

单晶材料涡轮叶片的循环蠕变分析*

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【摘要】对 DD3 材料单晶涡轮叶片进行了应力循环和应力、温度同时循环下蠕变计算, 得到了叶片在两种情况下的循环蠕变结果, 并对两种结果和静态蠕变作了对比分析, 从而为了解叶片在实际变工况下的循环蠕变行为提供了理论依据。

主题词: 单晶 涡轮 叶片 蠕变

分类号: V 232. 4

1 概 述

航空发动机热部件重要结构设计准则之一是要提供足够的蠕变/应力断裂寿命, 即防止过大的蠕变变形和蠕变应力断裂。在结构完整性的军用标准中, 规定为: 在金属工作温度下和在此温度的持续时间内, 设计应力不得超过 0. 2% 蠕变强度最低许用值^[1]。由于蠕变是与时间有关的不可恢复的塑性变形, 而叶片的蠕变损伤是累积损伤。发动机是在多种变工况下工作的。因此, 预测发动机涡轮叶片的蠕变寿命时, 必须研究发动机在变动温度和变动应力下的循环蠕变特性。这种蠕变特性与恒定温度和恒定载荷下的静态蠕变特性相比, 不同材料, 其结论不同。试验表明, 有些材料循环蠕变的断裂寿命会缩短, 蠕变量增加; 有些材料的寿命反而会增加。针对我国自行设计的单晶涡轮叶片进行了循环蠕变计算分析, 并与静态蠕变作了对比, 这对单晶叶片的设计分析是有参考意义的。

2 DD3 单晶材料的本构方程和屈服准则

DD3 材料为正交各向异性材料, 其正交各向异性体现在材料特性为方向的函数, 若 X、Y、Z 方向与弹性主轴方向一致, 则正交各向异性材料的本构方程有 9 个独立的弹性常数, 而 DD3 单晶材料为面心立方晶体, 在 (100), (010), (001) 三个方向上具有完全相同的力学特性, 即有:

$$E_x = E_y = E_z, \quad \mu_{xy} = \mu_{yz} = \mu_{zx}, \quad G_{xy} = G_{yz} = G_{zx}$$

所以 DD3 单晶材料应有 3 个独立的弹性常数 E, μ, G 。 E, μ, G 等可由材料手册查得。

非线性循环蠕变分析是在正交各向异性材料热弹性蠕变计算基础上进行的。非线性蠕变计算是根据希尔理论及其相应的屈服函数和流动法则进行的。其屈服函数为:

$$\bar{\sigma} = [\alpha_x^2 + \alpha_y^2 + \alpha_z^2 - \alpha_x \alpha_y - \alpha_x \alpha_z - \alpha_y \alpha_z + A (\tau_{yz}^2 + \tau_{zx}^2 + \tau_{xy}^2)]^{1/2}$$

式中, $A = L/F$, 可由 (001), (111) 方向的拉伸屈服应力和剪切屈服应力来确定。

3 有限元计算

DD3 单晶涡轮叶片, 叶高为 24 mm, 本文在对该叶片进行有限元计算时, 采用三维 8 节点等参元。

表 1 DD3 蠕变常数

温度(°C)	A	n	p
760	4. 96508E- 16	4. 0588	0. 4047
850	9. 72280E- 15	4. 1382	0. 3573
1000	2. 51148E- 14	4. 6491	0. 2782

叶片所承受的载荷有转速为 45000 r/m in 的离心力; 叶片的不均匀温度场引起的热应力。叶片 1~ 7 截面上的温度(单位: °C)依次为: 892. 4, 931. 6, 942. 1, 930. 7, 897. 8, 825. 9, 679. 0。

