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博士学位论文

题目 航空金属部件飞秒激光表面强化耐磨损/抗疲劳机理研究

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摘 要

先进战机及发动机机械系统中大量金属接触部件通常在承受疲劳载荷的同时表面经历微动、滑动或滚动等摩擦载荷，诱发磨损/疲劳复合损伤，导致部件服役寿命大幅降低，严重影响飞行安全和部队战斗力。激光冲击强化、喷丸、涂层等表面强化技术是提升金属材料耐磨损或抗疲劳性能的重要手段，但对接触部件强化存在一定局限。主要原因是磨损与疲劳损伤机理不同，磨损是由局部接触载荷相对滑动导致的材料损失或表面破坏，而疲劳是由外界交变应力引起的材料表面裂纹萌生和扩展，并最终发生断裂。复合损伤不同于单一损伤模式，因此，亟需创新表面强化理论与工艺，同时兼顾材料磨损/疲劳性能，实现两者复合调控。

论文针对航空金属部件在磨损/疲劳交互作用下服役寿命提升的重大需求，在 xx 等项目支持下，创新提出利用飞秒激光在材料表层制备耐磨损表面周期性结构和抗疲劳梯度组织结构实现性能复合调控的学术思路，围绕飞秒激光辐照超快动力学特性、表面周期性结构形貌调控、梯度组织特征及强韧化机制、性能验证及强化机理等内容开展研究。主要结论如下：

（1）采用泵浦探测技术表征了钢材料飞秒激光辐照表面烧蚀形貌和冲击波瞬态演化过程，阐明了飞秒激光烧蚀机理及冲击波动力学特性。在飞秒激光辐照后的皮秒时间尺度，观测到材料熔化及随后熔融体不稳定性流动，结合 Drude 模型揭示了飞秒激光辐照诱导非热电子激发到晶格热熔化的固-液转移机制，同时证实该熔化现象与激光能量密度密切相关，随激光能量密度的提升，熔化时刻前移，熔融体流动加剧。阐明飞秒激光诱导冲击波传播形式、速度等本征参数，基于 Sedov 点爆炸理论建立了冲击波初始压强计算模型，计算得到冲击波初始压强为百 GPa 量级，揭示了激光能量密度和脉冲数对冲击波特性的影响规律，分析了高能量密度和多脉冲激光辐照导致冲击波初始压强降低机制。

（2）建立了飞秒激光诱导表面周期性结构形貌与工艺参数映射模型，揭示了表面周期性结构形成机制和磨损行为。表征了不同工艺参数下表面周期性结构形貌特征，基于能量累积效应建立了表面周期性结构形貌与工艺参数的映射模型，

发现随着激光沉积能量密度的提升，表面周期性结构形貌依次转变为条纹状高频结构→条带状低频/条纹状高频复合结构→包状低频结构。结合超快成像表征结果，基于电磁干涉与流体动力学理论揭示了其形貌演化机制，认为随着激光沉积能量密度的提升，熔融体不稳定性流动效应不断增强并逐渐占据主导作用，由此产生表面周期性结构形貌的改变。在微纳尺度表征了不同类型表面周期性结构磨损性能，基于能量势垒理论揭示了表面周期性结构磨损性能各向异性产生机制。

（3）阐明了钢材料飞秒激光冲击诱导梯度组织特征及力学性能，揭示了梯度组织变形行为及强韧化机制。表征了飞秒激光冲击作用下表层残余应力和硬度梯度分布特征，强化后表面残余压应力达到 500 MPa，影响层深度 60-110 μm，表面硬度提升 40%，硬化层厚度 60-130 μm。阐明飞秒激光冲击诱导梯度位错和表面纳米晶分布特征，结合分子动力学仿真揭示了超高压冲击波作用下位错形核和以位错主导的晶粒细化机制。研究了梯度组织在不同应变阶段的变形特征，阐明了梯度组织非均匀变形诱导的微观组织演化规律，认为梯度组织优异的强度-塑性匹配源于非均匀变形诱导的背应力对软质层的强化和前应力对硬质层软化的共同作用。

（4）验证了钢材料飞秒激光表面强化后磨损和疲劳性能增益，阐明了飞秒激光表面强化机理。对磨损/疲劳复合载荷进行解耦合分析，分别研究了飞秒激光表面强化层在单一载荷作用下的性能增益和损伤行为，强化后试件微动磨损量降低 48%，高周疲劳极限提升 6.4%。之后进行复合载荷性能验证试验，实现强化后航空液压导管部件旋弯疲劳寿命提高 4.8 倍。分析认为飞秒激光诱导的表面周期性结构主要通过转变磨损界面接触模式、应力分散和次表面加工硬化层抑制犁切等效应提升材料磨损性能，而在超高压冲击波作用下材料表层高幅值残余压应力和强韧化梯度组织结构的引入则延缓了疲劳裂纹的萌生和扩展速度，提升了材料的疲劳性能。

关键词：磨损/疲劳复合损伤，飞秒激光，表面周期性结构，冲击波，梯度组织

Abstract

A large number of metal contact parts in mechanical systems of advanced aircraft and engine usually experience friction loads such as fretting, sliding or rolling while bearing fatigue loads, which usually induces wear/fatigue compound damage. It would result in a significant reduction in the service life of the parts, and seriously affect the flight safety and fighting capacity of the army. Surface strengthening technologies such as laser shock peening, shot peening and coating are important means to improve the wear and fatigue properties of materials, but there are certain limitations on the strengthening of contact parts mentioned above. The main reason is that the mechanism of wear and fatigue damage is different. Wear is the material loss or surface damage caused by the relative sliding of local contact load, while fatigue is the crack initiation and propagation caused by external alternating stress. The compound damage is different from the single damage mode, so it is urgent to develop the novel surface strengthening theory and technology to achieve the synergitic regulation of both.

