单晶高温合金近服役环境下的变形损伤行为

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摘 要 镍基单晶高温合金是航空发动机和燃气轮机涡轮叶片的核心材料，其在高温、复杂应力及环境耦合作用下的变形损伤行为，直接影响叶片服役安全与寿命。本文系统综述了近年来单晶高温合金在蠕变、疲劳及热机械疲劳等方面的研究进展，重点分析了在多场耦合条件下微观组织的演化规律和损伤机制。在蠕变方面，总结了薄壁效应、热腐蚀及多轴应力对性能的影响，揭示了超高温、长时服役和非等温蠕变中的新现象与新机制；在疲劳方面，阐明了从低周、高周到超高周疲劳条件下裂纹萌生机制的转变规律，探讨了热-力-环境耦合与多轴应力的协同作用，并强调了表面状态和结构特征在构件疲劳中的关键影响；在热机械疲劳方面，探讨了相位关系、晶体取向、合金元素及涂层/基体交互作用对损伤行为的影响。最后评述了原位表征技术在揭示变形损伤机理中的应用和进展，并展望了本领域的未来研究方向。

关键词 单晶高温合金，近服役，蠕变，疲劳，热机械疲劳

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Deformation and Damage Behavior of Single Crystal Superalloys Under Near-Service Conditions

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ABSTRACT Ni-based single crystal superalloys are key materials for turbine blades in aero-engines and gas turbines. Their deformation and damage behavior under the coupled effects of high temperature, complex stress states, and harsh environments directly affects blade service safety and lifespan. This pa-

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per systematically reviews recent research progress on single-crystal superalloys with respect to creep, fatigue, and thermo-mechanical fatigue (TMF), with an emphasis on the evolution of microstructures and damage mechanisms under multifield coupling conditions. For creep, the effects of thickness debit, hot corrosion, and multiaxial stress on material properties are summarized, and emerging phenomena and mechanisms associated with ultra-high-temperature exposure, long-term service, and nonisothermal creep are discussed. For fatigue, the transformation of crack initiation mechanisms under low-cycle, high-cycle, and very-high-cycle fatigue conditions is clarified; the synergistic effects of thermo-mechanical-environment coupling and multiaxial stress are examined; and the critical roles of surface condition and structural characteristics in component fatigue performance are highlighted. For TMF, the influences of phase relationship, crystal orientation, alloying elements, and coating-substrate interactions on damage behavior are reviewed. Additionally, this paper reviews the application and progress of *in situ* characterization techniques for elucidating deformation and damage mechanisms. Finally, future research directions in this field are outlined.

KEYWORDS single crystal superalloy, near-service, creep, fatigue, thermal-mechanical fatigue

随着航空发动机和燃气轮机向高推重比、高效率和长寿命方向不断发展，其热端部件，特别是单晶涡轮叶片，面临着日益苛刻的服役环境。这些部件不仅长期承受高温、高应力的作用，还需应对循环载荷、剧烈温度变化以及氧化/热腐蚀等多场耦合的极端条件。在此背景下，单晶高温合金在近服役工况下的变形和损伤行为已成为决定涡轮叶片可靠性、安全性和寿命的关键因素，并构成了当前高温合金领域最重要的研究前沿和核心挑战之一。近年来，国内外学者借助先进的表征技术和模拟方法，在揭示微观损伤机理、建立宏微观性能关联以及发展性能优化策略等方面取得了显著进展。本文旨在综述近年来单晶高温合金在蠕变、疲劳及热机械疲劳等方面的研究现状，重点关注微观组织演化规律和损伤机制，以期为高性能单晶合金的设计和叶片安全服役提供坚实的理论依据。

1 蠕变行为

单晶涡轮叶片在服役过程中主要承受轴向离心载荷，由离心力导致的蠕变损伤是叶片的主要失效形式之一。目前，针对单晶高温合金在不同温度与应力区间内的蠕变行为已开展了广泛研究[1]。近年来，随着表征技术的进步和实验方法的创新，不断有新的微观变形和损伤机制被揭示，深化了对单晶高温合金蠕变行为的理解。例如，在高温蠕变稳态阶段就已出现大量在{100}面发生交滑移的a<100>超位错，并伴随Kear-Wilsdorf锁的形成[2]；借助X射线计算机断层扫描(X-ray computed tomography，XCT)技术，发现诱发蠕变断裂的微孔多为形态不规则的大尺寸孔洞及局部高密度聚集的孔洞群体[3]。然而，随着叶片设计向薄壁化发展，氧化、热腐蚀及多轴应力状态对材料蠕变性能的协同作用已成为当前研究的关键问题。同时，面对航空发动机涡轮进口温度不断提升的趋势，单晶叶片在超高温、长时服役及短时超温等极端工况下的蠕变损伤机理、微观组织演化规律及其与性能的关联等也受到越来越多的关注。

1.1 环境-结构-蠕变交互作用

1.1.1 氧化协同效应　随着发动机叶片设计日益趋向薄壁化，单晶高温合金蠕变性能对壁厚的敏感性——即“薄壁效应”(如图1[4~10]所示)逐渐成为研究焦点。普遍认为，蠕变过程中表面氧化层的形成以及氧化导致的γ'相贫化层会减小有效承载截面，从而显著劣化材料的蠕变性能。因此，氧化损伤被认为是薄壁效应的重要诱因之一。研究[10,11]发现，氧化与塑性变形在薄壁效应中存在竞争机制：随着壁厚减小，氧化对性能损失的贡献显著增大。例如，在1100 ℃、137 MPa实验条件下，对于壁厚介于0.3~1.5 mm的DD33合金薄壁管状试样，氧化对薄壁效应的贡献率从55%降至15%[10]。此外，氧化引起的近表面微观组织损伤也严重影响蠕变性能，例如，γ'贫化层内析出的AlN[2]以及表面裂纹附近出现的再

