ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology
Vol. 2, Issue 8, August 2015

Numerical simulation of gravity and suction casting for turbine blades

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Abstract: Suction investment casting processes of low-pressure turbine blades with high TiAl alloy were simulated by Procast software. Comparative results had shown that the surface of suction casting blade was more complete than that of gravity casting one. In gravity casting process, molten metal filled the thinnest trailing edge at last, resulting in the generation of misrun defects. Furthermore, the shrinkage porosity and crack defects of gravity casting were much more and dispersive. The internal and external quality of suction casting was much better than that of gravity casting.

Keywords: FEM simulation; ProCAST software; gravity and suction casting;

I. INTRODUCTION

For the high specific strength, excellent high temperature properties and good oxidation resistance, TiAl based intermetallic alloys are potential high-temperature structural materials for aerospace and automobile applications such as turbine blades, turbochargers and exhaust valves. The high Nb content addition has benefits of improving the service temperature, strength and the high temperature oxidation resistance. However, high Nb containing TiAl alloys have poor ductility at room temperature, resulting in a low machinability, which limits the industrial production. Investment casting process, which could product fine casts with little or no machining, is the preferred method of producing TiAl alloys.

However, casting TiAl alloys have harmful characteristics like large solidification shrinkage, high chemically reactivity and poor ductility, resulting in misrun, porosity and crack defects in casts. For getting perfect quality of castings, it is essential to select appropriate casting process and technological parameters. The numerical simulation technology shows great advantages over the conventional trial and error method on forecasting defects such as shrinkage and crack.

In this work, numerical simulation method was used to research on the investment casting process of high TiAl alloy for blade casts, including gravitational and suction processes.

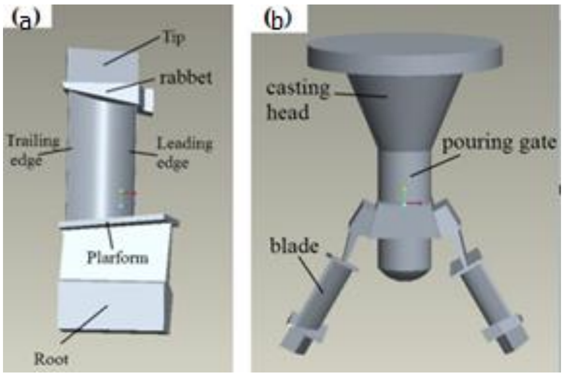

Fig.1 (a) 3D model of blade;
(b) casting system model design.

II. EXPERIMENTAL PROCEDURES

A. Mathematical model of casting simulation

The flow of liquid metal is assumed to be incompressible Newtonian fluid and the governing equations at the filling and solidification stages are given by Ref.

Navier-estokes equation:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (1\text{-}3)$$

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Heat transfer equation:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+L\frac{\partial f_s}{\partial t} \quad (5)$$

where ρ is the density; u, v, and w are the velocity vectors; t is the time; μ is the dynamic viscosity of the liquid metal; g_x, g_y and g_z are the gravitational acceleration vectors in the directions x, y and z, respectively; P is the pressure; C_p is the specific heat of molten metal; λ is the thermal conductivity; L is the latent heat; and f_s is the solid phase ratio at the solidification stage.

B. Model establishment and parameters setting of simulation

Virtual three-dimensional models of single blade and casting system were designed by Pro/E software, seen in Fig. 1a and b. Three dimensional size of the turbine blade was 10×4×2 cm, and the thinnest edge was only about 0.5 cm.

Finite element software, Procast was used to simulate filling and solidification process of investment casting. Thermophysical parameters of alloy and mold material, which calculated by the Pan-dat software were listed in Table 1.

DOI 10.17148/IARJSET.2015.2813

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Gravity casting process parameters were optimized using orthogonal experiment by early work, i.e. casting temperature of 1700℃, pouring speed of 0.5 m s^{-1}, mold preheated to 500 ℃, heat transfer coefficient of 500 $W m^{-2} K^{-1}$. Suction rotational speed was calculated by Kohctahthhob JI.C. formula according to the g-Force criteria:

Table 1 Thermophysical parameters of alloy and mold material.

Table 1
Thermophysical parameters of alloy and mold material.

Ti–45Al–8Nb–1.5(Cr, B, Si)	Value	Ceramic mold	Value
Conductivity/[$W \cdot m^{-1} \cdot K^{-1}$]	15–26	Conductivity/($W \cdot m^{-1} \cdot K^{-1}$)	0.83–0.97
Density/[$kg \cdot m^{-3}$]	4135–4513	Density/($kg \cdot m^{-3}$)	2780
Specific heat/[$kJ \cdot kg^{-1} \cdot K^{-1}$]	0.63–1.02	Specific heat/($kJ \cdot kg^{-1} \cdot K^{-1}$)	0.44–0.85
Enthalpy/[$kJ \cdot kg^{-1}$]	330		
Liquidus/[°C]	1578		
Solidus/[°C]	1405		
Viscosity/[$Pa \cdot s$]	$(4.65–8.8) \times 10^{-3}$		

