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Crystal orientation effect and multi-fidelity optimization of a solid single crystal superalloy turbine blade

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ABSTRACT

Single crystal (SC) turbine blade adopts directional solidification casting, traditional design approach requires the [0 0 1] crystal orientation coincide with the blade stacking axis, and the principal deviation angle is less than 10 deg, the other crystal orientation is random. This design philosophy result in random fatigue life of the formed blade even in the same service environment. Crystal orientation effect on mechanical response of a SC turbine blade is investigated using finite element calculation, then presents a multi-fidelity optimization procedure for crystal orientation optimizations of the blade. A nonlinear turbine blade FEM model with orientation dependent crystal plastic theory and coupled temperature conversion provides the high-fidelity model, the low-fidelity model involves a surrogate model technique. Through the multi-fidelity optimization of crystal orientation design, taking into account the efficiency and accuracy to reduce the maximum resolved shear stress (Rss) at the dangerous position of solid turbine blade and effectively improve the fatigue life of the blades. The results demonstrate that crystal orientation have an appreciable variation on Rss in the dangerous position of solid turbine blade. The influence of temperature and structure must be taken into consideration, especially the maximum Rss has the significant effect on evaluating the fatigue life of turbine blade. The optimization model based on the approximation theory can accurately describe the response between the design variables and optimization targets. The optimization reduces the Rss and deformation by 28% and 17%, respectively. The multi-fidelity optimization strategy can effectively optimizes the crystal orientation of the blade and improves the blade life.

1. Introduction

SC has been commonly used for the major material of aero-engines and gas turbine service as turbine blades because of the excellent high temperature mechanical characters. It has the same elastic constants in principal crystal orientations ([0 0 1], [0 1 0] and [1 0 0]) due to the special face-centered cubic crystal structure, at the same time, the mechanical properties are greatly different in different orientations [1–3]. Perfectly material and structure design which can fully display material function, ensuring materials maximum utilization make a serious challenge for the designers. As the stress response are sensitive to crystal orientation, the changes of crystal orientation will directly influence the mechanical properties and fatigue life of turbine blade [4,5]. Therefore, the reasonable use of crystal orientation characteristic to improve service performance of aero-engine turbine blade has its important engineering significance [6,7].

The casting process of turbine blade is directionally solidified, traditional design approach of crystal orientation based on test and experience, designer usually controlled [0 0 1] crystal orientation coincide with the blade stacking axis, the principal deviation angle is less than 10 deg, the other crystal orientation is generally not controlled. Great dispersion is exhibits when evaluating the fatigue life and other mechanical properties of turbine blade. The effect factors such as blade geometry structure, service environment, especially the crystal orientation [8,9]. To solve dispersion caused by crystal orientation, designers have made significant effort in explore orientation-dependent of SC. Recently many structure analysis and optimization design model have been proposed in order to choose the best crystal orientation, because of its low design cost, researchers gradually use numerical calculation instead of traditional design methods [10,11]. Many orientation dependent analysis model were proposed, which involve to temperature, crystallographic orientation, dwell types and thermo-mechanical fatigue, several damage accumulation models considering critical slip plane and resolved shear stress, especially, the number of active slip planes [12–15]. Moreover, from the perspective of view, research show that the crystal orientation has direct impact on fatigue

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crack resistance [16]. Under typical operating loads, the fatigue life assessment is difficulty due to the damage will significantly reduce the fatigue strength [17]. In general, randomness orientation effect on mechanical response of the blade, orientation optimization is necessary [18]. While a large number of research achievements are currently existed, there is no simple and effective approach to improve the crystal orientation design of SC turbine blade engine components. Therefore, it is essential to develop crystal oriented characteristic material constitutive, evaluating fatigue life method and optimization algorithm. Now crystal orientation design of turbine blade based on numerical calculation cannot be applied to engineering practice, the difficulty is: (1) high precision numerical calculation need a reasonable constitutive considering crystal anisotropic characteristic and potential critical plane, especially, a life prediction model. (2) the complex of blade structure makes grid singularity, temperature and strength analysis involves interdisciplinary conversion. (3) the design cost of direct simulation-based optimization is too expensive to realize, especially the complex structure of turbine blade. (4) the design space multi-dimensional, high nonlinearity and other characteristics will lead to optimization is difficult to converge due to numerical noise.

Multi-fidelity optimization is integrating different levels of granularity or cost, which is introduced to efficiency and accuracy of high and low fidelity [19]. High-fidelity model performs a higher prediction, while low-fidelity model effectivity increases calculation speed, decreasing calculation cost and numerical noise [20–24]. The present work efforts propose a design approach through multi-fidelity optimization method to obtain the optimum crystal orientation which turbine blade has the longest fatigue life. Based on the rate-dependent crystal plasticity theory, dangerous position of the blade (maximum Rss) under service environment was obtained using finite element analysis. An exponential life model was employed to calculate blade fatigue life. The effect of crystal orientation on Rss in the dangerous position of the blade was investigated. Three Eulerian angles were set as design variables, the sample points were generated through optimal Latin hypercube sampling method, the surrogate model was established through numerical calculation and Kriging functions. Finally, with the objective of maximum fatigue life, the crystal orientation optimization was complete using adaptive simulated annealing algorithm. The optimization results demonstrate that the method can quickly select the best crystal orientation of the formed turbine blade with low design cost.

