复杂载荷高温超高频疲劳原位测试仪器设计研制与试验研究

Development and Experimental Research of High-temperature Ultra-high-frequency Fatigue In situ Test Apparatus under Complex Loads

摘 要

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航空发动机被誉为现代工业的“皇冠”，是国家经济水平、科技水平和军事水平等的综合体现。转子叶片是决定航空发动机性能的核心部件，其服役工况非常恶劣：高速旋转导致的巨大离心力，叠加于离心力上由于高速气流吹拂导致的弯曲载荷和扭转载荷，归因于空气动力学因素以及机械原因的高频振动，燃料燃烧引起的高温环境，以及湿热环境、腐蚀环境等。目前，正确评估叶片材料在极端环境与复杂条件下的超高周疲劳行为已经成为了广大工程设计人员持续关注的热点工作。然而，由于缺乏专用的测试仪器与测试方法，上述工作的开展受到严重制约。因此，开展专用超高周疲劳测试仪器研制与测试方法研究，进而评估叶片材料在极端环境与复杂条件下的超高周疲劳行为，对于保障航空发动机服役安全性、指导新一代叶片的材料选取、结构设计与制造意义重大。

面向航空发动机叶片材料极端环境与复杂条件下超高周疲劳测试的重大需求，以及专用测试仪器与测试方法匮乏的现状，本文对现有复杂条件超高周疲劳测试技术进行了系统调研，并从理论角度分析了高温和复杂静动态载荷对材料力学性能的耦合影响规律。在上述基础上，设计研制了性能稳定可靠的复杂载荷高温超高频疲劳原位测试仪器。基于自研仪器，开展了典型航空发动机叶片材料高温复杂载荷下的静力学行为研究以及超高周弯曲疲劳行为研究。本文的主要研究工作如下：

(1) 高温复杂静动态载荷下材料力学性能测试理论研究。截止目前，高温和复杂载荷对叶片材料复合变形和弯曲振动的耦合影响规律尚未得到充分了解。在上述背景下，本文对高温复杂静动态载荷下的材料力学性能测试理论开展研究。推导了一维均质梁在高温组合拉伸-弯曲下的复合变形理论，分析了高温、拉伸和弯曲载荷对一维弹性梁复合变形的耦合影响规律。推导了悬臂梁在高温组合拉伸-弯曲下的动态测试理论，研究了高温环境和轴向拉伸载荷对一维弹性梁一阶和二阶弯曲振动频率的影响。

(2) 复杂载荷高温超高频疲劳性能原位测试仪器的研制。本文面向航空发动机叶片材料极端环境与复杂条件下超高周疲劳测试的重大需求，开展了仪器功能分析与架构设计，研制了静动态力学加载、超高频加载、温度加载、原位监测、数据采集与控制等软硬件模块。开展了仪器整机的集成调试与标定校准，形成了性能稳定可靠的复杂载荷高温超高频疲劳性能原位测试仪器。开展了仪器各模块性能测试和特色功能验证试验，验证了仪器的可靠性与适用性。

(3) 典型航发叶片材料高温复杂载荷下的静力学行为试验研究。基于自制仪器，开展了典型航发叶片材料 TC4 合金和 Inconel 718 合金高温复杂载荷下的静力学行为的试验研究。揭示了高温、拉伸载荷和弯曲载荷对 TC4 合金和 Inconel 718 合金复合变形行

为的耦合影响规律，系统对比了等轴、双态和魏氏组织 TC4 合金的组合拉伸-弯曲性能。此外，揭示了高温、拉伸载荷和弯曲载荷对双态组织 TC4 合金的弹塑性力学行为和失效机制的耦合影响规律。

(4) 典型航空发动机叶片材料复杂载荷下超高周弯曲疲劳行为试验研究。基于自制仪器，开展了典型航发叶片材料 TC4 合金和 Inconel 718 合金复杂载荷下超高周弯曲疲劳行为试验研究。通过试验研究了轴向拉伸载荷对 TC4 合金和 Inconel 718 合金超高周弯曲疲劳行为的影响，得出了组合拉伸-弯曲下材料的应力-寿命关系。此外，基于 Webull 理论初步建立了组合拉伸-弯曲下材料的超高周疲劳寿命预测模型，从理论角度揭示了拉伸载荷和弯曲载荷对材料超高周疲劳寿命的耦合影响规律。

本文面向航空发动机叶片材料服役性能测试的重大需求，攻克了静动态机械载荷复合、高低温连续变温、复杂静动态力-热耦合等关键技术，研制了性能稳定可靠的复杂载荷高温超高频疲劳原位测试仪器。该仪器为航空发动机叶片材料极端环境与复杂条件下的服役性能测试提供了一种可行性技术手段，仪器在航空、航天、核工业、汽车、轨道交通等领域核心零部件材料测试中具有广泛的应用前景。

关键词：

复杂载荷，高温，仪器，航空发动机，叶片材料，原位测试

Abastract

Development and Experimental Research of High-temperature Ultra-high-frequency Fatigue In-situ Test Apparatus under Complex Loads

