

# 激光选区熔化钛合金超声辅助铣削性能研究

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**摘要:** **目的** 针对激光选区熔化钛合金开展超声振动辅助铣削性能和作用机理研究, 提高增材制造钛合金表面加工质量、加工精度及加工效率, 推动增材制造钛合金构件在高端装备业领域的广泛应用。**方法** 在传统铣削和超声振动辅助铣削下, 采用聚晶金刚石刀具开展激光选区熔化钛合金铣削试验研究, 分析不同条件下的表面硬度、切削力、表面形貌、表面粗糙度和切屑黏结的差异性。**结果** 激光选区熔化钛合金硬度单次测量及其平均值均高于传统钛合金。常规干铣削激光选区熔化钛合金时, 切削力随着转速的增大而呈现下降趋势, 随着进给速度和切削深度的增加表现出逐渐增大的趋势。在传统铣削下, 传统钛合金表面形貌存在明显的刀具划痕, 而超声振动铣削时, 激光选区熔化钛合金表面形貌总体表现出更加的光滑和平整。激光选区熔化钛合金在常规铣削和超声辅助铣削过程中, 刀具前后刀面都出现了严重的钛合金切屑黏结现象。**结论** 激光选区熔化钛合金常规干铣削时, 增大转速或降低进给速度和切削深度能够降低切削力。在相同切削参数下, 激光选区熔化钛合金超声铣削质量优于传统钛合金常规铣削表面质量。激光选区熔化钛合金表面质量改善的作用机理主要归因于激光选区熔化钛合金的金相组织特性及超声振动时断续切削特性的综合效应。相对于传统铣削方式, 超声振动辅助铣削对改善激光选区熔化钛合金加工过程中的刀具抗黏结性效果有限。

**关键词:** 激光选区熔化钛合金; 聚晶金刚石刀具; 超声辅助; 表面质量; 切屑黏结

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## Machining Performance of Ultrasonic Assisted Milling of Titanium Alloy Fabricated by Laser Selective Melting

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**ABSTRACT:** The work aims to study performance and mechanism of action of ultrasonic vibration assisted milling of laser-selective melting titanium alloy, to improve the surface machining quality, machining accuracy and machining efficiency of additive manufacturing titanium alloy, and to promote the extensive application of additive manufacturing titanium alloy components in high-end equipment industry. Methods of conventional milling and ultrasonic vibration assisted milling were employed in milling of laser-selective melting titanium alloy by using polycrystalline diamond tools, and the differences of surface hardness, cutting force, surface morphology, surface roughness and chip adhesion were analyzed under different conditions. The surface hardness of laser-selective melting titanium alloy is higher than that of conventional titanium alloy by single measurement value and its average value. During the process of dry milling of the laser-selective melting titanium alloy using conventional milling way, the cutting forces decreased with the increase of rotational speed, and they increased with the increase of feed speed and cutting depth. Under the condition of conventional milling, there were some obvious tool scratches on the surface morphology of the conventional titanium alloy. However, more smooth and flat surface morphology of laser-selective melting titanium alloy were successfully achieved under the method of ultrasonic vibration assisted milling. In addition, it was found that there were serious chip adhesion on the surface of rake face and flank face using the conventional titanium alloy or the ultrasonic vibration assisted milling. Cutting forces can be reduced by the methods of increasing rotation speed, decreasing feed speed and cutting depth in conventional dry milling of the laser-selective melting titanium alloy. In addition, the experiments indicate that the machining quality of the laser-selective melting titanium alloy using ultrasonic vibration assisted milling is better than that of the conventional titanium alloy. Compared with the machined quality of conventional milling of the conventional titanium alloy, the better surface quality of the laser-selective melting titanium alloy can be obtained by using the ultrasonic vibration assisted milling under the same cutting parameters. The action mechanism in improving surface quality of laser-selective melting titanium alloy is mainly attributed to several aspects. On one hand, the fine microstructure and higher hardness of laser-selective melting titanium alloy leads to its higher brittleness and lower plastic flow. On the other hand, compared with conventional milling way, the discontinuous cutting characteristics of ultrasonic vibration machining, which can contribute to increasing the tool-workpiece separation time and decreasing the actual cutting time, thus further improving chip breaking, reducing cutting friction of tool-workpiece or tool-chip and surface roughness of machined workpiece. The results demonstrates that the ultrasound-assisted milling has hardly effect in improving the chip adhesion on the tool surface. This may be caused by a combination of factors including the characteristics of strong adhesion and plastic fluidity of the laser-selective melting titanium alloy, the low friction coefficient of polycrystalline diamond cutter and the small brittleness difference between the laser-selective melting titanium alloy and the traditional titanium alloy.

