中国激光

面向金属增材制造的拓扑优化设计研究进展

刘博宇[1]，王向明[2]，杨光[1*]，邢本东[2]

[1]沈阳航空航天大学机电工程学院，辽宁 沈阳 110136；

[2]中国航空工业集团公司沈阳飞机设计研究所，辽宁 沈阳 110035

摘要 结构拓扑优化设计以寻求材料最优分布形式与最佳承力路径为目的，在符合结构材料力学特性的前提下，实现结构的轻量化设计。然而拓扑结构往往比较复杂，传统制造技术难以实现精准、快速制造。金属增材制造技术可实现复杂零件的快速制造，极大地拓宽了设计空间。综述了面向金属增材制造技术的结构拓扑优化设计研究进展，从优化拓扑算法的角度，归纳了基于单元网格与边界演化的拓扑优化方法在改善结构连续性与可制造性方面的有效措施；从金属增材制造约束的角度，总结了考虑几何约束、成形约束、材料性能约束的拓扑优化方法，并结合金属增材制造与拓扑优化技术的发展趋势进行了展望。

关键词 激光技术；拓扑优化；金属增材制造；拓扑算法；增材制造约束

中图分类号 TH164 **文献标志码** A **DOI**：10.3788/CJL221485

1 引 言

随着我国航空航天事业的持续发展，航空结构件需满足轻质高效、长航时、高机动性等要求，因此，进一步降低结构质量系数是结构优化设计领域面临的一项严峻挑战[1-3]。传统轻量化设计大多是基于经典结构的等效替换，例如通过新工艺、新材料等精益改善和挖掘结构潜能，现已趋近“天花板”[4]。

拓扑优化技术作为结构优化设计的重要分支[5]，通过定义材料属性、载荷工况与约束条件，寻求给定设计域内材料的最优分布形式，是结构轻量化设计、获得高性能创新构型的有效设计方法，现已被广泛应用到航空航天[6-9]、汽车制造[7-8]等领域中。例如，应用填充微观点阵结构的卫星支架多尺度拓扑优化设计，使卫星支架减重 17%，动态响应减少 25%[8]；考虑切口、保持传统钣金轮廓的涡轮发动机支架的拓扑优化设计，使发动机支架减重 25%；考虑增材制造工艺、扩大设计空间的拓扑优化设计，使发动机支架减重 66%，最大位移减少约 50%[9]；由 30 多个单独部件组成的稳定器前翼梁支架，应用拓扑优化一体化设计，成功实现前翼梁支架减重 30%，显著改善结构性能，提升加工效率[8]。

然而拓扑构型通常较为复杂，受制于传统制造工艺限制，设计人员往往需要简化最优拓扑构型，这导致拓扑优化的结构优势不能充分体现。增材制造技术使用高能束热源，采用“自下而上”材料逐层熔化沉积的叠加方式，无需模具，可实现复杂拓扑构型的快速“自由制造”，解决了结构优化存在的“制造决定设计”的问题[10-11]，极大地拓宽了设计空间。但金属增材制造技术并不是完全“自由制造”技术，仍存在特有的制造约束，如当拓扑构型最小尺寸小于设备精度时，则会出现打印失败现象[12]；受制于设备成形腔与结构热变形限制，增材制造大型构件时，需进行分块与连接处理[13]；增材制造零件有时会沿构建方向出现 20%～40% 的强度损失[14]；对于粉末床增材制造技术，在制造含有封闭孔洞的拓扑结构时会出现内部粉末与支撑难以去除[15]等问题。因此，在拓扑优化设计中考虑增材制造约束，发展面向金属增材制造的拓扑优化设计方法具有重要意义[2,15]。

本文首先介绍了连续体结构拓扑优化的常用方法与特点，对比了不同方法的拓扑优化结果，从算法优化的角度，总结了改善拓扑构型连续性的有效措施。随后，阐述了金属增材制造技术的原理、加工特点与适用范围，归纳了考虑金属增材制造几何尺寸约束、结构成形约束、材料性能约束的拓扑优化方法。最后，讨论了现有拓扑优化与金属增材制造领域的发展方向，为学者们深入研究面向金属增材制造的拓扑优化技术提供参考。

2 连续体结构拓扑优化常用方法与特点

根据优化算法迭代与更新的不同形式，连续体结构拓扑优化可分为：基于单元网格的拓扑优化方法，如

收稿日期：2022-12-05；修回日期：2023-03-09；录用日期：2023-03-23；网络首发日期：2023-03-31

基金项目：国家重点研发计划(2022YFB4600901)、辽宁省教育厅系列项目(LJKZ0198)

通信作者：*yangguang@sau.edu.cn

均匀化法、变密度法、渐进结构法等；基于边界演化的拓扑优化方法，如水平集法、移动可变形组件法、特征驱动结构拓扑优化法等。表 1 列出了连续体结构拓扑优化常用方法与特点。

表 1　连续体结构拓扑优化常用方法与特点

Table1　Common methods and characteristics of continuum structure topology optimization

Common method		Advantage	Shortcoming
Topology optimization based on elements	Homogenization	➢ Classical method, mature principle ➢ Rigorous mathematical model, existing optimal solution	➢ Complex models, being difficult to implement ➢ More intermediate density
	Variable density	➢ Fewer design variables, higher calculation efficiency ➢ Widespread application	Existing numerical instability
	Evolutionary structural optimization	➢ Practical principle, simple algorithm ➢ Avoiding solving difficulties	➢ More iterations and lower calculation efficiency ➢ Existing numerical instability
Topology optimization based on boundary evolution	Level set	➢ Simple principle, clear boundaries ➢ No numerical instability	➢ Stronger initial dependence, being unable to open holes ➢ Weaker convergence
	Moving morphable components/voids	➢ Fewer explicit design variables, higher calculation efficiency ➢ Seamless connection with CAD/CAE software ➢ Clear boundaries	➢ Stronger initial dependence ➢ Existing unsmooth boundary
	Feature-driven	➢ Collaborative design of features and topology optimization ➢ Fewer design variables, higher calculation efficiency, clear boundaries	Stronger dependence on characteristic number and layout

2.1　基于单元网格的拓扑优化方法

均匀化方法[16]通过调整单胞结构的几何尺寸与空间方位函数，寻求结构最优拓扑形式，但是所采用的较为复杂的数学模型限制了其普遍应用。变密度法[17]通过定义每个单元的“伪密度”在 0～1 区间变动，建立了伪密度与弹性模量的关联函数，通过调整惩罚因子(p)，减小中间密度，获得较为清晰的拓扑结构。该方法设计变量较少，计算效率较高，应用更为广泛[图 1(a)]。渐进结构法[18]根据单元灵敏度及应力值等参数，评估并逐步删除低效能材料单元，输出最优拓扑结构，但结构边界处存在锯齿效应[图 1(b)]。

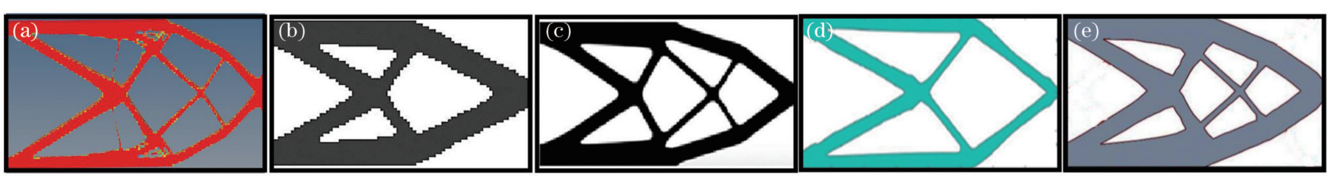

图 1　悬臂梁连续体结构拓扑优化。(a)基于 HyperWorks 的变密度法；(b)渐进结构法[19]；(c)水平集法[20]；(d)移动可变形组件法[21]；(e)特征驱动法[22]

Fig. 1　Continuum structure topology optimization about cantilever beam. (a) Variable density method using HyperWorks; (b) evolutionary structural optimization method[19]; (c) level set method[20]; (d) moving morphable component method[21]; (e) feature-driven method[22]

相较于基于边界演化的拓扑优化方法[图 1(c)～(e)]，基于单元网格的拓扑方法存在着灰度单元、棋盘格式、网格依赖性及局部极值等数值不稳定现象[23]。棋盘格式和灰度单元的存在为拓扑构型的特征提取和制造增加了难度；网格依赖性使拓扑构型中的杆状单元数量增加，可靠性下降；局部极值使拓扑构型难以得到全局最优解。因此，消除拓扑优化结果中的数值不稳定现象，提升拓扑构型的可制造性尤为重要。

如图 2 所示，为了改善灰度单元，可调节材料插值模型的惩罚因子[24-25]与灰度过滤函数[26-27]，减小中间密度值，获得收敛性较好的拓扑结构。棋盘格式和网格依赖性总是同期出现、同时消失，棋盘格式是网格依赖性的另一种表现方式[28]。一般改善网格依赖性的方式也能有效减少结构中的棋盘格式，八节点与九节点等高阶单元法[29]、非协调元法[30]、周长约束法[31-32]及梯度约束法[33]在一定程度上可抑制棋盘格式。或采取基于卷积的滤波方法，如灵敏度过滤法[34]、密度过滤法[35]，通过修改目标函数的单元相对密度与灵敏度，改善数

值不稳定现象。该方法无须增加额外的约束，收敛性较好，计算效率较高，应用更为广泛。此外，选择更加稳定的有限元模式[36]，对拓扑结构进行形状优化，采用光顺处理法[37]及灵敏度再分配技术[38-39]等，可抑制棋盘格式的产生。改善局部极值可以从两方面考虑：一方面，可以优化拓扑算法，寻求更适用于非凸优化问题的全局优化方法，规避一些局部最优解，以输出全局最优解；另一方面，可通过完善迭代初始值与多起点优化，选取更多组初始变量，找到全局最优解，从而获得更好的优化效果。但该方法效率较低，仅适用于简单模型的参数优化，仍有较大发展空间。

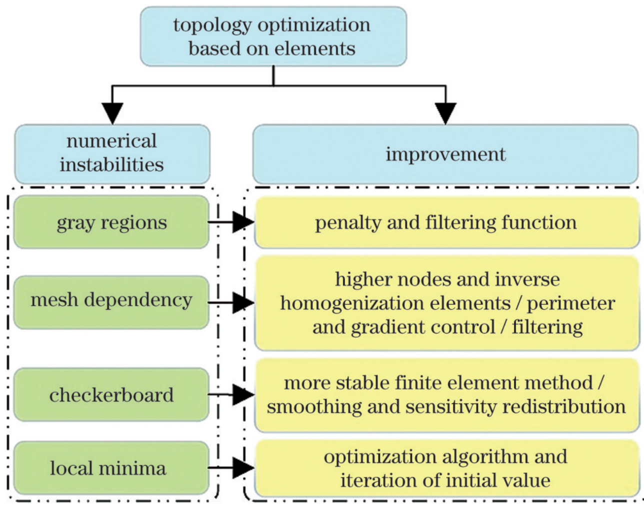

图 2 基于单元网格的拓扑优化方法的数值不稳定现象与改善措施

Fig. 2 Numerical instability and improvement of topology optimization method based on elements

2.2 基于边界演化的拓扑优化方法

水平集法[40]使用零值水平集函数描绘结构边界，使用 Hamilton-Jacobi 方程更新水平集函数，结合形状导数与灵敏度分析技术，寻求最佳拓扑结构。移动可变形组件（MMC）法[41]与移动可变形孔洞（MMV）法[42]通过优化设计域中一系列组件轮廓/孔洞边界的尺寸、位置等显式几何信息，得到不同工况下的最优承力路径。相较于传统水平集方法，MMC/MMV 法所采用的设计变量明显较少，计算效率较高，可与 CAD/CAE 软件无缝连接。特征驱动结构拓扑优化方法[43]结合隐式水平集函数描述的结构轮廓工程特征，通过基于梯度的优化方式控制特征结构的移动、缩放等，实现结构特征与拓扑优化的有效融合。

