第 51 卷 第 4 期/2024 年 2 月/中国激光 特邀综述

中国激光

超声复合激光制造技术研究进展(特邀)

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摘要 超声复合激光制造技术通过施加外部超声以提升激光制造的加工能力与质量,已成为国内外研究热点。分析了当前超声复合激光制造技术涉及的耦合机理,并综述了超声在激光制造过程中的作用机制。根据超声振动模块与基体的接触模式将超声引入方式划分为固定接触式、移动接触式、非接触式,并分别阐述三种超声引入方式的优势与缺点。进一步,从增材、等材、减材制造三个方面全面讨论了不同超声引入方式和不同激光制造技术相结合的超声复合激光制造技术,探讨了不同复合制造技术的原理和技术特点,归纳了超声振动在激光制造过程中的影响规律。在当前研究进展基础上对超声复合激光制造技术的发展方向进行了展望。

关键词 激光制造;复合制造;超声振动;耦合机制;超声引入方式

中图分类号 TN249 **文献标志码** A **DOI:** 10.3788/CJL231534

1 引 言

激光制造技术在我国经济体量大、应用场景多的军用与民用制造业领域发挥着重要作用,服务于国家关键领域制造需求和国民经济主战场。五部委联合印发的《加强"从0到1"基础研究工作方案》[1](国科发基〔2020〕46号)中将"3D打印和激光制造"列为国家科技计划突出支持关键核心技术中的重大科学问题。激光作为加工手段具有非接触、选区可控的突出优势,但非接触的特性也使得加工区域欠缺外力作用,在增材制造中难以调控熔池流动,而在减材加工中易导致材料去除后的堆积,对激光制造的控形控性带来挑战。

为此,激光复合制造技术逐渐受到国内外学者广泛关注,该技术在激光制造过程中同步耦合或异步协同地施加外部能场(如电、磁、声、热等),实现对材料缺陷抑制与形性调控,产生"1+1>2"的加工效果[2]。其中,超声能场兼具体积效应与表面效应,既能在固态材料中实现应力叠加、冲击振荡以及声软化[3],也能在半固态/液态材料中通过声空化和声流效应影响流动与凝固行为[4],进一步提升制造过程中的形性调控能力。同时,超声作用和激光加工均具有选区可控的特点,便于与其他制造工艺灵活高效地复合或叠加。

本文以超声-激光复合能场对加工区域的作用机制为切入点,概述了当前激光制造过程中常见的超声耦合方式及相应作用装置。在此基础上,综述了近年来增材、等材、减材制造过程中典型的超声复合制造技术研究现状,分析超声的引入方式、作用机理及其加工效果,并就该技术发展过程中当前面临的挑战与行业的发展趋势进行了展望。

2 超声-激光复合能场对加工区域的作用机制

激光可使加工区域急热骤冷,作用时间极短,导致非平衡固态相变、固液相变或汽化烧蚀。为达到对激光加工效果的调控,须在激光加工过程同步施加外加能场或协同其他工艺。超声场能够引起介质中粒子之间强烈的相对运动,对于作用区域产生声辐射力、黏滞力、惯性力等额外的高频作用力,进而促使声场中的粒子在力的作用下引发一系列物理现象[5]:在流体中表现为空化与声流效应,引起局部射流并加速对流;在固体中表现为激烈的粒子碰撞,促进分离与排逸,也可进行应力和组织调控。

激光辐照可导致材料发生固液相变形成熔池,进而开展增材制造或焊接成形。将超声同步作用于熔池,在制造过程中产生空化效应和声流效应[6],这两种非线性效应显著影响熔池中的对流和凝固过程。空化效应在熔体内部声压达到空化阈值时产生[7],空化泡在熔池正负压交替变化作用下不断膨胀、压缩,最终空

收稿日期: 2023-12-16;**修回日期:** 2024-01-22;**录用日期:** 2024-01-29;**网络首发日期:** 2024-02-02

基金项目: 国家重点研发计划(2023YFB4604300)、国家自然科学基金(52175443,52205221)、浙江省"领雁"研发攻关计划(2022C01117)

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化泡溃灭产生瞬时高温、高压[8]，瞬态高压导致液相过冷、枝晶断裂或破碎[9]，影响对流换质[10]。声流效应是液体介质吸收声波振动的动量从而稳定地产生流动，超声沿传播方向形成声压梯度促使液体介质发生快速流动，加剧熔体搅拌，促进熔池整体温度及元素等分布均匀性[11]。空化效应与声流效应之间存在着耦合，由空化导致的破碎枝晶在声流的作用下可在熔池中扩散，有效促进晶粒异质形核与生长[12]。超声能够降低熔池整体温度梯度，使得熔池内黏度分布更为均匀、声压梯度更为平滑，有助于减少超声能量传递衰减，从而有效促进熔池凝固、晶粒形核与生长。

激光加热软化会使材料表面变得更加可塑，并且软化后的材料在高温下晶体结构和组织排列更容易发生变化。超声振动周期性地加载和卸载引起材料塑性变形和再结晶，分子间的相互作用变弱，材料的分子结构发生解聚的效果，材料内部应力场发生改变，残余应力显著降低。超声可降低位错攀移的能量阈值，促进亚晶界的形成，且超声引起的局部应变和晶格畸变将为再结晶行为提供驱动力，内部引发剧烈的再结晶晶形成等轴晶带[13]。因此在超声的作用下位错累积发生改变，位错强化引发固溶强化、晶界强化和第二相强化及弥散强化。

当采用激光进行金属/非金属材料去除时，高能量激光束可直接引起材料的物态变化，发生溶解、熔化或蒸发，起到去除表面污染物或产生精细结构的作用。超声引起高频振动及辐射压力在熔体中形成有效的搅动驱动熔体溢出，显著降低熔体的表面张力和摩擦力[14]，一部分熔体汽化重新凝固形成碎屑，一部分熔化凝固外溅形成熔渣，超声振动的动量转移到这些颗粒上，以高速迸射的形式逃逸材料表面，进而改善材料去除区域表面质量。并且由于碎屑熔渣被及时清除，激光束在加工区域不再受到熔体遮蔽，提高了激光加工的效率。

3　激光制造过程中的超声耦合方式及其装置

目前，超声复合激光制造过程采用了多种不同的超声振动装置以及引入方式，超声振动装置通常包括超声发生器、超声换能器、变幅杆等元件，需要根据特定的应用场景和作用目标来进行定制化设计。超声的产生方式为通过超声发生器生成高频电信号，再通过超声换能器将电输入转化为机械振动，呈现往复伸缩运动，变幅杆将换能器的输出振幅进一步放大，最终超声波以传导或冲击的形式传递到目标点位，实现超声振动与激光制造的耦合。超声以不同的方式引入到激光增材制造(AM)、等材制造(FM)、减材制造(SM)三种制造方式中，不同的引入方式涉及到超声振动装置的区分，根据超声振动装置与工件之间的接触情况，可以将引入方式分为三类：固定接触式、移动接触式和非接触式，如图 1 所示。

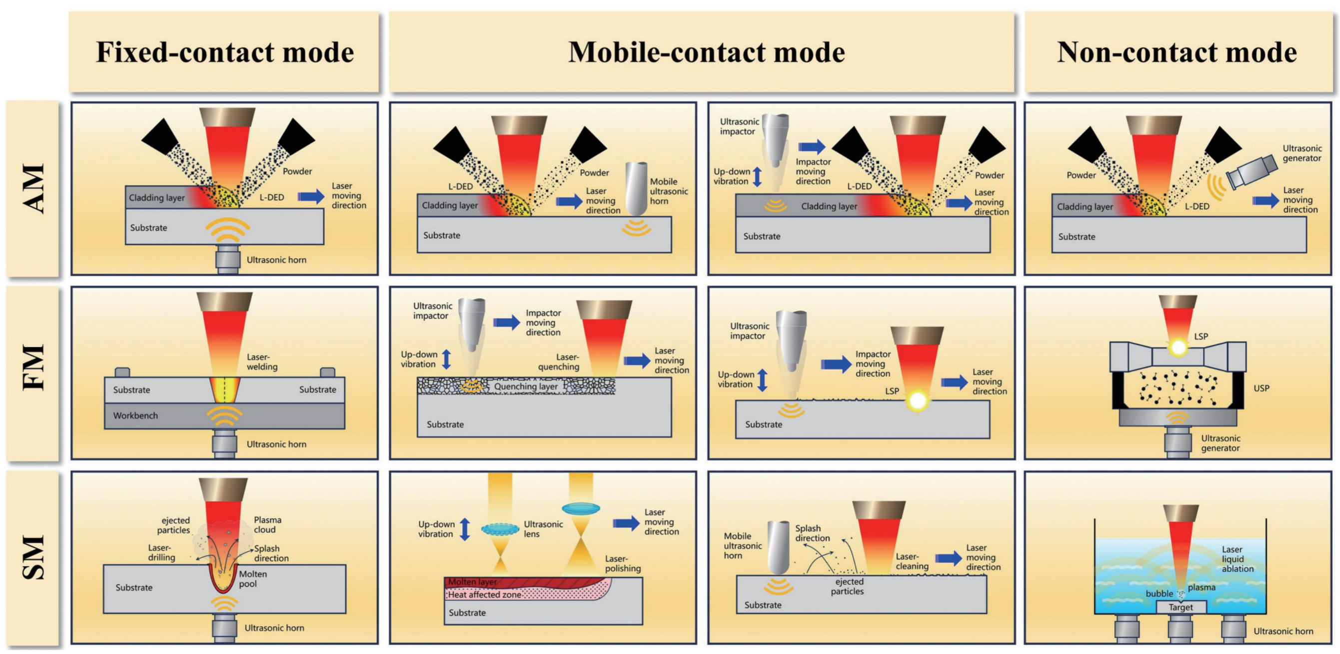

图 1　激光制造过程中的超声耦合方式及其装置示意图

Fig. 1　Diagram of ultrasonic coupling modes and devices in laser manufacturing process

固定接触式通常采用螺钉或夹具等紧固件将工件与变幅杆相互连接，使工件表面与变幅杆始终接触，超声波从变幅杆经过工件以垂直或平行的方向传递至目标点位。由于超声波在紧固件与变幅杆/基体结合界面时会发生衰减，因此紧固件的连接可靠性对超声传输十分关键。由于该引入方式引入的超声波在工件内传导稳定、持续、可控，能够使熔池中形成稳定的声流，驱动熔体持续振荡，因而该方式在基础研究中被广泛