Aiming at the major demand of improving the service life of aviation metal components under wear/fatigue interaction, this paper creatively puts forward an academic idea of using femtosecond laser to induce wear-resisting periodic surface structure (LIPSS) and fatigue-resisting gradient structure on the surface of materials to achieve the regulation of both with the support of XX Project. In this paper, ultrafast dynamics characteristics of femtosecond laser irradiation, LIPSS structure and morphology regulation, gradient structure characteristics and strengthening-toughening mechanism, performance verification and strengthening mechanism are studied. The main conclusions are as follows:

(1) The transient evolution of ablation morphology and shock wave induced by femtosecond laser for steel are studied using pump and probe technique, and the

femtosecond laser ablation mechanism and shock wave dynamics are elucidated. On the picosecond time scale after femtosecond laser irradiation, the material melting and the subsequent unstable flow of molten mass are observed. Combined with the Drude model, the solid-liquid transfer mechanism from non-thermal electron excitation to the lattice thermal melting by femtosecond laser irradiation is revealed. And it is also confirmed that this melting phenomenon is closely related to the laser energy density. With the increase of the laser energy density, the melting time moves forward and the melt flow intensifies. The intrinsic parameters of femtosecond laser-induced shock wave such as propagative form and velocity are elucidated, and the initial pressure calculation model of shock wave is established based on Sedov’s point explosion theory. The initial pressure of shock wave is calculated to be on the order of hundreds of GPa, and the influence of laser energy density and pulse number on shock wave characteristics is revealed. The mechanism of initial pressure reduction caused by high energy density and multiple pulse laser irradiation is analyzed.

(2) A mapping model between LIPSS morphology and process parameters is established, the forming mechanism and wear behavior of different types of LIPSS is revealed. The morphology characteristics of LIPSS under different process parameters are characterized. Based on energy accumulation effect, a mapping model between the LIPSS morphology and process parameters is established. It is found that with the increase of laser deposition energy density, the LIPSS morphology evolves as following: high spatial frequency ripple-like LIPSS→high spatial frequency ripple-like/low spatial frequency ribbon-like compound LIPSS→low spatial frequency hill-like LIPSS. Combined with the results of ultrafast imaging, the mechanism of morphology evolution is revealed based on electromagnetic interference and fluid dynamics theories. It is believed that with the increase of laser deposition energy density, the unstable flow effect of the molten mass is continuously enhanced and gradually occupies a dominant role, thereby resulting in changes in LIPSS morphology. In addition, the wear performance of different types of LIPSS are characterized at

micro-nano scales, and the friction anisotropy mechanism of LIPSS is revealed based on the geometry-induced energy barrier theory.

(3) The distribution characteristics and mechanical performance of gradient microstructure induced by femtosecond laser shock peening are illustrated, and the deformation behavior and strengthening-toughening mechanism of gradient microstructure are revealed. The gradient distribution characteristics of surface residual stress and hardness under the effects of shock wave are characterized. After processing, the surface compressive residual stress reaches 500 MPa, and the depth of affected layer is 60-110 μm. Moreover, the surface hardness is increased by 40%, and the thickness of hardened layer is 60-130 μm. The characteristics of gradient dislocation and surface nanocrystallization are elucidated. Based on the results of molecular dynamics simulation, the dislocation nucleation and the dislocation-dominated grain refinement mechanism under the effects of ultra-high pressure shock wave are revealed. The deformation characteristics of gradient microstructure at different strain stages are studied, and the gradient microstructure evolution induced by non-uniform deformation is revealed. It is considered that the superior strength and plasticity of gradient microstructure is due to the joint action of the strengthening effects of back stress on the soft layer and the toughening effects of forward stress on the hard layer.

(4) The effect of femtosecond laser surface strengthening technology on the wear and fatigue performance of steel is verified, and the strengthening mechanism of LIPSS and gradient microstructure indcud by femtosecond laser is revealed. The performance gain and damage behavior of the processed specimens under single load are studied by decoupling analysis of wear/fatigue load. After processing, the fretting wear mass is reduced by 48% and the high-cycle fatigue limit is increased by 6.4%. Then, the fatigue test under wear/fatigue compound loads is carried out, and the bending fatigue life of the treated aircraft hydraulic pipe is increased by 4.8 times as compared with that of untreated one. It is analyzed that the LIPSS induced by femtosecond laser improves the wear performance of the material mainly through

changing the contact mode of the wear interface, stress dispersion effects and ploughing inhibition effects by subsurface work-hardened layer, while the fatigue performance improvement is attributed to the introduction of high amplitude compressive residual stress and gradient structure induced by ultra-high pressure shock wave to prevent the fatigue cracks initiation and propagation.

Keywords: Wear/fatigue compound damage, Femtosecond laser, Periodic surface structure, Shock wave, Gradient microstructure