水平集法具有清晰的结构边界，无数值不稳定现象，但该类方法高度依赖初始参数值，存在不能自主开孔[44]（图 3）与弱收敛等问题。利用拓扑导数[45-46]［图 4(a)］和反应扩散方程[47-50]，可有效解决自主开孔问题。针对初始依赖性，可利用共轭法计算二维与三维线弹性模型的形状导数[51]，或采用最速下降法更新设计变量[52]，或结合基于全局与局部元胞分割框架的遗传算法[53]，改善优化结果初始依赖性。

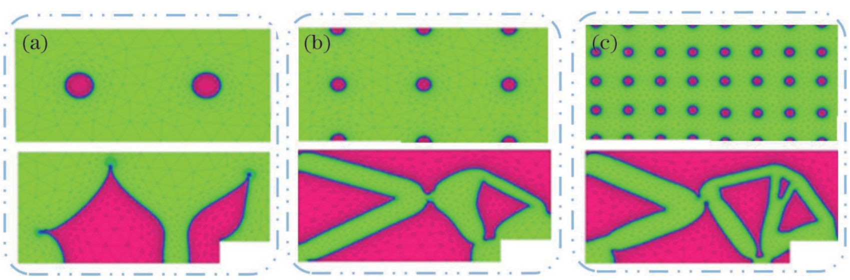

图 3 水平集法初始依赖性与不能自主开孔问题[44]。(a) 2 个初始孔洞；(b) 9 个初始孔洞；(c) 40 个初始孔洞

Fig. 3 Initial dependence and inability to open holes of level set method[44]. (a) 2 initial holes; (b) 9 initial holes; (c) 40 initial holes

针对弱收敛问题，Luo 等[54]提出基于紧支撑径向基函数，采用更稳定、更高效的积分形式，实现 Hamilton-Jacobi 方程在时间与空间上的解耦，改善传统水平集法求解困难等弱收敛问题。Guirguis 等[55]基于 Kriging［图 4(b)］与 RBF 插值模型，提出一种无导数的水平集方法，使用模式搜索的算法，减少有限元分析时间，改善结构初始依赖性及边界振荡等弱收敛问题。Dunning 等[56]提出一种求解多约束问题与优化非水平集设计变量的新方法，获得了平滑的速度函数，改善了计算稳定性与收敛性。Yaji 等[44]提出对流水平集方法，将符号距离函数映射为光滑的双曲正切函数，将初始化过程嵌入到时间演化方程中，减少额外的计算过程，获得了结构稳定、收敛性较好的拓扑结构。曲东越等[50]提出拉格朗日乘子直接与间接控制法，减少了迭代过程中拉格朗日乘子的振荡现象，有效改善了优化结果的收敛性。此外，采用优化形状导数[57-58]、扩展有限元方法[59-60]、有限胞元方法[61-63]、等几何分析法[64-65]和协调网格[66]等方法，可有效限制迭代步长，提升计算精度与稳定性，改善水平集法的弱收敛问题。

尽管基于显式拓扑框架的移动可变形组件/孔洞法设计变量较少，计算效率较高，优化设计结果边界清晰，可与 CAD/CAE 软件实现无缝衔接，但该方法存在一定的初始依赖性[67-68]及结构低连续性［图 1(d)］。引入卷积算子与 KS 函数[69]，构建基于 R 函数和格雷维尔配点策略的显式拓扑框架[70]，利用兼顾超弹性与有限变形的显式拓扑框架[71]，可有效改善迭代收敛性与结构低连续性。

现有拓扑优化方法往往仅考虑结构力学性能提

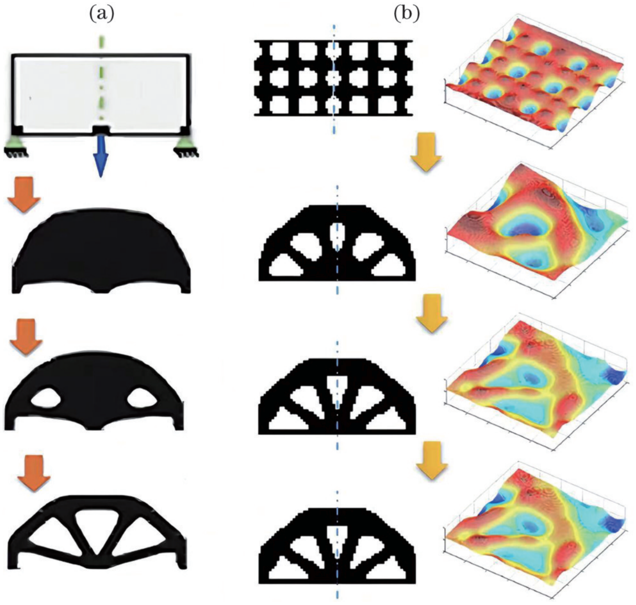

图4 MBB梁水平集拓扑优化。(a)拓扑导数[45];(b)PS-Kriging插值[55]

Fig. 4 MBB beam level set topology optimization. (a) Topological gradient[45]; (b) PS-Kriging interpolation[55]

升,而忽视了拓扑结构工程特征属性,常采取先性能后特征的设计模式,可能难以同时满足结构力学性能与工程特征的设计要求。特征驱动结构拓扑优化方法将结构工程特征贯穿到模型构建、有限元分析与拓扑优化整个流程中,设计变量规模较小,在求解大型工程问题时具有明显优势。然而,其优化结果对特征数目与布局有较强的依赖性。借助拓扑导数可以改善与消除结构初始依赖性,结合一阶符号距离函数与KS函数,可获得结构清晰的优化模型[72]。

3 金属增材制造技术原理与特点

增材制造技术是制造业的"革命性"飞跃,打破了传统制造技术的局限,解决了产品研发存在的"制造决定设计"问题。金属增材制造技术作为重要分支,已成为当前实施技术创新、提振本国制造水平的关键着力点[73-74]。如图5所示[73,75-78],主流的金属增材制造热源形式有激光、电子束与电弧,依据预先铺粉或同步送粉/送丝的不同材料进给方式,金属增材制造包括粉末床熔融[79-80]技术和定向能量沉积[81]技术两类,其中,基于粉末床熔融的增材制造技术主要有激光选区熔化技术[82]和电子束选区熔化[83]技术,基于定向能量沉积的增材制造技术主要有激光金属沉积[84-86]技术、电子束自由成形制造[87]技术、电弧增材制造[88]技术。

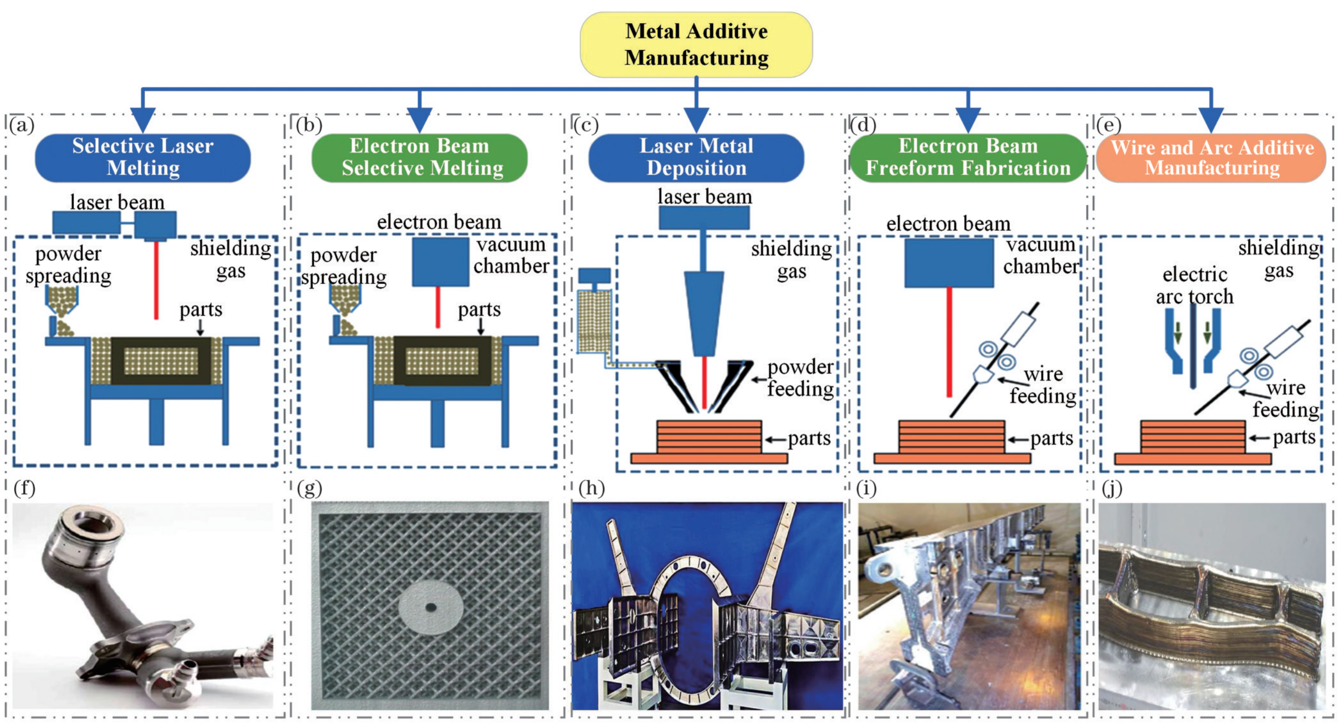

图5 金属增材制造技术。(a)~(e)原理图[75];(f)~(j)产品[73,76-78]

Fig. 5 Metal additive manufacturing technologies. (a)-(e) Schematics[75]; (f)-(j) products[73,76-78]

3.1 粉末床熔融增材制造技术

粉末床熔融技术通过对三维模型进行分层切片处理来提取每层轮廓信息,规划热源(激光、电子束)扫描路径与打印方向,逐层熔化预先铺放的金属粉末,实现自下而上的材料逐层叠加的零件快速制造。成形件精度较高、表面质量较好,结构复杂性基本不受限。但成形效率较低,成形尺寸受限,故主要应用于小批量、中小尺寸、结构较为复杂的零件加工与模具制造。

3.1.1 激光选区熔化技术

激光选区熔化(SLM)技术基于惰性气体的工作

环境[图 5(a)],使用激光高能束有选择性地逐层熔化金属粉末,实现复杂结构"净成形"制造。SLM 技术中的粉末粒径较小,分层层厚较薄,可实现粉末完全熔化与快速凝固。激光功率与光斑直径较小,成形材料晶粒细小,成形件尺寸精度和表面质量优于其他增材制造技术[77,89],在飞机栅格、发动机喷油嘴等复杂构件制造方面具有明显优势。但成形尺寸受限,成形效率较低,材料与设备成本较高,加工过程中易出现翘曲及粉末未熔合与球化等现象。这项技术主要适用于具有复杂内腔结构的中小尺寸零件制造[90]。

3.1.2　电子束选区熔化技术

电子束选区熔化(EBSM)技术使用电磁线圈精准且快速地驱动电子束逐层熔化金属粉末[图 5(b)],实时调节束流参数,控制零件表面温度,减少缺陷与变形。在真空环境下,材料无污染、无反射,预热温度可达到 1000 K 以上,可消除残余应力、抑制变形[75],加工精度与表面质量较高,成形件力学性能较好[77]。EBSM 技术中的电子束能量密度高,成形速度快,是 SLM 技术的数倍[77],但扫描速度更快,导致表面质量不如 SLM[91]。真空环境限制了零件制造空间,设备成本高,故更适用于裂纹倾向较高的钛、铝等硬脆金属材料的快速加工[92]。