**KEY WORDS:** laser-selective melting titanium alloy; polycrystalline diamond tools; ultrasonic vibration assisted milling; surface quality; chip adhesion

激光选区熔化成形 (Selective Laser Melting, SLM) 是目前金属增材制造成型最普遍的技术之一, 激光选区熔化钛合金 (SLM Ti6Al4V) 已经广泛应用于航空、航天、医疗器械及生物植入物等众多领域的关键复杂构件, 并具有极其重要的地位和应用前景<sup>[1]</sup>。由于 SLM Ti6Al4V 在致密度、力学性能及显微结构等方面与传统钛合金 (CAL Ti6Al4V) 存在较大差异, 且激光成形过程中因热变形而造成的低尺寸精度、低形状精度及低表面质量问题<sup>[2-3]</sup>, 通常难以满足精密零部件的精度要求。因此, 开展 SLM Ti6Al4V 钛合金的高效切削加工, 改善加工质量, 降低刀具磨损、提高加工效率及其加工精度对推动金属增材制造钛合金在高端装备业领域的应用具有重要的研究意义及应用价值。

目前, 降低刀具磨损、提高切削性能及加工质量的方法包括: 应用微量润滑和低温冷却润滑技术<sup>[4-7]</sup>、

刀具涂层<sup>[8]</sup>、电火花和激光辅助加工<sup>[9-10]</sup>、仿生织构技术<sup>[11-14]</sup>。近些年, 超声辅助切削在提高刀具切削性能方面得到了国内外学者的广泛关注<sup>[15-18]</sup>, 现有研究表明, 与传统的切削加工相比, 超声辅助加工可以获得低切削力、低切削温度、良好的切屑断屑、低表面粗糙度及良好的加工质量, 已成为有效改善表面质量、提高切削性能, 延缓刀具磨损的重要方法之一。

综上所述, 针对 SLM Ti6Al4V 成形后存在的表面质量和形貌精度问题, 开展 SLM Ti6Al4V 的超声振动辅助切削加工, 提高加工质量及切削性能, 并逐渐成为增材制造钛合金高效优质切削研究面临的新挑战和新热点。本文选择具有低摩擦和抗磨损性能优异的聚晶金刚石(PCD)作为刀具材料, 开展传统铣削 (CM) 和超声振动辅助铣削 (UAM) 下的 SLM Ti6Al4V 切削力、表面质量、表面黏结及其作用机理研究。

## 1 试验

本次试验加工如图 1 所示, 试验选择的工件为: 传统 Ti6Al4V 钛合金 (CAL Ti6Al4V) 和激光选区熔化 Ti6Al4V 钛合金 (SLM Ti6Al4V); 两刃的 PCD 刀具, 刀刃直径为 4 mm, 刀具前后角分别为  $0^\circ$  和  $15^\circ$ ; 切削参数为: 主轴转速 4 000~8 000 r/min, 进给速度 120~960 mm/min, 切削深度 0.1~0.8 mm, 切削长度约 612 mm。超声参数: 超声频率 30 kHz, 振幅 6  $\mu\text{m}$ 。本次试验采用干切削方式, 实验设备涉及铣床 HAAS OM-2A、测力仪 (奇石乐 Kistler9257B)、电荷放大器 (Kistler 5080A)、扫描电子显微镜 (Phenom XL) 及 MH-5LD 显微硬度计。

