

增材制造金属零件超快激光抛光技术研究进展

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摘要: 增材制造 (AM) 具有加工步骤简单、可原位制造、可定制零件等突出特点, 在航空航天、生物医疗、汽车制造等领域获得了广泛认可。但是增材制造的金属零件表面粗糙度较高、成形尺寸精度较差, 需要进行表面抛光才能使用, 这限制了该技术优势的发挥。如何突破这一技术瓶颈成为当前的研究热点, 原位抛光是其中一个分支。基于此, 综述了超快激光抛光增材制造金属零件的新进展。概述了金属增材制造的主要工艺、零件表面的主要缺陷以及主要的抛光技术, 总结归纳了传统激光抛光的不足和超快激光抛光的加工优势; 重点综述了金属的超快激光抛光发展、超快激光抛光机制、金属 AM 零件的超快激光抛光发展现状、设备集成发展等方面的内容; 最后指出了超快激光抛光增材制造零件及其设备的发展方向, 对该技术将得到广泛应用的前景进行了展望。本文填补了在增材制造金属零件表面超快激光抛光方面的综述空白。

关键词: 增材制造; 表面后处理; 激光技术; 超快激光; 激光抛光

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Advances in the Research of Ultrafast Laser Polishing Technologies for Additive Manufacturing Metal Parts

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ABSTRACT: Recently, advancements in artificial intelligence have brought new opportunities to additive manufacturing (also known as 3D printing), especially in digital model construction, process path optimization, and human-machine interaction. This technology offers several advantages, such as fabricating complex structures that are unattainable with traditional manufacturing methods, personalized customization, shortening development cycles, simplifying processes, enabling in-situ manufacturing, and reducing material waste. Therefore, it engenders the transformation and upgrading of the manufacturing industry. Components produced by metal additive manufacturing have been widely applied in fields such as aerospace, biomedicine and automotive industry. However, these surfaces have a high roughness, which affects their function, including appearance, assembly, and service performance. As a result, it is necessary to polish the surface to reduce constraints on the widespread application of the technology. In order to overcome this obstacle, the research focuses on enhancing the accuracy of additive

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manufacturing and reducing its roughness, as well as implementing in-situ polishing post-fabrication. Ultrafast laser polishing technology can effectively improve surface quality, which broadens the industrial application scope of additive manufacturing technology.

Ultrafast laser polishing technology retains its traditional advantages, which include characteristics such as flexibility, non-contact processing, intelligence, in-situ processing, and environmental friendliness. It can achieve high precision and cold processing and is capable of handling almost all known materials. Currently, widely adopted methods such as abrasive flow and electrochemistry have their own advantages, but they cannot be compared with ultrafast laser polishing technology in terms of in-situ processing and integration with laser additive manufacturing equipment. Traditional laser polishing methods, primarily based on hot working, long pulse and continuous laser polishing may lead to remelted surfaces, large heat-affected zones, and microcracks. Challenges include difficulties in polishing thin-walled, microstructured, and complex geometries (e.g., grids and foams), suboptimal polishing of multilayer, thermally sensitive, brittle materials, and inefficiency in polishing hard and refractory materials. Ultrafast laser polishing technology can effectively overcome these challenges.

It is a short time since ultrafast laser polishing technology has been applied in the field of additive manufacturing for metal parts. This technology integrates ultrafast laser processing with additive manufacturing techniques. Meanwhile, it is primarily based on the rapidly developing cold polishing mechanism. Experimental studies and microscopic analyses have confirmed that the technology achieves small heat-affected zones and high-precision polishing. According to the relative angle between the polishing beam and the processed surface, the technology can be divided into vertical incidence and grazing incidence. Based on the number of repetitions in the processing, the technology can be categorized into single-pass and multi-pass polishing strategies. At present, this technology has refined the surface roughness R_a value from tens of micrometers or several micrometers down to the nanometer level. However, there is little literature available on roughness values less than 0.1 microns. Compared to traditional laser polishing technology, ultrafast laser polishing is in a stage of rapid development, and there is still potential to improve the quality of the polishing.

The concept of integrating 3D printing with ultrafast laser polishing was proposed before 2018. In 2018, Ghosh and Worts independently proposed their respective design schemes for this integration. Ghosh also achieved a polishing effect with an average sidewall roughness of (4.7 ± 1) mm and a sidewall taper angle of approximately $3^\circ \pm 1^\circ$ through experimentation. Bouet further advanced this technology in 2019, developing an integrated device capable of directly manufacturing Ti-6Al-4V parts with biologically functional surfaces, eliminating subsequent processing steps. Studies have also shown that during additive manufacturing (AM), in-situ ultrafast laser polishing can increase part density and reduce porosity, thereby improving the overall quality. The emergence of ultrafast laser 3D printing equipment opens up a new direction for integrated printing and polishing systems that utilize a single laser source. This approach offers advantages in miniaturization and functional integration compared to devices equipped with dual laser sources.

This review delves into the application and addresses the challenges of ultrafast laser polishing technology within the domain of metal additive manufacturing. Although this technology is considered as an effective method for improving the quality of surface treatment, it still encounters technical challenges in reducing surface roughness and increasing polishing efficiency, especially when processing internal surfaces and complex-shaped components. To overcome these challenges, the ongoing research and development of ultrafast laser polishing equipment increasingly focuses on miniaturization, lightweight design, multifunctionality, and intelligent operation. These technological advancements are of great significance for meeting the manufacturing and repair needs in extreme environments within industries such as aerospace and energy. With the increasing demand for high surface quality in additive manufacturing products such as biomedical implants, automotive parts, industrial molds, and everyday commodities, the application of ultrafast laser polishing technology is becoming increasingly critical. Consequently, it is predictable that as technology continues to advance, ultrafast laser polishing will play an increasingly prominent role in the post-processing stage of additive manufacturing.

This research bridges the gaps in comprehensive reviews regarding ultrafast laser polishing for the surfaces of metal components fabricated through additive manufacturing.

KEY WORDS: additive manufacturing; surface post-treatment; laser technique; ultrafast laser; laser polishing

增材制造 (AM) 或 3D 打印已经在航空航天、汽车模具、生物医疗等不同领域大量应用并具有广阔的发展前景^[1-4]。增材制造常用的材料包括金属、聚合物和陶瓷等, 其中金属材料在工业中的应用相对更加广泛。金属增材制造的工艺主要分为两大类^[5]: 一是“粉床熔融”, 即选择性激光烧结(SLS)、选择性激光熔化(SLM)和电子束熔化(EBM)技术; 二是“直接能源沉积”, 即激光工程网络成形 (LENS) 技术, 也称为直接金属沉积 (DMD)、直接激光沉积 (DLD) 和增材激光制造 (ALM)。其中, 比较有代表性和用途广泛的是 SLM 技术。采用 SLM 技术制造的金属零件精度较高, 但将只有 40 μm 的粉末在较大面积均匀铺开较为困难且制造过程需在加工室中进行, 因此主要用于中小尺寸金属零件制造^[5-6]。