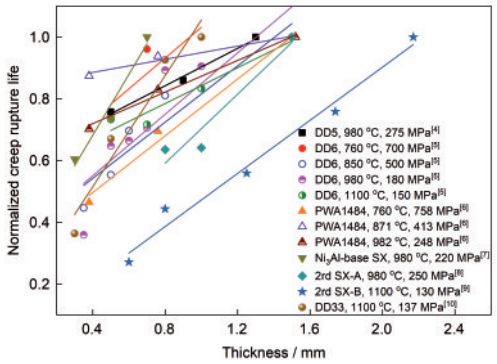


图1 单晶高温合金蠕变性能的薄壁效应[4~10]

Fig.1 Thickness debit effect of creep property of single crystal superalloys[4~10] (SX—single-crystal)

结晶晶粒[12]，均可作为裂纹萌生与扩展的路径，进一步加速材料失效。

1.1.2 热腐蚀协同效应　在燃气及海洋服役环境中，单晶叶片表面易沉积盐膜，引发热腐蚀。与纯氧化相比，热腐蚀对单晶高温合金蠕变性能的危害更为严重。研究[13~16]显示，热腐蚀层通常厚度较大、结构疏松多孔且富含微裂纹，其附近往往还伴随γ'贫化层的形成，这些因素共同导致合金的有效承载截面显著减小。Liu等[16]通过有限元模拟指出，表面腐蚀坑处存在明显应力集中，是微裂纹萌生的主要位置。在蠕变载荷作用下，裂纹向基体内部扩展，同时S、Cl、O等腐蚀性元素沿裂纹渗入。γ相与S、Cl等元素的反应活性高于γ'相，易生成硫化物、氯化物及微孔洞，从而进一步加剧材料性能退化[13]。值得注意的是，S元素因具有较强的扩散能力，其形成的硫化物甚至可在合金较深区域析出，对合金性能造成损害。

1.1.3 多轴应力效应　单晶涡轮叶片结构复杂，诸如冷却孔、叶根转接区等部位在服役中常处于多轴应力状态，导致其变形和损伤机制复杂。为模拟此类部位的蠕变行为，科研人员多采用带缺口试样进行研究。Caccuri等[17]通过设计V型缺口试样，引入应力三轴度(η)表征多轴应力状态，发现γ'筏排形貌与η之间存在显著相关性：当η = 0.33时，形成典型N型筏排；当η = 0.6时，筏排方向与加载轴呈45°；而当η = −0.33和−0.6时，均出现P型筏排。Cao等[18]则认为，最大主应力对筏排形貌的影响大于应力三轴度。近期研究[19~21]显示，缺口试样在高温蠕变下的寿命显著高于光滑试样。在宏观层面，Yang和Li[19]提出最大主应力与应力三轴度之间的竞争机制是导致缺口强化效应的主要原因。在微观机制方面，Huang等[20]发现，多轴应力状态可使γ基体通道宽度减小，增大位错运动阻力，抑制局部变形，并延缓裂纹扩展；Bao等[21]则指出，蠕变初期缺口根部形成的高位错密度有助于协调变形、释放应力集中，同时致密的界面位错网可削弱多轴应力分量的不利影响，维持晶体取向稳定性。

1.2 超高温蠕变/长时蠕变/短时超温蠕变行为

1.2.1 超高温蠕变行为　随着发动机涡轮进口温度的不断提升，单晶高温合金在超高温(> 1100 ℃)环境下的蠕变行为日益受到关注。在该温度区间，γ'强化相发生明显溶解，导致合金蠕变抗力显著下降。研究表明，超高温蠕变的变形和损伤机制总体上与高温蠕变行为相似，但由于元素扩散加剧和位错运动机制更趋复杂，近年来也观察到若干新现象：其一，界面处形成沟槽或凸起结构，其尖端富集的难熔元素可对界面位错产生钉扎作用，从而提高蠕变抗力[22,23]；其二，出现位错对耦合形成的位错网，该结构常伴随γ'相的剧烈剪切，对整体蠕变强化的贡献有限[24]；其三，台阶状位错网可作为超位错源，反而促进变形、降低蠕变性能[2,25]。

在损伤方面，超高温蠕变过程中产生的过饱和空位数量显著多于高温蠕变，导致在蠕变后期沿γ/γ'相界面形成更多孔洞，加速材料断裂失效[2]。此外，尽管传统认为氧化对块状试样的蠕变性能影响较小，但在超高温条件下，氧化作用仍可能显著加剧蠕变损伤。研究[26]表明，DD33合金棒状试样在1150 ℃、80 MPa条件下蠕变时，会形成较厚的表面氧化层和γ'贫化层，导致局部有效应力增加约35 MPa，从而促进蠕变进程。为提高超高温蠕变性能，目前主要通过调整合金成分(如添加Re、Ru、Ta、Al等元素)，以提高γ'相的溶解温度，使其在超高温下仍能维持较高的体积分数[21,27~29]。

1.2.2 长时蠕变行为　燃气轮机叶片通常在较低应力下长期运行，其设计寿命可超过24000 h，因此对材料的长时组织稳定性和蠕变性能提出了更高要求。早在20世纪60年代，国际学术界已针对燃机用单晶高温合金开展了系统的长寿命性能测试、数据积累与寿命预测研究，但有关其长时蠕变微观机制的研究仍较为有限。Lukáš等[30]通过对比CMSX-4与CM186LC合金在长时(超过1000 h)蠕变后的组织演变，发现在750和850 ℃下γ'相形貌基本保持不变，仅在950 ℃条件下出现明显的γ'筏化。最近，对某型低γ'体积分数、低错配度燃机用单晶合金在900 ℃下进行的短时与长时(约5589 h)蠕变对比结果表明，两者变形机制相似，但长时蠕变中筏化过程极为缓慢，表现出显著的“持续时间效应”，即微观结构演化强烈依赖于蠕变时间[31]。

