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飞秒激光制备微纳结构的研究现状

娄鑫鑫

长春理工大学物理学院，吉林 长春

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摘 要

得益于微纳结构表面独特的功能特性及其在各个领域的广泛应用，设计和制备表面微纳结构已成为当前重要研究方向之一。飞秒激光微纳加工作为一种先进的制造技术，凭借其“冷加工”、极高峰值功率和极强的三维加工能力，可对任意材料实现跨尺度精密加工，展现出显著的工业化应用潜力。本文系统综述了飞秒激光微纳结构制备的最新进展，首先回顾了飞秒激光与物质相互作用的基本理论，并引入双温模型及高空间频率条纹(HSFL)的多种形成机理假说以深化机理阐述。进而分类总结了飞秒激光制备亚微米周期结构、纳米孔阵列及微纳复合结构的典型方法与机理。在此基础上，本文通过量化技术对比，重点探讨了飞秒激光微纳加工在产业化进程中面临的工艺稳定性、加工效率、成本控制及规模化制备等关键工程挑战，并展望了通过智能化控制、在线监测与工艺优化等技术路径推动其走向实用化的发展方向，以期为该领域的研究与工程应用提供参考。

关键词

飞秒激光，微纳结构，先进制造，跨尺度加工，工业稳定性，工业应用

Micro-Nanostructures Fabrication Utilizing Femtosecond Laser: A Review

Xinxin Lou

School of Physics, Changchun University of Science and Technology, Changchun Jilin

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Abstract

Owing to the unique functional characteristics and wide applications of micro-nanostructured surfaces, the design and fabrication of surface micro-nanostructures have become one of the important research directions. As an advanced manufacturing technology, femtosecond laser micro-nano processing enables cross-scale precision processing of any material by virtue of its cold processing,

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extremely high peak power and strong three-dimensional processing capability, showing significant industrial application potential. This paper systematically reviews the recent progress in femtosecond laser fabrication of micro-nanostructures. Firstly, the basic theory of femtosecond laser-matter interaction is reviewed, and the two-temperature model and various hypotheses for the formation mechanism of high-spatial-frequency LIPSS (HSFL) are introduced to elaborate the mechanism. Then, the typical methods and mechanisms of femtosecond laser fabrication of submicron periodic structures, nanopore arrays and micro-nano composite structures are summarized by category. On this basis, through quantitative technical comparison, the key engineering challenges in the industrialization process of femtosecond laser micro-nano processing are discussed, including process stability, processing efficiency, cost control and large-scale preparation. Finally, the development direction of promoting its practical application through intelligent control, on-line monitoring and process optimization is prospected, so as to provide reference for the research and engineering application in this field.

Keywords

Femtosecond Laser, Micro-Nanostructures, Advanced Manufacturing, Multiscale Fabrication, Process Stability, Industrial Application

1. 引言

伴随着对表面微纳结构独特功能特性的深入研究，各类功能性表面微/纳结构已在光学[1] [2]、防覆冰[3]、能源转换[4] [5]、化学催化[6]、自清洁[7]和流体减阻[8]等领域被广泛应用(如图 1 所示)。这些微/纳结构在提升材料界面性能并实现跨尺度功能集成等方面展现出极高的应用价值。因此，设计和制备微/纳结构的新技术对深入研究功能性微/纳结构至关重要。当前，光刻技术[9]、刻蚀技术[10]和纳米压印技术[11]等被用于制备微/纳结构。然而，这些方法普遍存在成本高、工艺复杂、加工效率低以及对非平面或异形材料适应性差等问题，限制了其在大面积、复杂结构和多材料表面的工业化应用。近年来，飞秒激光微/纳加工技术被认为是一种极具工业化应用潜力的微/纳结构制备方法[12]。得益于飞秒激光具备的超快(脉冲持续时间远小于材料内部受激电子弛豫时间) [13]和超强(极大的峰值功率引发的非线性光吸收电离过程) [14]的特点，使得飞秒激光微/纳加工技术能够显著抑制热扩散效应，实现冷加工并且能在几乎所有类型的材料表面实现从微观尺度到宏观尺度上区域上的微/纳结构跨尺度可控构建，包括金属[15]、半导体[16]、玻璃[17]和聚合物[18]等。更重要的是，飞秒激光微/纳加工技术具有极强的三维加工能力，能够实现非平面表面处理以制备具备各种功能特性的微/纳结构表面以满足当前结构功能器件的多样化需求[19]。

为更直观地展示飞秒激光的技术定位，表 1 将飞秒激光与几种主流微纳加工技术进行了多维度对比。可以看出，飞秒激光在材料通用性、三维加工能力和热影响方面具有显著优势，但其加工速度和设备成本仍是主要短板。此外，与皮秒或纳秒激光相比，飞秒激光虽然热扩散长度更短(可低至亚纳米量级)，加工精度更高，但其单脉冲能量通常较低，加工大面积结构时需依赖高重复频率光源或多光束并行技术。当前，工业级飞秒激光源正朝着高平均功率(>100 W)、高重复频率(>1 MHz)和脉宽可调谐方向发展，这为提升加工效率、降低成本提供了新的可能。

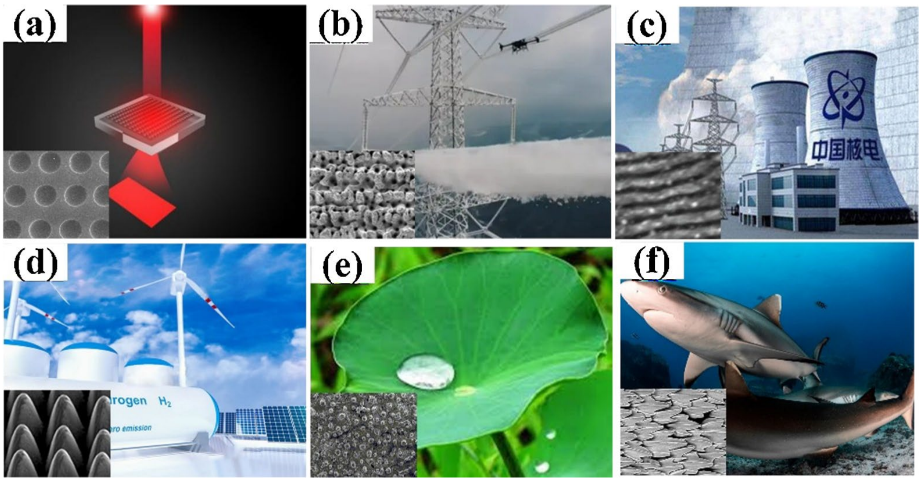


Figure 1. Applications of various micro-nanostructures in different fields (a) Optics [2], (b) Anti-icing [3], (c) Energy conversion [5], (d) Chemical catalysis [6], (e) Self-cleaning [7], (f) Fluid drag reduction [8]

