

# 飞秒激光非金属微孔加工研究进展

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**摘要** 微孔作为一种常见结构,已被广泛应用于航空、生物、化工、新能源等领域。飞秒激光具有的超短脉冲宽度和超强峰值功率使其在高质量、高深径比微孔加工方面独具优势。综述了近年来飞秒激光非金属微孔加工方法及其应用的研究进展,包括飞秒激光时域/空域整形的电子动态调控微孔加工、飞秒激光辐照辅助化学刻蚀微孔加工、真空环境微孔加工、后表面液体辅助微孔加工以及控制环境温度微孔加工等,并分析了飞秒激光非金属微孔加工在机理以及工艺等方面面临的挑战。

**关键词** 激光技术; 飞秒激光; 非金属微孔; 整形脉冲; 加工环境

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## Research Progress of Femtosecond Laser Microhole Drilling on Non-Metallic Materials

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**Abstract** Microholes are extensively used as a common structure in various fields, including aviation, biology, chemical industry, and new energy. The femtosecond laser pulse possesses unique advantages with respect to drilling high-quality and high-aspect-ratio microholes owing to its ultrashort duration and ultrahigh peak intensity. In this study, the research progress of femtosecond laser microhole drilling on non-metallic materials and its applications in recent years, including the temporally/spatially shaped femtosecond laser pulse microhole drilling based on electron dynamic control, laser irradiation followed by chemical etching microhole drilling, vacuum environment microhole drilling, back-surface liquid-assisted microhole drilling, and environment-temperature-controlled microhole drilling, are reviewed. Furthermore, the challenges associated with the mechanisms and methodologies of femtosecond laser microhole drilling on non-metallic materials are analyzed.

**Key words** laser technique; femtosecond laser; non-metallic microhole; shaped pulse; machining environment

**OCIS codes** 140.7090; 140.3390; 140.3300; 220.4000

## 1 引言

微孔在航空航天、高灵敏度光纤传感器、消费类电子产品、生物工程、三维集成电路封装等领域具有广泛应用。例如:冷却空气均匀地通过热障涂层叶片上加工的气膜冷却孔,可以降低航空发动机涡轮叶片的温度<sup>[1-3]</sup>;在实心光纤上加工微孔结构可实现

高灵敏度传感<sup>[4-8]</sup>;借助电泳驱动分子逐一通过纳米孔,可以实现分子筛选或 DNA 测序<sup>[9-11]</sup>;在硅晶中加工出贯穿上下表面的微孔,然后向微孔内填充金属,这样的结构可用于三维集成电路封装<sup>[12-13]</sup>。然而,传统的微孔加工方式都存在一定限制,如:电子束及聚焦离子束加工微孔的适用条件较为苛刻,且所需设备昂贵<sup>[14]</sup>;电火花只能用于加工导电材料,

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且加工效率较低<sup>[14-17]</sup>；由于腐蚀过程无方向性，因此电化学方法加工出的微孔深径比较小<sup>[17]</sup>；电液束微孔加工过程中存在排屑困难、电解液可能污染被加工样品等问题<sup>[18-19]</sup>；机械钻孔难以加工硬脆材料，且所形成的微孔深径比很小<sup>[14,19]</sup>。

连续激光及长脉冲激光已被广泛应用于金属材料的微孔加工。但对于非金属材料，特别是硬脆透明材料，其自身不存在大量自由电子，因此对于连续激光及长脉冲激光的吸收率通常较低，难以实现高效加工，且所加工的微孔存在明显的热效应、重铸层等缺陷<sup>[20-24]</sup>。飞秒激光脉冲超短的持续时间、超高的峰值功率等特点所带来的非线性(多光子电离、隧道电离等)、非平衡(电子间非平衡、电子与晶格间非平衡)以及非热相变(库仑爆炸、静电烧蚀等)，使飞秒激光微孔加工具有非接触、阈值效应明显<sup>[25-26]</sup>、重铸层及热影响区极小<sup>[27-28]</sup>、精度高<sup>[20,29-30]</sup>等优势。衰减之前的飞秒激光脉冲能量可高达数千微焦，即使被衰减 99.9%，剩下的能量也在微焦量级。这种量级的激光脉冲经透镜聚焦后可形成面积为数平方微米的光斑，该光斑对应的功率密度可达  $10^{13} \sim 10^{15} \text{ W/cm}^2$ 。该功率密度所对应的电场强度与原子核束缚电子的库仑场强度相当，可以使绝缘体材料因束缚电子被剥离成为自由态而发生击穿<sup>[31-32]</sup>。即使很小的一部分聚焦飞秒激光能量被材料吸收，被辐照区域的温度也会在瞬间升至数千摄氏度甚至更高，并在材料内部产生超高的压缩应力与拉伸应力，而后通过各种机制蚀除材料<sup>[32]</sup>。因此，飞秒激光脉冲可以加工几乎所有的导电及导热性能很差的非金属材料，如宽禁带绝缘体、坚硬的金刚石、柔软的有机组织等。包括本课题组在内的很多研究团队都开展了飞秒激光非金属材料微孔加工方面的研究，并取得了很多有影响的研究成果，如飞秒激光时域/空域整形的电子动态调控微孔加工、飞秒激光辐照辅助化学刻蚀微孔加工、真空环境微孔加工、后表面液体辅助微孔加工、控制环境温度微孔加工等。同时，飞秒激光非金属微孔加工也面临着一些新的挑战：微孔加工效率通常较低，国家重大需求及工业生产应用对微孔质量(热影响区、重铸层等)的要求不断提高。通常情况下，飞秒激光微孔加工很难同时兼顾加工精度、质量和效率，从而制约了它的进一步发展与应用。本文将对近年来国内外研究人员在提高飞秒激光非金属微孔加工深径比、效率等方面所做的工作进行综述，并概述当前飞秒激光非金属微孔加工中存在的问题。

## 2 传统的飞秒激光微孔加工方法

国内外学者基于石英等电介质材料及硅等半导体材料，对飞秒激光微孔加工中的脉冲能量、脉冲数量、脉冲脉宽、聚焦光斑与材料的相对位置等因素进行了大量研究，对微孔加工机理(如激光能量吸收、等离子体膨胀等)及加工工艺(单脉冲加工、多脉冲叩击加工、环切加工及螺旋钻孔等)有了更深刻的理解。

1) 在影响微孔质量的因素方面。Varel 等<sup>[33]</sup>将飞秒激光脉冲用于石英玻璃等非金属材料的微孔加工，通过改变飞秒激光脉冲的参数来提高微孔加工能力；Shah 等<sup>[34]</sup>使用长焦距透镜将飞秒激光脉冲聚焦在硅酸盐玻璃上，加工出了高深径比的微孔结构；Kononenko 等<sup>[35]</sup>在不同的脉冲脉宽下于 PMMA 等材料上加工微孔，对不同脉宽情况下微孔加工速度与微孔深度之间的关系进行了研究；Ashcom 等<sup>[36]</sup>在熔融石英上进行了改变数值孔径(NA)的加工实验，研究了 NA 值对飞秒激光脉冲与材料相互作用过程的影响。

