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飞机起落架损伤机制与再制造关键技术研究进展

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摘要：飞机起落架长期承受复杂载荷与严苛环境，易发生损伤。再制造技术可高效修复损伤并恢复性能，对保障飞行安全具有重要意义。围绕起落架综合性能的提升，结构与材料设计不断迭代优化，传统固定式起落架逐步演变为以可收放式为主的轻量化、高强度结构体系，材料设计理念也由单纯的静强度设计向兼顾损伤容限、疲劳寿命与可维修性的多目标优化方向演进。本文综述了飞机起落架的类型、材料、结构组成、典型损伤机制及再制造技术，重点分析了起落架服役中的典型失效模式及损伤机理，系统梳理了再制造过程中关键技术环节，包括精确的无损检测与损伤评估、高能束修复与表面强化技术、尺寸恢复与精密装配修复工艺等，指出新型高性能材料应用、智能化制造技术与绿色再制造工艺等未来发展趋势。本综述为飞机起落架再制造技术的工程应用与系统化发展提供了理论依据与技术参考。

关键词：飞机起落架；损伤机制；无损检测；再制造技术
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Research progress in damage mechanisms and key remanufacturing technologies for aircraft landing gears

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Abstract：The aircraft landing gear endures complex loads and harsh service environments over extended periods，making it susceptible to various forms of damage. Remanufacturing technology provides an efficient means of repairing such damage and restoring performance，playing a vital role in ensuring flight safety. Focusing on the enhancement of overall performance，the design of both structure and materials has undergone continuous iterations and optimization. Traditional fixed landing gear gradually evolves into lightweight，high-strength retractable systems，while material design philosophies shift from static strength-based approaches toward multi-objective optimization that simultaneously considers damage tolerance，fatigue life，and maintainability. This paper reviews the types，materials，structural composition，typical damage mechanisms，and remanufacturing technologies of aircraft landing gear，emphasizes the typical failure modes and damage mechanisms encountered during service，and systematically summarizes key technological aspects of the remanufacturing process，including precise non-destructive testing and damage assessment，high-energy beam repair and surface strengthening techniques，as well as dimensional restoration and precision assembly repair processes. Furthermore，it highlights future trends such as the application of advanced high-performance materials，intelligent manufacturing technologies，and green remanufacturing processes. This review provides theoretical foundations and

technical references for the engineering application and systematic development of aircraft landing gear remanufacturing technologies.

Key words: aircraft landing gear; damage mechanism; nondestructive testing; remanufacturing technology

飞机起落架是支撑飞机在起飞、着陆及滑行等阶段的核心承力部件，其结构完整性和功能可靠性直接决定飞行安全与航空运营效率[1-3]。在长期服役过程中，起落架需要承受高频冲击载荷、交变应力以及复杂环境影响，包括温度、湿度、腐蚀介质及颗粒冲击等。这些多因素作用下，起落架极易发生疲劳损伤、过载失效、腐蚀退化、磨损以及热损伤等多模式失效[4-6]。再制造作为区别于传统维修的高级工程技术，能够通过系统化的检测、修复及性能增强工艺，将退役或损伤部件恢复至等同或优于原始性能水平。再制造不仅显著降低新部件采购成本，而且能够延长使用寿命，减少停机周期[7-8]。如波音、空客已将再制造广泛应用于起落架、发动机及其他关键部件，取得了显著的经济效益和环境价值。国内随着航空工业的发展，再制造技术研究与应用也在加速推进，政策和标准体系逐步完善，但整体水平与国际先进水平仍存在一定差距，需要进一步提升技术研发能力和产业化应用水平。尽管再制造技术发展迅速，飞机起落架再制造仍面临多项技术挑战。首先，复杂的损伤模式及其累积效应使得结构内部隐蔽缺陷的精确检测成为关键问题；其次，高强度、多材料结构的起落架在修复工艺匹配、性能恢复及表面强化方面存在较高技术难度；再次，如何实现再制造过程的全过程标准化控制，确保质量可追溯、性能可验证，也是急需解决的难题[9]。总体而言，起落架再制造涉及检测评估、材料修复、表面工程、装配调试及工艺优化等多个环节，每个环节都对技术精度、材料性能和经济性提出更高的要求。其发展方向应结合先进无损检测技术、高效表面修复与强化工艺，构建系统化、安全可靠的起落架再制造技术体系。同时，通过标准化、智能化及可持续化手段，推动关键航空部件再制造向产业化、规模化发展，为提升航空安全、降低运营成本及实现绿色航空提供坚实技术支撑。

基于上述背景，如图 1 所示，本文系统综述了飞机起落架的相关研究进展，包括起落架系统及其典型损伤机制、主要类型与关键材料、结构特点及服役损伤模式，同时深入分析了起落架再制造技术的发展现状与关键环节，涵盖无损检测技术、材料修复与表面强化工艺、装配调试方法以及整体工艺优化策略，还探讨了起落架再制造的技术挑战与发展趋势，旨在为构

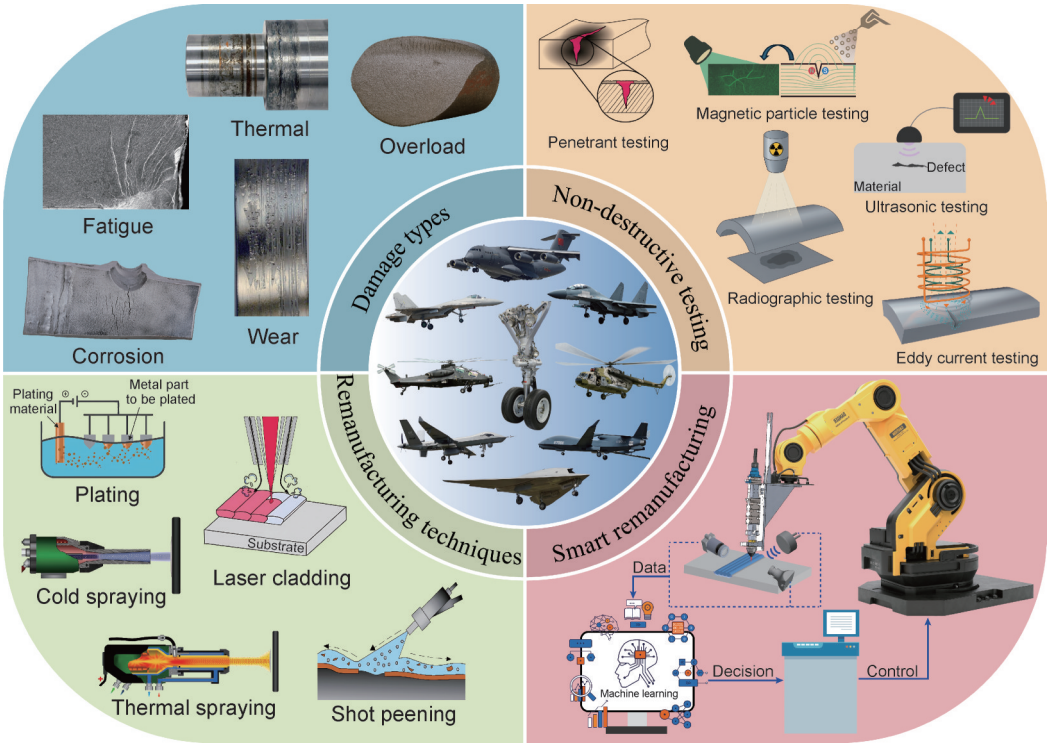


图 1　飞机起落架的损伤类型、无损检测技术、再制造与智能再制造修复技术

Fig.1　Damage types, non-destructive testing techniques, and remanufacturing and intelligent remanufacturing repair technologies of aircraft landing gear