Dubiel和Czyrska-Filemonowicz[32]对实际服役12700 h的燃机叶片组织分析显示，不同部位的γ'相形貌存在明显差异：叶根区域γ'相仍保持立方体形态，变形以位错交滑移为主；而叶身中部则发生γ'筏化，变形受位错攀移控制。作者团队在对比燃机叶片(服役20000 h)和航空发动机叶片(累计服役900 h)时也发现，前者叶身仅出现γ'相合并粗化，而后者已发生显著筏化。这一结果表明，航空发动机叶片中常见的蠕变机制并不完全适用于燃机叶片的长时服役环境。因此，亟需深入开展针对燃机用单晶高温合金的长时蠕变微观机制与寿命预测研究。

1.2.3 短时超温蠕变行为　单晶涡轮叶片在稳

态运行中主要发生等温蠕变损伤，但在特殊工况下，叶片温度可能瞬间超过最高允许工作温度(例如1100 ℃)，导致短时超温蠕变。受限于能够模拟快速升降温过程的非等温蠕变实验设备，该领域研究自2007年起才逐步展开，且目前以欧美国家为主。

超温过程中最显著的组织变化是γ′强化相的大量溶解。Giraud等[33]发现，对CMSX-4单晶合金进行1200 ℃、1 min超温处理后，γ′相的体积分数从75%急剧下降至约48%，严重削弱了沉淀强化效应。Cormier等[34]进一步指出，γ′相溶解温度越低的合金，其非等温蠕变抗力通常越差。然而，超温造成的γ′相溶解也会导致基体中过饱和的γ′形成元素在后续冷却过程中重新析出细小弥散的γ′颗粒，使体积分数恢复至超温前水平[35]。尽管这些细小析出相可在一定程度上改善非等温蠕变抗力，特别是形成γ′微筏排后进一步阻碍位错运动[36]，但超温仍会显著降低总体蠕变寿命[34,36]，且寿命损失随超温频次增加而加剧[37]。研究[38]还表明，超温发生的蠕变阶段对蠕变性能影响显著：在蠕变初期或γ′筏化过程中发生超温将导致寿命显著缩短；而在筏化完成后的超温处理，则对寿命的负面影响相对较小。这表明，超温引发的γ′相溶解与再析出过程对非等温蠕变性能的影响存在竞争关系。

现有研究多集中于超温后γ/γ′微观结构演变对蠕变性能的宏观影响，而对非等温条件下位错层次的变形机制理解仍较匮乏。目前有限的研究主要关注超温对γ/γ′界面位错网的影响。Ge等[39]研究发现，超温处理后界面处形成大量锯齿状沟槽；Schwalbe等[40]则报道了在蠕变初期超温处理后，位错网呈现复杂形貌，部分从常规的{001}面转移至{111}面，表明超温使位错网处于非平衡状态。Duan等[41]进一步指出，随着超温次数增加，界面位错网逐渐失稳。一些研究[38,42]认为，蠕变初期的超温会促进位错攀移和湮灭，增大位错网间距，这是非等温蠕变寿命下降的关键因素；但Hantcherli等[43]在循环变温实验中并未观察到位错网形貌和间距的显著变化，表明该问题仍存在争议。Viguier等[44]提出，*a*<100>超位错的攀移是非等温蠕变的主要变形机制，但未能解释为何*a*<100>超位错在γ′相中极少出现。总体而言，短时超温影响非等温蠕变变形机制的具体途径尚不明确，制约了对超温服役条件下叶片寿命的准确预测和材料性能优化。

2 疲劳行为

航空发动机长期在高温、高机械载荷环境下运行，疲劳失效已成为其关键结构件(如单晶涡轮叶片)破坏的最主要形式[45]。据统计，疲劳相关问题可占航空发动机研发阶段总故障的50%以上[46]。因此，深入探究单晶高温合金的疲劳变形机制和损伤行为，已成为该领域的关注热点。近些年，学者们围绕近服役工况和近构件结构条件下的疲劳行为开展了初步探索，对提升发动机可靠性、延长部件服役寿命具有重要的工程和科学意义。

2.1 疲劳变形机制

单晶高温合金的疲劳变形机制主要受γ′相强度、层错能和反相畴界能等参数之间交互作用的影响，这些参数的交互作用决定了不同温度下的位错运动模式。在低温区间(室温~650 ℃)，变形以平面滑移为主，*a* / 2<101>位错对、*a*<101>超位错及层错等剪切γ′相，并伴随层错环或反相畴界的形成，高密度位错聚集可发展为明显的滑移带。随着温度升高，γ′相强度及层错能逐渐增大[47]，进入中温范围(650~850 ℃)后，位错运动由平面滑移逐步过渡为波状滑移，主要表现为γ通道内的滑移与交滑移、γ/γ′界面处形成不规则位错网，以及少量层错剪切γ′相[48~52]。在高温阶段(850~1100 ℃)，位错难以直接切割γ′相，在热激活作用下，更容易发生交滑移、攀移以及Orowan绕过γ′相等行为[49]。

2.2 疲劳裂纹萌生机制

上述对单晶高温合金疲劳变形机制的分析主要基于疲劳断口附近及中断试样显微组织的观察。研究[53,54]表明，合金的疲劳寿命主要消耗在裂纹萌生和早期扩展阶段。因此，深入理解疲劳裂纹萌生机制对提升材料疲劳性能具有重要意义。当前研究需重点关注裂纹源区附近的微观组织演化，通过精细表征与机理分析，揭示裂纹萌生的本质过程。

研究表明，疲劳裂纹萌生行为与加载条件密切相关[55,56]：高应力幅下，低周疲劳裂纹主要源于碳化物[53,57~59]；随应力降低，萌生位置逐渐转变为铸造孔洞，铸孔成为高周疲劳阶段最主要的裂纹源[60~65]；应力进一步降低时，裂纹亦可起源于残余共晶[62,66]或表面氧化区域[54,57]。

