

液体辅助激光微孔加工研究进展

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摘要: 随着微孔加工技术的逐渐成熟, 激光微孔加工的应用越来越广泛, 但依靠单一激光束进行微孔加工仍存在一些问题, 尤其是在深孔加工方面, 出现了以激光束为主、多能量场辅助的复合打孔技术, 并逐渐成为了热点。针对液体辅助激光微孔加工研究领域, 总结了水基辅助激光打孔、水基超声振动辅助激光打孔、水基超声-磁场辅助激光打孔和电解液/水射流辅助激光打孔等方法。在水基的基础上, 加入了超声、磁场和温度场, 使得辅助场变得多元化, 在多层面上进行复合加工。介绍了不同辅助加工方法的去除材料机理及加工后材料特性的变化, 水起到冷却的作用, 但在水层下会形成空化气泡, 超声振动可以击溃气泡, 磁场和温度场为材料残渣提供了能量, 具体表现在热效应、材料去除速率、打孔深度、重铸层及裂纹等方面。影响微孔质量的因素有微孔锥度、深径比、孔的圆度、重铸层厚度、热影响区、微裂纹和粗糙度等, 主要对微孔锥度、深径比及其他指标进行了分析, 总结了加工方法对微孔质量的影响。

关键词: 辅助加工; 液体辅助; 激光打孔; 加工材料; 打孔质量

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Research Progress of Liquid-assisted Laser Micro-hole Processing

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ABSTRACT: With the rapid progress of laser processing technology, micro-hole processing with laser is becoming more and more popular. However, it is still away from qualifying real applications, especially when high aspect ratio micro-hole is required. Facing the situation, hybrid micro-hole drilling methods, i.e., laser beam-based and multi-energy field-assisted hole drilling techniques gradually emerge. With the purpose of elucidating the inspiring development in this important field, the work aims to summarize the methods of underwater laser drilling, water-based ultrasonic vibration-assisted laser drilling, water-based ultrasonic & magnetic field assisted laser drilling and electrolyte/water jet assisted laser drilling. The advantages and shortages of each method are provided and discussed as follows. Compared to laser beam drilling, underwater laser drilling means that the workpiece is immersed into water and the laser beam passes through water to drill holes. By tuning water layer thickness and laser parameters, the quality of micro-hole can be improved. On the one hand,

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the existence of water takes away accumulated heat thus achieving more accurate edge quality; on the other hand, the cooling effect makes it easy for the expelled slags to re-accumulate inside the drilled voids, which seriously affects the incoming laser beam absorption. The latter one limits its applicability in industry. Water-based ultrasonic vibration assisted micro-hole processing is based on underwater laser drilling. In addition, ultrasonic vibration source is employed. The ultrasonic vibration can break the bubbles generated during the drill course. It can also decrease the interference of bubbles on the laser beam and reduce debris repositioning in the processing area. All the above effects favor a cleaner surface profile and a better aspect ratio. As for water-based ultrasonic-magnetic field assisted laser micro-hole drilling method, an ultrasonic vibration field and a magnetic field are coupled simultaneously into the underwater micro-hole drilling procedures. The addition of magnetic field can weaken the shielding effect of the plasma on the incident laser beam, increase the effective energy injection of the incident laser beam and enhance the mixing effect caused by the electromagnetic force inside the molten metal. It can improve the laser energy absorption inside the drilled hole and promote material removal efficiency. Meantime, it can also suppress the formation of recast layers and reduce residual stress. Water jet assisted micro-hole drilling method is another novel way for micro-hole drilling. In this procedure, water jet is used not only for putting workpiece inside water tank. Water jet provides powerful water flow. The water flow can cool down the generated slags and take them away, which is unavailable for underwater laser drilling. Water jet can also wash the recast layer to improve the quality of the drilled hole. Furthermore, electrolyte can be introduced into the water flow to become into hybrid liquid flow. By virtue of its corrosive effect and the laser beam ablation, material removal rate speeds up. As the results, hole drilling efficiency is obviously increased.

As for the criterions to evaluate the quality of laser drilled micro-holes, several parameters are usually considered, e.g., taper angle of micro-hole, aspect ratio, roundness of hole, thickness of recast layer, heat-affected zone, micro-crack and inner side surface roughness. In the study, these indicators of each processing methods are classified and analyzed. Finally, the laser micro-hole drilling procedures are summarized. Based on the above analysis, short prospects of potential research on micro-hole drilling are also given.

KEY WORDS: auxiliary processing; liquid-assisted; laser drilling; processing materials; drilling quality

激光加工利用高能量激光束去除材料,广泛应用于工业生产中。激光去除材料常见的方法包括激光打孔、激光切割、激光烧蚀和激光光刻等^[1-5]。近年来,激光打孔引起了广泛关注,并被广泛应用于许多领域,包括医疗卫生、微机电系统和航空航天^[6-8]。激光加工微孔的效率,适合于自动化连续加工,加工孔径可小于 10 μm ,深径比可达 50 : 1 以上,并可以加工异型孔^[9]。在激光钻孔过程中,钻孔效率和孔质量主要由材料去除机制决定。通常,重铸层出现在非圆柱形孔侧壁周围,导致孔侧壁表面伴随一些不规则的微米级、纳米级结构、不完全的熔融体和残余物,产生了不均匀的微结构、晶粒、应力集中及孔壁微裂纹,从而降低了钻孔的质量,重铸层和孔壁微裂纹是激光打孔的主要缺陷^[10]。水辅助激光加工作为一种先进的制造工艺,可以有效减少或消除上述缺陷^[11]。Hwang 等^[12]用水辅助超短脉冲激光加工玻璃材料,在其内部制造三维结构。Wang 等^[13]研究了水辅助飞秒激光钻孔 4H-SiC。Iwatani 等^[14]研究了在空气和水中激光对碳化硅晶片打孔的影响,提出了碳化硅晶片通孔加工的最佳参数。Ren 等^[15]使用水辅助飞秒激光钻孔方法在氧化铝陶瓷上钻孔,获得了较低锥度的孔。不过,水的冷却作用使得熔渣聚集,造成激光束