采用。

移动接触式的超声振动装置以无固定连接或移动的方式与工件或器件接触，例如超声振动装置与工件表面通过一定的压力发生接触，将超声头和激光头固定于同一机械手上，保持相对位置实时同步移动[15-16]，或超声头将超声波从工件侧边引入[17]，这种非固定的接触形式由液压或气动装置施加恒定压力以保持超声头与基体之间的声能传导，可见变幅杆与基体间的有效接触是超声引入基体的关键[18]，然而该方式下超声头和工件表面断触的现象难以完全避免。超声冲击通常以后处理或同步后处理的形式对激光制造后的工件表面冲击锻打，引发材料的塑性变形和晶粒细化，从而提升材料的结构和性能。

非接触式是指超声振动装置未与工件直接接触，而通过空气、水等介质将能量传递至工件。超声波以空气作为媒介传播时能量衰减严重，振动能量难以准确作用于目标点位[19]，因此变幅杆末端与工件的距离是影响超声激光耦合有效性的关键因素。超声波以水等液体为介质传播使整个工件上产生高频均匀的振动[14]，有助于加剧液体中的空化效应，降低加工区域的热效应，但存在声能衰减和散射的影响，同时由于液体流动和气泡产生溃灭的不稳定性和复杂性，难于定量分析。超声波以固体颗粒为介质传递振动，将超声振动传递到一定数量的弹丸中，使这些弹丸重复和随机高速冲击工件表面，导致工件表面被加工硬化[20]，运用于激光制造后强化后处理。

无论是接触式还是非接触式的引入方式，它们都在超声复合激光制造领域中发挥着关键作用，为不同工件的处理提供了灵活性和效率。同时，在复合制造工艺过程中，也要考虑到工艺参数的细致调整和优化，以提升制造效果。

4 不同复合制造工艺中的超声作用效果及其机制

为探究超声-激光耦合作用机制，针对增材制造、等材制造和减材制造三类制造方式，分别归纳了超声振动的作用效果及其影响规律。在同一类型的激光制造技术中，超声振动的作用机理有共通之处。例如：在增材制造中，尽管材料的添加方式与超声的引入方式各异，但超声振动以影响熔池流动和凝固行为为主；在等材制造中，超声振动通常作用在固体表面，影响残余应力分布，从而增强成形质量；在减材制造中，超声振动的引入可显著促进材料去除。超声振动在不同激光复合制造工艺中产生的作用效果如表 1 所示。

表 1 超声复合激光制造过程中超声振动的作用效果

Table 1 Effects of ultrasonic vibration in ultrasonic assisted laser manufacturing processes

Affected behavior	Effects of ultrasonic vibration
Solidification behavior	Accelerate the flow of molten pool[21-22] Promote the convective heat transfer of the molten pool, reduce the temperature gradient and increase the cooling rate[23-25] Promote the uniform distribution of elements and inhibit the precipitation of hard and brittle phases[15,26-27] Break dendrites and refine grain size[4,28-29]
Defect formation	Inhibit the formation of pores, cracks and other defects, improve density[30-31]
Particle distribution	Improve the local aggregation of particles and improve the uniformity of particle distribution[32-33]
Residual stress	Realize the transformation of residual tensile stress to compressive stress[34-36]
Dislocation	Induce entanglement of long-range and short-range dislocations around and inside the grain boundaries[37-38]
Surface quality	Promote the debris separation, break surface oxide, and improve surface quality of the formed parts[14,39]
Forming accuracy	Acoustic softening increase the plastic flow ability and decrease yield stress of the materials, improve forming accuracy[40]
Mechanical property	Improve the hardness, wear resistance, toughness, plasticity, and other properties of the formed parts[41-45]

4.1 超声复合激光增材制造

4.1.1 *超声同步复合激光能量沉积技术*

激光定向能量沉积(L-DED)技术凭借其高灵活性，被用于表面改性、增材修复和涂层制备[46]，在该工艺中可采用材料体系设计如添加稀土元素、活性元素[47-49]或优化工艺参数[50-51]等方法来提高涂层质量。由于增材制造过程中快热和快冷的特点，易产生气孔、夹杂和微裂纹等缺陷[52]，并且容易产生柱状晶导致微观组织各向异性降低机械性能，而超声的引入为解决上述问题提供了新的思路[4,25]。

Todaro等[4]采用超声复合激光能量沉积技术实现了柱状晶向粒径约为 100 μm 的细小等轴晶的完全转变，提升了 Ti-6Al-4V 力学性能。Xiao 等[53]发现增大超声功率能够增厚基材与非晶态涂层之间的梯度结晶结构，结晶区能够释放内应力抑制涂层开裂。Wu 等[15]研究发现超声对链状金属间化合物的破碎能

够有效地阻止裂纹的扩展。Zhu 等[26]采用高强度超声使 Laves 相发生了较大程度的破碎，并发现超声对过冷度和瞬时高压的影响随振幅和频率的增大而增大，过冷度的增加又伴随着自由能差的增大，从而进一步促进晶粒的固相成核[18,26]，起到晶粒细化的作用。作者团队在该领域也开展了研究工作[25,31-32]，图 2 结果表明：空化泡破裂产生的高压使局部熔点和过冷度增加，同时，在声流作用下热对流增加，促进了温度梯度的减小，两者共同促进等轴晶粒的形成[25]；三维振动引入的能量可以促进固溶强化，减小初生枝晶间距，进而增加显微硬度并提高硬度均匀性[32]；在振动的作用下，熔池中气泡上升速度加快，气泡内部压力增加导致气泡破裂，有助于降低孔隙率[31]。此外，超声振动不仅会改变金属或合金熔体的凝固组织，抑制元素偏析和有害相的析出[15]，还会影响熔体中原位析出第二相粒子的形核及生长行为，采用超声复合激光沉积制备原位陶瓷颗粒增强金属基复合涂层的过程中，超声振动可增加活化原子数量、促进原位反应进行，增加第二相粒子形核率，并且对改善陶瓷颗粒的润湿行为和促进细小粒子的弥散分布等方面具有良好作用效果。

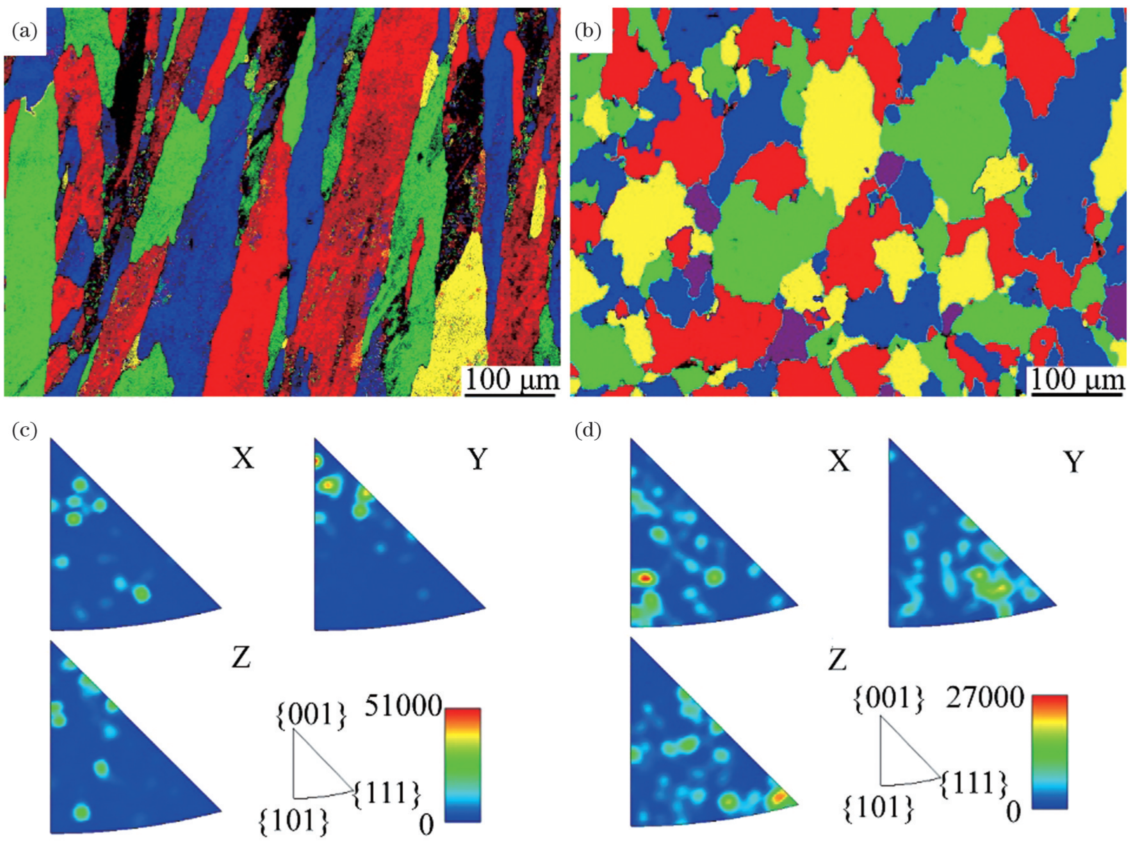

图 2　316L 有无超声电子背散射衍射分析[25]。(a)无超声晶粒分布；(b)有超声晶粒分布；(c)无超声反极图；(d)有超声反极图

Fig. 2　Electron backscattered diffraction analysis of 316L with or without ultrasound[25]. (a) Grain distribution without ultrasound; (b) grain distribution with ultrasound; (c) inverse pole figure without ultrasound; (d) inverse pole figure with ultrasound

