

电弧熔丝增材及局部塑性变形复合制造技术研究进展



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摘要: 电弧熔丝增材制造是一种适用于大型金属构件快速成形的技术, 具有设备成本低、材料利用率高、沉积效率高、自动化水平高和灵活方便等优点, 也存在组织性能不良等缺陷。塑性变形是一种改善电弧熔丝增材制造气孔缺陷、组织性能不均匀和残余应力分布的有效方法。由电弧熔丝增材与局部塑性变形结合的复合制造工艺利于实现零件的“控性”, 但其复杂的路径规划、复合工具头、振动和压力等增加了形状精度控制难度。总结了层间冷轧、在线热轧、机械冲击、超声冲击、激光冲击等局部塑性变形工艺对电弧熔丝增材制造试件微观组织、残余应力、各向异性和表面质量的影响, 分析了复合制造工艺的困境和问题。结合塑性变形对焊接组织的强化规律和电弧增材在线控制, 从电弧熔丝增材及局部塑性变形复合制造的“形性双控”的角度展望了未来发展趋势, 为电弧增材制备复杂件提供参考。

关键词: 电弧增材; 复合制造工艺; 层间轧制; 超声冲击; 激光冲击; 塑性成形

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电弧焊具有高效、便捷、易实现自动化等优点, 广泛应用于钢材、铝合金、镁合金、钛合金、镍合金等金属的焊接, 并衍生出双丝焊、激光—电弧复合焊、TIG—MIG 复合焊、等离子—MIG/MAG 复合焊等高效率电弧焊焊接方法^[1]。电弧熔丝增材制造(WAAM)以电弧焊接技术为基础, 结合三维模型数字化切片和自动化控制软硬件, 将金属丝材逐层堆积成复杂零部件, 常采用 MIG、TIG、PAW 或多种组合形式为热源, 具有高效率、短流程、低成本、高柔性、响应快等特点^[2-4], 已成功试制出机翼^[5]、锥筒件^[6]、涡轮叶片^[7]、曲面薄壁墙^[8]、火箭贮箱^[9]、桥^[10]、挖掘机臂^[11]、空间螺旋管^[12-13]和炮弹壳体^[14-15]等钢零部件, 机翼翼梁^[5]、起落架支撑外翼肋^[5]和襟翼肋骨^[16]等钛合金零部件, 梁框^[17]、带筋筒体^[17]、管路支架^[18]、火箭壳体^[18]、空客飞机整体壁板^[19]和整体舱段等铝合金零部件, 航空发动机机匣和火箭发动机喷管等高温合金零部件, 船用螺旋桨^[20]等铜合金零部件, 如图 1 所示。

在英国 Cranfield、澳大利亚 Wollongong、比利时天主教鲁汶大学、美国肯塔基大学等研究机构推动下, Airbus、Rolls-Royce、BAE System 和 Bombardier Aerospace 等企业已经开展电弧熔丝增材制造产品或装备的研究及生产。国内部分高校、研究所及民营企业也开展了电弧熔丝增材研究, 聚焦于三维模型切片和路径规划、在线监测及控制、成形组织和性能调控、残余应力及精度控制等方面。

电弧熔丝增材制造为规划路径下的堆焊过程, 热输入量较大且不稳定, 制造的零件兼具了电弧熔丝焊接和三维路径规划引入的缺陷^[21], 如电弧熔丝过程中的化学元素损耗及凝固过程引起的成分不均, 由气体、水分和杂质卷入熔池引起的气孔、夹杂、飞溅和表面质量差等缺陷, 由逐层堆积及热累积导致的组织分层、晶粒粗大、组织不均匀等冶金缺陷, 由路径规划下堆焊材料周期性加热和冷却引入的非均匀温度场导致的残余应力、尺寸畸变、累积尺寸误

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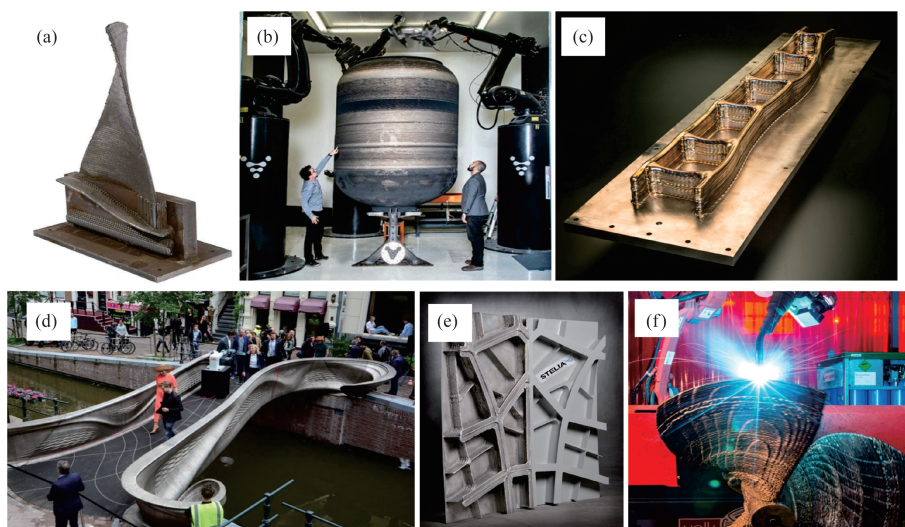


图1 电弧熔丝增材典型构件

Fig.1 Typical components of WAAM

差甚至开裂等缺陷。这些缺陷影响了WAAM工艺在一些高端零部件生产制造中的应用。部分学者开展了焊接热源、熔滴过渡、旁路电弧熔丝、焊接速度、电压、电流、送丝速度、起收弧点、层间冷却、脉冲电源、保护气体流量和基板预热等工艺参数优化研究,具有一定效果,但并未从电弧熔丝制造整个过程的复杂轨迹,以及动态控制的角度全盘考虑,尚未彻底改变电弧熔丝增材制造零件的铸态本质和组织性能缺陷,疲劳等力学性能不良,只得其“形”未得其“性”。

塑性变形是焊缝改性的通用方法,常用方法包括冷轧、热锻、机械冲击、超声冲击、喷丸、激光冲击等,通过这些方法进行焊后表面改性和改变应力分布。Cranfield^[22]和华中科技大学^[8]分别采用电弧熔丝增材后增加层间冷轧和微热锻的方法,引入局部塑性变形改善了WAAM零件的微观组织、各向异性和残余应力,显示了电弧熔丝增材制造与局部塑性变形相结合的良好效果^[23]。多位学者先后开展了电弧熔丝增材与机械冲击、超声冲击、激光冲击和热锻造的复合制造工艺研究。目前,国内学者已申请了电弧熔丝增材与深冷轧制^[24]、旋压^[25]、高频锻造^[26]、超声冲击^[27]、斜辊组合轮热碾压^[28]等复合成形的专利。

电弧熔丝增材及局部塑性变形复合制造是WAAM制造高性能零部件的有效方法,也引出了各类亟待解决的科学和工程难题。本文综合分析了WAAM与局部塑性变形复合制造的研究现状,讨论了增材和等材复合制造工艺的解决途径,以实现微观组织、宏观性能和尺寸精度的协同控制。

1 电弧熔丝增材及局部塑性变形复合制造工艺

1.1 层间冷轧工艺

由于热积累效应和不均匀温度场,电弧增材钢制零件的粗糙晶粒尺寸达宽 $100\mu\text{m}$ 、长 $500\sim 600\mu\text{m}$,增材制造的残余应力导致了零件形状畸变^[29-30]。为改善残余应力和微观组织,Cranfield的研究人员开展了电弧增材和层间高压冷轧复合制造工艺研究。Colegrove^[22-31]和Martina^[32]等在数控机床的基础上研制了电弧增材的层间冷轧装置,如图2所示。

层间冷轧效果受到轧辊形状、冷轧压力和冷轧道次等多因素影响^[22]。对CMT电弧增材G3Si1/ER70S-6单道试件进行25kN、50kN和75kN压力的层间冷轧后,晶粒尺寸明显细化,残余应力显著降低。在50kN压力下,经过带半径3.6mm圆弧辊轮轧制,单道电弧增材试件高度由39.5mm压缩至28mm,宽度由5mm增至7mm。采用宽度5.2mm、深10mm沟槽的辊轮轧制后,由于受深沟槽辊轮两侧侧壁的约束,试件高度无明显变化,而单道次增材制造墙的两侧变平整。经过深沟槽轧辊50kN压力冷轧后,扫描方向最大残余应力从600MPa降至250MPa以下,硬度从HV180提升至HV220。

Martina等^[32-34]研究了TC4钛合金的TIG电弧增材和层间冷轧复合制造工艺,不同参数的试样金相如图3所示。其中图3(a)为未层间冷轧;图3(b)为带半径3.6mm圆弧辊轮轧制(50kN);图3(c)为带半径3.6mm圆弧辊轮轧制

