Abstract: The addition of rare earth yttrium (Y) can improve the performances of high temperature titanium alloys, such as the tensile ductility, thermal stability and creep property, etc. However, few studies on the effect of Y on the castability of titanium alloys have been carried out, which is significant to fabrication of thin-walled complex titanium castings by investment casting. In this study, the microstructure and mold filling capacity of a Ti-1100 alloy with different Y additions (0, 0.1wt.%, 0.3wt.%, 0.5wt.% and 1.0wt.%) were investigated systematically through investment casting experiments, and the casting experiments were carried out in a centrifugal titanium casting machine. The microstructures of the alloy were observed via the optical microscopy, scanning electron microscopy and transmission electron microscopy. The mold filling capacity was tested by using of a grid pattern and was evaluated by the number of segments completely filled by the cast alloy. The results indicate that the grain size is decreased and the mold filling capacity is improved significantly with increasing the addition of Y from 0 to 1.0wt.%. The average primary β grain size of Ti-1100 alloy is reduced from 250 μm to 50 μm and the mold filling capacity is increased from 61.5% to 100%. Considering the potential harmful effect on tensile properties of titanium alloys due to high concentrations of Y, it is suggested that Y addition should be about 0.3wt.%.

Key words: high temperature titanium alloy; yttrium; mold filling capacity; investment casting

1 Experimental procedure

The matrix alloy used in the present study was the near-α high temperature titanium alloy Ti-1100 with a nominal compositions of Ti-6Al-2.7Sn-4.0Zr-0.4Mo-0.45Si (wt.%). The raw materials were high-purity sponge Ti (99.99wt.%), pure Al (99.99wt.%), Sn (99.9wt.%), Zr (99.9wt.%), Mo (99.9wt.%), Si (99.9wt.%) powders and Al-80wt.%Y master alloy. The ingots of Ti-1100 alloy with different Y additions...
(0, 0.1wt.%, 0.3wt.%, 0.5wt.% and 1.0wt.%) were prepared using a tungsten arc-melting furnace under a protective argon atmosphere. Three ingots (about 50 g each) were made for each composition and each ingot was cut in half by EDM wire cutting. The grid pattern used in this study was connected to two runner bars 3.0 mm in diameter along the two perpendicular edges, as shown in Fig. 1(a). Each opening in the grid measured 2 mm × 2 mm, making a total of 338 segments. The diameter of the grid bars was 1 mm. The mold filling capacity was determined by the number of completely cast segments as a percentage of the 338 segments in the grid pattern. The criterion for determining complete and incomplete segments was defined according to the method of Hinman et al.[8]. Wax patterns used in this study were produced by injecting wax into an aluminum metal mold on a wax injection machine, as shown in Fig. 1(a). CaO- stabilized ZrO₂ powder mixed with zirconia sol binder were prepared for the primary coating slurry. Mullite refractory and colloidal silica binders were prepared for the back-up layers. The ceramic mold was fabricated according to the traditional investment casting process. All ceramic molds were heated in an electric furnace at a temperature of 950 °C for one hour in order to achieve sufficient strength. Figure 1(b) shows the baked mold. The casting experiments were carried out in a centrifugal titanium casting machine (LZ5, made by Luoyang Ming Tao Science and Technology Co. Ltd., China), with about 25 g alloy and 25 s melting time for each casting. All casting experiments were carried out under the same conditions. Five castings were made for each experiment.

![Fig. 1: Wax pattern (a) and ceramic mold (b)](image)

After casting, the ceramic mold was manually removed from the grid casting. The mold remaining on the surface of the casting was carefully removed by air-abrading with 50 μm aluminum oxide particles, and digitally photographed.

Samples for microstructural observation were sectioned by electric discharging from the same position of the grid castings, as indicated by arrow in Fig. 1(a). The microstructures were observed via the optical microscopy (OM, Olympus microscope), scanning electron microscopy (SEM, FEI Quanta 200F) and transmission electron microscopy (TEM, Philips CM12). The polished surface for OM and SEM was etched using Kroll’s reagent of 10vol.% HF, 5vol.% HNO₃ and 85vol.% H₂O. Samples for TEM observation were prepared according to standard procedures by ion beam thinning.

