第 7 卷 第 2 期 航空动力学报 Vol. 7 No. 2
1992 年 4 月 Journal of Aerospace Power Apr. 1992

TC-11 钛合金高低周复合疲劳及损伤累积研究

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【摘要】 本文系统地研究了 TC-11 钛合金在室温和高温下高、低周复合疲劳行为，其中包括高低周循环应力比 m、试验温度、缺口试样的预应力超载对复合疲劳寿命 N_fL 的影响。结果表明：复合疲劳寿命随 m 值的增加而明显降低，尤其是 $m=35\%$ 时，其 N_fL 降低十多倍，并在 $m-\lg N_fL$ 曲线上，当 $m=10\%$ 时出现一个拐点。在相同的 m 值和低周应力为 900MPa 时，当温度从室温升高到 150℃时，其 N_fL 下降约 1/3，当温度继续升高到 300℃时，其 N_fL 接近零。此外，还提出了复合疲劳的损伤累积模型，$1/N_fL=1/NL+n/N_h$。

针对 14 号机压气机叶片，研究 TC-11 钛合金在各种条件下的复合疲劳特性，为叶片榫齿部位的疲劳强度设计和寿命估算提供依据，探索其损伤累积模型，为寿命预测积累经验。

一、材料和试验程序

试样从 14 号机Ⅳ、Ⅴ级压气机转子叶片用 TC-11 钛合金 Φ22mm 棒材上纵向切取，化学成份如表 1 所示，工作部分直径为 5mm。热处理制度为 950±10℃保温 1 小时空冷；530±10℃，保温 6 小时空冷。常规力学性能如表 2 所示。

表 1 TC-11 钛合金的化学成份（重量，%）

Al	Mo	Zr	Si	Ti	Fe	C	N	H	O
6.40	3.66	1.78	0.28	余	0.08	0.03	0.01	0.007	0.12

试验时先加以频率 $f=8.3$ 周/分、应力比 $R=0$ 的梯形波，然后在梯形波上迭加一个频率约为 10Hz 的高周应力波，如图 1 所示。其梯形波的最大循环应力分别为 900 和 1000MPa。

表 2 TC-11 钛合金的常规力学性能

温度 ℃	σ_b MPa	$\sigma_{0.2}$ MPa	δ %	ψ %	HB (mm)	a_k (kgm/m²)
室温	1169	1068	16	37	3.36	4.6
	1160	1048	12	45	3.38	4.6
500	825		18	57		
	823		19	57		

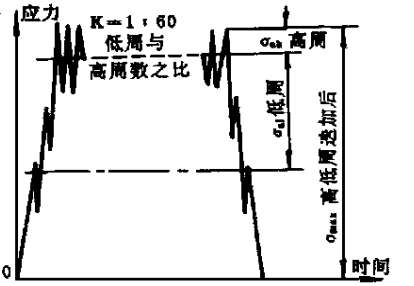


图 1 高、低周复合波型示意图

高周应力幅与低周应力幅之比值称为复合循环应力

本文于 1991 年 12 月收到。 ** 北京航空材料研究所（81 号信箱 23 分箱） 100095

比 m，即 $m=\sigma_{ah}/\sigma_{aL}$，试验在ESH-50E型电液伺服疲劳试验机上进行。

二、试验结果和分析

1. 不同 m 值对复合疲劳性能的影响　一般来说，在其它试验条件不变的情况下，m 值越大其疲劳寿命越低，原因是 m 值越高意味着所迭加的高周应力越大。当低周梯形波的最大应力分别为 1000 和 900MPa 时，得到的 m 值对复合疲劳寿命的影响如图 2 所示（1. $m=0\%$，$\sigma_{max}=900$MPa，$\log N_{fL}=4.524-0.0319m$；2. $m=0\%$，$\sigma_{max}=1000$MPa，$\log N_{fL}=4.1068-0.0426m$）。