超声在金属熔体中产生的声空化效应和声流效应能改变金属凝固过程中的结晶行为，促使液相过冷度增加并促进固相成核，进而改善组织结构，降低孔隙率，抑制裂纹萌生[18,23-24,26]。因此，激光能量沉积过程中同步施加到熔池内的超声振动将直接影响熔池的流动和凝固特性，进而实现对熔覆层组织的调控[18,23,26]。如图 3 所示，超声波在熔池中能引发声空化、声流效应等物理现象，空化泡溃灭产生的微射流可以破碎枝晶和晶间化合物聚集区，促进液相凝固组织晶粒细化[4,28]。超声在凝固过程中改变过冷度和形核率，同时温度梯度、凝固速度和冷却速度均呈下降趋势，这种效应将促进熔池凝固后晶粒组织细化[26]。振幅随着超声功率的增大而增大，将使熔池更容易达到空化阈值产生空化效应，并且空化泡溃灭产生的瞬时高压增大从而增大空化泡破裂的冲击力，更有利于晶粒细化[26]；增大频率同样将引起频繁强烈的破碎效应，促进颗粒尺寸进一步减小。超声的空化效应将提升过冷度和形核率，在激光增材制造的熔池凝固初期，陡峭的温度梯度限制了固液界面前沿的成分过冷[54-55]，而施加超声后固液界面前的温度梯度降低了约 50%，增加了生长晶粒前的成分过冷[24]。高强度超声产生的空化效应破碎了枝晶，为凝固提供更多的有效形核粒子，同时较大的成分过冷区将保证空化产生的微晶远离固液界面不被重熔。

超声对熔池的影响机制复杂，金属熔池内部行为的演化过程难以实时观测，因此通过数值模拟对超声

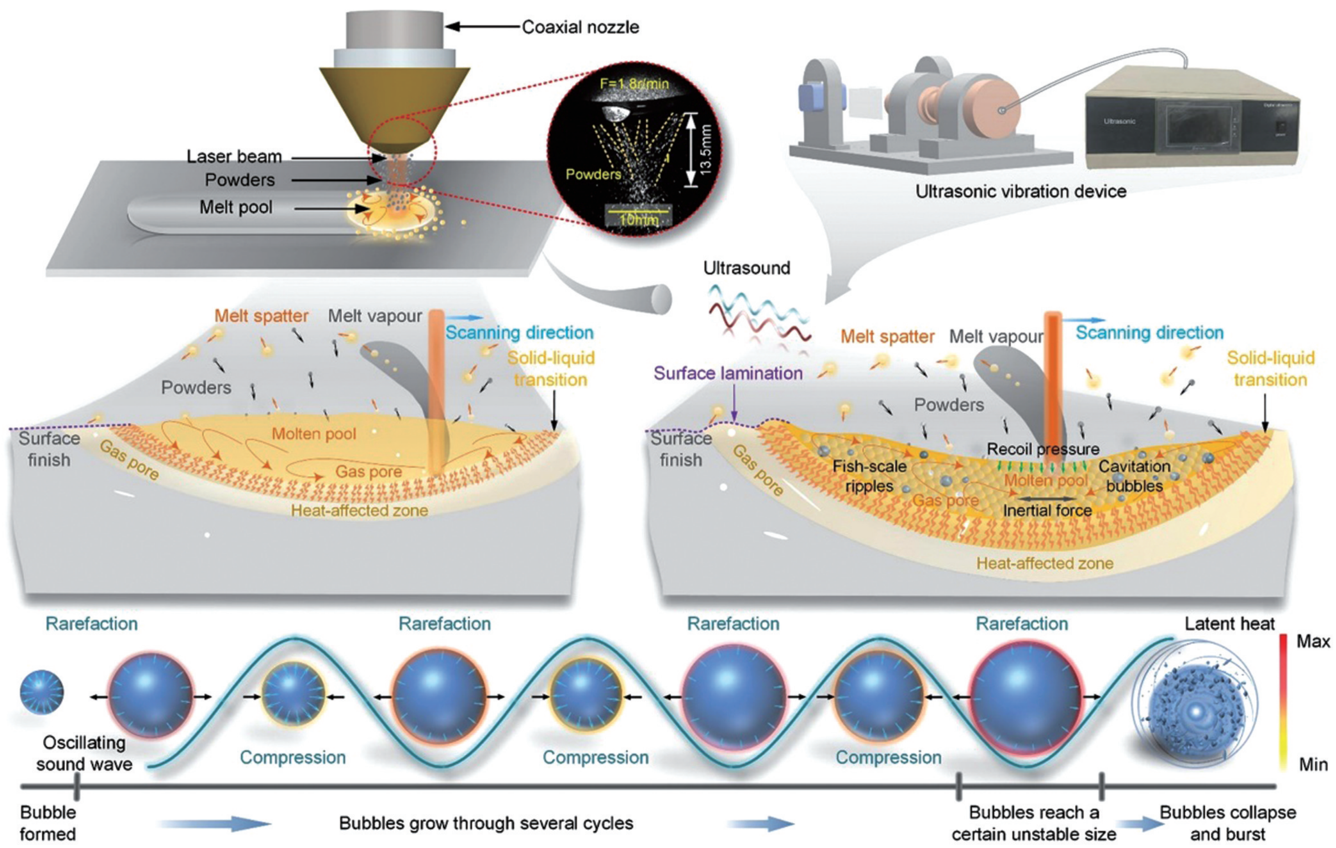

图 3 L-DED 过程中多尺度多物理现象示意图[28]

Fig. 3 Schematic diagram of multi-scale and multi-physical phenomena in the L-DED process[28]

施加后熔池内部的温度场、流场、凝固行为进行研究成为揭示超声作用机制的有效方法之一[28]。采用元胞自动机法建立的熔覆轨迹轮廓和温度场计算模型[56]为优化超声复合激光熔覆工艺、减少微缺陷、提高熔覆层质量提供了重要的理论依据。基于相场法的单晶和多晶凝固生长的变化规律，定量分析了超声振动差异化分布对熔池定向凝固行为的影响[52]，有助于缩短涂层组织调控研究周期。如图 4 所示，对超声复合 IN718 熔覆过程熔池流动行为的数值分析[28]揭示了表面鱼鳞纹的形成与超声作用下的对流有关，糊状区流动应力接近材料的屈服强度，促进枝晶臂疲劳断裂，进而细化晶粒。

4.1.2 超声同步复合激光粉末床熔融技术

激光粉末床熔融（L-PBF）技术，目前被广泛应用于快速制造复杂构件，L-PBF 制造的金属零件在力学性能方面常表现出各向异性[9]和较高的残余应力[57]。为了进一步提升性能，以引入超声来克服性能缺陷的激光复合制造技术正在兴起[58]。

Yan 等[59]采用如图 5 所示工艺，研究了超声功率范围以减小超声对粉末床的影响，在超声波作用下熔池扰动更加强烈，实现额外的搅拌效果[60]，获得更平滑的熔融轨迹。同时，声流和空化的作用增强了熔池中的混合、晶体分散和成核，有利于晶粒细化和材料成分均匀[61]。如图 5(b)、(c)所示，超声振动激光粉末床熔融制备合金的平均晶粒尺寸由 80.91 μm 减小到 53.02 μm，晶粒细化提升了零件的综合力学性能，避免了激光粉末床熔融技术中零件易出现的各向异性问题。

除了将超声导入熔池外，超声也可与送粉器耦合，构成超声波驱动粉末分配装置。该方法可将多材料粉末根据预设沉积至指定位置，辅助粉末分配和铺粉[62-63]。英国曼彻斯特大学研究团队研制了多喷嘴超声粉末沉积方法，用于 Cu/H13 粉末的选择性激光熔化[64]。依靠多通道超声选择性粉末输送系统可实现复杂的空间梯度功能材料金属部件的 3D 打印，粉末材料密度和材料组成百分比对粉末颗粒流动性有显著影响[65]，同时粉末颗粒的流动性、振动加速度产生的分配力和反作用力将显著影响粉末分配的稳定性[66]。

4.1.3 超声冲击协同激光增材制造技术

超声除了能对熔池进行直接调控以外，在改善增材制造件非平衡微观结构、高残余应力、微孔甚至裂纹等缺陷的后处理工艺中也发挥着重要作用[41-43]。经激光增材制造后的样品在表面进行诸如超声冲击等后处理工艺可实现对材料非平衡作用下的深层强化、缺陷抑制与形性调控。并且通过有限元分析可得到优化的增材制造和超声后处理工艺参数，进一步指导超声冲击晶粒细化。