考虑叶片的实际工作条件, 叶片循环蠕变的载荷谱如图 1 所示。

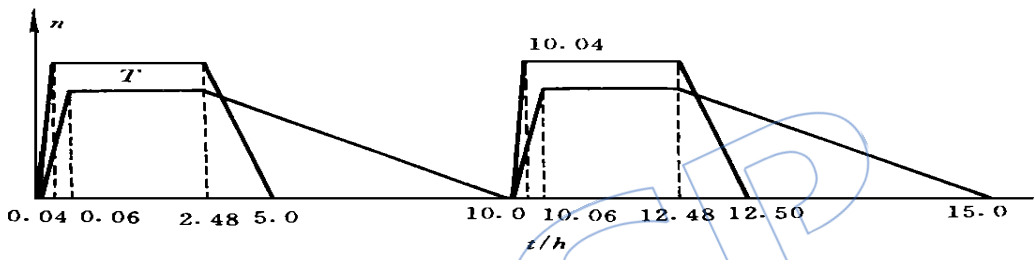


图 1 循环载荷谱

经过试验拟合和修正后的DD3 材料的蠕变常数如表 1 所示^[2]。

4 计算结果和分析

(1) 叶片在各个时间的最大 Z 向位移见表 2。

表 2 叶片 Z 向最大位移 u_{zmax} (单位: mm)

时间(h)	0.1	1.0	10	50	100	200	300
应力循环	0. 4176	0. 4183	0. 4204	0. 4222	0. 4232	0. 4245	0. 4254
双重循环	0. 4178	0. 4184	0. 4204	0. 4222	0. 4232	0. 4245	0. 4254
静态蠕变	0. 4183	0. 4194	0. 4215	0. 4248	0. 4260	0. 4291	0. 4309

可以看出, 两种循环计算结果完全一致, Z 向位移主要是由静应力产生的, 循环蠕变引起的位移较小。

(2) 叶身 1/3 叶高处循环下的应力和蠕变应变计算结果如图 2 和图 3 所示。

由此可以看出, 两种计算结果非常吻合, 一旦加载, 就会产生蠕变应变和应力松弛现象, 卸载后, 蠕变应变随即停止, 再加载后的蠕变应变速率明显降低。

(3) 图 4 和图 5 为叶片中截面循环蠕变 300 小时的应力松弛和等效应变曲线的包络线。

由此可以看出, 节点等效蠕变应变的包络线基本符合蠕变规律, 有明显的第 1, 2 阶段, 开始蠕变速度较快, 之后, 蠕变速度明显降低, 在蠕变 300 小时时, 两种循环蠕变应变达到 0. 1% 左右。

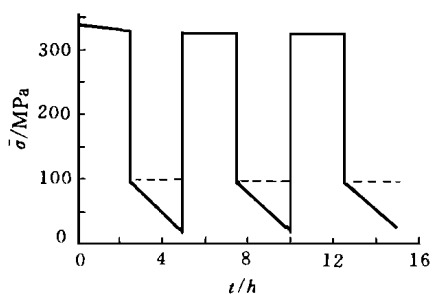


图 2 147 节点的等效应力—时间曲线

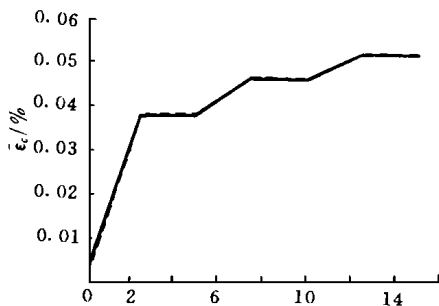
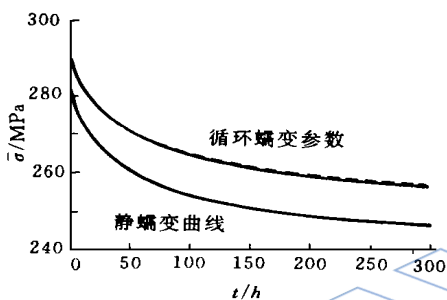
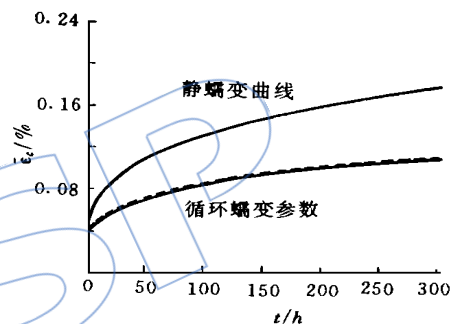