由于在制造过程中, 增材制造金属零件具有固有缺陷, 主要包括球化缺陷、未熔化的粉末颗粒、阶梯效应、表面孔隙、缺乏熔合和微裂纹等^[1]。就 SLM 技术而言, 虽然通过优化工艺参数 (比如激光能量、扫描速度、颗粒尺寸和加工室环境等) 可以进一步提高零件的质量, 但是固有的路径扫描和逐点、逐层加工的过程, 使得其表面缺陷 (比如部分熔融颗粒的黏附、阶梯和球化效应等^[7]) 难以完全避免。SLM 成型金属的表面粗糙度仍然有待提高 (4~40 μm), 成形尺寸精度也不够高 ($\pm 50 \mu\text{m}$)^[8-9]。粗糙表面的高峰和低谷结构容易形成微小的缺陷, 这些微缺陷可能会对材料的疲劳性能产生不利影响。因此, 增材制造零件的表面粗糙度对其美观度、装配以及服役的可靠性与安全性等方面具有显著影响, 必须进行后处理 (也称为表面精加工^[10])。这种后处理主要是对零件的外表面和内表面进行抛光处理, 当前主流的表面抛光技术有机械抛光 (磨料流等)、化学抛光、电化学抛光、激光抛光(LP)等^[11]。根据材料去除方法的不同性质可以分为化学、机械、热以及混合去除 4 种类型^[4]。与前面的抛光方法不同, 激光抛光具有柔性、非接触、智能加工、可以在增材制造零件完成后原位进行加工等优点^[1,12]。但是传统的激光抛光主要是热抛光, 长脉冲和连续波激光抛光会造成表面重熔、热影响区较大和微裂纹等新问题。除此之外, 该技术还面临以下挑战^[13]: 一是难以对薄壁、微尺度以及复杂结构 (例如网格和泡沫结构等) 进行抛光; 二是对多层材料、热敏性和脆性材料的抛光效果较差; 三是对高硬度、难熔材料的抛光难度大、抛光效率较低。

以上问题因为超快激光应用于抛光而出现转机。超快激光技术突破以后, 人们对空间和时间的微观尺度的认识更加深刻。超快激光^[14]又称为超短脉冲激光, 其脉冲宽度一般在 10 ps (1 ps= 10^{-12} s) 以下, 峰值功率可达 10^{12} W 以上, 几乎可以实现对任何材料的精细抛光。与之前的传统抛光不同, 超快激光在极

短时间内的辐照, 引发了材料表面抛光的根本变化。根据物质内部热传递的时间尺度和过程的不同, 抛光技术明确划分为热抛光和冷抛光^[15]。一般认为超快激光抛光属于冷抛光。该技术特别适合于薄壁及多层结构、热敏及脆性材料的处理。由于极窄的脉冲宽度、极高的峰值功率, 超快激光与材料作用时发生了非线性吸收, 电子的跃迁更加容易。因此, 超快激光抛光也适用于传统方法难以加工的高硬度、高熔点的材料。超快激光抛光具有确定的烧蚀阈值、热影响区小以及加工分辨率高 (高空间选择性) 等显著优点^[16]。与传统抛光技术相比, 超快激光抛光技术不依赖机械力或化学反应, 能够实现精确的选择性加工, 提供更高的加工精度, 并最大程度地保持材料的原始属性。该技术适用于多种材料, 其环境友好性和自动化程度也显著高于现有抛光技术。

因此, 增材制造金属零件的超快激光抛光也引起了研究人员的关注。超快激光抛光与激光增材制造 (LAM) 的结合可以实现原位抛光, 能够解决增材制造需额外后处理 (抛光) 步骤的不足, 最大程度地发挥增材制造的优势。该技术在需要原位制造、灵活定制零件的领域具有巨大的应用价值。除了在增材制造领域, 超快激光抛光作为一种先进的原位抛光技术, 在不可拆卸或难拆卸构件的现场原位修复等场合 (例如航空航天、能源动力领域) 也能够发挥巨大的社会和经济价值。

虽然关于增材制造零件表面激光抛光的文章较多, 但是大多数集中于利用热能的连续波 (CW) 或长脉冲激光抛光, 聚焦于超快激光抛光的综述很少。本文着眼于这一需求, 立足增材制造金属零件需要原位抛光的现实需求, 以金属的超快激光抛光研究为切入点, 综述了目前该技术的研究现状及最新研究进展。

1 金属的超快激光抛光研究

1.1 金属激光抛光的发展历程

激光抛光的研究始于 20 世纪 90 年代^[17-19]。初始阶段的研究重点集中在硅等非金属材料的抛光, 针对金属材料的激光抛光研究则是在此之后逐渐展开的。1997 年, Erdemir 等^[18]采用激光对硅片或金刚石薄膜进行了抛光。2000 年以后, Scopus 数据库中关于激光抛光的研究逐年增加^[19]。2001 年, Ramos 等^[20]对间接选择性激光烧结 (SLS) 制备的金属零件表面进行了激光抛光, 并指出存在部分熔化和过熔化 2 种机制。2007 年, Lamikiz 等^[17]系统地研究了工具钢 (DIN 1.2344) 和 SLS 制造的合金 (激光成型 ST100) 的激光抛光, 证实了激光抛光在降低表面粗糙度的同时, 形状误差或其他宏观偏差保持不变。早期激光抛光领

域的研究几乎全部集中于使用连续波或长脉冲激光技术。对于金属材料,采用超快激光进行抛光的研究起步相对较晚。最迟到 2007 年,Guo 等^[21]在对钛的植入物表面进行处理时发现飞秒激光处理可以获得光滑的表面。2010 年,Dadbakhsh 等^[22]对激光金属沉积(LMD)制备的 Inconel 718 进行了激光抛光,证明了激光抛光 LAM 金属的可行性。进入 21 世纪以来,金属的激光增材制造技术和固体超快激光器获得了快速发展^[23]。增材制造金属零件的超快激光抛光研究也取得了较大进展。

金属激光抛光的发展历程如图 1 所示。在早期阶段,激光抛光金属材料的工艺主要侧重于利用熔化机制来降低表面粗糙度,而对材料去除关注不够。随着皮秒和飞秒激光技术的进步,基于烧蚀气化机理的超快激光抛光技术在金属材料处理上取得了显著进步,并在多个领域展现出广泛的应用潜力。该技术通过高效的材料去除,大幅降低了材料的表面粗糙度。此外,激光增材制造技术(LAM)的迅猛发展为金属零件的应用提供了新的机遇。在此背景下,超快激光抛光技术因其能够显著提升零件表面质量,正逐步成为研究焦点。具体而言,在增材制造过程中,超快激光抛光技术的应用可分为 2 个主要研究方向:一是同步抛光,即在增材制造的同时进行表面处理;二是异步抛光,即在增材制造完成后对零件进行独立的表面处理。

1.2 金属超快激光抛光研究现状

在发展初期,超快激光抛光技术由于加工精度高而加工效率低,主要应用于金刚石、半导体、陶瓷及陶瓷基复合材料等难加工材料的精密激光抛光。随着技术的不断进步,其高精度、“冷加工”以及适用于多种材料等技术优势引起更多关注,加工效率不断提升,应用领域不断拓展。目前,该技术已被广泛应用于各种材料体系,包括硬脆材料(如石英^[24]、聚晶金刚石^[25]、氧化钇稳定氧化锆 YSZ^[26]、碳化硅 SiC 陶

瓷及陶瓷基复合材料^[27-34])、半导体材料(如锗^[35]和氮化镓 GaN^[36])、聚合物材料(如聚乳酸 PLA^[37])、金属及金属基复合材料(如金属铬铝钼 MCrAlY^[38])等。表 1 给出了超快激光抛光处理的一些材料的具体特性,可见不同领域均在关注超快激光抛光技术。超快激光抛光技术主要适用的零件结构有复杂三维结构(如蜂窝芯薄壁结构^[39]等)、高精度零件(如光学元件^[40-41]等)、微纳结构(如 MEMS 部件^[42]、微光学元件^[35]等)、表面质量要求高的零件(如医用植入物^[21,43]等)。

