

专题—能场复合激光表面改性

## 脉冲激光辅助激光增材制造研究进展

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**摘要:** 针对辅助脉冲激光作用在固相区的情况, 分别论述了非同步式表面、非同步式层间以及同步式脉冲激光辅助激光增材制造的工艺特点, 分析了增材制造构件组织、成形缺陷以及应力分布的调控机理, 并系统对比了非同步式和同步式脉冲激光辅助激光增材制造的调控效果, 总结了同步式脉冲激光辅助激光增材制造的工艺优势。针对辅助脉冲激光作用在熔池区的情况, 研究了脉冲激光功率密度、频率对熔池热动力学行为的作用机理 (Marangoni 对流、超声波搅拌空化、冲击波效应等), 进而明晰了辅助脉冲激光冲击熔池对增材制造构件组织、成形缺陷的影响机理。最后, 对脉冲激光辅助激光增材制造技术的研究进展进行了总结, 并对下一阶段的发展方向进行了展望。

**关键词:** 激光增材制造; 脉冲激光冲击; 组织; 成形缺陷; 残余应力

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## Research Progress on Pulse Laser-assisted Laser Additive Manufacturing

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**ABSTRACT:** Laser additive manufacturing is an additive manufacturing technology that uses high-energy laser beams as a heat source to gradually form materials point by point and layer by layer with computer-assisted control. Typical laser additive manufacturing technologies include laser powder bed fusion and laser directed energy deposition. Among them, laser directed energy deposition technology can be used for component manufacturing, repair, and surface treatment. When used for surface treatment, it is also known as laser cladding technology. Compared with traditional manufacturing technologies, laser additive manufacturing reduces the reliance on molds and fixtures, enables rapid formation of complex components, shortens the product development cycle and manufacturing process, and has huge potential application demand in aerospace, automotive, biomedicine, and many other fields. However, during the laser additive manufacturing process, the high temperature gradient in the melt pool leads to a strong tendency for the solidification structure to grow epitaxially along the deposition direction. For example, the grain growth of titanium alloy formed by laser directed energy deposition can penetrate multiple deposition layers or even the entire specimen, resulting in anisotropy of the mechanical properties of the components. Additionally, the strong interaction between the laser and the material, as well as rapid solidification, lead to the formation of defects such as pores during the forming process. Furthermore, high residual tensile stresses are formed on the component surface, reducing the comprehensive mechanical properties of the formed components. In order to address these issues, scholars at home and abroad

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have attempted to improve the forming quality and mechanical properties of components by combining other technologies in the laser additive manufacturing process, such as electromagnetic field-assisted laser additive manufacturing, ultrasonic vibration-assisted laser additive manufacturing, and pulsed laser-assisted laser additive manufacturing. Among these technologies, the pulsed laser-assisted laser additive manufacturing is a non-contact composite manufacturing technology with advantages such as good processing flexibility and high controllability, which can effectively regulate the component structure, suppress formation defects, and improve residual stress distribution. In the process of pulsed laser-assisted laser additive manufacturing, the control mechanisms differ significantly depending on the target of pulsed laser action. This paper divides pulsed laser-assisted laser additive manufacturing into two cases: pulsed laser acting on the solid phase zone and acting on the melt pool zone. When pulsed laser acts on the solid phase zone, this technology is also known as laser shock peening-assisted laser additive manufacturing. Depending on the timing relationship between laser additive manufacturing and pulsed laser impact, it can be divided into asynchronous and synchronous laser shock peening-assisted laser additive manufacturing. The asynchronous type includes surface laser shock and interlayer laser shock. When pulsed laser acts on the melt pool zone, this technology is also known as pulsed laser shock melt pool-assisted laser additive manufacturing. This paper reviews recent research results from domestic and foreign sources for the cases where pulsed laser acts on the solid phase zone and the melt pool zone, respectively, summarizing the organizational, defect, and stress control mechanisms under different conditions. Finally, the research progress of pulsed laser-assisted laser additive manufacturing technology is summarized, and the future development direction is prospected.

**KEY WORDS:** laser additive manufacturing; pulse laser impact; microstructure; formation defects; residual stress

激光增材制造是以高能激光束为热源,通过计算机辅助控制材料逐点逐层成形的增材制造技术<sup>[1-2]</sup>。典型的激光增材制造技术包括激光粉末床熔融(Laser Powder Bed Fusion, L-PBF)和激光定向能量沉积(Laser Directed Energy Deposition, L-DED)技术。其中, L-DED 技术既可用于构件的成形制造,也可用于构件的修复及表面处理,当其被用于表面处理时,又称为激光熔覆(Laser Cladding, LC)技术。相比传统制造技术,激光增材制造技术降低了对模具和工装夹具的依赖,可实现复杂构件的快速成形,缩短了产品的研发周期与制造流程,在航空航天、汽车工艺、生物医疗等诸多领域的潜在应用需求巨大<sup>[3-5]</sup>。

在激光增材制造成形过程中,熔池底部区域的温度梯度较高,凝固组织沿沉积方向外延生长的倾向性较大。例如, L-DED 成形钛合金的晶粒外延生长可贯穿多个沉积层,甚至整个试样,导致构件的力学性能出现各向异性<sup>[6-7]</sup>。同时,激光与材料的强相互作用、快速凝固等特点导致成形过程中易出现气孔等缺陷,并在构件表层形成较高的残余拉应力,降低成形构件的综合力学性能<sup>[8-12]</sup>。为了解决上述问题,国内外学者尝试在激光增材制造过程中复合其他技术来提高构件的成形质量和力学性能,比如电磁场辅助激光增材<sup>[13-15]</sup>、超声振动辅助激光增材<sup>[16-19]</sup>、脉冲激光辅助激光增材<sup>[12,20-21]</sup>等。其中,脉冲激光辅助激光增材制造作为一种非接触式的复合制造技术,具有加工柔性好、可控性高等优势,可有效调控构件组织,抑制成形缺陷,并改善残余应力分布。