2.2.1 低周疲劳　在低周疲劳条件下，碳化物在氧化与循环载荷协同作用下发生开裂[67~69]。大尺寸骨架状碳化物中产生的高应力集中促使微裂纹迅速跨越碳化物/基体界面并扩展，导致疲劳失效[64,65]。

2.2.2 高周疲劳　尽管碳化物可能开裂，但由于裂纹尖端应力场强度因子(ΔK)低于碳化物/基体界面的扩展门槛值($\Delta K_{\text{th-MC}}$)，裂纹难以穿越界面，故疲劳裂纹主要萌生于铸造孔洞。

孔洞边缘局部应力集中促进不可逆位错运动[54,60,63,70]，形成侵入/挤出形貌进而诱发裂纹[70~72]。近期，作者团队[73]通过中断实验识别出三种与铸孔相关的裂纹萌生机制：孔边塑性变形与滑移带剪切开裂、空位扩散导致Kirkendall微孔形成进而诱发裂纹、孔内残余氧致界面碳化物氧化开裂。

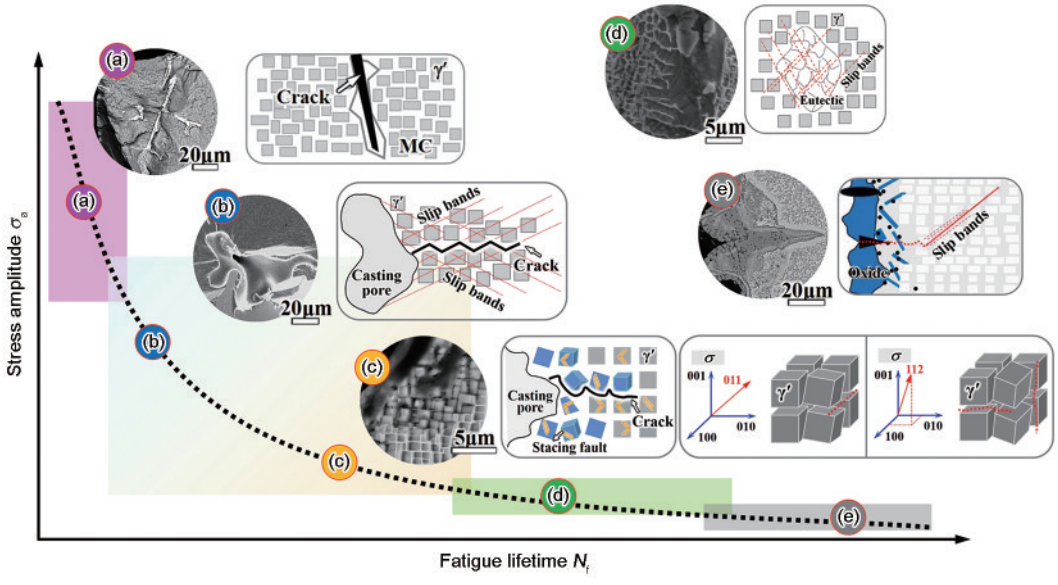
2.2.3 超高周疲劳　当加载应力幅进一步降低至远低于屈服强度时，单晶叶片特定部位(如前缘、尾缘和叶尖等)在振动载荷作用下可能发生超高周疲劳(very high cycle fatigue，VHCF)损伤[74~76]。通常开展VHCF研究需借助超声疲劳试验机[75,76]，其频率约20 kHz，与叶片轮廓的自然频率(1~10 kHz)较为接近，可显著缩短实验周期。

研究[75,77~81]表明，VHCF寿命主要受最大铸孔尺寸控制，裂纹萌生阶段占据绝大部分寿命。孔周常出现粗糙区(rough zone，RZ)，其面积与寿命正相关。目前关于粗糙区形成机制的研究较少，Cervellon等[75]研究发现，该区域存在晶体转动、再结晶及拓扑密堆(TCP)相析出等现象，与高度局域化的γ′相剪切密切相关，导致孔周应力强度因子门槛值下降，促进裂纹萌生。作者团队前期研究[82]显示，粗糙区内γ′相发生晶体转动(通常沿[112]或[110]与[112]合成的方向偏转)，与孔边复杂应力状态下{111}<110>和{111}<112>滑移系启动有关。γ′相转动导致γ/γ′界面分离，从而诱发VHCF裂纹。

高温度梯度液态金属冷却定向凝固和热等静压(hot isostatic pressing，HIP)处理可减小铸孔尺寸，使裂纹源转移至共晶区。极低应力下，表面氧化成为VHCF裂纹萌生的主导诱因[82,83]，氧化损伤主要通过改变局部错配度、促进元素扩散与γ′筏化、降低应力强度因子及有效承载面积等机制影响疲劳寿命。

综合近年国内外研究工作，可以明确单晶高温合金的疲劳裂纹萌生行为强烈依赖于加载条件，并呈现出系统的转变规律(图2)。其中，铸孔在较宽加载范围内始终是疲劳裂纹萌生的关键诱因，区别在于：高周疲劳条件下，铸孔周边存在局部应力集中和塑性变形累积，诱发不同方向滑移带及其交互作用(图2b)；而超高周疲劳条件下，低应力水平使铸孔周边应力集中减弱，难以引发剧烈局部塑性变形，转而激活多滑移系和γ′晶体转动(如图2c所示，同时展示了γ′向[110]和[112]方向转动的两种典型类型)。

除了上述不同加载条件下单一疲劳裂纹萌生诱因外，不同疲劳裂纹萌生诱因之间的耦合作用(如目前已经观测到碳化物/氧化[64,65,84]、铸孔/氧化[85]、碳化物/铸孔/氧化[73])也会显著影响裂纹的萌生与扩展。然而，对于共晶/碳化物/铸孔/氧化等多因素交互作



Color online

图2 不同加载条件下单晶高温合金的疲劳裂纹萌生机制

Fig.2 Fatigue crack initiation mechanism under different loading conditions

(a) cracking of carbides is attributed to the combination of oxidizing and cyclic loading