建安全可靠、高效经济、标准化和可持续的起落架再制造体系提供理论参考和技术支撑，为航空安全提升、运营成本降低及绿色航空发展提供科学依据。

1 飞机起落架系统与损伤机制

飞机起落架作为保障安全起降的核心承力系统，在起飞、滑行、着陆及停放过程中承担着支撑飞机质量、实现地面运动以及缓冲着陆冲击的关键功能。深入理解起落架的类型、结构组成及材料特性，不仅是掌握其工作原理与维护策略的基础，也是开展精确故障诊断的前提。针对复杂工况下的损伤机制进行系统分析，有助于提高维护效率，保障飞行安全，并为高价值部件的再制造提供技术依据。随着航空技术的不断进步，起落架的设计、材料及再制造策略持续创新，以满足更高的性能要求并适应愈发严苛的使用环境。

1.1 飞机起落架的类型

飞机起落架的类型及设计取决于飞行器的用途、起降环境、质量分布和性能需求。按布局分类，飞机起落架包括传统式起落架、三轮式起落架、自行车式起落架和多轮式起落架[10-13]；按功能分类，包括固定式起落架和可收放式起落架[10,14]；按特殊功能分类，包括弹射式起落架[15-16]、浮筒式起落架[17]和滑橇式起落架[18]。表 1[10-18]汇总了各类起落架的结构特点，剖析了其优缺点，并列举了相应的典型机型。传统式起落架结构简单，适合粗糙地面，但操作困难，曾广泛应用于早期螺旋桨飞机；三轮式起落架地面稳定性好，广泛用于现役飞机；自行车式起落架适用于机腹狭窄的军用机，但需要辅助轮维持平衡；多轮式起落架则广泛用于大型飞机，其通过分散载荷满足跑道承重要求；固定式起落架的成本和维护低，适合低速通用飞机；可收放式起落架减少飞行阻力，常用于高速飞机；弹射式起落架用于舰载机短距起飞；浮筒式起落架用于水上起降；滑橇式起落架常用于直升机，适应复杂地形。总体而言，飞机起落架的设计是气动效率、结构强度、环境适应性和经济性综合权衡的结果，不同配置直接反映飞行器的任务特性和技术演进。

表 1 飞机起落架类型：结构、优缺点及代表机型[10-18]

Table 1 Types of aircraft landing gear: structure, advantages and disadvantages, and representative aircraft model[10-18]

Type	Structural feature	Advantage and disadvantage	Typical aircraft model
Taildragger landing gear	Main wheels ahead of the aircraft's center of gravity, tailwheel/skid supports rear, naturally nose-up attitude	Suited for unpaved runways, simple structure, low-maintenance, but harder to handle, less stable, longer takeoff/landing	Air Tractor AT-602, Douglas DC-3, Piper J-3 Cub
Tricycle landing gear	Nose wheel ahead of the aircraft's center of gravity, main wheels aft of the aircraft's center of gravity, level aircraft attitude	Stable taxiing, easy control; nosewheel bears high load, prone to damage, poor off-field suitability	Boeing 737, B-2
Bicycle landing gear	Main wheels arranged in tandem along fuselage, requires auxiliary wheels for balance	Suited for narrow-fuselage aircraft; compact, low-drag, lightweight; poor lateral stability, hard to handle, complex maintenance	B-52, Lockheed U-2
Multi-wheel landing gear	Main landing gear uses multiple wheels to distribute load	High load capacity, lowers tire ground pressure, safe, stable; complex structure, heavier, high maintenance	Airbus A380, C-5
Fixed landing gear	Non-retractable, fixed to fuselage or wings, equipped with spring or strut shock absorbers	Simple structure, lightweight, reliable, easy to maintain; high drag, for low-speed aircraft only	AURA AERO Integral R, Cessna 408 SkyCourier, Cirrus SR20 G7
Retractable landing gear	Retractable, stowed within fuselage or wings, operated by hydraulic or electric systems	Reduces drag, widely applicable; complex structure, heavier, high maintenance	Airbus A320neo, Fly Synthesis Texan, F-22
Landing gear for catapult operations	Designed for carrier-based aircraft, nose landing gear with arrestor hook, reinforced to withstand catapult launches and arrested landings	Enables short takeoff, strong structure; heavier, complex maintenance, catapult-dependent, high failure risk	F-35C
Float landing gear	Floats installed under or on sides of fuselage	Capable of water operations, highly adaptable, stable; high drag, limited operational environment	TL-3000 Sirius, Daher Kodiak 100
Skid landing gear	Wheel-less design with metal or composite skids	Lightweight, suited for rough terrain, easy to maintain; limited mobility, high friction, needs external ground equipment	Robinson R44, Bell 505 Jet Ranger X