图 1. 各种不同的微纳结构在(a) 光学[2]、(b) 防覆冰[3]、(c) 能源转换[5]、(d) 化学催化[6]、(e) 自清洁[7]和(f) 流体减阻[8]等领域的应用

Table 1. Key performance comparison of different micro-nano processing technologies

表 1. 不同微纳加工技术的关键性能对比

技术方法	最小特征尺寸	材料通用性	三维能力	热影响	加工速度	设备成本
光刻技术	<10 nm	低(需光刻胶)	差	小	高(批量)	极高
纳米压印	<10 nm	中(需模板)	差	小	高(批量)	高
聚焦离子束	<5 nm	高	中	小	极低	高
纳秒激光	~1 μm	高	中	大	中	低
飞秒激光	~100 nm	极高	强	极小	低	高

在本综述中，首先简述了飞秒激光与物质相互作用的基本原理，并引入双温模型及 HSFL 形成机理假说以深化物理理解。然后，分类并总结飞秒激光制备各种尺度与形貌的微/纳结构的典型制备方法。最后，通过细化技术–经济挑战和前瞻技术路径，展望了当前飞秒激光制备微/纳结构的机遇和挑战，为飞秒激光制备微/纳结构提供思路并为该领域的研究和工程应用提供参考与启发。

2. 飞秒激光与物质相互作用机理

由于飞秒激光的脉冲宽度处于飞秒尺度，远低于材料对能量输入的热响应时间(纳秒到毫秒尺度)，并且瞬时的高能量沉积能触发从纳米尺度到毫米尺度的形貌演变，使得飞秒激光与物质发生相互作用过程时具备从飞秒到毫秒的跨时间尺度以及从纳米到毫米的空间尺度。

从时间尺度上看，飞秒激光入射到材料表面之后会在数十飞秒内通过非线性吸收机制迅速将能量吸收到材料内部[20]并经历电子–电子散热而导致电子的热化[21]和强电场电离[22]。随后通过电子–声子相互作用发生晶格升温[23]和相变[24]过程，并在皮秒尺度内达到平衡[25]，这一动态过程可使用双温模型[26]进行描述。双温模型将电子和晶格视为两个相互耦合的子系统，分别用电子温度 T_e 和晶格温度 T_l 描述，通过两个偏微分方程耦合求解：

$$C_e \frac{\partial T_e}{\partial t} = -\frac{\partial Q_e(z)}{\partial z} - G(T_e - T_l) + S(z,t) \tag{1}$$

$$C_l \frac{\partial T_l}{\partial t} = G\left(T_e - T_l\right) \tag{2}$$

其中 C_e 和 C_l 分别为电子热容和晶格热容。

从而定量预测激光辐照后材料内部的温度演化、烧蚀阈值及结构形成窗口。随着晶格温度的不断升高并超过烧蚀阈值时，材料会在几皮秒到数百皮秒内发生相变[27]，包括熔化、非热烧蚀和膨胀。随后，在纳秒时间尺度内发生等离子体膨胀、辐射和物质喷流等现象[28]，从而导致材料发生能量弛豫与重组。此时，材料表面以极高的速率发生冷却[29]而快速凝固到表面形成特定的微纳结构。综合来看，当飞秒激光入射到材料表面之后，将能量传递给电子后由电子传递到晶格致使其温度上升并引发材料相变而形成不同的表面结构。

此外，由于金属材料和非金属材料之间的电子能级结构和晶格结构之间的根本差异，飞秒激光与金属和非金属相互作用时存在显著不同。非金属材料中缺少自由电子，因此飞秒激光与其发生相互作用时首先通过多光子吸收与隧道电离激发出初始自由电子[30]。这种初始自由电子会发生雪崩电离[31]产生更多的自由电子而迅速提升非金属内部的自由电子密度及局部电子温度。随后将能量传递到晶格而导致非金属材料发生热相变(熔化与汽化) [32]和非热相变(静电烧蚀和库伦爆炸) [33]。对于金属材料而言，自由电子的存在导致飞秒激光的能量能够直接传递到电子上并通过电子－声子散射对晶格进行缓慢加热。但由于声子质量远大于电子质量，导致传递时间更长[34]。随着飞秒激光的持续辐照，晶格最终被加热到临界温度，从而引发金属材料熔化[35]、分裂[36]和相爆炸[37]。

3. 飞秒激光制备亚微米周期结构

激光诱导周期表面结构(LIPSSs, Laser-Induced Periodic Surface Structures)是一种由激光辐照表面时形成的典型周期性纳米结构。这种结构最初由 Birnbaum [38]等人在使用激光烧蚀半导体材料时观察到。这种表面结构的形成被归结为入射激光与材料表面激光的表面等离激元相互干涉(如图 2(a)所示) [39] [40]，这种干涉机制会在表面形成周期性的能量分布而对材料表面形成周期性作用。对于金属表面的 LIPPSs 结构而言，其周期 Λ 由[41]给出

$$\Lambda = \lambda_{\text{laser}} \Big/ \left(\eta^2 - \sin^2\theta\right)^{1/2} \approx \lambda / \cos\theta \quad \text{with } \boldsymbol{g} \parallel \boldsymbol{E} \tag{3}$$