3.2　定向能量沉积增材制造技术

定向能量沉积技术选用金属粉末/丝材为原材料,依据三维模型进行分层切片与轮廓提取,规划沉积路径,使用高能束(激光、电子束、电弧)为热源,逐层熔化与沉积,实现零件快速制造。相比粉末床熔融技术,定向能量沉积技术具有成形效率更高、成形结构尺寸更大的技术优势[93],但成形复杂度较低,成形精度较差,须结合后处理技术改善零件表面质量。

3.2.1　激光金属沉积技术

激光金属沉积(LMD)技术是在惰性气体的工作环境下,利用激光逐层熔化金属粉末,实现结构零件的"近净成形"[图 5(c)]。LMD 技术的沉积速率可达 0.5 kg/h[94],材料利用率较高,成形尺寸基本不受限制,可实现与锻件力学性能相当的复杂结构的快速制造[87]、多种材料复合及梯度材料的制备与修复[95]。但结构零件成形精度(毫米级)较低[96-97],表面质量较差[98],故 LMD 技术适用于大尺寸金属零件毛坯的加工及薄壁形状整体构件的快速成形[99]。

3.2.2　电子束自由成形制造技术

电子束自由成形制造(EBF)技术是基于真空环境,运用高能量密度的电子束冲击并熔化金属丝材,依据预设轨迹移动与逐层累积,实现零件的快速加工与制造[图 5(d)]。电子束扫描系统对熔池进行旋转搅拌,残余应力较小,结构内部质量较好,沉积速率较高[78]。EBF 技术可实现钛、铝合金等材料的加工与制造,特别适用于太空微重力真空环境下的零件成形,对于航天器维修与维护及深空探测具有重要现实意义[100]。但 EBF 技术需要较高真空度,设备造价高,零件成形精度较低,表面质量较差,故主要适用于大型非关键件的制造。

3.2.3　电弧增材制造技术

电弧增材制造(WAAM)技术利用熔化极惰性气体保护焊、非熔化钨极惰性气体保护焊及等离子弧焊等焊接方法产生的电弧作为热源[图 5(e)],以金属焊丝为原材料,在惰性气体的环境下,通过逐层熔化与沉积的方式,实现零件快速成形。WAAM 技术沉积速率高,成形件具有较好的强度与韧性[78],采用电弧为热源,可加工铜合金与铝合金等高反射率的金属材料[95]。设备成本低,材料利用率较高,成形尺寸几乎不受限制[101]。但热影响区较大,易受到多重因素影响,导致缺陷累积[101],成形件尺寸精度与表面质量相对较差,主要适用于较大尺寸的中低复杂度零件的高效、快速、经济加工。

4　面向金属增材制造的拓扑优化设计研究进展

金属增材制造技术虽有效解决了复杂拓扑结构可制造性差的问题,但仍存在某些制造约束,如当结构最小尺寸小于束斑直径时,零件实际打印轮廓会超出设计轮廓;激光选区熔化技术所能制造的零件几何尺寸受限;当悬垂角度选择不当时,会产生零件装配孔材料塌陷[图 6(a)]、支撑结构断裂[图 6(b)]等现象;采用粉末床增材制造技术时,制造的含有封闭孔洞的结构存在内部粉末与支撑无法去除[102]等问题[图 6(c)]。因此,在拓扑优化设计中需同时考虑结构几何约束、成

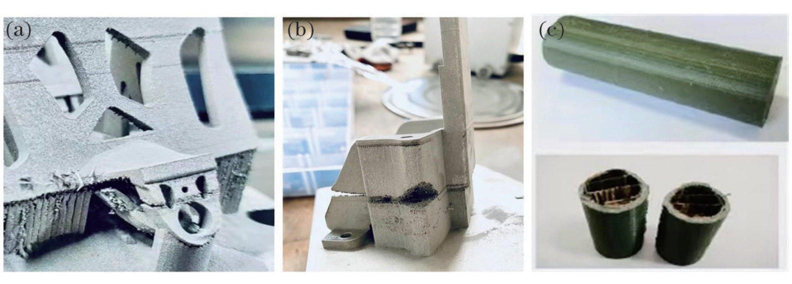

图 6　增材制造打印失效[102]。(a)装配孔材料塌陷;(b)支撑结构断裂;(c)内部支撑无法去除

Fig. 6　Additive manufacturing printing failure[102]. (a) Assembly hole material collapse; (b) fracture of support structure; (c) internal support cannot be removed

形约束、材料性能约束等多种增材制造约束(图 7),从产品拓扑优化设计源头改善制造工艺局限性,以实现结构设计制造的一体化[103-104]。表 2 列出了考虑金属增材制造约束的拓扑优化常用方法。

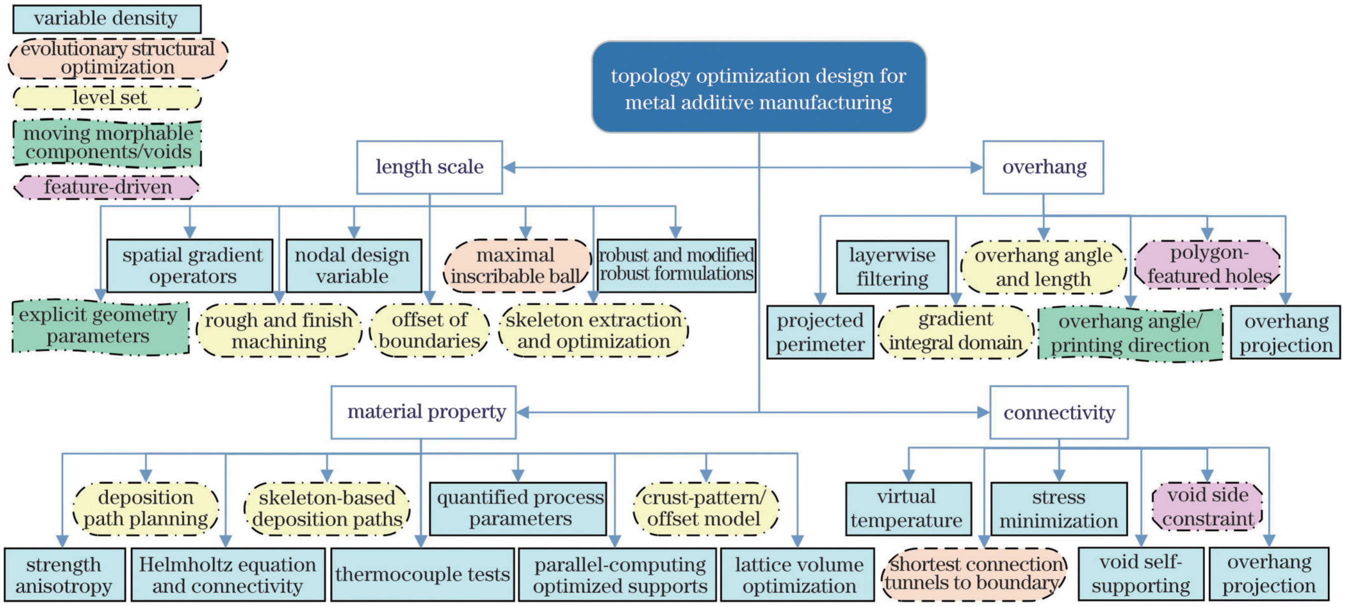

图 7　面向金属增材制造的拓扑优化设计

Fig. 7　Topology optimization design for metal additive manufacturing

表 2　考虑金属增材制造约束的拓扑优化常用方法

Table 2　Topology optimization common methods considering constraints of metal additive manufacturing

Constraint	Method based on element		Method based on boundary evolution		Prospect
	Name	Characteristic	Name	Characteristic	
Geometric constraints	Projection functions	No additional constraints, but boundary fading effects	Skeleton extraction	Smooth convergence, but additional calculation	➢ New methods with clear structure, stable convergence, and precise dimensional control ➢ New methods for specific additive manufacturing processes
	Robust formulations	Stable convergence, eliminating one-node hinges, but more calculation	Quadratic energy functions	High calculation efficiency, but not accurately controlling	
	Spatial gradient operators	Less calculation, but appropriate selections of parameters	MMC	Explicit geometry parameters, accurately controlling	
Forming constraints	Projection and filtering	No additional constraints, but more gray units; less calculation efficiency	Gradient integral domain	Simpler shape derivatives, better convergence and performance	➢ Specific additive manufacturing 3D models with overhang length and angle ➢ Considering strength, building direction, size, and overhang constraints together
	N-VTM	Enclosed voids self-supporting, better performance	MMC/MMV	Better boundary and performance, but initial dependency	
	BESO	Connecting voids with boundary, less structural loss	Overhang length and angle	Controlling overhang length and angle, better performance	
	Electrostatic model	Strength-based, improving stress concentration	Side constraint	No additional constraints, but appropriate selections of parameters	
Material property constraints	Strength anisotropy	Considering building direction to improve bearing capacity	Deposition path planning	Fitting real print paths and improving structure performance based on fixed geometry	➢ Accurate anisotropic models for multiple additive manufacturing process parameters ➢ Accurate models for non-uniform deformation ➢ Considering geometry's influence on inherent strain value
	Quantified process parameters	Anisotropic data matrix to optimize complex structures			
	Inherent strain model	Predicting residual distortion and stress, but mainly improving layered distortion			

4.1　考虑结构几何约束的拓扑优化方法

拓扑构型往往有细小的杆状分支，若杆状最小尺寸小于高能束的束斑直径、结构最大几何尺寸大于设备成形腔尺寸，则存在无法制造的难题。因此合理设计结构构型及分块与连接方式，利用考虑增材制造成形件几何约束的拓扑优化方法，可有效降低加工难度，减少结构热变形。学者们主要从最大、最小尺寸约束两个方面出发。

4.1.1　考虑最小尺寸约束的拓扑优化设计

基于单元网格的最小尺寸优化方法主要有投影滤波函数、鲁棒公式、功能梯度函数等。Guest 等[105]使用节点体积分数为设计变量，将其投影到由单元质心和最小允许半径确定的单元空间，提出线性投影函数和使用正则化 Heaviside 阶跃函数的非线性投影函数，实现最小尺寸控制。但线性投影函数在边界处存在衰落效应[图 8(a)]，拓扑构型存在单节点铰链问题。Sigmund[106]提出基于三场映射的鲁棒公式模型，该方法收敛稳定、结果清晰且尺寸特征可控[图 8(b)]，但隐式表述的模型不能准确控制结构尺寸，计算量较大。随后 Wang 等[107]提出改进鲁棒公式，消除数值伪影，改善单节点铰链问题，实现拓扑结构局部与全局收敛。Zhou 等[108]基于滤波阈值和正则化物理场，定义结构指标函数与几何约束，提出一种计算成本低、易于应用的最小尺寸控制新方法[图 8(c)]。随后 Yang 等[109]比较了不同梯度算子，在鲁棒公式中施加最小尺寸约束，提出新的结构指标函数，更准确地捕捉结构拐点区域与空间梯度信息，优化结构最小尺寸。Rong 等[110]使用两组协调设计变量的密度过滤器及 Heaviside 函数，实现了固相与空相最小尺寸控制。