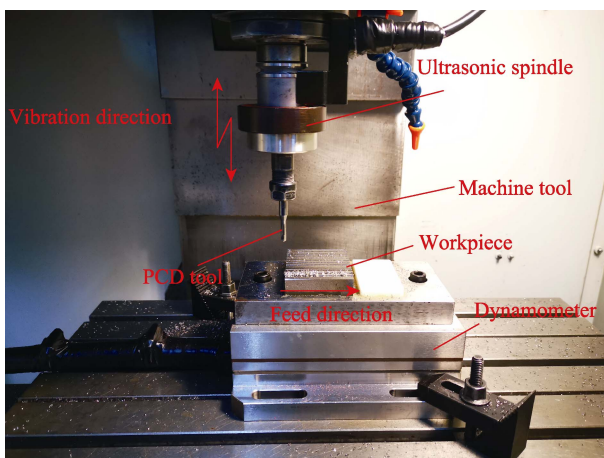


图 1 超声辅助铣削 SLM Ti6Al4V  
Fig.1 Ultrasonic assisted milling of SLM Ti6Al4V

## 2 结果分析与讨论

### 2.1 SLM 钛合金硬度测量

针对 SLM Ti6Al4V 和 CAL Ti6Al4V 工件进行维氏 (HV) 硬度测量, 每种工件的硬度测量重复 3 次, SLM Ti6Al4V 的维氏硬度 3 次测量值分别为 307.5、309.8 和 311.4, 3 次测量平均值为 309.6。而 CAL Ti6Al4V 的维氏硬度 3 次测量值分别为 257.1、235.8 和 274.4, 3 次测量平均值为 255.8。图 2 为 SLM 钛合金和 CAL 钛合金 3 次维氏硬度测量数值的比较和分析。因此, 根据上述分析并结合图 2 可以看出, 激光选区熔化成形后的钛合金表面 3 次重复测量的维氏硬度值及其平均维氏硬度值均高于传统钛合金。

### 2.2 切削参数对 SLM 钛合金切削力的影响

图 3 为转速对切削力的影响。从图 3 知, 当  $v_f = 360 \text{ mm/min}$ ,  $a_p = 0.3 \text{ mm}$ , 转速从 4 000 r/min 增加到 8 000 r/min 的过程中, PCD 刀具铣削过程中 3 个方向的力 ( $F_x$ 、 $F_y$ 、 $F_z$ ) 均表现出逐步减小, 且  $F_x$ 、 $F_y$  和  $F_z$  分别降低了约 37.7%、55.4%和 36.0%。试验

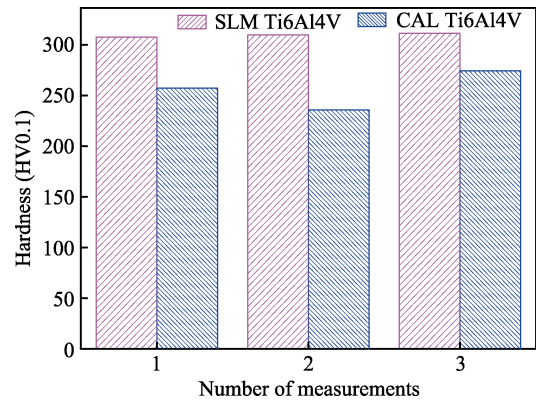


图 2 SLM 钛合金和 CAL 钛合金硬度  
Fig.2 Hardness of SLM titanium alloy and CAL titanium alloy

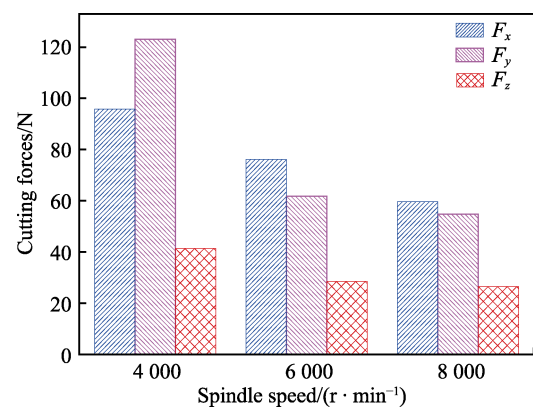


图 3 转速对 SLM 钛合金切削力的影响  
Fig.3 Effect of spindle speed on cutting force of SLM titanium alloy

表明, 通过增大转速能够有效降低切削增材制造钛合金过程中刀具的铣削力<sup>[19]</sup>。

图 4 为进给速度对增材制造钛合金铣削力的影响。从图 4 知, 当  $n = 6 000 \text{ r/min}$ ,  $a_p = 0.3 \text{ mm}$ , 进给速度从 120 mm/min 增加到 960 mm/min 的过程中,  $F_x$ 、 $F_y$  及  $F_z$  均表现出逐步增大, 且  $F_x$ 、 $F_y$  和  $F_z$  分别增大了约 1.66、0.66、3.45 倍。