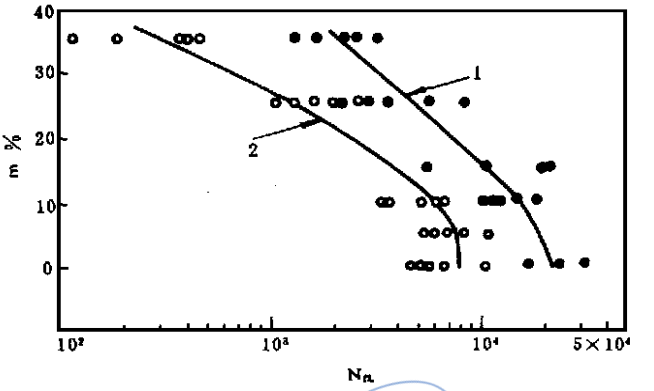


图 2　不同 m 值对复合疲劳寿命 N_fL 的影响

从图 2 可以明显地看出，其低周疲劳寿命在 10^4 范围内，N_fL 随 m 值的增加而大大下降，这种情况与文献[1]所得到的结果很相似，如图 3 所示。另外，当复合循环比 $m=10\%$ 时，在其 m-N_fL 曲线上出现拐点。当 $m<10\%$ 时，高周振动应力的迭加对复合疲劳寿命影响不明显，但是当 $m>10\%$ 时，影响十分明显，且曲线很陡。若将 $m>10\%$ 的数据点，利用线性回归进行工程应用处理，得到当梯形波的最大应力为 1000 和 900MPa 时，其 m-N_fL 的关系式分别为：$\log N_fL=4.1068-0.0426m$，$\log N_fL=4.5240-0.0319m$。以上两式其数据拟合的相关系数 γ 分别为 0.9439 和 0.9704。

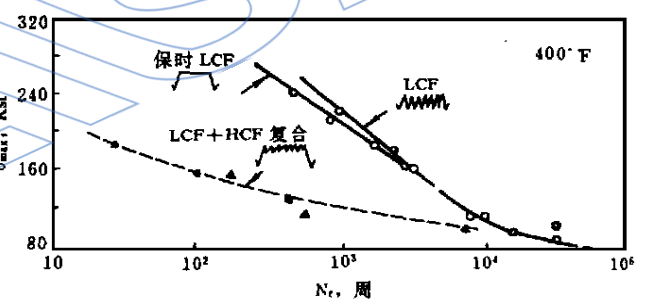


图 3　马氏体不锈钢的高低周复合疲劳 S-N 曲线[7]

2. 试验温度对 TC-11 钛合金复合疲劳性能的影响　温度对复合疲劳寿命的影响是在固定的 m 下进行的，图 4 为 $m=10\%$，σ_{max} 分别为 945 和 840MPa 时所得到的结果。从图中可以看出，当 $\sigma_{max}=945$MPa 时，温度从室温升高 150℃，TC-11 合金的复合疲劳寿命大大下降。当温度继续升高到 300℃时，其复合疲劳寿命接近于零，即没有加到预定应力时试样就断裂。因此，将应力水平降低到 840MPa 进行试验，获得了 150、300 和 450℃下的结果如图 4 所示。将所得的数据作线性回归，得到温度与复合疲劳寿命 N_fL 的关系式，并推算得室温下的 N_fL 为 38905 周。$\log N_fL=4.6478-0.0029t$℃，其数据线性拟合的相关系数 $\gamma=0.9832$。根据这个关系式，可以预测各种温度下的计算值。

图 4 的情况说明，随着温度的升高，TC-11 钛合金的复合疲劳性能急剧下降，室温 150℃、300℃和 450℃，其结果差别都很大。这与文献[2]的结论“该热强钛合金在高温下使用更能发挥材料的优势，尤其在长期使用中材料的常规疲劳性能比较稳定”有较大差别，与常规强