其中 λ_{laser}、θ、$\boldsymbol{g}$ 和 $\boldsymbol{E}$ 分别表示激光入射波长、激光入射角度、光栅矢量和入射激光电场矢量方向。η 为表面等离子体在介电金属界面处有效折射率且：

$$\eta = \left[\varepsilon_{\text{d}}\varepsilon_{\text{metal}} \Big/ \left(\varepsilon_{\text{d}} + \varepsilon_{\text{metal}}\right)\right]^{1/2} \tag{4}$$

其中 ε_{d} 和 $\varepsilon_{\text{metal}}$ 分别为周围介质的介电常数以及基底金属的介电常数。

飞秒激光的出现，促使飞秒激光诱导周期性结构(FLIPSS, Femtosecond Laser-Induced Periodic Surface Structures)被广泛研究。这种结构被认为是当激光能量略高于材料烧蚀阈值时的多脉冲辐照所形成的[42]，这一过程伴随着在电子和晶格系统之间热不平衡时的多光子吸收和材料表面的周期性结构形成。此外，FLIPSS 主要被分为低空间频率(LSFL, Low Spatial Frequency LIPSS)和高空间频率(HSFL, High Spatial Frequency LIPSS)周期结构[39] [43] [44]。对于 LSFL 而言，结构周期为~ $\lambda/2 \le \Lambda \le \lambda$ 并垂直于激光偏振方向；HSFL 的结构周期为 $\Lambda < \lambda/2$ [45]。HSFL 的形成机理目前尚未完全统一，主要有三种主流假说：1) 二次谐波产生：在特定材料中，激光诱导的强烈非线性效应可激发频率倍增的表面波，其波长减半从而导致亚波长周期结构；2) 自组织机制：认为高激发态下的表面不稳定性(如漂移扩散过程)会自发形成周期性纳米结构；3) 瞬态纳米空位机制：飞秒激光诱导的电子剥离产生的纳米尺度空位通过应力场相互

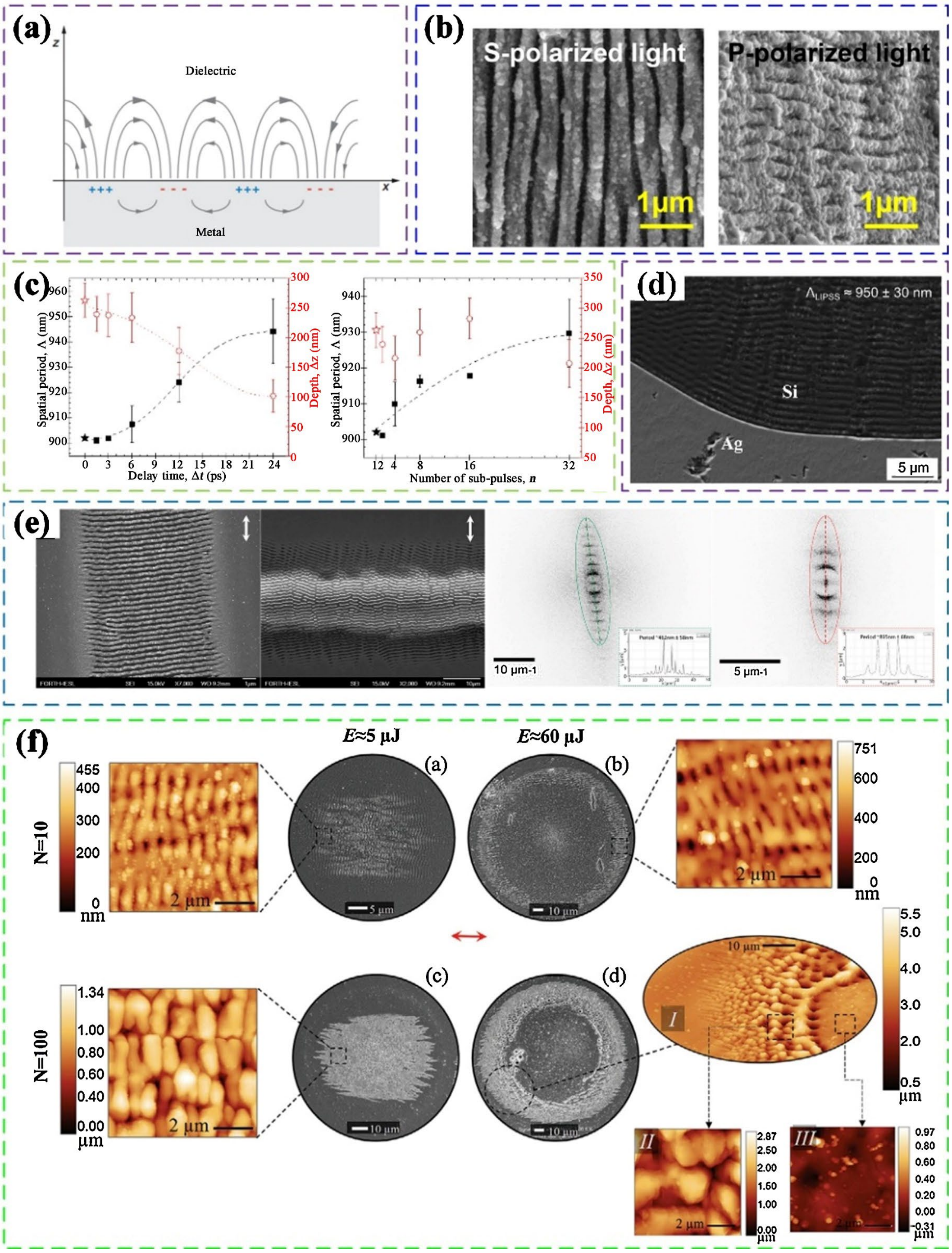


Figure 2. Formation mechanism and influence factor characterization of femtosecond laser-induced periodic surface structures (a) Schematic diagram of surface plasmon [40]; (b) SEM of LIPSS under s-polarized and p-polarized femtosecond laser [46]; (c) Variation of LIPSS period and depth with pulse delay and number of pulses [47]; (d) SEM of Ag-Si alloy after femtosecond laser treatment [48]; (e) LIPSS under 513 nm/1026 nm femtosecond laser, 2D FFT and power spectrum [49]; (f) SEM and AFM images under different pulse energy E and pulse number N [50]