2 Results and discussion

2.1 Effect of yttrium on microstructure

The microstructures of Ti-1100 alloy with different Y contents are given in Fig. 2. It can be seen from Fig. 2 that the microstructures of Ti-1100 alloy are all equiaxed and present a typical α-β Widmanstätten structure. As shown in Fig. 2(a), the Y-free Ti-1100 alloy consists of coarse primary β grains outlined by grain boundary α, and an α colony structure consisting of thin, parallel α laths with the same crystallographic variant. With increasing the Y content, both the primary β grain size and α colony size decrease, and α laths are also narrower and finer [Fig. 2 (b) to (e)]. However, there is no remarkable difference in the microstructures between Ti-1100-0.5wt.%Y and Ti-1100-1.0wt.%Y from the optical microstructure. Variation of prior β grains size with Y addition is shown in Fig. 3. It can be observed that the addition of 0.1wt.% Y significantly decreases the size of prior β grain from 250 μm to 150 μm, while the change rate of grain size becomes more and more slowly when the Y addition is increased from 0.3wt.% to 1.0wt.%, which indicates that the refinement effect is weakened when Y addition is more than 0.3wt.%. Cui et al.[4] found the average size of primary β grain reduced from 950 μm to 230 μm when 0.1wt.% Y was added to Ti-1100 alloy. In the present study, the addition of 0.1wt.% Y results in a reduction in primary β grain size from 250 μm to 150 μm. It is noted that their work was carried out in ingot casting under gravity field. The increasing centrifugal force can decrease the grain size and the lamella thickness of titanium alloy[9]. In this case, the refinement effect of Y under the centrifugal force field is weaker than that under gravity field.

Figure 4 shows the morphologies of Y-bearing particles in Ti-1100 alloy. According to the previous study by Cui et al.[4], the bright and spherical or ellipsoidal particles are identified as Y₂O₃ phase [Fig. 4(a)]. It can be seen that most of Y₂O₃ phases aggregate along grain boundaries and gradually form closed networks. Moreover, some fine particles are distributed within the grains. The size of Y₂O₃ particles ranges from about 0.5 μm to 4 μm in diameter. It seems that the size of particles is not uniform due to arc melting. In Fig. 4(b), spherical (about 250 nm in diameter) and
much finer \( \text{Y}_2\text{O}_3 \) particle was observed within \( \alpha \) platelets. This is because that \( \text{Y}_2\text{O}_3 \) oxide has a much higher melting point and stability than titanium metal, which can serve as heterogeneous nucleation substrates and enhance the nucleation rate of the solid phase \[10\]. On the other hand, as a surface active element, \( \text{Y} \) reduces the specific interface energy and the nucleation energy and hence enhances the nucleation rate \[11\]. Thus, the primary \( \beta \) grains as well as \( \alpha \) platelets are refined.

### 2.2 Effect of yttrium on mold filling capacity

The mold filling capacity for Ti-1100 alloy with different \( \text{Y} \) contents and its standard deviation are summarized in Table 1:

<table>
<thead>
<tr>
<th>Y addition (wt.%)</th>
<th>Measured mold filling capacity (%)</th>
<th>Mean value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.8  59.7  63.2  62.3  60.5</td>
<td>61.5±1.4</td>
</tr>
<tr>
<td>0.1</td>
<td>68.1  65.6  69.5  68.1  64.2</td>
<td>67.1±2.1</td>
</tr>
<tr>
<td>0.3</td>
<td>70.9  69.6  73.5  73.2  75.3</td>
<td>72.5±2.3</td>
</tr>
<tr>
<td>0.5</td>
<td>77.5  76.2  77.3  80.9  79.6</td>
<td>78.3±1.9</td>
</tr>
<tr>
<td>1.0</td>
<td>100  100  100  100  100</td>
<td>100±0</td>
</tr>
</tbody>
</table>
1. It can be seen that the mold filling capacity increases with increasing the Y content. Furthermore, with the content of Y up to 1.0wt.%, the highest mold filling capacity with no standard deviation is obtained, which indicates that Ti-1100-1.0Y can give much higher mold filling capacity if the size of the grid pattern is large enough. Figure 5 shows a group of grid casting images randomly selected, which provides a clear trend of the mold filling capacity. Ti-1100 alloy with 1.0wt.% Y produced a sound casting with a clearly grid. Therefore rare earth Y is confirmed to be beneficial to the mold filling capacity of Ti-1100 alloy.