2) 在微孔加工机理方面。Shah 等<sup>[37]</sup>研究发现光丝状态的激光束在传播过程中不稳定。随着脉冲数量增加，等离子体开始分段并变得不均匀，这可能导致激光不能连续作用于微孔底部的同一位置，最终导致微孔无法继续加工。Vázquez de Aldana<sup>[38-39]</sup>对石英玻璃中飞秒激光的烧蚀饱和效应进行了实验研究与理论模拟，他们使用稍高于烧蚀阈值能量的飞秒激光验证了微孔深度随着脉冲数量增加而最终饱和的行为；此外，他们还考虑了已形成的微孔对后续脉冲的衍射、反射等效应，通过求解激光传播的波动方程来获得激光的电场分布，并对飞秒激光微孔加工过程进行了理论模拟。Tao 等<sup>[40]</sup>对激光孔壁反射的传播方式进行了建模分析，研究了传播过程的非均匀性以及微孔直径、激光偏振等因素在激光传播中的作用。Kongsuwan 等<sup>[41]</sup>通过改变相邻激光脉冲的间隔以及激光参数，研究了微孔重叠对长微孔形成的影响；同时在考虑激光、材料以及透镜特性的基础上建立了数值模型，用该模型预测样品表面以下不同聚焦深度处的吸收体形状及尺寸；最后利用实验获得的试样的内部特征及通道长度的变化验证了该模型的有效性。

3) 在观测方面。魏健等<sup>[42]</sup>基于飞秒激光抽运-探测原理的时间分辨阴影成像平台，直接获取了飞秒激光脉冲烧蚀石英形成微孔的超快过程图像，在不同

能量密度、时间延迟、脉冲数量下观察到了随时间延迟变化的等离子体通道衰退、冲击波膨胀以及微孔伸长现象; Esser 等<sup>[43]</sup>将激光脉冲时域整形引入到微孔加工中,通过观测、对比传统模式和脉冲串模式下等离子体的发光现象,展示了脉冲串对等离子体的加热过程; Xia 等<sup>[44]</sup>对多个飞秒激光脉冲连续叩击 PMMA 过程中微孔末端的弯曲现象进行了研究,发现叩击加工微孔过程中产生的等离子体、碎屑等对后续飞秒激光脉冲光场的扰动,是造成微孔末端弯曲的主要因素。减小微孔加工环境的大气压力可以促进烧蚀生成物的扩散及喷发,从而减小微孔末端的弯曲程度,明显提高加工微孔的质量以及深度。

然而,传统的飞秒激光微孔加工方式很难满足不断发展的科学技术对微孔尺寸、质量、深径比等提出的愈发苛刻的要求。近年来,国内外学者在飞秒激光脉冲时域/空域整形脉冲加工微孔、激光辐照辅助化学刻蚀加工微孔、改变微孔加工环境等方面进行了大量的研究工作,极大地提高了微孔的质量及深径比。这些研究成果对促进飞秒激光非金属微孔加工技术的发展具有重要意义。

### 3 飞秒激光时域/空域整形的电子动态调控微孔加工

飞秒激光脉冲的脉宽短于大多数材料物理化学过程的特征时间(如电子与晶格的热平衡时间、电子弛豫时间)。大量研究表明,利用飞秒激光脉冲序列等时域/空域整形的脉冲可以调控半导体及电介质受激发过程中的导带电子密度,选择性地电离原子,控制分子基态旋转动力学及化学反应过程等。Jiang<sup>[45-49]</sup>建立了描述飞秒激光脉冲与材料相互作用过程的等离子模型,该模型大幅提高了飞秒激光脉冲烧蚀的预测精度,并成功预测了多种反常效应,如:飞秒激光脉冲烧蚀电介质时会产生平底烧蚀坑。该效应已被多个国家的研究团队通过实验确认。在模型预测的基础上, Jiang 等<sup>[5,50-58]</sup>提出了飞秒激光时域/空域整形的电子动态调控加工原理与方法,首次实现了加工过程中材料局部瞬时电子状态的主动调控;他们通过飞秒激光时域/空域整形(如脉冲序列的子脉冲数量、子脉冲强度比、子脉冲间隔、偏振等参数)来调控光子能量的吸收、电子激发及复合、电子密度时域/空域分布等特性,进而调控材料局部的瞬时特性(光学与热力学特性),控制材料的相变过程,最终实现了高质量、高精度、高可控性的飞秒激光加工。

#### 3.1 飞秒激光时域整形脉冲微孔加工

Jiang 等<sup>[54]</sup>提出了采用飞秒激光双脉冲烧蚀后表面的方法加工高深径比微孔,通过调控被辐照材料自由电子密度分布等局部瞬时特性提高烧蚀效率的方法;他们发现,在相同的实验条件下,与未整形脉冲相比,双脉冲使材料的去除率提高了 56 倍,微孔的最大长度增加了 3 倍,如图 1(a)所示。

Stoian 等<sup>[59]</sup>研究了脉宽为 90 fs 的飞秒激光脉冲及具有不同时间间隔的三脉冲序列辐照熔融石英的阈值以及加工微孔的质量,如图 1(b)所示;他们研究后发现,相对于未整形的脉冲,时域整形的脉冲序列能显著提高加工微孔的质量;同时,他们发现存在最优的脉冲序列,它能最大限度地减少微孔壁上的裂纹。

Jiang 等<sup>[50]</sup>与 Fang<sup>[60]</sup>采用不同波长的飞秒激光单脉冲及双脉冲进行微孔的叩击加工试验,发现双脉冲所形成的微孔深度可达到 890  $\mu\text{m}$ ,深径比为 91:1,微孔孔壁更加光滑,如图 1(c)所示;他们认为未整形脉冲加工微孔质量恶化的原因是未整形脉冲辐照时产生了高密度的自由电子,电离区域反射率随之增强,后续脉冲能量被大量反射,所产生的再次烧蚀增大了微孔的尺寸及内壁粗糙度。然而,使用双脉冲加工时,微孔底部等离子体的自由电子密度较小,其反射率也会显著降低,有更多的激光能量沉积到微孔底部,因此增大了微孔深度。Götte 等<sup>[61]</sup>将脉宽为 30 fs 的飞秒激光脉冲整形为等效脉宽约为 1.5 ps 的时域对称脉冲序列及非对称脉冲序列,在能量远低于自聚焦阈值的情况下使用单发未整形脉冲以及时域整形脉冲序列烧蚀熔融石英加工微孔;实验结果表明,飞秒激光时域整形脉冲序列能明显提高所加工微孔的质量及深径比,如图 1(d)所示。Götte 等<sup>[61]</sup>认为:未整形脉冲在靶材表面之下几百纳米范围内的区域被强烈地反射和吸收,阻止了激光能量在这个范围之外的沉积;而整形脉冲由短且强的子脉冲组成,其峰值强度远低于产生临界电子密度所需的强度,因此激光能量可以穿透进入材料内部。该研究再次验证了时域整形脉冲在微孔加工中的优势。