金属材料具有优异的导热和导电性,这些属性使得精密微细抛光加工面临特定的技术挑战。对于高热导率和较低熔点的普通金属(如钢、铜、铝等),传统激光抛光技术(包括连续波和长脉冲激光抛光)难以在其表面取得精细的加工效果。而对于难熔金属如钨、钼、铌、铪等,因其熔点高达数千摄氏度,即使使用长脉冲激光也很难对其进行加工,更难于实现精细抛光^[44]。超快激光凭借其超短脉冲宽度和极高的峰值功率,能够有效减少热效应,已经成为金属高精度抛光的重要方法。针对金属的超快激光抛光成为了当下的一个研究热点。Yang 等^[45]研究了飞秒激光抛光 Ti-6Al-4V 的激光参数与表面粗糙度之间的关系,获得了加工精细表面粗糙度的加工参数。Bao 等^[46]针对飞秒激光烧蚀引起的潜在损伤的问题展开研究,通过详细表征纯超细晶粒和粗晶粒 Cu 的表面粗糙度和亚表面微观结构,证明了飞秒激光微加工用于高效可靠机械评估的可行性。Chang 等^[47]研究了在油润滑环境下,飞秒激光功率和光斑重叠率对 SKD61 工具钢表面织构的粗糙度参数、接触角和摩擦学性能的影响。除了基于烧蚀机理的超快激光抛光之外,研究人员也开展了基于重熔机制的超快激光抛光研究。例如 Sassmannshausen 等^[48]采取高脉冲频率飞秒激光对工具钢进行了抛光处理,有效减少了表面烧蚀。随着超快激光器技术的日趋成熟,目前该领域的研究正在飞速发展。

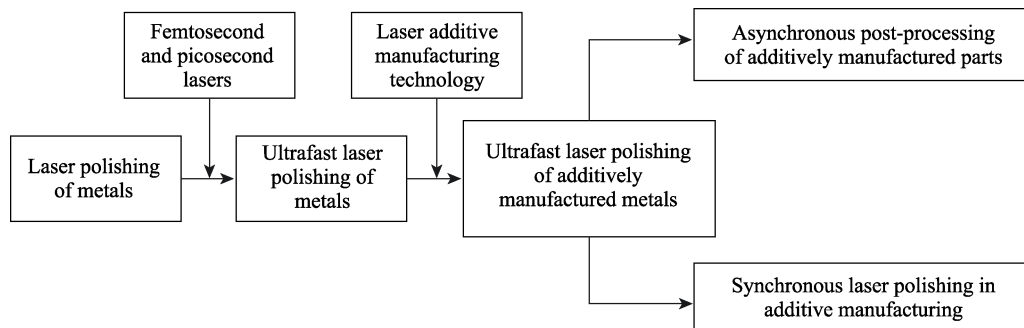


图 1 金属激光抛光的发展历程
Fig.1 Development history of laser polishing of metal

表 1 难加工材料超快激光抛光的研究
Tab.1 Research on ultrafast laser polishing of difficult-to-process materials

Serial No.	Materials	Characteristics	Application field
1	Silicon carbide (SiC) ceramics and ceramic matrix composites ^[27-34,49,51]	High hardness, wear resistance, thermal conductivity, low thermal expansion, and chemical stability	Aerospace and energy fields: engine hot-end components, thermal protection structures, nuclear reactor materials, etc
2	4H-SiC ^[50]	High electron mobility, breakdown field strength, thermal conductivity, low defect density	High-power electronics, optoelectronics, sensors, etc
3	RB-SiC ^[51-53]	High strength, specific stiffness, thermal conductivity, low expansion	Optical systems, high-temperature structural materials, etc
4	Quartz material ^[24]	High hardness, melting point, chemical stability, piezoelectricity	Glass industry, ceramic industry, building materials, electronic industry, etc
5	Polycrystalline diamond ^[25]	Extreme hardness, wear resistance, corrosion resistance, chemical stability	Semiconductors, photodetectors, and LEDs, etc
6	Germanium ^[35]	High melting and boiling points; strong chemical inertness, insoluble in most acids and alkalis; excellent semiconductor, optical, and thermal properties	Electronics, optics, thermosensitive materials and medicine, etc
7	GaN ^[36]	High electron mobility, breakdown field strength, thermal conductivity, chemical stability	LEDs, microwave communication, power electronic devices, etc
8	Yttria-stabilized zirconia (YSZ) ceramic materials ^[26]	High chemical stability, melting point, low thermal conductivity	Aerospace, automotive, electronics, medical and energy sectors, etc
9	MCrAlY metal matrix composite ^[38]	High hardness, strength, toughness, wear resistance, anti-oxidation	Aerospace, steel, shipbuilding and oil industries, etc
10	Polylactic acid (PLA) ^[37]	Low melting point, thermally sensitive, low impact toughness	3D printing, packaging, textiles, and medical devices, etc

2 超快激光抛光机制

从热效应角度来说，激光抛光(LP)可以分为热抛光和冷抛光 2 类^[54]。一般的激光抛光属于热抛光，表现形式主要是材料表面熔化以及烧蚀气化。抛光表现为表面熔化时，材料由固相到液相再到固相的过程，一般不考虑发生材料去除；表现为烧蚀气化时，材料直接由固相变为气相，材料去除占主要部分。冷抛光的热效应较小，表现形式主要是材料表面光化学分解以及烧蚀气化，属于材料去除。冷抛光主要表现为光化学分解^[55]，此时材料的原子在与激光发生作用时，由于“单光子吸收”和“多光子吸收”效应，使得其化学键和晶格结构发生断裂；当表现为烧蚀气化时，采用的多是超快激光抛光，此时材料中的热还没有传递到晶格，加工过程就已经结束。

采用热抛光还是冷抛光，需要综合考虑材料的性质（是否耐热）、抛光的最终目的（抛光效率、抛光效果等）以及现实的条件（抛光设备）等来确定。一般来说，脆性材料（或热敏材料）以冷抛光为主，塑性材料则以热抛光为主^[56]。金属材料大多属于塑性材料，但其具有良好的导热性，可以根据具体的加工需要采用不同的激光源进行抛光。

2.1 金属的热抛光机理

热抛光主要是通过激光照射使得材料表面熔化，材料在表面张力和重力作用下平滑表面的起伏并凝固，从而降低表面粗糙度^[10,57]。激光抛光的效果主要与 3 个因素有关^[58]：零件的初始表面粗糙度、表面的材料以及激光束的能量密度。热抛光采用的激光源^[59]主要是连续波激光以及脉冲激光（脉冲宽度 $>10^{-9}$ s）。热抛光的过程如图 2 所示^[19]。

2.2 金属的冷抛光机理

金属的冷抛光是指采用超快激光（也称为超短脉冲激光）作为能源，通过使材料的表面烧蚀气化，从而达到平滑表面的目标。超短的脉冲宽度以及在焦点附近极高的峰值功率，使得超快激光可以在极短的时间内对物质进行选择性的加工。这使得超快激光加工可以在极小的作用区域注入极大的能量，突破传统激光的加工限制。在该加工区域，材料的温度瞬间急剧攀升，材料以等离子体形式向外喷发，减少了热效应和冲击波作用。

超快激光与金属材料的作用，首先发生在电子层面。电子吸收光子后，携带能量向晶格传递，伴随晶格温度升高，电子温度持续降低，最终实现温度平衡。

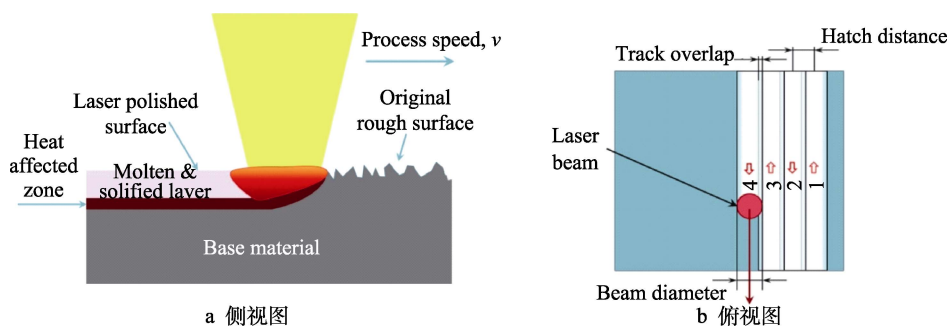


图 2 激光热抛光原理^[19]
Fig.2 Laser polishing principle^[19]: a) side view; b) top view

脉冲能量密度达到材料的烧蚀阈值时,发生材料的去除^[51]。材料的激发态电子向晶格弛豫能量所需时长的时间尺度大致在 10^{-12} s 以上,如图 3 所示^[60]。材料加工所用的超快激光脉冲持续时间一般短于材料的弛豫时间,因此可以实现冷加工。在材料去除过程中,金属的电子电离以雪崩电离为主。根据资料^[15],一般的金属材料加工需要 1~10 ps 脉宽的脉冲,有些则需要更短的脉宽(比如钢铁材料的加工需要数百飞秒量级的脉宽)。超快激光与长脉冲激光分别对材料表面进行烧蚀的过程如图 4 所示^[43,61]。超快激光抛光具有明显的低热效应、低表面重铸层、低表面裂纹、固定的烧蚀阈值以及几乎可以抛光所有已知材料等技术优势。