在脉冲激光辅助激光增材过程中,脉冲激光作用对象不同,其调控机理将截然不同。本文将脉冲激光

辅助激光增材分为脉冲激光作用于固相区和作用于熔池区 2 种情况。当脉冲激光作用在固相区时,该技术亦被称为激光冲击强化(Laser Shock Peening, LSP)辅助激光增材制造,通过产生冲击波作用于固相材料,使其发生塑性变形,可起到细化晶粒、抑制缺陷、改善应力分布的调控效果。根据激光增材和脉冲激光作用的时序关系,可分为非同步式和同步式激光冲击强化辅助激光增材制造。其中,非同步式又包含表面激光冲击和层间激光冲击 2 种类型。当脉冲激光作用在熔池区时,该技术也被称为脉冲激光冲击熔池辅助激光增材制造,通过改变熔池的热动力学特征,可细化凝固组织,促进气孔逸出。近年来,研究者们围绕脉冲激光辅助激光增材制造技术开展了一系列研究。本文分别针对脉冲激光作用于固相区和熔池区的国内外近期研究成果进行了综述,总结了不同技术条件下(脉冲激光作用于激光增材构件的不同区域、激光增材和脉冲激光作用的不同时序关系)的组织、缺陷及应力调控机理,整体结构如图 1 所示。最后,对脉冲激光辅助激光增材制造技术的研究进展进行了总结,并对下一阶段的发展方向进行了展望。

## 1 脉冲激光冲击强化辅助激光增材制造

### 1.1 非同步式激光冲击强化辅助激光增材制造

非同步式激光冲击强化辅助激光增材制造可分为表面激光冲击和层间激光冲击 2 种类型。其中,前

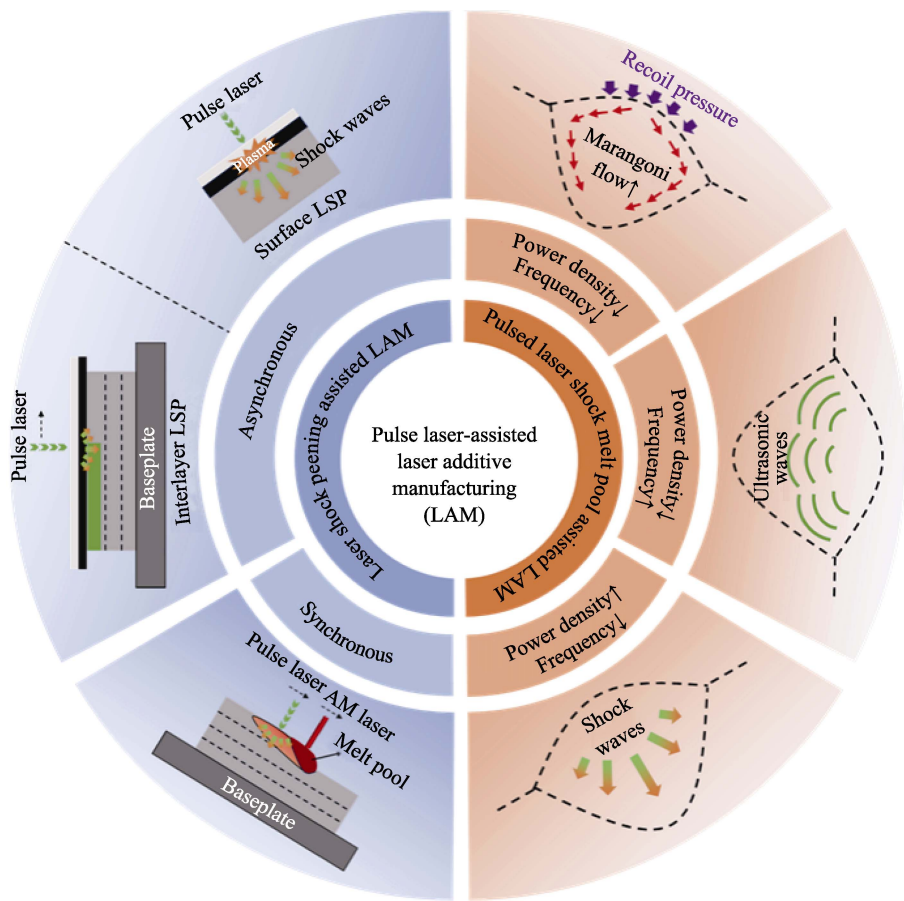


图 1 脉冲激光辅助激光增材制造的技术分类及调控机理  
Fig.1 Classification and control mechanisms of pulse laser-assisted laser additive manufacturing technology

者是在激光增材制造工序结束后对构件或制备的试样表面进行激光冲击强化,后者是在激光增材制造过程中每隔单层或数层施加一次激光冲击强化。目前,激光冲击强化辅助激光增材制造主要以非同步的方式进行。

1.1.1 表面激光冲击强化辅助激光增材制造

表面激光冲击强化辅助激光增材制造将激光冲击强化作为一种后处理工艺来优化构件的组织 and 性能,其作用机理与激光冲击强化处理其他技术成形构件的作用机理类似,如图 2 所示。在该过程中,材料表面受到短脉冲(几十纳秒)、高功率密度( $>10^9\text{ W/cm}^2$ )激光辐照,在极短时间内吸收大量能量,并产生高温( $>10^7\text{ K}$ )、高压( $>1\text{ GPa}$ )等离子体<sup>[21]</sup>。等离子体吸收能量,向四周极速膨胀,在材料表层形成冲击波,并向材料内部传播。为了获得较高的激光吸收效率,并防止材料表层被烧蚀,通常会在材料表面覆盖能量吸收层(如黑色胶带、铝箔)。此外,吸收层外再覆盖一层透明约束层(如流动去离子水或玻璃),用以约束冲击波,使其向构件内部传播,减少冲击波能量在空气中的耗散,提高激光能量利用率<sup>[22]</sup>。当激光诱导冲击波的峰值压力超过激光增材构件材料的 Hugoniot 弹性极限时,材料表层会以极高的应变速率

发生塑性变形,并形成高密度位错和残余压应力,进而调控激光增材制造构件的组织、缺陷和应力分布,改善其抗疲劳、抗应力腐蚀、抗氧化和抗磨损等性能。

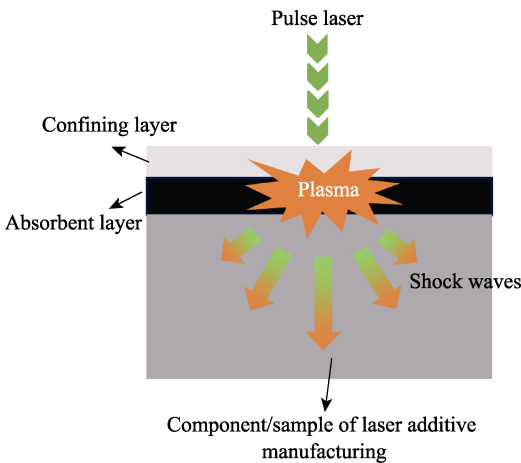


图 2 表面激光冲击强化辅助激光增材制造的原理  
Fig.2 Principle of surface laser shock peening-assisted laser additive manufacturing