1.2　飞机起落架的关键材料

飞机起落架承载材料的演进历程，反映了航空工业对材料性能要求的不断提升。根据关键零件的服役工况特征，起落架主要包括结构承力件（支柱、扭力臂）、作动与收放系统零件（作动筒、锁钩）、减震与密封部件（衬套、隔圈）和机轮与刹车系统（机轮、刹车盘）。作为支撑整机质量、承受着陆冲击的核心结构，结构承力件材料的选择直接影响飞机的安全性和使用寿命。如表 2[19-30]所示，起落架材料的发展经历了 3 个重要阶段：第一代起落架材料遵循静强度设计理念，主要使用抗拉强度为 1175 MPa 的 AISI 4130、30CrMnSiA 等低合金高强度钢，此类钢材多采用手工电弧焊等传统工艺制造[19-21]。随着静强度设计的局限性显现，第二代起落架材料的设计思路转向安全寿命设计，主承力构件开始采用强度范围在 1580～1760 MPa 的 30ХГСН2А、4330M 和 AISI 4340 等超高强度钢。此外，飞机起落架材料不仅需要具备超高的强度和刚度，还需要兼备优良的疲劳性能[20]。为进一步提高起落架的综合性能，美国成功研发出强度高达 1900 MPa 的 300M 钢，该材料一度成为强度最高、综合性能最优的起落架用钢之一[22]。同时，我国也通过双真空冶炼工艺自主研制出国产 300M 钢（40CrNi2Si2MoVA），该材料在保持同等强度的同时显著提升综合性能[19,22-23]。在引入损伤容限设计理念后，300M 钢逐渐暴露出断裂韧性不足的短板[20]。鉴于此，第三代起落架材料采用安全寿命与损伤容限相结合的设计原则。为同时满足钢材高断裂韧性与高强度的严苛要求，美国成功研发出强度超过 1900 MPa 的 AerMet100 钢，成为制造飞机起落架特别是新型战机起落架结构件和先进战机重要承力构件的首选材料[24-27]。我国研发出 23Co14Ni12Cr3MoE（A-100）钢，该材料具有超高强度、高断裂韧性、卓越的抗疲劳性能、良好的抗应力腐蚀性以及出色的抗冲击载荷能力，已成为舰载机和新一代战机的首选材料[28-30]。这一突破标志着我国在航空超高强度钢领域已跻身世界先进行列，未来将向 2200 MPa 级超高强钢、低成本钢等方向发展，以满足更高性能的需求。

表 2　飞机起落架关键材料设计准则、性能与特点[19-30]

Table 2　Design criteria, performance, and characteristics of key materials for aircraft landing gear[19-30]

Generation stage	Design concept	Typical material	Tensile strength/MPa	Characteristic	Typical aircraft model
First	Static strength	AISI 4130, 30CrMnSiA	1175	Conventional electric arc furnace melting, manual arc welding, high static strength, insufficient fatigue performance, meets only basic load-bearing requirements	MiG-15, Tu-16
Second	Service life	30ХГСН2А, 4330M, AISI 4340, 300M	1580-1900	Vacuum induction melting, double vacuum refining, significantly improved fatigue performance, fracture toughness remains limited	F-15, F-16
Third	Service life and damage tolerance	A-100, AerMet100	1900-2000	Ultra-pure melting, precision forging and heat treatment, ultra-high strength, high fracture toughness, good resistance to stress corrosion overall performance reaches optimal level	F-22, F-35

作动与收放系统零件包括收放作动筒、锁钩等，其核心要求是高可靠性和长寿命疲劳性能。作动筒筒体为减轻质量，多采用高强度铝合金（7075-T73）或钛合金（TI-6Al-4V），而作动筒活塞杆因需在液压油环境中长期工作，则优先选用耐腐蚀性优异的沉淀硬化不锈钢（17-4PH），关乎安全的锁钩、锁环等关键锁闭机构，则与主结构件看齐使用 300M 等超高强度钢。减震器外筒作为高压密封容器，通常与主支柱一体采用 300M 钢锻造，其内部的隔圈、衬套等摩擦件，则依赖青铜合金（铝青铜）的自润滑性和耐磨性来保证减震过程的平顺与密封。机轮与刹车系统是高温、高磨损区域，机轮需要兼顾滚转疲劳强度和刹车热管理，高强度锻造铝合金（7050-T74）因其轻质、高强和优良导热性成为首选，而刹车盘作为热端部件，工作时瞬间温度可达上千摄氏度。现代飞机已普遍采用碳/碳复合材料，其以极佳的耐热性、高比热容和轻量化优势，完全取代了早期的钢或铍合金刹车。

1.3　飞机起落架的结构

飞机起落架是支撑飞机在地面、起降及滑行时的关键承力结构。图 2 为支柱套筒式飞机起落架典型组成结构，主要包括起落架支柱、减震器、机轮和轮胎、刹车系统、收放机构和转向系统等[10,31-32]。起落架支柱是连接飞机机身和机轮的核心承力部件，具有支撑飞机机身、吸收着陆冲击和地面载荷的功能；减震器是安装在起落架支柱内的一种液压或气动装置，可减轻着陆时的冲击力，防止飞机结构损坏；机轮使飞机

能够在滑行、起飞和降落时在地面上移动；轮胎能够承受重载和高速，确保地面操作的安全；刹车对于飞机接地后和滑行过程中的减速至关重要，确保飞机能够安全停在跑道上；收放机构允许起落架在起飞后收起至机身或机翼内，以提高空气动力学性能和燃油效率；转向系统用于控制地面滑行方向，确保灵活机动。

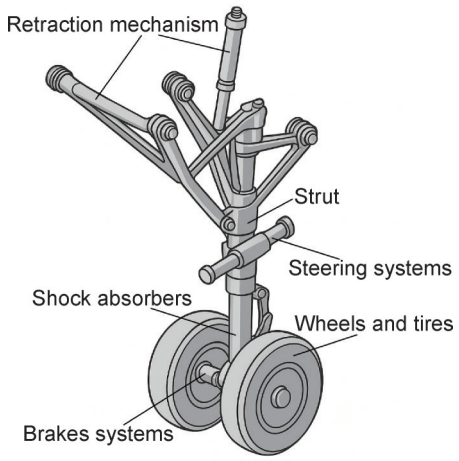


图2 支柱套筒式飞机起落架典型组成结构

Fig.2 Typical structure of strut-tube type aircraft landing gear

1.4 飞机起落架的损伤机制

飞机起落架作为飞机着陆与滑行过程中承受高载荷的关键部件，其损伤形式复杂多样。损伤机制与机械应力、环境腐蚀及材料疲劳等因素相关[3]，其主要分为疲劳损伤、过载损伤、腐蚀、磨损和热损伤，各类损伤相互独立，又有内在关联。飞机反复起降过程中，起落架在交变载荷作用下，易在焊缝、螺栓孔等应力集中区域产生疲劳损伤，主要表现为微裂纹的萌生与扩展。随着载荷循环的不断累积，裂纹逐步加深并扩展，最终导致起落架结构失效。飞机起落架高强钢材料的疲劳裂纹萌生是表面缺陷、应力集中与微观组织三者相互作用的结果。表面缺陷（如加工刀痕、磕碰伤）作为直接的应力提升源，显著降低裂纹萌生寿命。应力集中则从宏（结构缺口）微（缺陷根部、夹杂物界面）观两个尺度驱动裂纹萌生，其局部应力峰值是萌生的直接驱动力。而微观组织则决定萌生的具体机制与位置，裂纹多萌生于晶界、与非金属夹杂物或脆性第二相粒子的界面处，因为这些位置是材料中的薄弱环节。因此，当前研究主要集中于通过改善表面完整性、优化结构设计以及净化材料、调控微观组织来协同提升起落架材料抗裂纹萌生的能力。