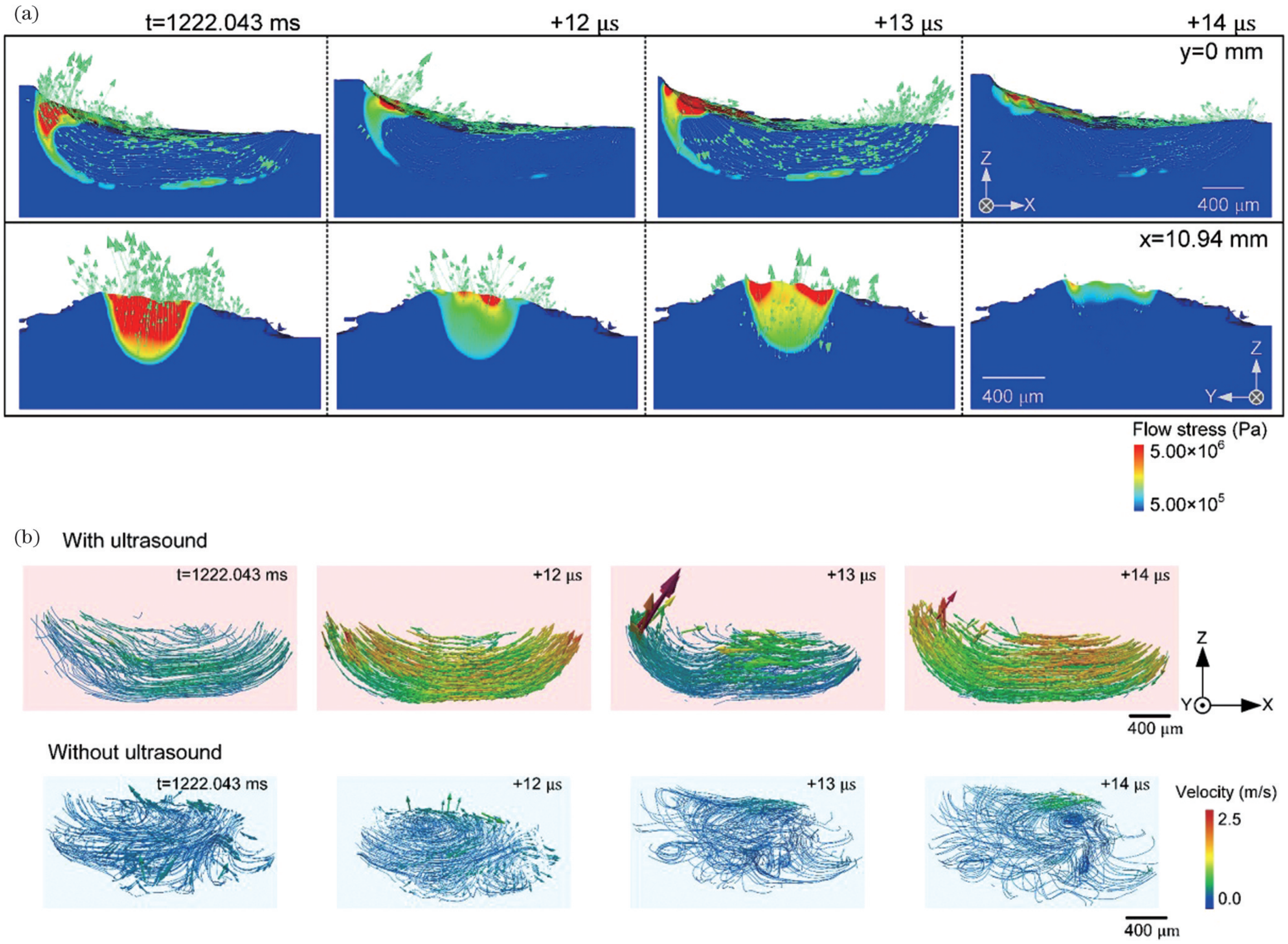

图 4　超声施加效果数值模拟[28]。(a)超声复合激光沉积过程中糊状区的流动应力；(b)超声引起熔池内溶质的剧烈对流

Fig. 4　Numerical simulation of ultrasonic effect[28]. (a) Flow stress in mushy zone during ultrasonic assisted laser deposition; (b) severe convection of solute in molten pool caused by ultrasound

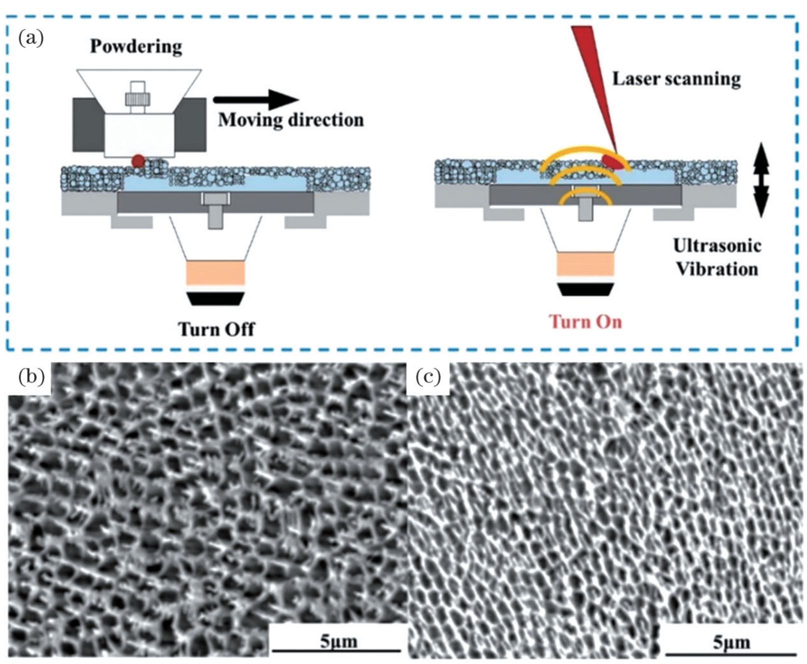

图 5　超声复合激光粉末床熔融[59]。(a)工艺流程示意图；(b)无超声亚晶结构；(c)有超声亚晶结构

Fig. 5　Ultrasonic assisted laser powder bed fusion[59]. (a) Schematic illustrations of technological process; (b) sub-grain structure without ultrasound; (c) sub-grain structure with ultrasound

Wang 等[41]采用如图 6 所示的激光熔覆和超声冲击协同工艺使得涂层的显微硬度和耐磨性能大幅提升。在超声复合激光定向沉积技术加工过程中，位错堆积的出现阻碍了位错在其内的运动，合金的冲击韧性、延展性、拉伸强度和显微硬度均有所提高。

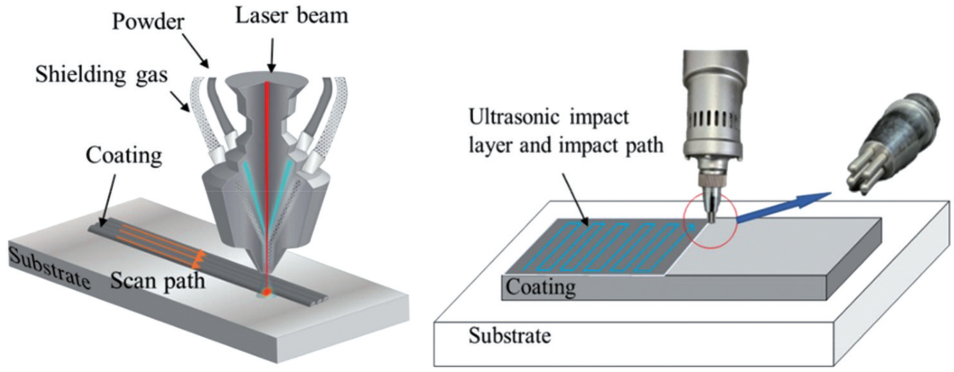

图 6　激光熔覆和超声冲击协同工艺示意图[41]

Fig. 6　Schematic diagram of collaborative technology of laser cladding and ultrasonic impact[41]

激光加热引起的高温度梯度导致残余应力和气孔缺陷的产生，超声冲击工艺具有显著降低作用区残余应力的优势，超声冲击改变了原有的应力场，产生有益的压应力。同时高冲击能量使涂层产生较大的压缩塑性变形，在塑性变形和再结晶的影响下，表层金属组织晶粒获得细化，降低了材料内的孔隙率[67]。激光能量沉积原始微观结构为粗大柱状晶粒，如图 7 所示经超声波冲击处理后，产生大量位错。位错壁通过进一步的位错运动和重组而形成晶界，促进亚晶粒转变为新生的再结晶晶粒，因此，可以从材料顶部自上而下获得具有等轴晶粒梯度结构。材料的力学性能由于晶粒细化强化和位错强化的协同作用而得到提高，晶粒细化强化和位错强化的竞争效应决定了最终的塑性性能[45]。

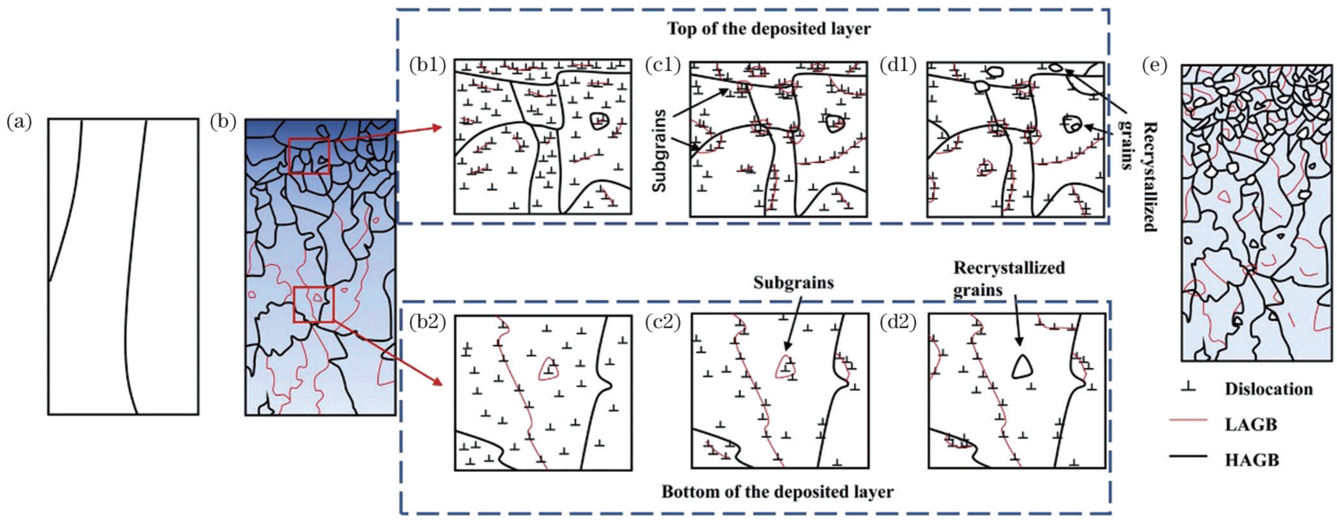

图 7　超声冲击定向能量沉积 304 不锈钢组织演变图[45]。(a)原始微观结构；(b)蓝色的深度表示超声波冲击作用后的局部位错密度；(b1)(b2)相应位置的放大图；(c1)(c2)亚晶粒形成；(d1)(d2)再结晶晶粒形成；(e)最终状态

Fig. 7　Microstructure evolution of 304 stainless steel deposited by ultrasonic directional energy deposition[45]. (a) Original microstructure; (b) depth of blue represents the local dislocation density after ultrasonic impact; (b1)(b2) magnification map of the corresponding position; (c1)(c2) subgrain formation; (d1)(d2) recrystallized grain formation; (e) final status

通过冲击应力场计算模型可预测工艺参数与冲击应力强度之间的关系[44]。超声冲击的振幅对超声的作用深度尤为重要，增大超声冲击的振幅有助于增加其在材料中的穿透深度，从而提高晶粒细化程度。为准确获得冲击过程所需超声大小，Zhou 等[68]建立了激光冲击回弹过程的有限元模型分析冲击回弹过程的关键参数，研究发现只有当冲击头速度、冲击应力和动能大于临界值时才会发生塑性变形，使样品组织发生晶粒细化以及位错强化。

4.2　超声复合激光等材制造

4.2.1　超声复合激光焊接技术

激光焊接技术凭借其精度高、效率高、热影响区小的优势被广泛应用，但因其焊接过程骤热骤冷，容易出现混合不完全、二次相析出、元素分布不均

匀、孔隙率高[69]、残余应力大[70-71]等问题。超声复合激光焊接技术[72]将超声振动引入熔池中，通过声空化、声流等效应影响其凝固行为，进而调控焊接头组织[73-75]，并抑制其中缺陷产生，实现高质量焊接。

