casting defect simulation result once again.

5.3. Mechanical Properties of the Casting Sample. A comparison of tensile properties of casting samples in this article with those of Ti-6Al-4V casting samples is shown in Table 4. Compared with Ti-6Al-4V alloys, the mechanical properties of the casting remain unchanged.

### Table 3: Temperature of characteristic points of the casting at different solidification stages.

| Time, s | Point 1 | Point 3 | Point 4 | Maximum temperature difference |
|---------|---------|---------|---------|-------------------------------|
| Model 1 | 200     | 1448.1  | 1296.3  | 1309.6                        |
|         | 700     | 1251.9  | 1164.2  | 1154.5                        |
|         | 1200    | 1091.2  | 1036.7  | 1009.0                        |
| Model 2 | 200     | 1334.6  | 1328.5  | 1289.3                        |
|         | 700     | 1168.1  | 1147.9  | 1115.8                        |
|         | 1200    | 1021.2  | 1011.4  | 968.2                         |

### Table 4: Tensile and impact properties of casting samples.

| Alloys    | $R_m$/MPa | $R_{p,0.2}$/MPa | A% | $a_{k,1}$ (J/cm²) |
|-----------|-----------|-----------------|----|------------------|
| Casting sample | 964       | 875             | 6.0 | 31.7             |
| Ti-6Al-4V  | 961       | 868             | 8.0 | 36.4             |
|           | 957       | 853             | 7.0 | 34.7             |

6. Conclusions

Investment casting of the titanium alloy gearbox was investigated in this study. Unigraphics software was utilized to carry out three-dimensional modelling, and ProCAST software was used for process simulation and practical experiments. The defects located around the square hole and round hole on the side of the gearbox are predicted by the simulation. The shrinkage and porosity are observably alleviated by remoulding the casting mould. The casting flow, temperature field, and time to solidus simulation results show that casting defects arise from hot spots with heat accumulation. The temperature-time curves of different representative location nodes of the casting further confirm the defect simulation results. The use of low-cost alloy elements reduces raw material costs. Compared with TC4 alloys, the mechanical properties of the casting remain unchanged. Eventually, this study is expected to save experimental expenses and provide guidance for industrial production.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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