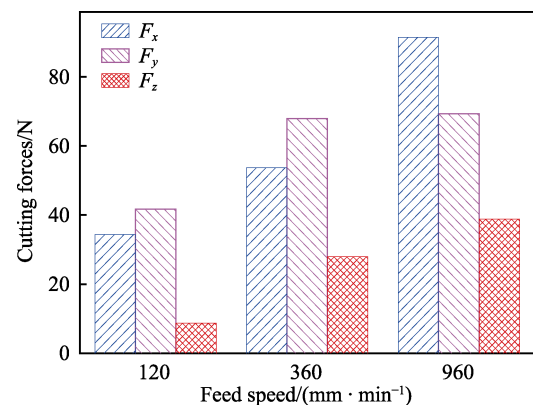


图 4 进给速度对 SLM 钛合金切削力的影响  
Fig.4 Effect of feed speed on cutting force of SLM titanium alloy

图5为切削深度对增材制造钛合金铣削力的影响。从图5知,当 $n=6\,000\text{ r/min}$ ,  $v_f=360\text{ mm/min}$ , 切削深度从0.1 mm增加到0.8 mm的过程中,PCD刀具铣削过程中3个方向的力也均表现出逐步增大,且 $F_x$ 、 $F_y$ 和 $F_z$ 分别增大了约10.68、4.58、7.85倍。由图4和图5结果表明,通过降低进给速度和切削深度能够有效降低切削力。这可能主要归因于:进给速度和切削深度的增大会增加切削层截面积,从而导致了切削力的增加<sup>[20]</sup>。

## 2.3 超声辅助对SLM钛合金表面质量的影响

图6和图7为CAL Ti6Al4V和SLM Ti6Al4V分

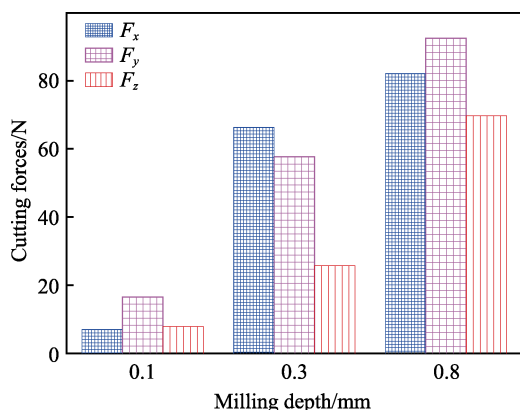


图5 切削深度对SLM钛合金切削力的影响  
Fig.5 Effect of cutting depth on cutting force of SLM titanium alloy

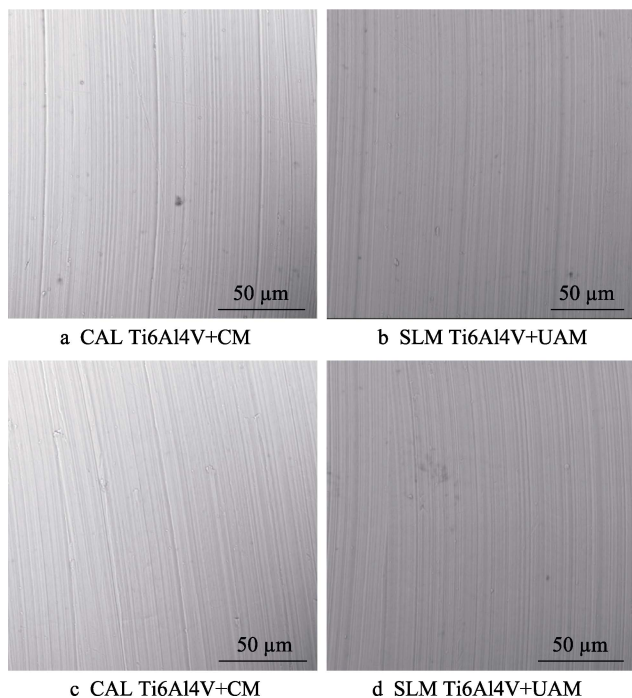


图6 不同条件下的加工表面

Fig.6 Machined surface at the different conditions: (a, b)  $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=6\,000\text{ r/min}$ ; (c, d)  $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=8\,000\text{ r/min}$