国内外学者针对铝基、镁基、镍基、铁基等合金开展了同种材料的超声复合激光焊接研究，发现超声的引入可影响熔体流动、匙孔稳定性，进而抑制焊缝表面周向裂纹的生成[76]。超声非线性扰动下焊缝表面拓扑结构变化机制与熔池的动力学行为直接相关，受生长速度、冷却速度、温度梯度和凝固速度等关键因素影响[77]。Tan 等[78]研究发现声空化效应和声流搅拌作用促使焊缝的柱状晶向等轴晶转变，受气泡逃逸速度增加影响，铝合金焊缝孔隙率从 5.66% 下降到 1.05%。李忠等[79]认为焊缝气孔数量减少主要归因于超声空化效应降低、铝合金熔体中的氢浓度以及气泡逃逸加快。郭亨通等[80]采用非固定接触式超声复合激光焊接 5A06 铝合金，通过调节变幅杆与工件间压力改变超声的传入效率，实现对焊缝控形控性（图 8）。Lei 等[81-82]通过表征示踪原子（微量铜元素）的分布反应超声振动对熔体流动行为的影响，进而利用超声将焊缝孔隙率由 4.3% 降至 0.9%，并细化晶粒，使拉伸强度由 235.1 MPa 增加到 274.1 MPa，延伸率由 6.6% 增加到 7.5%。Kolubaev 等[69]发现超声能够降低树枝状偏析的程度并抑制铁素体晶体的生长，从而提升焊接接头强度。

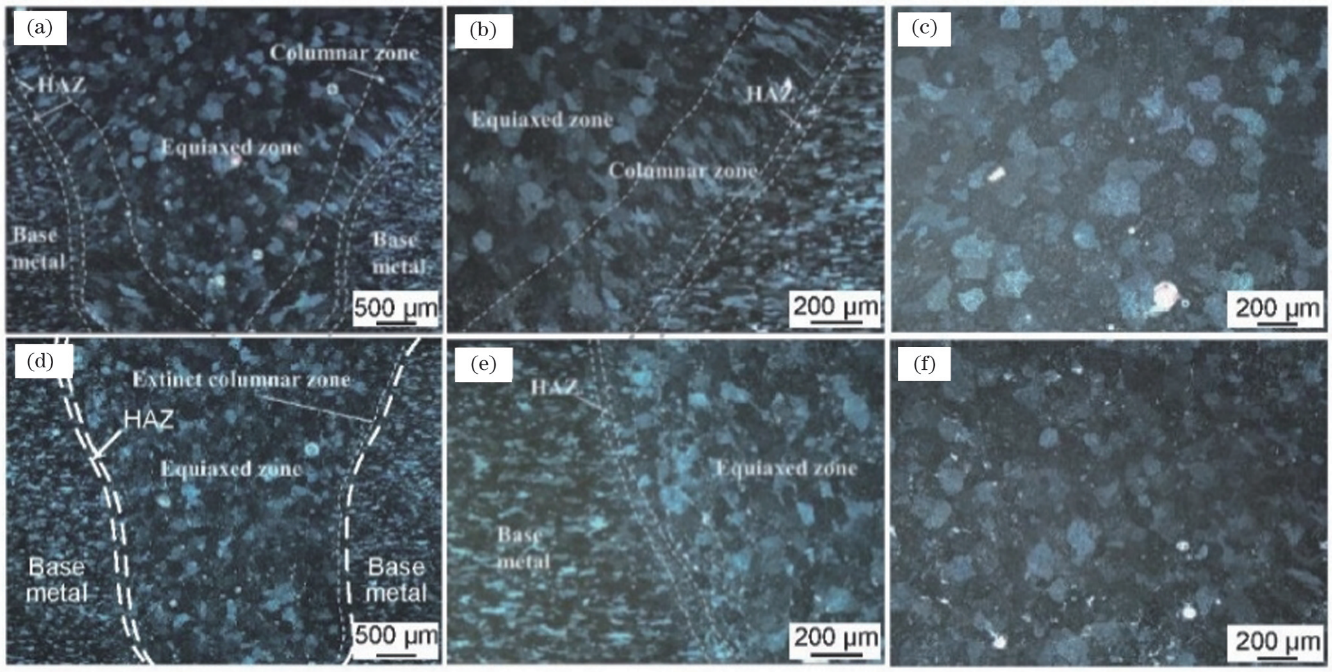

图 8 焊接接头光学显微组织[80]。(a)～(c)激光焊接宏观焊缝截面、熔合线及焊缝中心区域；(d)～(f)超声复合激光焊接宏观焊缝截面、熔合线及焊缝中心区域

Fig. 8 Optical microstructure of welded joints[80]. (a)–(c) Laser welding macroscopic weld cross-section, fusion line, and weld center area; (d)–(f) ultrasonic assisted laser welding macroscopic weld cross-section, fusion line, and weld center area

异种材料激光焊接中固液界面周围元素富集，在晶粒间相互竞争生长情况下，复杂的溶质分配机制导致局部溶质差异过大，进而造成元素偏析。超声能场可以主动调控熔体流动，促进元素均匀分配，影响焊缝区金属间化合物类型及生长形态，减少元素偏析[83-84]。Zhou 等[85]探讨了超声振动对异种焊缝的影响，发现超声振动的加入使未混合区宽度减小，二次相数量减少，Ni 元素的偏析得到了抑制。Zhou 等[86]发现超声振动引起的扩散系数和冷却速率的提升抑制了元素偏析，使析出相的数量从 2.15% 下降到 0.62%，提高了焊缝金属的抗晶间腐蚀能力。Li 等[87]采用超声波辅助钛夹层激光焊接的方法连接 SiC_p/6061Al 基复合材料，抑制了脆性相的形成，同时细小的 TiC 析出相在焊缝中均匀分布，接头强度相比无超声辅助激光焊接和钛夹层激光焊接分别提升了 27.8% 和 12.4%。

为深入理解焊接成形过程，通过数值模拟方法可辅助研究超声复合激光焊接的声压分布、温度分布、应力分布以及相互作用机制等，有助于进一步优化工艺参数。辐射面的高度、倾斜角及形状的变化将影响声压分布，声压随辐射面高度和倾斜角的增加而减小，在凹平面能够实现声聚焦[88]。不同特征频率下的声场状态和声压分布规律不同[89]，且不同的声压幅值引发的焊缝形状变化不同[90]。超声复合激光焊接的熔池温度梯度小于激光焊接的熔池温度梯度，有利于细晶的形成[72]。在超声复合激光焊接过程中，超

声振动对残余应力分布主要有两种影响机理，一种是超声振动加快熔池流动速度使熔池内温度分布更加均匀，降低焊缝的残余应力，另一种是超声振动产生压缩和塑性变形，最终增大超声振动附近焊缝的压应力[71]。

超声波产生的空化效应、声流效应影响待焊区材料的熔化与凝固行为[78]，加速了熔化过程中熔池对流和元素扩散[83-84]，降低温度梯度促使焊缝柱状晶向等轴晶转变[78]，进而抑制气孔缺陷[79]，改善焊缝成形[80]，细化焊缝组织[81-82]，降低接头残余应力，提升接头性能[69]。因此，激光焊接过程中施加的超声将直接影响熔体流动和凝固条件，进而实现对焊缝的形性调控，提升激光焊接工艺质量。

4.2.2 超声-激光协同冲击强化技术

激光冲击强化技术[91]基于激光诱导高压等离子体冲击下的构件表面强塑性变形在表层产生压缩残余应力场、诱导晶粒细化，而在激光冲击极短的作用过程中，强化以诱导位错结构变化为主，难以形成稳定的残余应力场和组织，且表面塑性变形严重，影响工件精度。超声-激光协同冲击强化技术[38]，兼具两者长处，利用超声振动在材料表层引发高频冲击，高效调控微观组织与表面残余应力，保障表面精度同时改善金属材料的力学性能，为表面冲击强化技术的发展引入了新的途径。

超声-激光协同冲击强化技术研究中，部分学者结合实验探讨此复合处理对表面完整性的影响，阐明其表面形貌、亚表面微观结构、显微硬度和残余应力分布演变规律[34-35]。相较单一激光冲击或超声冲击强化(UIT)，两者冲击协同下，强化层深度变大、力学性能变好，其中变化机制被诠释为激光、超声导致的位错产生交互，形成高密度、远近程严重纠缠的位错结构。孟宪凯等[37-38]在此机制指导下采用如图 9 所示超声冲击协同激光冲击在 2024-T351 铝合金的表面诱导了“纳米晶＋塞积位错”微观组织的形成，实现了与单一的激光冲击或超声冲击相比平均晶粒尺寸分别降低 53.3% 和 50.0%，残余压应力幅值与显微硬度显著提升的冲击强化。Maleki 等[36]发现在激光冲击强化协同超声纳米晶表面改性技术处理后屈服强度和抗拉强度得到了提高，距表面 517 μm 深度的亚表面孔隙得到闭合，孔隙率从 0.6% 降低到约 0.15%。还有学者将二维超声增量成形与激光冲击强化结合[92]，基于声软化、声硬化效应及激光冲击对表面二次补强，实现形状复杂的薄板的高质成形。

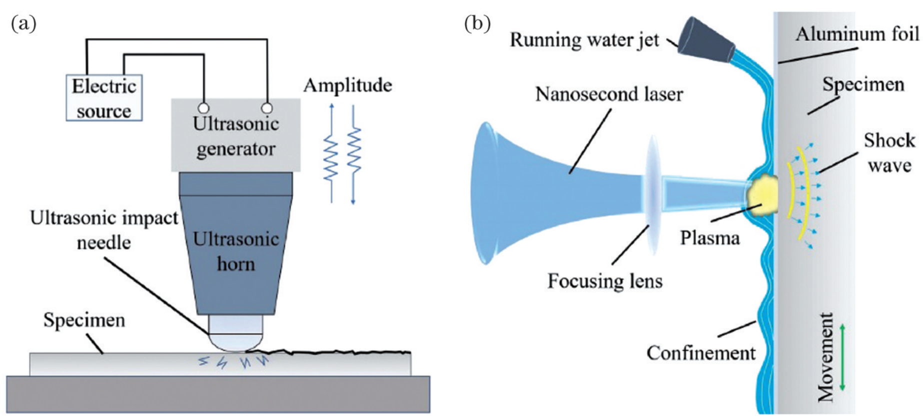

图 9 超声-激光协同冲击强化技术示意图[38]。(a)超声冲击强化；(b)激光冲击强化

Fig. 9 Schematic diagram of laser impact combined with ultrasonic impact peening[38]. (a) Ultrasonic impact peening; (b) laser impact peening