(b) crack initiating from slip band shearing around casting pore

(c) γ′-rotation within the rough zone around casting pore is related to the operation of {111}<110> and {111}<112> slip systems (σ—stress)

(d) slip bands with different direction observed within eutectic show more uniform deformation

(e) hot isostatic pressing (HIP) specimens mainly fail from the surface oxidation and present the best fatigue property

用，目前尚未见系统报道，其影响机制和规律仍有待深入研究。

2.3 近服役工况下单晶叶片的疲劳行为

单晶叶片在实际运行中同时承受离心力和循环应力，导致蠕变与疲劳交互作用，显著影响其耐久性[86]。高温条件下，蠕变/疲劳性能表现出显著的各向异性，且蠕变损伤在构件失效中起重要作用，损伤累积主要源于微孔的形成和长大[87]。有限元分析与实验结果表明，微孔尺寸和分布对试样应力状态及寿命具有重要影响，蠕变-疲劳交互作用会显著降低材料的循环寿命[88]。

氧化是高温热端部件面临的主要挑战之一，表面氧化层的形成和破裂明显促进裂纹的萌生和扩展，氧化-疲劳耦合作用严重缩短单晶铸件的使用寿命[89]。Meng 等[90]研究发现，强烈的预氧化或高氧化速率会促使裂纹在表面萌生，尤其在 1050 ℃下，裂纹均以 I 型方式从表面起源，导致疲劳强度显著降低。类似地，热腐蚀与氧化均会造成承载截面损失，削弱单晶合金的整体力学性能。研究[91]表明，随预腐蚀时间延长，材料表面形成多孔、脆性腐蚀层，产生大量疲劳裂纹起始点，从而劣化疲劳性能。随着研究的不断深入，环境-蠕变-疲劳-多轴应力等多场耦合作用及其对裂纹萌生与扩展行为的影响，已成为当前和未来研究的重点方向。

2.4 工程构件的疲劳行为

近年来，为更真实地反映工程实际并支持构件疲劳寿命预测和抗疲劳设计，人们开展了部分面向实际工程构件服役工况的单晶高温合金疲劳行为研究。例如，旋转弯曲疲劳(rotating bending fatigue，RBF)实验通过一端旋转、另一端施加横向载荷的方式实现全反转弯曲应力状态，其表面至内部存在的应力梯度可有效模拟实际部件表面及近表面的裂纹萌生与扩展行为[92]。研究[93,94]表明，旋转弯曲疲劳裂纹多起源于表面、近表面微观结构特征(如表面缺陷或组织不均匀性)，而非传统的内部铸造缺陷(如铸造孔洞)。由于表面应力集中效应更为显著，表面状态及近表面显微组织对 RBF 性能具有决定性影响。

振动疲劳是指材料或结构在振动、冲击、噪声等动态交变载荷作用下，因激励频率与固有频率接近发生共振而导致的疲劳破坏，是评价合金及构件综合性能的重要指标。构件的振动疲劳极限不仅取决于材料本身的振动疲劳性能，还受构件形状、尺寸及表面状态等因素的显著影响。尽管如此，材料级的振动疲劳性能仍是构件振动疲劳研究的基础[95]。振动疲劳行为受晶体取向[96]、薄壁厚度[97]、孔结构[98,99]等多因素调控。研究[97]发现，随试样厚度减小，其中温疲劳强度下降，该“厚度效应”主要归因于氧化介质渗透促进表面裂纹萌生。薄壁孔结构处易因应力集中诱发疲劳裂纹，在高温与交变应力耦合作用下，裂纹多源于孔边氧化损伤[98,99]。宏观上，高温下裂纹扩展方向受分解剪应力梯度控制；微观层面，中温裂纹扩展由位错滑移与攀移共同主导，而高温下则以位错攀移机制为主[99]。

然而，当前的相关研究仍存在明显不足：旋转弯曲疲劳侧重于材料微观组织的影响，而振动疲劳更关注结构力学响应，两者尚未充分融合。实际叶片构件的疲劳性能同时受材料本征特性、应力集中效应与结构约束效应的共同影响，因此建立材料-结构-性能之间的内在关联，是提升工程构件抗疲劳设计能力的关键挑战。

由于涉及核心工程技术，目前公开的实际叶片构件级疲劳研究极少，相关进展多集中于设计部门的数据积累。已有学者系统研究了晶体取向耦合对单晶叶片振动特性的影响，并通过理论与数值方法分析了一阶弯曲/扭转模态频率的变化规律[100]；另有工作探讨了喷丸强化对镍基单晶榫接头高温微动疲劳性能的影响机制[101]。基于现有数据积累，采用机器学习等先进方法，有望构建从试样级旋转弯曲疲劳、片状试样振动疲劳到全尺寸叶片振动疲劳的映射关系，推动疲劳预测理论的发展，为高性能单晶叶片构件的抗疲劳设计、制造与安全服役提供理论支撑。

3 热机械疲劳行为

航空发动机在起飞、爬升、巡航和降落阶段，以及重型燃气轮机在调峰运行中的频繁启停，使涡轮叶片处于温度、应力和应变复杂耦合的服役环境下，极易诱发多因素疲劳失效。传统的蠕变、低周/高周疲劳及热疲劳试验通常采用单一机械应变循环或独立热循环加载方式，难以准确模拟叶片实际多场耦合工况。为此，热机械疲劳(thermal-mechanical fatigue，TMF)试验方法应运而生，能够同步施加热循环与机械应变循环，更真实地反映叶片服役状态。基于 TMF 测试技术，国内外学者针对单晶高温合金基体及其涂层-基体体系开展了系统性研究，重点关注温度-机械载荷相位关系、晶体取向、合金元素作用以及涂层与基体交互行为等因素对 TMF 性能的影响。