图3为飞机起落架疲劳损伤[33-36]。Zhang等[33]研究了起落架支柱在偏心压缩载荷下的表面裂纹扩展机制，薄壁圆柱状起落架支柱在循环载荷作用下，表面裂纹逐渐扩展并最终穿透柱壁，裂纹扩展主要由偏心载荷产生的拉-弯应力驱动，并最终导致液压油泄漏和缓冲功能失效（图3(a)）。Infante等[34]研究了飞机前起落架叉臂的失效机制，如图3(b)所示，裂纹萌生于螺栓孔应力集中区，在水平拖曳载荷为主的循环应力作用下以疲劳方式扩展，断口呈现典型海滩纹和疲劳条纹。Asi等[35]研究了飞机前起落架液压作动筒中活塞杆端的断裂失效问题，如图3(c)所示，裂纹起源于装配时锤击造成的表面机械损伤，应力集中使局部应力显著升高，在循环应力作用下，裂纹从损伤处萌生并扩展，最终引发高周疲劳失效。Bussiba等[36]研究了起落架前耳轴断裂失效问题，如图3(d)所示，不当磨削导致表面形成未回火马氏体和过回火马氏体，引发应力集中和晶间断裂，磨削热和表面粗糙度降低了材料疲劳强度，促使疲劳裂纹在损伤区萌生扩展。

硬着陆、紧急制动或侧向冲击等极端载荷作用下可造成过载损伤，起落架结构所承受的应力超过材料的屈服强度或极限强度，典型过载损伤表现为起落架塑性变形、结构断裂或连接件失效等损伤形式。Tao等[37]认为，过载对损伤的作用具有应力状态依赖性，在压缩主导区域因残余拉应力效应加剧后续损伤，而在拉伸主导区域则通过引入残余压应力起到延缓损伤的作用，其总体机制取决于过载顺序及局部屈服情况。Ossa[38]分析了飞机主起落架断裂失效原因，如图4(a)所示，起落架锁定机构的耳轴螺栓在着陆过程中因剪切载荷作用发生断裂，通过材料性能测试和载荷估算，断裂是由异常剧烈的重着陆产生的瞬时冲击载荷所致。如图4(b)所示，Farias等[39]研究发现，起落架外筒的断裂是由疲劳裂纹引发的不稳定扩展所致，其机制与材料的微观结构各向异性密切相关，断裂为韧性晶间与穿晶混合断裂模式，是异常着陆载荷与预存裂纹共同作用的结果，其中晶界析出相分布和取向是影响裂纹行为的关键因素。

飞机起落架在潮湿、盐雾、融雪剂、燃油残留及工业污染物等复杂腐蚀介质中服役时，其防护层缺陷或局部损伤部位易发生电化学反应并引发点蚀、晶间腐蚀及应力腐蚀开裂，从而加速材料劣化导致结构失效。如图5(a)所示，Turan等[40]通过显微分析与能谱检测发现，铝铜合金主起落架连接轴承在含氯化物环境中发生电化学腐蚀并形成点蚀坑，这些缺陷在循环载荷作用下成为疲劳裂纹萌生源，并在腐蚀-疲劳协同作用下加速扩展，最终导致轴承失效。如图5(b)所

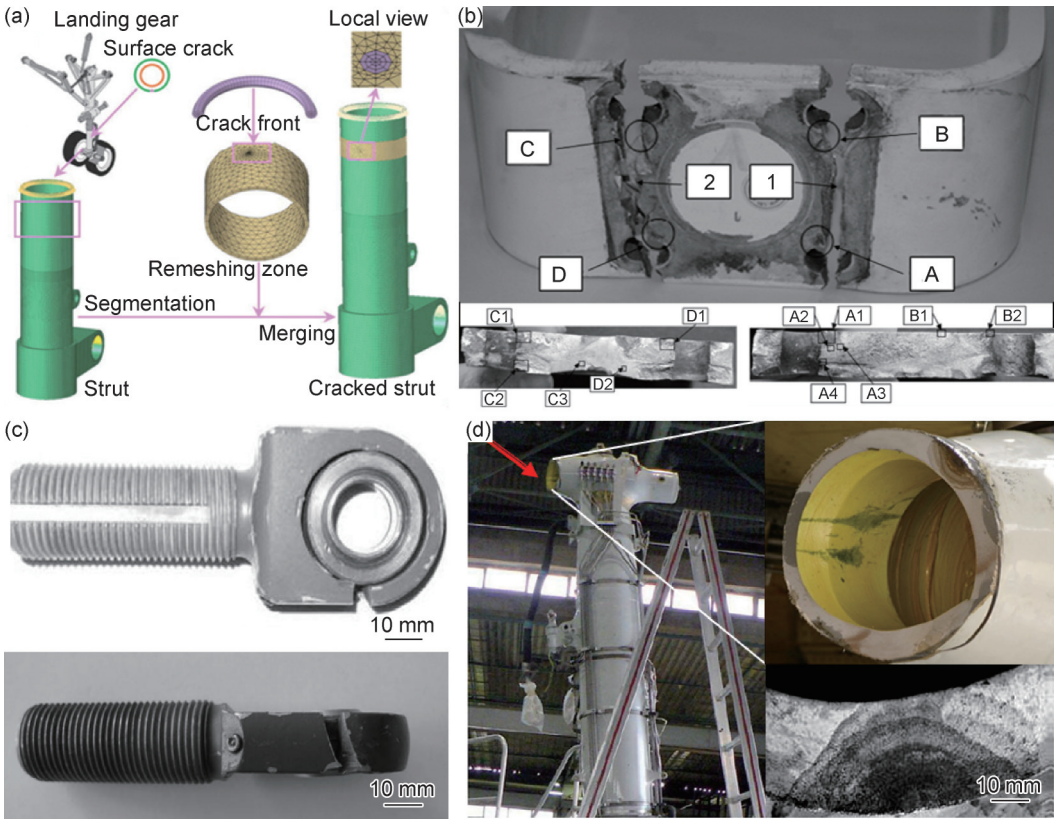


图 3　飞机起落架疲劳损伤

(a)起落架支柱裂纹有限元模型[33]；(b)前起落架叉臂断裂面[34]；(c)失效活塞杆端[35]；(d)断裂的左侧主起落架前耳轴[36]

Fig.3　Fatigue damage of aircraft landing gear

(a)finite element model of landing gear strut cracks[33]; (b)fracture surface of nose landing gear fork[34];

(c)failed piston rod end[35]; (d)fractured left main landing gear front trunnion[36]