#### 3.2 飞秒激光空域整形微孔加工

通过对高斯激光脉冲的振幅、相位以及偏振等空域特征进行整形,可以有效调控飞秒激光脉冲与材料的光子-电子相互作用过程,提高微孔加工的效率和深径比等。贝塞尔光束极细的中心主瓣可在自由空间传播很远距离且不发散,这一特性使其成为

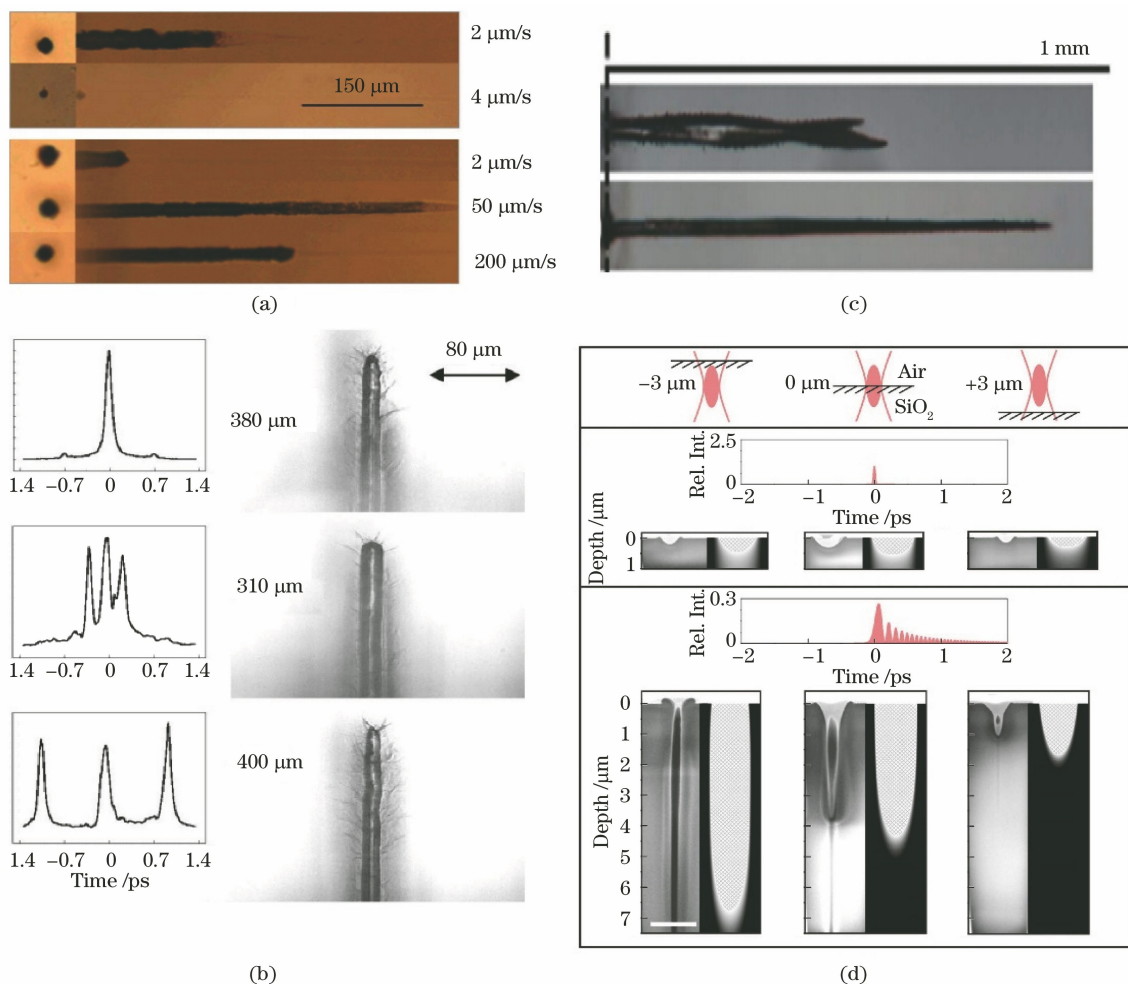


图 1 飞秒激光时域整形脉冲加工的微孔。(a)未整形脉冲(上)及间隔为 500 fs 的双脉冲(下)在水辅助下加工的微孔<sup>[54]</sup>；(b)单脉冲及间隔不同的三脉冲序列在  $\alpha$ -SiO<sub>2</sub> 上加工的微孔<sup>[59]</sup>；(c)1000 个脉冲能量为 20  $\mu$ J 的未整形脉冲(上)及间隔为 600 fs 的双脉冲(下)叩击 PMMA 加工的微孔<sup>[50]</sup>；(d)未整形脉冲及时域递减脉冲序列加工的微孔<sup>[61]</sup>

Fig. 1 Microholes drilled by femtosecond laser temporally shaped pulse. (a) Microholes drilled by unshaped pulse (up) and double-pulse (down) with an interval of 500 fs assisted by water<sup>[54]</sup> ; (b) microholes drilled in  $\alpha$ -SiO<sub>2</sub> by single unshaped pulse and three-pulses with different interval<sup>[59]</sup> ; (c) microholes drilled in PMMA by 1000 unshaped pulses (up) and double-pulses (down) with an interval of 600 fs when the energy is 20  $\mu$ J<sup>[50]</sup> ; (d) microholes drilled by unshaped pulse and temporal decreasing pulse trains<sup>[61]</sup>

加工高深径比微孔的最有效途径之一。Durnin 等<sup>[62]</sup>的实验研究表明,截断的贝塞尔光束为近似无衍射光束,其光强在较长的距离内也可以基本保持不变。在实验中,一般通过锥透镜、空间光调制器等元件将入射激光整形为贝塞尔光束,以获得小焦斑、长焦深的聚焦光场。贝塞尔光束焦斑示意图及其波矢量关系如图 2(a)、(b)所示。贝塞尔光束及高斯光束聚焦光斑沿传播方向的光强分布如图 2(c)所示,可见,在焦斑直径相近的情况下,贝塞尔光束能显著提高聚焦光斑的长度<sup>[63]</sup>。

Zhao 等<sup>[64]</sup>借助锥透镜将入射高斯光束转换为贝塞尔光束,将所形成的无衍射区域通过由平凸透

镜与显微物镜组成的缩束系统进行缩束后在样品上加工微孔;他们通过调节瞬时局部电子密度分布形成了一个长且均匀的相互作用区,通过优化脉冲能量以及聚焦光斑与样品之间的相对位置,采用单个能量为 20  $\mu$ J 的贝塞尔脉冲及高斯脉冲在 PMMA 上实现了小直径(1.4 ~ 2.1  $\mu$ m)、高深径比(>460:1)的微孔加工,如图 3(a)所示。Yao 等<sup>[65]</sup>从理论及实验上证明了可以使用空间光调制器产生非衍射长度可调节的类贝塞尔光束(Bessel-like beam);他们通过改变相位获得了焦深长度可调节且强度可控的焦场,并利用这种方式产生的类贝塞尔光束在 PMMA 材料上实现了深径比超过 560:1