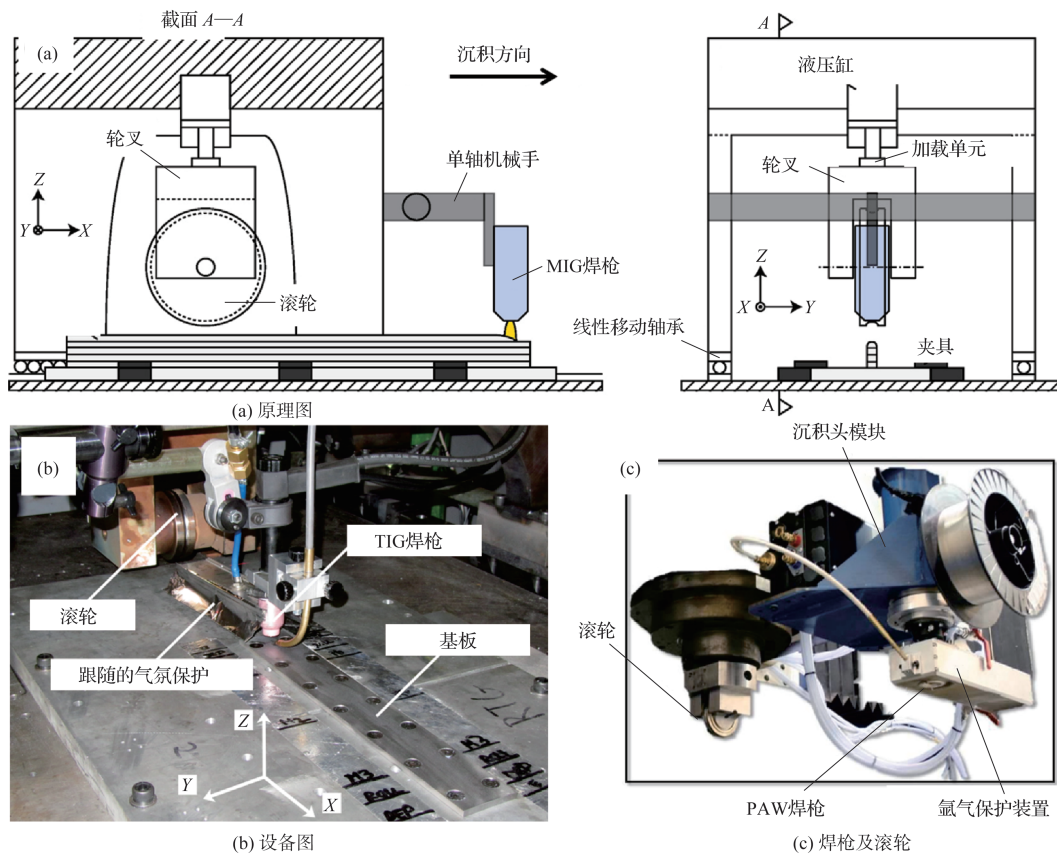


图2 TiG电弧增材及层间冷轧装置

Fig.2 Hybrid manufacturing process of WAAM and interlayer cold rolling

(75kN); 图3(d)为平辊轧制(50kN); 图3(e)为平辊轧制(75kN)。未经过层间冷轧的沉积态TC4内有粗大枝晶, 经过带半径3.6mm圆弧辊轮50kN和75kN压力冷轧后, 平均晶粒分别为 $125\mu\text{m}$ 和 $89\mu\text{m}$, 经过50kN和75kN压力平辊冷轧后, 平均晶粒分别为 $139\mu\text{m}$ 和 $56\mu\text{m}$ 。经过带半径3.6mm圆弧辊轮75kN压力冷轧后, 扫描方向和高度方向的抗拉强度从920MPa和885MPa都提高至1080MPa左右, 最大残余应力从500MPa降至250MPa。

Gu等^[35-36]研究了电弧增材2319铝合金在15kN、30kN和45kN压力下层间冷轧后的微观组织和力学性能。随着层间轧制压力增加, 改善效果得到提升。在45kN载荷下, 晶粒尺寸从未轧制的 $26.7\mu\text{m}$ 降至 $5\mu\text{m}$, 平均维氏硬度从HV68.3提高至HV102, 抗拉强度和屈服强度分别从260MPa和106MPa提高至315MPa和245MPa。经过T6热处理后, 抗拉强度和屈服强度分别达到450MPa和305MPa, 超过锻造2219-T6的强度。2319铝合金的层间轧制主要强化机制为位错密度增加、气孔闭合和塑性变形诱导的固溶强化。

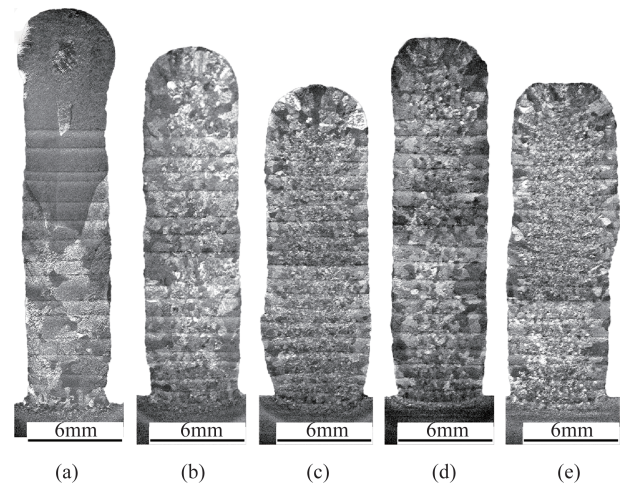


图3 TIG电弧增材TC4试样轮廓及金相

Fig.3 Outline and microstructure of TIG arc additive sample

Xu Xiangfang等^[37]研究了Inconel 718高温合金电弧增材及层间冷轧复合制造工艺。经75kN压力层间平辊轧制后, 抗拉强度从1102MPa提高至1348MPa, 高于锻造态的1276MPa。为降低轧制载荷, Zhang Tao等^[38]在提出通过火

焰将电弧增材 Inconel 718 合金加热至 450℃ 后,再用 50kN 压力进行层间轧制,应变量从冷轧的 8.51% 提高至 17.02%,抗拉强度和各向异性的改善效果都得到提升。

Colegrove^[39]和 McAndrew^[40]研究了侧向轧制和异形辊轧制对电弧增材组织性能和残余应力的影响,原理如图 4 所示。采用带凸圆的轧辊对厚截面电弧增材 TC4 进行层间轧制时,不同圆角得到的晶粒尺寸不同,带半径 3mm 圆角凸圆轧辊进行层间轧制的晶粒最细小。J.R. Hönnige 等^[41]对比研究了 2319 铝合金的高度方向轧制和侧向轧制,发现侧向冷轧的残余应力改善效果更好,利于形成压应力。Gornyakov 等^[42]通过有限元仿真分析了不同轧辊对电弧增材试件残余应力分布的影响,认为高度方向轧制可在试件的扫描方向引入塑性变形拉应力,抵消电弧增材产生残余拉应力,且带深沟槽轧辊对残余应力的改善效果更好。层间轧制过程中,电弧增材堆积材料的各处塑性变形量不同,这导致层间冷轧后的微观组织和力学性能仍不均匀^[43]。

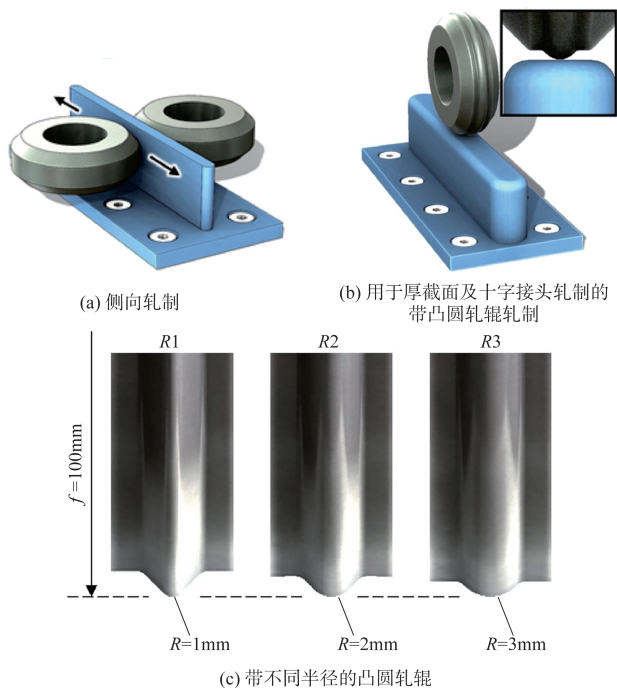


图 4 层间冷轧工艺

Fig.4 Interlayer cold rolling process

尽管通过层间冷轧可优化电弧增材构件的组织性能,改善残余应力,但当材料、轧辊形状、轧制工艺参数(载荷、温度、速率)等不同时,其改善效果差异明显。因此,在复杂零部件的电弧增材及层间冷轧复合制造工艺实施过程中,需要优化轧辊形状和工艺路径,以获得组织性能均匀的、残余应力分布合理的零部件。