的稳定性降低,产生的热空泡使成孔环境发生改变,使其热效应增加,这些限制了它在工业中的应用^[16]。Sun 等^[17]为了减少液体辅助激光加工过程中空化气泡的产生,采用超声波辅助水下飞秒激光在不锈钢上打孔,获得了高深径比、底部平坦的盲孔。Wang 等^[18]研究了一种采用水基超声辅助的毫秒脉冲冲击激光打孔技术,用于打孔厚度为 12 mm 的镍超合金 GH4037 板材。在实验研究的基础上,也需要采用科学的计算方法建立数学模型,以验证研究的正确性。Barnes 等^[19]采用实验与计算相结合的方法,研究了水辅助激光热冲击加工氧化铝。Zhang 等^[20]提出了电解液辅助激光加工孔形状的二维数学模型,实验与模型结果表明,电解液能有效提高打孔质量。文中主要总结了液体辅助激光微孔加工方法,探究了各种加工方法对微孔各项指标的影响,并对比了辅助加工和非辅助加工在打孔质量方面的优势,未来在某些特殊加工领域将会得到广泛应用。

1 液体辅助微孔加工方法

液体辅助激光微孔加工是在单一激光加工条件下加入了液体场,液体辅助形式主要包括改变水层

厚度、液体的种类及水射流等。为了获得更加优质的微孔, 通过将其他场与液体场叠加形成复合场或多复合场进行加工。液体辅助微孔加工的常用方法包括水基辅助微孔加工、水基-超声辅助微孔加工、水基超声-磁场辅助激光微孔加工和水射流/电解液辅助激光微孔加工。表 1 总结了辅助加工的一些材料。

1.1 水基辅助微孔加工

水下激光辅助微孔加工是在单一激光加工的基础上 (如图 1^[14]所示), 让工件浸入水中, 激光束穿过水层对材料进行加工, 通过水层来研究打孔质量的一种方法。

激光加工金属的过程按照时间顺序可以分为自由电子吸收激光能量、电子-声子能量耦合与弛豫, 以及材料的去除。当高功率激光聚焦在目标上时, 焦点处的小部分材料首先通过辐射过程蒸发和电离, 随后在目标表面形成高温高压等离子体, 通过爆炸去除材料^[28-29]。在水区域内加工时, 产生的等离子体膨胀过程受到限制, 从而引起等离子体对材料的反冲压力增加。在激光烧蚀过程中产生的等离子体吸收入射激

光脉冲能量, 导致激光与材料表面的耦合减少, 形成了等离子体屏蔽效应, 等离子体屏蔽效应取决于等离子体强度及其开始时间^[30]。弱的和延迟出现的等离子体降低了对入射激光束的屏蔽效应, 由于周围的水, 等离子体的尺寸比在空气中小得多, 等离子体在水中的寿命大约是在空气中的一半。Hong 等^[31]利用超快光电管诊断空气中等离子体产生的光信号, 并提供蒸汽帮助, 可得出结论, 水中等离子体的寿命和尺寸比空气中的短和小, 这导致其在水中的屏蔽效果较弱。也就是说, 等离子体吸收较少的入射激光能量, 更多的功率密度到达目标材料, 空化气泡是激光物质相互作用的一种特殊现象, 这种现象通常在液体中发生^[32-33], 它在流体力学和激光医学领域中起着重要的作用。当气泡在固体边界附近坍塌时, 产生高速的壁向液体射流^[34]。就热量而言, 液体的传导性比空气的传导性好, 在激光加工过程中过多的热量被水吸收带走, 因此该区域被冷却, 获得了更好的边缘。

Lu 等^[21]在空气和水中对不同厚度的铜、铁、铝, 以及不锈钢金属板进行钻孔, 通过观察发现, 在水中钻孔比在空气中钻孔需要更少的能量。通过比较扫描

表 1 液体辅助激光加工材料的用途、特性及加工方法
Tab.1 Materials' applications, properties and processing methods in liquid-assisted laser processing

Source	Materials	Material applications	Material properties	Processing methods
Iwatani et al. ^[14]	SiC	Functional ceramics	High quality thermal conductivity and wear resistance, stable chemical properties, small expansion coefficient	Underwater and non-underwater laser drilling
Zhang et al. ^[20]	321 Stainless steel	Manufacture of linings for wear-resistant acid vessels and wear-resistant equipment, transport pipes	Abrasion resistance, high temperature resistance, creep resistance, etc.	Electrolyte-assisted laser drilling
Lu et al. ^[21]	Copper, iron, aluminum and stainless steel	Wide range of uses in daily life	High quality electrical conductivity, machinability, flexibility, corrosion resistance, rigidity	Underwater laser drilling
Tan et al. ^[22]	Quartz glass	Semiconductors, medical devices, optical fibers, optical instruments.	Low coefficient of thermal expansion, high temperature resistance, chemical stability, electrical insulation	Laser drilling of the rear surface of the workpiece by immersion in pure water
Charee et al. ^[23]	Silicon	Semiconductor materials, ceramets, important materials for astronautics, optical fiber communications, etc.	Semiconductor electrical properties, large thermal conductivity and chemical stability	Ultrasound assisted underwater laser processing
Wang et al. ^[24-25]	Nickel GH4037	Aerospace, petroleum, chemical, machinery, marine, environmental protection, energy, food, etc.	High temperature strength, good resistance to oxidation, thermal corrosion, cold, thermal fatigue, plasticity and weldability, etc.	Water-based ultrasonic assisted laser processing
Yuan Gen-fu et al. ^[26]	Al ₂ O ₃ ceramics	Thick film integrated circuit	High hardness, excellent wear resistance, light weight	Laser machining hole in low pressure water jet compound field
Song Yi-zhi et al. ^[27]	0Cr18Ni9 stainless steel	Food equipment, general chemical equipment, industrial equipment for nuclear energy	High quality corrosion resistance, heat resistance, low temperature strength and mechanical properties	Electrolyte fluid assisted laser drilling

电子显微照片可见,在水中钻孔的表面形态得到大大改善。研究发现,在固体边界附近空化气泡溃灭引起的第一和第二液体射流脉冲,其幅度分别约为空气中激光烧蚀冲击的12.4倍和5.2倍。

Iwatani 等^[14]用纳秒脉冲红外激光在空气中和水下对碳化硅晶片进行了激光打孔,提出碳化硅晶片通孔加工的最佳参数为 10 J/cm^2 ,水层厚度为 1 mm ,评估了激光参数和聚焦位置的影响,发现它可以产生无碎片、无热影响区、无裂纹的通孔。实验装置如图1所示。