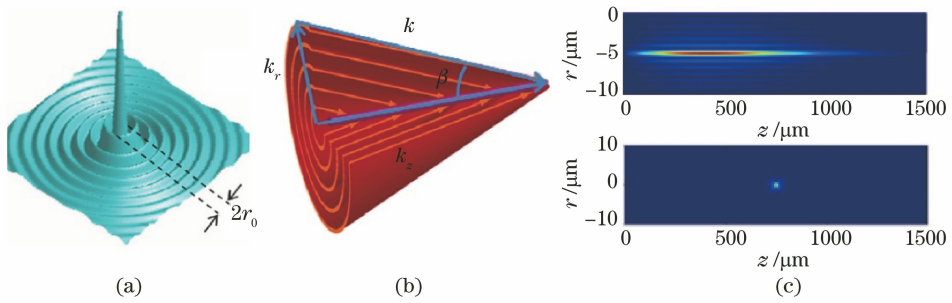


图2 贝塞尔光束<sup>[63]</sup>。(a)贝塞尔光束焦斑示意图；(b)贝塞尔光束波矢量关系示意图；  
(c)贝塞尔光束及高斯光束聚焦光斑沿传播方向的光强分布

Fig. 2 Bessel beam<sup>[63]</sup>. (a) Schematic of focal spot of Bessel beam; (b) schematic of wave vector relationship of Bessel beam; (c) focal spot intensity distribution of Bessel beam and Gaussian beam along propagation direction

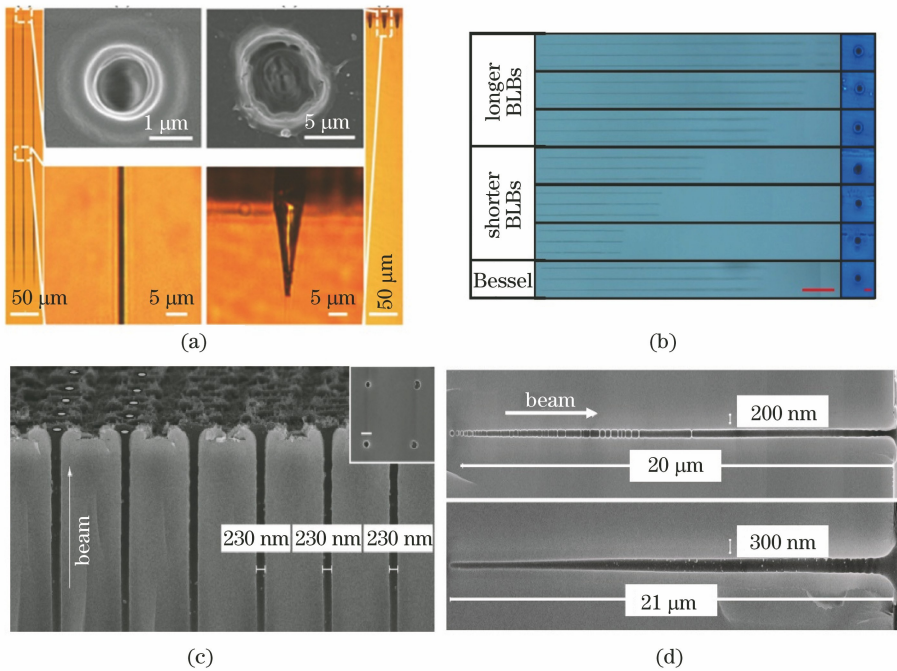


图3 飞秒激光贝塞尔光束加工的微孔。(a)单个能量为  $20 \mu\text{J}$  的贝塞尔脉冲(左)及高斯脉冲(右)在 PMMA 上加工的微孔<sup>[64]</sup>；(b)三种聚焦长度可调节的类贝塞尔光束在 PMMA 上加工的微孔<sup>[65]</sup>；(c)单个能量为  $0.70 \mu\text{J}$  的贝塞尔脉冲加工的微孔阵列<sup>[66]</sup>；(d)单个脉冲能量为  $0.65 \mu\text{J}$  和  $0.85 \mu\text{J}$  的贝塞尔脉冲加工的微孔<sup>[66]</sup>

Fig. 3 Microholes drilled by femtosecond laser Bessel beam. (a) Microholes drilled in PMMA by single Bessel pulse (left) and Gaussian pulse (right) when the energy is  $20 \mu\text{J}$ <sup>[64]</sup>；(b) microholes drilled in PMMA by three types of Bessel-like beam with adjustable focusing length<sup>[65]</sup>；(c) microholes array processed by Bessel pulse when the energy is  $0.70 \mu\text{J}$ <sup>[66]</sup>；(d) microholes processed by single Bessel pulse when the energy is  $0.65 \mu\text{J}$  and  $0.85 \mu\text{J}$ <sup>[66]</sup>

的高质量微孔的加工,如图3(b)所示。2010年, Bhuyan等<sup>[66]</sup>利用空间光调制器产生的贝塞尔光束在玻璃上加工出了深径比超过100的微孔阵列,如图3(c)、(d)所示。2014年, Bhuyan等<sup>[67]</sup>确定了激光脉宽及加工结构物理特性的脉冲能量依赖性,提出了基于非线性超短贝塞尔光束的轴向能量沉积进入熔融石英及随后材料致密(或变稀薄)的机制,并在此基础上使用零阶啁啾飞秒激光贝塞尔光束在熔融石英上加工出了直径为200~400 nm的孔。

#### 4 飞秒激光辐照改性辅助化学刻蚀微孔加工

玻璃等材料具有较高的烧蚀阈值及硬脆特性,因此利用单脉冲加工、多脉冲叩击式加工、环切式加工以及螺旋钻孔等加工方式在这类材料上形成的微孔的质量及深径比等指标不够理想。Marcinkevicius等<sup>[68]</sup>提出的利用飞秒激光脉冲辐照辅助化学刻蚀(FLICE)在玻璃类材料上加工微孔的

方法受到了国内外学者的广泛关注<sup>[55-57,68-77]</sup>。FLICE法加工微孔主要包括两个步骤:1)将飞秒激光脉冲聚焦到被加工样品内部,使被辐照区域形成永久性改性区;2)利用刻蚀液去除永久性改性区域从而形成微孔。为了提高FLICE法的刻蚀效率,Venturini等<sup>[70,78]</sup>采用低压气态的氢氟酸作为刻蚀剂,在被激光辐照后的熔融石英上加工出了长度为3 mm、深径比最高达到29的微孔,这一长度较刻蚀液所能得到的长度提高了约2倍。