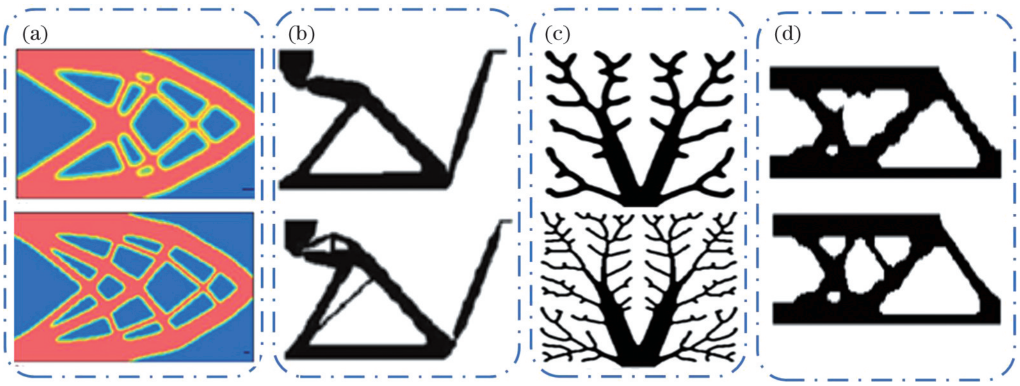

图 8　考虑最小尺寸约束的拓扑优化。(a)节点设计变量与投影函数[105]；(b)鲁棒公式[106]；(c)空间梯度算子[108]；(d)骨架提取与最小特征优化[12]

Fig. 8　Topology optimization considering minimum size constraint. (a) Nodal design variable and projection functions[105]; (b) robust formulation[106]; (c) spatial gradient operators[108]; (d) skeleton extraction and minimum feature optimization[12]

针对基于边界演化的拓扑方法，学者们提出一系列最小尺寸约束函数。Chen 等[111]在目标函数中引入二次能量泛函，将几何特征尺寸信息引入到水平集框架中，实现梁状柔性机构最小尺寸优化。随后 Luo 等[112]将二次能量泛函引入到无铰链柔性机构中，对原始目标函数进行增广处理，采用半隐式算法，避免了传统水平集方法存在的数值求解困难问题，实现了更为高效的结构最小特征尺寸控制与优化，但该方法未提供明确的几何信息，无法实现结构最小尺寸的精确控制。Liu 等[12]提取拓扑优化结果骨架[图 8(d)]，采用滤波函数优化尺寸较小的精细结构，提出一种自适应 B 样条曲线拟合方法，获得了边界点云密度更大、更为平滑的参数化拓扑结果，实现了结构最小特征尺寸控制与优化。Dunning[113]提出基于参数化隐式函数的显式最小尺寸约束函数，实现固相与空相的最小尺寸控制。Zhang 等[114]基于移动变形组件法，通过设置一组显式几何参数下限，直观、明确地控制结构最小尺寸。Liu 等[115]应用符号距离函数及计算边界曲率建立粗加工与精加工最小尺寸约束函数，实现两种加工状态的最小尺寸控制。

4.1.2　考虑最大尺寸约束的拓扑优化设计

Guest[116]以映射方法[105]为基础，构建基于局部区域体积比的最大尺寸约束，靳绍猛[19]基于双向渐进结构法定义最大尺寸约束，皆实现了结构最大尺寸控制。Zhang 等[117]基于固体各向同性材料惩罚模型，提取拓扑结构骨架，实现了结构最大/最小尺寸控制。

Guo 等[118]基于水平集框架提出显式几何尺寸控制方法，通过限制符号距离函数的最大/最小值，同时实现了结构最大/最小尺寸精确控制。Xia 等[119]引入内切圆的概念，通过约束结构边界到骨架的距离，实现了结构最大/最小尺寸控制。Wang 等[120]将结构边界与水平集轮廓曲线进行偏移，建立基于偏移距离的显式特征尺寸约束函数，实现了结构最大/最小尺寸精确控制，该方法不需要提取几何骨架，可有效提升计算效率。白伟等[121]通过构造映射新模型与全局约束函数，对违反最大尺寸约束的单元实行“挖孔”处理，结合鲁棒公式，实现结构最大/最小尺寸协同控制。Niu 等[122]基于移动可变形组件方法，通过调整组件宽度的上下

限，实现结构最大/最小尺寸控制。Liu[13]通过识别与分割结构骨架，提出基于分段长度的尺度控制与滤波方法，实现了结构动态极限尺寸控制。

总体来说，考虑结构几何尺寸约束的研究较为完善，几何尺寸约束现已集成到OptiStruct等商用软件中。但引入滤波器与非线性投影函数后，在结构边界处存在灰度单元，需结合适当的后处理技术加以完善。引入梯度约束、几何尺寸约束后，计算量较大，计算效率与稳定性有待提升。因此，结构清晰、稳定收敛及便于数值实现与精确控制特征尺寸的新方法有一定发展空间。此外，针对多喷头打印、打印方向精度等特定增材制造工艺的特征尺寸控制新方法仍有待完善。

4.2 考虑结构成形约束的拓扑优化方法

由于增材制造逐层加工的特征，大悬垂结构需调整悬垂角度与长度并添加支撑结构以防止材料坍塌；增材制造过程中存在较大的温度梯度，支撑结构可以将上层热量传递到基板，减小热应力与变形，提升结构精度与表面质量，但成形完成后支撑结构的添加与去除会增加材料成本与打印时间。此外，若结构内部存在封闭孔洞，粉末床增材制造技术易出现内部粉末与支撑无法去除等问题。因此，考虑结构成形约束的拓扑优化方法备受关注。

4.2.1 考虑悬垂角度与悬垂长度的拓扑优化设计

考虑悬垂角度与长度的结构自支撑优化设计可有效提升结构可制造性与经济性。学者们主要从悬垂角度与长度约束方面开展深入研究。Leary等[123]通过改变结构几何形状、角度等参数并采用适当的后处理技术，避免了大悬垂结构的材料坍塌现象。Brackett等[124]基于双向渐进结构法，设定悬垂角度与悬垂长度成正比，实现了自支撑优化。Langelaar[125]提出三维增材制造滤波器，严格将违反悬垂角约束的几何形状排除在设计空间之外，实现了三维结构的自支撑设计。Qian[126]提出基于投影周长约束和密度灰度约束的悬垂角度控制新方法，应用Heaviside投影积分函数，协同优化中间密度，引入基于侧区的投影周长约束，避免了边界不可打印现象。Gaynor等[127]在Heaviside投影中嵌入悬垂角度约束，实现了最小长度尺度与悬垂角度控制[图9(a)]，但引入滤波函数会使结构边界处出现中间密度，相较于其他方法[图9(b)～(d)]，结构性能牺牲较大。

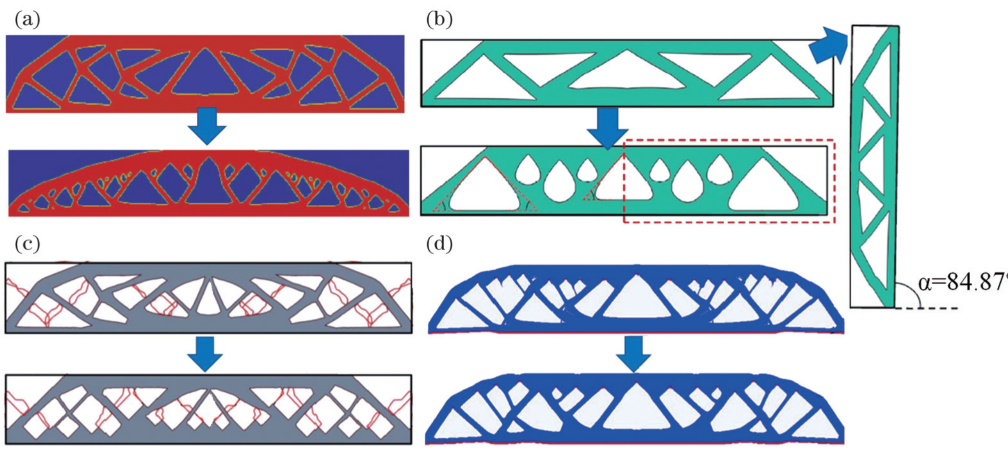

图9 MBB梁自支撑优化。(a)悬垂投影约束[127]；(b)优化悬垂角度与打印方向[21]；(c)多边形特征孔[22]；(d)非线性虚拟温度场[128]

Fig. 9 MBB beam self-supporting optimization. (a) Overhang projection constraint[127]; (b) optimizing overhang angle and printing direction[21]; (c) polygon-featured holes[22]; (d) nonlinear virtual temperature method[128]

Wang等[129]提出一种水平集函数梯度积分域的悬垂约束形式，使用单域积分代替点约束，利用水平集函数符号距离性质，简化悬垂约束形状导数，避免惩罚参数值过大导致的弱收敛问题，获得相对平滑、自然的结构边界。Guo等[21]提出基于移动可变形组件/孔洞的显式拓扑优化框架，协同考虑悬垂角度与工作平面倾斜角度，结构性能牺牲小，可以以更明确、更自然的几何处理方式实现结构自支撑优化[图9(b)]。Zhang等[22]基于固定网格和高阶B样条曲线，引入多边形特征孔作为设计源语，通过定义比率设计变量控制悬垂角度，自动检查并逐步优化V形不可打印区域，实现结构悬垂角度控制[图9(c)]。Liu等[130]基于熔融沉积制造技术，指出自支撑结构与悬垂角度、悬垂长度等多个因素相关，提出一种基于骨架提取的结构分解法，综合考虑悬垂长度与悬垂角度，实现了结构自支撑优化设计。

总而言之，采用基于单元网格投影与过滤的自支撑拓扑方法，优化后结构性能损失较大，存在边界振荡等不足，有待研究结构清晰、收敛性好的三维空间滤波器。采用基于边界演化的悬垂约束控制方法，结构性能损失较小，但存在V形不可打印区域，结构连续性有待完善。现有方法多是引入全局悬垂角度约束，针对支撑去除较为容易的外轮廓，可通过优化支撑质量与数量，减少结构性能损失。此外，考虑特定增材制造工艺，协同优化悬垂长度与倾角的拓扑优化具有一定发展前景。

4.2.2　考虑连通性约束的拓扑优化设计

考虑结构连通性约束的拓扑优化设计，主要从消除孔洞、构建孔洞与边界的连接隧道及实现孔洞自支撑入手。Liu 等[102]提出一种虚拟温度场，将含有封闭孔洞的连通性约束转为最大温度梯度约束，实现熔化粉末流动与水溶性支撑去除[图 10(a)]。Xiong 等[131]基于双向渐进结构(BESO)法，生成连接封闭孔洞与结构边界的最短隧道，结构性能牺牲较少[图 10(b)]。Zhou 等[132]提出将具有孔洞特征的中心点限制在设计域之外的边约束方法[图 10(c)]，改善了结构连通性，但相关参数的选择直接影响灵敏度计算精度。王超等[133]提出了基于泊松方程的静电场物理模型，协同考虑结构强度与封闭孔洞连通性，有效改善了结构应力集中与连通性(图 10(d))。

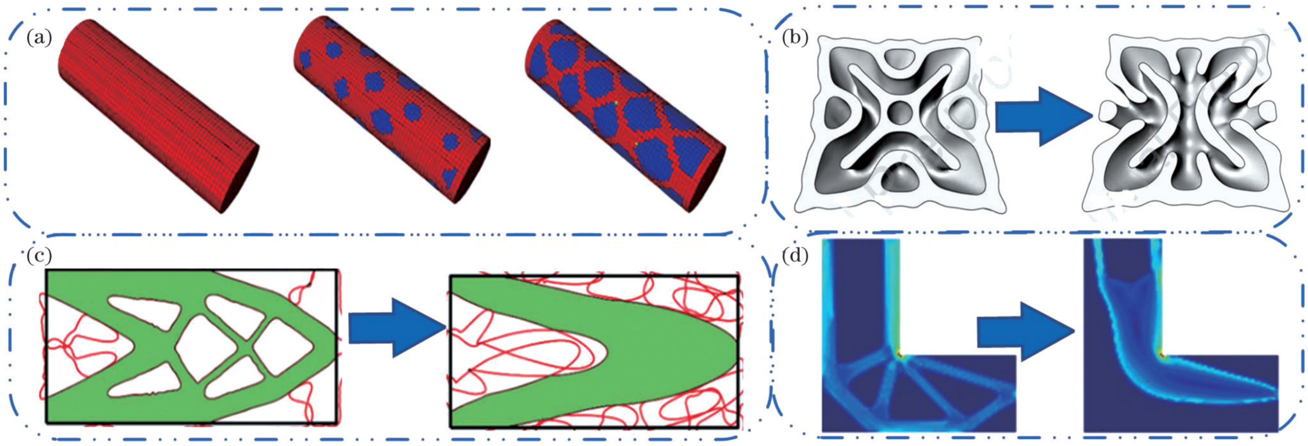

图 10　考虑连通性约束的拓扑优化。(a)虚拟温度场[102]；(b)最短连接隧道[131]；(c)边约束[132]；(d)应力最小化[133]