4.2.3 超声冲击协同激光淬火技术

激光淬火(LHT)通过激光的高能量密度实现部件表面固态相变强化，但激光淬火路径难免存在重叠，易导致辐照区组织发生局部回火和软化，进而影响组织力学性能。超声冲击强化过程中的高频冲击会引起金属表层压缩塑性变形，使位错密度增加，组织细化，同时产生均匀的压应力场，可有效提高工件力学性能和疲劳强度。

Lesyk 等[93-101]发现超声冲击塑性形变将在生成纳米孪晶、致密位错网的基础上使低温诱导形成被细晶界渗碳体固结的超细马氏体晶，进一步细化成碳过饱和残余铁素体组织，形成保护硬化层，使晶界被细小的二次碳化物固定，提升耐磨性能。如图 10 所示，该现象也导致了位错密度的增加和亚晶粒的形成，使成形件硬度与硬化深度均得到提升。同时超细马氏体晶的形成，激光加热过程中铁素体基体中渗碳体颗粒的强烈溶解，残余铁素体晶粒的碳过饱和，将增强工件的耐腐蚀性能。Dzhemelinskyi 等[102]基于热动力学模型分析了此强化过程中强塑性变形的温度变化，为超声冲击协同激光淬火大尺寸部件的变形控制提供理论支撑。

当加热到奥氏体化温度的亚表层处于冷却阶段时，对表面进行塑性变形将促进表层细晶组织的形成，超声铁素体-马氏体组织，在晶界上固定二次碳化物，强化位错，因此，超声冲击协同激光淬火技术[93]因其多循环特性及对表面结构和应变状态变化的优秀

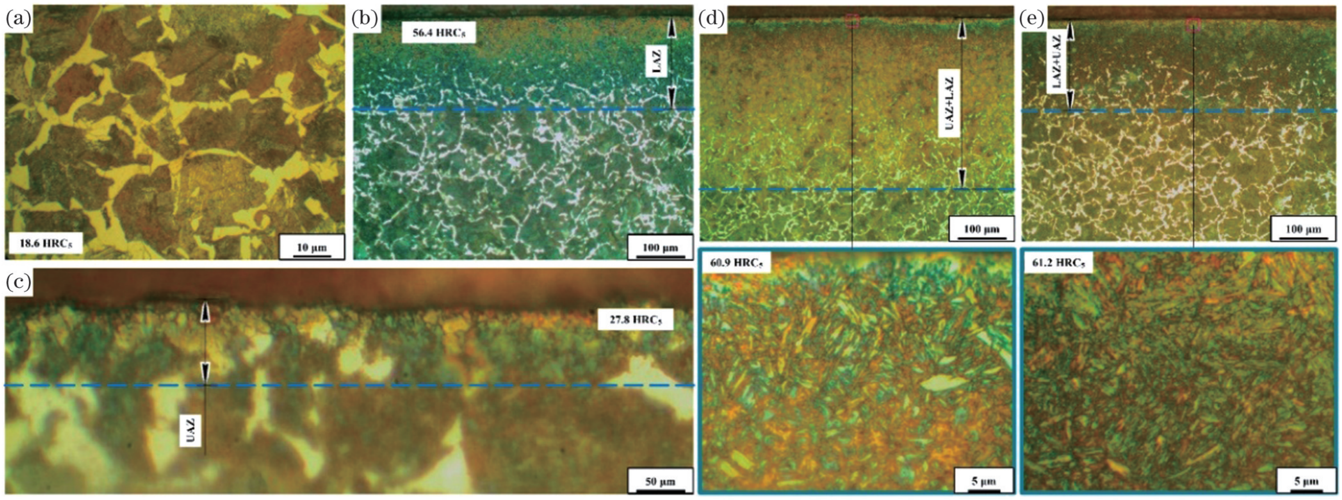

图 10 AISI 1045 近表层微观组织[93]。(a)初始状态下的钢材；(b)激光淬火；(c)超声冲击强化；(d)超声冲击强化＋激光淬火；(e)激光淬火＋超声冲击强化

Fig. 10 Microstructure of the near-surface layer of AISI 1045[93]. (a) Steel in the initial state; (b) LHT; (c) UIT; (d) UIT + LHT; (e) LHT + UIT

控制能力被用以实现力学性能更加优异的强化层强化[103-104]。

4.3 超声复合激光减材制造

4.3.1 超声复合激光烧蚀技术

激光制孔为激光烧蚀的主要目标之一，利用高能激光束去除材料，实现高效率高质量微孔加工[105-108]。然而，熔体排出不充分会导致孔侧壁表面的重铸层增厚，引发熔体飞溅、应力集中、晶粒不均匀和表面微裂纹等问题，同时打孔产生的高气压也会形成密度梯度场并改变介质折射率，导致激光束散焦影响材料去除效率和孔的成形质量。超声在熔体内部的垂直方向上会产生声压，进而对熔融物产生向上的驱动力，加快熔体排出。因此将超声应用于激光制孔，通过增加超声振动的频率和功率均能减少熔体溅射的起始时间和增加熔体排出量[109]，从而减小重铸层厚度[110]，改善加工表面质量。

超声振动能够有效抑制激光微纳加工的缺陷。不同激光照射时间下，超声振动对孔表面几何特征（孔深、孔径、锥度）和质量参数（熔体飞溅、重铸层厚度、热影响区）具有规律性影响[111]。Shi 等[14]和 Wang 等[39]研究发现超声振动主要通过细晶强化、硬质相析出和弥散强化等方式来改善微孔表面质量，可以有效改善孔入口形貌，减少微裂纹等冶金缺陷，如图 11 所示，重铸层厚度减少了 15.73%～31.82%，显微硬度提升了 19.43%。超声振动也可以抑制激光制孔过程中重铸区针状结构的形成[112]。除了改善微孔表面结构外，超声也可以降低应力集中。Wang 等[40]采用数值模拟分析了单孔和多孔在有无超声情况下产生的瞬态和残余应力分布特征，发现超声作用下瞬态/残余应力场的分布趋势发生较小变化，而超声诱导软化效应对激光开孔工件的影响表现为应力值的有效降低。通过数值模拟研究，进一步理解超声振动在激光烧蚀过程中的影响机理及效应[113]，超声振动频率对激光作用下光斑的温度场、尺寸和位置产生显著变化[114]，同时超声频率和激光频率对烧蚀轨迹具有复杂影响[115]，并可确定超声振动作用下熔体排出的临界体积[116]。

为解决超声复合激光制孔过程中热影响区过大的问题，图 12(a)展示了水基超声复合激光制孔方法[117]。超声加速制孔过程，使材料更容易穿透，促使水进入微孔，从而减小热影响区。激光加热使水迅速蒸发并产生膨胀的空化气泡[118]，激光强度由于激光束在水中的气泡发生折射和散射而衰减，导致激光能量不能均匀地传递到工件表面[119]，超声产生的高频振动能够加速气泡的溃灭，减小气泡对激光束的扰动[120-121]，从而提高加工效率，同时气泡溃灭时产生向上的水流，有助于减少微孔内壁的熔融残留物。另外，超声在水介质中还会产生空化泡进一步促进熔体的去除[122]。Wang 等[123-124]还通过毫秒脉冲 Nd:YAG 激光器（λ=1064 nm）超声改善微孔形貌，使孔壁相对清洁，轮廓更好，锥度更小。此外，超声振动还可以提高热影响区硬度，降低内孔壁表面粗糙度。图 12(b)展示了微孔的进出口形貌，在出口处熔体排出和喷射引起的残留物明显减少[117]。Charee 等[125]研究了超声波辅助水下激光加工硅，采用波长为 1064 nm、最大平均激光功率为 30 W、脉冲持续时间为 120 ns 的纳秒脉冲激光器在硅片上形成深槽，超声振动加速气泡破碎，减少激光能量流失，加快残渣排出，超声复合水下激光微加工技术相比其他水下激光微加工工艺具有更高的材料去除率和更好的表面质量。因此，采用水基超声复合激光制孔方法，结合水的冷却效应与流动性，以及超声减少对激光束

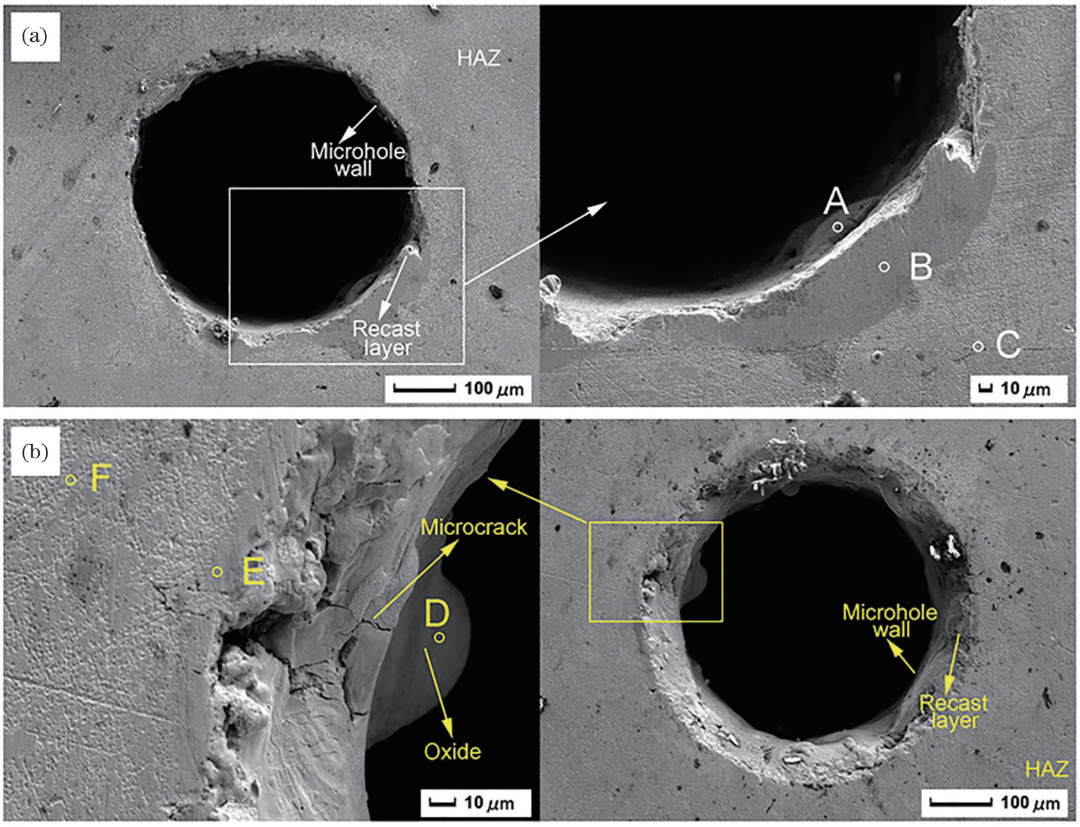

图 11 微孔入口扫描电镜(SEM)分析[14]。(a)有超声;(b)无超声

Fig. 11 Scanning electron microscope (SEM) analysis of micropore inlet[14]. (a) With ultrasound; (b) without ultrasound