图 2. 飞秒激光诱导周期表面结构的形成机制及影响因素表征(a) 表面等离子体示意图[40]；(b) 飞秒激光 s 偏振光和 p 偏振光方向的 LIPSS 的 SEM [46]；(c) LIPSS 周期和深度随着飞秒激光脉冲时间延迟和脉冲数量的变化[47]；(d) 飞秒激光作用银硅合金后的表面 SEM [48]；(e) 从左往后依次为 513 nm 飞秒激光辐照后的 LIPSS、1026 nm 飞秒激光辐照后的 LIPSS、513 nm 飞秒激光辐照后及 1026 nm 飞秒激光辐照后的二维快速傅里叶变换图像，以及 SEM 图像的功率和频率图[49]；(f) 脉冲能量 E 和脉冲数 N 取不同值时辐照样品的 SEM 和 AFM 图像[50]

作用，自组织形成高空间频率条纹。

如图 2(b)所示，飞秒激光诱导形成 LIPSS 的空间方向始终(或其方向)与入射激光的偏振方向垂直，并且干涉机制的电场矢量方向起到对结构空间方向的主导作用[46]。如图 2(c)，飞秒激光辐照过程中通过调控激光脉冲延迟和数量改变等离子体激发模式并产生等离子体屏蔽效应来影响 LIPSS 深度和周期[47]。而材料本身的物理特性，例如热导率[51]、烧蚀阈值[48]等也会影响 LIPSS 结构的形成(如图 2(d)所示)。基于这一现象能够实现在合金表面选择性制备 LIPSS。此外，Skoulas [49]、Xu [52]等人和 Zhang [53]等人发现使用飞秒激光制备 LIPSS 时的激光参数(激光波长、激光功率、扫描时间和脉冲次数)、加工环境和材料特性(材料带隙和表面粗糙度等)会对 LIPSS 的形貌造成显著影响(如图 2(e)所示)。Hu[50]等人则发现飞秒激光高斯分布的特征会导致光束中心区域的能量密度高于光束边缘区域，从而在材料表面形成熔融层厚度差异来影响 LIPSS 的形成(如图 2(f)所示)。

4. 飞秒激光制备纳米孔及纳米孔阵列

高斯分布的飞秒激光光束在略高于材料损伤阈值的能量密度时能够利用烧蚀机制在材料表面制备出单个纳米孔[54]。在此基础上通过在金属表面辐照一个小孔径飞秒激光光斑获得更高质量的纳米孔结构[55]并可以进一步通过控制飞秒激光的加工参数来减少激光辐照对材料表面所造成的损伤[56]来优化表面烧蚀质量[57]。如图 3(a)所示，通过调节飞秒激光辐照材料表面时的脉冲数量和扫描速度能实现 LIPSS 到纳米孔阵列的结构转变[58]。而通过将高数值孔径聚焦方式和球差调控能够有效调控聚焦光斑在材料表面的分布，从而在中心区域引发表面等离子体屏蔽效应，边缘能量绕过屏蔽区实现深层自聚焦，收缩光斑至亚衍射极限，实现单脉冲飞秒激光在二氧化硅表面深度 $> 10\ \mu m$、直径 200~500 nm 的高纵横比的纳米孔制备[59]。Nakashima[60]等人则开发了一种湿化学辅助的飞秒激光激光多扫描烧蚀技术，成功在氮化镓表面制备出如图 3(b)所示的纵横比为 1.6 的纳米孔阵列。

从工程应用角度看，虽然上述方法展示了飞秒激光在制备高深宽比纳米孔方面的潜力，但其加工效率、一致性与大面积均匀性仍是产业推广中的关键挑战。例如，湿化学辅助虽能改善结构质量，但引入了化学处理步骤，增加了工艺复杂性与环保成本。未来研究需着力于开发干法、高速、在线监测的飞秒激光纳米孔加工策略，以满足半导体、光电子等领域对高精度纳米结构的量产需求。

如图 3(c)，Liu [61]等人利用光束整形技术，通过将飞秒激光与贝塞尔光束相结合，突破传统高斯分布的飞秒激光光束热影响的限制，实现了石英表面纳米孔阵列的飞秒激光直写。Lu [63]等人则通过贝塞尔光束聚焦技术将飞秒激光在材料内部和表面形成如图 3(d)所示的双高能量密度区域。这种双高能区域会在材料表面形成表面热斑，导致表面材料快速蒸发；同时会在内部区域形成内部热斑引发材料的熔融膨胀，并通过表面热斑导致的微结构向外喷射，最终形成直径~20 nm 的纳米小孔。

Atanasov [64]等人开发了一种利用金属纳米颗粒的局部表面等离激元共振增强近场光强的方法，在纳米颗粒和硅基底之间形成强电磁区域以去除硅表面的材料，实现直径~150 nm 纳米孔的可控制备。而通过聚苯乙烯微球的近场增强效应，直接利用时间整形的飞秒激光脉冲烧蚀硅表面能够突破衍射极限，获得 50 nm 大小的圆形、规则且无裂纹的纳米孔阵列[62] (图 3(c))。此外，利用干涉技术将飞秒激光形成的干涉图案聚焦到金属表面进行烧蚀，能够在材料表面形成纳米孔阵列[65] [66]。