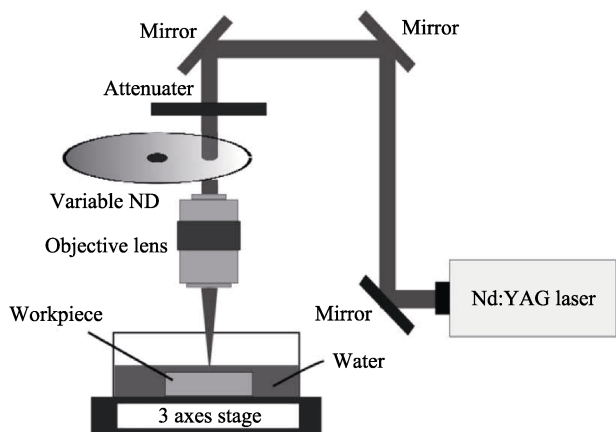


图1 水下激光打孔实验装置示意图^[14]

Fig.1 Schematic diagram of experimental device for underwater laser drilling^[14]

徐思佳等^[35]在厚度为 $350 \mu\text{m}$ 的碳化硅样品上加工了直径为 $200 \mu\text{m}$ 的微孔,通过对比实验证明,水的作用降低了加工区域的温度,避免形成热影响区,减少了氧化反应,降低了表面粗糙度,加工出的微孔侧壁较光滑。Tan 等^[22]研究了水辅助飞秒激光在石英玻璃的后表面制备三维高深宽比微通道,在厚度为 10 mm 的硅玻璃基板中产生了高纵横比为30的直微通和弯曲微通道。

通过以上研究发现,在水辅助激光加工微孔过程中,水的冷却作用可以获得更好的孔径边缘和光滑清洁的孔壁,在水层下激光冲击作用和气泡溃灭冲击对材料产生了复合冲击,使得加工效果更佳。在加工过程中调整加工参数和水层厚度可以加工出无裂纹、热

影响区和碎片的通孔。

1.2 水基超声振动辅助微孔加工

水基超声振动辅助微孔加工是一种在水下激光打孔的基础上,加入超声振动场辅助的加工方法。水下激光加工相较于在空气中加工能够有效地避免一些缺陷,但水的冷却作用使熔渣聚集,造成激光束辐射稳定性降低,产生的热空泡会使成孔环境发生改变,使得热效应增加,这些均限制了其在工业中的应用。

超声振动能够有效地改善结晶组织、细化晶粒、消除应力、减少内部缺陷和提高力学性能^[36]。材料和辐射区域周围的水迅速蒸发,这导致在激光照射区域的顶部附近形成了一些膨胀的空化气泡^[37]。气泡的持续和不可预测的膨胀和衰减动态地改变了激光束在水下的折射和散射,导致实际激光强度比没有气泡的激光弱^[38]。烧蚀表面形貌和加工性能取决于气泡的尺寸,因此消除气泡或减小气泡尺寸有助于提高加工质量^[39]。超声辅助产生的高频振动可以明显地将空化气泡破碎成更小的气泡,减小气泡对激光束的扰动^[17,40],其原理如图2所示。采用此法还可以减少加工区域的碎屑再沉积,从而产生更清洁的表面轮廓和更好的径深比。

Charee 等^[23]研究了水下激光加工硅,在硅片上加工出干净的深槽,工件在水中被激光束烧蚀的同时伴随超声振动。这会使空气气泡雾化,加快残渣的排出,与其他水下激光烧蚀方法相比,超声辅助水下激光微加工技术可以作为一种替代的微加工工艺,以获得比其他方法更高的材料去除率和更好的表面质量。

Wang 等^[24]提出了一种水基超声辅助激光钻孔技术,以提高钻孔效率和质量。通过在水介质中以均匀频率振动整个工件,改变激光参数,提升加工速率。通过研究水基超声辅助引起加工孔周围的晶体变化发现,采用超声波辅助提高了环孔周围区域的显微硬度。这主要是由于超声波辅助诱导的强化颗粒沉淀和晶粒细化引起其微观结构发生改变,如图3所示。与常见激光钻孔相比,由于螺旋钻孔的持续时间短,沉淀的强化颗粒少,热影响区中的晶粒细化未受到明显

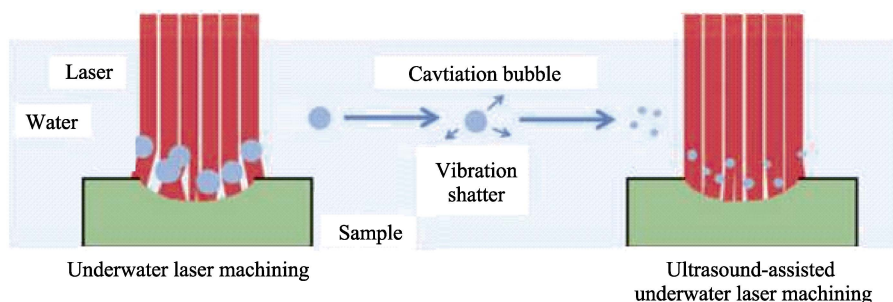


图2 超声振动破碎气泡提高激光加工质量的原理示意图^[17]

Fig.2 Schematic diagram for the principle of improving the quality of laser processing by breaking bubbles by ultrasonic-assisted vibration^[17]