1.2 在线热轧

与 Cranfield 的层间冷轧工艺研究同一时期,张海鸥等^[8, 44-46]开发了电弧增材和在线热轧复合制造技术,原理及设备如图 5 所示。通过调整轧辊与焊枪间距离,可调控轧制温度。通过两侧轧辊和高度方向轧辊共同作用,既可平整最上层材料利于下一层的熔覆,又可利用侧向轧制增加变形量和整形零件。该工艺利用增材制造余热进行热加工,具有效率高、铸锻同步、短流程和柔性高等优点,解决了层间冷轧的低效率、设备吨位大、成形零件简单等问题。

304 不锈钢电弧增材和在线热轧复合工艺试验结果表明^[44]:相比于未热轧试样,扫描方向上的屈服强度从 526.7MPa 提高至 547.9MPa,抗拉强度从 765.9MPa 提高至 816.7MPa,延伸率从 37.9% 提高至 40.7%;高度方向的屈服强度从 510.2MPa 提高至 557.8MPa,抗拉强度从 677.8MPa 提高至 689.8MPa,延伸率从 20.1% 提高至 22.2%。热轧后,奥氏体晶粒明显细化,并成功研制出复杂曲面的薄壁件,如图 6 所示,其中,图 6(a)为纵向截面,未热轧;图 6(b)为纵向截面,热轧后;图 6(c)为 1.2m 高×1.5m 长的复杂曲面试件。

为研究贝氏体钢电弧增材和热轧复合制造过程中试样的高温变形行为和微观组织演变规律,Fu Youheng 等^[45]采用 Gleeble-3500 开展了电弧增材沉积态材料的热模拟试验研究。随着温度提高和应变速率降低,贝氏体钢的高温变形抗力减小。在 900℃ 下,采用 5000N 压力和 10min/s 轧制速度时,变形量为 44%,应变速率为 0.8s⁻¹,得到了平均晶粒尺寸为 7μm 的组织,材料接近各向同性,在扫描方向、宽度方向、高度方向的抗拉强度和延伸率分别为 1275MPa 和 17.4%、1256MPa 和 16.6%、1309MPa 和 17.7%。采用二维元胞机和有限元法,可实现电弧增材及在线热轧复合工艺中材料凝固和动态再结晶仿真预测^[46]。当轧制力和下压量较大时,塑性变形压透性较高,晶粒细化区域较深。Gao Yifeng 等^[47]研究了电弧增材和在线热轧复合工艺制备 TC4-DT 钛合金的疲劳性能。相比于未热轧制试样,β 基体的平均晶粒尺寸从 5.4mm 降至 1~2.42mm,α 片层晶粒宽度从 3.67μm 降至 2.26μm,抗拉强度从 823MPa 提高至 855MPa,疲劳系数从 2.11×10⁻⁵降至 2.15×10⁻⁶。

目前,电弧增材和在线热轧复合制造工艺展现了良好的前景,但研究文献较少,复合制造工艺的在线监测、组织性能协调控制及全流程优化等研究尚不充分。电弧熔丝增材试件的温度分布与工件形状、材料等密切相关,且呈非均匀、动态分布。

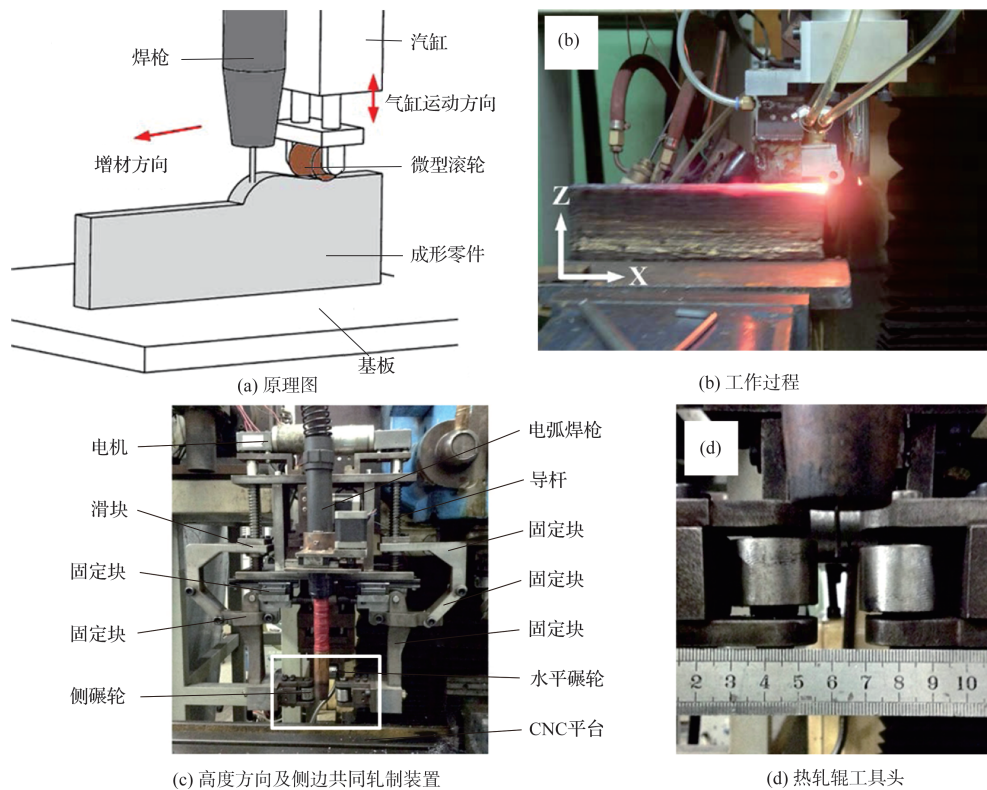
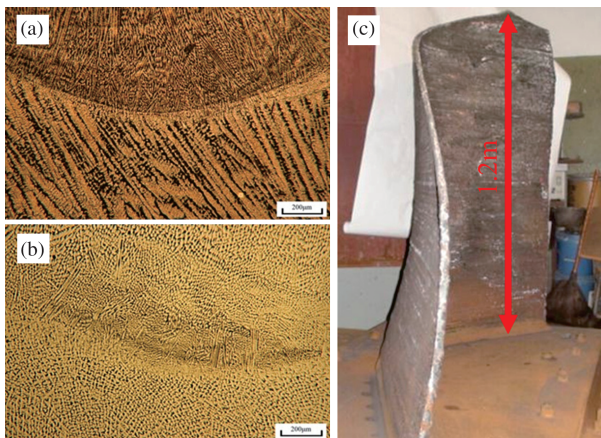


图5 电弧增材及在线热轧复合制造工艺

Fig.5 Hybrid manufacturing process of WAAM and hot rolling

图6 电弧增材及在线热轧复合制造 304 不锈钢
微观组织及试件Fig.6 Microstructure and specimens of 304 stainless steel
manufactured by arc additive and hot rolling

1.3 高频机械冲击

利用机械冲击、气动冲击、电动冲击和喷丸处理等高频微锻造工艺,在增材制造材料表面直接锤击,实现焊后塑性变形,达到了破碎粗大枝晶、平整构件表面、改善残余应力

分布等有益效果。

Almangour 等^[48]研究了喷丸工艺对尺寸为 20mm×10mm×5mm 的激光烧结 17-4PH 不锈钢表面质量和机械性能的影响。用 70~140μm 粒径的氧化铝丸以 340kPa 的压力处理表面 30s,再用 70~140μm 粒径的玻璃丸以 380kPa 的压力处理表面 30s。经过喷丸后,表面粗糙度由 4008nm 降至 1164nm,晶粒尺寸由 46nm 减至 24nm,残余应力由 119MPa 拉应力改善为 700MPa 压应力,抗拉强度由 1130MPa 提高至 1136MPa,表面形成高位错密度变形组织,耐磨性能明显提高。Ma 等^[49]开发了电弧增材和在线高频冲击的集成装置,通过汽缸施加应力,通过线性振动发生器实现高频锻造,辊轮内侧通水冷实现冷却,通过压力传感器、热电偶和振动测试仪分别测试了压力、温度和振动,如图 7(a)所示。利用该装置研究了 ER70s-6 碳钢焊丝复合制造,图 7(b)为连续三道次增材后构件的温度随时间变化曲线。随着焊枪和滚轮间距离降低、压力增加和冲击加速度提高,碳钢塑性变形增加,晶粒细化程度提高。在焊枪和滚轮间距离 16mm、压力 136N 和冲击加速度 45m/s²下,晶粒从 9.6μm 降至 6.4μm,抗拉强度从 480MPa 提高至 550MPa 左右。

