Numerical study of crucial parameters in tilt casting for titanium aluminides

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Abstract: Numerical modeling of the tilt casting process for TiAl alloys was investigated to achieve a tranquil mould filling and TiAl castings free of defects. Titanium alloys are very reactive in molten state, so they are widely melted in cold crucible, e.g. the Induction Skull Melting (ISM) furnace. Then the crucible holding the molten metal together with the mould is rotated to transfer the metal into the mould — ISM+ tilt casting. This paper emphasizes the effect of crucial parameters on mould filling and solidification of the castings during tilt casting. All crucial parameters, such as rotation rate, rotation profile, venting, initial mould temperature, casting orientation, feeder design, change of radius in ‘T’ junction and mould insulation have been discussed using numerical modeling data. Simulations were performed using a 3D CFD code PHYSISCA implemented with front tracking, heat transfer algorithms and a turbulence model (which accounts for an advancing solid front).

Key words: crucial parameters; numerical modeling; tilt casting; TiAl alloy

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The γ–TiAl alloys have been investigated for years since they offer excellent mechanical and physical properties at temperatures up to 800°C. They have a high melting point, high strength, minimal creep and low density. Titanium aluminate inter-metallics are about 50% lighter than equivalent Ni-based super-alloys and are resistant to oxidation/corrosion. These characteristics are ideal for producing high performance components servicing at high temperature, for example the exhaust valves, turbocharger rotors and turbine blades for aero-engine and modern power stations [1-4]. But all titanium alloys are reactive in the liquid phase. The alloy is commonly melted in a water-cooled copper crucible using a medium/high frequency induction coil, called ‘Induction Skull Melting (ISM)’ process to prevent contamination, as illustrated in Fig. 1(b). The induction field is designed to push the melt away from the water-cooled crucible wall so as to minimize heat loss [5]. The process is employed to melt the metal with high purity but only a limited superheat [6-7] which makes it difficult to achieve a sound casting of TiAl alloys.

Although there are some other casting methods, e.g. gravity casting, centrifugal casting [8] and counter gravity casting, tilt casting is considered an ideal way to achieve a tranquil mould filling for TiAl alloys. In tilt casting, the mould is attached to the crucible holding the melt and then the liquid metal is transferred into the mould under a computer-controlled rotation speed. Tilt casting has a long history, first used and patented by Durville [9] for the quiescent pouring of aluminium bronze. Although many advances have been made after years’ development, the principle remains the same, as indicated in Fig. 1(c). The main feature of the tilt casting process is that it is possible to transfer much of the metal horizontally into the mould without any surface turbulence if the rotation speed is well designed and controlled. The tilt cycle is a crucial factor to make a quiet metal transfer. At the end of the melting, the coil current is switched off and the crucible is rotated to pour out the metal simultaneously. To avoid more loss of superheat, rapid filling of the mould is required. However, this inevitably results in the furnace atmosphere (either argon gas or vacuum) being entrained into the metal flow by wave action, or simply trapped as the exits from the mould are blocked by the inflowing metal. Gas trapped in the casting leads to bubble defects in the castings, even when melting and casting processes are carried out in vacuum. Slow mould filling avoids the surface turbulence and allows the gas to evacuate sufficiently. However, this leads to severe superheat loss and incomplete castings due to cold shuts. A balance between the rotation speed and heat loss to complete the mould filling is critical for tilt casting. In other words, the ideal process suppresses both turbulence and premature freezing. Besides the tilt cycle, there are more important parameters in this particular casting process, such as rotation rate, rotation

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profile, venting, initial mould temperature, casting orientation, feeder design, change of radius in 'T' junction and mould insulation. The effects of these crucial parameters on the casting are numerically studied in this paper.

The modeling of the tilt casting process is very complex because many physical phenomena based on the process have been involved including complex free surface fluid flow, heat transfer and solidification, combined with the complexity of full three-dimensional geometries. The PHYSICA code was used to model the filling and solidification processes of tilt casting, using the two-phase SEA algorithm. Free surface is captured by using of the CDM implicit free surface algorithm, which automatically accounts for the proximity of solidifying boundaries to the flow. A 3D/1D transient heat transfer model was employed to calculate the heat transfer at the mould-casting interface.