The rotor blades of aircraft engine are the key components that determine the performance of the engine, and they are subject to extremely harsh service conditions: the huge centrifugal force resulting from high-speed rotation, the bending and torsional loads caused by the high-speed airflow, the high-frequency vibration caused by the aerodynamic factors and mechanical reasons, the high-temperature environment caused by fuel combustion, as well as the wet and hot environment, and corrosive environment. At present, it has become a hot issue for engineers to correctly evaluate the very-high-cycle fatigue behavior of blade materials under extreme conditions and complex conditions. However, the development of such work is severely restricted due to the lack of dedicated test apparatus and testing methods. Therefore, it is of great significance to develop dedicated very-high-cycle fatigue testing apparatus and testing methods to evaluate the very-high-cycle fatigue behavior of blade materials under extreme conditions and complex conditions, to safeguard the safety of aircraft engine operation, guide the selection of materials, structure design and manufacturing of new generation blades.

The paper systematically investigates the existing complex condition very-high-cycle fatigue testing technology, and analyzes the coupling effect of high-temperature and complex loads on the mechanical properties of materials from a theoretical perspective. On this basis, a high-temperature ultra-high-frequency fatigue in-situ test apparatus under complex loads is developed. Based on the self-developed apparatus, the static and dynamic behavior research of typical aeroengine blade material under high-temperature and complex loading, as well as the very-high-cycle bending fatigue behavior research are carried out. The main research work of this paper is as follows:

(1) The theoretical research of material mechanics performance test under high-temperature and complex static-dynamic load. Up to now, the coupling influence rule of composite deformation and bending vibration of blade material under high-temperature and complex load has not been fully understood. In this context, this paper carries out the theoretical research of material mechanics performance test under high-temperature and complex static-dynamic load. The composite deformation theory of one-dimensional homogeneous beam under the combination of high-temperature tension-bending was deduced, and the coupling influence rule of high temperature, tension and bending on the composite deformation of one-dimensional elastic beam was analyzed. The dynamic test theory of cantilever beam under the combination of high temperature tension-bending was deduced, and the influence of high-temperature environment and axial tension on the first-order and second-order bending vibration frequency of one-dimensional elastic beam was studied.

(2) Development of high-temperature ultra-high-frequency fatigue in-situ test apparatus under complex loads. In response to the major needs of very-high-cycle fatigue test under extreme environment and complex conditions of aero-engine blade material, this paper conducts a functional analysis and framework design of the apparatus, develops the modules of static-dynamic mechanical loading, ultra-high frequency loading, temperature loading, in-situ monitoring, data acquisition and control, and so on. The integration and debugging of the whole apparatus and calibration are carried out, forming the high-temperature ultra-high-frequency fatigue in-situ test apparatus under complex loads with stable and reliable performance. Various module performance tests and characteristic function verification tests are conducted to verify the reliability and applicability of the apparatus.

(3) Experimental study on the static behavior of typical aero-engine blade materials under high-temperature and complex loading. Based on the self-made apparatus, this paper carries out experimental study of the static mechanical behavior of typical aero-engine blade materials TC4 alloy and Inconel 718 alloy under high-temperature and complex loading. The coupling effect rules of high-temperature, tension and bending on the composite deformation behavior of TC4 alloy and Inconel 718 alloy were revealed. The combined tension-bending performance of equiaxed, bimodal and Widmanstatten structures of TC4 alloy were systematically compared. In addition, the coupling effects of high-temperature, tension and bending on the elastic-plastic mechanical behavior and failure mechanism of bimodal structured TC4 alloy were revealed.

(4) Experimental study of very-high-cycle bending fatigue behavior of typical aero-engine blade materials under complex loading. Based on the self-made apparatus, an experimental study on the very-high-cycle bending fatigue behavior of typical aero-engine blade materials TC4 alloy and Inconel 718 alloy under complex loading was carried out. The effect of axial tension load on the fatigue behavior of TC4 alloy and Inconel 718 alloy in very-high-cycle bending was investigated, and the stress-life relationship of the materials under combined tension-bending was derived. In addition, based on Weibull's theory, the prediction model of very-high-cycle fatigue life of materials under combined tension-bending was initially established, and the coupling effect law of tension and bending on the very-high-cycle fatigue life of materials was revealed from the theoretical point of view.

This article is aimed at the major requirements of aviation engine blade material service performance testing, and overcomes the key technologies of composite static and dynamic mechanical loads, continuous temperature change of high and low temperatures, complex static and dynamic force-thermal coupling, etc. A performance stable and reliable high-temperature ultra-high-frequency fatigue in-situ test apparatus under complex loads is developed. The apparatus provides an innovative technical means for the performance testing of aviation engine blade materials under extreme environment and complex conditions, and has a wide range of

applications in the testing of key components and materials in the fields of aviation, aerospace, nuclear industry, automobile, rail transportation, etc.

Key words:

Complex loads, High-temperature, Apparatus, Aero engines, Blade materials, In-situ testing