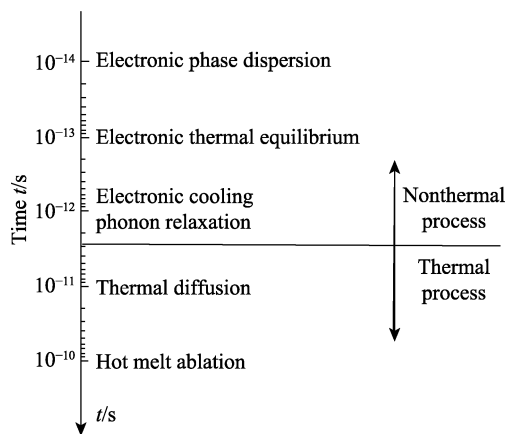


图 3 受激电子弛豫过程的时间尺度^[60]
Fig.3 Various processes of excited electron relaxation^[60]

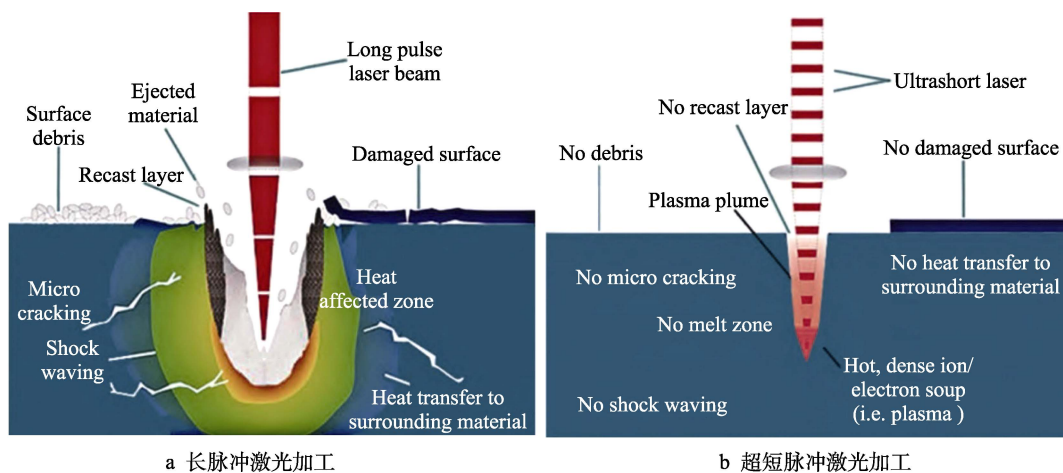


图 4 长脉冲激光与超短脉冲激光刻蚀材料的比较^[43,61]
Fig.4 Comparison of long-pulse lasers and ultrashort pulsed laser etching material^[43,61]:
a) long-pulse laser processing; b) ultrashort pulsed laser processing

3 金属 AM 零件超快激光抛光发展现状

超快激光抛光增材制造金属零件的早期研究进展。最迟到 2013 年, Mingareev 等^[62]采用飞秒激光对 SLM 和 LMD 技术制造的镍基和钛基高温合金进行了抛光研究,表面粗糙度从 22~45 μm 降低到几微米。2014 年, Mingareev 等^[62-65]宣称首次实验证明了用超快激光抛光激光增材制造 (LAM) 镍基金属零

件的可行性,指出该方法在热敏和薄壁几何形状(多孔结构、网格、泡沫)的零件表面后处理中具有更大优势。除了直接的抛光研究以外,研究人员在飞秒激光增材制造方面也进行了探索。2015 年, Bai 等^[66]宣称首次采用飞秒激光增材制造了以铁和钨为原材料的零件。这使得超快激光增材与减材(抛光)一体加工成为了可能。尽管金属 AM 零件超快激光抛光的研究只有最近十多年的历史,但发展速度很快。其发展脉络如图 5 所示。

超快激光抛光增材制造金属零件的优势与特点。2018 年, Worts 等^[65]对激光粉末床熔合(LPBF)制造零件(Ti-6Al-4V 合金材料)表面的超快激光抛光与未处理区域进行图像区域对比分析, 定性说明了飞秒激光烧蚀对 AM 材料的晶粒结构几乎没有影响, 处理区域没有额外热影响区, 如图 6 所示^[65]。该研究通过实验观察证实了前文提到的冷抛光机理, 超快激光抛光的优势在实践中不断得到验证。2019 年, Yang 等^[45]

宣称首次采用飞秒激光对 Ti-6Al-4V 进行了抛光。研究表明, 该抛光方法在降低 Ti-6Al-4V 表面粗糙度的同时, 不会造成微裂纹, 也不会改变其表面的化学成分, 如图 7 所示^[45]。2023 年, Liu 等^[67]对比研究了连续波(CW)、纳秒和飞秒(FS)激光对 LPBF 制造的 316L 不锈钢材料的抛光效果。指出超快激光的冷加工效应降低了材料熔化造成的重铸层(如图 8 所示^[67]), 热应力诱发的微裂纹也受到抑制(如图 9 所示^[67])。

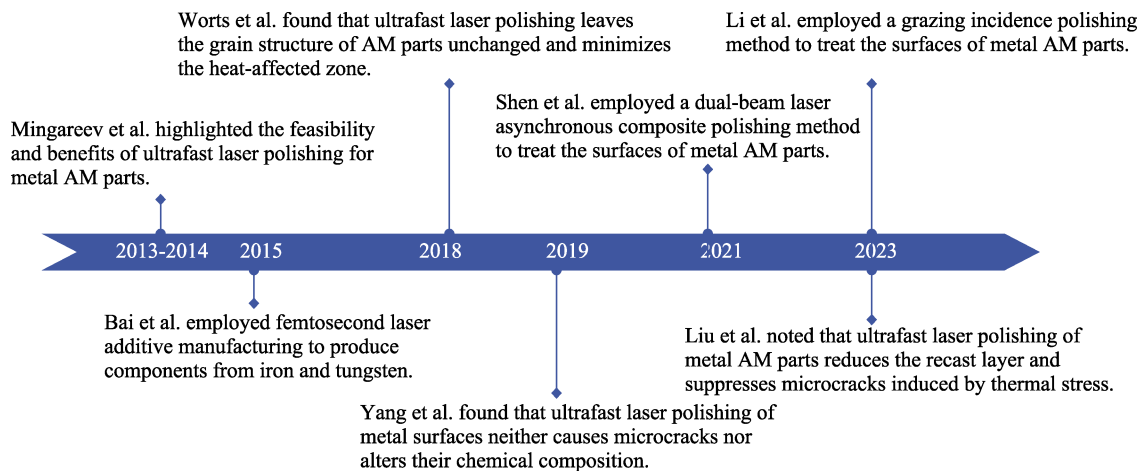


图 5 金属 AM 零件的超快激光抛光发展历程
Fig.5 Evolution of ultrafast laser polishing for metal AM Parts