3.1 单晶高温合金的热机械疲劳行为

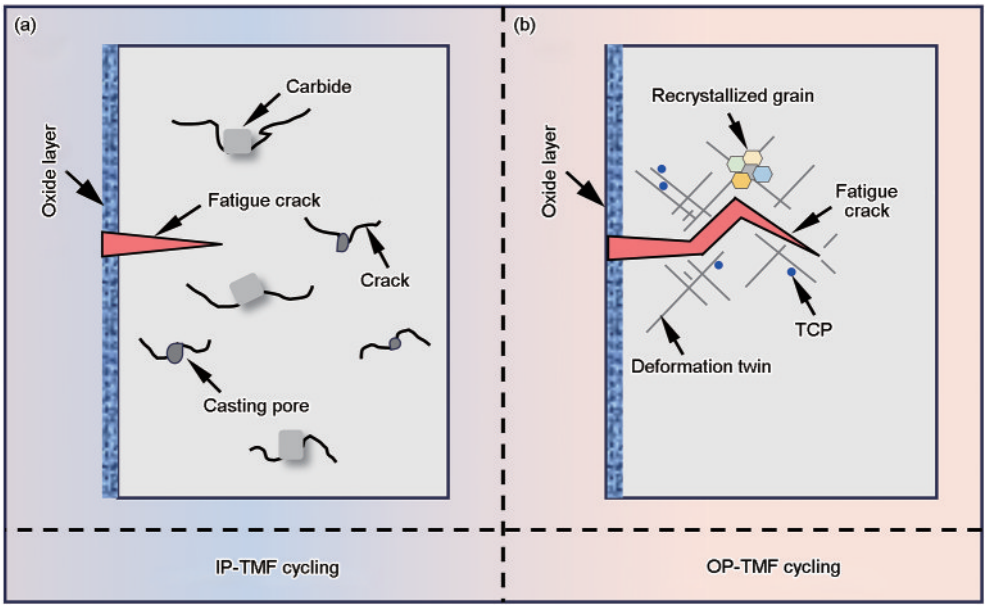
3.1.1 相位关系　单晶高温合金的 TMF 行为强

烈依赖于温度与机械载荷之间的相位关系，其本质源于氧化、蠕变和疲劳等多种损伤机制在时间上的耦合与竞争。为模拟涡轮叶片的实际服役条件，通常采用同相位(in-phase，IP)和反相位(out-of-phase，OP)两种TMF加载模式。在IP-TMF中，最大拉应变与最高温度同步出现，高温阶段材料承受持续拉伸应力，低温阶段发生压缩塑性变形，近似模拟叶片冷却孔或内腔表面工况；而在OP-TMF中，最大拉应变对应最低温度，高温阶段材料处于压缩状态，主要用于模拟叶片外表面服役环境。

相位关系对TMF寿命与变形机制具有决定性影响。如图3所示，IP-TMF以高温蠕变损伤为主导，裂纹多萌生于碳化物/基体界面；而OP-TMF因氧化、孪晶与位错交互及TCP相析出等多重机制协同作用，损伤行为更为复杂，疲劳寿命通常显著低于IP-TMF[102]。OP-TMF条件下，高度局域化的孪晶成为主要变形方式，不同取向孪晶交汇处易诱发再结晶，裂纹沿孪晶面快速扩展导致{111}面晶体学断裂[103]。Hong等[104]进一步指出，OP-TMF在最低温度时施加的最大拉应变会加速表面裂纹的萌生与扩展；当裂纹达到临界尺寸后，尖端区域沿{111}面形成多组平行孪晶，为裂纹提供快速扩展通道，导致OP-TMF寿命明显低于等温低周疲劳，孪晶形成与{111}<112>滑移系中不全位错运动密切相关。另有研究[105]表明，当测试机械应变幅、试样晶体取向相近时，IP和OP-TMF的寿命与变形机制差异不大，合金失效主要源于局部变形带及由此引发的裂纹萌生；断裂模式取决于应变幅大小：高应变幅下{111}面滑移系广泛激活导致晶体学断裂，低应变幅下则因内部铸造缺陷、氧化裂纹扩展及γ′相筏化引发非晶体学断裂。

3.1.2 晶体取向　在单晶叶片铸造过程中，通常优先将生长方向与[001]晶向保持一致。这一方面是由于[001]方向在定向凝固中具有最优生长速率，有利于获得完整单晶；另一方面，[001]取向的弹性模量较低，有助于提升抗疲劳性能。然而，实际生产中叶片取向常会偏离理想[001]方向。由于单晶材料力学性能的各向异性，晶体取向显著影响其拉伸[106,107]、低周疲劳[108~110]及蠕变[111,112]等行为。

近年来，晶体取向对TMF损伤与失效行为的影响引起广泛关注。Segersäll等[113]对比了<001>和<011>取向CMSX-4合金在OP-TMF下的行为，结果表明，相同机械应变范围内<001>取向试样寿命更高。随应变幅增大，两种取向均呈现从非晶体学断裂向



Color online

图3 单晶高温合金热机械疲劳(TMF)变形机制示意图

Fig.3 Schematics of the thermal−mechanical fatigue (TMF) deformation mechanism in single-crystal superalloys (OP—out-of-phase, IP—in-phase)

(a) during IP-TMF cycling, alloy deformation mechanism is dominated by creep damage, with cracks preferentially initiating at carbides and casting pores

(b) under the OP-TMF cycling, highly localized twinning is the major deformation mechanism, and cracks propagate rapidly along the twinning planes. Recrystallization occurs within the deformation bands, with the interception of twins in different orientations serving as initiation sites (TCP—topologically close-packed phase)

{111}面晶体学断裂的转变，且<011>取向变形机制由孪生逐渐转为变形带剪切γ/γ'组织。TMF性能的晶体取向依赖性不仅源于弹性模量差异，更与滑移系激活能力密切相关。取向接近[001]的试样能够激活更多滑移系，促进变形协调和分散，延长疲劳寿命；而取向介于[011]和[111]之间时，可启动滑移系有限，导致变形局部化，降低TMF寿命[114]。Luo和Yuan[115]进一步验证了不同取向TMF寿命顺序为[001] > [011] > [111]，[001]取向因低模量和高滑移系激活能力，表现出最优疲劳性能。