目前,研究者们已针对不同材料(如钛合金<sup>[23-30]</sup>、不锈钢<sup>[31-35]</sup>、高熵合金<sup>[36-39]</sup>、铝合金<sup>[40-43]</sup>等)开展了表面激光冲击强化辅助激光增材制造的研究,且取得

了一定的成果,因此本节首先总结了表面激光冲击强化辅助激光增材制造不同材料的研究进展。对于 TC4 钛合金,其增材制造组织主要由  $\beta$  相和  $\alpha/\alpha'$  组成,由于体心立方结构的  $\beta$  相比具有六方紧密排列结构的  $\alpha/\alpha'$  相具有更多的滑移体系,在激光冲击强化过程中, $\beta$  相中更容易出现位错滑移,而在  $\alpha/\alpha'$  相中会同时出现位错滑移和机械孪晶,其相互作用使晶粒发生细化<sup>[25]</sup>。同时,激光冲击强化会在构件表层形成一定深度的残余压应力。位错强化、细晶强化以及表面残余压应力被认为是改善激光增材钛合金抗拉强度、疲劳性能的主要原因<sup>[24,26]</sup>。对于不锈钢材料,激光冲击强化除了可细化其晶粒外,还可能诱发沉淀强化<sup>[34-35]</sup>,提高其力学性能。比如,对于激光增材 316L 不锈钢,激光冲击强化可以通过细化晶粒和引入表面残余压应力提高其耐磨性能<sup>[32]</sup>。对于激光增材 17-4 PH 马氏体不锈钢,表面激光冲击强化所形成的高密度位错可作为形核位点,诱导析出更多细小弥散的含 Cu 强化相,从而提高试样的拉伸性能<sup>[34]</sup>。对于高熵合金,由于其晶格畸变相比传统合金更严重,激光冲击作用下位错形核更困难,因此表面激光冲击强化处理后,其位错密度比传统合金低<sup>[36]</sup>。此外,经过表面激光冲击强化处理后的激光增材制造高熵合金,呈现出更加优异的耐磨、抗氧化等性能<sup>[37-39]</sup>。对于铝合金,由于氢在铝合金固、液中的溶解度差异较大,在增材制造铝合金过程中,容易出现气孔缺陷<sup>[44-45]</sup>。研究表明,激光冲击强化可促进孔隙的闭合,虽然这种闭合不是冶金结合,但是孔隙周围的残余压应力可以抑制孔隙处的裂纹形核,从而提高抗拉强度和疲劳寿命<sup>[42]</sup>。为了使读者更加清晰了解表面激光冲击强化对激光增材制造构件的影响,表 1 总结了部分典型材料表面激光冲击强化后的性能变化及其调控机理。

表面激光冲击强化辅助激光增材制造的强化效果取决于脉冲激光的工艺参数。通过实验获得不同工

艺参数对强化效果的影响耗时耗力,因此许多研究人员采用数值模拟的方法来研究激光工艺参数对残余应力和应变的影响规律,以优化特定金属材料的脉冲激光工艺参数。激光冲击强化过程的数值模拟通常是基于均匀的初始应力状态<sup>[46-48]</sup>,而激光冲击强化辅助激光增材制造过程的数值模拟需要考虑激光增材过程引入的初始非均匀应力状态。Gong 等<sup>[49]</sup>采用 ANSYS/LS-DYNA 软件实现了表面激光冲击强化辅助 L-DED 成形过程的应力场模拟,首先计算了 L-DED 过程的应力演化,并将该过程的应力计算结果作为后续计算激光冲击强化过程的初始状态,通过该模型研究了激光单脉冲能量对残余应力的影响规律。结果显示,脉冲激光能量越大,应力调控效果越显著。Li 等<sup>[50]</sup>采用 ABAQUS 软件建立了激光冲击强化辅助 L-PBF 过程的应力场模型,通过模拟发现,L-PBF 的残余应力场分布不均匀,而激光冲击强化可以将不均匀的拉应力转化为均匀的压应力。同时,研究发现,对塑性变形影响最大的是冲击波的峰值压力。

#### 1.1.2 层间激光冲击强化辅助激光增材制造

表面激光冲击强化辅助激光增材制造仅能改善激光增材构件表层的组织、缺陷和应力状态。为此,有学者提出了层间激光冲击强化辅助激光增材制造技术,也被称为“3D LSP”技术<sup>[51-52]</sup>,即在成形过程中每隔单层或数层施加一次激光冲击强化。在该过程中,构件组织、缺陷及应力的演化除了受到激光冲击强化处理的影响外,还会受到后续激光增材过程热输入的影响,作用原理如图 3 所示。目前的研究表明,层间激光冲击强化方法可以优化激光增材构件的内部组织,消除构件内部的气孔缺陷,调控构件整体残余应力的分布,更为有效地提升构件的成形质量和综合力学性能。

表 1 表面激光冲击强化辅助增材制造部分材料的性能调控机制  
Tab.1 Property regulation mechanism of surface laser shock peening-assisted additive manufacturing for different materials

Materials	Property optimization	Mechanisms	References
TC4	Tensile strength and fatigue property $\uparrow$	Grain refinement strengthening; Dislocation strengthening; Compressive residual stress	[24,26]
316L stainless steel	Wear property $\uparrow$	Grain refinement strengthening; Compressive residual stress	[32]
17-4 PH stainless steel	Tensile strength and elongation $\uparrow$	Grain refinement strengthening; Dislocation strengthening; Precipitation strengthening; Compressive residual stress	[34]
CrMnFeCoNi high-entropy alloy	Wear and corrosion properties $\uparrow$	Grain refinement strengthening; Compressive residual stress	[39]
2 319 aluminum alloy	Tensile strength and fatigue properties $\uparrow$	Collapsed pores; Compressive residual stress	[42]