度随温度的变化规律也截然不同。因此，当设计和预测 TC-11 钛合金的高温部件寿命时，高、低周复合疲劳问题应引起足够的重视。

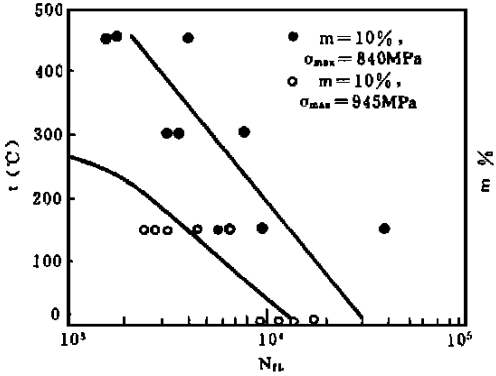


图 4　试验温度对复合疲劳寿命的影响

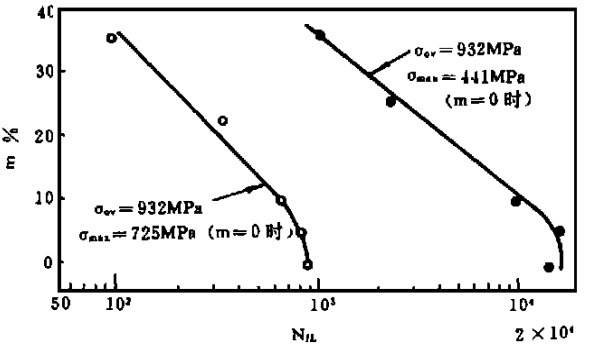


图 5　予拉伸超载条件下不同 m 值对高低周复合疲劳性能的影响

3. 预拉伸超载对单边缺口(SEN)试样高低周复合疲劳性能的影响　与其它材料相比，钛合金对变幅载荷及其序列效应非常敏感[3]，超载问题在现实飞行中却屡见不鲜，但并不因此而消耗使用寿命或提前破坏。这说明超载使局部应力集中区屈服，产生对疲劳有利的残余压应力，从而起着提高疲劳寿命的作用。

当预拉过载应力 σ_{ov}= 932MPa，后续疲劳应力 σ_{max}= 392MPa 时（应力比 R= 0.1），室温疲劳寿命增 6 倍。但 450℃下，由于过载所产生的残余压应力消失，其寿命的提高就很轻微。

预拉伸应力为 932MPa，其主循环梯形波的最大应力分别为 725 和 441MPa 时，不同 m 值对 TC-11 钛合金室温下高低周复合疲劳性能的影响如图 5 所示。由图可知，其规律与前述的 m 值对复合疲劳性能的影响完全相同，即 m-N_fL 曲线的拐点也大致在 m= 10%处，当 m> 10%时，m 与 N_fL 的关系明显地为一直线。当 m< 5%时，高周振动力的迭加几乎对复合疲劳寿命没有影响。

4. 高低周复合疲劳损伤累积模型及寿命预测　复合疲劳寿命预测的指导思想是已知常规的低周和高周疲劳寿命（N_L 和 N_h），应用合适的损伤累积模型，计算出其复合循环下的寿命 N_fL。作者[4]对 GH901 合金的复合疲劳及损伤累积进行过详细研究，其中包括线性、非线性和双线性累积损伤理论的分析。结果发现只要按照合适的波形分解方式来分解复合循环波，然后采用线性累积损伤模型可以得到满意的结果。分解波形的分析基础在于复合循环中，高周循环载荷与低循环载荷所造成的损伤是独立的，由此提出了三种波形的分解方式。表 3 列出了作者在 GH901 合金复合疲劳寿命估算过程中采用三种分解波形的方法进行预测的效果。

从表 3 可知，波形分解方式 c 的寿命预测效果最佳，所采用的损伤累积方程为：$1/N_fL = 1/N_L + n/N_h$，式中 N_L、N_h 分别为纯低周和高周的疲劳寿命，n 为迭加在梯形波平台上的高周循环数。

显然，a 方式的波形分解，使材料在峰值载荷上造成两次重复保载损伤，因此使实测值大大低于预测值。日本冈田友信等人采用第二种 b 分解波形方法，也得到了比较满意的结果。