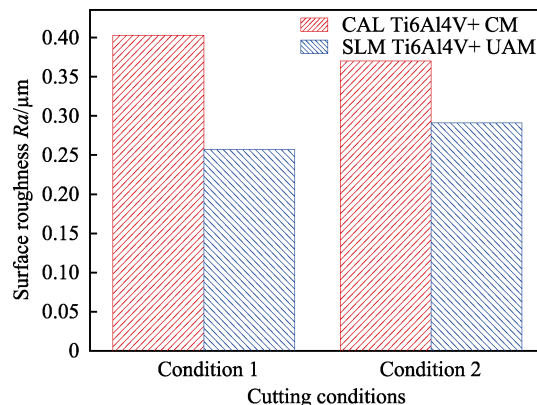


图7 不同条件下的表面粗糙度比较

Fig.7 Comparison of surface roughness under different conditions (Condition 1:  $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=6\,000\text{ r/min}$ ; Condition 2:  $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=8\,000\text{ r/min}$ )

别在传统铣削(CM)和超声振动辅助(UAM)铣削后表面质量的形貌对比。其中,图6a和图6b的切削参数为 $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=6\,000\text{ r/min}$ ;图6c和图6d切削参数为 $a_p=0.3\text{ mm}$ ,  $v_f=360\text{ mm/min}$ ,  $n=8\,000\text{ r/min}$ 。

在传统铣削下,CAL钛合金表面的SEM形貌如图6a、图6c所示,从SEM形貌可以看出,这4个工件表面存在明显的刀具划痕。而超声辅助铣削下,SLM钛合金工件表面SEM形貌,总体表现出更加的光滑和平整(如图6b和图6d所示)。图7为不同条件下的表面粗糙度比较,其中,图6a和图6b参数对应于图7中的condition1,图6c和图6d参数对应于图7中的condition2。从图7可明显看出,相同切削参数条件下,超声辅助加工有助于降低工件表面粗糙度 $R_a$ 。因此,从图6和图7可以看出,在相同切削参数下,超声辅助加工的SLM钛合金表面(图6b、图6d)分别优于对应的传统铣削CM钛合金表面质量(图6a、图6c)。

## 2.4 超声振动对刀具抗黏结性能的影响

图8为超声辅助干铣削SLM钛合金后,PCD刀具后刀面的SEM形貌及EDX分析。通过EDX面扫结果可以初步获知,PCD后刀面区域分布的元素包括Titanium、Carbon、Aluminium、Cobalt、Tungsten及Vanadium。为了确定图8h靠近切削刃附近覆盖的一层黏结物,选取点4为对象进行分析,根据图8i点4区域黏结物EDX成分分析结果可知,该黏结层的元素成分为Titanium、Aluminium及Vanadium,其主要成分是Titanium,据此可基本判定该黏结层来自SLM钛合金超声切削过程中产生的切屑黏结物,同样的黏结现象在刀具前刀面也非常明显。