由于高斯光束的聚焦光斑焦距较短,因此在利用FLICE法加工微孔时一般需要采用扫描的方式增加改性区域的长度,如图4(a)所示。当采用纵向扫描方式时,改性区域长度会受到透镜聚焦深度的影响<sup>[30]</sup>;当采用横向扫描方式时,高斯光束聚焦光斑的不对称性(径向尺寸小于光传播方向尺寸)导致刻蚀后所形成的微孔的横截面为椭圆,如图4(b)所示。为了避免出现该缺陷,研究者利用狭缝、透镜像

散系统、柱面透镜等方式来改变聚焦光斑的空间分布,获得了近似圆形截面的微孔<sup>[79-82]</sup>。Cheng等<sup>[81]</sup>利用一个狭缝对激光场进行整形,扩大聚焦光斑的横向分布,使其与纵向尺寸匹配,获得了截面圆度较高的微孔结构,如图4(c)所示。由于微孔入口刻蚀时间较长且该位置的刻蚀液易于交换,而微孔底部刻蚀时间较短且刻蚀液交换困难,因此一般利用FLICE法得到的是入口直径较大、底部直径较小的锥状微孔,如图4(b)所示。Vishnubhatla等<sup>[77]</sup>利用扫描补偿的方式在深度方向上形成了锥形改性区域,对其进行刻蚀之后得到了截面尺寸均匀的微孔,如图4(d)所示。Hnatovsky等<sup>[83]</sup>在研究中发现,当扫描方向与激光偏振方向垂直时,激光辐照所形成的微结构更有利于刻蚀液的渗透。也有研究者利用KOH溶液作为刻蚀液<sup>[69]</sup>,其主要依据是KOH溶液对改性区域与未改性区域的刻蚀速率差异更大,更有利于形成高深径比的微孔。

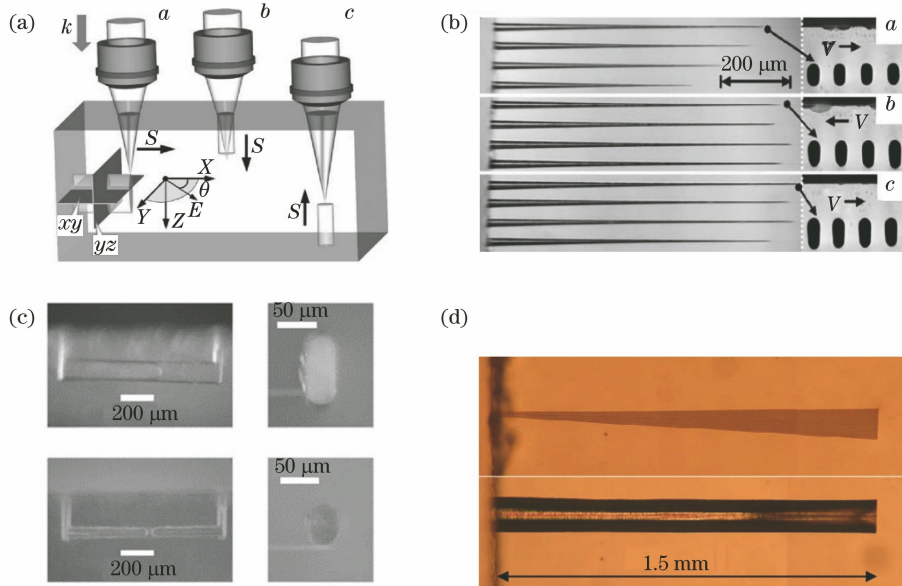


图4 未整形飞秒激光辐照改性辅助化学刻蚀加工的微孔。(a)飞秒激光扫描改性玻璃示意图<sup>[83]</sup>; (b)采用横向扫描方式在玻璃内部形成的刻蚀微孔<sup>[83]</sup>; (c)通过光束整形方式优化微孔截面形状<sup>[81]</sup>; (d)通过扫描路径补偿得到的截面均匀的微孔<sup>[77]</sup>

Fig. 4 Microholes drilled by FLICE using unshaped femtosecond laser. (a) Schematic of glass modified by femtosecond laser scanning<sup>[83]</sup>; (b) etching microholes in glass using transverse scanning<sup>[83]</sup>; (c) optimizing the cross section shape of microhole by beam shaping<sup>[81]</sup>; (d) etching microholes with uniform cross section obtained by scanning path compensation<sup>[77]</sup>

利用飞秒激光时域整形脉冲结合FLICE法可以在更大程度上提高微孔的质量及深径比。Liu等<sup>[55]</sup>利用飞秒激光双脉冲辐照熔融石英,而后将被辐照的样品浸入氢氟酸溶液中进行刻蚀加工微孔;结果发现,在相同的实验条件下,双脉冲能明显提高所形成微孔的长度,如图5(a)所示。Wang等<sup>[56]</sup>采

用飞秒激光贝塞尔-双脉冲辐照熔融石英后再采用化学刻蚀的方法加工微孔;他们先将高斯光束整形为贝塞尔光束以延长聚焦光斑沿光传播方向的长度,然后通过调节双脉冲时域间隔来提高光子能量的沉积效率,从而在熔融石英上加工出了更大深径比的微孔,如图5(b)所示。使用贝塞尔-双脉冲辐

照熔融石英后再经刻蚀所形成的微孔深度较相同实验条件下使用贝塞尔光束加工出的微孔深度提高了约13倍。Du等<sup>[51]</sup>先利用时域递减脉冲序列辐照熔融石英,再利用氢氟酸溶液进行化学刻蚀;实验结果表明,时域递减脉冲序列不但可以增加激光辐照辅助化学刻蚀的效率,还会影响刻蚀坑的形貌,如图

5(c)所示。该实验再次证实了飞秒激光脉冲序列具有调控电子动态的能力。Yan等<sup>[57]</sup>提出了利用飞秒激光双脉冲实现偏振无关加工微孔的方法;实验结果表明,飞秒激光双脉冲能明显减弱未整形脉冲辐照熔融石英时所形成的纳米结构的偏振依赖性,明显提高微孔的长度,如图5(d)所示。