Fig. 10　Topology optimization considering connectivity constraints. (a) Virtual temperature method[102]; (b) shortest connection tunnels[131]; (c) side constraint[132]; (d) stress minimization[133]

Luo 等[128]使用非线性虚拟温度场(N-VTM)识别封闭孔洞[图 9(d)]，应用多重滤波与投影函数识别悬垂界面，应用基于对数函数的约束，控制悬垂角度，在结构性能牺牲较少的前提下实现封闭孔洞自支撑优化设计。Gaynor 等[134]考虑到增材制造逐层加工的工艺特点，结合空相投影法与悬垂结构投影法，通过连接封闭孔洞与零件外表面，消除了结构封闭孔洞。

考虑结构连通性约束的拓扑优化设计可有效提升结构可制造性，但消除封闭孔洞往往以牺牲柔度为代价。构建孔洞与边界的最短连接隧道以实现封闭孔洞自支撑等方法可有效减少结构性能损失，具有重要参考价值。此外，现有方法往往是基于单一特征的优化，协同考虑结构强度、构建方向、尺寸约束与成形约束具有重要现实意义。

4.3　考虑材料性能约束的拓扑优化方法

相较于传统制造技术，金属增材制造技术制备的零件存在材料各向异性、残余热应力与变形、翘曲与开裂等缺陷与不足，因此，考虑材料性能约束的拓扑优化方法具有重要现实意义。

4.3.1　考虑材料各向异性的拓扑优化设计

增材制造逐层叠加的成形方式使显微组织与力学特性具有一定的方向性，呈现出材料各向异性，因此合理规划沉积路径与构建方向，设计考虑材料各向异性的拓扑结构，可有效提高结构的承载能力与使用寿命。

Liu 等[135]通过提取等值水平集轮廓来计算沉积路径，消除了域积分项，简化了灵敏度分析结果，大部分沉积路径与主应力方向保持一致；针对固定几何形状，提出一种多步方法，实现了优化结果的快速光滑收敛。Liu 等[136]采用多个水平集函数表示每层切片轮廓，提出基于轮廓偏移和骨架提取的沉积路径优化模式，实现了材料各向异性与自支撑约束的协同优化。Mirzendehdel 等[14]提出一种基于广义失效准则的各向异性强度灵敏度分析方法，考虑了构建方向拉伸强度低于其他方向各向异性强度的设计准则，提升了构建方向的极限承载能力[图 11(a)]。Dapogny 等[137]引入地壳模型与偏移模型，模拟增材制造过程中分层切片与打印路径导致的材料各向异性，假设结构边界地壳材料和内部填充区域存在不同的力学性能，并将模型扩展到沿轮廓偏移的路径规划模型，两种简化模型仅依赖于形状几何参数，优化结果更加贴近真实打印路径。Li 等[138]提出一种增材制造驱动拓扑优化的方法，量化打印参数与材料各向异性相关函数，将各向异性实验数据引入到弹性矩阵中，协同优化构建方向及拓扑结构[图 11(b)]。王天赐等[139]基于各向异性 Helmholtz 方程，实现了封闭孔洞连通性约束与材料各向异性协同优化。

现阶段考虑材料各向异性的拓扑模型过于简化。结合增材制造过程，建立多元工艺参数下的各向异性精准三维模型，构建特定增材制造工艺参数与材料性能的定量相关性，提升数值稳定性与计算效率等方面仍有待完善。

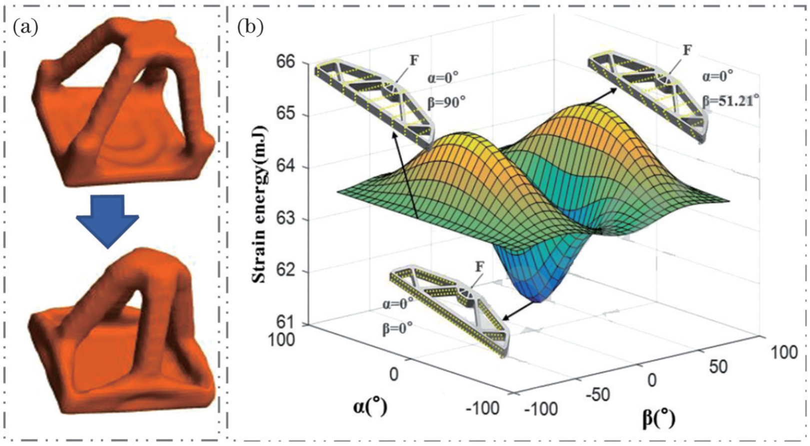

图 11　考虑材料各向异性的拓扑优化。(a)强度各向异性[14]；(b)量化增材制造工艺参数[138]

Fig. 11　Topology optimization considering material anisotropy. (a) Strength anisotropy[14]; (b) quantified additive manufacturing process parameters[138]

4.3.2　考虑残余应力与变形等制造缺陷的拓扑优化设计

金属增材制造技术在逐层快速加热与迅速冷却过程中，较大的温度梯度易引起结构内部残余热应力累积，导致结构翘曲变形与开裂等问题。因此，考虑残余应力与变形等制造缺陷的拓扑优化设计，可有效提升拓扑结构工艺性与可靠性。Chen 等[140]基于固有应变法，通过热电偶实验修正热源参数与热边界条件，提取固有应变作为热膨胀系数，预测零件残余应力与变形。Zhang 等[141]提出密度拓扑优化与固有应变法的并行计算模型，设计仅在重力与残余应力下的刚性更好的支撑结构，改善了结构残余变形，提升了计算效率。Takezawa 等[142]提出基于逐层固有应变法的晶格结构分布优化方法，结合灵敏度分析技术，模拟增材制造逐层叠加的过程，输出有效弹性模量，控制残余变形。

该领域现有研究主要集中在固有应变法的分层变形研究方面，轮廓扫描对表面残余应力的影响尚未量化，过程仿真模型仅模拟各层内部区域扫描，忽略了激光扫描速度较高、功率较低的边界轮廓扫描。为提高零件残余应力与变形的预测精度，应考虑零件几何形状对固有应变值的热效应影响，不同高度层可能经历不同的热积累。此外，非均匀变形的固有应变精确模型对提升预测精度与效率具有一定现实意义。

5　结束语

拓扑优化设计可以依据材料属性、约束条件及载荷工况，在给定设计区域内寻求材料最佳分布形式与最优承力路径，实现高性能轻量化设计。金属增材制造技术基于高能束热源，采用快速熔化与逐层叠加的成形方式，可实现复杂拓扑构型的快速原型制造与实体自由制造。将拓扑优化设计与金属增材制造结合，归纳了基于单元网格与边界演化的拓扑优化方法在改善结构连续性与可制造性方面的有效措施，总结了考虑金属增材制造几何尺寸约束、成形约束及材料性能约束的拓扑优化方法，为学者们进一步研究面向金属增材制造的拓扑优化设计提供了参考。

拓扑优化设计存在设计变量巨大、计算效率较低、求解困难、弱收敛等不足，现有拓扑优化算法往往难以输出可直接应用于增材制造的结构性能最优解，学者们往往基于最优拓扑构型进行二次简化设计，损失了结构性能。因此，结合并行计算技术，开展设计变量较少、收敛性较好的算法研究以输出可直接应用于增材制造的最优拓扑结构具有重要现实意义。

宏观拓扑优化与微观点阵结构研究日趋完善，将宏观拓扑优化设计与微观点阵结构有效融合，建立多尺度结构之间的高度衔接性，充分利用拓扑优化的高性能构型及增材制造提供的广阔设计空间，追求高性能的轻量化设计具有广阔发展前景。

考虑金属增材制造约束的拓扑优化方法采用较为理想的材料模型，与金属增材制造技术实际打印过程存在一定的差异，因此，通过建立多元工艺参数下的材料各向异性精准拓扑模型，量化金属增材制造设备工艺参数，模拟金属增材制造加工过程及预测零件翘曲变形与开裂，可有效减少残余应力与变形，改善成形精度与表面质量。

面向金属增材制造的拓扑优化往往是基于单一材料的优化，将多材料、拓扑优化及金属增材制造有效结合，研究功能梯度材料的拓扑优化设计与金属增材制造技术，实现材料、结构、工艺、性能一体化设计，是追求高性能、多功能、轻量化的又一突破点。

参　考　文　献

[1]　Zhu J H, Zhang W H, Xia L. Topology optimization in aircraft and aerospace structures design[J]. Archives of Computational Methods in Engineering, 2016, 23(4): 595-622.

[2]　朱继宏, 周涵, 王创, 等. 面向增材制造的拓扑优化技术发展现状与未来[J]. 航空制造技术, 2020, 63(10): 24-38.
Zhu J H, Zhou H, Wang C, et al. Status and future of topology

optimization for additive manufacturing[J]. Aeronautical Manufacturing Technology, 2020, 63(10): 24-38.

[3] 全栋梁，时光辉，关成启，等. 结构优化技术在高速飞行器上的应用与面临的挑战[J]. 力学与实践, 2019, 41(4): 373-381, 415.
Quan D L, Shi G H, Guan C Q, et al. Applications and challenges of structural optimization in high-speed aerocraft[J]. Mechanics in Engineering, 2019, 41(4): 373-381, 415.

[4] 王向明. 飞机新概念结构设计与工程应用[J]. 航空科学技术, 2020, 31(4): 1-7.
Wang X M. New concept structure design and engineering application of aircraft[J]. Aeronautical Science & Technology, 2020, 31(4): 1-7.

[5] White D A, Voronin A. A computational study of symmetry and well-posedness of structural topology optimization[J]. Structural and Multidisciplinary Optimization, 2019, 59(3): 759-766.

[6] Shi G H, Guan C Q, Quan D L, et al. An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing[J]. Chinese Journal of Aeronautics, 2020, 33(4): 1252-1259.

[7] Jankovics D, Barari A. Customization of automotive structural components using additive manufacturing and topology optimization [J]. IFAC-PapersOnLine, 2019, 52(10): 212-217.

[8] Zhu J H, Zhou H, Wang C, et al. A review of topology optimization for additive manufacturing: status and challenges[J]. Chinese Journal of Aeronautics, 2021, 34(1): 91-110.

[9] Taylor B, Zeinalov J, Kim I Y. Topology optimization of large scale turbine engine bracket assembly with additive manufacturing considerations[M]//Schumacher A, Vietor T, Fiebig S, et al. World congress of structural and multidisciplinary optimization. Cham: Springer, 2018: 1211-1223.

[10] DebRoy T, Wei H L, Zuback J S, et al. Additive manufacturing of metallic components-process, structure and properties[J]. Progress in Materials Science, 2018, 92: 112-224.

[11] Ligon S C, Liska R, Stampfl J, et al. Polymers for 3D printing and customized additive manufacturing[J]. Chemical Reviews, 2017, 117(15): 10212-10290.

[12] Liu S T, Li Q H, Liu J H, et al. A realization method for transforming a topology optimization design into additive manufacturing structures[J]. Engineering, 2018, 4(2): 277-285.

[13] Liu J K. Piecewise length scale control for topology optimization with an irregular design domain[J]. Computer Methods in Applied Mechanics and Engineering, 2019, 351: 744-765.

