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Thermo-Mechanical Numerical Analysis for Distortions introduced in Titanium Alloy Blades by Post-Forge Cooling

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Abstract

This paper presents a numerical method to predict the distortions of alloy blades, caused by uneven temperature distribution and its thermal stress in cooling phase. A simplified thermo-mechanical model is presented, considering the actual production conditions. A simulation model of TC11Titanium Alloy Blade is established and performed to evaluate the transient temperature field and deformation by using ANSYS. The simulation results also are compared to the experiment results at the end.

Keywords: alloy blades; distrotions; numerical method; thermo-mechanical;

1. Introduction

Titanium alloy blades are important components of aircraft engines, which have high requirements in accuracy and quality combined with a complex shape and difficult material conditions[1], generally manufactured by precision forging now. Thermal conductivity of titanium alloys is only about 1/15 of aluminum alloy and 1/5 of steel alloy. Low thermal conductivity and complex structure lead to uneven temperature distribution in blade cooling phase. Uneven temperature distribution causes thermal stress, and further introduces distortions.

Only a few published papers have conducted analysis of distortions induced in blades by cooling. Bariani et al.[2-3] Integrating physical and numerical simulation techniques to design a cooling path for obtaining near-net-shape blades. Bruschi et al.[4] established a finite element model of cooling phases, in order to investigate the effects of different cooling modes after forging on final geometry of blades. The analysis showed that distortions are maximized when dissimilar cooling conditions are applied to the different sides of the blade. The literature[5-6] study the thermal and mechanical characterize during cooling, using numerical simulation tools.

This paper is aim to develop a numerical environment to predict the distortions induced in blades of titanium alloy by cooling, which is a coupled thermo-mechanical process. The main idea of a simplified modelling framework is presented in Fig.1, under the assumption which is put forward in Chapter 2. Distortions are influenced by thermal expansion/contractions and flow stress dependent both on temperature.

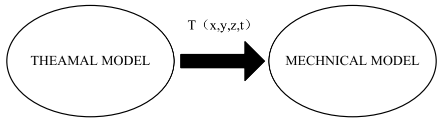

Fig.1. Modeling framework

A simulation model of TC11 titanium alloy blade is established in Chapter3. The simulation results are presented and discussed with experiment result in Chapter 4.

2. Thermo-Mechanical Model

2.1. Basic assumptions

The deformation, caused by the thermal stress and residual

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stress, interact with heat conduction, during cooling. That is a complex thermal-mechanical coupling. Takeuchi Hiroichiro[7] point out that if the volume of the object remains unchanged or changes very slowly, then the influence of deformation on temperature will be small. Liu[8] investigated the difference of Coupling and un-coupling temperature field. The result shows that the maximum temperature difference is 0.05℃. There is a little residual stress and thermal stress in blades, during cooling, without external loading. Therefore the thermal analysis of the cooling process can ignore the influence of mechanical stress. And then the mechanical analysis is aimed at the deformation caused by Thermal Stress.

(2) External heat transfer mode

In the process of blades cooling, there are three modes of external heat transfer: heat conduction, convection, radiation. Due to the large space of actual production site, the radiation can be negligible without irradiated subject. Besides blades are not in contact with the external object. So the blade is considered to only heat the surrounding environment with natural convection mode.

2.2. Thermal model

The temperature of objects at any point over time is generally called as transient temperature field, can be expressed as (1):

$$T = T(x, y, z, \tau) \tag{1}$$

Where T is the temperature, τ is the time, (x, y, z) is the spatial variables.

The transient temperature field $T(x, y, z, \tau)$ satisfy the differential equation (2) according to the first law of thermodynamics.

$$k(\frac{\partial^2 T}{\partial^2 x} + \frac{\partial^2 T}{\partial^2 y} + \frac{\partial^2 T}{\partial^2 z}) + \rho Q - \rho c \frac{\partial T}{\partial t} = 0 \tag{2}$$

In the equation (2) k is the thermal conductivity, ρ is the thermal conductivity, c is the specific heat capacity of the material, Q is the density of the heat source.

In order to solve the equation (2), Initial temperature and external heat-transfer term, also called heat transfer boundary condition, should be given.

Initial temperature is generally expressed as follows:

$$T\big|_{\tau=0} = T(x, y, z, \tau) \tag{3}$$

Blades only heat the surrounding environment with natural convection mode, has been assumed in 2.1. Therefore natural convection is used as the heat-transfer boundary condition, as follows:

$$hA(T_w - T_f) = -(\frac{\partial T}{\partial n}) \tag{4}$$

Where h is the convective heat transfer coefficient between the surface and the surrounding medium, A is the heat transfer area, Tf is the temperature of surrounding medium, w represents surface, n is the outer normal coordinates to the surface.

The transient temperature field can be Obtained by equation (2), when equation (3) and (4) are given.

2.3. Sequential mechanical model

In the heating or cooling phase of an object, strain consists of two parts: Thermal strain caused by thermal expansion and contractions; Elastic strain caused by the internal stress, generated by uneven temperature distribution

Stress-strain relationship can be represented by the equation:

$$\varepsilon = [D]^{-1}\{\sigma\} + \{\varepsilon_0\} \tag{5}$$

Where ε is the total strain, σ is the elastic stress, ε_0 is the thermal strain which is given by:

$$\{\varepsilon_0\} = [\alpha T \ \ \alpha T \ \ \alpha T \ \ 0 \ 0 \ 0]^T \tag{6}$$

Where α is the coefficient of linear thermal expansion. Temperature function can be expressed as (7):

$$T = \sum_{i=1}^{n} N_i T_i \tag{7}$$

Thermal stress can be expressed as (8:)

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon_0\}) \tag{8}$$

Where [D] is elastic constant matrix.

3. Simulation Model

In this section, a simulation model of TC11Titanium Alloy Blade is established.

(1) 3D Model of The Blade

The TC11 Ti alloy blade is mainly composed of tenon, concave, convex, shroud (see Fig.2). The concave and convex together are defined as wing.

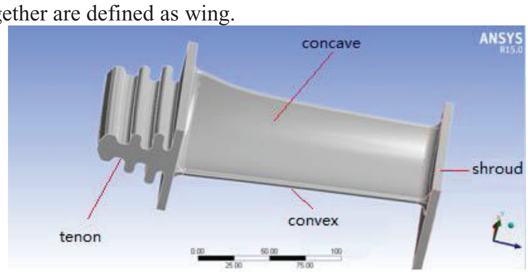

Fig.2. 3D model of the blade

(2) Material Parameters[9-10]

The thermal physical parameters and mechanical properties of TC11 alloy are as follows: the density p = 4.4g / cm3; the linear expansion coefficient is equal to 10.4; The curve of thermal conductivity versus temperature is shown in Figure 3;the curve of specific heat capacity versus temperature is shown in Figure 4; the Poisson's ratio v = 0.33; the curve of Elastic Modulus versus temperature is shown in Figure 5;