在镍基单晶涡轮叶片铸造过程中，通常控制叶片的[001]晶体生长方向与主应力轴的偏离角不大于15°，而叶片的二次取向保持随机。已有研究表明，二次取向对带气膜冷却孔单晶试样的TMF行为有显著影响。研究[116]发现，在OP-TMF测试条件下，二次取向靠近[110]的气孔裂纹扩展速率高于靠近[010]的气孔裂纹扩展速率，大部分主裂纹扩展发生在低温循环阶段。在IP-TMF中，[110]取向气膜孔附近的Schmid应力更高，导致更严重的损伤和更短寿命[117]。Zhang等[118]研究还发现，在相同IP-TMF载荷条件下，将叶片尾缘附近的扰流柱圆角二次取向由[010]转变为[110]，叶片尾缘附近吸力侧扰流柱圆角的TMF损伤减小，而压力侧扰流柱圆角的TMF损伤增加。因此，在对叶片进行结构设计和TMF寿命评估时应考虑二次晶体取向对叶片疲劳性能的影响。

3.1.3 合金元素　合金元素对高温合金TMF行为及变形机制有显著影响。例如，添加0.25%Si (质量分数，下同)可显著提高合金在OP-TMF下的寿命，增幅可达2倍，这主要归因于Si提高了合金在低温下的屈服强度，细化滑移带并增强抗再结晶和抗开裂能力。相比之下，添加2%Re虽能明显改善合金的蠕变性能，但对TMF寿命的提升效果并不显著[119]。Ge等[120]研究了Ru对含Re单晶高温合金TMF行为的影响，发现添加3%Ru可显著延长合金在OP-TMF条件下的寿命。其强化机制主要包括两方面：一方面，Ru元素增强了基体强度，并在TMF初期促进层错的形成与稳定化；另一方面，Ru有效抑制了孪晶的形成，从而提高了合金在复杂热-机械载荷下的抗损伤能力。

3.2 带涂层高温合金热机械疲劳行为

为提高发动机推重比和热效率，先进燃气涡轮发动机的涡轮进口温度不断提升，对叶片材料的耐温能力提出了更高要求。除通过合金化提高基体承温能力外，在叶片表面施加涂层已成为降低表面温度、提升抗高温氧化与热腐蚀性能的有效途径。然而，涂层的引入会改变基体表面状态，可能对其力学性能产生复杂影响。疲劳裂纹易萌生于涂层/基体界面的孔洞及喷砂预处理引入的颗粒处，并向基体内部扩展，导致合金疲劳性能下降[121]。高温下涂层与基体间的互扩散会形成互扩散区(inter-diffusion zone，IDZ)、二次反应区(secondary reaction zone，SRZ)并析出TCP相。SRZ通常具有再结晶组织，可减少有效承载面积，并可能成为裂纹源[122]；而涂层下方析出的TCP相则在疲劳中促进裂纹过早萌生，显著降低合金的抗疲劳性能[123]。另有研究[124]指出，尽管IDZ/SRZ会减小承载截面，并导致涂层合金在950 ℃时的抗疲劳性能降低，但疲劳裂纹仍多起源于合金内部缺陷而非扩散区本身。

涂覆热障涂层(thermal barrier coating，TBC)的叶片在服役中面临热-机械载荷耦合作用，易发生TBC过早开裂或剥落。TBC失效会加剧基体局部氧化甚至熔化，严重威胁叶片安全。TMF试验可较好地模拟此类工况。TBC在TMF下的损伤行为受机械应变幅的显著影响：高应变幅下，裂纹从黏结层/热生长氧化物(thermally grown oxide，TGO)界面萌生，穿透黏结层进入基体；低应变幅下，裂纹沿黏结层/TGO界面扩展，导致陶瓷层剥落[125]。损伤行为还受相位影响：OP加载下易形成垂直于应力方向的分割裂纹[126]；IP加载下因高温氧化，裂纹多集中于陶瓷层/TGO界面[127]。

随着单晶叶片复杂冷却技术和TBC的应用，叶片内部与表面间形成显著温度梯度，实际工况更接近温度梯度热机械疲劳(temperature-gradient mechanical fatigue，TGMF)。相比TMF，TGMF测试中冷却气体降低了基体温度，延缓裂纹扩展，从而提高疲劳寿命[128]。此外，TGMF条件下温度梯度与机械应力的协同作用可能导致黏结层内部萌生疲劳裂纹，裂纹沿平行于陶瓷/黏结层界面的方向扩展，加剧陶瓷层剥落，此类行为为TGMF所特有[129,130]。近期，Zhan等[131]采用外覆TBC、内通冷却气的管状试样开展了TGMF研究，发现在300~1000 ℃、0.45%机械应变幅的IP-TGMF测试中，陶瓷层内裂纹扩展与合并导致剥落；而当温度升至1100 ℃、应变幅增至0.65%时，裂纹可贯穿陶瓷层进入黏结层及基体。当前，先进表征技术(如同步辐射)已被用于原位分析TBC在TGMF过程中的应变分布[132]，但温度梯度与机械载荷耦合作用下TBC系统的损伤机制仍不明确，界面微观组织演化对裂纹行为的影响也有待深入研究。

4 原位表征技术在损伤行为研究中的进展

近年来，原位表征技术开始应用于单晶高温合金的损伤行为研究中，涵盖从微观尺度(如原位扫描电镜、透射电镜)到介观尺度(如同步辐射、中子衍射和散射)的多种先进手段。这些技术能够实时捕捉高温、应力及环境耦合条件下微观结构及关键参数的动态演化过程，从而在原子至介观尺度上揭示单晶高温合金的损伤机理。