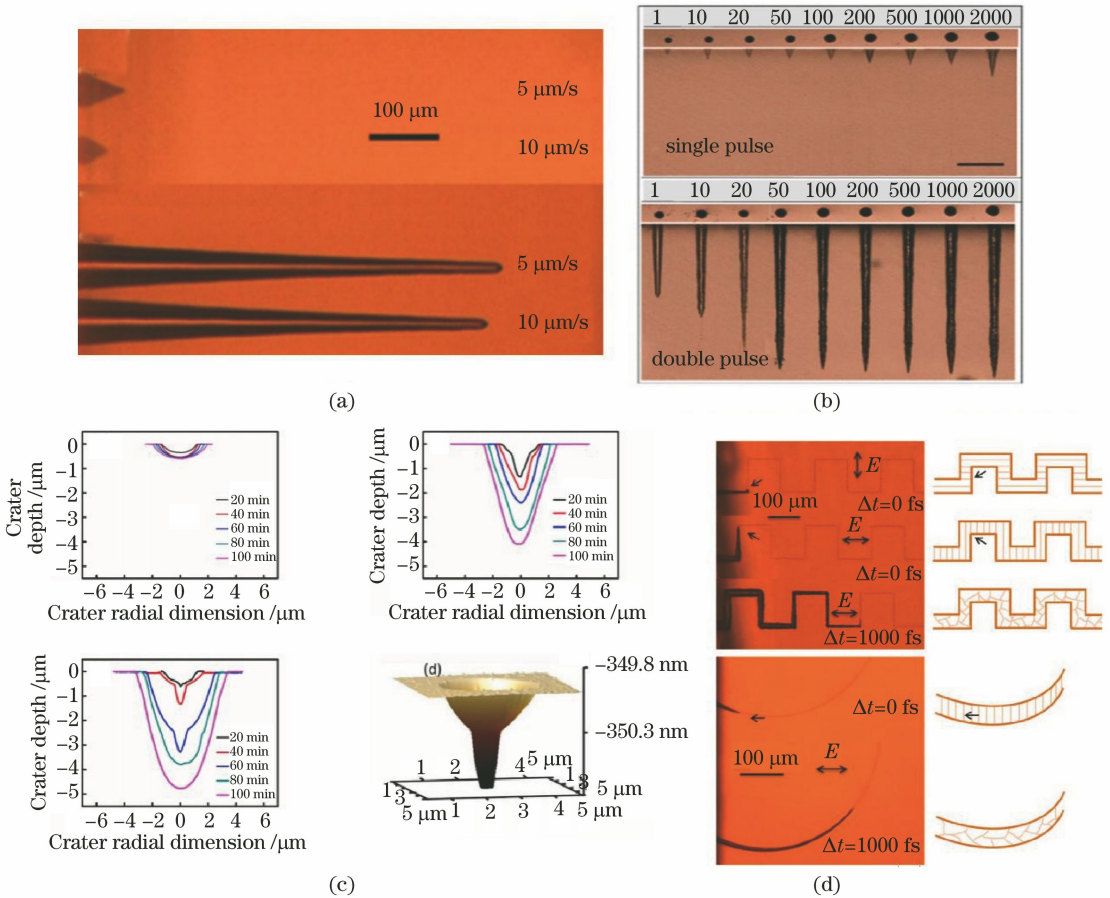


图5 整形及未整形飞秒激光辐照改性辅助化学刻蚀加工的微孔。(a)经未整形脉冲(上)及间隔为500 fs的双脉冲(下)辐照再经刻蚀形成的微孔<sup>[55]</sup>; (b)贝塞尔脉冲(上)及贝塞尔-双脉冲(下)所加工的微孔形貌随脉冲数量的变化情况<sup>[56]</sup>; (c)未整形脉冲以及子脉冲间隔不同的递减脉冲序列辐照熔融石英再经化学刻蚀所形成的坑形貌<sup>[51]</sup>; (d)偏振方向沿竖直和水平方向的未整形脉以及双脉冲辐照熔融石英再经化学刻蚀所形成的折线微孔及弧形微孔<sup>[57]</sup>

Fig. 5 Microholes drilled by FLICE using shaped and unshaped femtosecond laser. (a) Microholes formed by FLICE using unshaped pulse (up) and double-pulse with an interval of 500 fs (down)<sup>[55]</sup>; (b) microhole morphologies vary with pulse number which formed by FLICE using Bessel pulse (up) and Bessel-double pulse (down)<sup>[56]</sup>; (c) crater cross section and morphologies formed by FLICE using unshaped pulse and decreasing pulse trains with different sub-pulse intervals<sup>[51]</sup>; (d) zigzag microholes and arc microholes formed by FLICE using unshaped pulse and double-pulse along the vertical and horizontal directions in polarization<sup>[57]</sup>

## 5 环境控制的飞秒激光微孔加工

### 5.1 真空环境中的微孔加工

多个飞秒激光脉冲连续叩击样品加工微孔时,已加工好的微孔会影响后续脉冲的光场分布,且后续脉冲会被未充分弥散开的碎屑干扰,这可能导致

激光能量无法向微孔底部有效传播,导致所形成的微孔末端逐渐弯曲;而且,加工过程中产生的碎屑也会沉积在微孔入口附近,降低微孔的表面质量。科研人员发现,真空环境能够有效提高烧蚀物的排出效率,且可迅速降低加工区域的温度,确保后续脉冲到达时材料已经恢复到相对稳定的状态。Juodkazis

等<sup>[84]</sup>发现真空条件下碎屑易排出,所加工微孔的重铸层更薄、表面质量更高。Bliss 等<sup>[85]</sup>对比了真空及空气环境中的烧蚀坑形貌,发现真空环境中材料的去除率更高,且重新沉积在微孔边缘的颗粒更少。Xia 等<sup>[44,86]</sup>发现真空环境可以明显提高多脉冲叩击加工微孔的质量及深径比,如图 6 所示。他们认为在真空

环境中加工微孔时,前续激光脉冲所形成的等离子体以及碎屑等更容易从微孔中喷发出来,微孔内部的残留物明显减少,其对后续脉冲光场的影响也将减弱,激光脉冲能量可以更有效地向微孔底部传递。因此,在真空环境中所加工的微孔质量及深径比等指标都明显优于在空气中加工的微孔。

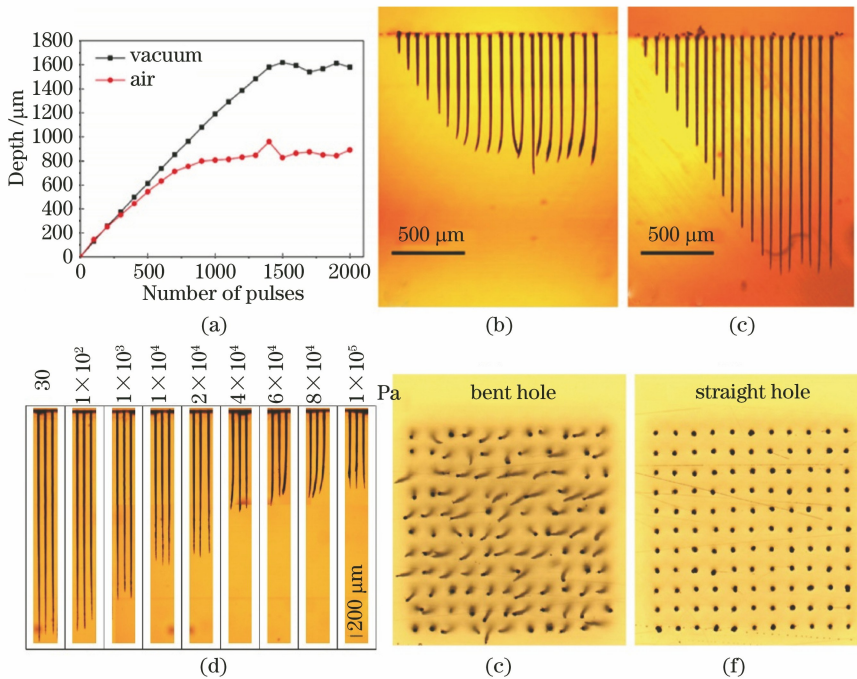


图 6 飞秒激光在不同气压环境中加工的微孔<sup>[44,86]</sup>。(a)在空气及真空环境中加工的微孔深度随脉冲数量的变化情况;(b)(c)在空气及真空环境中加工的微孔形状,对应(a)中的数据;(d) 5000 个能量为  $50 \mu\text{J}$  的脉冲所加工的微孔形貌随气压的变化情况;(e)(f)在空气中及真空环境中加工的阵列微孔的出口