作者认为从损伤累积原理出发，将复合波分解为三角波以及在某一平均应力下的高周波块之和更切合实际即 c 方式。事实证明了这种分解方式得到的估算效果更好。

据此，本文对 TC-11 钛合金室温下的复合循环疲劳寿命，同样用 c 分解方式进行预测，其

结果列于表 4, 从表中的数据可看出, 其预测值与实测值符合的较好。其预测寿命在两倍散度以内, 一般认为这样的结果是可以令人满意的。

表 3 用线性累积损伤模型预测值与实验值的比较

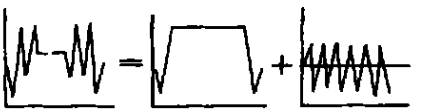
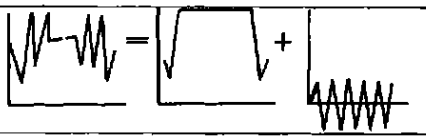
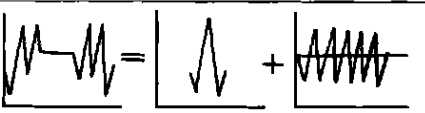
波形分解方法	试样	n	$N_{预测}/N_{实验}$	备注
a. 	圆形光滑	10 30	3.101 6.007	断裂
b. 	圆形光滑	10 30	0.988 0.908	断裂
c. 	圆形光滑	10 30	1.046 0.926	断裂
	板材	30	1.044	0.6mm 裂纹

表 4 当 m= 0、σ_{max}= 1000MPa 时, 复合疲劳寿命预测值与实验值的比较

m (%)		5	10	25	35
N_fL 预测 (周)		8094	3284	1515	298
N_fL 实验	平均值 (周)	8005	3934	1808	307
	单个试样值 (周)	8742、7335、12093 5007、6147	3561、5538、6541 3495、5515	1321、2833、1678 1135、2077	198、401、404 119、415

结论 (1) 模拟压气机叶片工况, 在梯形波上迭加高周振动应力对 TC-11 钛合金的疲劳寿命有明显影响, 尤其当 m= 35% 时, 其寿命降低 10 倍多, 因此, 设计时必须加以考虑。(2) 复合循环比 m 越大, 其寿命下降得越多, 在 m-lgN_fL 曲线上, 当 m= 10% 附近呈现出拐点。在拐点前曲线呈线性关系, 并可用本文给出的数学表达式估算各 m 值下的寿命; 在拐点之后高周应力的迭加对寿命的影响不明显。(3) 试验温度对 TC-11 钛合金复合疲劳性能的影响很强烈。当 m= 10%, σ_{max}= 945MPa, 从室温到 150℃其复合疲劳寿命约下降 1/3; 当温度升高到 300℃时, 没有加到预定应力试验就断裂。当 m= 10%, σ_{max}= 840MPa, 从 150℃升高到 450℃时, 其寿命下降十分厉害, 450℃下约为 150℃下的 1/7。(4) 预拉伸超载对该合金室温疲劳寿命的提高很明显, 当 σ_{ov}= 932MPa, 后续疲劳 σ_{max}= 392MPa 时, 其疲劳寿命增加约 6 倍。但在 450℃下, 由于拉伸过载所产生的残余压应力消失, 其疲劳寿命提高则很轻微。(5) TC-11 钛合金室温复合疲劳寿命可以用本文提出的线性损伤累积模型进行寿命预测。

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[2] 侯静泳, "TC-11 钛合金叶片振动疲劳特性研究", 技术总结, 621 所内部资料, 1987 年。

[3] Dundes R. E., "The Use of Performance Moniting to Prevent Compressor and Turbine Blade Failures", ASME, 82-GT-66.

[4] Hou J. Y., Dau B. F., and Xie J. Z., "The Investigation of High and Low Cycle Complex Fatigue Behaviours and Accumulative Damage for Alloy GH901", The Proceedings of ICM-6, Japan, 1990.

K_{IC}, additional extension δ_c and deviation of natural frequency f_c of the cracked blade, the failure criterion of the compressor blade is discussed and the critical crack length is determined. By the use of Pris formula and in consideration of the influence of high cycles on low cycle fatigue crack propagation, the damage tolerance life of the blade is obtained. As an example, a calculation of a certain compressor blade is given. In order to investigate the relation of natural frequency versus crack length, the vibration of compressor blades has been tested. The presented method can be used for the strength evaluation of turbo-jet engine.