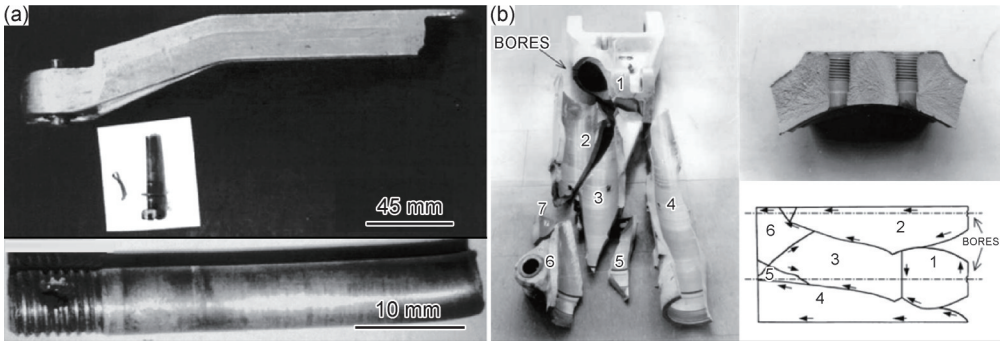


图 4　飞机起落架过载损伤

(a)起落架锁定机构耳轴螺栓断裂[38]；(b)起落架外筒断裂[39]

Fig.4　Overload damage of aircraft landing gear

(a)fracture of trunnion bolt in landing gear locking mechanism[38]; (b)fracture of landing gear outer cylinder[39]

示[41]，起落架开锁作动筒堵盖的裂纹源于应力腐蚀。腐蚀介质侵入螺纹区域破坏保护膜后，裂纹沿分模面晶界扩展形成应力腐蚀开裂。Eliaz 等[42]对 SAE 4340 钢货机起落架转向架梁的开裂失效进行了研究，如图 5(c)所示，断口表面呈现海滩状疲劳条纹，扫描电镜和金相分析表明裂纹萌生于镀铬层下的腐蚀坑，属于应力腐蚀开裂。该失效起因于镀铬后不当打磨引发的热损伤及微裂纹形成，裂纹在拉应力与腐蚀介质作用下逐步扩展直至断裂。

飞机起落架摩擦副表面主要发生磨粒磨损，伴随少量黏着磨损及疲劳磨损等损伤。随磨损加剧，可能引发部件尺寸超差、配合松动或密封失效等问题。孙同明等[43]研究了起落架作动筒磨损特性，结果显示内筒下部磨损主要沿轴向分布且周向分布不均匀。受

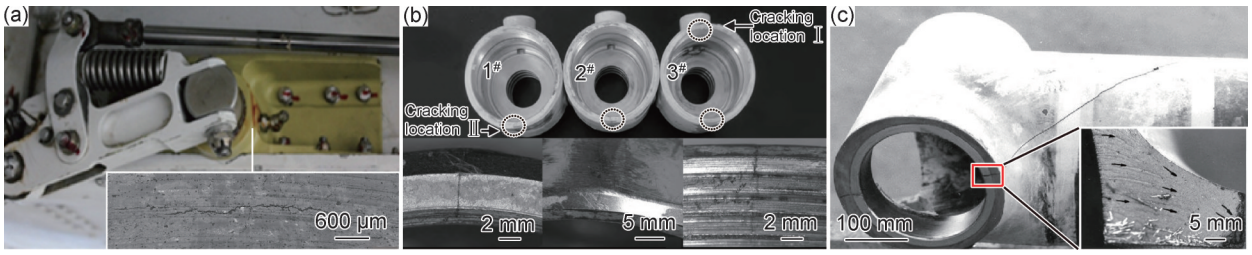


图5 飞机起落架腐蚀损伤

(a)起落架连接轴承失效[40];(b)主起落架开锁作动筒堵盖开裂[41];(c)起落架转向架梁开裂失效[42]

Fig.5 Corrosion damage of aircraft landing gear

(a)failure of landing gear connecting bearing[40];(b)cracked end cap of main landing gear unlock actuator cylinder[41];(c)cracking and failure of landing gear steering beam[42]

运动方向及间隙影响:作动筒收起时磨损以活塞前段为主,放下时则相反;小间隙下摩擦力大、磨损均匀但严重,大间隙下摩擦力小但磨损集中。起落架收上锁固定螺栓断裂属于多源疲劳断裂,工作过程中与支臂产生异常磨损并形成应力集中,从而显著降低疲劳强度,导致裂纹萌生、扩展[44]。

在高温工况下,飞机起落架关键部位(如刹车盘接触面、轮轴及缓冲支柱)易发生材料性能退化、微观组织变化及热应力裂纹扩展,进而导致结构强度下降或功能失效。Heirendt 等[45]建立的热-摩擦-机械耦合模型表明,滑行和起飞过程中,减震器轴承及活塞在高载荷与摩擦作用下产生热量,降低润滑性能与强度,热损伤主要集中于摩擦更大的下轴承区域,跑道振幅为主要影响因素。Korba 等[46]研究显示,刹车过程中推力盘在循环载荷下将动能转化为摩擦热,引发高温塑性变形及应力集中区裂纹萌生,最终导致失效。

2 飞机起落架再制造技术

飞机起落架再制造技术作为航空装备全生命周期管理的重要组成部分,是实现航空资源循环利用和降低运营成本的关键途径。通过先进的结构修复工艺、材料性能提升手段以及精密装配技术,退役起落架不仅能够恢复至原设计标准,更有可能在某些性能指标上实现优化。再制造过程涵盖多项核心环节,包括退役部件的非破坏性检测与损伤评估、疲劳寿命预测、关键部位的表面强化与材料改性、精密机械加工、焊接与热处理修复,以及最终的装配调试和性能验证。其中,检测与评估技术是确保再制造部件可靠性的前提,表面工程技术(如喷丸强化、热喷涂、激光熔覆等)能够有效改善摩擦磨损性能和抗疲劳寿命,而装配调试与精度控制则保障系统级功能的精确匹配与稳定性。随着绿色航空理念的推广与再制造技术的持续发展,现代起落架再制造体系已能够显著延长部件使用寿命,降低航空材料消耗和环境负荷。同时,智能化再制造与数字化质量监控的融合,如基于物联网的状态监测、数字孪生技术和人工智能驱动的缺陷预测与优化调控,正在推动起落架再制造向高效化、精密化、可追溯化方向发展。

2.1 飞机起落架无损检测技术

通过对退役起落架进行精确检测,可以识别飞机起落架服役状态与损伤特征,从而指导精确修复或材料替换方案,确保再制造后的起落架能够达到甚至超越原有性能标准。无损检测技术是实现这些目标不可或缺的工具。无损检测技术通过非侵入式评估手段,在保持构件服役性能的前提下,实现对材料缺陷和结构损伤的精确诊断。如表 3[47-48]所示,常见的起落架无损检测技术主要包括目视检测、渗透检测、磁粉检测、涡流检测、超声波检测和射线检测。

