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基于双尺度损伤理论的高温结构寿命预测方法及应用

摘要

高温结构的长寿命安全运行与其严苛服役环境之间的矛盾日益凸显，基于单一损伤驱动力模型的寿命设计方法无法有效评估多损伤交互模式和多尺度损伤特性，从而对高温结构的失效机理和服役寿命缺乏精准的预测。本文从涡轮盘用材料镍基高温合金GH4169损伤致裂的物理本质出发，系统研究了该材料在不同循环载荷下的多损伤交互行为和失效机理，从而发展了基于宏观连续介质-微观晶体塑性的双尺度建模方法、损伤理论和寿命预测技术，以服务于双尺度理论体系的工程化应用。论文主要研究工作与结论如下：

（1）多损伤交互行为和失效机理。为了探究材料在高温下的多损伤交互行为，对GH4169合金在650 ℃下展开了一系列循环性能试验，包含低周疲劳、蠕变-疲劳以及高低周复合蠕变-疲劳试验。首先，基于宏观力学行为和微观表征手段，揭示了该合金在不同循环加载模式下的损伤机理，其中高低周复合蠕变-疲劳寿命显著低于低周疲劳和蠕变-疲劳寿命，这种多损伤交互的加载模式诱导了晶内多滑移系的开动，从而位错沿着不同滑移方向滑动并形成交叉滑移带。其次，通过建立考虑静力回复项的晶体塑性模型，以描述该合金在不同载荷工况下的应力松弛行为，并基于改进的晶体塑性模型提出了一种考虑能量耗散的损伤指示因子，该指示因子可以有效地揭示GH4169合金在不同加载模式下的损伤演化规律。最后，发展了一种基于损伤指示因子的寿命预测方法，该方法可以精准地预测多损伤交互模式下的裂纹萌生寿命。上述工作基于宏-微观试验和晶体塑性理论，初步建立了多损伤交互作用下实现精准寿命预测的技术途径，为后续双尺度损伤理论体系的构建提供了扎实的理论基础。

（2）双尺度损伤理论体系。为了满足晶体塑性模型在高温结构件中的适用性，本文提出了基于全局连续介质-局部晶体塑性的双尺度理论体系，以实现高温结构宏观几何特征和微观损伤机理的定量关联。在建模方法层面，以单边缺口蠕变-疲劳试样为研究对象，分别建立缺口试样宏观有限元模型和缺口根部晶体塑性有限元模型，并将宏观模型的位移场作为局部晶体塑性模型的边界条件以实现关键位置的微观模拟。通过与传统建模方法对比发现，所提出的双尺度建模方法具有较高的计算效率以及较精准的损伤评估。基于此，探究了晶粒取向与应力集中系数对 GH4169 合金蠕变-疲劳裂纹萌生行为的共同影响，并建立了一种用于描述高温结构蠕变-疲劳裂纹萌生行为的特征区域图。在损伤理论与寿命预测层面，以高温含孔结构为例，所发展的双尺度损伤理论不仅可以合理地揭示含孔结构蠕变-疲劳裂纹萌生机理，还可以精准地预测蠕变-疲劳裂纹萌生寿命，从而为高温结构的寿命设计和工程应用提供了重要的理论支撑。

（3）双尺度损伤理论的工程化应用。表面强化技术是提升高温结构服役寿命和可靠性的重要手段，而表面强化效应体现了双尺度的本质，即宏观几何尺寸的改变以及微

观梯度组织的形成，因此基于上述双尺度理论可以精准地揭示高温结构寿命增益的强化机制。在试验方面，针对高温结构中常见的含孔结构和缺口结构，分别通过冷挤压和水射流工艺进行表面强化，以显著提升高温结构疲劳和蠕变-疲劳寿命。在模拟方面，通过双尺度模拟方法定量评估了残余应力和塑性层对寿命性能的影响规律，确定了高温结构疲劳寿命提升的主导因素，从而构建了一套考虑表面强化效应的工艺-性能-预测一体化集成系统。此外，针对表面强化技术对提升高温结构的蠕变-疲劳性能存在一定局限性的问题，进一步发展了一种考虑蠕变晶界退化的双尺度损伤理论，揭示了表面强化结构的蠕变-疲劳损伤机理，从而丰富了双尺度理论体系的物理内涵。为了实现双尺度损伤理论在表面强化上的工程应用，发展了一种耦合多损伤机理和双尺度理论的代理模型以及寿命预测系统。

以承受蠕变-疲劳载荷的某型航空涡轮盘为例，利用本文提出的双尺度损伤理论体系，系统评估了涡轮盘危险区域在起飞-低空巡航-高空巡航-降落阶段的损伤演化，有效预测了高温结构在循环加载工况下的裂纹萌生行为，从而证明了该双尺度损伤理论体系具有潜在工程应用推广的价值。本文研究成果对丰富和发展高温结构的寿命设计理论，促进我国先进航空发动机长寿命的自主创新具有一定的工程应用价值。

关键词：双尺度建模；蠕变-疲劳；损伤理论；寿命预测；高温结构

A Life Prediction Method Based on Dual-Scale Damage Theory and Its Application on High-Temperature Structures

