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In-phase thermal–mechanical fatigue investigation on hollow single crystal turbine blades

Wang Rongqiao *, Jing Fulei, Hu Dianyin

School of Energy and Power Engineering, Beihang University, Beijing 100191, China

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Abstract Thermal–mechanical fatigue (TMF) is the primary cause of failure of nickel-based single crystal turbine blades. TMF experiments have been performed on the critical section which is subjected to the most serious damage and determined by numerical calculation combined with service failure experience. An experimental system including the loading, heating, air cooling, water cooling, and control subsystems, is constructed to satisfy the TMF experimental requirements. This experimental system can simulate the stress field, temperature field, air cooling process, and TMF spectrum on the critical section under service conditions in a laboratory environment. A metal loading device and a new induction coil are developed to achieve the required stress and temperature distributions on the critical section, respectively. TMF experimental results have indicated that cracks initiated at the trailing edge of the suction surface on the critical section. Based on these experiments, life prediction and failure analysis of hollow single crystal turbine blades can be investigated.

1. Introduction

The development of aero engines is continuously linked with a rise of turbine inlet temperature. As a result, the working environment of turbine blades has become increasingly severe. Advanced structural materials such as nickel-based single crystal superalloys and cooling schemes such as hollow blades with complex inner cavity and film cooling holes have been proved to be suitable for turbine blades.

The life-limiting factors for first-stage turbine blades are low cycle fatigue (LCF), thermal fatigue (TF), creep, and oxidation.[1] In particular, the combination of LCF, TF, and creep can introduce thermal–mechanical fatigue (TMF) which is identified as the primary cause of failure of single crystal turbine blades.[2,3]

So far, the majority of TMF experiments have been based on standard specimens[2–13] and blade-shaped samples.[1,14] However, few experimental investigations have been focused on the TMF of full-scale turbine blades.[15,16] Some features such as the multiaxial stress state generated in the blades and the temperature gradients generated in the edge regions of film cooling holes and pin-fins during start-up and shut-down operations cannot be well simulated with standard specimens as well as blade-shaped samples. Besides, the differences between turbine

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* Corresponding author. Tel.: +86 10 82313841.
E-mail addresses: wangrq@buaa.edu.cn (R. Wang), jingfulei@163.com (F. Jing).

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blades and standard specimens in manufacturing and processing may cause significant differences in their mechanical performances and life distributions.[15] On the other hand, it is difficult to estimate the life of turbine blades because of the complexity of simulation of the damage factors acting under service conditions.[16] Therefore, it is necessary and important for life prediction and failure analysis to carry out TMF experiments on full-scale turbine blades.

The objective of this study is to develop an experimental method, which can simulate the loading and anisothermal conditions experienced by hollow single crystal turbine blades.

2. Experimental scheme

2.1. Experimental requirements

Laboratory testing of entire turbine blades is both difficult and uneconomic.[15,17] Generally, it is believed that the life of turbine blades depends on the life of the critical section which is subjected to the most serious damage.[16] Therefore, TMF experiments have been performed on the critical section determined by numerical calculation combined with service failure experience of turbine blades. The cyclic stress and temperature fields experienced by the critical section during service have been simulated in these experiments.

The specimens are first-stage turbine blades made of nickel-based single crystal superalloy DD6. As shown in Fig. 1, the critical section is located in the middle of the blade. Six points on the critical section are chosen as the test points for measuring stresses and temperatures as shown in Fig. 2.

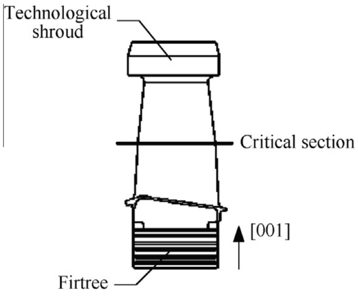

Fig. 1 Critical section (front view).

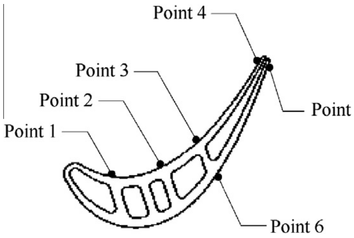

Fig. 2 Test points on the critical section (top view).

The temperature and stress distributions generated in turbine blades under service conditions are calculated with thermal and mechanical analysis, respectively. Then, as shown in Table 1, the peak stresses in the orientation [0 0 1] and the temperatures at the test points on the critical section are regarded as the targets of experimental simulation. Because test points 1, 2, and 6 are located near the film cooling holes, the temperatures at these points are lower than those at others. It can be seen from Table 1 that test points 3, 4, and 5 are subjected to more damages than others, and hence the errors between the calculation and the experiment at these critical points should be minimized.

Table 1 Peak stresses and temperatures at the test points.

Test point	Stress (MPa)	Temperature (°C)
1	216	755
2	232	874
3	254	895
4	167	1022
5	230	926
6	172	711

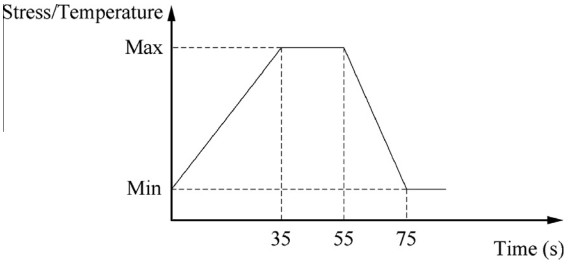

Fig. 3 TMF spectrum.

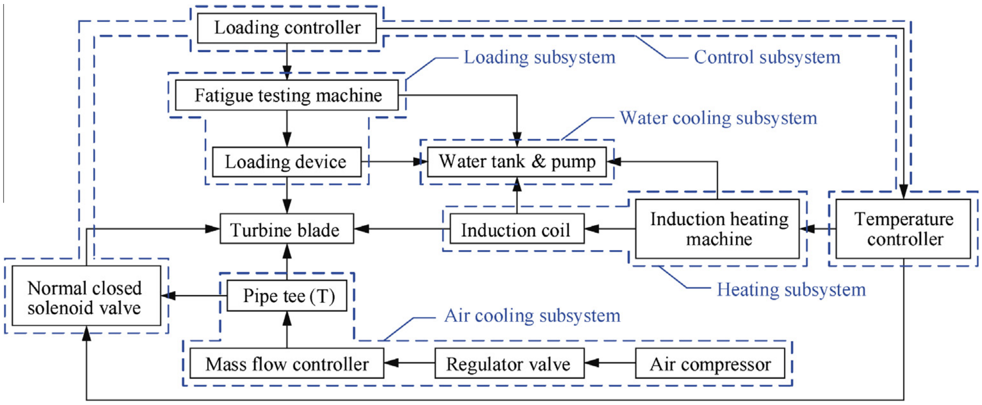

Fig. 4 TMF experimental system.

In addition, the TMF spectrum is simplified as a trapezoidal wave, and the temperature is in phase with the mechanical load as shown in Fig. 3. Meanwhile, the changes of cooling air