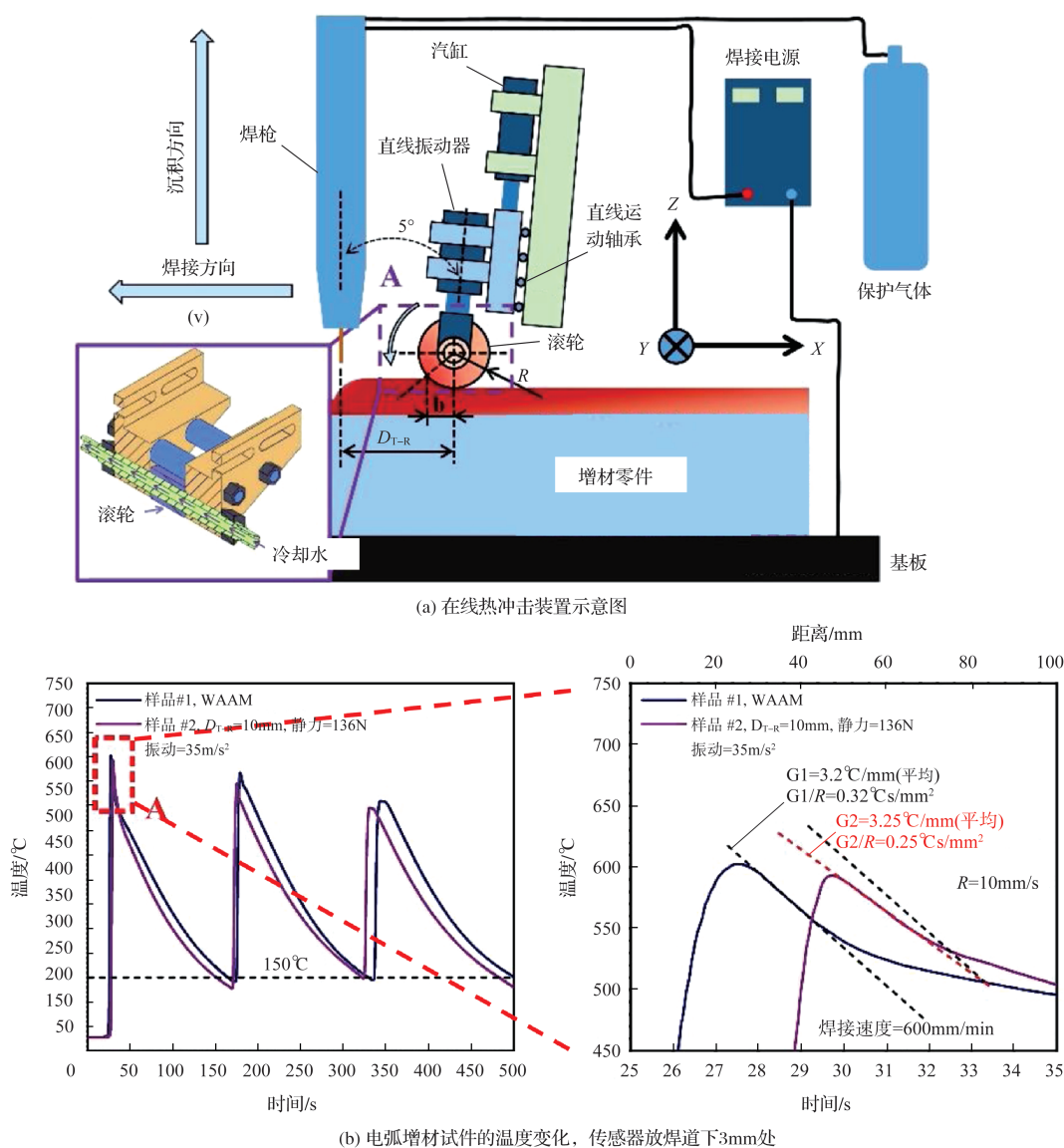


图7 电弧增材和机械冲击复合制造

Fig.7 Hybrid manufacturing process of WAAM and mechanical peening

Duarte等^[50]采用频率为10Hz的气压驱动直径10mm圆柱冲头和电弧增材制造装置,研究了AIS316L不锈钢的电弧增材和在线锤锻复合制造工艺。高频冲头与焊枪距离14mm,焊接速度360mm/min,经过55N压力锻造后,平均晶粒尺寸从2.4 μ m降至1.2 μ m,抗拉强度从574MPa提高至622MPa。Xiong Xiaochen等^[51]搭建了双机器人电弧增材及在线电动锤击平台,开展了AWS ER70S-6焊丝的验证试验研究。经过电动锤击后,抗拉强度从561MPa提高至662MPa。

Hönnige等^[52-53]利用气动冲击装置对TC4钛合金单道电弧增材进行层间和两侧冷锤击塑性变形,锤击汽缸的气压

6bar(1bar=100kPa),锤头直径4mm,频率180Hz,在TC4表面形成深度0.1mm左右的凹坑,强化深度约0.5mm。经气动锤击处理后,TC4钛合金残余应力得到优化,不同深度残余应力分布如图8所示。0.25mm深度的纵向和横向残余应力分别为-1380MPa和-750MPa。随着深度的增加,残余应力的改善作用减弱,在深度1.1mm时转为残余拉应力。但是,由于钛合金室温变形抗力大,冲击变形影响程度有限,因此增材TC4钛合金性能明显不均匀,在距表面1.8~3.4mm的硬度为HV420 $\pm$ HV10,而在0.5~1.2mm,硬度增加到HV492。

Fang Xuewei等^[54]研究了2319铝合金电弧增材和层间气动锤击复合工艺。经锤击后,材料变形量达到50.8%,气

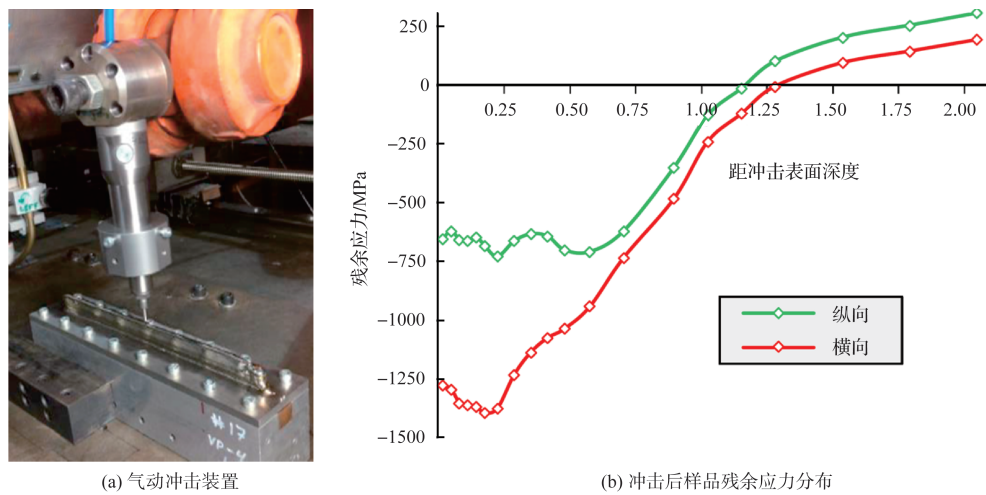


图8 气动冲击后增材试样残余应力分布

Fig.8 Residual stress distributions of the additive samples after aerodynamic impact

孔总体积由 1.2mm^3 降至 0.46mm^3 , 屈服强度从 148.4MPa 提高至 240.9MPa , 抗拉强度从 288.6MPa 提高至 334.6MPa 。图9为气锤冲击后试样的EBSD结果, Y1为单层沉积态组织, Y2为单层冲击后组织, Y3为只在第一层冲击的双层试样组织, Y4为双层冲击的试样组织。经多道次锤击和电弧增材后, 出现组织分层和不均匀, 即气动锤击作用深度不能完全细化单道次材料。这种组织不均匀性, 也给复合制造结构件的服役稳定性带来不确定性。

1.4 超声冲击

20世纪70年代, 由乌克兰Paton焊接研究所提出焊后超声冲击强化技术, 联合Quantum研究所研制了设备, 改善了

构件焊后疲劳强度等^[55]。同时, 超声冲击可使增材金属表面发生塑性变形, 实现气孔闭合、晶粒细化和残余压应力改善等效果, 提高疲劳性能^[56-57]。图10为电弧增材和超声冲击复合制造工艺装置^[58]和三向超声冲击原理图^[59]。在面积为 2mm^2 的冲头上施加 200N 恒定压力, 超声冲击枪与焊枪间距 20mm , 超声冲击枪与焊道夹角 45° , 频率和振幅分别为 20kHz 和 $16\mu\text{m}$, 采用 1200W 激光器对直径 1.2mm 的TC4焊丝进行增材, 得到的初生 β 相晶粒尺寸为 $152\mu\text{m}$, 减弱了织构^[58]。对电弧增材的TC4钛合金进行三向超声冲击, 超声功率 1500W , 频率和振幅分别为 20kHz 和 $100\mu\text{m}$, 冲头直径为 3mm , 初生 β 相晶粒长度从 18.5mm 缩短 9.6mm , 扫描方向的