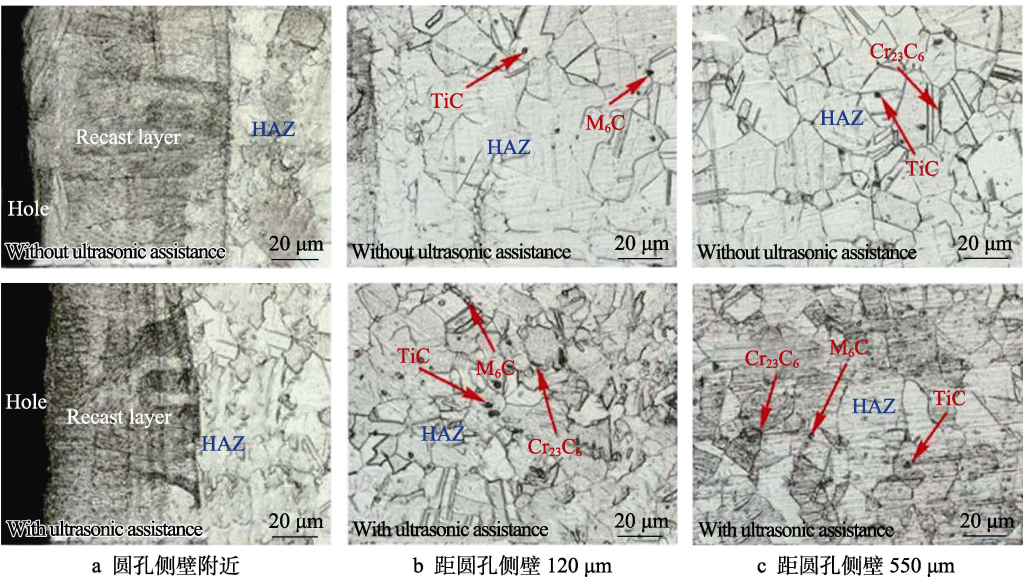


图 3 水基超声辅助毫秒激光钻孔^[24]
Fig.3 Water-based ultrasonic-assisted millisecond laser drilling^[24]: a) near sidewall of round hole;
b) 120 μm away from round hole sidewall; c) 550 μm away from round hole sidewall^[24]

的影响, 通过使用超声辅助可以明显细化热影响区中的晶粒。

综上所述, 在水基辅助的基础上, 形成了水基-超声的加工方法。研究表明, 超声场可以击溃在水下激光加工过程中产生的空化气泡, 使更多的激光束辐射到材料表面, 从而提高加工效率, 振动可以加快排出碎屑, 并使晶粒细化、强化颗粒沉淀, 从而获得质量更好的孔。

1.3 水基超声-磁场辅助激光微孔加工

水基超声-磁场辅助激光微孔加工方法是在水基加工的基础上引入了超声振动场和磁场, 将水基超声振动与外部横向磁场集成并耦合, 用于辅助冲击式激光打孔。

Wang 等^[25]研究了一种新型磁-超声-水温辅助激光打孔技术, 报道了采用水基磁场超声场辅助激光打孔技术时水温对打孔质量的影响。磁场的加入主要增强了 3 个方面的打孔性能: 减弱了等离子云对入射激光束的屏蔽作用; 增加了入射激光束打孔的有效输入

量; 增强了激光熔化金属内部电磁力引起的混合效应。水温对钻孔周围相应区域的晶粒尺寸和显微组织形貌的影响不大, 孔入口、出口附近辐射位置的硬度随着水温的升高而有所增加, 再铸层随之减少, 这有利于减小残余应力。在这种先进的磁-超声-激光技术中, 由水基超声波传播引起的均匀机械振动与用于辅助冲击激光钻孔过程的横向单向磁场耦合, 出现了等离子体衰减、微尺度流动和对流/流动的组合效应。加工通孔实验结果见表 2, 结果表明, 磁超声耦合辅助通过提高钻孔内部的激光能量吸收效率、增强材料去除、增加钻孔深度、减少重铸层形成和孔锥度, 改善了显微组织和显微硬度性能, 消除了残余应力, 残余应力降低了约 89.1%, 有效地提高了激光钻孔性能。

在以上研究中, 不断地加入更多的外加场, 对微孔加工有着积极的影响。如磁场的加入可以进一步提高金属微孔加工材料去除率, 增加钻孔深度。另外, 磁场可进一步降低残余应力。水基中水温的变化对孔附近组织形貌的影响不大, 孔口附近的硬度会随着温度的增加而增加, 达到阈值时变化不大。

表 2 加工通孔实验结果
Tab.2 Experimental results of through-hole processing

Cases	Parameters					
	Hole entrance diameter/ μm	Hole exit diameter/ μm	Taper angle/($^{\circ}$)	Through hole recast layer thickness/ μm		
				Entrance	Middle	Exit
Without ultrasonic/magnetic assistance	319.121	227.012	2.638	25.959	19.662	13.258
With ultrasonic assistance	327.421	237.355	2.58	22.92	17.189	10.111
With magnetic assistance	310.256	221.784	2.534	24.269	18.088	11.122
With magnetic-ultrasonic assistance	337.252	249.138	2.524	21.015	18.275	9.099

1.4 水射流/电解液辅助激光微孔加工

液体加工的方式大致分为 2 种, 一种为水基辅助, 通过改变加工时水层的厚度来削弱缺陷; 另一种为水射流辅助, 通过水流来辅助冲击加工孔, 水能够冷却熔渣, 在冲击作用下带走熔渣, 去除重铸层, 从而提

高打孔质量。Liu 等^[41]采用纳秒激光在同轴水射流辅助环境下对镍基单晶涡轮叶片进行气膜冷却钻孔, 实验证明可获得高质量的微孔, 如图 4 所示。电解液作为液体层或水射流, 在微孔加工过程与水的作用相似, 区别在于电解液中存在电解质, 电解液对加工材料有一定的腐蚀作用, 能够辅助材料的去除, 提高材料去除率。

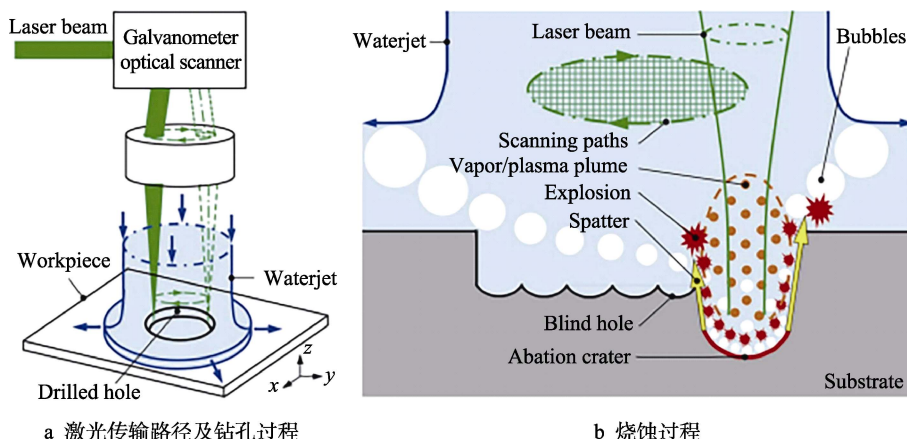


图 4 同轴水射流辅助激光钻孔示意图^[41]

Fig.4 Schematic diagram of the coaxial water jet-assisted laser drilling^[41]: a) laser transmission path and drilling process; b) ablation process