5. 飞秒激光制备微纳复合结构

通过将不同尺度的结构进行复合能够协同微米结构和纳米结构对表面功能特性的增强机制[67] [68]，因此利用飞秒激光制备微纳复合结构一直受到学者的广泛关注。

Yong [2]等人利用飞秒激光直接烧蚀聚二甲基硅氧烷表面，一步式快速大面积制备如图 4(a)所示的

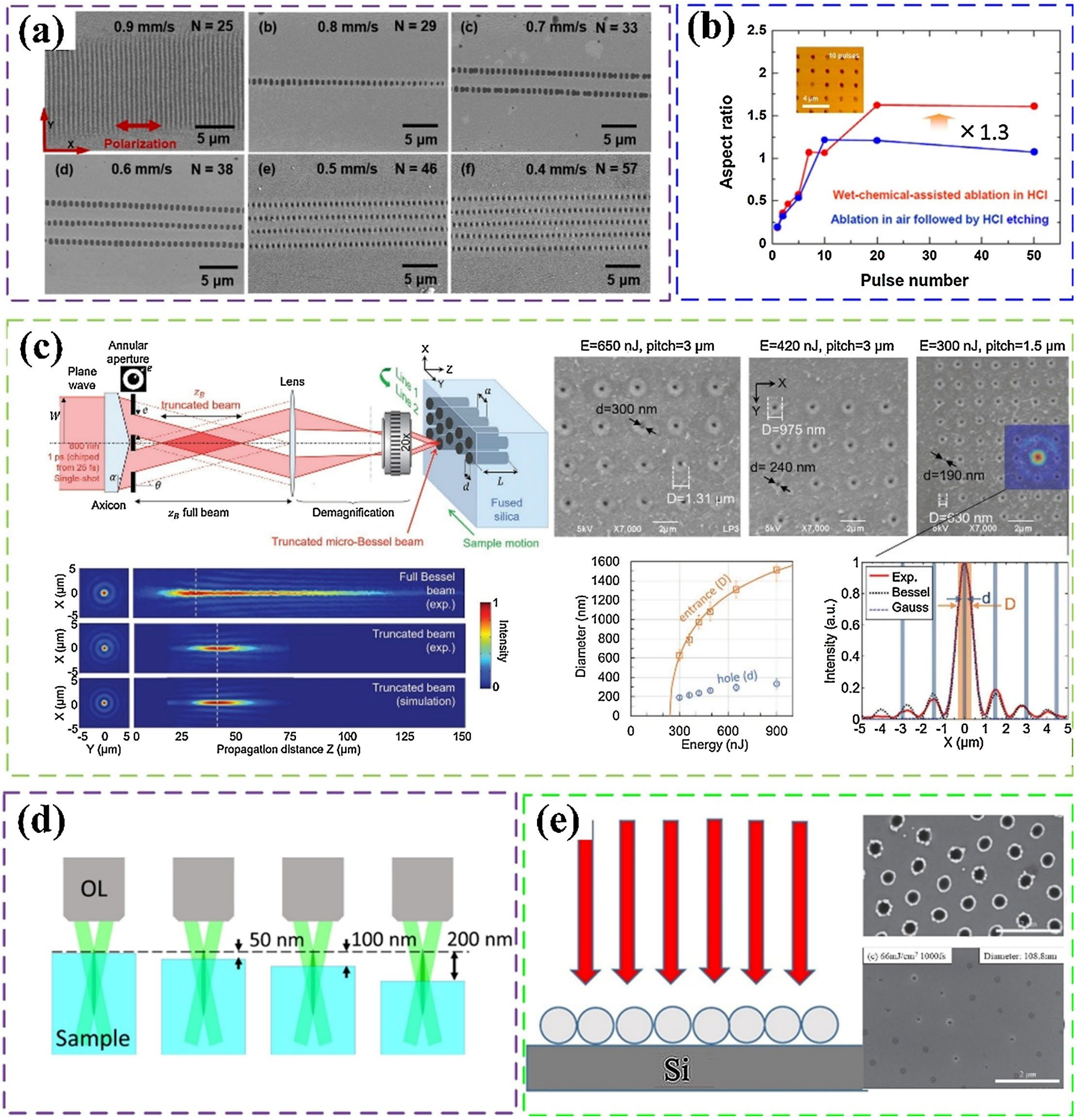


Figure 3. Process parameters and structural characterization of nanopores and nanopore arrays fabricated by femtosecond laser (a) SEM images of the structures formed at scanning speeds of 0.4 mm/s, 0.5 mm/s, 0.6 mm/s, 0.7 mm/s, 0.8 mm/s, and 0.9 mm/s, respectively [58]; (b) AFM of nanopore arrays and aspect ratio variation with pulse number; (c) Experimental setup, beam intensity distribution, SEM of holes and diameter vs. energy [61]; (d) Focus position diagram of Bessel beam and sample; (e) Schematic of PS microsphere monolayer mask and SEM of nanopores [62]

图 3. 飞秒激光制备纳米孔及纳米孔阵列的工艺参数与结构表征。(a) 扫描速度分别为 0.4 mm/s、0.5 mm/s、0.6 mm/s、0.7 mm/s、0.8 mm/s 和 0.9 mm/s 时形成的结构的 SEM 图像[58]；(b) 纳米孔阵列的 AFM 图像及湿化学辅助烧蚀(红色实心圆)和两步处理(蓝色实心圆)中长宽比随脉冲数的变化；(c) 实验装置示意图、熔融石英样品表面的光束强度分布、不同能量和孔距组合的激光加工孔的 SEM 图像、直径 D 随入射激光能量的变化以及实验光束的横向剖面(红色)、非截断贝塞尔光束的数值拟合(黑色虚线)以及中心峰的高斯数值拟合(蓝色虚线) [61]；(d) 贝塞尔光束与样品相对位置聚焦位置示意图；(e) PS 微球飞秒单层掩模版在飞秒激光脉冲照射示意图及纳米小孔 SEM 图像[62]