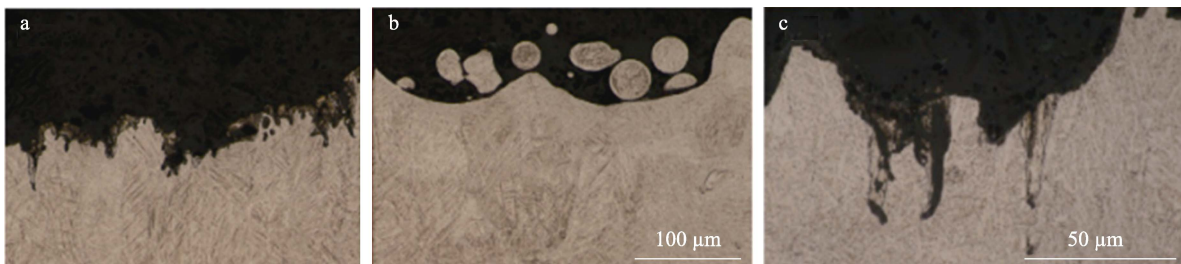


图 6 增材制造零件表面(SAP)的烧蚀和 SAP 部分(未烧蚀)的横截面视图^[65](红线表示用飞秒激光烧蚀表面的区域(a)与未处理的(SAP)表面(b)部分在 20 倍放大率下的分割, 在 SAP 侧易于观察到部分熔融的金属颗粒, (c)是烧蚀区域的高分辨率图像, 显示增材制造部分在 100 倍的放大下没有热影响区)

Fig.6 Cross-section views of the ablated and SAP portions of an AM part surface^[65]: the red line denotes the separation of the zone where the surface is ablated with the femtosecond laser (a) and untreated (SAP) (b) portions of the surface at a magnification of 20 \times ; partially fused metal particles are easily observed on the SAP side; (c) is a higher resolution image of an ablated area which shows the lack of a heat affected zone in the AM part at a magnification of 100 \times

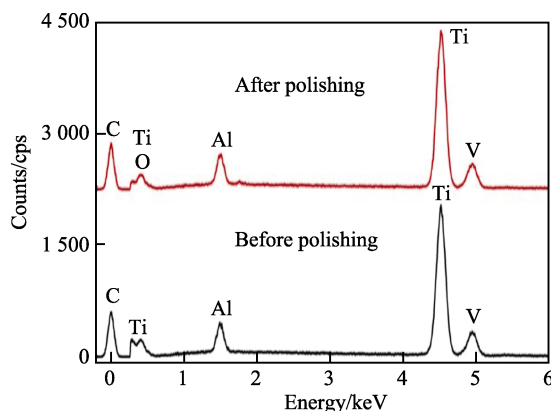


图 7 抛光前后样品的 EDS 谱图^[45]

Fig.7 EDS spectra of the sample before and after polishing^[45]

超快激光抛光增材制造金属零件的应用现状。超快激光的抛光按照光束入射角度可以分为 2 种工艺: 垂直入射和掠入射抛光。一是激光束与加工面垂直的抛光。2013 年, Mingareev 等^[64]分别采用飞秒和皮秒激光对 SLM 制造 Inconel 718 合金以及激光金属沉积制造(LMD) Ti-6Al-4V 合金零件进行表面抛光, 表面粗糙度从几十微米到上百微米降低到几微米。2018 年, Worts 等^[65]采用飞秒激光对增材制造 Ti-6Al-4V 合金零件表面抛光, 单次抛光表面粗糙度 R_a 从 4.23 μm 降低到 0.8 μm 。二是激光束与加工面成角度的掠入射抛光。2023 年, Li 等^[68]采用 3 次抛光的方法, 用飞秒激光在初始粗糙度 $S_a > 20 \mu\text{m}$ 的增材制造不锈钢零件上实现了 $S_a < 200 \text{ nm}$ 的镜面表面,

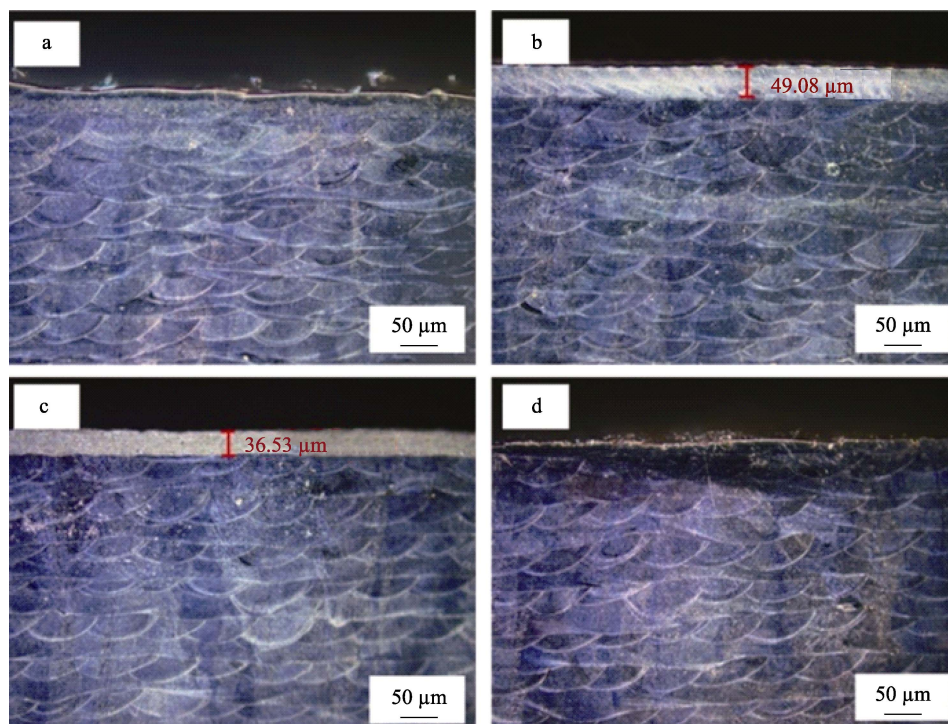


图 8 原始 (a)、连续波 (CW) (b)、纳秒 (NS) (c) 和飞秒 (FS) (d) 激光抛光 316L 不锈钢表面的横截面显微照片^[67]
Fig.8 Cross-sectional micrographs of the original (a), CW (b), NS (c), and FS (d) laser-polished 316L stainless steel surfaces^[67]