Fig. 6 Microholes drilled by femtosecond laser in different atmospheric pressure environments<sup>[44,86]</sup>. (a) Variatin of microholes depth drilled in air and vacuum with pulse number; (b) and (c) are the microholes processed in air and vacuum, corresponding to the data in (a); (d) variation of microholes morphology drilled by 5000 pulses with energy of  $50 \mu\text{J}$  with ambient pressure; (e) and (f) are the outlet of arrayed microholes drilled in air and vacuum, respectively

## 5.2 液体辅助微孔加工

如前文所述,在飞秒激光多脉冲连续叩击加工微孔过程中,已成形的微孔及碎屑的喷射会影响后续脉冲能量向微孔底部的传导及烧蚀过程,降低微孔的加工质量。减小微孔加工环境的气压能有效减弱碎屑喷射对微孔加工过程的影响,但已形成微孔的孔壁对后续脉冲光场的影响依然存在。为此,科研人员针对透明材料提出了将激光聚焦在材料下表面,同时将样品下表面浸入液体(一般为蒸馏水或去离子水)中进行微孔加工的方法,如图 7(a)所示。聚焦光斑相对于样品自下而上移动实现微孔加工,从而避免了已形成的孔壁对加工过程的影响<sup>[54,87-89]</sup>。入射激光会在气/液界面产生反射、折射等现象,被反射、折射到孔壁的激光可以再次去除孔

壁材料,从而提高微孔的圆度以及激光能量的利用率<sup>[90]</sup>。高能量密度的激光脉冲会使液体发生光学击穿,所产生的等离子体冲击波以及高速射流冲击<sup>[90-91]</sup>等有利于加快碎屑的排出。除此之外,液体还可以有效抑制孔内壁形成的重铸层以及伴随重铸层产生的微裂纹<sup>[90,92]</sup>。当所使用的激光能量较大时,激光辐照加工微孔产生的热量将向孔壁四周传导,而液体能起到快速冷却的作用。此外,液体环境中的含氧量较低,有利于减弱加工过程中热效应引起的氧化现象<sup>[30]</sup>。Li 等<sup>[93]</sup>提出了利用水辅助飞秒激光加工的方法,该方法在透明介质背面进行微孔加工,有效避免了已加工结构对后续激光的影响;他们利用该方法获得了直径为  $4 \mu\text{m}$ 、深度超过  $200 \mu\text{m}$  的微通道结构,其深径比可达到  $50:1$ 。



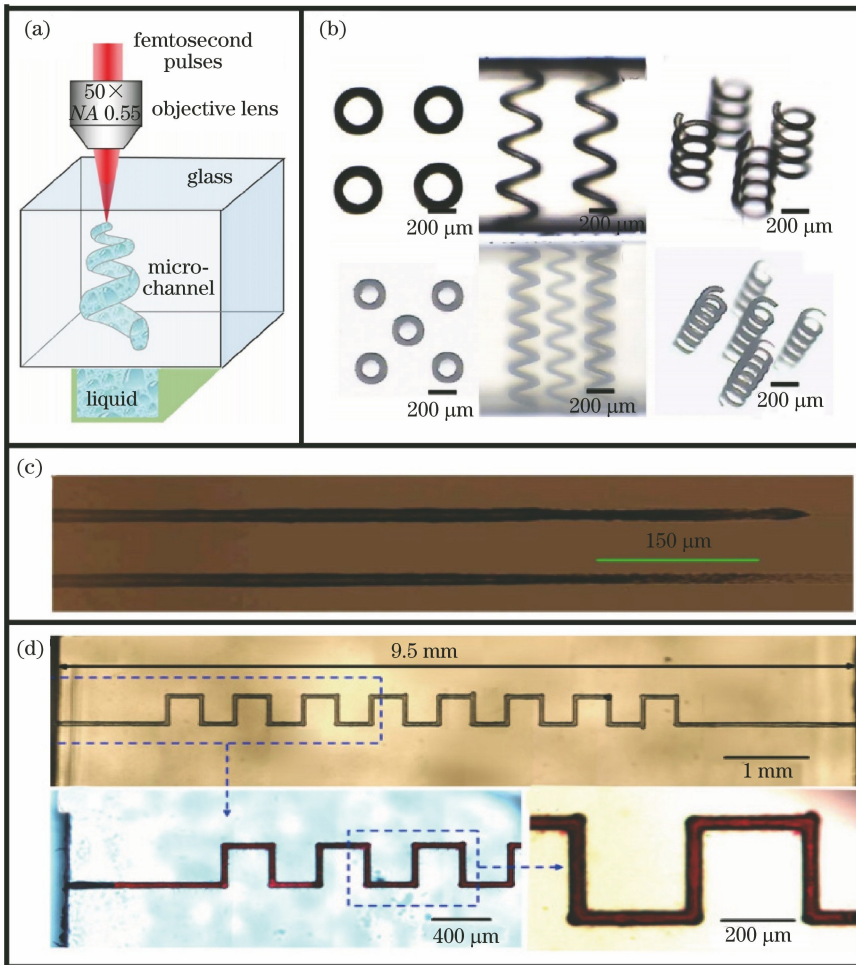


图7 水辅助的飞秒激光微孔加工。(a)后表面水辅助微孔加工示意图<sup>[87]</sup>;(b)飞秒激光脉冲在去离子水辅助下于石英玻璃上加工的螺旋微孔阵列<sup>[89]</sup>;(c)双脉冲后表面水辅助加工的高深径比微孔<sup>[54]</sup>;(d)水辅助加工的多孔玻璃内的微孔<sup>[94]</sup>

Fig. 7 Microholes drilled by femtosecond laser assisted by liquid. (a) Schematic of microhole processing assisted by water on the rear surface<sup>[87]</sup>; (b) helical microholes array processed in silica glass by femtosecond laser pulse assisted by distilled water<sup>[89]</sup>; (c) high-aspect-ratio microholes processed using double-pulse assisted by water on the rear surface<sup>[54]</sup>; (d) square-wave like channel processed in porous glass assisted by water<sup>[94]</sup>