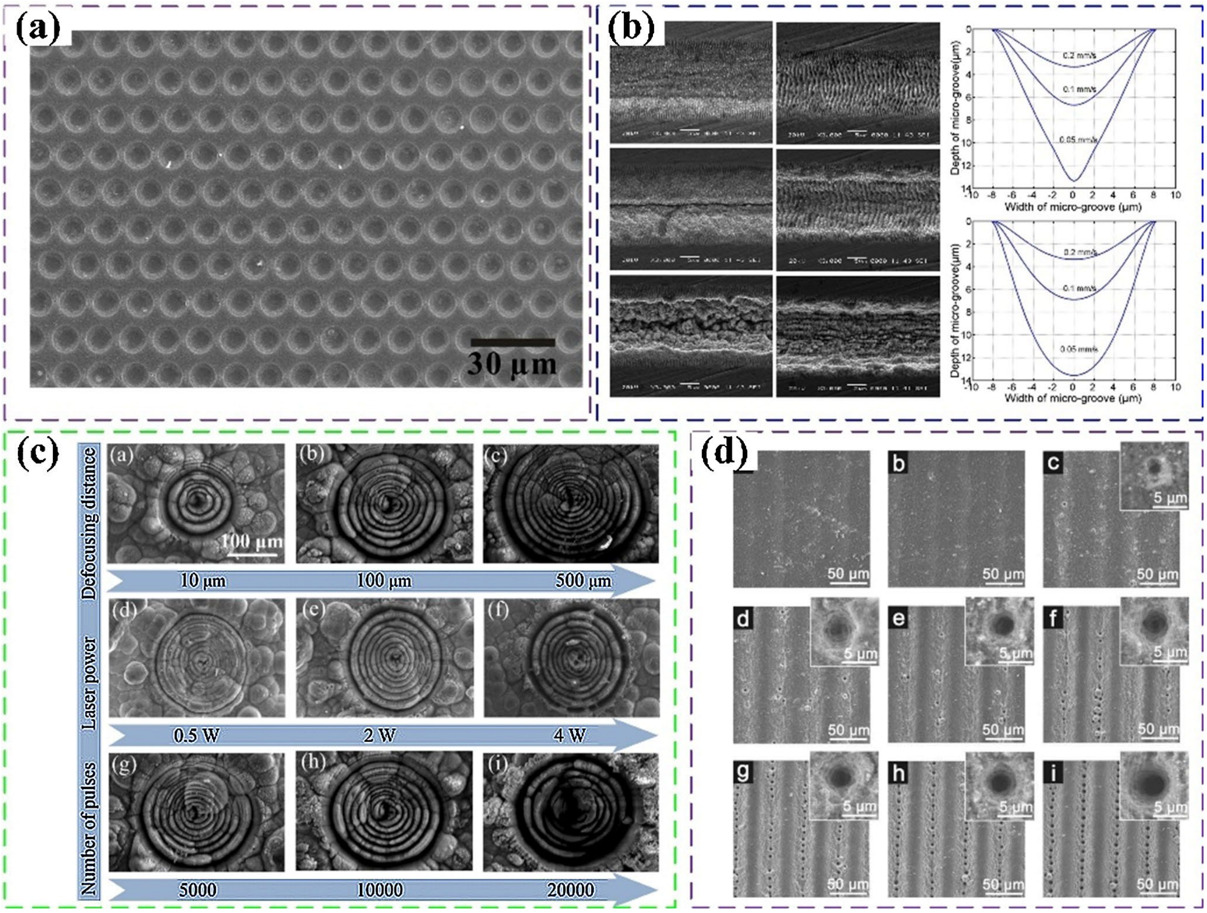


Figure 4. Typical morphologies of micro-nano composite structures fabricated by femtosecond laser and the influence of process parameters (a) SEM of microlens array [2]; (b) SEM images of micro-grooves ablated in steel by convergent and divergent laser beams at a laser energy of 1.9 mJ with different scanning speeds, and the simulated cross-sectional shapes of the micro-grooves [72]; (c) Effects of defocus distance, laser power and pulse number on multi-layer concentric rings[73]; (d) Micropores formed on the aluminum surface with increasing scanning times under femtosecond laser irradiation at a scanning speed of 5 mm/s and a laser power density of 1.17 J/cm^2 [75]

图 4. 飞秒激光制备的典型微纳复合结构形貌及工艺参数影响。(a) 微透镜阵列 SEM 图像[2]；(b) 激光能量为 1.9 mJ，以不同的扫描速度会聚光束和发散光束烧蚀钢中微槽的 SEM 图像及微槽模拟横截面形状[72]；(c) 由上到下分别散焦距离、激光功率和脉冲数对多层同心环结构的影响[73]；(d) 扫描速度为 5 mm/s 和激光功率密度为 = 1.17 J/cm^2 时，激光辐照金属铝表面随扫描次数增加而形成的微米孔[75]

微透镜阵列。这种方法成功实现 50 分钟内在 2 × 2 cm^2 的二甲基硅氧烷表面制备约 278 万个微透镜。Biswas [69]等人利用累积脉冲能量研究了飞秒激光重复率对表面微结构的影响。结果表明，材料特性差异会导致对飞秒激光脉冲数量产生不同的响应进而造成材料表面熔体动力学的差异。对于高导热率材料(金属铜)而言，飞秒激光脉冲所形成的熔融物质会持续到下一个脉冲的到来并充当后续激光脉冲的电介质；而对低导热率材料(金属钛)而言，熔融物质会快速固化而无法充当后续脉冲的电介质。将飞秒激光与振镜扫描系统相结合，并通过调控脉冲能量、扫描速度等参数能实现对玻璃和熔融石英的深度加工并显著优化微结构边缘质量和结构均匀性[70]。Qiu [71]则利用飞秒激光实现了玻璃材料内部光波导、微透镜和达曼光栅等微结构的三维直写。

飞秒激光在聚合物与玻璃内部的三维直写展示了其在集成光学与微流控器件制造中的潜力，但加工速度与结构一致性仍是产业化的瓶颈。尤其在批量生产中，如何保证每个微透镜或光波导的光学性能一