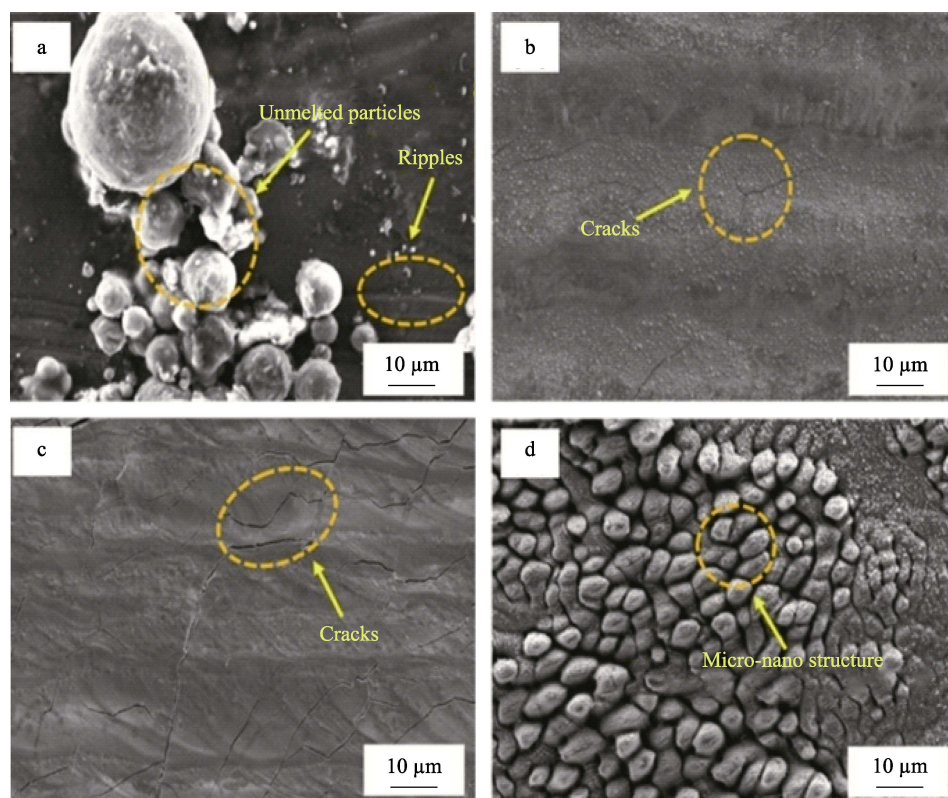


图 9 原始 (a)、CW (b)、NS (c) 和 FS (d) 激光抛光 316L 不锈钢表面的表面形态^[67]
Fig.9 Morphologies of the original (a), CW (b), NS (c), and FS (d) laser-polished 316L stainless steel surfaces^[67]

如图 10 所示^[68]。除此之外, 研究人员也开展了复合抛光研究。2021 年, Shen 等^[69]对 LMD 制备的 Ti-6Al-4V 零件表面采用双束激光异步复合抛光。皮秒激光用于精确去除材料表面波纹 (即皮秒激光加

工, PLM), 连续波激光用于进一步抛光。与初始 LMD 粗糙度 ($Ra=6.62\ \mu\text{m}$) 相比, 表面粗糙度降低了 90% 以上 ($Ra=0.55\ \mu\text{m}$)。加工过程如图 11 所示^[69]。值得注意的是, 随着技术的发展, 近些年出现了利用脉冲

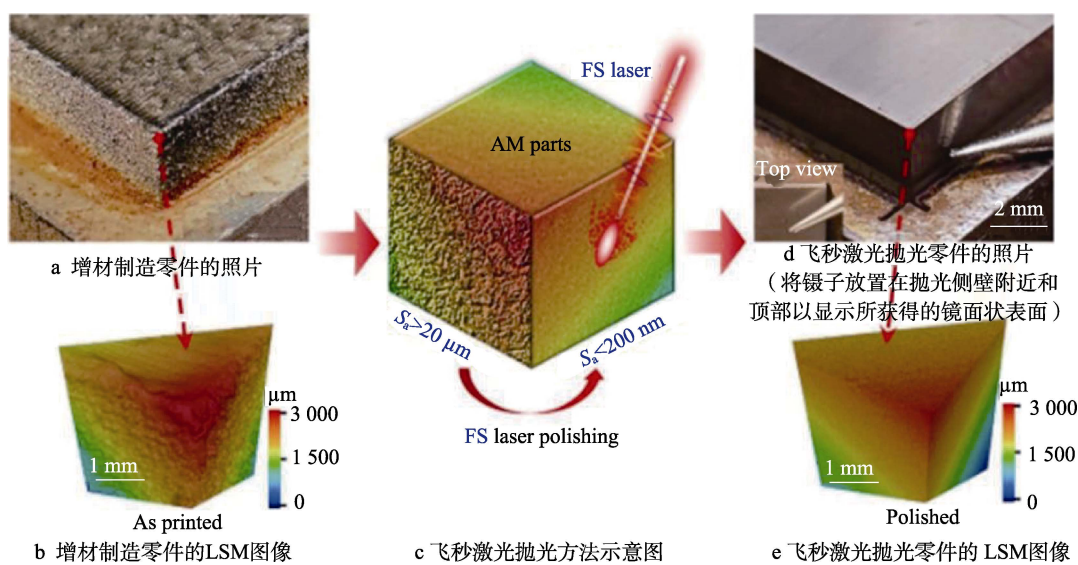


图 10 激光抛光及代表性结果^[68]
Fig.10 Laser polishing and representative results^[68]: a) photo image of the additive manufacturing part; b) LSM image of the additive manufacturing part; c) schematic diagram of the FS laser polishing approach; d) photo of the FS laser polishing part (a tweezer is positioned near the polished sidewall and the top surface to show the mirror-like surfaces achieved); e) LSM image of the FS laser polishing part

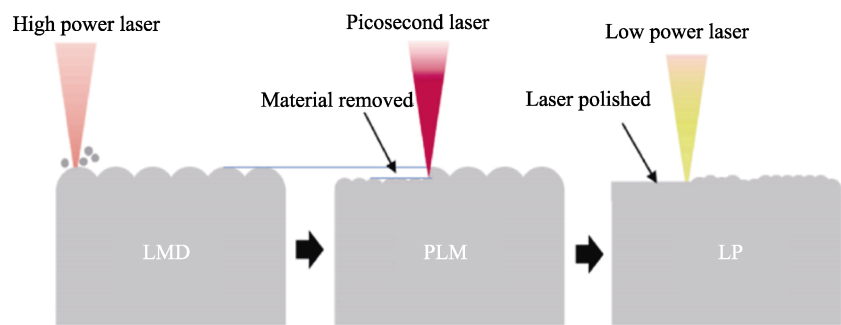


图 11 LMD 零件的激光处理策略^[69]
Fig.11 Strategy in laser treatment of LMD parts^[69]

序列加工^[70]的工艺，这使得加工效率更高，但是加工过程更加复杂。尽管目前该方法还未见被报道用于抛光，但是值得做进一步研究。

近几年，增材制造金属表面的超快激光抛光取得了较大进步，但是对于表面粗糙度 $Ra < 0.1 \mu\text{m}$ 的要求依然不容易达到。Simon 等^[71]指出即使通过激光抛光将增材制造的 AISi10Mg 合金样品的表面粗糙度从 $Ra = 9.78 \mu\text{m}$ 降低到 $Ra = 0.45 \mu\text{m}$ ，依然不能满足后续的超快激光直写光栅的加工需要，需要更光滑的表面（暗示表面粗糙度需接近或达到 $Ra = 0.1 \mu\text{m}$ ）。Liu 等^[67]采用飞秒激光对 LPBF 制造的金属零件（316L 不锈钢）进行抛光，初始表面粗糙度 S_a 从初始的 $16.28 \mu\text{m}$ 可以降低到 $11.2 \mu\text{m}$ ，初始表面粗糙度（经过预处理后） S_a 从 $0.97 \mu\text{m}$ 降低到 $0.85 \mu\text{m}$ ，这也说明了超快激光抛光对表面粗糙度的降低目前仍存在瓶颈。

需要指出的是，目前增材制造金属零件的超快激光抛光研究相对较少，主要原因是该技术兴起时间较

短，相对于传统激光抛光来说还不够成熟，抛光质量有待提高。但是由于其独特的加工优势，该技术正处于快速发展之中。

4 超快激光抛光与 AM 集成设备及应用现状

增材制造与超快激光抛光集成设备的设想，源自增材制造零件原位抛光的现实需求。最迟到 2018 年，出现了将激光增材制造（LPBF）和超快激光烧蚀（抛光）结合在一个处理系统中的理念和设备。Ghosh 等^[72]提出并实现了一种集成设备。将连续波激光器（用于增材制造）与超快激光器（用于加工增材制造零件的表面）集成在同一光路中，通过逐层选择性烧蚀单个 LPBF 制造层轮廓的方法，实现了准同步制造工艺，激光加工的多层 LPBF 零件的平均侧壁粗糙度为 $(4.7 \pm 1) \mu\text{m}$ ，侧壁锥度角低至约 $3^\circ \pm 1^\circ$ 。Worts 等^[65]也提出了将飞秒激光系统完全集成到 LPBF 系统中的