[14] Mirzendehdel A M, Rankouhi B, Suresh K. Strength-based topology optimization for anisotropic parts[J]. Additive Manufacturing, 2018, 19: 104-113.

[15] 李取浩. 考虑连通性与结构特征约束的增材制造结构拓扑优化方法[D]. 大连: 大连理工大学, 2017.
Li Q H. Topology optimization methods for additive manufacturing structures with connectivity constraint and structural feature constraints[D]. Dalian: Dalian University of Technology, 2017.

[16] Bendsøe M P, Kikuchi N. Generating optimal topologies in structural design using a homogenization method[J]. Computer Methods in Applied Mechanics and Engineering, 1988, 71(2): 197-224.

[17] Mlejnek H P. Some aspects of the genesis of structures[J]. Structural Optimization, 1992, 5(1): 64-69.

[18] Xie Y M, Steven G P. A simple evolutionary procedure for structural optimization[J]. Computers & Structures, 1993, 49(5): 885-896.

[19] 靳绍猛. 引入最大结构尺寸约束的渐进式拓扑优化设计[D]. 武汉: 华中科技大学, 2020.
Jin S M. Evolutionary structural optimization design with maximum structural scale constraint[D]. Wuhan: Huazhong University of Science and Technology, 2020.

[20] 吝战军. 结构拓扑优化设计密度惩罚法与水平集法[D]. 济南: 山东建筑大学, 2010.
Lin Z J. Solid isotropic material with penalization and level set method in structural topology optimization design[D]. Jinan: Shandong Jianzhu University, 2010.

[21] Guo X, Zhou J H, Zhang W S, et al. Self-supporting structure design in additive manufacturing through explicit topology optimization[J]. Computer Methods in Applied Mechanics and Engineering, 2017, 323: 27-63.

[22] Zhang W H, Zhou L. Topology optimization of self-supporting structures with polygon features for additive manufacturing[J]. Computer Methods in Applied Mechanics and Engineering, 2018, 334: 56-78.

[23] 陈拥平，何志义. 结构拓扑优化中去除数值计算不稳定性研究方法综述[J]. 技术与市场, 2015, 22(6): 40-42.
Chen Y P, He Z Y. Summary of research methods for removing numerical instability in structural topology optimization[J]. Technology and Market, 2015, 22(6): 40-42.

[24] Kim T S, Kim Y Y. Mac-based mode-tracking in structural topology optimization[J]. Computers & Structures, 2000, 74(3): 375-383.

[25] 昌俊康，段宝岩. 连续体结构拓扑优化的一种改进变密度法及其应用[J]. 计算力学学报, 2009, 26(2): 188-192.
Chang J K, Duan B Y. An improved variable density method and application for topology optimization of continuum structures[J]. Chinese Journal of Computational Mechanics, 2009, 26(2): 188-192.

[26] Hsu M H, Hsu Y L. Interpreting three-dimensional structural topology optimization results[J]. Computers & Structures, 2005, 83(4/5): 327-337.

[27] 李翔，王皓. 连续体结构拓扑优化的过滤变密度法[J]. 复旦学报(自然科学版), 2012, 51(4): 400-405, 414.
Li X, Wang H. A new variable density method with gray-scale filter function for topology optimization of continuum structures[J]. Journal of Fudan University (Natural Science), 2012, 51(4): 400-405, 414.

[28] Zhou M, ShyyY K, Thomas H L. Checkerboard and minimum member size control in topology optimization[J]. Structural and Multidisciplinary Optimization, 2001, 21(2): 152-158.

[29] Díaz A, Sigmund O. Checkerboard patterns in layout optimization [J]. Structural Optimization, 1995, 10(1): 40-45.

[30] 袁振，吴长春. 复合材料周期性线弹性微结构的拓扑优化设计[J]. 固体力学学报, 2003, 24(1): 40-45.
Yuan Z, Wu C C. Topology optimization for periodic linear elastic microstructures of composite materials[J]. Acta Mechanica Solida Sinica, 2003, 24(1): 40-45.

[31] Zhang W H, Duysinx P. Dual approach using a variant perimeter constraint and efficient sub-iteration scheme for topology optimization[J]. Computers & Structures, 2003, 81(22/23): 2173-2181.

[32] Yang X Y, Xie Y M, Liu J S, et al. Perimeter control in the bidirectional evolutionary optimization method[J]. Structural and Multidisciplinary Optimization, 2002, 24(6): 430-440.

[33] Bendsøe M P, Sigmund O. Topology optimization: theory, methods, and applications[M]. Berlin: Springer, 2003.

[34] Sigmund O, Petersson J. Numerical instabilities in topology optimization: a survey on procedures dealing with checkerboards, mesh-dependencies and local minima[J]. Structural Optimization, 1998, 16(1): 68-75.

[35] Borrvall T, Petersson J. Topology optimization using regularized intermediate density control[J]. Computer Methods in Applied Mechanics and Engineering, 2001, 190(37/38): 4911-4928.

[36] Fujii D, Kikuchi N. Improvement of numerical instabilities in topology optimization using the SLP method[J]. Structural and Multidisciplinary Optimization, 2000, 19(2): 113-121.

[37] 左孔天，王书亭，陈立平，等. 拓扑优化中去除数值不稳定性的算法研究[J]. 机械科学与技术, 2005, 24(1): 86-89, 93.
Zuo K T, Wang S T, Chen L P, et al. Research on algorithms to eliminate numerical instabilities in topology optimization[J]. Mechanical Science and Technology, 2005, 24(1): 86-89, 93.

[38] Li Q, Steven G P, Xie Y M. A simple checkerboard suppression algorithm for evolutionary structural optimization[J]. Structural and Multidisciplinary Optimization, 2001, 22(3): 230-239.

[39] 罗震. 基于变密度法的连续体结构拓扑优化设计技术研究[D]. 武汉:华中科技大学,2005.
Luo Z. Research on topology optimization design of continuum structure based on variable density method[D]. Wuhan: Huazhong University of Science and Technology, 2005.

[40] Sethian J A, Wiegmann A. Structural boundary design via level set and immersed interface methods[J]. Journal of Computational Physics, 2000, 163(2): 489-528.

[41] Guo X, Zhang W S, Zhong W L. Doing topology optimization explicitly and geometrically: a new moving morphable components based framework[J]. Journal of Applied Mechanics, 2014, 81(8): 081009.

[42] Zhang W S, Yuan J, Zhang J, et al. A new topology optimization approach based on Moving Morphable Components (MMC) and the ersatz material model[J]. Structural and Multidisciplinary Optimization, 2016, 53(6): 1243-1260.

[43] 张卫红, 周莹, 酒丽朋, 等. 特征驱动的结构拓扑优化方法[J]. 中国科学: 技术科学, 2019, 49(10): 1177-1185.
Zhang W H, Zhou Y, Jiu L P, et al. Feature-driven method for structural topology optimization[J]. Scientia Sinica: Technologica, 2019, 49(10): 1177-1185.

[44] Yaji K, Otomori M, Yamada T, et al. Shape and topology optimization based on the convected level set method[J]. Structural and Multidisciplinary Optimization, 2016, 54(3): 659-672.

[45] Burger M, Hackl B, Ring W. Incorporating topological derivatives into level set methods[J]. Journal of Computational Physics, 2004, 194(1): 344-362.

[46] Allaire G, Gournay F, Jouve F, et al. Structural optimization using topological and shape sensitivity via a level set method[J]. Control and Cybernetics, 2005, 34: 59-80.

[47] Allaire G, Jouve F. A level-set method for vibration and multiple loads structural optimization[J]. Computer Methods in Applied Mechanics and Engineering, 2005, 194(30/31/32/33): 3269-3290.

[48] Yamada T, Izui K, Nishiwaki S, et al. A topology optimization method based on the level set method incorporating a fictitious interface energy[J]. Computer Methods in Applied Mechanics and Engineering, 2010, 199(45/46/47/48): 2876-2891.

[49] Otomori M, Yamada T, Izui K, et al. Matlab code for a level set-based topology optimization method using a reaction diffusion equation[J]. Structural and Multidisciplinary Optimization, 2015, 51(5): 1159-1172.

[50] 曲东越, 张海兵, 徐建安, 等. 基于改进水平集结构拓扑优化方法的理论研究[J]. 应用力学学报, 2019, 36(4): 895-900, 1000.
Qu D Y, Zhang H B, Xu J A, et al. Theoretical research of structure topology optimization based on the level set method[J]. Chinese Journal of Applied Mechanics, 2019, 36(4): 895-900, 1000.

[51] Allaire G, Jouve F, Toader A M. Structural optimization using sensitivity analysis and a level-set method[J]. Journal of Computational Physics, 2004, 194(1): 363-393.

[52] Dijk N P, Langelaar M, Keulen F. Explicit level-set-based topology optimization using an exact Heaviside function and consistent sensitivity analysis[J]. International Journal for Numerical Methods in Engineering, 2012, 91(1): 67-97.

[53] Li H, Grandhi R V, Kobayashi M. Level-set based cellular division method for structural shape and topology optimization[C]// 2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, January 8-12, 2018, Kissimmee, Florida. Virginia: AIAA Press, 2018: 1837.

[54] Luo Z, Tong L Y, Kang Z. A level set method for structural shape and topology optimization using radial basis functions[J]. Computers & Structures, 2009, 87(7/8): 425-434.

[55] Guirguis D, Aly M F. A derivative-free level-set method for topology optimization[J]. Finite Elements in Analysis and Design, 2016, 120: 41-56.

[56] Dunning P D, Kim H A. Introducing the sequential linear programming level-set method for topology optimization[J]. Structural and Multidisciplinary Optimization, 2015, 51(3): 631-643.

[57] Challis V J. A discrete level-set topology optimization code written in Matlab[J]. Structural and Multidisciplinary Optimization, 2010, 41(3): 453-464.

[58] Allaire G, Dapogny C, Delgado G, et al. Multi-phase structural optimizationviaa level set method[J]. ESAIM: Control, Optimisation and Calculus of Variations, 2014, 20(2): 576-611.

[59] Wei P, Wang M Y, Xing X H. A study on X-FEM in continuum structural optimization using a level set model[J]. Computer-Aided Design, 2010, 42(8): 708-719.

[60] Kreissl S, Maute K. Levelset based fluid topology optimization using the extended finite element method[J]. Structural and Multidisciplinary Optimization, 2012, 46(3): 311-326.

[61] Parvizian J, Düster A, Rank E. Topology optimization using the finite cell method[J]. Optimization and Engineering, 2012, 13(1): 57-78.

[62] Zhang W H, Zhao L Y, Gao T, et al. Topology optimization with closed B-splines and Boolean operations[J]. Computer Methods in Applied Mechanics and Engineering, 2017, 315: 652-670.

[63] Groen J P, Langelaar M, Sigmund O, et al. Higher-order multi-resolution topology optimization using the finite cell method[J]. International Journal for Numerical Methods in Engineering, 2017, 110(10): 903-920.

[64] Hassani B, Khanzadi M, Tavakkoli S M. An isogeometrical approach to structural topology optimization by optimality criteria [J]. Structural and Multidisciplinary Optimization, 2012, 45(2): 223-233.

[65] Yamasaki S, Nishiwaki S, Yamada T, et al. A structural optimization method based on the level set method using a new geometry-based re-initialization scheme[J]. International Journal for Numerical Methods in Engineering, 2010, 83(12): 1580-1624.

[66] Yamasaki S, Nomura T, Kawamoto A, et al. A level set-based topology optimization method targeting metallic waveguide design problems[J]. International Journal for Numerical Methods in Engineering, 2011, 87(9): 844-868.

[67] 周建华. 考虑结构可制造性的显式拓扑优化研究[D]. 大连: 大连理工大学, 2018.
Zhou J H. Research on explicit topology optimization considering structural manufacturability[D]. Dalian: Dalian University of Technology, 2018.