图 3 147 节点的等效蠕变应变—时间曲线

图 4 115 节点在 3 种循环情况下
等效应力—时间曲线图 5 115 节点在 3 种蠕变情况下
等效蠕变应变—时间曲线

在实际的循环蠕变中, 载荷中断和产生蠕变应变的恢复现象, 再重复加载, 又会观察到蠕变的加速, 即瞬变现象, 而在计算中, 没有考虑这两种现象, 所以, 计算结果会有一定的误差, 又由文献[3]可知, 一般情况下, 循环试验下的蠕变变形大于计算的蠕变变形, 计算结果往往偏低, 这样在进行蠕变寿命分析时, 应该增大安全储备系数。

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measurements of the overall performance and element performance, especially the blade tip flow prove that the treated casings enhance the compressor efficiency, but make slight loss of stall margin. According to analyzing the effects of each structural parameter on the compressor efficiency and stall margin, an optimization of primary geometric parameters has been found out. Then the effects of the grooved casing treatments on the performance of the compressor rotor have been revealed and some valuable conclusions have been reasoned out.

Key Words Compressors Cascades Treatment Efficiency

**EXPERIMENTAL INVESTIGATION
OF FISH SCALE PATTERNED CASCADE**

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ABSTRACT Several cascades with different patterns have been tested with the purpose of turbulence drag reduction in compressor cascade, after the straight patterned cascade obtained notable effects. The fish scale patterned cascade is the best of them. The main performance comparison is shown as follows:

Cascade	M_{a1cr}	$\Delta\beta_{design}$	δ_{design}	$(P_2/P_1)_{2Dmax}$	$\xi_{=0.5^\circ}/\%$	Δi
reference	0.685	40.8°	6.7°	1.1810	5.7609	10.0°
straight pattern	0.735	41.7°	5.8°	1.1987	3.4261	10.4°
fish scale pattern	0.750	41.1°	6.4°	1.2127	3.0610	10.4°

The above test data indicate that most of performance indices of the fish scale patterned cascade, such as critical Mach number M_{a1cr} , maximum two-dimensional static compression ratio $(P_2/P_1)_{2Dmax}$ and total pressure loss coefficient at maximum attack angle $\xi_{=0.5^\circ}$ are improved over the straight patterned cascade. The other performance parameters, namely attack angle range Δi , flow deflection angle at design point $\Delta\beta_{design}$ and corresponding deviation angle at design point δ_{design} , are superior to the reference cascade as well. It is particularly worth to point out that the fish scale pattern and the straight pattern can be together applied to the same blade to obtain advantageous performance.

Key Words Compressors cascades Drag reduction Experiment

**CYCLIC CREEP ANALYSIS
OF TURBINE MONOCRYSTALLINE BLADE**

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ABSTRACT Stress cycling creep and stress-thermal cycling creep of monocrystalline turbine blade have been analyzed. The results are compared with static

creep. This work lays the theoretical foundation for understanding the behaviours of the cycling creeps at varying regimes

Key Words Monocrystal Turbines Blades Creep

MEASUREMENT OF THERMAL RESIDUAL STRESS IN THERMAL BARRIER COATING BY MEANS OF PHASE-SHIFT MOIRÉ INTERFEROMETRY

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ABSTRACT There are many difficulties in measuring thermal residual stress in thermal barrier coatings, because of their microstructure and microdeformation. Phase-shift moiré interferometry is provided which can precisely measure the deformation of solid bodies under various loading conditions. The fundamental theory and experimental technology of the phase-shift moiré image-processing technique are introduced. By combining it with relaxation method, a new technique for measuring thermal residual stress is proposed. With the aid of high temperature moiré gratings, the distributions of thermal residual stresses in the EB-PVD (electron beam-physical vapour deposition) coating has been measured, and compared with those other of methods.

Key Words Thermal barrier Coatings Residual stress Phase-shift Moiré method

ADAPTIVE RECTIFICATION OF PARAMETERS IN AEROENGINE SIMULATION MODEL

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ABSTRACT An adaptive simulation model has been developed by means of modification factors. A modified conjugate gradient algorithm is employed for solving the nonlinear programming problem in the model. According to the parameter measurements of the engine on test rig and in flight, the component characteristics of the engine are rectified by the adaptive model, as a result, outputs of the model are in accordance with the measurements. As an example, the method provided was adopted to rectify the parameters in the simulation model of a given twin-spool reheated turbojet engine, and the simulation achieved satisfactory accuracy.

Key Words Aircraft engines simulation Parameters Nonlinear programming Adaptive control