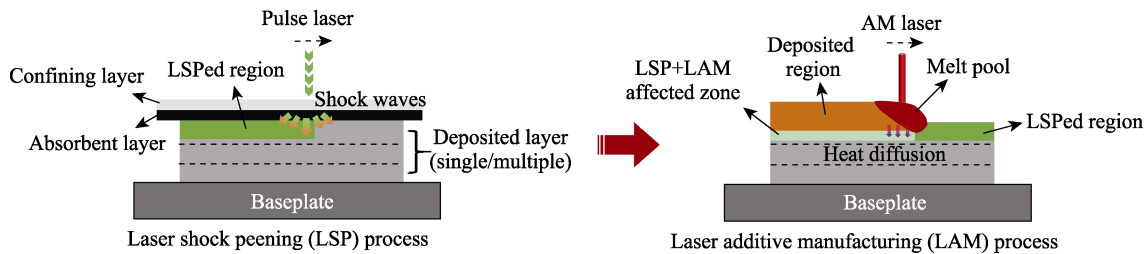
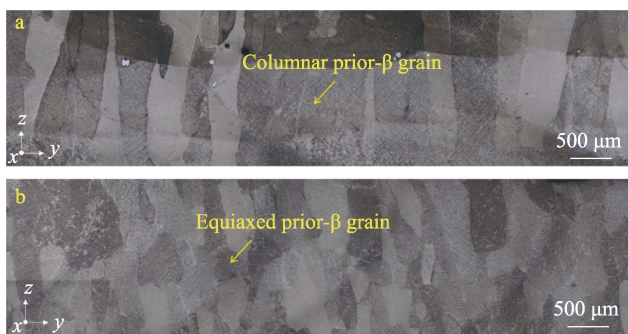


图 3 层间激光冲击强化辅助激光增材制造

Fig.3 Interlayer laser shock peening-assisted laser additive manufacturing

研究者们主要从组织、缺陷和应力变形等 3 个方面对层间激光冲击强化辅助激光增材制造技术开展了研究。在组织调控方面, Lu 等<sup>[53-55]</sup>针对层间激光冲击强化辅助激光增材制造 TC4 钛合金开展了大量的研究, 他们在 L-PBF 成形 TC4 钛合金过程中, 每 5 层施加 1 次激光冲击强化, 发现片状和针状  $\alpha'$  相会显著细化, 拉伸断裂方式由不加激光冲击强化的脆性断裂转变为韧性断裂, 且激光冲击方向垂直于沉积平面时, 强化效果更好<sup>[53]</sup>。之后他们研究了层间冲击强化对 L-DED 成形 TC4 钛合金整体晶粒组织的影响, 研究发现, L-DED 成形 TC4 钛合金组织呈现外延生长的柱状晶形貌, 如图 4a 所示。由于激光冲击强化影响区域为 0.8 mm, 而 L-DED 过程重熔深度为 0.3 mm, 激光冲击强化影响区域中未被重熔过程消除的位错将成为再结晶的形核位点, 促进再结晶的发生, 而熔池中的晶粒仍保持外延生长的柱状晶形貌, 因此最终成形构件整体呈现柱状晶和等轴晶交替的竹节状晶粒结构, 如图 4b 所示<sup>[54]</sup>。近期, 他们研究了 L-PBF 成形 TC4 钛合金过程中, 层间无涂层激光冲击强化对微观组织演化的影响, 发现层间无涂层激光冲击强化辅助 L-PBF 会产生 3 种不同类型的晶粒, 且这种非均匀的晶粒结构会使抗拉强度和伸长率同步提升<sup>[55]</sup>。

图 4 L-DED 成形 TC4 钛合金的粗大柱状晶粒 (a)、等轴晶和竹节状结构 (b) <sup>[54]</sup>Fig.4 Large columnar grains (a) and bamboo-like structure composed of alternating equiaxed grains (b) of typical cross-sectional OM images of LDEDed specimen<sup>[54]</sup>

在缺陷调控方面, Zhou 等<sup>[56]</sup>在激光冲击强化辅助 L-DED 成形 AlSi10Mg 合金的研究中发现, 冲击

波峰值压力对孔隙消除的影响最大, 脉冲激光的光斑直径、冲击次数对其影响较小。该研究中, 表面激光冲击强化和层间激光冲击强化分别使孔隙的直径减小了 6.3% 和 12.6%, 意味着层间激光冲击强化可以更有效地调控激光增材制造构件的内部缺陷。Jing 等<sup>[57]</sup>研究了层间激光冲击强化对增材制造 2319 铝合金构件孔隙的影响, 结果表明, 激光冲击强化会使孔隙周围聚集大量位错, 这些位错在后续沉积过程的热影响作用下, 会诱发形成再结晶晶粒, 从而促进孔隙闭合, 并形成了冶金结合, 其层间激光冲击强化过程缺陷的演化机制如图 5 所示。

在应力变形方面, Kalentics 等<sup>[51]</sup>研究发现, 相比于未处理的激光增材构件和仅对表面进行激光冲击强化的“2D LSP”构件, “3D LSP”可进一步提高激光增材构件的几何精度, 减小变形量。Madireddy 等<sup>[58]</sup>在 L-PBF 成形 AlSi10Mg 过程中, 每 10 层进行 1 次激光冲击强化, 发现可以使变形量降低约 45%。Klein 等<sup>[59]</sup>通过钻孔法对“3D LSP”处理后的应力分布进行了实验测量, 研究发现, 层间激光冲击强化引入的压应力深度为 550  $\mu\text{m}$ , 而后续激光增材过程局部“退火”作用深度仅为 160  $\mu\text{m}$ , 证实了这种“3D LSP”复合制造工艺在应力调控上是可行的。Madireddy 等<sup>[60]</sup>使用 ABAQUS 软件实现了激光增材和激光冲击强化的顺序耦合, 其模拟框架如图 6 所示。他们分别模拟了无激光冲击、仅表面激光冲击、每 10 层进行 1 次激光冲击 (L10)、每 5 层进行 1 次激光冲击 (L5)、每层进行 1 次激光冲击 (L1) 条件下的应力演化, 结果显示, 激光冲击的频率越高, 形成的残余压应力深度越大, 但是当达到每 5 层冲击 1 次时, 残余压应力深度不再随频率增加而变化, 即 L1 和 L5 产生的残余压应力深度是一样的, 因此他们认为每数层 (<5 层) 冲击 1 次可以实现和每层冲击一样的效果。此外, 他们发现层间激光冲击强化辅助激光增材制造构件的应力同时, 受到机械冲击作用和增材热作用的影响, 其演化过程更加复杂。

虽然层间激光冲击强化辅助激光增材制造在组织、缺陷和应力的调控上具有更显著的效果, 但是由于层间激光冲击强化需要激光增材和激光冲击反复交替进行, 成形效率极大降低。此外, 由于层间激光冲击强化通常需要将激光增材构件从设备中移出和