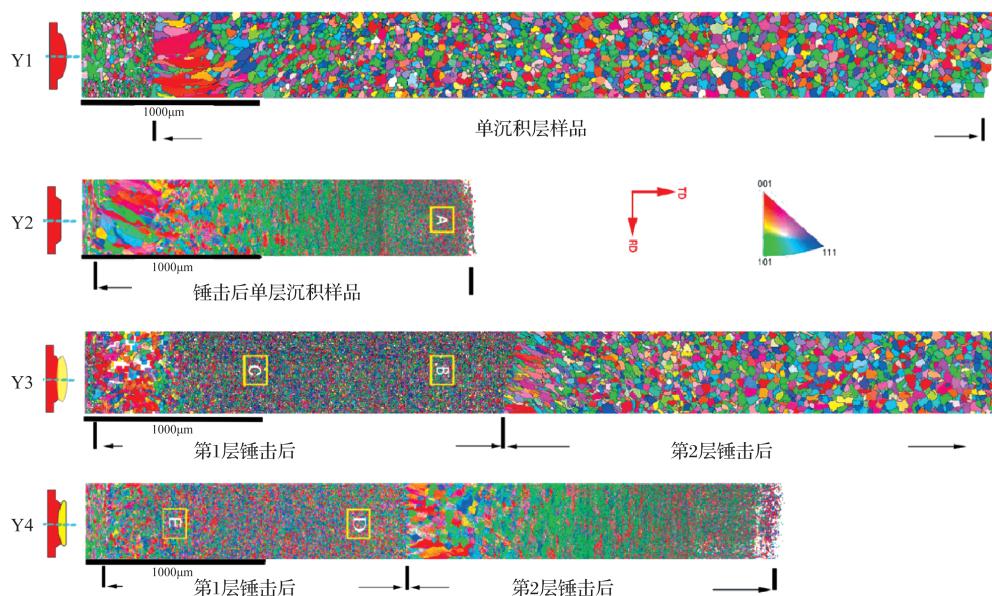
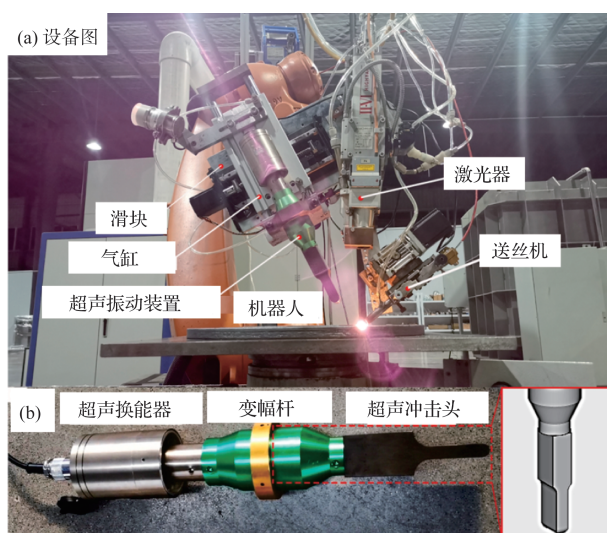
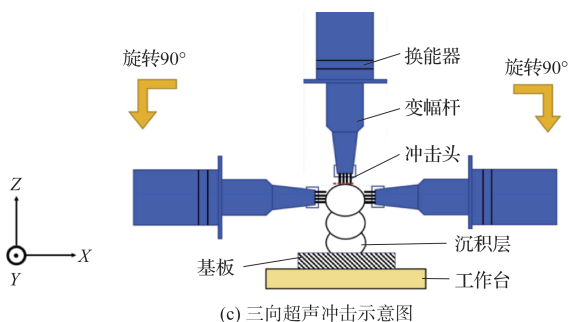


图9 不同试样的微观组织

Fig.9 Microstructure of the different WAAM specimens



(b) 超声冲击枪及冲击头



(c) 三向超声冲击示意图

图10 电弧增材及超声冲击复合制造

Fig.10 Hybrid manufacturing process of WAAM and ultrasonic peening

抗拉强度从966MPa提高至1055MPa^[59]。

在超声冲击作用下,电弧增材ER4043铝合金内的球形空洞发生压缩变形,孔径减小且形状复杂,金属表面晶粒明显细化,形成了高位错密度和位错缠结的200~400nm等轴晶粒区域^[60],如图11所示。

何智等^[61]研究了超声冲击道次对TC4电弧增材组织和性能的影响。随着冲击道次增加,晶粒发生一定程度的细化,并向等轴晶转变,材料的各向异性减弱,水平方向和高度方向差距从12.5%降至1.5%。武永等^[62]和Yang Yichong等^[63]也分别研究了层间超声冲击对电弧增材2219铝合金和TC4的强度和微观组织的影响,经层间超声冲击后,抗拉强度提高10%左右。Zhou Changping^[64]研究了超声冲击对增材制造304和316L不锈钢的作用深度,在100~400 μm 强化效果最明显,在400~1000 μm 强化效果呈幂指数递减,在深度1000 μm 以上时强化效果不明显。Prangnell等^[65]采用EBSD观察了超声冲击的微观组织, β 相晶粒被细化,微观

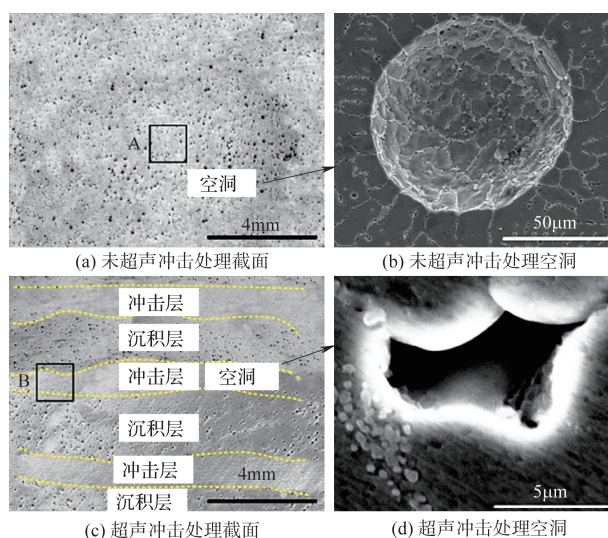
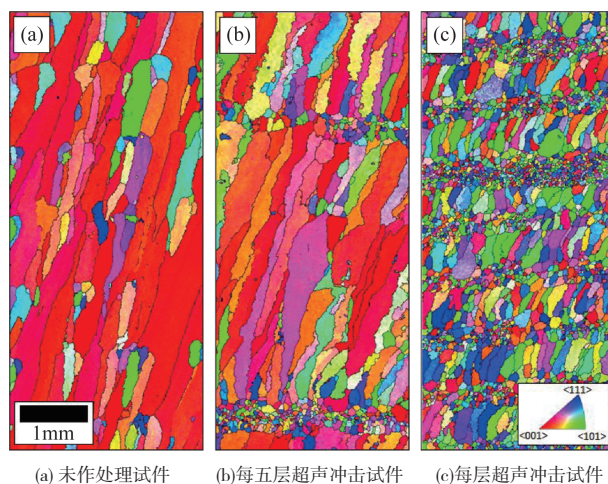


图11 电弧增材4043铝合金中的空洞

Fig.11 Voids of the aluminum alloy prepared by WAAM

组织不均匀分层,层间有 β 相细小晶粒,如图12所示。西北工业大学Zhou Yinghui等^[66]和哈尔滨工业大学Dong等^[67]研究了层间冷却对电弧增材2219铝合金组织及性能的影响,结果表明层间冷却可明显细化层间晶粒,获得了与层间超声处理相似的微观组织,如图13所示。其中,图13(a)为顶部区域;图13(b)为上区域;图13(c)为中部区域;图13(d)为底部区域;图13(e)为横截面;图13(f)为3D IPF照片。



(a) 未作处理试件 (b) 每五层超声冲击试件 (c) 每层超声冲击试件

图12 超声冲击后的EBSD微观组织

Fig.12 EBSD microstructure after ultrasonic peening

因此,相比于层间轧制,超声冲击具有效率高、自由度高、结构受限情况少等优点,也暴露了其冲击力小、作用深度有限、设备不稳定等问题,获得的组织性能不均匀。

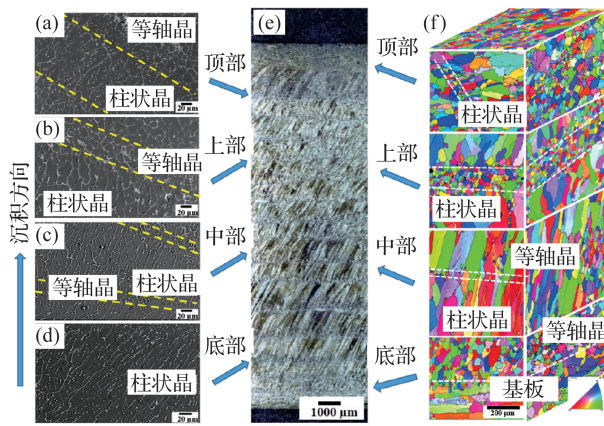


图13 采用层间冷却工艺电弧增材试样的微观组织
Fig.13 Microstructure of the WAAM specimen with interlayer cooling