1 Problem description and governing equations

An Induction Skull Melting (ISM) crucible is positioned inside a vacuum chamber and the tilt casting is carried out inside the chamber. The experimental setup and the mechanism is shown in Fig. 1. Figure 1(a) shows an overall view of the equipment used to perform the casting, and detailed description can be found in references [13–14]. A co-axial power feed is attached to the ISM crucible for the crucible rotation. It is also a part of the cooling system, through which water containing ethylene glycol is supplied to the ISM crucible and the induction coil. Figure 1(b) illustrates the schematic view of the ISM furnace. As the induction field penetrates through the segmented crucible wall to melt the loaded metal, the molten metal is repelled from the side wall to minimize superheat loss. The mould itself is surrounded by a low thermal mass clamshell mould heater. After evacuating the vacuum chamber, the mould is heated to the required temperature (1,200°C maximum) and the vessel is back-filled with argon to a partial pressure of 200 mbar prior to melting. This prevents the evaporative loss of the volatile aluminum contained in the alloy. The power applied to the induction coil is increased according to a pre-determined power vs. time curve so that a reproducible final metal temperature is achieved. At the end of melting (7–8 min), the mould heater is opened and moved away. While the induction melting power is ramped down, the ISM crucible and mould are rotated by 180° and start to transfer the metal into the mould. The mould containing the casting is held vertically as the casting solidifies and cools down.

The simulation starts from the point when the metal is completely melted to mould filling and the end of solidification. The whole process involves fluid flow including the free surface development, turbulent flow, heat transfer and solidification. The motion of the molten metal in this process is governed by the Navier-Stokes equations. The 3D model solves the incompressible time-dependent flow for both the gas and liquid phases. In order to avoid solving a separate set of fluid flow equations for the gas phase, the SEA method is used with a marker variable \( \Phi \) (0 for gas and 1 for metal). Near the free surface or where bubbles/droplets occur \( \Phi \) represents the volume fraction of metal in each cell volume along the interface. Then the volume fraction of gas is \( 1 - \Phi \). As mentioned in reference [10], an accurate explicit time stepping scheme such as that by Van Leer may be used to prevent smearing. However, the scheme is then limited to extremely small time-steps for stability, leading to very lengthy computations. To overcome this problem, a new tracking method, the Counter Diffusion Method (CDM) was developed as a corrective mechanism to counter this ‘numerical diffusion’. This method discretizes the free surface equation into a stable, fully implicit scheme which makes the computations an order of magnitude faster.

The transient heat flow is solved by the heat conservation equation. When phase change is considered, for example, during mould filling or solidification, a resistive force (Darcy
term) is added to the model to stop the flow \(^{12}\) where a second marker variable \(f_s\) represents the liquid fraction of the metal with \((1 – f_s)\) being the volume fraction of solidified metal. Through the casting-mould interface and the mould wall, a 3D/1D transient heat transfer model has been developed to calculate the heat transfer. This model is devised based on the fact that the thermal conductivity of the mould material is very low compared with that of the metal. Heat transfer in the mould is assumed to occur only in a direction perpendicular to the mould wall (called 1D heat transfer) while 3D heat transfer is computed in the castings. The 1D model does not mean one dimension in geometry, but the heat only transfers in ‘one’ direction in the mould. In the 3D/1D model, no mesh is needed in the mould wall. Instead, the coordinates of cell center and the temperature within the mould wall can be easily calculated by the model. Heat transfer in the mould is computed via the FD solution of a 1D heat transfer equation with a radiation boundary condition as \(q = \varepsilon_w\sigma(T^4 - T^4)\), where \(q\) is heat flux per unit area; \(T_m\) is the outside temperature of the mould; \(T_s\) is the atmosphere temperature in the chamber, as shown in Fig. 1(a); \(\varepsilon_m\) is the emissivity of the mould material; \(\sigma\) is the Stefan-Boltzmann constant \((\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4})\). At the mould/metal interface, the interface temperature is updated during the 3D FV solution procedure by considering heat balance at the interface.

Even at low filling speeds, the Reynolds number is as high as that of the turbulent flow. The simple and robust LVEL method of Spalding \(^{16}\) is used to model the turbulence. This method involves solving a diffusion type equation \(\nabla \cdot (\nabla \psi W) = -1\) (where \(W\) is an auxiliary variable in the regions occupied by the moving fluid with boundary conditions \(W = 0\) on all solid walls) and using the distance \(L\) and the local velocity (VEL) as input. The distance \(L\) to the nearest wall is estimated as \(L = \sqrt{(\nabla W)^2 + 2W - |\nabla W|}\). This distance is used with the laminar viscosity \(v_l\) and the local velocity to calculate the local Reynolds number, \(Re = \text{VEL} \cdot L/v_l\). The value of the local effective viscosity \(v_e\) is obtained by using a universal dimensionless velocity profile away from the wall and \(Re\). The extended LVEL method takes the moving solid boundaries into account. In the solidifying regions, re-solving \(\nabla \cdot (\nabla \psi W) = -1\) and \(L = \sqrt{(\nabla W)^2 + 2W - |\nabla W|}\) at each time step by setting \(W = 0\) in the area where no fluid movement is present.