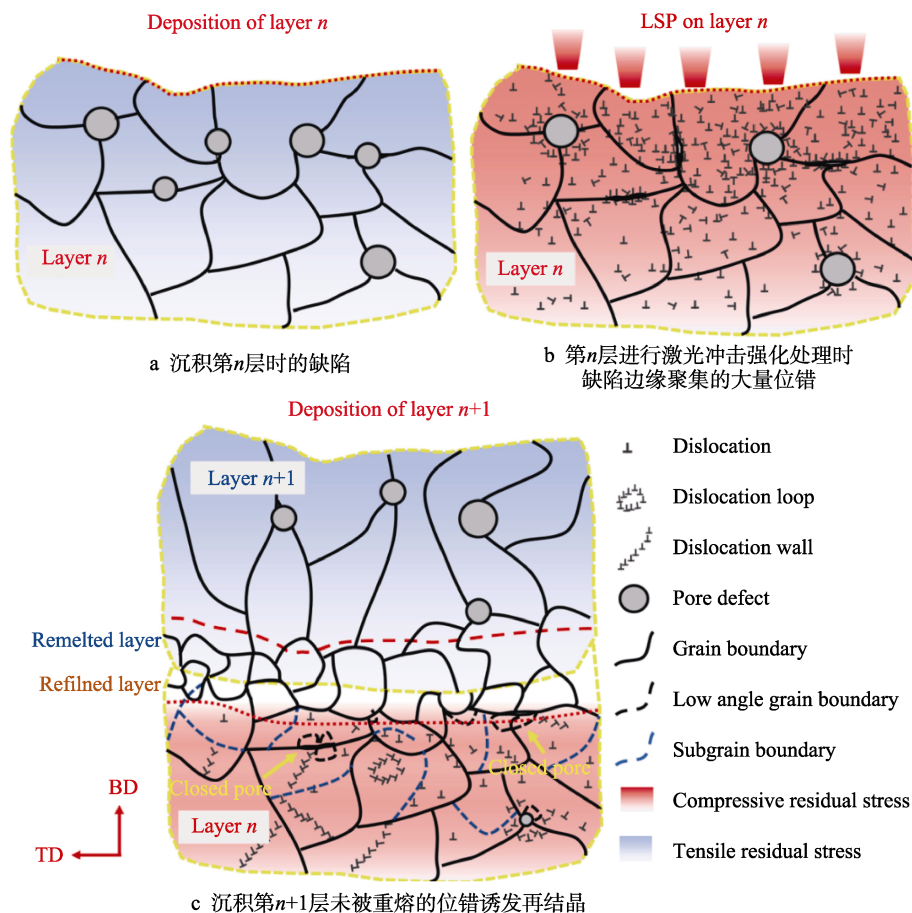
图 5 层间激光冲击强化过程缺陷的演化<sup>[57]</sup>

Fig.5 Schematic diagram of pore evolution in DED-LSP process<sup>[57]</sup>: a) pore in deposition of layer  $n$ ; b) a large number of accumulated dislocations at defect edges during LSP on layer  $n$ ; c) recrystallization induced by dislocations which are not remelted during deposition of layer  $n+1$

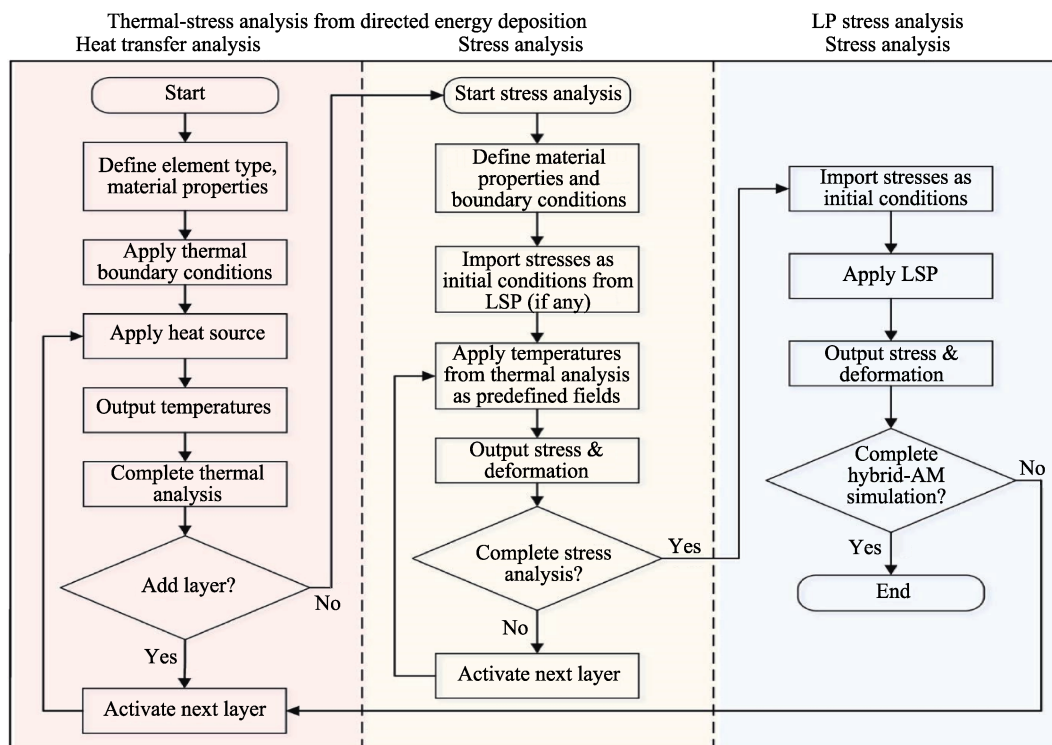
图 6 激光增材和激光冲击强化顺序耦合的计算流程<sup>[60]</sup>

Fig.6 Flow chart for calculation of sequential coupling of laser additive and laser shock peening<sup>[60]</sup>

再放入, 对于以粉末床为特征的 L-PBF 技术, 该过程需要反复将粉末清除和再填入, 且需要实现精确的重复定位, 可操作性较差。

1.2 同步式激光冲击强化辅助激光增材制造

近几年, Zhang 等<sup>[61]</sup>提出了同步式激光冲击强化辅助激光增材制造技术, 即激光熔锻 (Laser Shock Forging, LSF) 技术。在成形过程中, 增材激光与脉冲激光保持一定距离同步移动, 且脉冲激光作用于激光增材制造熔池后方的高温固相区, 整个过程不添加吸收层和约束层, 如图 7 所示。同步式激光冲击强化辅助激光增材制造对构件组织、缺陷和应力的调控机理与层间激光冲击强化类似, 均受到激光冲击强化过程和后续激光增材过程热输入的共同影响。在同步模式下, 增材制造激光和辅助脉冲激光“双激光”同步移动, 成形效率相比非同步的层间激光冲击强化有大幅提高。但激光熔锻过程难以添加约束层, 其冲击强度相对较弱。根据研究, 材料的动态屈服强度随温度