设想,即让飞秒激光器与增材制造激光器共线,将两束光束置于正交偏振,使它们可以与薄膜偏振器(TFP)组合。然后,两束光束可以由相同的扫描透镜引导,以打印和处理 AM 部分。系统的组合示意如图 12 所示^[65]。

增材制造与超快激光抛光集成设备的应用。2019 年, Bouet 等^[73]设计并制造了集成设备,将飞秒激光加工(波长 1 030 nm)与 SLM 制造(连续波激光器,

波长 1 060 nm)组合在一个设备中,该设备一步即可完成制备具有生物功能表面的 Ti6Al4V 零件,不需要后处理。具体加工过程如图 13 所示^[73]。通过逐层沉积后烧蚀表面的方法,飞秒激光沿着物体周长烧蚀工件的边缘,粗糙度 R_a 值降低到原来的 35%, S_a 值也从 11 μm 降低到 4 μm 。Basha 等^[74]指出在 SLM 制造中,逐层采用激光抛光可以提高堆积密度,即使只对零件的外表面进行激光抛光,也可大大提高表面密度。这种集成设备满足了增材制造原位后处理的需求,同时也给出了一种提高增材制造零件质量的新方法:在 SLM 制造过程中,通过逐层采用飞秒激光表面抛光,再逐层沉积制造,可以进一步提高增材制造零件的密度并减少孔隙的形成。

除了以上的抛光应用以外,2021 年 Henna 等^[2]针对增材制造零件难于加工宽度小于 100 μm 的深窄狭缝的挑战,采用波长相同的(1 030 nm)的连续波激光与超快激光(脉冲持续时间 8 ps)一体混合加工的设备加工不锈钢增材制造的零件,加工的平均狭缝宽度约为 50 μm ,槽的平均总深度约为 1.3 mm,高度与宽度的纵横比约为 26 : 1。实验装置如图 14 所示^[2]。

设备集成化的新方向。Kaligar 等^[75]指出超快激光增材制造技术相对传统激光增材制造的热影响区较小,可以解决因此造成的微裂纹、多孔结构和残余应力问题。尽管该技术当前正在起步阶段,但发展迅速。图 15^[75]为采用飞秒激光源的选择性激光烧结-粉末床熔融工艺原理。需要指出的是超快激光增材制造设备的出现为采用单一激光光源的增材材加工设备

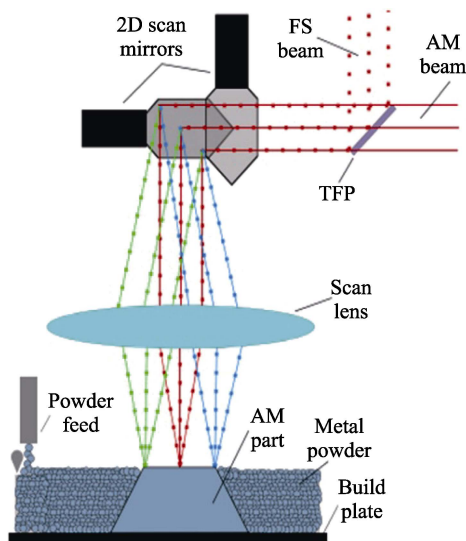


图 12 包含增材制造和飞秒激光器的组合系统示意图^[65]
Fig.12 Schematic diagram of the proposed combination system entailing the additive manufacturing and femtosecond lasers^[65]

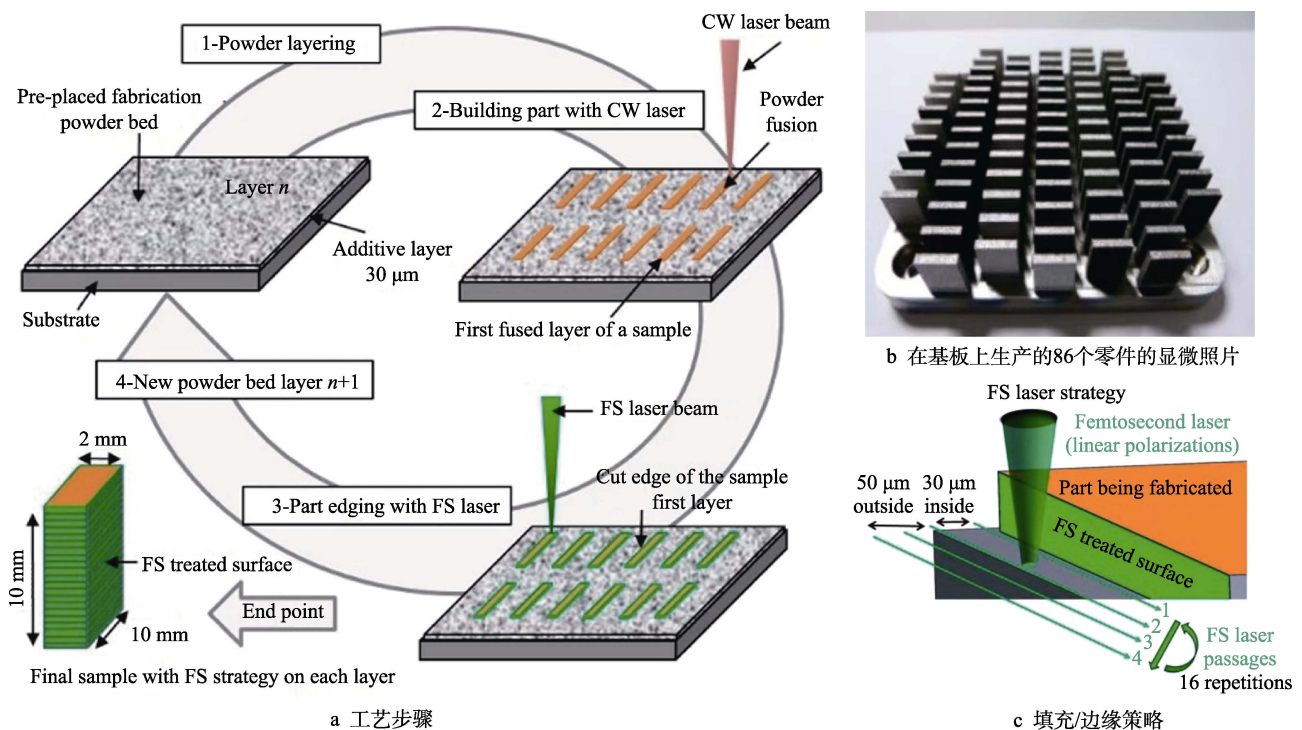


图 13 AM+FS 试样的制作方法^[73]
Fig.13 Fabrication method of AM+FS samples^[73]: a) process steps; b) micrograph of 86 parts produced on a substrate plate; c) filling/edging strategy

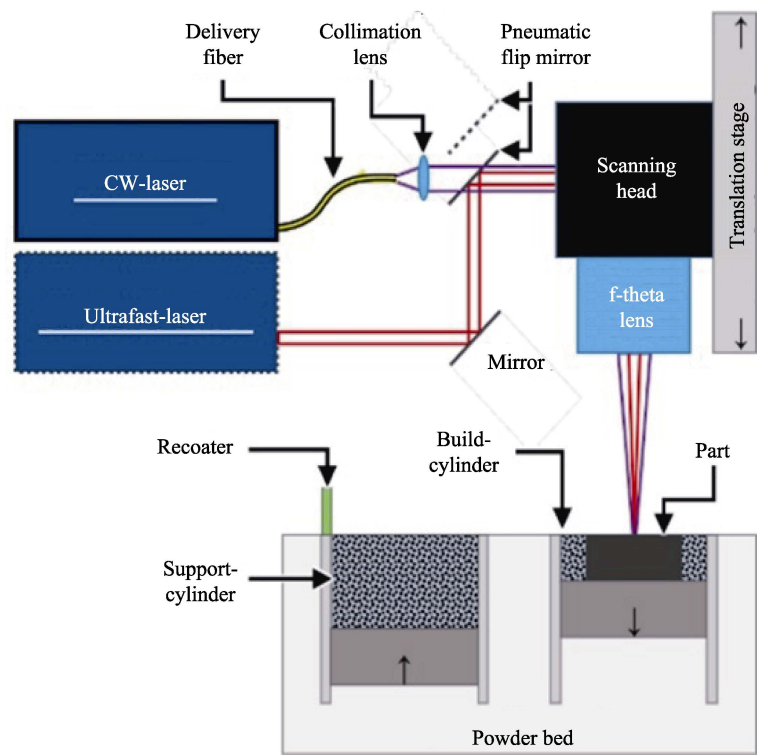


图 14 实验装置示意图^[2]
Fig.14 Schematic illustration of the experimental setup^[2]