目视检测作为飞机起降前后的常规检查手段,主要针对起落架的结构、部件及其周边区域,通过直接观察或借助放大镜等工具识别潜在损伤或异常,直接发现重载制动导致的疲劳裂纹。在目视检查发现可疑迹象或需全面排查时,渗透检测可有效识别非铁磁性材料表面开口缺陷。该方法利用低表面张力渗透液渗入缺陷,通过显像剂显现能够无损检测表面间隙或不连续性。如图 6 所示[49],Kurdelski 等针对战斗机主起落架拉杆疲劳失效问题,利用着色渗透检测发现焊接区域存在微裂纹,表明渗透检测对早期裂纹识别具有关键作用。Freitas 等[50]通过目视检测发现,前起落架轮轴在着陆过程中因意外载荷断裂,结合光学显微镜和扫描电子显微镜分析断裂面,揭示韧窝形貌与剪切塑性变形特征,确认失效原因为载荷超过材料强度极限。

表 3　飞机起落架再制造典型无损检测技术[47-48]

Table 3　Typical non-destructive testing technologies for aircraft landing gear remanufacturing[47-48]

Technique	Applicable part	Typical detectable defect	Detection resolution	Advantage and disadvantage
Visual testing	Surfaces, joints, assembly areas	Macroscopic cracks, deformation, corrosion	About 0.1-0.2 mm visible by naked eye, micron level with magnifier	Simple and fast, low cost, limited to surface visible defects, sensitive to lighting and surface conditions
Penetrant testing	Smooth and non-porous materials external surface	Cracks, pores	Detectable defects≥0.5 μm	Suitable for complex shapes, simple operation, low cost, limited to surface defects, requires clean surface, unsuitable for rough or porous materials
Magnetic particle testing	Ferromagnetic materials surface and near-surface regions	Cracks, inclusions, welding defects	Detectable defects≥0.1 mm	Sensitive to ferromagnetic materials, intuitive defect visualization, fast detection, limited to ferromagnetic materials, requires demagnetization, difficult for complex geometries
Eddy current testing	Conductive materials surface and near-surface regions	Cracks, corrosion, material degradation	Detectable defects≥0.1 mm	No couplant required, fast detection, automatable, sensitive to small defects, limited to conductive materials, limited penetration depth, difficult for complex geometries
Ultrasonic testing	Internal structures of metals and non-metals, thick-walled components, bolts	Cracks, pores, inclusions, delamination, lack of fusion	Detectable defects≤1 mm	High penetration capability, quantitative defect sizing and localization, applicable to large components, requires couplant, influenced by surface roughness, difficult for complex geometries
Radiographic testing	Internal structures of metals and non-metals, welds, castings	Cracks, pores, inclusions, lack of fusion	Detectable defects with size ≥1% of wall thickness	Intuitive imaging, display defect morphology and location, suitable for hidden areas, radiation hazard, expensive equipment, radioactive waste disposal required

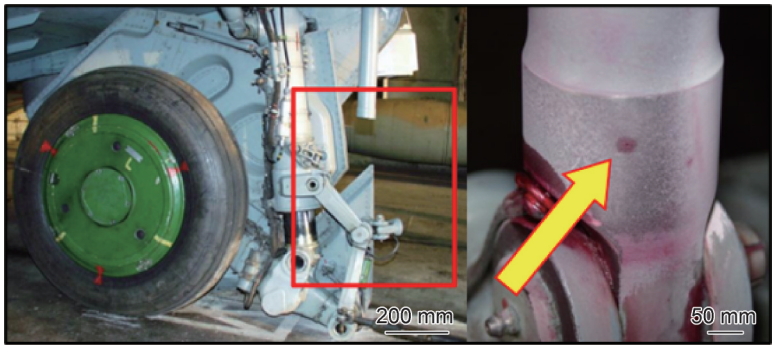


图 6　起落架拉杆渗透检测[49]

Fig.6　Penetrant inspection of landing gear tie rod[49]

磁粉检测是高强度钢等铁磁性材料起落架部件无损检测的首选方法。铁磁材料磁化后，缺陷处形成漏磁场，吸附磁粉可显现缺陷形貌。Malec 等[51]结合纵向和环向磁化技术，对起落架锁舌进行检测，通过紫外光观察发现锁舌与作动器连接处存在裂纹。张昕[52]针对大型复杂锻件，通过优化磁化方式、磁场强度及磁悬液浓度，实现全表面高灵敏度检测。涡流检测基于电磁感应原理，可检测导电材料表面及近表面缺陷。黄善强[53]提出基于涡流检测的支柱预判系统，通过内插式及穿透式线圈检测支柱内外壁缺陷，实现早期故障预警。Sun 等[54]对 A-320 起落架复杂曲面裂纹进行了检测，开发出改进型远程场涡流滑动探头与高增益系统，稳定识别表面及亚表面微裂纹，提高了复杂构件检测可靠性。

超声波检测是探测材料内部缺陷（如夹杂、气孔、内部裂纹）及精确测量缺陷深度和尺寸的核心手段。该方法通过高频声波在材料中的传播，分析反射波时间与幅值确定缺陷特性。Eaton 等[55]采用主成分分析声发射技术检测起落架疲劳裂纹，有效区分了裂纹信号与背景噪声。Duoba[56]提出矩阵相控阵超声检测技

术，通过电子扫描优化检测区域，实现高聚焦性和三维缺陷识别，避免机械定位误差。射线检测基于材料对X射线、Γ射线或中子射线的差异吸收，可直观探测内部缺陷。Park等[57]利用X射线双壁检测直升机阻力梁内部腐蚀，通过光子衰减模型量化厚度损失，结合应变与强度分布分析结构安全性。Kim[58]利用X射线评估液压系统钎焊接头质量，揭示内部孔洞和制造缺陷，验证射线检测结合显微结构分析在内部缺陷识别中的有效性。

2.2 飞机起落架再制造修复技术

飞机起落架作为航空器的关键承力部件，在长期服役过程中承受复杂应力与恶劣环境作用，极易产生裂纹、腐蚀和疲劳损伤等失效问题。传统维修手段往往局限于局部性修补或直接更换受损部件，虽能在一定程度上恢复构件性能，但在经济性与资源利用方面存在明显不足。相比之下，再制造修复技术作为区别于常规维修的一种先进工程方法，凭借系统化、科学化的工艺流程，能够在满足适航性要求的同时，实现部件寿命的延长与性能的恢复[59]。常见的再制造修复技术包括电镀、激光熔覆、超音速火焰喷涂、冷喷涂等。如表4[60-65]所示，各种修复方法各具特点与适用范围。电镀工艺可有效恢复部件的耐蚀性和尺寸精度，适用于轻度磨损和腐蚀损伤的修复[60]；激光熔覆技术则可实现修复层与基体的冶金结合，显著提升耐磨损与抗疲劳性能[61]；超音速火焰喷涂能够获得高致密度涂层，从而增强构件的耐蚀性和热稳定性[62-63]；而冷喷涂技术避免了热影响区对基体的潜在损伤，尤其适合修复热敏感合金部件[64-65]。通过上述多元化修复工艺的合理选择与组合应用，受损起落架部件不仅能够在力学性能和服役寿命上得到有效恢复，甚至可在某些性能指标上超越原始设计水平。这一修复策略不仅显著降低航空器维护成本，还促进了资源的循环利用，为绿色航空和可持续发展提供了重要的技术支撑。