袁根福等^[26]针对 Al_2O_3 陶瓷激光打孔中存在的重铸层、微裂纹等问题, 提出低压水射流激光复合打孔方法, 有效地去除了重铸层, 减小了受热引起的微裂纹, 避免了加工过程中陶瓷温度梯度的影响导致的崩裂。如图 5 所示, 研究证实了低压水射流激光复合加工的优势和可行性。

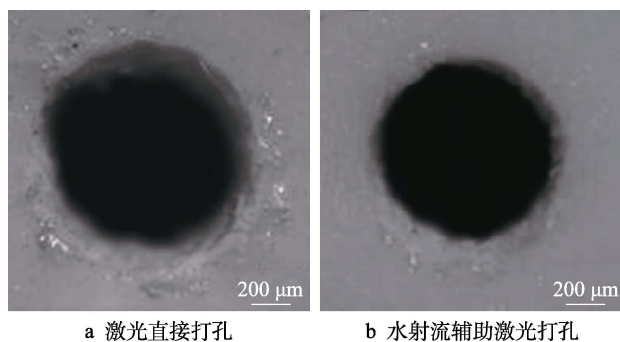


图 5 陶瓷材料的直接激光打孔与水射流辅助打孔形貌对比^[26]

Fig.5 Comparison of morphology between ceramic materials under direct laser drilling and water jet-assisted drilling^[26]: a) direct laser drilling; b) water jet-assisted laser drilling

Zhang 等^[20]提出了电解液辅助激光打孔的二维数学模型。通过对加工过程进行理论分析, 构建了电解质射流引导激光打孔的数学模型和喷射电化学加工的数学模型, 开发了一种结合激光钻孔和喷射电化学加工的新型混合工艺来提高激光打孔的整体质量。采用 321 不锈钢试件, 将激光束与电解液射流同轴, 并撞击在材料表面的相同位置。在此过程中, 电解液

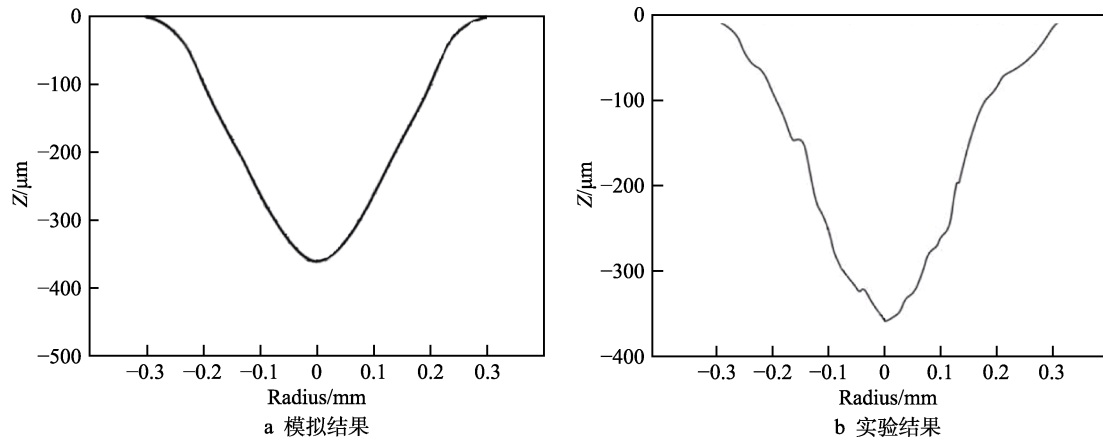
与材料表面发生了化学反应, 并腐蚀材料, 有效地冷却加工表面, 并带走了加工过程中的残渣。将模拟结果与实验结果进行对比发现 (如图 6 所示), 2 种结果的吻合性良好, 验证了此模型可行性。在电子显微镜下观察发现, 电解液辅助激光打孔能有效地去除重铸层和残渣, 并且可防止裂纹和热影响的产生。

Marimuthu 等^[42]在铝碳化硅金属复合材料上加工航空中常用的孔 (0.5~1 mm), 实验采用水射流与激光束同轴的方法。水射流激光钻孔是先进材料 (如铝基复合材料) 的最佳选择, 可以产生高质量的孔, 包括高水平的孔圆度、无热影响区和无重铸层。

宋义知等^[27]根据电解液辅助激光打孔的特点, 建立了加工过程的物理模型和数学模型, 考虑了激光束空间分布和材料相变潜热, 给出了温度场的瞬态分布和界面的演化过程。利用有限元分析软件 ANSYS 的重启和生死单元技术, 并进一步结合 APDL 编程语言, 分析了机械加工过程中的温度场。为实际加工中选择最佳参数提供了理论依据。

Hu 等^[43]提出, 将激光束和腐蚀性电解液喷射束同轴地施加到工件上, 并建立温度场的数学模型, 分析其加工原理, 研究了激光耦合电解质射流的机理, 建立了电解液水射流辅助激光打孔过程中的流场。进一步研究了激光参数、电解液浓度和电解液喷射速度对材料重铸层厚度和微裂纹数量的影响, 初步掌握了电解液喷射辅助激光微加工的基本加工技术, 为进一步研究电解液喷射辅助激光打下了基础。

根据以上研究可知, 水射流/电解液辅助激光微孔加工对加工起着冷却作用, 减小了热影响区, 水射

图 6 电解液辅助激光打孔的剖面模拟和实验对比^[20]Fig.6 Comparison of profile simulation and experiment of electrolyte-assisted laser drilling^[20]:
a) simulation result; b) experimental result

流冲击工件带走了更多的残渣, 电解液可以腐蚀某些加工材料, 从而提高了加工速率。在未来的加工实践中, 在制备不同材料的微孔时, 可以考虑材料的化学特性, 选择合适的辅助加工条件, 以提高加工效率和质量。

2 液体辅助对加工微孔的影响

微孔通常指直径小于 300 μm 的孔, 它在航空航天、医疗器械、汽车、电子封装及新能源领域具有极其重要的作用^[44-47]。目前, 微孔结构朝着小尺寸、大深径比、高表面质量和尺寸精度方向发展, 因此其加工制造成为技术难题^[48]。在研究过程中, 对比有无辅助加工条件发现, 辅助加工可以降低微孔的锥度、扩大深径比、增加圆度、减少重铸层、减小热影响区、避免微裂纹和减小粗糙度, 从而提高微孔加工的质量。