2 Methods and simulation discussion
Rotation rate, rotation profile, venting, initial mould temperature, casting orientation, feeder design, change of radius in ‘T’ junction and mould insulation are crucial parameters to achieve defect-free castings. In the following section, the impacts of those parameters on castings are investigated by modeling a generic turbine blade, which was supplied by one of the IMPRESS partners. Computational mesh of the whole assembly (including crucible, blade, feeder and basin) is shown in Fig. 2.

2.1 Rotation rate and rotation profile
The tilt casting technique is numerically modeled by keeping the geometry stationary and rotating the gravitational force vector. A mathematical expression relating the tilting speed to the tilting angle \(\theta\) has been proposed so that optimal values of tilting speed can be set to minimize metal splash. Assume angle \(\theta\) is measured from the vertical and the tilting is in the \(x\)-\(z\) plane, the gravitational force vector components become:

\[
g_x = -g \sin(\theta)
g_y = 0
g_z = -g \cos(\theta)
\]

and they are also functions of time as \(\theta\) varies with time. The new gravitational force vector is used in the source term of general transport equation for the tilt casting process. This technique neglects rotation forces within the fluid (i.e. centrifugal and Coriolis forces).

The molten metal in the ISM crucible is poured across the basin/feeder into the mould by rotating the assembly at a certain rotation speed. The tilt cycle is designed to achieve a tranquil filling with minimum heat loss to the water-cooled crucible wall and the mould wall. Three near-parabolic tilt cycles (4 s, 5 s, and 6 s) had been employed to study the effect of the rotation speed. As shown in Fig. 3, all curves are featured with three stages. The rotation speed is high at the early stage of mould filling, and then the whole assembly decelerates to a nearly zero rotational velocity to allow most of the metal to horizontally fill the mould and minimize the risk of forming back-wave and surface turbulence. In the final stage, the rotation speed is resumed to be high so as to rapidly complete the filling to reduce the heat loss.

![Fig. 2: Mould (crucible + basin/feeder + casting blade) and mesh of the whole assembly](image)

![Fig. 3: Three parabolic cycles: 4 s, 5 s, 6 s](image)
In an attempt to speed up the filling and to minimize the heat loss, 4 s, 5 s and 6 s parabolic tilt cycles are used to perform the calculations. Figure 4 shows the effect of the filling speed on the mould filling. It can be seen that the surface turbulence is present with the tilt cycles of 4 s and 5 s (as in Fig. 4 (a) and (b)) due to the fast rotation. With the tilt cycle of 6 s, the metal is smoothly transferred into the mould and no surface turbulence is developed, as shown in Fig. 4 (c). One second difference in the total filling time makes a great difference in the free surface development during mould filling. Figure 5 shows the effect of the rotation profile. A steady filling is achieved with a parabolic tilt cycle whilst surface turbulence is developed with a constant tilt speed for a total filling time of 6 s. The mould filling is affected not only by rotation rate, but also by the rotation profile.

![Surface turbulence](image1)

![Surface turbulence](image2)

![Surface turbulence](image3)

**Fig. 4:** Effect of the filling speed on surface turbulence (with $\phi = 0.5$): (a) 2.7 s/4 s; (b) 3.5 s/5 s; (c) 4.6 s/6 s at the 114 degrees tilting angle

![Surface turbulence](image4)

**Fig. 5:** Effect of tilt cycle on mould filling (filling completed at 6 s): (a) parabolic tilt cycle; (b) constant tilt speed at 123°–125° rotating angle (with $\phi = 0.5$)

Figure 6 compares the effect of the rotation speed on the temperature field (presented in contour plots of the liquid fraction) with 4 s, 5 s and 6 s tilt cycles. The modeling results indicate a slight difference among 4 s and 5 s or 6 s tilt cycles in the cases of filling with an initial mould temperature of 1,000°C. For all the cases, the metal starts to solidify and a mushy zone is present along the trail edge (thin edge) and at the shroud of the blade. One second difference in the filling time does not produce much benefit on reducing heat loss. But, the filling speed (or filling time) has great impact on the mould filling, e.g. the development of surface turbulence as illustrated in Fig. 4.