致，需要开发更稳定的激光源、更精密的运动控制与在线质量监测系统。

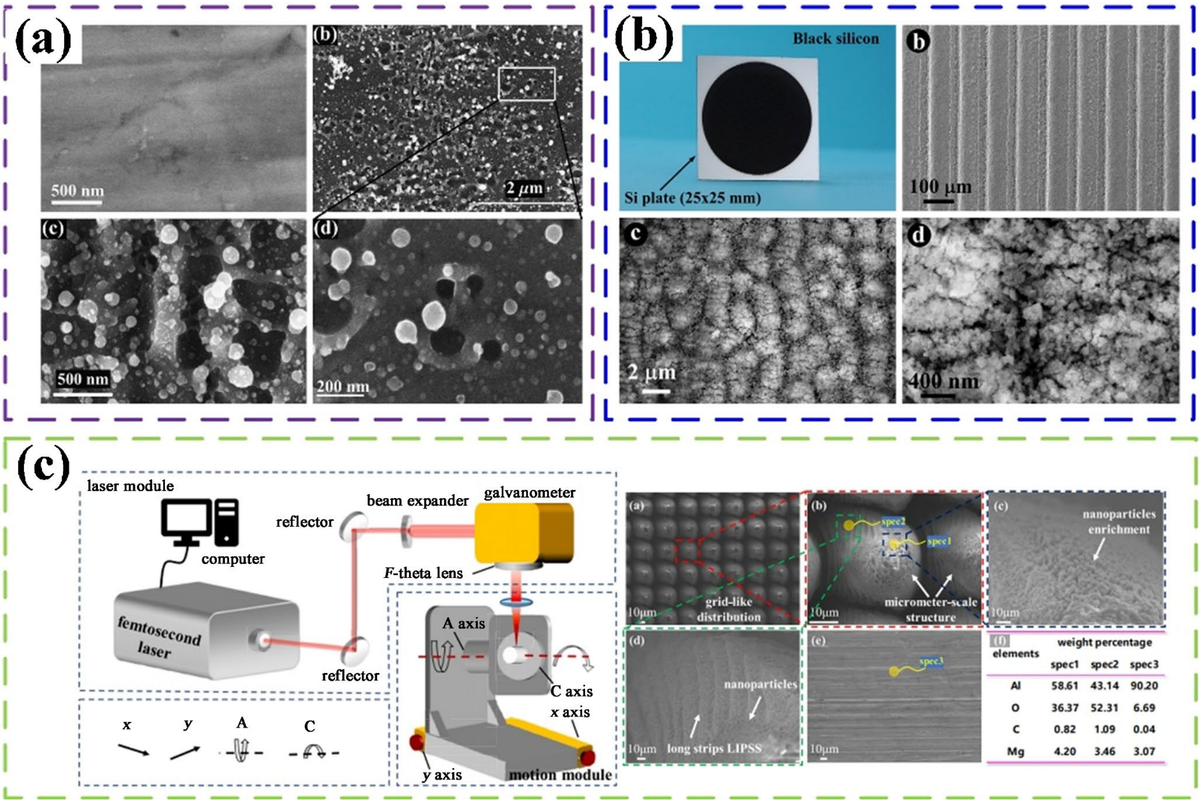
此外，飞秒激光辐照金属表面时激光的聚焦特性(发散/汇聚)对微结构形貌的影响也被深入研究[72]。如图 4(b)所示，当飞秒激光焦平面位于样品上方时激光为发散光束，烧蚀过程中光斑尺寸随着脉冲的累积而逐渐增大，能量分布更加均匀，从而形成平底微结构；当飞秒激光焦平面位于样品下方时激光为汇聚光束，光斑尺寸会随着烧蚀而逐渐汇聚，能量集中于结构中心，进而形成具备尖锐底部的微结构。利用飞秒激光也能够对高强度、高硬度的材料进行改性，例如，在 C/SiC 复合材料表面制备如图 4(c)所示的多层同心环微米结构[73]，并可以通过控制焦点位置、功率和脉冲数量调节结构尺寸和深度以及在金刚石内部实现高纵横比石墨化微米结构的生长并通过调控能量密度和扫描速度实现形貌的控制[74]。Liu [75]等人利用飞秒激光孵化效应首次在金属铝表面制备出如图 4(d)所示小于聚焦激光光斑大小的微米孔阵列并发现微米孔周期及直径和激光能量密度的高度依赖性。他们认为这种阵列微米孔的形成是飞秒激光诱导金属材料熔化之后由马兰戈尼效应驱动的熔体流动所导致的。具体地，激光诱导的温度梯度引起表面张力梯度，驱动熔融物质从高温区向低温区迁移，从而在光斑中心形成孔洞。这一过程的强度可用马兰戈尼数$\left(Ma=\partial\sigma/\partial T\cdot\Delta T\cdot L/\left(\mu\cdot\alpha\right)\right)$来表征，其中$\partial\sigma/\partial T$为表面张力温度系数，$\Delta T$为温差，$L$为特征长度，$\mu$为动力粘度，$\alpha$为热扩散系数。此外，Liu [76]等人使用飞秒激光加工蓝宝石时，发现飞秒激光辐照能将蓝宝石表面的 α-Al_2O_3 转变为易蚀刻的 γ-Al_2O_3。他们结合 KOH 溶液对表面进行化学刻蚀，从而实现微结构的制备。

对于硬脆材料(如 C/SiC、金刚石、蓝宝石)的飞秒激光加工，虽然能够实现高精度结构，但加工过程中的热应力控制、裂纹抑制与表面粗糙度优化是工程应用中的关键难题。特别是对于航空航天、精密模具等领域的零部件，需要在保证结构功能的同时满足高疲劳寿命与可靠性要求，这要求飞秒激光加工工艺与后续处理(如退火、抛光)相结合，形成完整的制造链。

另一方面，通过调节飞秒激光加工参数(能量密度、脉冲数量和加工环境等)能够在不同的金属表面(钛、铝和不锈钢等)表面制备自组装的微/纳复合结构[77]。这些自组装的微/复合结构是由于当飞秒激光与材料作用时，会首先通过干涉机制在材料表面形成纳米级起伏并在后续多脉冲的作用下通过材料烧蚀和重分布，表面张力驱动熔融物质流动而逐渐演化为锥形结构[77] [78]。如图 5(a)所示，在柱状微米结构上复合精细的纳米结构，例如纳米颗粒[78]和 FLIPSS [79]，是飞秒激光基于该机制制备的典型微/纳复合结构。而使用飞秒激光直接对硅材料进行烧蚀形成周期性的微沟槽结构后，进一步利用沟槽结构的非均匀性对激光能量形成二次吸收制备纳米结构(突起和空腔)，进而形成如图 5(b)所示的微米沟槽与纳米毛细、空腔相复合的微/纳结构[80]。这种方式还能够在金属钛[81]和玻璃[82]表面制备微/纳复合结构。Fadeeva [83]等人则在金属钛表面制备出微槽和类莲花结构，他们认为飞秒激光脉冲重叠能进一步引发能量的非均匀累积并以此前产生的微米结构作为模版诱导形成纳米结构。

自组装微纳复合结构在生物医学、传感等领域具有重要应用前景，但其形貌的可控性与重复性仍是工程化应用的难点。未来研究应结合机器学习算法，通过大量实验数据建立加工参数–结构形貌–功能特性之间的映射关系，实现结构的定向设计与稳定制备。