FINITE ELEMENT ANALYSIS OF COMPLEX DISK BODY WITH ECCENTRIC HOLE

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ABSTRACT A strategy of discretization process for the 3-D disk body of complex cross-section has been developed on the basis of available functions of I-DEAS system. The cutting and mending techniques are employed to realize the mesh formation at the local regions of eccentric holes. In result, it is possible to solve effectively the contradiction between element distortion and over-large scale of solution, and thus the 3-D analysis of the disk with eccentric hole can be completed at one time. Also in this paper an engineering optimum method is provided by adjusting the thickness of the disk so as to control the stress level at the edge of holes.

HOLOGRAPHIC VIBRATION MEASUREMENT OF DISC-BLADE COUPLING IN HIGH-SPEED ROTATION

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ABSTRACT A new measuring technique is presented which combines holographic interferometry and image derotation to determine the behaviour of disc-blade coupling vibration during high-speed rotation. The measuring technique and its optical system have been verified by the test of a model circular disc. The primary test results of a real disc-blade coupling are given which show the obtained holograms of rotating members to correspond to the results of vibration theory analysis and frequency spectrograms. Therefore, it is possible to expect this technique to be an effective testing measure for aeroengine designing and troubleshooting.

RESEARCH ON HIGH-LOW CYCLE COMPLEX FATIGUE AND ACCUMULATIVE DAMAGE FOR Ti-ALLOY TC11

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ABSTRACT The high-low cycle complex fatigue behaviours of Ti-alloy TC11 were researched systematically at room and elevated temperatures. At the same time, the effects of complex stress ratio m, test temperature and prestress overload for SEN specimen on complex fatigue life N_{fL} were taken into consideration. The work comes to the conclusion that: The complex fatigue life decreases obviously with m increased, especially when $m=35\%$, the N_{fl} decreases more than 10 times, and there occurs a knee on the $m-\log N_{fL}$ curve near $m=10\%$. The complex fatigue of the alloy TC11 is very sensitive to test temperature

under the same m-ratio and LCF stress, as test temperature rises from room temperature to 150℃, the complex fatigue life N_{fL} drops by 66% under m= 10% and σ_{max}= 945MPa. If the temperature comes up continuously to 300℃, its fatigue life approaches to zero. In addition, a model of the accumulative damage for complex cyclic fatigue is formulated as follows: $1/N_{fL} = 1/N_L + n/N_h$.

A REAL-TIME RAIN-FLOW METHOD OF CYCLE COUNTING AND ITS PROGRAM DESIGN FOR AEROENGINE SERVICE LOADS

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ABSTRACT The paper presents briefly a real-time rain-flow method of cycle counting and its program design for the service loads of aeroengines. The concept of real-time counting and its value to engineering application are also discussed. A detailed program flow chart is given which can be used in software programming of small size airborne data processing equipment.

EXPERIMENTAL RESEARCH ON BLADE CONTAINMENT

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ABSTRACT This paper describes the blade containment tests for six sets of single model blade on a vertical breaking-down tester with excess revolution. The experimental results indicate that the blade body fragment flying off impacts against the model aeroengine case time and again. The incident angle of the blade fragment against the case in the initial impact is smaller than in the later impacts, the case damage of the first impact is smaller than that of the final impact, and the impacts of the blade fragment against the case make the blade fragment crimple. In principle the experimental results of the blade fragment containment and non-containment are consistent with the containment curve of single compressor blade (for use only in case of the blade body) in the Spey MK202 Stressing Standards (EGD-3) and are on the safe side. It is the preliminary conclusion that the containment curve of single compressor blade (for use only in case of the blade body) in EGD-3 can be used to predict the containment of the similar blade.

THE LOW-CYCLE-FATIGUE LIFE PREDICTION OF A MEMBER WITH HOLES

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ABSTRACT The stress and strain field and the low-cycle-fatigue life of a structure member with holes are calculated theoretically and investigated experimentally. The calculated results show that it is reliable to calculate the stress and strain field of a member with holes by using the shell-structural elasto-plastic finite element program, which has been designed and developed by the author. The satisfactory results are obtained from LCF life prediction of a member with holes by the advanced local stress and strain method. The calculation and tests show that the stress concentration of the tensile plane member is intensified and the fatigue life reduces drastically when its holes are densified in the direction perpendicular to that of tensile; the stress concentration is mitigated slightly but the fatigue life is also shortened when they are densified in the tensile direction.