Zhang等[133]结合扫描电子显微镜和优化的斑点制备技术，开发了可用于原位拉伸和疲劳测试的实验装置，系统研究了第四代镍基单晶高温合金的变形行为。通过数字图像相关(digital image correlation，DIC)技术和晶体塑性有限元(crystal plasticity finite element，CPFE)模拟，揭示了裂纹萌生与扩展的微观机制，并建立了基于位错密度的模型，有效表征了不同温度下滑移系阻力、位错密度和累积应变的动态演变，为联系微观变形机制与宏观力学响应提供了重要依据。Yang等[134]则在透射电镜中实现了高温力学测试与高分辨表征的同步进行，从原子尺度上解析了DD6合金的断裂过程，明确了60°全位错在裂纹尖端扩展中的作用，提出了沿γ/γ'相界面断裂的新模式。

高能同步辐射和中子源凭借其强穿透能力和无损探测特性，结合专用原位加载/加热装置，可实现单晶高温合金内部结构的动态表征，为合金设计和工艺优化提供关键数据。目前相关研究主要集中在原位技术开发和组织演化分析两个方面。

在同步辐射原位技术方面，Tréhorel等[135]提出了一种新型的远场双晶衍射(double-crystal diffractometry，DCD)技术，可以实时监测高温蠕变过程中的瞬态变化。DCD使用远场相机，在透射几何下捕获衍射斑点，结合高能同步辐射X射线(67 keV)，通过快速二维探测器实现高角度精度(10^{-5})和高速记录(7 s/frame)，比传统三晶衍射(triple-crystal diffractometry，TCD)快40倍。并采用DCD成功捕捉到AM1单晶高温合金在950 ℃高温突变载荷条件下错配度($\delta_{\perp}$)的实时变化。该技术为时间分辨原位同步辐射研究奠定了良好的基础。

在高温/载荷下组织演化研究方面，多项工作[35,136~139]借助同步辐射分析了γ/γ'相错配度、γ'相体积分数及位错密度等在热-力耦合条件下的演变规律。例如，Bruno等[136]发现SC16合金的错配度随温度升高而增大，且与热膨胀行为一致；Ge等[137]在上海光源BL14B线站通过原位加热实验，证实Ta元素的添加显著提高750 ℃下合金的错配度，增强错配应力，从而提升蠕变性能；le Graverend等[138]利用原位同步X射线衍射技术研究了AM1合金非等温蠕变中γ'相分数、位错密度和错配度的演化，指出高温跃升(> 120 ℃)促进γ'相发生屈服和位错攀移，显著加速蠕变进程。

目前关于中子原位研究的报道相对较少。Lu等[140]通过原位中子衍射分析了PWA1484合金在拉伸和蠕变过程中的弹性微应变，揭示了γ/γ'晶格错配与变形机制的关联；Strunz等[141]采用小角中子散射研究了预变形SCA425合金中γ'相的高温演化，发现预变形量直接影响γ'形态转变；Ratel等[142]则探索了SC16合金冷却过程中γ'相的形貌变化。

尽管同步辐射与中子源已为理解单晶高温合金损伤机制提供重要支持，但由于机时限制，针对长时蠕变与疲劳的原位研究仍较为有限。未来需进一步发展方法创新、专用原位装置与加速试验策略，推动长时损伤行为的动态表征。此外，虽然同步辐射与中子结果具有统计代表性，但需与微观原位扫描/透射等技术相结合，相互验证、补充，从而全面深化对单晶高温合金损伤机制的理解。因此，多尺度原位表征技术的联合应用是未来研究的重要方向。

5 总结与展望

近年来，单晶高温合金作为航空发动机和燃气轮机热端部件的关键材料，其近服役环境下的变形损伤行为研究已取得显著进展。本文系统综述了单晶高温合金在蠕变、疲劳及热机械疲劳等多场耦合条件下的微观组织演化、损伤机制和环境-结构交互作用，揭示了γ'相演化、位错运动、孔洞缺陷、元素协同效应以及氧化、热腐蚀等环境因素对材料性能的复杂影响。研究表明，单晶高温合金的变形损伤行为具有明显的温度、应力、时间、环境及晶体取向依赖性，尤其在极端条件(如超高温、长时、短时超温、多轴应力等)下，其损伤机制更趋复杂。

在蠕变方面，研究已从传统的等温蠕变拓展至非等温、多轴应力及环境耦合条件下的蠕变行为，并揭示了γ'相溶解与再析出、位错网稳定性、微孔演化等关键机制。疲劳研究则从裂纹萌生诱因(如铸孔、碳化物、共晶、氧化)出发，探讨了高周、超高周疲劳中裂纹萌生与早期扩展的微观机制，并初步建立了疲劳裂纹萌生机制随加载条件的转变规律。在热机械疲劳方面则开展了相位关系、晶体取向、合金元素及涂层/基体交互作用对TMF寿命与损伤行为的影响研究，为叶片在复杂热-机械载荷下的寿命预测提

供了重要依据。

然而，当前研究仍存在若干挑战与不足：

(1) 极端条件下(如超高温、超长时、非等温)的蠕变损伤机制尚不清晰，尤其是位错动力学与微观组织演化的原位表征仍较为缺乏；

(2) 疲劳裂纹萌生机制虽已初步建立，但多种诱因(如铸孔/氧化、共晶/碳化物等)的耦合效应及其对裂纹萌生与扩展的影响仍需系统研究；

(3) 关于实际叶片构件在复杂几何、多轴应力、冷却效应及涂层保护下的疲劳和TMF行为研究仍较少，试样级结果与构件级行为之间的映射关系尚未建立；

(4) 环境-结构-载荷多场耦合下的损伤演化模型与寿命预测方法仍需进一步发展，尤其是在考虑微观组织退化、界面失效、元素扩散等复杂过程时。

未来需通过多尺度原位表征技术、跨尺度建模及机器学习等先进方法，深化对损伤机制的理解，推动高性能单晶合金的设计与叶片寿命可靠性的提升。

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