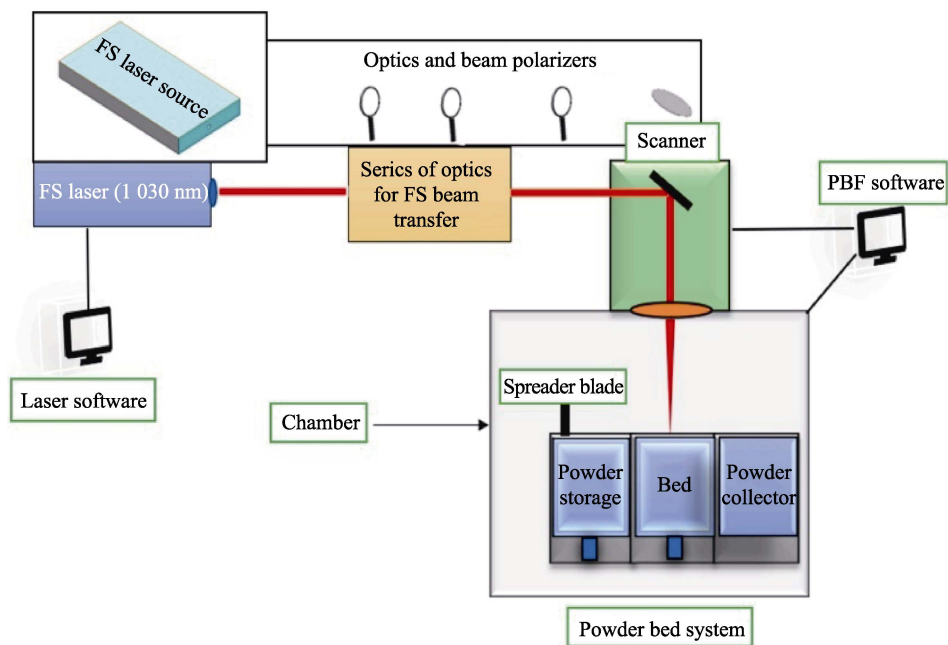


图 15 基于飞秒激光的选择性激光烧结-粉末床熔合工艺示意图^[75]
Fig.15 Schematic diagram of the Fs-laser-based selective laser sintering-powder bed fusion process^[75]

集成提供了一种新的方案。相对于双光源系统，该方案有望进一步实现集成设备的小型化，在功能上也不局限于增材制造与抛光功能的结合。

设备集成制造的实现使得增材制造零件可以原位进行后处理，抛光质量的不断提高将极大地拓展增材制造的工业应用领域，新近出现的超快激光增减材加工设备的研制将给这一研究注入新的发展动力。

5 存在问题及发展趋势

该研究涉及增材制造与超快激光加工 2 种技术，目前的发展方兴未艾，限于篇幅这里研究的方面还不够深入和全面。该技术可以用于增材制造常用的金属、陶瓷、聚合物（例如聚乳酸^[59]）等材料。基于超

快激光的抛光技术有望解决传统激光抛光面临的现实问题(例如抛光副作用、不适用于热敏性及硬脆材料抛光等),可以应用在航空航天、能源等领域中的现场原位修复。该技术与增材制造技术的结合可以解决增材制造的零件需要取出后进行抛光处理的问题,使增材制造具有的原位制造、灵活定制、快速投入使用等优势得到充分发挥,应用领域得到极大拓展。但是该技术目前也面临着一些挑战,其抛光设备也亟待进一步发展。

超快激光对增材制造金属零件表面抛光存在的主要问题及原因:(1)零件的初始表面粗糙度对抛光效果影响很大,低粗糙度(例如几个微米)表面的抛光可以降低到亚微米级^[65,71],高粗糙度(十几个微米以上)表面的抛光则只能降低到几个微米^[64,67,73],继续降低难度较大^[68];(2)超快激光的光斑直径在微米量级,工艺参数不当可能会造成表面的粗糙度增加。常用的高斯光束具有细长焦点,垂直入射加工工艺下材料表面的峰和谷可能会同时去除,进而形成新的峰和谷。掠入射加工可以有效避免该问题,但工艺相对复杂,加工效率有待提高^[68];(3)超快激光抛光的高分辨率选择性加工,需要相应的设备及软件配合来控制离焦量,加工成本较高。这主要是由于常用的高斯光束的能量主要分布于有限的焦点附近。(4)由于存在激光光束可达性的限制,零件内表面,特别是复杂形状零件的抛光效果有时还不够理想。这往往需要定制特殊的导引装置。总之,以上问题存在的根本原因在于激光与材料相互作用的复杂抛光机理。其中材料属性(①④)、激光参数(②)、机械参数(②③)是影响抛光效果的重要因素^[76]。这些参数并不是完全独立的,它们是由激光与材料相互作用的整体平衡决定的,共同决定了材料表面的粗糙度和加工精度^[63]。

增材制造技术希望能在原位对零件进行处理,这样生产的零件可以尽快地投入使用。超快激光抛光技术的出现满足了这种现实需要。超快激光抛光设备未来可能朝着以下方向发展:(1)更高的抛光质量。目前的超快激光抛光平均可达到几微米的表面粗糙度,但还不能满足精密、超精密以及纳米加工领域的需要。随着超快激光器功率等性能参数不断提升、加工稳定性以及加工工艺的发展,超快激光抛光的效果将有望媲美其他抛光方法。(2)更快的抛光效率。超快激光抛光由于其光斑较小,主要用于小面积的抛光,对大面积抛光来说效率较低。随着光束整形技术以及振镜扫描技术的发展,多光束、复合光束加工和快速扫描将极大地提高抛光效率。(3)高度融合人工智能。随着大数据模型的发展,最佳抛光策略以及最优激光加工工艺的匹配,将主要由人工智能决定,有望实现“傻瓜式”加工。(4)更小的体积、更轻的重量。随着光源共用、光路优化等技术的发展,设备的集成化程度会不断提高,超快激光抛光模块体积、重量的优化会

使得设备应用在更多的场合。(5)更全面的功能。随着技术的进步,零件表面抛光以后,有望直接用超快激光进行功能化表面等加工。

6 结束语

本文从金属的超快激光抛光研究、超快激光的抛光机理、金属AM零件超快激光抛光工艺、超快激光抛光与AM集成设备及应用、存在问题及发展趋势等方面总结梳理了近些年来增材制造金属零件表面超快激光抛光的发展情况。必须指出,还有一些研究与金属AM零件的超快激光抛光密切相关,比如零件表面的微纳加工、表面织构等。超快激光抛光可以作为这些后处理工作的基础,而这些后处理工作对表面质量的要求又反过来促进超快激光抛光技术的发展。

增材制造金属零件表面采用超快激光抛光的时间较短。当前,以超快激光作为能源的增材制造技术的兴起,将为超快激光抛光技术带来新的发展机遇。随着航空航天、能源等极端环境下制造、原位修复需求的增大,以及生物植入物、汽车、工业模具、日用品等领域的增材制造产品质量要求的不断提高,超快激光抛光技术必将在增材制造后处理中发挥越来越大的作用。

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