表4 飞机起落架再制造表面修复关键技术[60-65]

Table 4 Key technologies for surface repair in aircraft landing gear remanufacturing[60-65]

Technology	Principle	Applicable scope	Advantage and disadvantage
Plating	Depositing a metallic layer on damaged surfaces *via* electrolysis to repair wear or corrosion	Minor wear repair, surface corrosion repair	Mature and low cost, suitable for complex shapes, thin coating, limited bonding strength, hydrogen embrittlement risk, environmental concerns
Laser cladding	High energy laser melts metal powder/wire and metallurgically bonds with the substrate to form a dense repair layer	Deep wear and crack repair, strengthening of high stress regions	Strong metallurgical bonding, low dilution rate, customizable materials, large repair thickness, high cost, precise control to prevent thermal distortion
High-velocity oxygen-fuel	High velocity combustion gas heats and sprays metal/ceramic powder onto substrate to form dense coating	Wear/corrosion-resistant coatings repair, surface strengthening	Dense coating with high bonding strength, suitable for large-area protection, limited coating thickness, high temperature may cause substrate oxidation
Cold spraying	High pressure gas accelerates metal powder to supersonic speed and deposits it through plastic deformation to form a coating	Temperature-sensitive materials, thin-layer repair	No heat affected zone, preserves material properties, suitable for spraying sensitive alloys, high cost, high particle velocity required, high surface roughness

飞机起落架作为航空器的关键承力结构，在服役过程中长期暴露于复杂环境中，易受到腐蚀、磨损及疲劳损伤。电镀技术作为一种成熟的表面工程手段，通过在起落架关键部位（如轮轴、销轴、支柱）沉积耐腐蚀或高硬度金属层，可有效增强表面耐腐蚀性和耐磨性，同时改善疲劳性能。此外，在退役或局部损伤部件的再制造过程中，电镀可用于恢复表面尺寸精度和几何形状，实现经济高效的修复。近年来，电镀工艺常与喷丸强化、热处理等表面改性技术相结合，形成复合表面工程体系，以满足起落架在高载荷、高摩擦及复杂环境下的性能要求，为其长期可靠运行提供保障。Zu等[66]研究了不同金属电镀涂层对30CrMnSiNi2A钢磨损性能的影响，结果表明，铬镀层凭借高硬度和低表面粗糙度表现出最佳耐磨性，其磨损体积和磨损率显著低于基体及其他涂层。Akhtar等[67]对SAE 4140钢进行了铬电镀研究，发现镀层显著提升硬度、耐磨性、耐腐蚀性及抗弯强度，其中厚度为0.381～0.508 mm的镀层表现出最佳综合性能。Sadananda等[68]系统考察了高强钢的牺牲性Zn-Ni电镀涂层，结果显示，当Ni含量为14%（质量分数，下同）时形成的Γ相涂层具有最佳性能，而通过过电流密度周期性调制制备的纳米多层结构涂层可进一步增强耐腐蚀性及抗氢脆能力。

尽管电镀技术在提高起落架耐腐蚀性和耐磨性方面作用显著，但其存在环境污染、使用有毒化学品及回收处理难度高等问题[69-70]。为应对这些限制，近

年来研究者开始探索绿色、环保且性能可比拟的替代表面处理技术。如激光熔覆、热喷涂以及冷喷涂等表面工程技术，能够在不产生有害废液的情况下形成高硬度、耐腐蚀或复合功能表面层[71-73]。同时，复合表面强化技术（如喷丸＋激光熔覆＋热处理）也逐渐应用于起落架关键部件，以实现耐磨、耐腐蚀及疲劳性能的综合优化。这些替代技术为航空器起落架的绿色制造与再制造提供了新的解决方案。激光熔覆、超音速火焰喷涂及冷喷涂是航空部件表面修复与性能提升的关键技术。激光熔覆通过高能激光束实现金属粉末与基体的冶金结合，显著提升耐磨、抗疲劳及耐腐蚀性能。Chen 等[74]在 30CrMnSiNi2A 钢表面制备 WC-Ni 涂层，发现 WC 质量分数为 20% 时性能最优，组织致密，结合良好。Aditya 等[75]熔覆 AerMet-100 粉末于 AISi-4340 钢表面，经过热处理后硬度、强度及耐磨性得到增强。Xiao 等[76]优化了 30CrMnSiA 钢熔覆参数，形成熔覆区马氏体、热影响区回火索氏体的分层结构，显微硬度和屈服强度显著提升。超音速火焰喷涂利用高温超音速火焰加速熔融或半熔融粉末至基体，获得低孔隙率、高硬度及优异耐磨耐蚀涂层（图7）。如Chen等[77]在TC18钛合金表面制备WC-12Co涂层，Padmavathi 等[78]制备 VC 增强的 WC-Co 涂层用于高负荷工况，Yao 等[79]通过 VC/Cr_3C_2抑制剂抑制 WC 脱碳，细化晶粒，实现硬度、耐磨性及耐腐蚀性能优化。冷喷涂是在低温下以超音速高速撞击粉末形成致密涂层。Tortuero 等[80]在 Ti6Al4V 表面制备涂层，表现出块体合金般的抗侵蚀性。Sienicki 等[81]在 4330 钢表面制备纯钛涂层，实现高硬度与抗疲劳性能，同时规避电镀环境风险。Chen 等[82]通过高压冷喷涂制备 WC 强化 MS300 钢复合材料，经固溶-时效处理显著提升界面结合强度和耐磨性。上述研究系统阐释了 3 类先进涂层技术在航空关键部件修复与性能增强中的应用潜力及工艺优化策略。