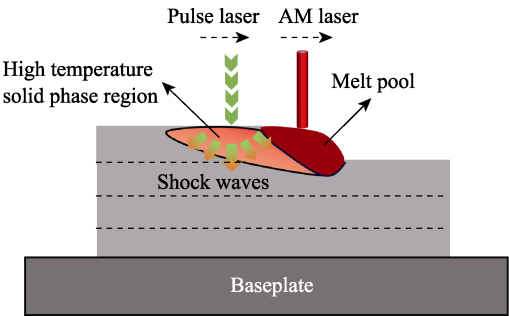


图 7 同步式激光冲击强化辅助激光增材制造  
Fig.7 Synchronous laser shock peening-assisted laser additive manufacturing

的升高而降低, 即材料在较低冲击力作用下就可发生塑性变形, 但过高的温度也会不利于压应力的形成。因此, 优化该过程锻打温度区间将是提升无约束层条件下冲击强化效果的重要手段。

Zhang 等<sup>[61]</sup>利用经典 bar-frame 模型揭示了同步式激光冲击强化辅助激光增材制过程中应力的演化机制, 实验结果表明, 同步式激光冲击强化处理构件的最大压应力比表面激光冲击强化处理的构件高出 57%, 且作用深度增加了 53.8%。此外, 该研究还认为激光冲击强化作用区域的温度在锻造温度范围(文中所用材料为 316L 不锈钢, 对应于 800~1 250 ℃)时更有利于压应力的积累。这是因为在高温下材料更容易屈服, 从而产生足够的塑性变形, 而且在后续过程中也不会发生残余应力的完全释放。此外, 张弛等<sup>[62-63]</sup>针对激光熔锻过程中, 脉冲激光频率对激光熔覆 H13 钢涂层的组织、应力和硬度的影响进行了研究。他们首先通过激光熔覆过程温度场的数值模拟, 确定了脉冲激光的冲击位置。随后的实验结果表明, 随着脉冲激光频率和能量的增大, 晶粒细化程度更均匀, 硬度更高, 涂层表面的残余拉应力逐渐减小, 并转变为残余压应力。

表 2 从多个方面展示了非同步式表面、非同步式层间、同步式激光冲击强化辅助激光增材制造的调控效果对比情况。由表 2 可知, 非同步式层间和同步式激光冲击强化的方式均比非同步式表面激光冲击强化的方式产生更大范围、更有力的调控效果。但是目前关于同步式激光冲击强化辅助激光增材制造的研究较匮乏, 其与层间激光冲击强化的调控机理及效果差异也有待进一步研究。

表 2 非同步式 (表面/层间) 及同步式激光冲击强化辅助激光增材制造调控效果对比  
Tab.2 Comparison of performance regulation effects between asynchronous (surface/interlayer) and synchronous laser shock peening-assisted laser additive manufacturing

Type	Materials	Comparison of performance regulation effects	References
Distortion angle	TC4 alloy	Asynchronous (interlayer) LSPed part is 34% lower than that of the asynchronous (surface)	[51]
Maximum compressive residual stress	316L stainless steel	Synchronous LSPed part is 57% higher than that of the asynchronous (surface)	[61]
Depth of compressive residual stress	316L stainless steel	Synchronous LSPed part is 53.8% higher than that of the asynchronous (surface)	[61]
Pore size reduction	AlSi10Mg alloy	Asynchronous (interlayer) LSPed part is 6.3% higher than that of the asynchronous (surface)	[56]
Microstructure	TC4 alloy	Asynchronous (surface) LSPed part—only the surface layer of the grain is equiaxed; Asynchronous (interlayer) LSPed part—alternating distribution between the equiaxed and columnar grains	[54]

2 脉冲激光冲击熔池辅助激光增材制造

与激光冲击强化的作用机理不同, 脉冲激光作用

于增材制造熔池区, 可直接影响熔池的热动力学行为, 进而改变凝固条件, 优化成形构件的组织及性能。其中, 脉冲激光的功率密度、脉冲频率对熔池演化的影响重大, 不同脉冲激光参数对应的影响机理也存在



较大差异,如图 8 所示。当脉冲激光功率密度较小时,熔池上表面局部温度升高,促进熔池 Marangoni 对流,如果局部温度升高到沸点,还会产生周期性反冲压力,搅动熔池。当脉冲频率增加到 20 kHz 以上时,可使熔池中形成超声波,从而产生搅拌和空化作用。当脉冲激光功率密度达到材料的击穿阈值<sup>[64]</sup>时,就会形成等离子体,随着等离子体的快速加热膨胀,会在熔池表面形成冲击波,并向熔池内部传播。冲击波在强度上比超声波至少高 2 个数量级,其不仅会显著改变熔池的温度梯度、压力等凝固条件,还更易引起枝晶臂的破碎<sup>[65]</sup>。

国内外学者对脉冲激光冲击熔池辅助激光增材制造已开展了初步工作。下文将按照不同脉冲激光参数对目前相关研究进展进行归纳。当脉冲激光功率密度未达到材料的击穿阈值时,熔池可能受到周期性反冲压力或者超声波的作用。Chen 等<sup>[66]</sup>在增材制造 304 奥氏体不锈钢中施加了脉冲能量为 1~3 J、频率为 200 Hz、脉宽为 1 ms 的脉冲激光,研究发现,脉冲

激光诱导的周期性反冲压力对熔池的扰动可使温度梯度降低,促进奥氏体晶粒由柱状晶转变为等轴晶。Fan 等<sup>[67]</sup>在 LC 成形 316L 不锈钢过程中施加了频率为 20 kHz、脉宽为 130~140 ns、峰值功率为 300 W 的高频脉冲激光,发现在高频脉冲激光作用下,熔池表面形成了高频环状振动波(如图 9 所示),熔池流速提高了 27.92%,冷却速度也增加了约 154.99%。同时,高频脉冲激光引起的高频振动波和空化效应促进了形核率的增加和温度梯度的降低,从而使熔覆层的组织得以细化。

当脉冲激光功率密度达到材料的击穿阈值时,熔池会受到冲击波作用。Lu 等<sup>[68-69]</sup>在 L-DED 成形 FeCoCrNi 高熵合金中施加了脉冲能量为 1~3 J、频率为 10 Hz、脉宽为 10 ns 的脉冲激光,研究发现,当脉冲激光能量为 1 J 时,冲击波的作用使晶粒平均尺寸显著降低,但随着脉冲激光能量的进一步增加,熔池会产生飞溅现象。他们通过有限元模拟研究了脉冲激光冲击熔池的力学效应,结果表明,脉冲激光诱导