图9为超声辅助和传统干铣削SLM钛合金约612 mm后,PCD刀具表面切屑黏结SEM形貌。常规铣削后,后刀面和前刀面黏结情况分别如图9a和



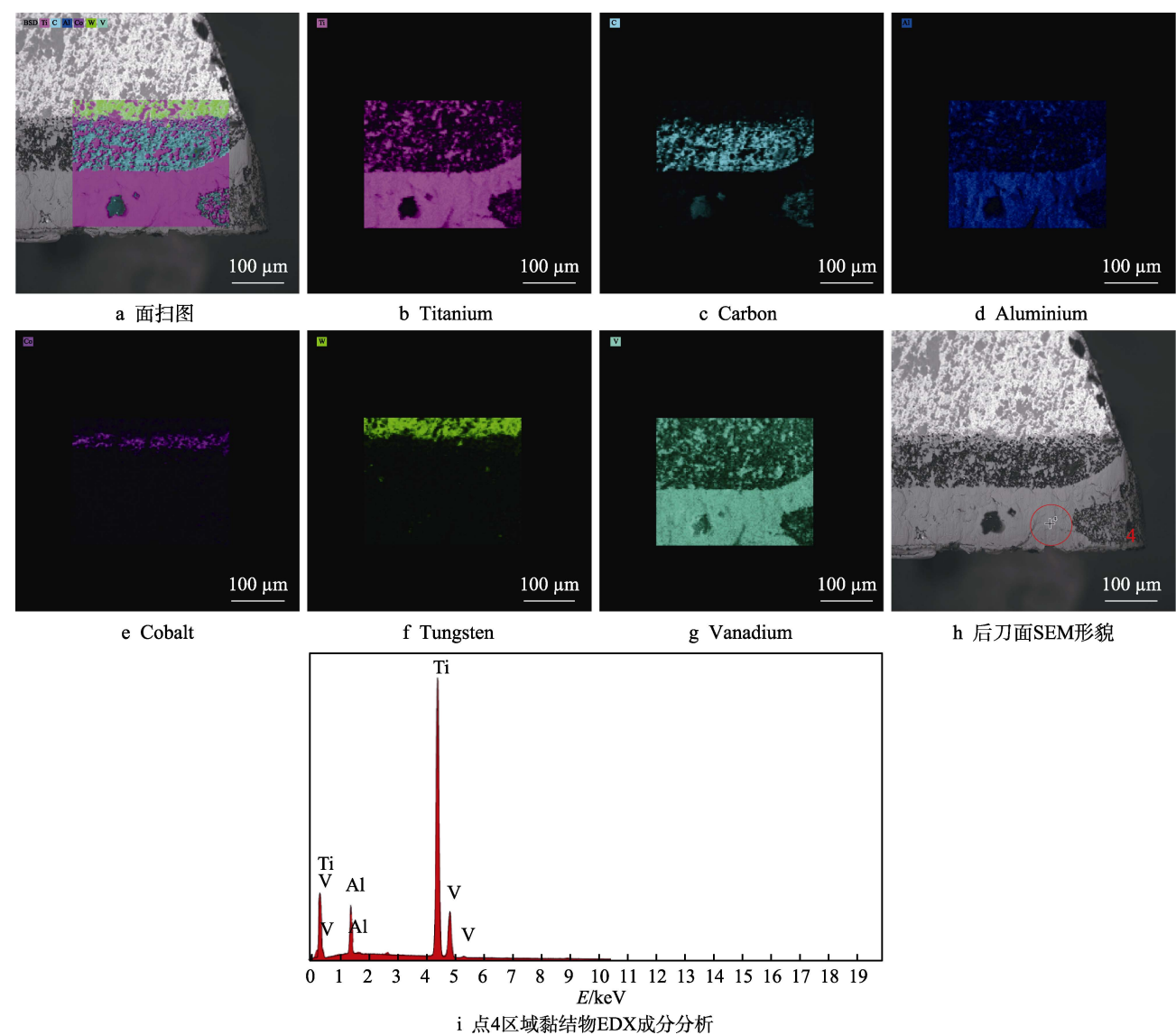


图 8 PCD 刀具后刀面黏结物分析  
Fig.8 Analysis of adhesion material on the flank face of PCD tool

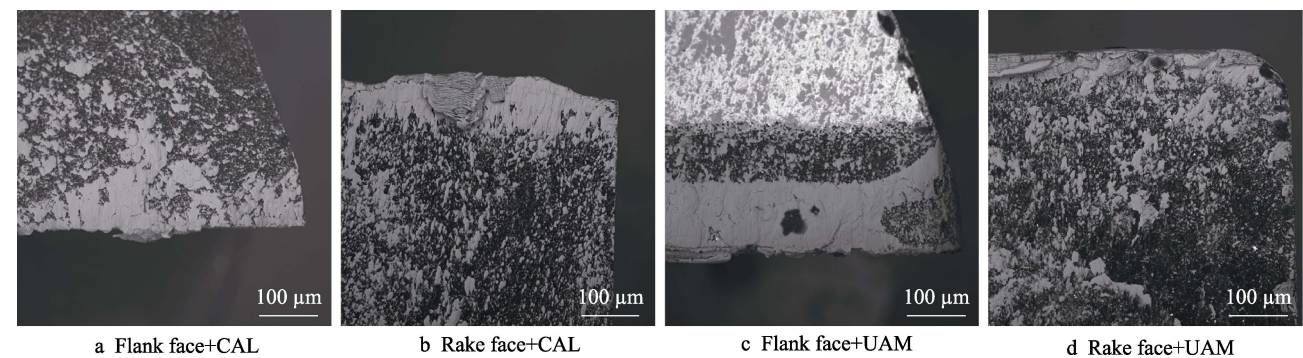


图 9 SLM 钛合金超声辅助和常规铣削下的刀具表面切屑黏结  
Fig.9 Chip adhesion of tool surface in UAM and CM of SLM titanium alloy

