◀◀◀上接A3版

激光增材制造过程中使用激光诱导击穿光谱学技术对多种元素进行原位分析的研究

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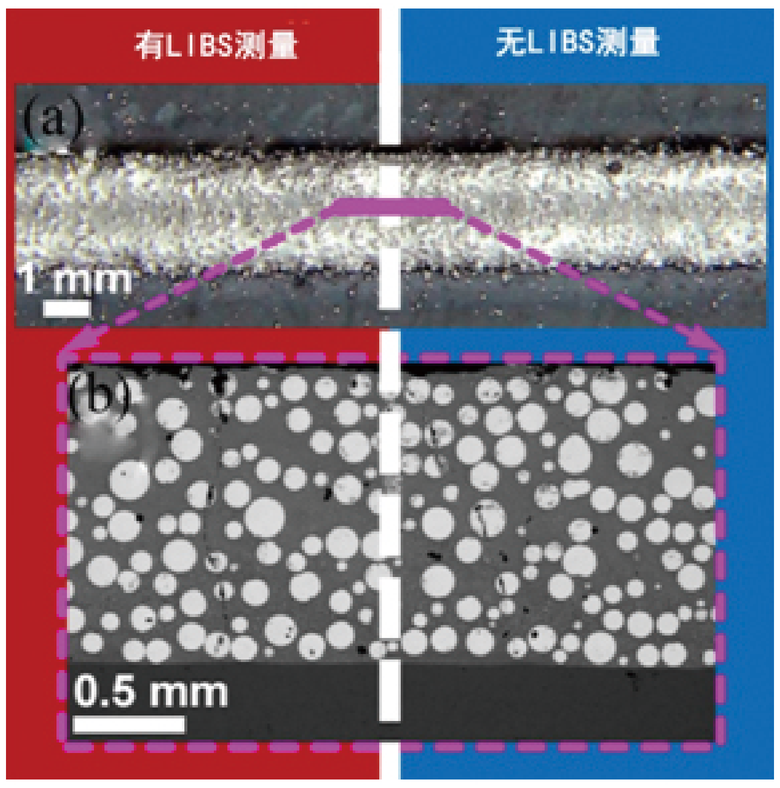

图6(a)熔覆层顶部光学显微镜图片；(b)熔覆层横截面SEM图片（左为有LIBS测量的样品；右边为无LIBS测量的样品）

基于这些分析，我们建议将LIBS应用于同轴激光熔覆过程的在线分析。分别使用EDX和燃烧红外吸收法（Combustion infrared absorption method-CIAM）校准LIBS中的钨元素和碳元素，钨和碳的校准曲线与抛物线吻合度很高，见图7。

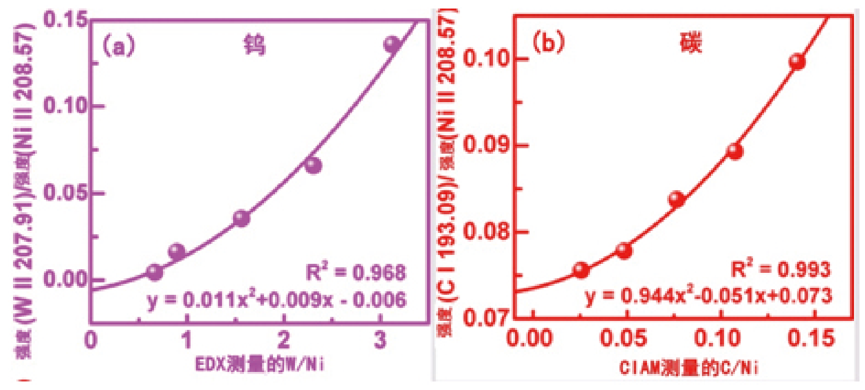

图7(a)LIBS中的钨校准曲线；(b)LIBS中的碳校准曲线

为了证明利用LIBS能对具有梯度浓度的熔覆层中的元素进行原位定量分析，设计了改变WC的送粉率并通过LIBS对W和C元素进行测量的实验，送粉率通过编程实现调节，送粉率的变化见图8(a)，WC的送粉率从0g/s增大到20g/s、35g/s，Ni-Fe-B-Si的送粉率从在第200秒的时候从20g/s减小为10g/s，经过100秒之后又恢复到20g/s。LIBS测量的频率为10Hz，并且LIBS光谱在10个连续激光脉冲上取平均以提高精度。钨和碳的LIBS原位测量结果分别见图8(b)和(c)。待熔覆层冷却之后，使用XRF对钨的LIBS测量结果进行验证，使用CIAM对碳的LIBS测量结果进行验证，观察图8(b)和(c)可以发现钨元素含量的一致性很好，而碳元素含量的一致性稍差些，这是由于LIBS光谱信噪比较低。