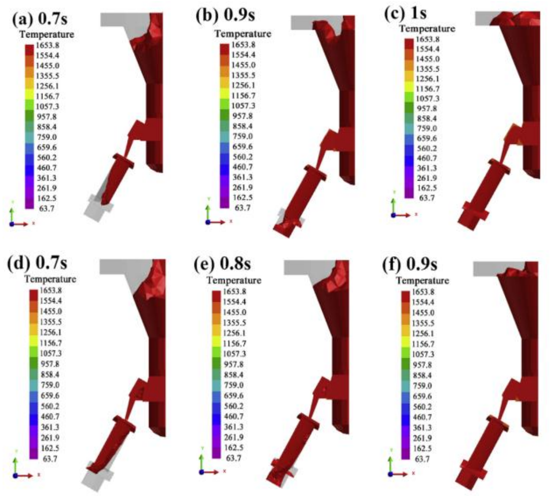

Fig. 2. Gravity (a)-(c) and Suction (d)-(f) processing simulation.

$$n = 29.9\sqrt{\frac{G}{r}} \quad (6)$$

where n is the suction rotational speed (r/min); r is the radius of inner surface of casting mold (mm); G is gravity coefficient and the value usually is 40-110. According to Eq.(6), the suction rotational speed was 400e600 r min^{-1}. The actual value used in simulation and experiment was median value 500 r min^{-1}.

III. RESULTS AND DISCUSSION

A. Processing simulation and analysis

Fig. 2 shows the gravity and suction casting simulation processes and blade castings. Gravity casting simulation results (Fig. 2a-c) show that molten metal flows along the suction side of blade. After reached the blade tip, molten metal flows back into the pressure side of blade. Metal fluid fully filled the mold cavity 1 s after pouring. Due to the effect of suction force, on the contrary, the molten metal flows along the pressure side at first, shown in Fig. 2d-f.

B. Casting defects

TiAl alloys have a lower castability and larger solidification shrinkage rate than typical Al casting alloys, which not only causes misrun defects on the surface of components, but also results in shrinkage porosity and crack defects frequently. Shrinkage and crack defects of turbine blades in this research were studied by simulation and actual experimental verification.

Fig.3 shows the location distribution of shrinkage porosities. Fig. 3a and c are the simulation results. The gravity casting simulation picture (Fig. 3a) displays that the porosities mainly concentrated in the middle of blade body and rabbet. The actual porosity position disperses in blade which is basically consistent with the simulation one.

Fig. 4 shows the effective stress simulation results and crack defects in the components. Fig. 4a and c are simulation results. Bright parts pointed out by red arrow are the location of crack defects.

Effective stress of gravity casting simulation result shown in Fig. 4a indicates that the stress is mainly concentrated in where existence of large structural deformation, i.e. connective position of rabbet/blade, blade/platform, and the thinnest trailing edge.

In conclusion, the suction casting turbine blade has much more complete surface and less internal and external defects, i.e. shrinkage porosities and cracks, than those of gravity casting blade.

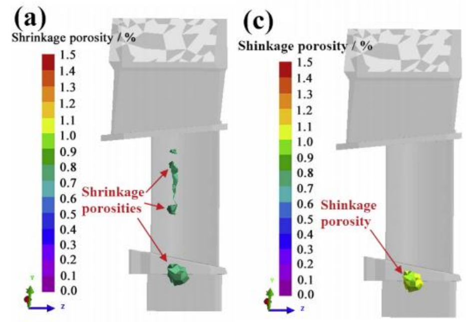

Fig. 3. Positional distribution of shrinkage porosities: (a) (c) simulation results
(a)gravity casting; (c)suction casting.

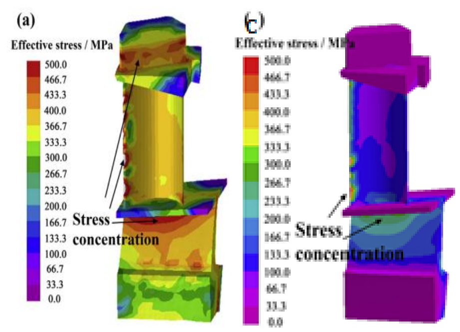

Fig. 4. Stress concentration and cracks: (a) (c) simulation results;
(a) gravity casting; (c) suction casting.

IV. CONCLUSION

Gravity and suction investment casting processes were simulated with a high TiAl alloy for turbine blades. Casting defects, including porosities and cracks were analyzed. The simulated results show good consistency and get the following conclusions.

(1) Suction casting blade has more complete surface than gravity casting blade. In gravity casting process, the

thinnest trailing edge is filled at last resulting in the generation of misrun defect

(2) Simulation results of shrinkage porosity show that shrinkage porosity defects in gravity casting blade are much more and dispersive than those in suction casting blade

(3) In gravity casting blade, the stress and cracks are mainly concentrated in where existence of large structural deformation, i.e. connective position of rabbet/blade, blade/platform, and the thinnest trailing edge. In suction casting blade, the cracks are much less than gravity casting and exist in connective position of blade and platform.

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