1.5 激光冲击

激光冲击是一种先进的表面处理技术,可用于修饰表面微观结构,增强金属部件的力学性能^[68]。它将高功率密度和超短持续时间的脉冲激光应用于金属组件表面,在表层引入塑性变形和残余应力,可提高材料显微硬度、抗疲劳和耐腐蚀等性能^[69]。激光冲击不仅可诱导更高值和更大深度的残余应力,还可以在表层中产生更细小微观结构。Sun Rujian等^[70]研究了激光冲击对电弧增材2319铝合金微

观组织和力学性能的影响,如图14所示。采用脉冲能量15J、波长1064nm、脉冲15ns的直径4mm、能量密度为7.95GW/cm²的激光光斑处理后,作用深度达0.75mm,平均晶粒径从59.7 μ m减小到46.7 μ m,亚晶界比例从34%增加到70%,残余应力从拉应力转变为最大100MPa的压应力状态。虽然抗拉强度无明显变化,但屈服强度提高了72%。

Chi Jiaxuan等^[71]研究了热处理与激光冲击对TIG电弧增材Ti17试样微观组织和力学性能的影响。在600℃保温4h后,采用脉冲能量120J、波长1064nm、脉冲15ns的直径4mm的激光光斑处理后,表面发生严重塑性变形,产生最高-763MPa的残余压应力,抗拉强度从1153MPa提高至1181MPa,硬度从413Hv提高至461Hv。尽管激光冲击强化效果明显,但需要在增材制造零件表面铺一层约2mm厚的约束层,以增大层间强化应用的复杂程度。

1.6 其他复合制造工艺

随着电弧增材与塑性变形复合制造技术的快速发展,衍生出各种新工艺。德国西马克集团^[72]开展了ER70S-6低碳钢的电弧增材制坯及后续热环轧工艺研究,降低了制坯费用,提高了成形效率,经过1100℃环轧和900℃热处理后,显著降低了材料各向异性。英国帝国理工大学^[73]研究了热锻造对激光增材316L不锈钢组织和性能的影响,在1040℃锻造30%变形量时,材料致密度提高到99%以上,

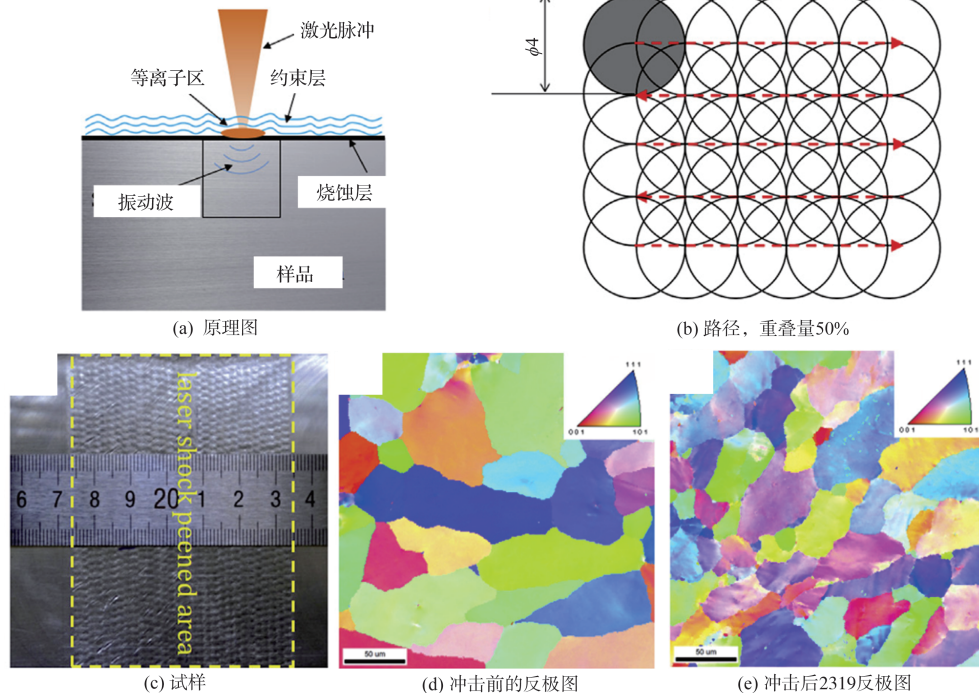


图14 电弧增材2319激光冲击

Fig.14 Laser shock peening for WAAM 2319 aluminum specimen

晶粒尺寸从 $65\mu\text{m}$ 降至 $15\mu\text{m}$,延伸率从12%提高至22%,抗拉强度从 450MPa 提高至 550MPa 。熊逸博等^[74]研究了多向锻造对电弧熔丝增材制造300M钢微观组织和力学性能的影响,打碎了沉积枝晶,消除了气孔,得到了均匀等轴晶,高度方向抗拉强度从 1185MPa 提高至 1390MPa ,扫描方向强度从 1072MPa 提高至 1354MPa 。

M. Bambach等^[75]研究了在TC4钛合金锻造零件上局部电弧增材复合工艺和电弧增材后热锻造复合制造工艺,如图15所示。既可利用电弧增材在锻件局部加强,也可利用电弧增材制造复杂毛坯或在锻件基础上局部制坯,再高温锻造提高机械性能和疲劳性能。电弧增材材料的抗拉强度为 945MPa ,高于锻造最低标准的 900MPa 。电弧增材TC4热锻造后,材料的强度和延伸率都优于标准要求。这些组合制造工艺可大幅提高零件生产效率、降低制造成本,为电弧增材在工业中的应用提供了更多生命力。

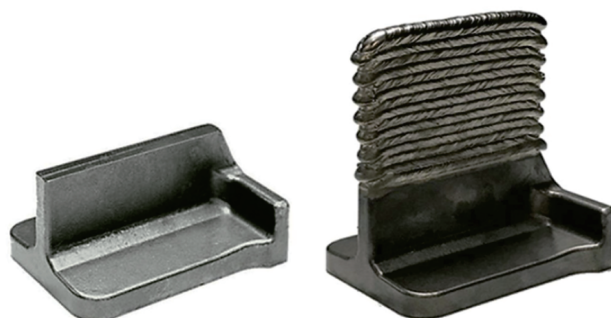
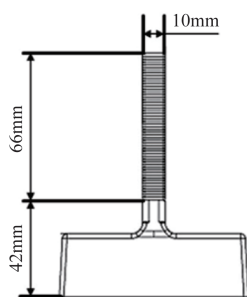
此外,在电弧增材过程中增加特殊处理,也可强化材料性能。Zhang Chen等^[76]研究了平台振动对Al-Mg合金电弧增材组织和性能的影响。经过高频振动后,晶粒尺寸减小22.5%,抗拉强度 343MPa ,比未振动前提高了 30MPa 。

Zhao Wenyong^[77]在Al-5%Mg电弧增材过程中引入纵向交变磁场进行电磁搅拌,通过施加磁场冲击改变熔池形状及熔池固化行为,抑制了液滴飞溅、细化了晶粒,气孔最大尺寸从 $80\mu\text{m}$ 降至 $31\mu\text{m}$ 。

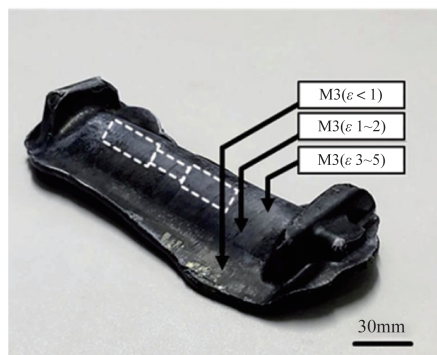
2 塑性变形强化规律及在线控制

2.1 塑性变形强化规律

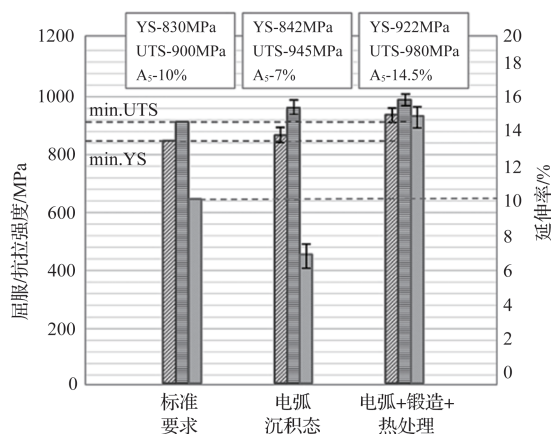
电弧增材的沉积态金属存在宏观分层、定向优先生长的柱状晶、溶质偏析、元素损失、组织不均匀、晶粒粗大、气孔、各向异性、残余应力和热裂等缺陷。与传统的铸造后开坯锻造工艺相似,电弧增材的塑性变形强化机制可描述为:在塑性应力的作用下,粗大枝晶碎化,材料发生位错滑移、孪生或晶界滑移等,位错密度增加,在后续热环境中发生再结晶细化晶粒;在压应力作用下,气孔、缩松和裂纹发生闭合和焊合,组织更加致密,且静水压应力越大,除去缺陷效果越好;经反复锻打后,晶格畸变加剧,元素扩散程度增加,可改善宏观分层和溶质偏析,使化学成分更均匀;部分沉积态组织中的杂质在塑性变形中被打碎,细小杂质在晶界钉扎,强化材料;塑性变形促进部分材料第二相固溶,时效生成细小第二