Abstract

The contradiction between the long-term safe operation of high-temperature structures and harsh service environment is becoming increasingly prominent. The life design methods based on single damage driving-force model cannot effectively evaluate the multi-damage interaction and multi-scale characteristics, resulting in a lack of accurate prediction for the failure mechanisms and in-service life of high-temperature structures. The physical essence of damage induced cracking in nickel-based superalloy GH4169 is investigated by a series of experiments. Then, dual-scale modelling approach, damage theory and life prediction model are developed by combining continuum mechanics and crystal plasticity. Finally, the proposed dual-scale numerical theory is further applied by means of a certain type of aero-engine turbine disk. The main conclusions have been drawn as follows:

(1) Multi-damage interation and failure mechanisms. In order to expore the interaction of multi-damage modes at high temperatures, a series of high-temperature fatigue properties tests, containing low cycle fatigue, creep-fatigue and high-low combined creep-fatigue, are carried out in nickel-based superalloy GH4169 at 650 °C. Firstly, the damage mechanisms of this alloy under different cyclic loadings are revealed based on macro-scale mechanical behavior and microstructure characterization methods. The crack initiation life under high-low combined creep-fatigue loading is significantly lower than that under low cycle fatigue and creep-fatigue loading. This multi-damage interaction mode induces the activation of multi-slip systems in grains, resulting in dislocations sliding along different slip directions and forming cross slip bands. Moreover, the crystal plasticity model is improved by introducing a static recovery term in the kinematic hardening rule to describe stress relaxation behavior under different loading levels. A life prediction method is developed based on a damage indicator parameter represented by accumulated energy dissipation, which can accurately predict the crack initiation life under different loading conditions. The technical approach of accurate life prediction under multi-damage interactions is preliminarily explored based on the macro-and-micro experiments and crystal plasticity theory, which provides a plastic theoretical foundation for subsequent dual-scale modeling approach.

(2) Dual-scale damage theory system. In order to meet the applicability of crystal plasticity model in high-temperature structures, a dual-scale theoretical system is developed based on the combination of macro-scale continuum mechanics and crystal plasticity to achieve the quantitative correlation between geometric characteristics and damage

mechanisms. From the modelling perspective, the macro-scale finite element model of the notched specimens and the crystal plasticity finite element model at the notched root are established, respectively. The displacement field of the macro-scale model is used as the boundary condition of the local crystal plasticity model to achieve micro-scale simulation at the critical positions. The proposed dual-scale modeling apparoach exhabits high computational efficiency and accurate damage assessment by comparising with traditional modelling methods. Based on this, the effects of grain orientation and stress concentration factor on creep-fatigue crack initiation are investigated. In addition, a feature region map is established based on the quantitative analysis of grain orientation and stress concentration factor to describe creep-fatigue crack initiation behavior. From the perspectives of damage theory and life prediction, taking high-temperature holed structures as the example, the developed dual-scale theoretical model can not only reasonably reveal creep-fatigue crack initiation mechanism, but also accurately predict creep-fatigue crack initiation life. It provides an important theoretical support for the life design and engineering application of high-temperature structures.

(3) Engineering application of dual-scale damage theory. Surface strengthening technology can effectively improve the in-service life and reliability of high-temperature structures. The surface strengthening effect reflects the essence of dual-scale, namely the changes in macro-geometric dimensions and the formation of gradient microstructures. Thus, the strengthening mechanisms in cyclic life of high-temperature structures can be effectively clarified with the aid of the dual-scale theoretical system. From the experimental perspective, the high-temperature holed and notched structures are strengthened by close-loop cold expansion cold and abrasive waterjet peening to significantly improve the fatigue performance of the structures. From the simulation perspective, the effects of residual stress and plastic layer on fatigue life improvement are quantitatively evaluated, where residual stress is the dominated factor to improve fatigue life. Then, a close-loop process-performance-prediction integration is developed by considering surface strengthening effect based on the dual-scale modelling approach. In order to address the limitations of surface strengthening technology in improving the creep-fatigue life of high-temperature structures, a dual-scale damage theory considering the combination of plastic slip and grain boundary degradation is further developed. Based on this, the creep-fatigue damage mechanism of surface strengthening structures is revealed and the physical connotation of the dual-scale theoretical system is enriched. Finally, in order to realize the engineering application of the dual-scale damage theory, a surrogate model and life prediction system were developed by combining the multi-damage mechanisms and dual-scale theory.

The creep-fatigue behavior in a certain type of aero-engine turbine disk is described based on the dual-scale damage theory system. The damage evolution of the dangerous location of the turbine disk are systematically evaluated under steady-state cycles. The creep-fatigue crack initiation behavior of the structure effectively predicted, thereby proving the profound significance of the dual-scale damage theory system for engineering application. The outcomes of this dissertation not only offer an accurate life design theory for high-temperature structures, but also demonstrate its potential application to long service life and high reliability of advanced aviation engines.

Keywords: Dual-scale modelling; Creep-fatigue; Damage theory; Life prediction; High-temperature structures