Dong [84]等人提出了矢量偏振飞秒激光加工碳化硅的方法并借助共焦拉曼光谱对材料表面的损伤进行表征，解决了飞秒激光加工硬脆材料时表面质量差和裂纹等问题，成功制备出微米结构(沟槽和多环阵列)和纳米结构(纳米颗粒和 LIPSS)相复合的微纳复合结构。如图 5(c)所示，Long [85]等人将飞秒激光与四轴运动平台相结合，突破了飞秒激光曲面加工的技术瓶颈并在曲面材料上成功制备微米沟槽、LIPSS 和纳米颗粒三级复合结构。他们认为这是由于飞秒激光触发的多光子吸收导致材料气化并迅速冷却形成微米尺度沟槽结构并且产生的等离子体会与空气中的氧气反应形成三氧化二铝纳米颗粒沉积到结构表面所导致的。此外，Xuan [86]等人利用飞秒激光在聚苯乙烯和多壁碳纳米管的复合材料表面制备出表面微锥、



elements	weight percentage		
	spec1	spec2	spec3
Al	58.61	43.14	90.20
O	36.37	52.31	6.69
C	0.82	1.09	0.04
Mg	4.20	3.46	3.07

Figure 5. Morphologies and characterization of self-assembled and curved surface micro-nano composite structures fabricated by femtosecond laser (a) SEM image of random nano-roughness on titanium surface after femtosecond laser treatment at a near-damage-threshold fluence of F = 0.067 J/cm^2 [78]; (b) Optical photo and SEM of micro-groove/nano-structure on black silicon[80]; (c) 3D curved surface processing platform and surface morphology/element distribution of aluminum plate [85]

图 5. 飞秒激光制备的自组装与曲面微纳复合结构形貌及表征。(a) 在近损伤阈值能量密度 F = 0.067 J/cm^2 下飞秒激光处理后钛表面随机纳米粗糙度的 SEM 图像[78]；(b) 飞秒激光处理后的黑硅光学照片及表面微槽结构和纳米结构的 SEM [80]；(c) 3D 飞秒激光曲面加工平台和加工后的铝板的表面形貌和元素分布[85]

纳米颗粒复合层和内部空心微柱相复合的微纳复合结构，实现了有机材料表面的多级微纳结构制备。

曲面与复杂构件的飞秒激光加工是走向实际工程应用的重要方向，多轴运动平台的引入显著提升了加工的灵活性，但也带来了路径规划、焦点跟踪与能量均匀性控制等新挑战。开发智能化的加工轨迹优化软件与实时焦点补偿系统，将是实现复杂构件高质量、高效率飞秒激光微纳加工的关键。

6. 总结与展望

本文概述了飞秒激光与物质相互作用时的核心机制，并简要介绍了飞秒激光在微纳结构制造领域的研究进展。作为当前先进微纳加工领域的重要技术手段，飞秒激光凭借其超短脉冲宽度、高峰值功率以及对材料热影响小等优势，已广泛应用于多种功能性微纳结构的制备，并展现出巨大的工业化应用潜力。然而，目前飞秒激光微纳结构制造正处于从结构设计导向向功能导向转变的关键阶段，在实现以功能特性需求为导向的多尺度结构协同设计和制造中仍面临一定挑战。此外，飞秒激光加工制备的微纳结构一致性与可控性较差，也制约了其在工程化应用中的推广。从工业应用的角度看，当前飞秒激光微纳加工仍面临若干关键技术−经济挑战：工艺稳定性方面，微纳结构的一致性和重复性受激光参数波动(脉冲能量、脉宽、重复频率)、环境扰动(温度、湿度、气流)及材料批次差异的显著影响。其中，激光脉冲能量的长期稳定性(通常要求在 8 小时连续运行中波动<1% RMS)和光束指向稳定性(<10 μrad)是工业化必须满足

的硬性指标。加工效率与成本控制方面，虽然飞秒激光具备“冷加工”优势，但其设备成本高(工业级飞秒激光器通常为10~50万美元)、单脉冲能量有限(通常<1 mJ)，导致大面积结构加工速度较慢(典型值<1 mm²/s)。为此，近年发展的多光束并行加工(如空间光调制器分光)、高重复频率飞秒激光源(>1 MHz)与多边形扫描振镜技术，有望将加工效率提升1~2个数量级。规模化生产中的设备可靠性与维护方面，飞秒激光系统对环境敏感，平均无故障时间(MTBF)和平均修复时间(MTTR)是衡量其工业适用性的关键参数。当前，采用全光纤化、全固态设计的飞秒激光源正逐步提升系统的鲁棒性，降低维护成本。

针对上述挑战，未来研究不仅应关注结构创新与功能集成，更应着力于工艺的稳健性优化、在线监测与闭环控制技术的开发，以及低成本、高可靠性的飞秒激光光源与扫描系统的研制。

在在线监测方面，多种技术已展现出良好前景：(1) 光学相干断层扫描(OCT)可实现加工区域的实时三维形貌监测，纵向分辨率可达微米级，适用于透明材料和表面结构监测；(2) 等离子体光谱监测通过分析激光诱导等离子体的发射光谱，可实时反馈材料去除状态和加工深度；(3) 泵浦－探测成像可捕获超快动力学过程，用于研究结构形成的瞬态机制，但系统复杂、成本高，目前主要限于实验室；(4) 基于声波、热辐射等信号的间接监测方法，具有成本低、易于集成的优势。引入人工智能与机器学习技术，实现加工参数的智能优化与自适应调控，有望显著提升加工一致性、降低对操作人员经验的依赖。例如，采用贝叶斯优化、高斯过程回归等方法，可以在较少的实验次数内找到最优加工参数组合；结合卷积神经网络(CNN)对加工后的结构图像进行快速质量评估并反馈到激光控制系统，实现闭环调控。已有研究表明，基于机器学习的飞秒激光加工参数优化可将结构质量一致性提升30%以上。这些技术的发展将共同推动飞秒激光微纳加工从实验室走向规模化工业应用。

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