(a) 在复杂锻件上局部电弧增材



(b) 电弧增材出叶片毛坯后热锻造



(c) 几种不同工艺TC4钛合金机械性能

图15 电弧增材与塑性变形组合工艺

Fig.15 Some hybrid Manufacturing processes of WAAM and plastic forming

相组织;沉积态金属塑性变形后,内部应力由拉应力状态转变为压应力状态,减弱了材料的残余应力和各向异性。

电弧增材时,电弧焊枪熔池、焊道及工件温度分布不均匀,动态变化。沉积材料在塑性变形工具头的作用下发生非均匀塑性变形,高温区域的材料应变速率高、应变量大,低温区域的材料应变速率低、应变量少。局部塑性变形过程受沉积材料外形、工具外形、应变量、应变速率、变形温度、应变状态等因素影响,易导致局部变形量过大,易导致内部剪切变形带和焊道鼓肚,变形不均匀导致微观组织不均匀、反复冲击导致表面材料折叠等缺陷。钢、铝合金、镁合金、镍合金和钛合金等材料的塑性变形机理差异明显,其工艺参数也差异明显。

Zhou Yinghui 等^[78]研究了电弧增材的 2219 铝合金在 300~480℃ 温度区间和 0.01~10s⁻¹ 应变速率的等温压缩变形行为及组织演变规律。在定应变 0.7 下,在 360℃ 和 0.01s⁻¹ 条件下获得晶粒细小的均匀组织;当应变速率增至 10s⁻¹ 时,材料出现不均匀变形和局部剪切带,同时存在 50μm 以上的粗大晶粒和成簇出现 5μm 以下的细小晶粒区;当温度降至 300℃ 或升至 480℃ 时,其晶粒尺寸及均匀程度都比 360℃ 的差。图 16 为 GH4169 的高温热加工图,其在 920~1010℃ 和 0.01~1s⁻¹ 的变形参数范围内,不同热变形工艺参

数得到的微观组织及力学性能存在较大差异^[79]。

为控制塑性变形过程,可对轧辊或冲击工具头的形状进行优化设计,改善沉积材料塑性变形分布。Wang Tao 等^[80]在研究 Cu-Al 复合薄板轧制时,采用了波纹辊和平辊组合轧制的方法,波纹辊的剪切变形增大了两种材料的啮合及塑性变形、细化材料晶粒、降低轧板压力,如图 17 所示。这种非完全对称工具及多工具头组合方式为电弧增材后局部塑性变形提供了新思路。

2.2 复合制造工艺的在线控制

电弧增材为金属材料反复加热、冷却和堆积过程中,因不稳定电弧、不均匀焊丝、保护气体气流、工件表面质量、焊接轨迹交叉点、起收弧点、复杂曲率等干扰因素,电弧增材质量不稳定,在增材制造形状外貌和组织性能表现出时空非连续“遗传”特性,并持续影响后续道次增材。Nguyen 等^[12]在研究中空曲面管件的电弧增材时,发现因截面特征和热应力的作用而发生管件截面畸变、位移偏差、壁厚不均等,如图 18 所示。当复杂异形零件结构不同时,电弧增材制造出的零件与设计结构的尺寸偏差不同。采用 LS-DYNA 分析非均匀温度场的热膨胀及热应力对管件形状的影响,并在电弧增材路径中进行位置补偿,经过反复优化可大幅缩小偏差。

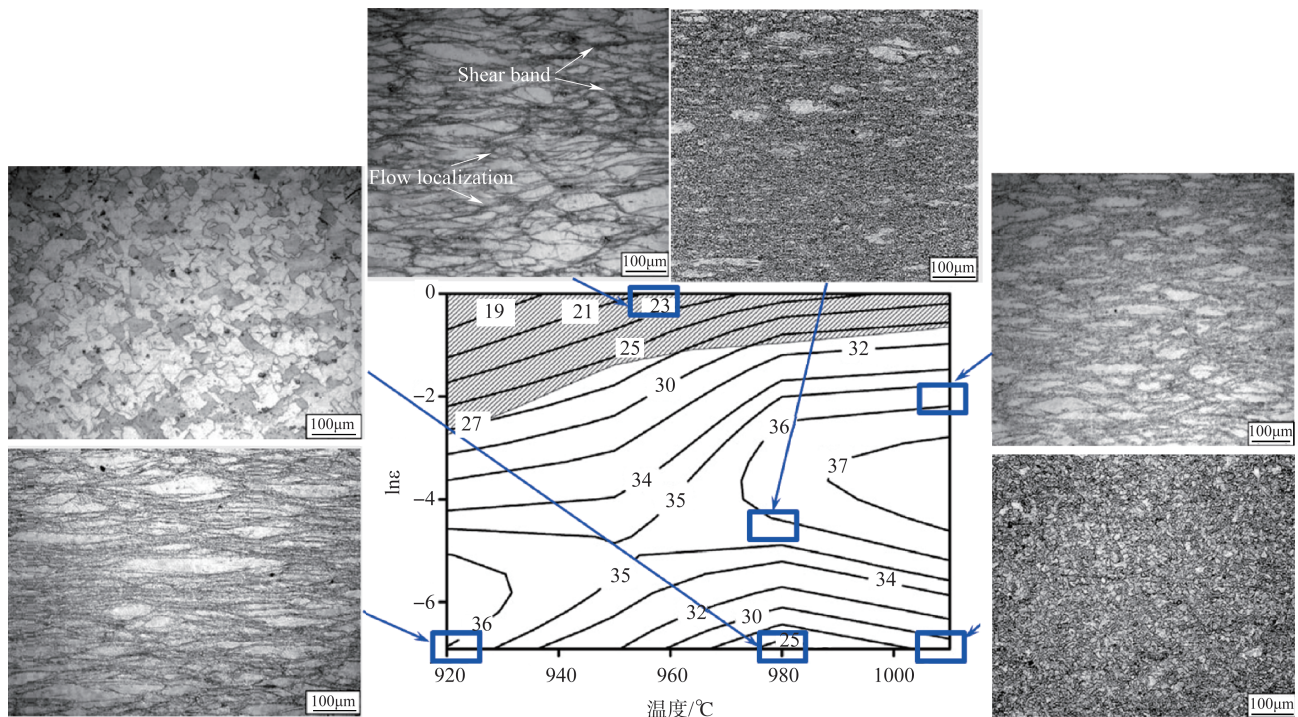


图 16 GH4169 高温合金在真应变 0.6 的热加工图及微观组织

Fig.16 Hot processing map and microstructure of GH4169 at true strain 0.6

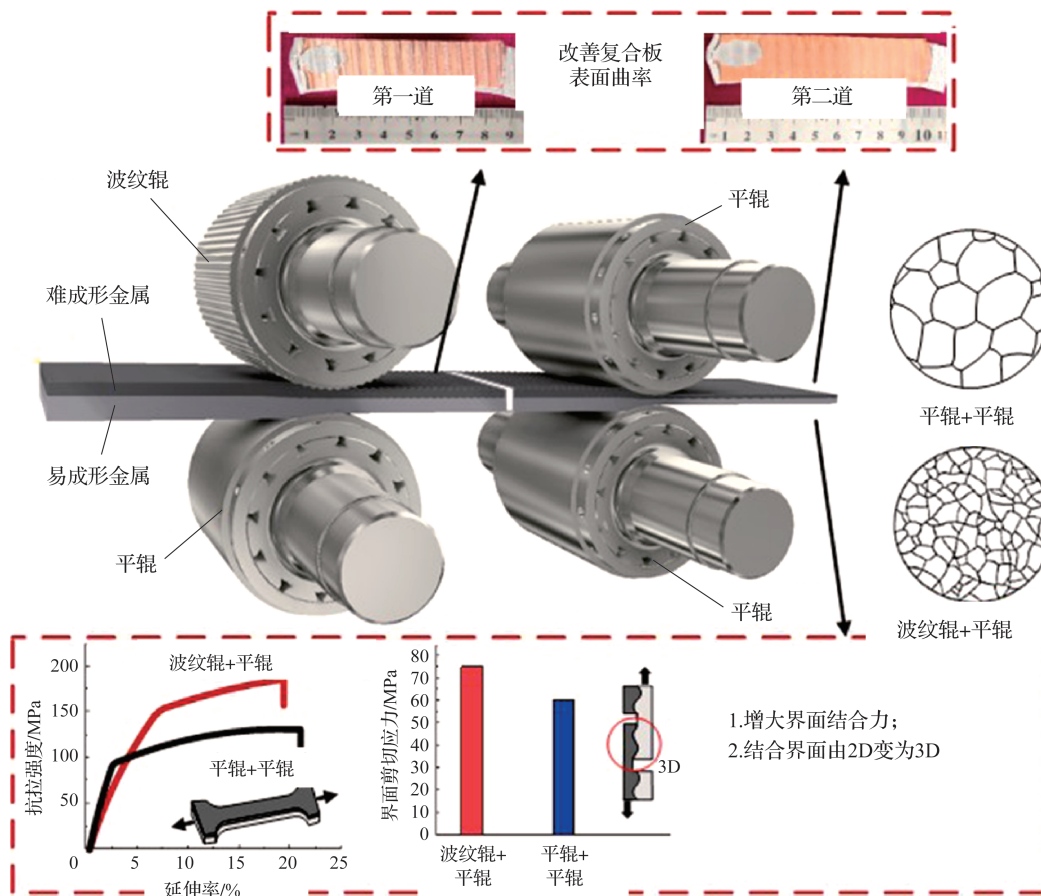


图 17 Cu-Al 复合板的波纹辊和平辊组合轧制工艺

Fig.17 Hybrid manufacturing process of corrugated rolling and flat rolling for Cu-Al laminated composite