图 9b 所示。同样, 超声辅助铣削后, 后刀面和前刀面黏结情况分别如图 9c 和图 9d 所示。根据图 8 和图 9 可以看出, 无论是常规铣削还是超声辅助铣削后, PCD 刀具前后刀面, 特别是靠近切削刃附件的区域明

显覆盖一层切屑黏结物, 这严重影响了刀具切削性能及表面加工质量的提升。此外, 从图 9 可以看出, 相比较常规铣削来说, 超声辅助似乎对切屑黏结抑制没有改善效果。

## 2.5 讨论与分析

由图 2 结果显示, SLM Ti6Al4V 表面硬度单次测量和 3 次测量平均值, 均比传统 Ti6Al4V 略高, 这主要由激光选区熔化钛合金和传统钛合金自身金相组织结构差异性引起的<sup>[21-23]</sup>, 由于制备工艺的不同, 前者具有比后者更加精细的显微组织结构, 从而导致激光选区熔化钛合金往往具有更高的硬度和脆性等。

根据图 6 和图 7 可知, 对同一组切削参数下, 超声振动辅助下 SLM Ti6Al4V 加工表面质量优于传统铣削 CAL Ti6Al4V 表面质量, 其作用机理可能归因于: 首先, 相对于传统锻造钛合金来说, 金属增材制造钛合金具有更细密的显微组织, 从而导致了其具有相对较高的硬度, 提升了工件的脆性, 一定程度上降低了钛合金切削过程的塑性流动特性, 对切削加工质量起到了积极的改善作用<sup>[22]</sup>; 其次, 相对于传统铣削方式来说, 借助于超声振动辅助铣削, 能够有效增加刀具/工件分离时间, 减少实际切削时间, 也有助于改善切削摩擦、降低切削力、降低切削温度、表面粗糙度, 从而最终改善了加工质量<sup>[24-25]</sup>。

根据文中图 8 和图 9 试验结果可以明显看出, 在超声干铣削条件, PCD 铣刀表面黏结现象十分严重, 超声辅助对 SLM 钛合金铣削过程抗黏结效果改善不佳。一方面, 本次试验是在干切削条件下, 钛合金本身很强的黏结性和塑性流动性; 其次, 尽管 SLM 钛合金金相显微组织比传统钛合金精细, 具有更高的脆性, 在一定能够程度上有助于降低铣削过程中材料的塑性流动性, 可能它们金相显微组织的差异性不大, 从而对黏结流动性能的改善效果有限; 最后, 由于 PCD 刀具的低摩擦系数, 也使得切屑在刀具表面易于流动和黏结区域的扩张。在上述 3 种可能的因素综合作用下, 导致了超声辅助下刀具表面抗黏结效果不佳。

## 3 结论

1) 在常规干铣削 SLM 钛合金时, 切削力随着转速的增大而呈现下降趋势, 随着进给速度和切削深度的增加表现出逐渐增大的趋势。

2) 在相同切削参数下, SLM Ti6Al4V 超声铣削加工质量优于 CAL Ti6Al4V 传统铣削加工质量, 其作用机理可能归因于: SLM Ti6Al4V 精细的金相组织和更高的硬度, 导致更高的脆性和较低的塑性流动; 与传统铣削相比, 超声振动的断续切削特性, 导致了刀具-工件分离时间增加和实际切削时间减少, 有助于断屑、降低切削摩擦、降低表面粗糙度。

3) 在常规铣削和超声辅助铣削下, PCD 刀具前后刀面均产生严重的切屑黏结, 这可能归因于 SLM Ti6Al4V 自身很强的黏结和塑性流动性、PCD 刀具较低的摩擦系数及 SLM 钛合金和传统钛合金脆性差异小等综合因素造成的。

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