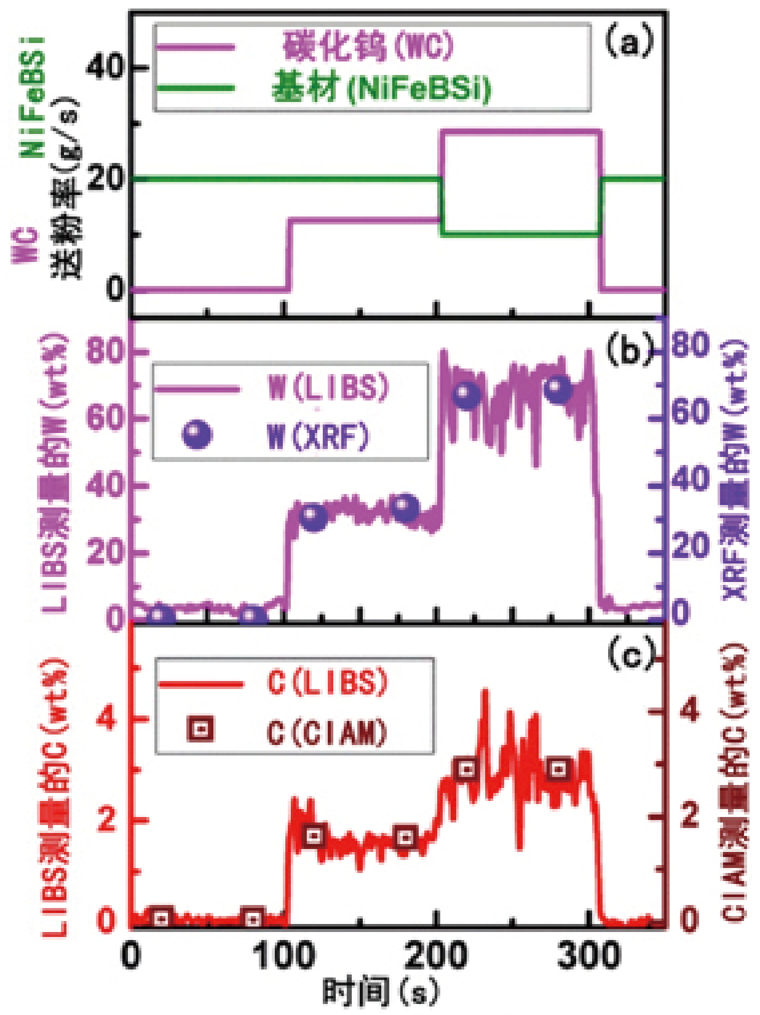

图8(a)WC粉末和Ni-Fe-B-Si粉末在熔覆过程中的变化；(b)钨元素含量的LIBS和XRF原位分析结果；(c)钨元素含量的LIBS和CIAM原位分析结果

四 结论

本研究首次证明了使用LIBS技术对有AM技术制造的零件进行原位定量多元素分析的可行性。同轴激光熔覆是一种基于金属粉末流动并通过连续激光熔化粉末的AM技术，该技术可用于合成基于WC增强的Ni-Fe-B-Si合金的高耐磨涂层。为了实现这一目标，我们设计了一个安装在激光熔覆头上的低重量紧凑型LIBS探头，我们的目的是开发一种远程LIBS系统，能通过该系统分析复合涂层合成过程中定量分析轻元素（如碳）和重元素（如钨）。通过LIBS探针对热固化的熔覆层和熔池进行采样，但仅在对熔池进行采样时得到了有分析意义的结果，这是因为熔覆层上表层中的WC颗粒分布不均匀且存在镍富集现象，这种分布对任何在线分析和离线分析都是挑战，且LIBS对熔池进行取样不会影响熔覆层的特性，因此选择LIBS对熔覆层的熔池进行采样。钨和碳的LIBS结果分别通过EDX和CIAM进行校准，校准结果精确度很好。关键组分（碳和钨）的定量LIBS实时分析已经在梯度浓度涂层合成过程中得到了证实。

增材制造技术具有强大的金属零件生产能力和破损零件的修复和快速再制造能力，如果能通过增材制造生产出具有特定元素组成梯度的零件，那么增材技术将应用到更多领域，零件生产过程中的元素在线定量元素分析正成为未来增材制造中实现特定元素组成梯度的强制性要求。LIBS能为任何材料中的任何元素进行原位分析，未来如果可以在3D打印机中安装上LIBS元素定量原位分析系统，那么在制造或者修复零件时可以得到该零件完整的三维元素分布图，从而得到该零件的“元素身份证”，通过这种“元素身份证”可以设计生产出具有特定元素组成梯度的零件。

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