相比于电弧增材制造工艺,电弧增材和局部塑性变形复合工艺更复杂。例如,在复杂零件的电弧增材和在线热轧复合制造工艺中,热轧过程受温度分布、压力、轧制速率等工艺参数影响。温度分布受零件形状、焊枪与轧辊距离、冷却条件、工件预热温度等影响。薄壁处材料散热速度小于厚壁处的散热速度,两处材料变形规律和应变量不同,并累积成大偏差。

为抑制和控制复合制造工艺中各缺陷,基于电弧焊接工艺、热传导及应力分析、塑性变形规律等大量试验数据及模型,改变既往增材制造的路径预先规划,增加在线监测、数据采集及快速优化、工艺参数实时调整等过程控制,为复合工艺制造零件提供“形”与“性”的精密控制方法。西南交通大学的熊俊等^[81-82]利用双目视觉测量的方法实时测量电弧增材的高度和宽度,以宽度为优化对象,构建了焊接电流、层间温度等参数的闭环控制。Dryburgh 等^[83]研究了电弧增材及层间冷轧复合工艺制造的 TC4 钛合金表面条纹与轧制变形之间的关系,为层间冷轧的在线测量系统提供了

基础数据。

因此,基于多传感器的在线监测和工艺参数控制对电弧增材及塑性变形复合制造工艺至关重要。图 19 为激光选区熔化增材制造在线监测中可能用到的各类物理信号、传感器和监测技术^[22]。利用 X 射线可实现材料内部气孔和裂纹的检测,利用热成像仪可完成温度分布在线测量,利用高速相机可实现表面质量和塑性变形应变分布测试等,配合数据分析软件和数据优化算法,可开发出面向整个零件的全过程监测及控制技术体系。

3 总结与展望

电弧增材制造是电弧熔丝焊接与自动化控制深度结合的技术,正处于高速发展时期,工艺参数、组织演变、理论模型等正在逐渐完善,其应用前景逐渐清晰,知识产权保护意识增强^[84]。电弧增材与局部塑性变形复合制造工艺为多物理场、多学科交叉的制造方法,面临工艺参数众多、增量累计效应明显、复合制造工艺与装备不成熟、成形件宏微观控制难、时空

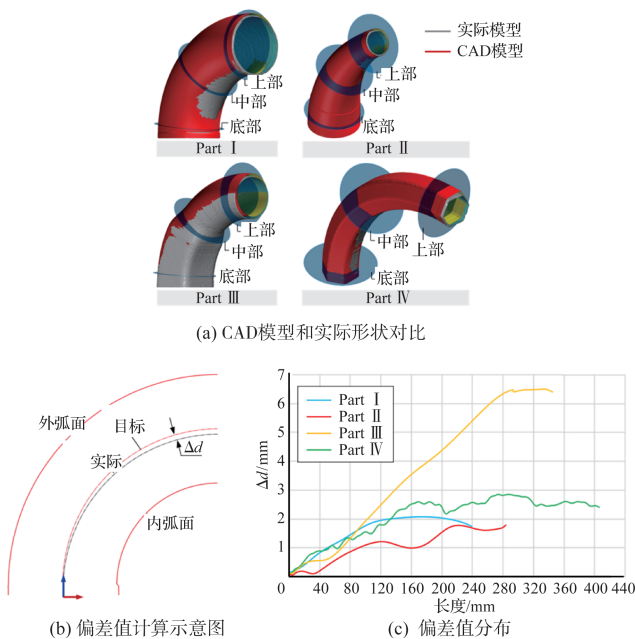


图18 复杂管件的电弧增材

Fig.18 WAAM for the complex tubular part

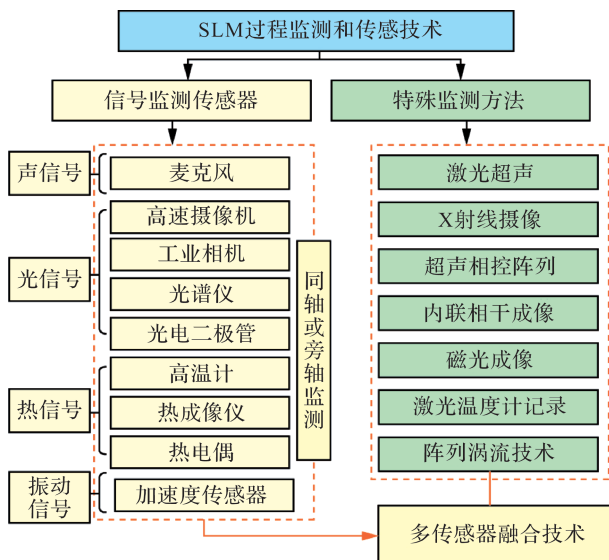
图19 传感器及监测技术分类^[22]

Fig.19 Classification of sensors and monitoring techniques

非线性遗传特性等问题,其研究工作集中于以下几个方面:

(1)新型电弧增材及塑性成形复合制造技术。目前,几种复合制造工艺都存在一定的不足,层间冷轧变形抗力较大、效率低、微观组织改善效果不明显,不适用于复杂构件制造;在线热轧工艺,变形量不足,组织性能改善尚需改进;高频表面冲击技术,作用深度有限。迫切需要开发新型复合制造工艺,如引入电磁搅拌新能场,增加熔池超声冲击,采用多异形轧辊组合轧制等。

(2)工艺参数—形状尺寸—组织性能对应的数据库及定量分析模型。电弧焊接工艺参数、塑性变形工艺参数、特种辅助能场等参数的变化,将影响到制造零件形状尺寸、微观组织和力学性能。以宏微观跨尺度仿真为工具,构建完整的工艺参数、零件宏观尺寸、微观组织和力学性能数据库,梳理相互之间的对应关系,为形性协同控制的大型复杂零件提供理论基础。

(3)在线监测、闭环控制和智能产线。利用多传感多源信号的在线监测,构建采集信号—制造缺陷—工艺参数间的定量关系,通过算法在线优化工艺参数,实时反馈,实现闭环控制。识别误差,实时计算误差补偿,反馈调整工艺参数纠正偏差。基于电弧增材及塑性成形复合工艺单设备的稳定运行,组建多机器协调的智能制造产线,是电弧熔丝增材及局部塑性变形复合制造工艺走向工业生产的必经之路。

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Progress of Hybrid Manufacturing for Wire Arc Additive Manufacturing and Partial Plastic Forming Technology

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Abstract: Wire arc additive manufacturing technology is a technology suitable for rapid prototyping of large metal components. It has the advantages of low equipment cost, high material utilization, high deposition efficiency, high automation level, flexibility and convenience, as well as defects such as poor microstructure property and performance. Plastic forming is an effective technology to improve welding porosities, the microstructure property and residual stress distribution of components manufactured by wire and arc additive. The hybrid manufacturing technology of wire arc additive manufacturing and partial plastic forming is beneficial to realize the "mechanical property controlling" of parts. However, the complicated additive manufacturing path planning, combination tool head of printing and knocking, vibration and pressure stress increase the difficulty of shape precision controlling. The effects of local plastic deformation processes such as interlayer cold rolling, hot rolling, mechanical shock, ultrasonic peening and laser shock on the microstructure, residual stress, anisotropy and surface quality of specimens manufactured of wire arc additive are summarized. Combined with the hardening law of plastic deformation on welding structure and the control of arc additive process, the development trend of hybrid manufacturing technology for wire arc additive manufacturing and partial plastic forming is discussed from the coordinate controlling of mechanical property and shape precision, which provides references for the manufacturing of complex parts.

Key Words: wire arc additive manufacturing; hybrid manufacturing process; interlayer rolling; ultrasonic peening; laser shock peening; plastic deformation

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