2.1 辅助微孔加工对孔锥度的影响

微孔的锥度通常用式 (1) 来计算。

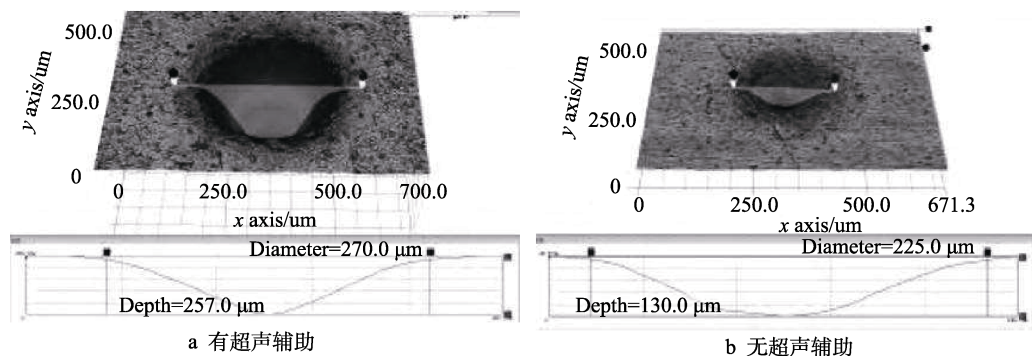
$$\theta = \arctan\left(\frac{d_{\text{ent}} - d_{\text{exit}}}{2t}\right) \quad (1)$$

式中: θ 为锥度角; d_{ent} 为孔入口直径; d_{exit} 为孔出口直径; t 为厚度。

针对水下激光打孔存在的锥度大等缺陷, 吴浩等^[49]采用水基超声辅助打孔技术对不锈钢进行打孔, 分析了超声辅助和非超声辅助水下激光打孔的三维形貌, 实验结果如图 7 所示。研究表明, 改善了孔形和壁面粗糙度, 减少了结渣, 提高了孔洞质量。在超声波辅助下, 孔洞的形态明显优于无超声波辅助下的孔洞形态。

针对基体热变形大、微孔锥度大、孔形貌均匀性不足等问题, 朱帅杰等^[50]提出了水辅助激光微孔加工方法。该方法利用水进入微孔时的毛细现象、光管效应、水压作用、水的空化效应和冷却作用, 提高了孔的质量。实验结果表明, 在相同的工艺参数下, 后表面水辅助法生产的微孔再铸层减少, 热影响区减小, 过滤器变形减小, 改善了微孔的一致性。激光钻孔的示意图如图 8 所示。

Ren 等^[15]使用水辅助飞秒激光钻孔方法在氧化铝陶瓷上钻孔。研究了孔的形态、直径、锥度、横截面积和侧壁特征, 并将在空气存在下获得的孔特征与在水辅助下获得的孔特征进行了比较。在水辅助下, 锥度减小了 64.19%, 达到 4.20°, 孔横截面积增加了 46%。此外, 水辅助可以减少孔侧壁上的残留碎片和烧蚀材料的再沉积, 并且在孔出口附近的孔侧壁上基

图 7 超声辅助对水下激光成孔三维形貌的影响^[49]Fig.7 Effect of ultrasonic assistance on three-dimensional morphology by underwater laser drilling^[49]:
a) with ultrasonic assistance; b) without ultrasonic assistance

本无残留碎片和烧蚀材料再沉积。锥度与频率曲线如图9所示。

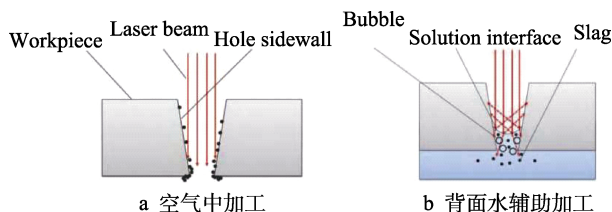


图8 水辅助激光打孔示意图^[50]

Fig.8 Schematic diagram of water-assisted laser drilling^[50]: a) processing in air; b) water-assisted processing on back side

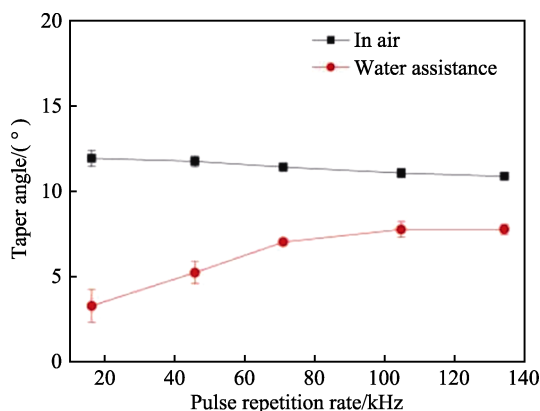


图9 脉冲频率对飞秒激光在空气和水中钻孔锥度的影响^[15]

Fig.9 Effect of pulse frequency on taper of femtosecond laser drilling in air and water^[15]

2.2 辅助微孔加工对孔深径比的影响

深径比即微孔的深度与直径的比值,是衡量加工微孔质量的重要标准。德国 Rofin-LASAG 公司利用飞秒激光实现了深径比达 100:1 的微孔加工^[51]。大的深径比一直是微孔加工技术的难点和重要的质量评价标准。

Krstulović 等^[52]在水和空气中对铝块体样品进行了脉冲激光烧蚀,研究了激光打孔中水层厚度对孔体

积和深度的影响。实验结果表明,在空气中,由于烧蚀材料的迅速冷却后再凝固和再沉积,抑制了打孔。在水的约束下,铝靶的钻孔效率更高,孔体积增加了 28 倍,孔深度增加了 18 倍,避免了在孔口形成火山口形态和材料再沉积,孔口表面更加光滑,通过改变水的厚度可以进一步提高打孔效率,如图 10 所示。这使得水下获得的孔在粗糙度、形状、体积和再现性方面具有更好的特性。