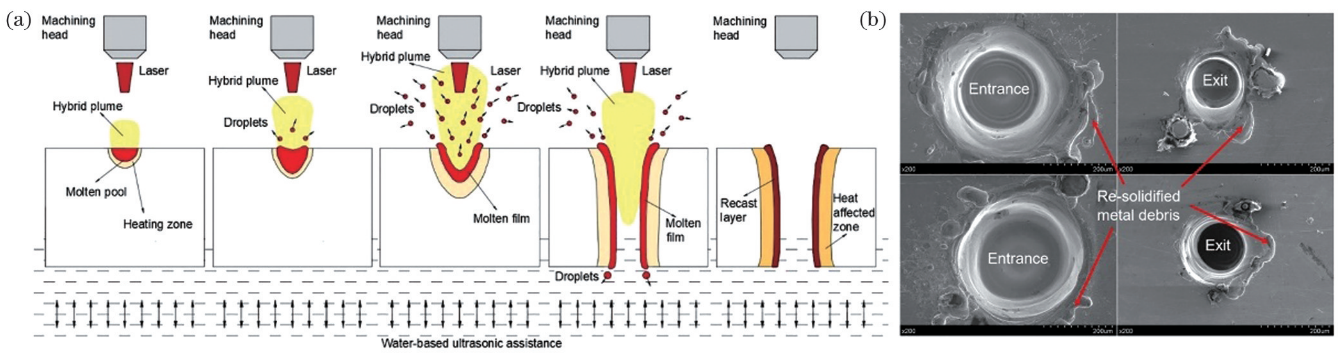

图 12 水基超声复合激光制孔[117]。(a)机理图;(b)微孔表面形貌图

Fig. 12 Water-based ultrasonic assisted laser drilling[117]. (a) Diagram of mechanism; (b) surface morphology of micropore

的扰动、促进熔体排除的优点,从而在提高制孔效率的同时优化加工质量。

液相激光烧蚀已被广泛应用于制备不同形状和大小的纳米结构,包括金属[126]、合金[127]和氧化物[128],由于具有较大的比表面积和量子尺寸效应,与本体材料相比具有特殊而优越的物理和化学性质,在光化学、催化、生物医学等领域具备广泛的应用前景[129]。

通过调整脉冲激光的波长、脉宽和频率等参数,可以有效控制纳米粒子的形态和尺寸。激光液相烧蚀法制备纳米粒子所用脉冲激光的波长一般为 1064 nm 或 532 nm,毫秒脉冲激光与靶材相互作用时会形成熔融状态的金属液滴[130],而纳秒脉冲激光产生的致密等离子体[126]则限制了粒子的膨胀。在这两种激光烧蚀过程中,靶表面形成烧蚀点,生成空化泡[127],其中的粒子喷射到水中并在空化泡内凝结成纳米粒子。通过施加超声,能够调控空化泡的形成和崩溃,进一步烧蚀纳米颗粒,提高合成速率[131-132]。在超短脉冲激光烧蚀中,高能量的脉冲激光使材料表面形成高强度电场,导致物质被剥离[130],突显了不同激光类型在制备纳米粒子中的层次和效应差异。图 13 所示为一种超声辅助液体激光烧蚀法制备铋基纳米片生长机理,该方法烧蚀诱导的空化泡在液相激光烧蚀合成纳米颗粒中作为反应场,并且该反应场的高压有助于具有晶体结构的纳米颗粒的生长。超声会影响纳米颗粒的尺寸[133]和结构形态[134-135]。值得注意的是,这些空化泡比没有超声时形成的气泡具有更大的尺

寸[134-135]。这种尺寸的变化导致在较大的气泡体积上的烧蚀物质浓度较低，限制了它们的冷凝形成纳米颗粒。同时，这些激光诱导的空化泡在超声场的作用下，被推向低压区域。这有利于聚集体的形成，这些聚集体通过二维各向异性定向生长形成纳米片后自组装而增大其尺寸[129]。

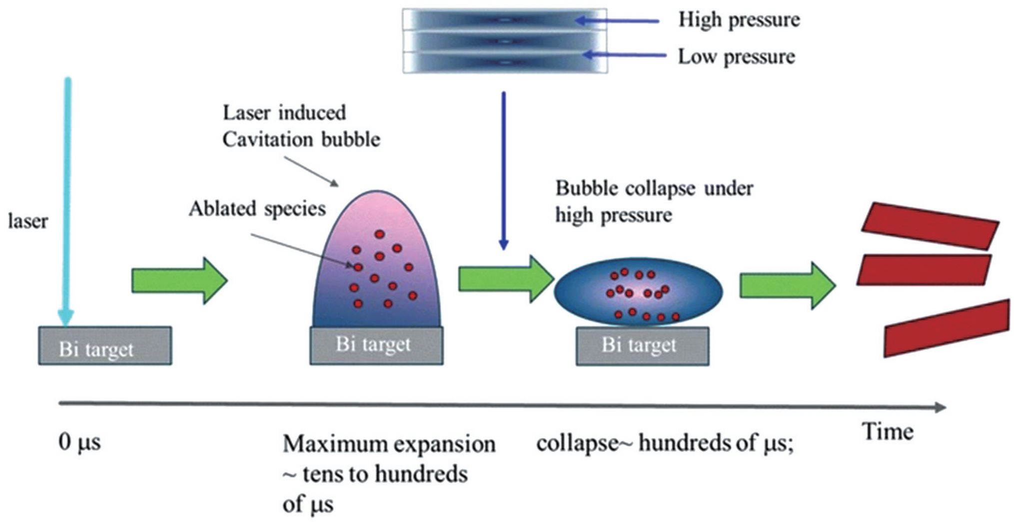

图 13　超声复合液体激光烧蚀法制备铋基纳米片生长机理示意图[134]

Fig. 13　Growth mechanism of bismuth-based nanosheets prepared by ultrasonic assisted liquid laser ablation[134]

4.3.2　超声复合激光抛光技术

激光抛光属于激光热抛光，主要是利用激光和金属材料作用所产生的热效应，通过熔化、蒸发等热作用机理去除表面材料，从而得到抛光的效果。激光束高斯分布导致熔池中能量密度分布不均匀，造成工件表面针状凹坑和空洞的问题。超声振动可以避免热量分布过于集中，从而抑制激光抛光过程热积累引发的缺陷。

超声振动可应用在光学透镜上以改变工件表面激光能量分布[136]，通过调节振幅和频率将激光抛光转化为间歇抛光过程，并可精确调节激光能量密度[137]。超声波也可通过振动和微温效应松动表面颗粒，而激光则在局部加热的同时蒸发或熔化材料，使其更易于去除。在工艺中通过精确控制超声波和激光的照射，实现所需表面质量的提升。如图 14 所示，在超声复合激光抛光过程中，超声振动的近场对流增强作用可以使烧蚀颗粒和碎屑更好地冷却，避免颗粒与材料表面结合倾向，减少表面氧化，增加材料去除率，降低抛光表面粗糙度[138]。赵振宇等[139]采用超声复合激光抛光装置提升陶瓷表面熔池再分布和加强对流冷却效果。Wang 等[140]利用超声振子端面与样品表面的空化效应作用使金刚石颗粒以极高的速度冲击激光辐照表面，对改善多脉冲烧蚀热累积形成的环形山表面形貌有显著效果。因此，超声复合激光抛光技术能改变激光能量密度，影响表面激光能量分布，可以有效地提高抛光表面的质量。

4.3.3　超声复合激光清洗技术

激光清洗利用短脉冲高能量激光束照射工件表面，使表面的污物、锈斑或涂层发生瞬间蒸发或剥离，广泛应用于航空、船舶、高铁、汽车等行业领域[141]，但激光清洗仍存在碎屑沉积、激光诱导的热效应缺陷、有害的表面残余拉应力等问题。为此，研究人员引入超声振动发展了超声复合激光清洗技术。刘世光[142]采用超声激光清洗完全去除表面油漆，对基体影响相比无超声更低，且基体表面无明显痕迹。王静轩等[143-144]提出了超声辅助激光表面清洗方法和液流超声复合辅助激光清洗光学元件的方法，前者通过激光和超声振动同时作用到清洗样品表面，有效防止样品表面热积累，有助于均化激光光斑作用在样品表面的能量分布，改善激光清洗表面质量的均一性；后者采用超声振动产生的热量起到清洗前预热的作用，消除或减小清洗过程中的残余应力，以实现光学元件的高效高质量清洗。冯爱新等[145]将激光与超声波同时作用在工件表面，强化超声空化、水射流等现象，实现对工件表面的再清洗，从而提升激光微加工质量。

超声可利用高频振动清理碎屑，为碎屑颗粒提供额外动能，有助于表面清理，防止表面过热并减少清洗过程中残余应力，并抑制激光高温能量热效应缺陷。因此，采用超声复合激光表面清洗技术能充分发挥激光在高温剥离难加工和难清洗涂层方面的优势，结合超声高频振动可显著提升加工效率和表面清洁质量。

此外，超声可与激光加工过程复合达到实时清洁的效果，例如超声波的引入可及时清除加工过程中产生的材料颗粒，解决微粒去除和磨屑清理的问题。Chiu 等[146]采用超声及时解决碎屑颗粒重新掉落回材料表面从而遮蔽激光束影响激光能量传输的问题，使