### 2.2 Venting

When the metal is poured into the mould, it compresses the gas originally contained in the mould and causes a "piston" effect assuming the mould has a confining space. An artificial vent should be added to allow the gas to evacuate at the end of the blade. It is clear that the ends of the components furthest from the basin would need to be vented to avoid a ‘piston’ effect caused by the advancing metal flow. Such vents are generally connected back to the pouring basin. The basin contains a port to allow any fume from the melt to escape.

![Surface turbulence](image5)

**Fig. 6:** Effect of the total filling time on temperature field at the end of filling with an initial mould temperature of 1,000°C: (a) 4 s; (b) 5 s; (c) 6 s
In the experiment, a vent is actually a hole with a small diameter of about 2 mm. The flow through the vent can be described as a pipe flow in terms of pressure drop. However in the numerical simulation, it is hard and almost impractical to mesh such a small diameter cylinder. In the current study, we assume that the gas leaks out of the bigger area, as in porous medium (described as Darcy's law), instead of through an exact area of the vent. But the molten metal will be trapped somewhere in the porous medium (in the mould) due to the difference of the viscosity. As a result, the metal ultimately solidifies in the porous medium and is prevented from leaking out of the mould.

The numerical comparison of mould filling with and without venting is shown in Fig. 7. Apparently, venting is efficient in evacuating gas during casting, so as to prevent porosity defect in the investment casting.

2.3 Feeder design

It is well known that feeder is designed to compensate the solidification shrinkage, and thereby to prevent the shrinkage porosity defect in casting. Feeder design is dependent on many factors, such as the number, location, shape, dimension of feeder and so on. In this study, one geometric feature is the blade root whose taper is in the reverse direction of solidification. That means it is easy to form hot spots inside the blade root. Besides the compensation for solidification shrinkage, another main consideration is the fluid dynamics effect of the feeder design on the mould filling. Two alternative designs are considered in this study based on Chvorinov’s rule (a mathematical relationship that correlates the solidification time of a simple casting with the volume and surface area). One is a cubic feeder with a volume to cooling surface area ratio of 14.5 mm, and another is a cylindrical feeder with a slightly lower volume to surface area ratio of 13.8 mm.

Figure 8 demonstrates the effect of the feeder design on the mould filling. The connection of feeder/blade with the cubic feeder slows down the pouring of the molten metal from the crucible to the feeder due to the narrow gate, as shown in Fig. 8 (a). The sudden step between the feeder and the root of the blade with the cubic feeder causes turbulent flow and gas mixture, whilst tranquil filling presents in the system with a cylindrical feeder as shown in Fig. 8(b), where no surface turbulence or gas mixture are observed.

2.4 Initial mould temperature

One disadvantage of ‘cold crucible’ melting process is that only a limited superheat is provided. Pre-heating the mould is a way to reduce heat loss to the mould. If the pre-heating (initial) mould temperature is low, premature freezing occurs during the mould filling and the mould easily cracks due to the thermal shock. However, too high pre-heating temperature increases the risk of the mould-metal reaction which may change the surface properties of the casting.

Figure 9 demonstrates the effect of the initial mould temperature on the temperature field (in contour plots of the liquid fraction) at the end of the mould filling. As can be seen from Fig. 9, the casting is still in liquid at the end of the filling with the initial mould temperature of 1,200 °C. However, with the initial mould temperature of 1,000 °C or 1,100 °C, a mushy zone is readily formed along the trail edge which could lead to a misrun. The large temperature difference between the liquid metal and the mould results in the rapid heat loss from the metal to the mould during the mould filling. As a rule of thumb, a higher initial mould temperature is preferred in the case of insignificant or no mould-metal reaction.
2.5 Casting orientation
As has been described in refs. [15-16], casting orientation is also one of the important parameters in the tilt casting. As can be seen in Fig. 2, the casting component is not only geometrically complex but has the feature of very thin, e.g. thin blade edge in the aerofoil part. To avoid misrun at the thin edge of the blade, three orientations are proposed to make sure the thinnest part first filled: orientation 1 – long axis of the root parallel to the tilt plane; orientation 2 – mould oriented at 30° to tilt axis; orientation 3 – long axis of the root perpendicular to the tilt plane.