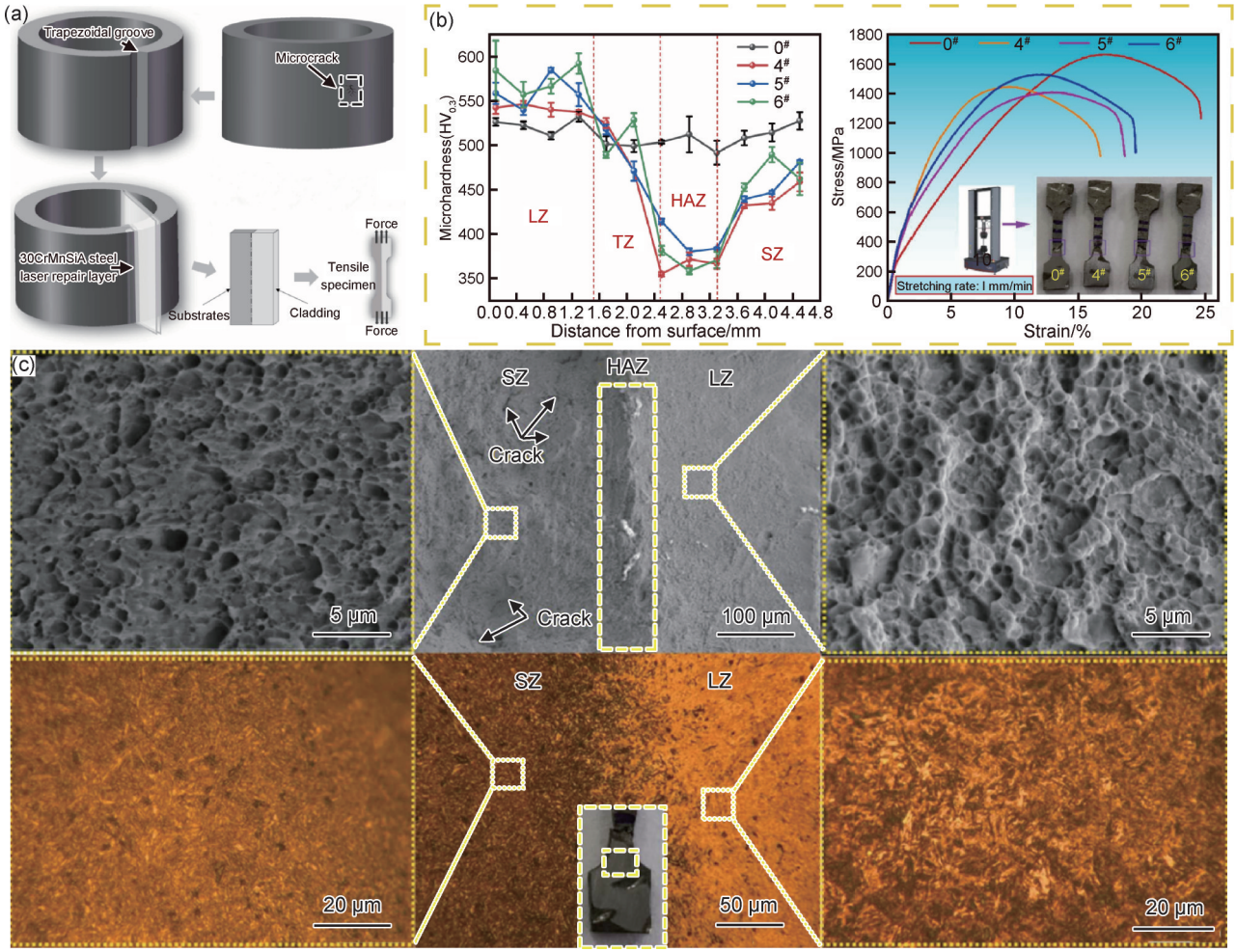


图 7　激光熔覆修复 30CrMnSiA 钢组织演变机制及力学性能[76]

（a）样品制备；（b）力学性能；（c）断裂形貌和金相显微组织

Fig.7　Microstructure evolution and mechanical properties of 30CrMnSiA steel repaired using laser cladding[76]

(a)sample preparation; (b)mechanical properties; (c)fracture morphologies and metallographic microstructures

2.3 飞机起落架再制造装配技术

近年来，飞机起落架再制造装配技术取得了显著进展，旨在确保退役起落架在再制造后达到甚至超越原有性能标准。研究主要集中在高精度装配、柔性自动化和智能化监控方面[83-85]：针对起落架服役过程中产生的微观磨损、塑性变形及修复后的几何偏差，多传感器融合技术（激光扫描、光学测量、超声检测及力/位移传感）与主动补偿、微调控制相结合，实现关键部件的精确匹配；为适应起落架部件结构复杂、尺寸大且质量高的特点，开发了多自由度装配平台、协作机器人和可调夹具系统，实现从初步定位、粗装到精装的柔性自动化操作，提高装配效率和一致性；结合数字孪生、实时传感及机器学习算法，对装配过程中可能出现的缺陷进行预测并自适应调整，同时对全过程数据进行分析，实现全生命周期追溯和可靠性评估。此外，振动控制、温控及润滑优化等技术的引入，有效降低了残余应力、摩擦磨损及热膨胀对装配精度的影响。总体来看，飞机起落架再制造装配技术正朝着高精度、自适应、柔性自动化和智能化方向发展，为提升再制造部件性能与可靠性、延长服役寿命及推动航空装备绿色循环提供了坚实的技术支撑。

3 结束语

本文系统综述了飞机起落架再制造技术，分析了其结构特性、典型损伤机制及关键再制造工艺，总结了起落架主要失效模式（疲劳、过载、腐蚀、磨损及热损伤），归纳了再制造无损检测技术（目视、渗透、磁粉、超声、涡流和射线检测）、先进修复工艺（激光熔覆、超音速喷涂、冷喷涂等）与装配技术，阐明了面向飞机起落架再制造的损伤评估、性能恢复与质量保证核心技术体系。近年来，飞机起落架再制造技术发展迅猛，仍面临诸多挑战。材料与工艺的协同优化需要大量实验验证，多传感器数据融合算法的可靠性亟待提升，新工艺获得民航适航认证周期长，而市场接受度仍需通过完善的质量保证体系进一步增强。

飞机起落架再制造技术的未来发展将集中于新型材料、智能化制造技术及绿色工艺3大核心方向，以提升性能、延长寿命并降低成本[86]：

（1）在材料创新方面，高性能合金和复合材料正在重塑传统起落架制造标准。钛合金、复合材料及纳米涂层技术不断提升承载能力与表面性能。同时，纳米涂层技术的进步，如自修复涂层、超疏水涂层及梯度功能涂层，实现了表面性能的精确调控[87-89]。金属增材制造拓展了复杂结构修复与一体化制造的新路径。

（2）在智能化先进制造技术方面，多模态无损检测与智能识别算法的结合显著增强了缺陷检测能力。数字孪生技术为全生命周期健康管理提供了新的方法，智能机器人系统与自适应激光加工技术实现了高精度自动化修复，而增强现实与力反馈遥操作等人机协作技术优化了维修作业流程。

（3）在绿色再制造领域，低温修复技术（如激光熔覆、冷喷涂）避免了传统焊接的热影响问题，同时降低能源消耗。新型高能束表面改性技术正在逐步替代污染严重的电镀铬工艺，资源循环利用技术的进步使旧件回收率提高，形成从材料再生到部件再利用的完整循环经济链。

飞机起落架再制造技术正处于快速创新期，其发展不仅提升起落架性能与可靠性，也为航空业的可持续发展和碳中和目标实现提供重要支撑。

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