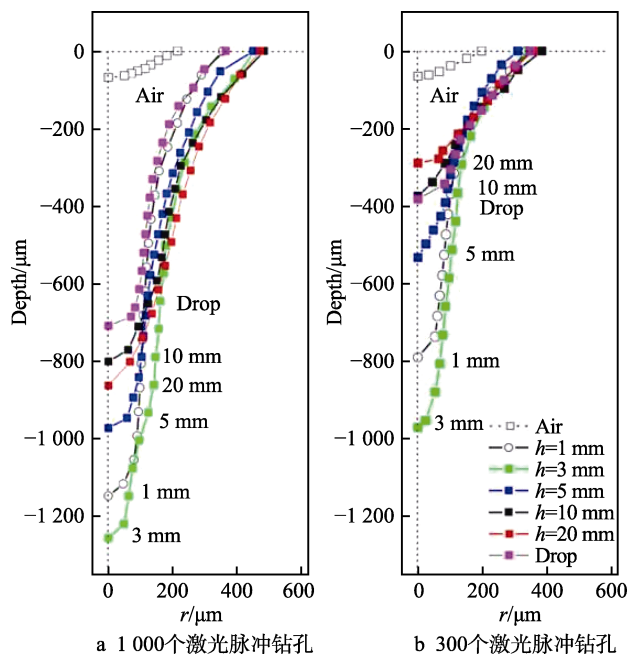


图10 不同水膜厚度下获得的激光钻孔半剖面示意图^[52]

Fig.10 Schematic diagram of half-section obtained by laser drilling under different water film thickness^[52]: a) with 1 000 pulses; b) with 300 pulses

Sun 等^[17]为了减少液体辅助激光加工过程中的空化气泡,采用超声波辅助水下飞秒激光在不锈钢上打孔,这种方法大大减小了空化气泡的光学扰动。通过分析激光参数对孔形貌的影响发现,超声波可以形成底部干净、平坦的孔,并且减少加工区域周围的碎屑再沉积,深径比提高了约 20%,钻孔轮廓如图 11 所示。

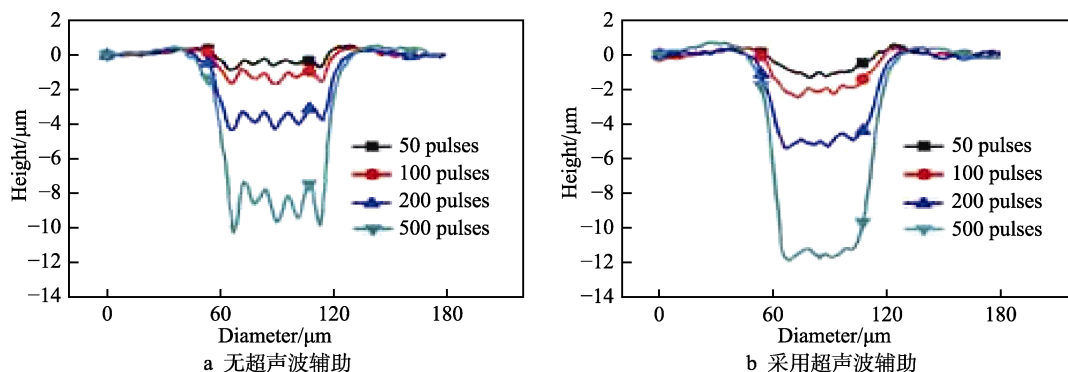


图11 超声波辅助水下飞秒激光钻孔效果对比^[17]

Fig.11 Comparison of ultrasonic-assisted underwater femtosecond laser drilling effects^[17]: a) without ultrasonic assistance; b) with ultrasonic assistance

胡坤等^[53]利用纳秒激光在空气和近轴水射流辅助下, 对 In 718 高温合金进行了单脉冲激光打孔。由于水流的冷却作用和冲击作用, 提高了激光打孔的去除效率, 获得了孔径更深、表面更光滑的微孔, 如图 12 所示。激光加工孔的截面轮廓表明, 2 种情况下加工孔的底部均为锥形, 这与激光能量的高斯分布有关。在相同的工艺参数下, 水射流辅助激光可以加工较深的孔洞, 且孔洞内表面质量较好。

2.3 辅助微孔加工对孔其他指标的影响

在辅助微孔加工过程中主要研究的指标是孔进出口的圆度、锥度、深径比, 其他指标有毛刺、飞溅、裂纹、重铸层再沉积和应力集中等, 它们对微孔质量也有一定的影响。

Lv 等^[54]在空气和水中对铬镍铁合金 718 样品进行了钻孔, 采用共聚焦激光扫描显微镜和扫描电子显微镜分析了表面、横截面和壁内形态。在空气中钻孔时, 随着材料去除量的增加, 孔表面的熔化凝固区域变得越来越大。当在水下使用不同的脉冲能量处理时, 飞溅很少, 孔径周围毛刺、飞边明显减少, 这可以归因于水的作用。加工后获得的盲孔形貌如图 13

所示。

Wang 等^[55]采用一种超声辅助激光打孔技术在镍超合金样品上加工盲孔和通孔, 通过对比发现, 超声振动对孔再铸层和力学性能有着积极的影响。在无超声波辅助的情况下使用相对较小的辅助气体压力的深盲孔, 由于飞溅、流动、排出动量、能量有限, 加上熔化材料和液滴有一定的重力, 孔底附近的重铸层通常比孔中部附近的重铸层厚。另外, 由于水引起的底部覆盖和冷却效应, 更多的熔融金属将在孔侧壁上重新固化, 特别是在再铸层形成的孔出口附近。在有超声振动时, 熔融材料和液滴可以获得额外的能量和动力用于排出、飞溅和流动。当增大超声波功率时, 更多的熔融材料将被移除, 并从盲孔底部向上喷射出熔融流。重铸层减少的百分比大约为 15.73%~31.82%, 再铸层附近的热影响区会诱导晶粒细化和强化颗粒及相的析出, 硬度大约提高了 19.43%, 硬度的提升会减小应力集中。

如表 3 所示, 研究人员采用不同加工方法和加工参数, 导致微孔的锥度、深径比, 以及其他参数有所不同。可以根据加工要求的不同, 改变加工方法和加工参数来得到高质量的微孔, 这些加工方法对微孔加工具有指导意义。