The mold filling capacity, as an index of castability, is influenced by many factors including alloy composition, casting temperature, mold preheating temperature, wettability of the mold to molten metal, and mold thermal conductivity, in addition to casting method (casting machine) [12]. It should be emphasized that the mold filling capacity is the ability of the molten metal to fill the mold completely and copy the contour of mold cavity fully, especially the acute angles and thin-walled sections. It correlates with fluidity while is different from it. This may mean that molten alloys with the same fluidity may show a different mold filling capacity. The latter is mostly determined by the surface tension and wettability to the mold. Hence, the elements which reduce the surface tension and viscosity of alloys will enhance the mold filling capacity. Y as a surface active element has high affinity to oxygen [13]. Therefore, Y can purify alloys and reduce the oxygen concentration of alloys [13, 14]. In addition, Cui et al. [10] also pointed out that the high affinity of yttrium to oxygen causes some of the initially dissolved oxygen in the alloy to be scavenged by the formation of Y₂O₃ particles. In the study by Wunderlich et al. [15], a pronounced increase in the viscosity was observed for a specimen with a higher initial oxygen concentration. It is thus obvious that the lower oxygen concentration is associated with a lower viscosity of alloys.

In view of the above observations, it can be suggested that the addition of Y decreases the surface tension and viscosity by reducing oxygen concentration of titanium alloy. In this study, the bar diameter in the grid was only 1 mm and the flow path is complicated, which indicate that the negative effect of surface tension on the mold filling capacity is sufficiently strong. Hence, the lower surface tension and viscosity due to the addition of Y have a significant effect on enhancing the mold filling capacity.

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Chen et al. [16] reported that addition of 1.0wt.% Bi in Ti-6Al-4V enhances castability of the alloy, while larger amounts (3.0wt.% or 5.0wt.%) of Bi addition caused a reduction in castability. These phenomena are resulted from the formation of dendrites that cause resistance to fluid flow at the early stage of solidification.

In the present study, much more Y₂O₃ particles in Ti-1100 alloy were observed with increasing the Y addition. It seems that the mold filling capacity should decrease due to the resistance to fluid flow caused by Y₂O₃ particles. However, it was found that the mold filling capacity increases significantly with increasing the Y addition. It should be noted that the experiments in
this study were carried out by centrifugal casting whereas those experiments above were conducted in gravity casting. Furthermore, the mold filling was very rapid during the casting in this study. The centrifugal force appeared to overshadow the negative effects of oxide particles or dendrite formation. The lower viscosity of the molten alloy due to Y addition presented a positive and dominant effect on mold filling capacity.

According to classic Hall-Petch theory, \( \sigma_s = \sigma_0 + K_d^{1/2} \) (where \( \sigma_s \) is the yield strength of material, \( d \) is average grain diameter, \( \sigma_0 \) is the yield strength of single crystal material, and \( K \) is a constant), the tensile properties including strength and ductility can be improved with decreasing the grain size\(^{[17]}\). However, Liu et al.\(^{[18]}\) found that the mechanical properties can be obviously deteriorated by increasing Y addition to titanium alloys beyond 0.5wt.%. As shown in Fig. 2, there exists a significant segregation of \( Y_2O_3 \) particles in the primary \( \beta \) grain boundaries with increasing the addition of Y. In the areas of significant segregation or agglomeration of highly brittle hard particles, weak bonds are formed in the material which can lead to reduced mechanical properties\(^{[19]}\). During mechanical testing, the uneven distribution of \( Y_2O_3 \) particles can lead to premature failures under stress at relatively low strain. Thus too high Y addition will lead to reduced mechanical properties although the mold filling capacity is significantly improved. Considering the effect of Y on both microstructure and mold filling capacity of Ti-1100 alloy, it is suggested that proper Y addition should be about 0.3wt.%.

### 3 Conclusion

Yttrium is beneficial to the refinement of microstructure and the increase of mold filling capacity of a near-\( \alpha \) high temperature titanium alloy in centrifugal casting. With increasing the addition of Y from 0 to 1.0wt.%, the average primary \( \beta \) grain size of Ti-1100 alloy is reduced from 250 μm to 50 μm and the mold filling capacity is increased from 61.5% to 100%. The addition of Y increases the mold filling capacity of Ti-1100 alloy by decreasing the surface tension and viscosity of the melt. In considering the potential harmful effect on tensile properties of titanium alloys due to high concentrations of Y, it is suggested that Y addition should be about 0.3wt.%.

### References