Hwang 等<sup>[88]</sup>在液体辅助加工的基础上引入超声波来加速碎屑从微孔内排出,提高了后表面液体辅助微孔加工的效率。Li 等<sup>[89]</sup>利用水辅助加工的方式采用飞秒激光脉冲在石英玻璃内部扫描,实现了各种螺旋微孔阵列的加工,螺旋微孔的长度约为 1 mm,直径约为 50 μm,如图 7(b)所示。Jiang 等<sup>[54]</sup>结合电子动态调控的加工方法,利用液体辅助后表面加工技术在玻璃上加工出了深径比超过 40:1 的微孔,如图 7(c)所示,该方法的加工速度可达到 80 μm/s。Liao 等<sup>[94]</sup>利用飞秒激光烧蚀浸水的多孔玻璃直接形成空心微通道,而后在 1150 °C 下对玻璃进行退火处理,使多孔玻璃得到巩固,制备出了长度约为 1.4 mm、直径约为 64 μm 的方形波微通道,如图 7(d)所示。

### 5.3 改变微孔加工温度

一些材料所处的环境温度会明显影响其物理及化学性质,因此被加工样品所处环境的温度也会对加工的微孔产生明显影响。Day 等<sup>[95]</sup>使用高重复频率飞秒激光对材料进行局部加热,使被辐照区域的密度发生变化,然后与退火工艺结合得到了光滑的圆柱形微孔。除此之外,当改变温度时,某些材料性质的改变会影响飞秒激光与材料的相互作用过程:在较高的温度下,材料声子数明显增加,导致材料的光吸收系数增大,降低了材料的烧蚀阈值,从而可以得到具有更高深径比的微孔。Jiao<sup>[96]</sup>等研究了飞秒激光加工单晶硅时温度对微孔形貌及碎屑飞溅面积的影响,发现温度升高时激光加工效率提高,飞溅面积减小。Zhang 等<sup>[97]</sup>使用热板对 PMMA 进行

加热,以研究飞秒激光加工 PMMA 时温度对微孔几何形貌的影响;结果发现,当温度从 20 °C 升高到

80 °C 时,微孔加工深度从 0.9  $\mu\text{m}$  增大到 7.1  $\mu\text{m}$ ,如图 8 所示。

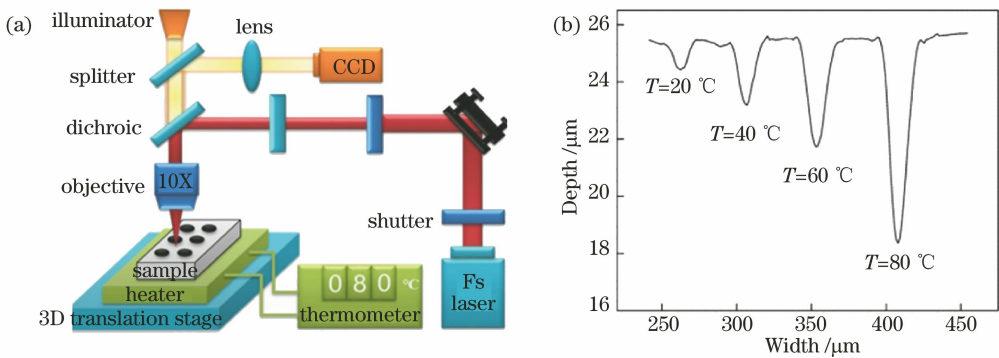


图 8 改变环境温度加工的微孔<sup>[97]</sup>。(a)改变环境温度加工微孔示意图;(b)微孔形貌随温度的变化

Fig. 8 Microholes drilled in variable temperature environment<sup>[97]</sup>. (a) Schematic of changing the ambient temperature of microhole processing; (b) variation of microhole morphology with temperature

## 6 结束语

飞秒激光非金属微孔加工已成为激光加工领域的研究热点之一。飞秒激光脉冲能够在绝大多数非金属材料上加工出高质量、高深径比的微孔,其相对于传统的微孔加工方式具有明显优势。然而,目前飞秒激光非金属微孔加工仍面临着许多挑战,主要体现在微孔加工机理以及微孔加工工艺等方面。

### 6.1 飞秒激光非金属微孔加工的机理研究

如何从机理上准确描述飞秒激光与材料的相互作用过程一直是飞秒激光加工领域的难点之一。飞秒激光脉冲在能量密度、作用空间、时间尺度及被加工材料吸收能量的可控性等方面都趋于极端,因此其加工过程所利用的物理效应、作用机理均不同于长脉冲激光加工。一般来说,可以将飞秒激光与材料的相互作用分为光子能量吸收、材料相变以及等离子体辐射与喷发等过程<sup>[98]</sup>。光子能量的吸收主要包括多光子电离、隧穿电离等机制,而材料的相变则主要有热相变(气化、熔化等)和非热相变(库仑爆炸、静电烧蚀等)机制<sup>[14]</sup>。在飞秒激光加工非金属微孔过程中,以上机制会受到脉冲宽度、重复频率、能量密度等参数以及被加工材料性质、聚焦情况等因素的影响。随着脉冲数量增加,激光能量通过孔壁反射、孔口衍射、等离子体吸收等方式传递至微孔底部,使得孔深度增加。在孔深度逐渐增加过程中,等离子体的传播和喷发不稳定,微孔深度增加变缓,最终不再增加。目前,已经发展了一些简化的或者针对特定材料的模型来描述飞秒激光微孔加工过程,比如:通过对激光光场分布及电子密度分布的研

究预测电介质被飞秒激光脉冲辐照时发生烧蚀的区域<sup>[45-47,49]</sup>,研究微孔入口衍射及孔壁反射对微孔加工极限深度的影响<sup>[38-39]</sup>。但是这些理论的适用范围有限,亟需从机理上研究飞秒激光与材料相互作用的非线性、非平衡、跨尺度过程。

### 6.2 飞秒激光非金属微孔加工的工艺研究

不断涌现的新技术、新器件、新应用对飞秒激光加工微孔的尺寸、圆度、锥度、深径比、微裂纹以及重铸层等方面的要求越来越高,例如微孔的尺寸已从微米尺度进入纳米尺度<sup>[14]</sup>。此外,在飞秒激光微孔加工中还需要兼顾效率。面对这些新挑战,必须要不断寻找新的加工工艺。比如,采用飞秒激光时域/空域同步聚焦的方式在玻璃样品中加工三维微通道来满足微流体技术更高功能性的需求<sup>[99]</sup>,采用时域脉冲序列调制与轴向进给相结合的方式加工微孔来满足航空发动机气膜孔更高的锥度及表面质量的要求<sup>[100]</sup>,同时对脉冲进行时域及空间整形以提高所加工非金属微孔的质量及深径比<sup>[56]</sup>,开发新的脉冲整形技术<sup>[53]</sup>,利用双光子吸收效应实现突破衍射极限的加工<sup>[101]</sup>,利用飞秒激光光丝在电介质上加工高深径比的亚微米孔<sup>[102]</sup>等。飞秒激光非金属微孔加工工艺的发展趋势主要是飞秒激光直写与其他多种工艺相结合的加工,例如飞秒激光时域整形与远场/近场空间整形相结合、飞秒激光直写与超声振动加工相结合、飞秒激光改性与干法/湿法刻蚀相结合等。

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