[68] 李鹏, 杜艺博, 彭嘉潮, 等. 可移动变形组件法中组件数对拓扑结构优化的影响[J]. 制造技术与机床, 2020(8): 84-88.
Li P, Du Y B, Peng J C, et al. Effect of component number on topology structure optimization in moving morphable component method[J]. Manufacturing Technology & Machine Tool, 2020(8): 84-88.

[69] 于承田. 基于光滑化技术的MMC拓扑优化方法[D]. 大连: 大连理工大学, 2021.
Yu C T. Topology optimization method of MMC based on smoothing technology[D]. Dalian: Dalian University of Technology, 2021.

[70] 谢贤达. 基于等几何分析的移动可变形组件拓扑优化方法及应用研究[D]. 武汉: 华中科技大学, 2021.
Xie X D. Research on moving morphable components topology optimization method and application based on isogeometric analysis [D]. Wuhan: Huazhong University of Science and Technology, 2021.

[71] 薛日野, 杜宗亮, 郭旭. 基于移动可变形孔洞方法的超弹性结构拓扑优化[J]. 计算力学学报, 2019, 36(4): 441-447.
Xue R Y, Du Z L, Guo X. Topology optimization of hyperelastic structures via Moving Morphable Void (MMV) approach[J]. Chinese Journal of Computational Mechanics, 2019, 36(4): 441-447.

[72] 周莹. 特征驱动的结构拓扑优化理论与方法研究[D]. 西安: 西北工业大学, 2018.
Zhou Y. Feature-driven structural topology optimization theory and method[D]. Xi'an: Northwestern Polytechnical University, 2018.

[73] 吴斌, 王向明, 玄明昊, 等. 基于增材制造的新型战机结构创新[J]. 航空材料学报, 2021, 41(6): 1-12.
Wu B, Wang X M, Xuan M H, et al. Structural innovation of new fighter based on additive manufacturing[J]. Journal of Aeronautical Materials, 2021, 41(6): 1-12.

[74] 顾冬冬, 张红梅, 陈洪宇, 等. 航空航天高性能金属材料构件激光增材制造[J]. 中国激光, 2020, 47(5): 0500002.
Gu D D, Zhang H M, Chen H Y, et al. Laser additive manufacturing of high-performance metallic aerospace components [J]. Chinese Journal of Lasers, 2020, 47(5): 0500002.

[75] Kuo Y L, Kamigaichi A, Kakehi K. Characterization of Ni-based superalloy built by selective laser melting and electron beam melting[J]. Metallurgical and Materials Transactions A, 2018, 49 (9): 3831-3837.

[76] Sing S L, Wiria F E, Yeong W Y. Selective laser melting of titanium alloy with 50wt% tantalum: effect of laser process parameters on part quality[J]. International Journal of Refractory Metals and Hard Materials, 2018, 77: 120-127.

[77] Jia H L, Sun H, Wang H Z, et al. Scanning strategy in selective laser melting (SLM): a review[J]. The International Journal of Advanced Manufacturing Technology, 2021, 113(9): 2413-2435.

[78] Cooke S, Ahmadi K, Willerth S, et al. Metal additive manufacturing: technology, metallurgy and modelling[J]. Journal of Manufacturing Processes, 2020, 57: 978-1003.

[79] Murr L E. Open-cellular metal implant design and fabrication for biomechanical compatibility with bone using electron beam melting [J]. Journal of the Mechanical Behavior of Biomedical Materials, 2017, 76: 164-177.

[80] 王华明. 高性能大型金属构件激光增材制造: 若干材料基础问题[J]. 航空学报, 2014, 35(10): 2690-2698.
Wang H M. Materials' fundamental issues of laser additive manufacturing for high-performance large metallic components[J]. Acta Aeronautica et Astronautica Sinica, 2014, 35(10): 2690-2698.

[81] 杨胶溪, 柯华, 崔哲, 等. 激光金属沉积技术研究现状与应用进展[J]. 航空制造技术, 2020, 63(10): 14-22.
Yang J X, Ke H, Cui Z, et al. Research and application progress of laser metal deposition[J]. Aeronautical Manufacturing Technology, 2020, 63(10): 14-22.

[82] 钦兰云, 谢永凯, 杨光, 等. 激光沉积制造形貌偏差检测与控制研究[J]. 中国激光, 2021, 48(10): 1002113.
Qin L Y, Xie Y K, Yang G, et al. Detection and control of morphology deviation in laser deposition manufacturing[J]. Chinese Journal of Lasers, 2021, 48(10): 1002113.

[83] 林鑫, 黄卫东. 应用于航空领域的金属高性能增材制造技术[J]. 中国材料进展, 2015, 34(9): 684-688, 658.
Lin X, Huang W D. High performance metal additive manufacturing technology applied in aviation field[J]. Materials China, 2015, 34(9): 684-688, 658.

[84] Wang F D, Williams S, Colegrove P, et al. Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V[J]. Metallurgical and Materials Transactions A, 2013, 44 (2): 968-977.

[85] 廉艳平, 王潘丁, 高杰, 等. 金属增材制造若干关键力学问题研究进展[J]. 力学进展, 2021, 51(3): 648-701.
Lian Y P, Wang P D, Gao J, et al. Fundamental mechanics problems in metal additive manufacturing: a state-of-art review[J]. Advances in Mechanics, 2021, 51(3): 648-701.

[86] 雷力明, 侯慧鹏, 何艳丽, 等. 金属增材制造技术在民用航空领域的应用与挑战[J]. 航空制造技术, 2019, 62(21): 22-30.
Lei L M, Hou H P, He Y L, et al. Application and challenges of metal additive manufacturing in civil aviation[J]. Aeronautical Manufacturing Technology, 2019, 62(21): 22-30.

[87] 巩水利, 锁红波, 李怀学. 金属增材制造技术在航空领域的发展与应用[J]. 航空制造技术, 2013, 56(13): 66-71.
Gong S L, Suo H B, Li H X. Development and application of metal additive manufacturing technology[J]. Aeronautical Manufacturing Technology, 2013, 56(13): 66-71.

[88] 许世娇, 权纯逸, 杨堃, 等. 金属增材制造技术在航空领域的应用现状及前景展望[J]. 粉末冶金工业, 2022, 32(3): 9-17.
Xu S J, Quan C Y, Yang K, et al. Application and prospect of metal additive manufacturing technology in aviation field[J]. Powder Metallurgy Industry, 2022, 32(3): 9-17.

[89] Chen D J, Wang P, Pan R, et al. Characteristics of metal specimens formed by selective laser melting: a state-of-the-art review[J]. Journal of Materials Engineering and Performance, 2021, 30(10): 7073-7100.

[90] Sun H K, Chu X, Luo C, et al. Selective laser melting for joining dissimilar materials: investigations of interfacial characteristics and *in situ* alloying[J]. Metallurgical and Materials Transactions A, 2021, 52(4): 1540-1550.

[91] Murr L E, Gaytan S M, Ramirez D A, et al. Metal fabrication by additive manufacturing using laser and electron beam melting technologies[J]. Journal of Materials Science & Technology, 2012, 28(1): 1-14.

[92] 郭超, 张平平, 林峰. 电子束选区熔化增材制造技术研究进展[J]. 工业技术创新, 2017, 4(4): 6-14.
Guo C, Zhang P P, Lin F. Research advances of electron beam selective melting additive manufacturing technology[J]. Industrial Technology Innovation, 2017, 4(4): 6-14.

[93] Gong X B, Anderson T, Chou K. Review on powder-based electron beam additive manufacturing technology[C]//Proceedings of ASME/ISCIE 2012 International Symposium on Flexible Automation, June 18-20, 2012, St. Louis, Missouri, USA. New York: ASME, 2013: 507-515.

[94] 乐方宾, 叶寒, 刘勇. 金属材料增材制造研究与应用[J]. 江西科学, 2020, 38(2): 157-161, 262.
Le F B, Ye H, Liu Y. Research and application of metal additive manufacturing[J]. Jiangxi Science, 2020, 38(2): 157-161, 262.

[95] Palčič I, Balažic M, Milfelner M, et al. Potential of laser engineered net shaping (LENS) technology[J]. Materials and Manufacturing Processes, 2009, 24(7/8): 750-753.

[96] Chen H, Ye L, Han Y, et al. Additive manufacturing of W－Fe composites using laser metal deposition: microstructure, phase transformation, and mechanical properties[J]. Materials Science and Engineering: A, 2021, 811: 141036.

[97] Izadi M, Farzaneh A, Mohammed M, et al. A review of laser engineered net shaping (LENS) build and process parameters of metallic parts[J]. Rapid Prototyping Journal, 2020, 26: 1059-1078.

[98] Wirth F, Arpagaus S, Wegener K. Analysis of melt pool dynamics in laser cladding and direct metal deposition by automated high-speed camera image evaluation[J]. Additive Manufacturing, 2018, 21: 369-382.

[99] 张立浩, 钱波, 张朝瑞, 等. 金属增材制造技术发展趋势综述[J]. 材料科学与工艺, 2022, 30(1): 42-52.
Zhang L H, Qian B, Zhang C R, et al. Summary of development trend of metal additive manufacturing technology[J]. Materials Science and Technology, 2022, 30(1): 42-52.

[100] 梁静静, 杨彦红, 金涛, 等. 金属材料空间3D打印技术研究现状[J]. 载人航天, 2017, 23(5): 663-669.
Liang J J, Yang Y H, Jin T, et al. Research status of 3D printing technology for metals in space[J]. Manned Spaceflight, 2017, 23 (5): 663-669.

[101] 何建斌, 许燕, 周建平, 等. 金属增材制造技术的研究进展[J]. 机床与液压, 2020, 48(2): 171-175.
He J B, Xu Y, Zhou J P, et al. Research progress of additive manufacturing technology for metal[J]. Machine Tool & Hydraulics, 2020, 48(2): 171-175.

[102] Liu S T, Li Q H, Chen W J, et al. An identification method for enclosed voids restriction in manufacturability design for additive manufacturing structures[J]. Frontiers of Mechanical Engineering,