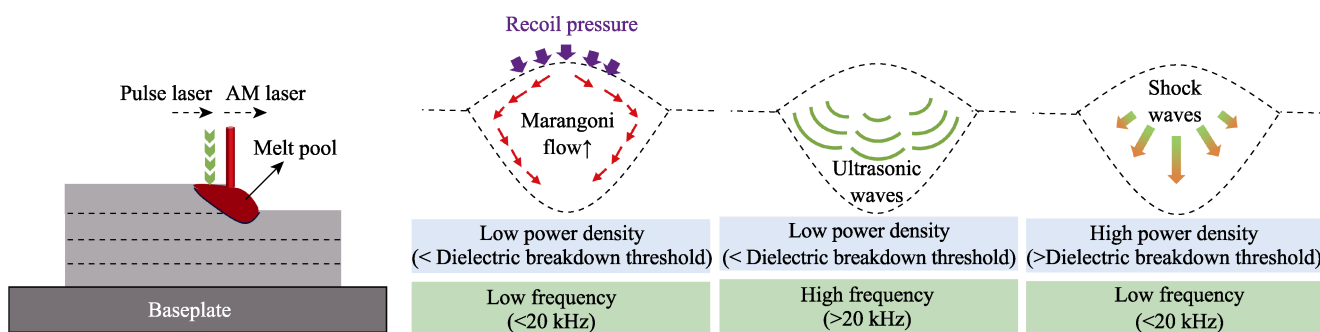


图 8 脉冲激光冲击熔池辅助激光增材制造的作用机理

Fig.8 Regulation mechanism of pulse laser-assisted laser additive manufacturing

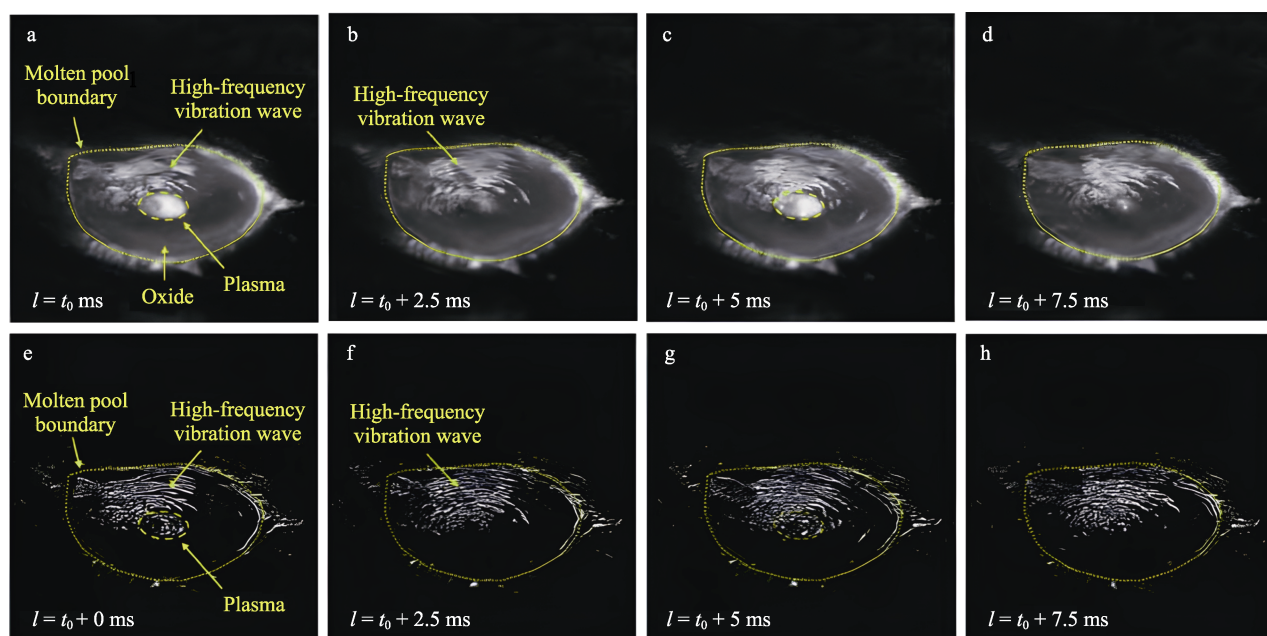


图 9 1 300 W 连续激光复合 300 W 高频脉冲激光条件下熔池的流动过程<sup>[67]</sup>

Fig.9 Flow process of molten pool under 1 300 W continuous laser combined with 300 W highfrequency pulse laser<sup>[67]</sup>

的冲击波可促进熔池流动模式从 Marangoni 对流向多对流环的转变, 并加速熔体流动, 提高冷却速率。但是受限于计算效率, 他们的模型中所采用的脉冲激光作用时间远大于实际作用时间, 这一改动降低了模型的可信度。Sohn 等<sup>[65]</sup>在 L-DED 成形 TC4 钛合金的过程中同步施加了最大脉冲能量为 11.5 mJ、频率为 100 Hz、脉宽为 10 ns 的脉冲激光冲击, 研究发现, 试样的孔隙数量降低了 91%。他们通过 Flow3D 软件进行数值模拟研究, 发现 10 mJ、10 ns 的脉冲激光作用在熔池之后, 热扩散距离为 10.35  $\mu\text{m}$ , 因此会在表层很薄的区域产生热效应, 该热效应可加快熔池 Marangoni 对流, 促进气孔的消除。

Sohn 等<sup>[20]</sup>深入分析了脉冲激光冲击熔池对 L-DED 成形 TC4 钛合金组织的影响, 发现成形构件  $\beta$  晶粒的平均长宽比从 3.5 下降到 2.5, 织构强度降低, 如图 10 所示。他们认为其主要是由于脉冲激光诱导产生的冲击波使成分过冷区增加, 促进了柱状晶-等轴晶转变 (Columnar to Equiaxed Transformation, CET) 行为。一方面, 脉冲激光加速 Marangoni 对流, 可以使枝晶臂前沿的温度梯度降低; 另一方面, 由于脉冲激光诱导出冲击波, 使熔池压强增加, 根据