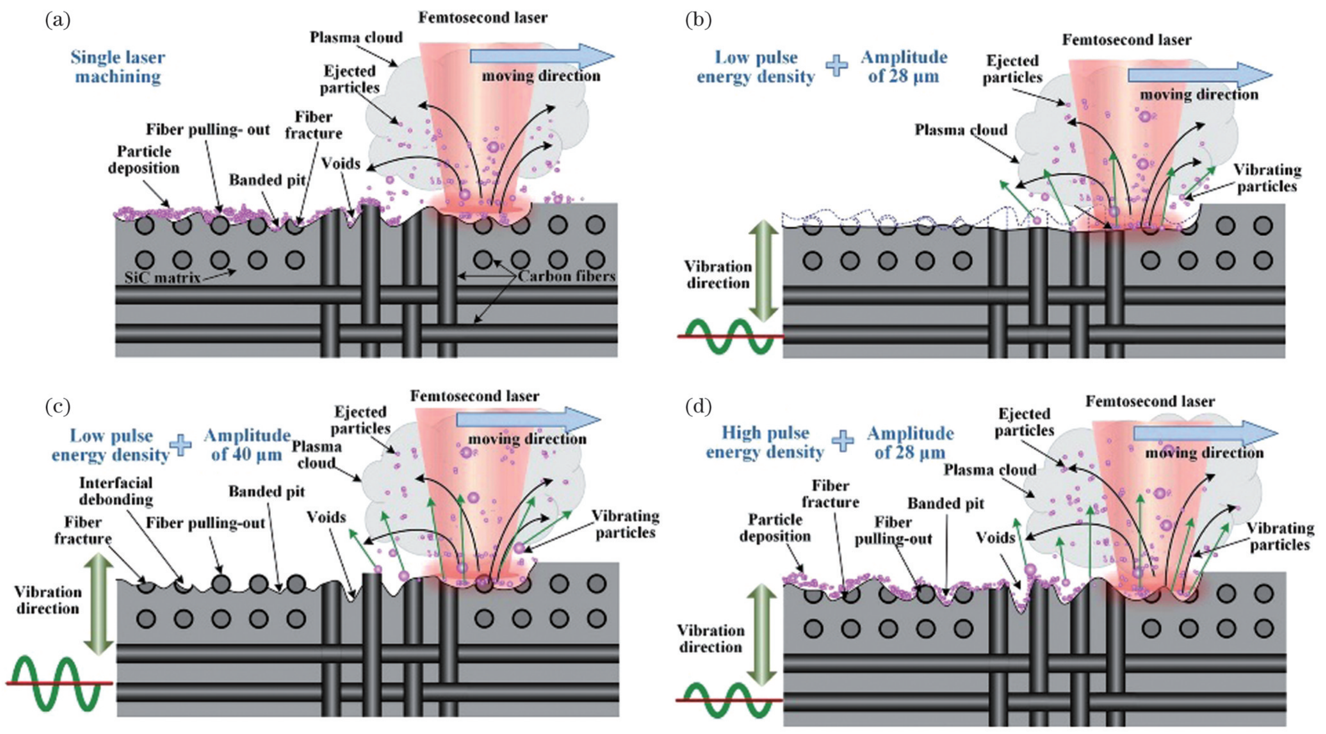

图 14 超声复合激光抛光去除材料机理图[138]

Fig. 14 Mechanism diagram of material removal by ultrasonic assisted laser polishing[138]

用相比传统更少的激光加工次数加工出深孔等高深宽比的结构，并使表面轮廓更加平滑。Alavi 等[147]在激光表面处理奥氏体不锈钢过程中同步施加超声振动，形成具有再结晶表面膜的清晰凹坑，且超声波输出功率越高表面清洁效果更有效。

5 结束语

在激光制造技术日新月异的发展中，超声能场作为激光制造技术的重要辅助途径，在各类激光制造领域崭露头角。本文总结归纳了超声激光复合作用机理和不同超声引入方式，概括了当前各激光制造技术的技术特点和现存缺陷，并基于最新研究进展阐述了超声能场作为复合能场引入激光加工过程的作用机制和影响效果。针对超声复合激光制造技术下一步的重点发展方向，展望如下：

1）深入揭示超声激光复合作用机理。由于超声激光复合作用时间短、交互作用极为复杂，现有研究多以原理解释和有无超声下的定性分析为主，其超声增益效果的定量研究仍较为欠缺。开展复合制造过程原位监测和原子层次数值模拟将对深入揭示超声激光复合作用机理提供重要支撑。

2）拓宽材料选择与工艺适用性。当前超声激光复合制造的研究多集中于金属材料，进一步研究超声在复合材料、陶瓷等材料加工的作用机制，探讨超声激光复合制造在多种材料加工中的适用性。多样的材料和工艺适用性将使得超声复合激光制造技术在多个领域展现出广阔的应用前景。

3）创新设计复合制造专用设备。为推进超声激光复合制造的应用，需研制集成化专用复合设备。一方面是创新超声引入方式，结合具体制造工艺和超声作用机制，设计适用不同场景的超声高效引入方式，另一方面是将超声复合装置与激光系统高度集成，提高整体设备便携性和智能化水平。

4）激发超声在新型激光制造技术中的耦合潜力。超紫外、超短脉冲、超大功率等新型光源不断涌现，基于新光源激光物质相互作用的制造革新将带来更多的机遇和挑战，同时光束整形技术的发展也给激光制造带来了新的机遇。在新型激光制造技术中耦合超声振动将进一步催生复合制造技术的发展，为制造技术创新和应用领域拓展提供有力支撑。

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Research Progress of Ultrasonic Assisted Laser Manufacturing Technology (Invited)

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Abstract

Significance Laser manufacturing technology is an efficient manufacturing approach with high precision, high efficiency, low energy consumption, and low cost. The sustained and rapid development of laser manufacturing technology has provided significant opportunities for the industry. To improve the manufacturing quality, laser hybrid manufacturing technology has received significant attention. Among these, ultrasound-assisted laser manufacturing has gradually become a research hotspot worldwide.

The ultrasonic energy field has both volume and surface effects, and can achieve stress superposition, shock waves, and acoustic softening in solid materials to optimize and control their mechanical properties. Ultrasonic vibration can also affect the molten pool flow and solidification behavior of semisolid/liquid materials through cavitation and flow effects and promote a uniform distribution of elements and grain refinement. The mechanical effect of ultrasound promotes the slag emission and reduces the shielding of the laser beam, leading to improvement the quality and efficiency of laser ablation. Therefore, ultrasonic vibrations play a significant role in laser manufacturing processes.

Progress Among various hybrid processes, three different ultrasonic application modes were adopted: fixed-contact, mobile-contact, and non-contact modes (Fig. 1). Applying ultrasonic vibration in fixed-contact mode leads to continuous and stable transmission of ultrasound with less energy dissipation but has significant limitations on workpiece shape and size. In the mobile-contact mode, the acoustic energy can be transmitted well at the interface and is less shape-restricted; however, there may be a disconnected contact phenomenon between the ultrasonic head and the workpiece. In the noncontact mode, the process is completely unaffected by the workpiece shape; however, there is significant energy attenuation when the acoustic wave is transmitted in a gas or liquid medium.

In this study, the mechanisms and effects of ultrasonic vibration on laser processing are reviewed based on a summary of the latest research progress. Ultrasonic-assisted laser manufacturing technology with various ultrasonic application modes was comprehensively discussed for laser additive manufacturing, laser formative manufacturing, and laser subtractive manufacturing. The principles and technical characteristics of each hybrid manufacturing technology are discussed, and the influence of ultrasonic vibration on the laser manufacturing process is summarized (Table 1).

In laser additive manufacturing, laser energy deposition technology, synchronously assisted by ultrasonic vibration, is widely used for surface modification, additive repair, and coating preparation. The application of ultrasound inhibits the generation of columnar crystals, resulting in a reduction in the microstructural anisotropy, pores, inclusions, and microcracks. In addition, laser powder bed melting synchronously assisted by ultrasonic vibration has been used in the rapid manufacturing of complex components. The influence of ultrasound on the melting process improved the comprehensive mechanical properties of the parts and reduced the anisotropy in laser powder bed melting. Laser additive manufacturing combined with ultrasonic impact peening can improve the properties of additive manufactured parts by conducting a post-treatment of the ultrasonic impact on the surface of the parts after laser additive manufacturing. The combined effects of grain refinement strengthening and dislocation strengthening result in deep strengthening, defect suppression, and shape and performance control.

For laser formative manufacturing, ultrasonic-assisted laser welding inhibits the defects caused by sudden heating and cooling by applying ultrasonic vibration to the welding pool and then regulates the welding microstructures to achieve high-quality welding. Laser impact combined with ultrasonic impact peening triggers a high-frequency impact on the surface of a material, which has the advantages of both ultrasonic and laser impacts. The microstructure and surface residual stress can be effectively regulated, and the surface accuracy and mechanical properties of the metallic materials can be improved. Laser quenching with ultrasonic impact can significantly improve the mechanical properties of the reinforced layer owing to the multicycle characteristics and excellent control ability of the surface structure and strain state.

In laser subtractive manufacturing, ultrasound increases the plastic flow capacity of a material in ultrasonic-assisted laser ablation technology. The surface melt discharge and surface evaporation of the material are considerably promoted, resulting in an improvement in the surface quality of the removal area and the quality of the hole. In ultrasound-assisted laser ablation for nanoparticle preparation, the ultrasound in the liquid causes cavitation bubbles to form and collapse repeatedly. Additional ablation of the nanoparticles induced by ultrasound enhances the density of the nanoparticles in the liquid and improves the synthesis rate. In ultrasound-assisted laser polishing technology, ultrasound can reduce the bonding tendency between particles and the material surface, leading to a reduction in surface oxidation, an increase in the material removal rate, and a reduction in surface polishing roughness. In ultrasonic-assisted laser cleaning, ultrasonic vibration not only makes the surface easier to clean, but also suppresses the defects induced by high temperatures, significantly improving the processing efficiency and surface cleaning quality.

Conclusions and Prospects Ultrasonic-assisted laser manufacturing has gradually become a popular approach for fabricating various structures. A developmental trend in the ultrasonic-assisted laser manufacturing technology is expected. Further fundamental studies on hybrid mechanisms will be conducted to understand complex hybrid manufacturing processes. Broadening the diversity of materials and process applicability will expand their application areas. An innovative design for the ultrasonic application mode and equipment will be developed to improve the integration. In addition, creative laser manufacturing technologies can generate new hybrid manufacturing processes through the development of new light sources, thereby providing significant support for manufacturing innovation and application expansion.

Key words laser manufacturing; hybrid manufacturing; ultrasonic vibration; coupling mechanism; ultrasonic application mode