2015, 10(2): 126-137.
[103] 王向明, 苏亚东, 吴斌. 增材技术在飞机结构研制中的应用[J]. 航空制造技术, 2014, 57(22): 16-20.
Wang X M, Su Y D, Wu B. Application of additive manufacturing technology on aircraft structure development[J]. Aeronautical Manufacturing Technology, 2014, 57(22): 16-20.
[104] 王向明, 崔灿, 苏亚东, 等. 飞机高能束增材制造结构研究[J]. 航空制造技术, 2017, 60(10): 16-21.
Wang X M, Cui C, Su Y D, et al. Aircraft structures technology based on power beam additive manufacturing[J]. Aeronautical Manufacturing Technology, 2017, 60(10): 16-21.
[105] Guest J K, Prévost J H, Belytschko T. Achieving minimum length scale in topology optimization using nodal design variables and projection functions[J]. International Journal for Numerical Methods in Engineering, 2004, 61(2): 238-254.
[106] Sigmund O. Morphology-based black and white filters for topology optimization[J]. Structural and Multidisciplinary Optimization, 2007, 33(4): 401-424.
[107] Wang F W, Lazarov B S, Sigmund O. On projection methods, convergence and robust formulations in topology optimization[J]. Structural and Multidisciplinary Optimization, 2011, 43(6): 767-784.
[108] Zhou M D, Lazarov B S, Wang F W, et al. Minimum length scale in topology optimization by geometric constraints[J]. Computer Methods in Applied Mechanics and Engineering, 2015, 293: 266-282.
[109] Yang K K, Fernandez E, Niu C, et al. Note on spatial gradient operators and gradient-based minimum length constraints in SIMP topology optimization[J]. Structural and Multidisciplinary Optimization, 2019, 60(1): 393-400.
[110] Rong X P, Rong J H, Zhao S N, et al. New method for controlling minimum length scales of real and void phase materials in topology optimization[J]. Acta Mechanica Sinica, 2020, 36(4): 805-826.
[111] Chen S K, Wang M Y, Liu A Q. Shape feature control in structural topology optimization[J]. Computer-Aided Design, 2008, 40(9): 951-962.
[112] Luo J Z, Luo Z, Chen S K, et al. A new level set method for systematic design of hinge-free compliant mechanisms[J]. Computer Methods in Applied Mechanics and Engineering, 2008, 198(2): 318-331.
[113] Dunning P D. Minimum length-scale constraints for parameterized implicit function based topology optimization[J]. Structural and Multidisciplinary Optimization, 2018, 58(1): 155-169.
[114] Zhang W S, Li D, Zhang J, et al. Minimum length scale control in structural topology optimization based on the Moving Morphable Components (MMC) approach[J]. Computer Methods in Applied Mechanics and Engineering, 2016, 311: 327-355.
[115] Liu J K, Yu H C, Ma Y S. Minimum void length scale control in level set topology optimization subject to machining radii[J]. Computer-Aided Design, 2016, 81: 70-80.
[116] Guest J K. Topology optimization with multiple phase projection [J]. Computer Methods in Applied Mechanics and Engineering, 2009, 199(1/2/3/4): 123-135.
[117] Zhang W S, Zhong W L, Guo X. An explicit length scale control approach in SIMP-based topology optimization[J]. Computer Methods in Applied Mechanics and Engineering, 2014, 282: 71-86.
[118] Guo X, Zhang W S, Zhong W L. Explicit feature control in structural topology optimization via level set method[J]. Computer Methods in Applied Mechanics and Engineering, 2014, 272: 354-378.
[119] Xia Q, Shi T L. Constraints of distance from boundary to skeleton: for the control of length scale in level set based structural topology optimization[J]. Computer Methods in Applied Mechanics and Engineering, 2015, 295: 525-542.
[120] Wang Y Q, Zhang L, Wang M Y. Length scale control for structural optimization by level sets[J]. Computer Methods in Applied Mechanics and Engineering, 2016, 305: 891-909.
[121] 白伟, 李取浩, 陈文炯, 等. 基于映射的拓扑优化最大尺寸控制方法[J]. 工程力学, 2017, 34(9): 18-26.
Bai W, Li Q H, Chen W J, et al. A novel projection based method for imposing maximum length scale in topology optimization[J]. Engineering Mechanics, 2017, 34(9): 18-26.
[122] Niu B, Wadbro E. On equal-width length-scale control in topology optimization[J]. Structural and Multidisciplinary Optimization, 2019, 59(4): 1321-1334.
[123] Leary M, Merli L, Torti F, et al. Optimal topology for additive manufacture: a method for enabling additive manufacture of support-free optimal structures[J]. Materials & Design, 2014, 63: 678-690.
[124] Brackett D, Ashcroft I, Hague R. Topology optimization for additive manufacturing[C]//Proceedings of the Solid Freeform Fabrication Symposium, August 17, 2011, Austin. [S.l.: s.n.], 2011: 348-362.
[125] Langelaar M. Topology optimization of 3D self-supporting structures for additive manufacturing[J]. Additive Manufacturing, 2016, 12: 60-70.
[126] Qian X P. Undercut and overhang angle control in topology optimization: a density gradient based integral approach[J]. International Journal for Numerical Methods in Engineering, 2017, 111(3): 247-272.
[127] Gaynor A T, Guest J K. Topology optimization considering overhang constraints: eliminating sacrificial support material in additive manufacturing through design[J]. Structural and Multidisciplinary Optimization, 2016, 54(5): 1157-1172.
[128] Luo Y F, Sigmund O, Li Q H, et al. Additive manufacturing oriented topology optimization of structures with self-supported enclosed voids[J]. Computer Methods in Applied Mechanics and Engineering, 2020, 372: 113385.
[129] Wang Y G, Gao J C, Kang Z. Level set-based topology optimization with overhang constraint: towards support-free additive manufacturing[J]. Computer Methods in Applied Mechanics and Engineering, 2018, 339: 591-614.
[130] Liu J K, Yu H C. Self-support topology optimization with horizontal overhangs for additive manufacturing[J]. Journal of Manufacturing Science and Engineering, 2020, 142(9): 091003.
[131] Xiong Y L, Yao S, Zhao Z L, et al. A new approach to eliminating enclosed voids in topology optimization for additive manufacturing[J]. Additive Manufacturing, 2020, 32: 101006.
[132] Zhou L, Zhang W H. Topology optimization method with elimination of enclosed voids[J]. Structural and Multidisciplinary Optimization, 2019, 60(1): 117-136.
[133] 王超, 徐斌, 段尊义, 等. 面向增材制造的应力最小化连通性拓扑优化[J]. 力学学报, 2021, 53(4): 1070-1080.
Wang C, Xu B, Duan Z Y, et al. Additive manufacturing-oriented stress minimization topology optimization with connectivity[J]. Chinese Journal of Theoretical and Applied Mechanics, 2021, 53(4): 1070-1080.
[134] Gaynor A T, Johnson T E. Eliminating occluded voids in additive manufacturing design via a projection-based topology optimization scheme[J]. Additive Manufacturing, 2020, 33: 101149.
[135] Liu J K, Yu H C. Concurrent deposition path planning and structural topology optimization for additive manufacturing[J]. Rapid Prototyping Journal, 2017, 23: 930-942.
[136] Liu J K, To A C. Deposition path planning-integrated structural topology optimization for 3D additive manufacturing subject to self-support constraint[J]. Computer-Aided Design, 2017, 91: 27-45.
[137] Dapogny C, Estevez R, Faure A, et al. Shape and topology optimization considering anisotropic features induced by additive manufacturing processes[J]. Computer Methods in Applied Mechanics and Engineering, 2019, 344: 626-665.
[138] Li H, Gao L, Li H, et al. Spatial-varying multi-phase infill design using density-based topology optimization[J]. Computer Methods in Applied Mechanics and Engineering, 2020, 372: 113354.

[139] 王天赐，刘龙，李智忠，等. 基于各向异性亥姆霍兹方程的空腔连通性约束拓扑优化设计方法[J]. 机械工程学报，2022，58(13): 240-250.
Wang T C，Liu L，Li Z Z，et al. Structural topology optimization with connectivity constraints based on anisotropic Helmholtz equation[J]. Journal of Mechanical Engineering，2022，58(13): 240-250.
[140] Chen Q，Liang X，Hayduke D，et al. An inherent strain based multiscale modeling framework for simulating part-scale residual deformation for direct metal laser sintering[J]. Additive Manufacturing，2019，28: 406-418.
[141] Zhang Z D，Ibhadode O，Ali U，et al. Topology optimization parallel-computing framework based on the inherent strain method for support structure design in laser powder-bed fusion additive manufacturing[J]. International Journal of Mechanics and Materials in Design，2020，16(4): 897-923.
[142] Takezawa A，To A C，Chen Q，et al. Sensitivity analysis and lattice density optimization for sequential inherent strain method used in additive manufacturing process[J]. Computer Methods in Applied Mechanics and Engineering，2020，370: 113231.

Research Progress on Topology Optimization Design for Metal Additive Manufacturing

Liu Boyu[1]，Wang Xiangming[2]，Yang Guang[1*]，Xing Bendong[2]
[1]*School of Mechanic Engineering, Shenyang Aerospace University, Shenyang* 110136, *Liaoning, China*;
[2]*Shenyang Aircraft Design Institute, Aviation Industry Corporation of China, Shenyang* 110035, *Liaoning, China*

Abstract

Significance Owing to the continuous developments in the Chinese aerospace industry，aviation structural parts need to ensure lightweight，high efficiency，long flight time，and high maneuverability characteristics. Therefore，it is a significant challenge in structural optimization design to further reduce the structural quality coefficient. Traditional lightweight designs are mostly based on the replacement of classical structures with equivalent parts，such as lean improvement and excavation of structural potential using the new processes and new materials，and have now approached the “ceiling”.

Topology optimization technology，as an important branch of structural optimization design，determines the optimal material distribution and best load-bearing path by defining material properties，load conditions，and constraints. It is an effective design method for obtaining lightweight structure design and high-performance innovative configurations，and has been widely used in aerospace，automobile manufacturing，and other fields.

However，topology configurations are usually complex. Limited by traditional manufacturing processes，designers often need to simplify the optimal topology configurations，which fails to fully reflect the structural advantages of topology optimization design. Additive manufacturing technology uses high-energy laser beams and adopts the superposition mode of “bottom to up” layer-by-layer material melting，which can realize rapid prototyping and solid-free manufacturing of complex topology configurations without molds. This method addresses the problem of “manufacturing determines design” in structure optimization，which greatly broadens the design space. However，additive metal manufacturing technology is not completely a “free manufacturing” technology，and it is limited by unique manufacturing constraints. Therefore，considering additive manufacturing constraints in topology optimization design，researching and developing topology optimization design for additive metal manufacturing has a broad application prospect.

Progress This study reviews the progress of structural topology optimization design for metal additive manufacturing technology. First，it summarizes the common methods and characteristics of continuum structure topology optimization (Table 1) and compares the cantilever beam topology optimization results obtained with different methods (Fig. 1). From the perspective of optimizing topology algorithms，it concludes the effective measures to improve structural continuity and manufacturability based on topology optimization methods of elements and boundary evolution (Figs. 2–4). Then，it expounds on the principle，processing characteristics，and application range of the mainstream metal additive manufacturing technology (Fig. 5). After that，it summarizes the topology optimization methods considering the geometric size (Fig. 8)，structural forming (Figs. 9 and 10)，and material property constraints (Fig. 11) of metal additive manufacturing technology (Fig. 7 and Table 2). Finally，it prospects the development directions of metal additive manufacturing and topology optimization technology.

Conclusions and Prospects In this study，the structural topology optimization of an advanced design technology is integrated with the metal additive manufacturing technology that is an advanced manufacturing technology. This study summarizes the methods，characteristics，and improvement measures of continuum structure topology optimization design. Moreover，it expounds on the principle，characteristics，and application of metal additive manufacturing technology. In addition，it summarizes and prospects the topology optimization methods considering the constraints of metal additive manufacturing，which will provide a reference for researchers to further study the topology optimization design for metal additive manufacturing technology.

Topology optimization design has shortcomings of numerous design variables，weak convergence，and low computational efficiency. It is often difficult for existing topology optimization algorithms to output the optimal structural performance solution that can be directly used in additive manufacturing. Therefore，combined with the parallel computing technology，it is crucial to carry out algorithm research with fewer design variables and better convergence, and output the optimal solution that can be directly used in additive manufacturing. The research on macroscopic topology optimization and microscopic lattice structure is becoming increasingly improved. By effectively integrating the two, fully leveraging the high-performance configurations of topology optimization design and broad design space provided by additive manufacturing technology, the pursuit of high-performance lightweight design has broad development prospects. The topology optimization methods considering the constraints of metal additive manufacturing adopt relatively ideal material models, which differ from the actual printing materials used in metal additive manufacturing technology. Therefore, establishing a precise topological model of material anisotropy under multiple process parameters, quantification of process parameters of metal additive manufacturing equipment, simulation of the metal additive manufacturing process, and prediction of warping deformation and cracking of parts can effectively reduce residual stress and deformation, and improve forming accuracy and surface quality. Topology optimization design for metal additive manufacturing technology is often based on the optimization of a single material. Effectively combining multi-material topology optimization and metal additive manufacturing, studying the topology optimization design and metal additive manufacturing technology of functional gradient materials, and realizing the integrated design of materials, structure, process, and performance, are breakthrough points in the pursuit of high-performance, multi-function, and lightweight.

Key words laser technique; topology optimization; metal additive manufacturing; topological algorithms; additive manufacturing constraints