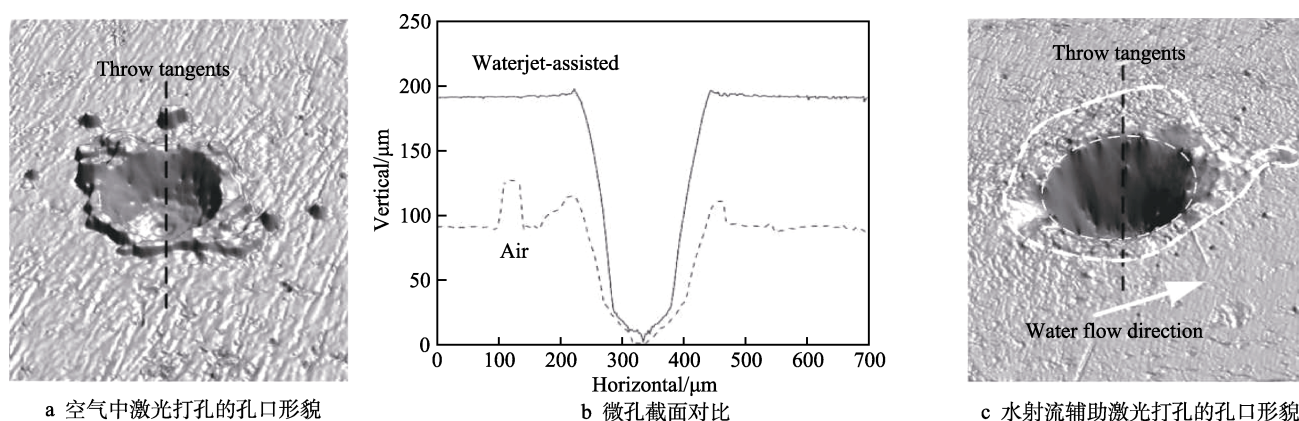


图 12 In718 高温合金单脉冲激光打孔对比^[53]

Fig.12 Comparison of single pulse laser Drilling for In718 superalloy^[53]: a) aperture morphology by laser drilling in air; b) comparison of micro-hole sections; c) aperture morphology by water jet-assisted laser drilling

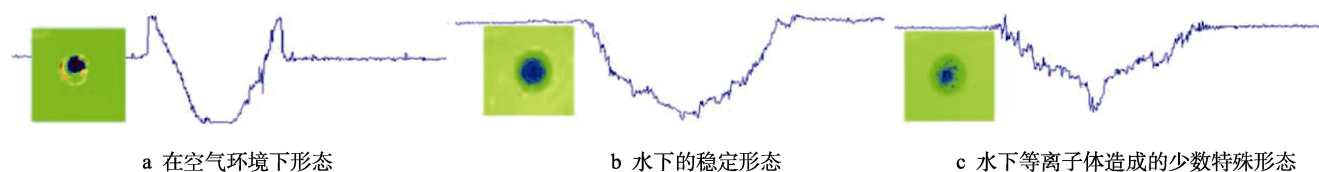


图 13 采用共聚焦显微镜获得的铬镍铁合金 718 样品在不同环境激光钻盲孔的形态^[54]

Fig.13 Morphology of blind holes drilled by laser in Inconel 718 samples obtained by confocal microscope under different environment^[54]: a) morphology in air; b) conventional morphology under water; c) special morphology caused by underwater plasma

表 3 微孔加工方法及评价指标
Tab.3 Micro-hole processing method and evaluation index

Source	Taper	Ratio of depth to diameter	Other indicators	Processing method
Ren et al. ^[15]	4.20°	—	The cross-sectional area of the hole is increased by 46%, the hole wall is clean, and there is almost no re-deposition	Water-assisted femtosecond laser drilling
Sun et al. ^[17]	—	20% increase	No burrs, splashes, recast layer, flat bottom	Ultrasonic assisted underwater femtosecond laser drilling
Wu Hao et al. ^[49]	Reduced	Increased	No obvious recasting layer, smooth surface	Ultrasonic assisted underwater laser drilling
Zhu Shuai-jie et al. ^[50]	Reduced	Increased	Reduced recast layer and suppress thermal deformation	Water-assisted laser micro-hole processing on the back
Krstulović et al. ^[52]	—	Increased	The recast layer is reduced, and the depth and volume of the hole are increased	Laser drilling underwater and in air
Hu Kun et al. ^[53]	—	Increased	Recast layer avoided, smooth surface	Air and paraxial water jet assisted laser drilling
Lv et al. ^[54]	—	—	Reduced debris and splashes, smooth hole walls, and increased hole depth	Laser drilling in air and water
Wang et al. ^[55]	—	—	Recast layer reduced to 31.82%; the hardness increased by 19.43%	Water-based ultrasonic assisted laser nesting

Note: "—" means there is no such item in the literature.

3 结语

综上所述,液体辅助激光加工微孔与传统单一激光加工微孔相比,在某些特定场合下具有明显的优势,水的冷却作用可以降低热影响,改善重铸层、裂纹等问题,防止残渣飞溅和孔口毛刺,水基辅助场可以有效地消除激光加工过程中的缺陷。水的冷却作用使得熔融残渣聚集,这会降低激光辐射度,同时会产生空化气泡。在水基辅助激光打孔的方法上加入超声振动场,由于超声振动可以打破水下激光打孔过程中产生的空化气泡,减小对激光束的搅动,因此可以提高深径比,获得平坦底部。超声波辅助引起高频均匀振动,有效地提高了材料的去除量和加工速率,减少孔壁流动的熔融金属再凝固,进一步减少重铸层。此外,还会引起加工孔周围晶体发生变化,诱导强化颗粒沉积和晶粒细化发生微观机构变化,能够提高孔周围区域的硬度,降低残余应力。将新型水基超声振动与外部横向磁场集成并耦合,由于水温可调,因此磁超声耦合提高了材料对激光的吸收率,进一步提高了材料去除率,增加了打孔深度。水基温度的升高提高了孔口附近的硬度,减少了重铸层的形成,减小了孔锥度,改善了显微硬度性能,磁场的加入使得残余应力的降低率更大,有效地提高了激光钻孔性能。水射流/电解液辅助激光打孔的液体种类有 2 种:水、电解液。在液体为水时,水可以起到冷却作用,并且冲击工件,带走更多的残渣。在液体为电解液时,与水相比,电解液对加工材料有腐蚀作用,会增加其加工

速率。

目前,液体辅助激光打孔是一种新型打孔技术,在精密加工方面具有一定优势,但也存在一定的局限性,可以从以下方面进一步思考研究。

1) 液体辅助加工中除水的辅助还有其他场的介入,如水下超声振动辅助和水下超声-磁场辅助等。这说明液体辅助加工可以通过多能量场来完成加工,具有积极的作用。从此方面可以看出,采用复合能量场来辅助加工是一种趋势,对制造业有一定的指导意义。

2) 电解液辅助激光微孔加工是在水辅助基础上根据加工材料的化学特性衍生出来的新型加工方法。考虑加工材料的物理化学特性,可以进一步精确辅助加工。

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