2. Material constitutive

2.1. Anisotropy elastic stiffness

The SC can be modelled as orthotropic material properties, Transformation of stress and strain between global and crystallographic axis coordinate system is necessary. Set the global reference coordinate system is OXYZ, a local crystal orientation coordinate system is created in the crystal cubic. We choose “ZXZ” rotation order in the global reference coordinate, as shown in Fig. 1.

The coordinate transformation formula for stress state of any point in the two coordinate systems is

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{T}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{bmatrix}\begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{1}$$

where l_i, m_i and n_i (i = 1,2,3) are the direction cosines in the two coordinate systems. α, β and γ represent three Eulerian angles, the transformation matrix in the two coordinate systems is

$$\mathbf{T} = [\mathbf{l}\ \ \mathbf{m}\ \ \mathbf{n}] = \begin{bmatrix} \cos\alpha\cos\beta\cos\gamma - \sin\beta\sin\gamma & -\cos\alpha\cos\beta\cos\gamma - \sin\beta\cos\gamma & \sin\alpha\cos\beta \\ \cos\alpha\sin\beta\cos\gamma + \cos\beta\sin\gamma & -\cos\alpha\sin\beta\sin\gamma + \cos\beta\cos\gamma & \sin\alpha\sin\beta \\ -\sin\alpha\cos\gamma & \sin\alpha\sin\gamma & \cos\alpha \end{bmatrix} \tag{2}$$

where **l**, **m** and **n** are the base vector in the local coordinate system. The stress–strain relationship in the crystal system is

$$\sigma = \mathbf{C}\varepsilon \tag{3}$$

where $\sigma = (\sigma_{11},\sigma_{22},\sigma_{33},\sigma_{12},\sigma_{13},\sigma_{23})$, $\varepsilon = (\varepsilon_{11},\varepsilon_{22},\varepsilon_{33},\varepsilon_{12},\varepsilon_{13},\varepsilon_{23})$. **C** is the elastic stiffness matrix according to the generalized Hook' law for orthotropic material in Cartesian coordinate OXYZ.

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \tag{4}$$

where the elastic constants are the functions of E and μ. The stiffness matrix in crystal coordinate system is given by the following transformation

$$\mathbf{C}^{XYZ} = \mathbf{TCT}^{T} \tag{5}$$

$$\mathbf{T} = \begin{bmatrix} l_1^2 & m_1^2 & n_1^2 & 2l_1m_1 & 2l_1n_1 & 2m_1n_1 \\ l_2^2 & m_2^2 & n_2^2 & 2l_2m_2 & 2l_2n_2 & 2m_2n_2 \\ l_3^2 & m_3^2 & n_3^2 & 2l_3m_3 & 2l_3n_3 & 2m_3n_3 \\ l_1l_2 & m_1m_2 & n_1n_2 & l_1m_2 + l_2m_1 & l_1n_2 + l_2n_1 & m_1n_2 + m_2n_1 \\ l_1l_2 & m_1m_3 & n_1n_2 & l_1m_3 + l_3m_1 & l_1n_3 + l_3n_1 & m_1n_3 + m_3n_1 \\ l_2l_3 & m_2m_3 & n_2n_3 & l_2m_3 + l_3m_2 & l_2n_3 + l_3n_2 & m_2n_3 + m_3n_2 \end{bmatrix} \tag{6}$$

Fig. 2 shows the relationship between the blade stacking axis and the crystal orientation primary axis of the turbine blade, traditional design approach only controlled the primary angle β less than 10 deg, the other crystal orientation is generally not controlled. Therefore, it is essential to obtain the corrected elastic stiffness constants relative to the loading direction in the finite element approach. The values of E in the local coordinate system occur in [1 0 0] and [1 1 1] orientations and when expressed as a ratio $E_{[1\,1\,1]}/E_{[1\,0\,0]}$ this provides a measure of anisotropy:

$$\frac{E_{[111]}}{E_{[100]}} = \frac{3C_{11}}{C_{11} + 2C_{12} + C_{44}} \tag{7}$$

where $1/E_{[1\,0\,0]} = C_{11}$, $1/E_{[1\,1\,1]} = (C_{11} + 2C_{12} + C_{44})/3$. The elastic stiffness in arbitrary crystal orientation can be calculate in the following:

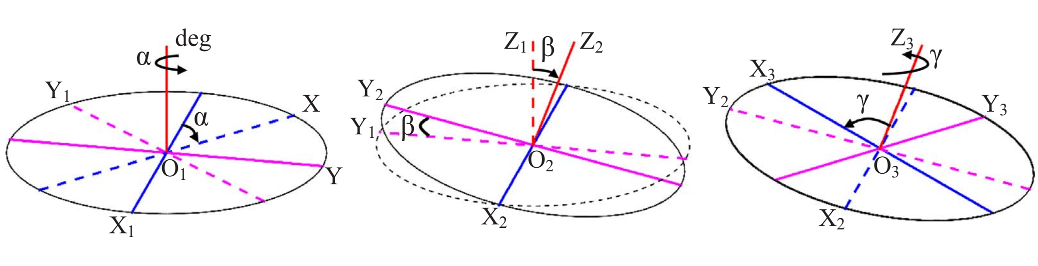

Fig. 1. “Z-X-Z” rotation of coordinate system, the lower corner represents rotation number, α, β and γ represents three Eulerian angle, the dot and solid line is the coordinate system before and after rotation.