The numerical comparison of mould filling with three orientations in contour plots of the free surface marker ($\Phi = 0.5$) at 5.1 s with a cubic feeder is shown in Fig. 10. It can be seen that orientations 1 and 3 (shown in Fig. 10 (a) and (c), respectively) have gate block at the connection of the basin and the feeder while orientation 2 has a clear gas evacuation path. Gate block makes the mould filling severely delayed. However, gas mixture has been found for all three orientations; this is possibly due to the sudden step at the connection of the feeder and the root of the blade. Gas mixture could lead to shrinkage porosity. Compared with orientations 1 and 3, orientation 2 has less effect by the gate sudden step and free of the gate block.

In summary, the orientation determines filling order and affects filling speed, which directly affect the casting quality.

2.6 Change of the radius in 'T' junction
To speed up the heat transfer and reduce the hot spot effect, the radius at the junction between the aerofoil and the platform is modified from "T" (0 mm) shape to "C" (7 mm). Figures 11 (b) and (c) show the effect of radius change on heat transfer. It is seen that temperature field at the junction between the aerofoil and the platform is changed. The change of the radius does minimize or eliminate the effect of the hot spot. This could reduce the risk of shrinkage porosity at the junction. The exact radius size effect on heat transfer is beyond this study and therefore will not be further discussed.

2.7 Mould insulation
It is widely accepted that refractory blanket as an insulation layer can be applied to the outside of the casting to control the temperature gradient during solidification and cooling processes. The insulation layer is applied on the root of the blade and the basin/feeder as seen in Fig. 12(a) to decrease or eliminate the shrinkage in the root of the blade.

Figure 12 (b) and (c) present the numerical results of the temperature field of the casting with and without insulation. Figure 12 (c) shows that the liquid metal can’t go through to
the end of the root to compensate the volume reduced by the solidification shrinkage since the fastest heat transfer occurs in the connection without insulation wrap. Hot spot could form in the root of the blade. Insulation in the root of the blade and basin/feeder is introduced to slow down the heat transfer in this part. Figure 12 (b) shows that the insulation is effective in maintaining continuous solidification in the connection part and no hot spot forms. However, it is noted that the insulation on the root and basin/feeder has no significant effect on the aerofoil and the shroud of the blade. In practice, the selection of the insulation layer thickness and the insulating location should be carefully designed to achieve the maximum insulation effect.

All the parameters have been involved in the experiments that carried out in the University of Birmingham, one close partner of IMPRESS (Intermetallic Materials Processing in Relation to Earth and Space Solidification) project. The numerical model was verified by the experimental results. Then the model was employed to help optimize the experimental process and the mould design. Under the support of the numerical model, a 400 mm long γ-TiAl turbine blade, nearly free of defects has been produced with the tilt casting process. Computational simulation is a strong tool to predict the casting defects and to achieve castings of good quality.

3 Conclusions

A numerical model of the tilt casting process for a TiAl turbine blade has been proposed and built. The model successfully simulated the mould filling and solidification involving a three-phase flow problem. The vital parameters in the tilt casting such as rotation rate, rotation profile, venting, initial mould temperature, casting orientation, feeder design, change of radius in 'T' junction and mould insulation have been studied by the model. Following conclusions can be drawn.
(1) Careful design of rotation profile is essential to achieve tranquil mould filling. Higher tilt speed increases the turbulence tendency, however with little benefit of reducing heat loss gained.

(2) Venting is very important to avoid gas entrainment.

(3) Preheated mould makes it work to produce a thin section casting. Initial mould temperature has a significant effect on the solidification pattern. When the initial mould temperature decreases from 1,200℃ to 1,000℃, solidification starts along the trail edge at the end of the filling.

(4) The feeder is used to provide molten metal to the casting as it solidifies. Further, the feeder can change the filling path and also affect flow stability, i.e. surface turbulence or gas mixture.

(5) Casting orientation can change the mould filling path, which is able to decide filling order and affect filling speed, and eventually affect the final casting quality. Current study shows that orientations 1 and 3 have gate block phenomenon.

(6) Change of radius in "T" junction is an approach to increase heat transfer area. When the radius in the junction between the root and the aerofoil of the blade increases from 0 mm to 7 mm, the heat transfer speeds up. This modification minimizes the risk of hot spot and avoid hot spot.

(7) Mould insulation alters the temperature field. Hot spot in the root of the blade could be avoided by properly applying insulation layer.

The tilt casting is a comprehensive process. To achieve a tranquil mould filling and a casting free of defects, all these parameters should be seriously considered and carefully selected.

References


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