Clausius-Clapeyron 公式可知, 压力的增加会导致熔点增加, 而熔点和温度梯度的变化共同导致了成分过冷区的增加, 因此促进了等轴晶的形成。

以上研究表明, 脉冲激光冲击熔池辅助激光增材可以通过改变熔池的热动力学特征, 促进熔池中的 CET 行为, 加快熔池内气孔逸出, 从而调控成形构件的组织缺陷。通过数值模拟获取脉冲激光作用下熔池的热动力学特征是揭示脉冲激光冲击熔池辅助激光增材制造组织、缺陷调控机制的关键。但目前对于脉冲激光作用于熔池的数值模拟仅开展了初步的研究工作, 并且多是在激光增材的计算流体力学模型基础上增加了激光冲击的热-力边界条件, 所采用的是传统的层流模型, 揭示熔池的温度场和流场变化。然而, 脉冲激光冲击熔池形成的冲击波会导致湍流的形成<sup>[70]</sup>, 层流模型难以准确描述熔池复杂的流动行为, 且超声波和冲击波会在熔池中引入声场和冲击压力场, 揭示其分布特征对于理解晶粒的演化具有重要意义。此外, 虽然该过程并未直接引入残余压应力, 但是其诱发的熔池凝固条件变化、组织特征变化也可能导致残余应力的变化, 这些问题有待进一步研究。

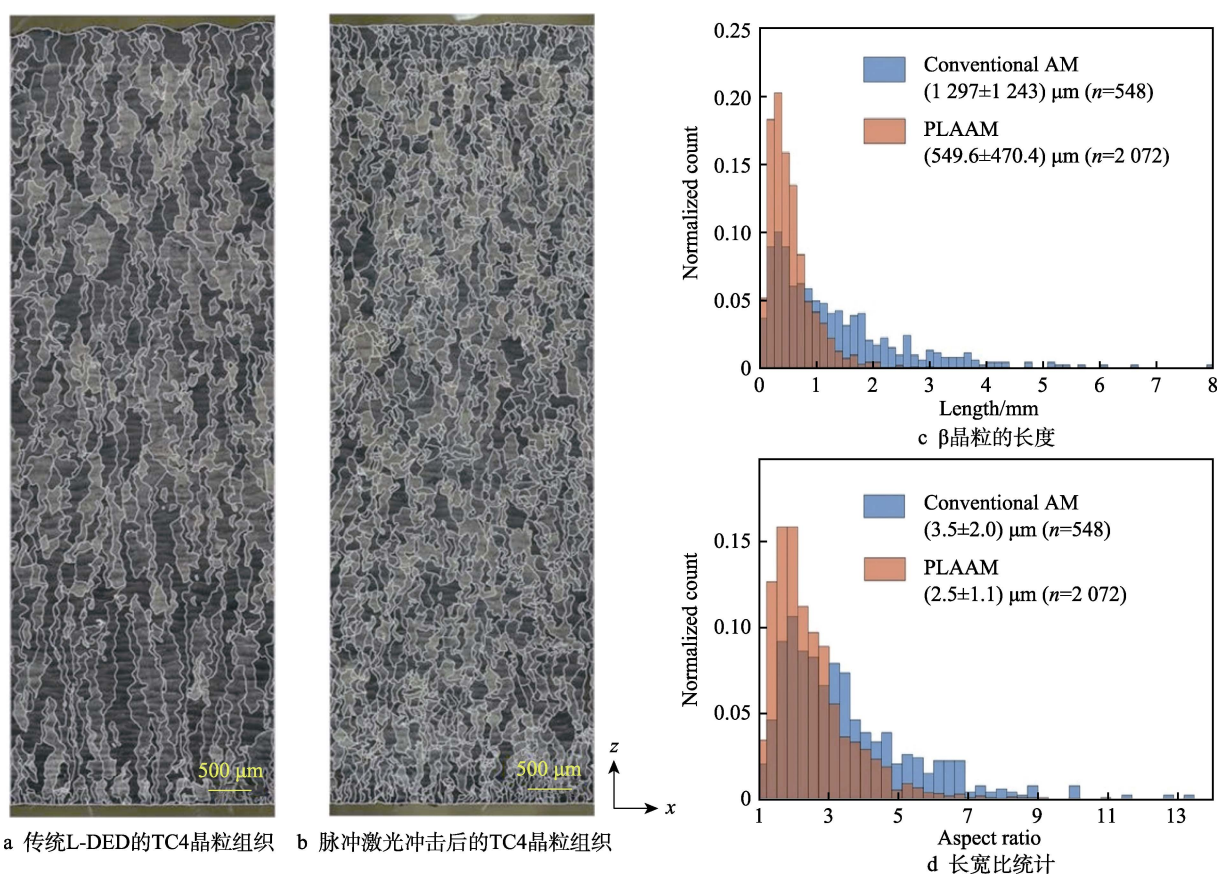


图 10 脉冲激光冲击熔池对 L-DED 成形 TC4 晶粒的影响<sup>[20]</sup>

Fig.10 Effect of pulsed laser shock molten pool on L-DED formed TC4 grain<sup>[20]</sup>: a) TC4 grain structure of traditional L-DED; b) TC4 grain structure after pulse laser shock; c) length of  $\beta$  grain; d) statistics of aspect ratio

### 3 结语

通过上述分析可知,研究者们围绕脉冲激光辅助激光增材已取得了一系列的研究成果。脉冲激光作用于激光增材构件的不同区域、激光增材和脉冲激光作用的不同时序关系将导致构件组织、缺陷及残余应力的调控机理存在差异。当脉冲激光作用于固相区时,主要通过冲击波的力学效应,使表层材料发生塑性变形,引入残余压应力,并改变微观组织。其中,对于非同步式层间和同步式激光冲击强化辅助激光增材制造过程,其组织、缺陷和应力的演化除了受到激光冲击强化过程的影响,还会受到后续激光增材过程热输入的影响,且均比非同步式表面激光冲击强化的方式具有更大范围、更有力的调控效果。当脉冲激光作用于熔池时,主要通过改变熔池的热动力学行为来影响凝固组织和成形缺陷,其调控机理取决于脉冲激光的功率密度、脉冲频率等参数。

由于同步式激光冲击强化辅助激光增材制造和脉冲激光冲击熔池辅助激光增材制造均是“双激光”同步移动的形式,成形效率更高,适用领域更广,因此未来的应用潜力更大。对于同步式激光冲击强化辅助激光增材制造技术,由于难以添加约束层,其冲击强度有限,未来需通过优化锻打温度区间,提高无约束层条件下冲击强化效果,并进一步揭示该过程组织、缺陷和应力的调控机理。对于脉冲激光冲击熔池辅助激光增材制造技术,未来需发展优化该过程的数值模型,定量揭示脉冲激光冲击熔池对熔池热动力学的影响机制和规律,优化脉冲激光工艺参数实现构件组织和缺陷的精准调控。

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