

# 钛合金新型切削加工技术及 切削行为研究进展

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**摘要:**随着航空航天领域对高性能钛合金构件的需求日益增长, 其切削加工技术面临高精度、高质量的严峻挑战。系统回顾了钛合金切削加工技术的最新进展, 深入分析了切削加工研究方法、切屑特征, 重点阐述了切削参数对切削性能及刀具磨损的影响机制, 并对刀具磨损方式及改进策略进行了归纳。针对当前研究的局限性, 进一步提出了未来钛合金切削加工技术的发展方向, 旨在为提升钛合金构件的加工效率和表面完整性提供参考, 并为相关研究提供理论基础。

**关键词:**钛合金; 切削技术; 切屑特征; 切削参数; 刀具

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## Research progress on advanced cutting technologies and cutting behavior of titanium alloys

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**Abstract:** As demand rises for high-performance titanium alloy components in the aerospace sector, cutting technologies encounter major hurdles in delivering high precision and quality. This paper presents a systematic review of the latest advances in titanium alloy cutting technology, along with an in-depth analysis of research methodologies in cutting and chip characteristics. Specifically, it focuses on elucidating how cutting parameters affect cutting performance and tool wear. It also summarizes tool wear modes alongside corresponding improvement strategies. Given the limitations of present study, this paper proposes future development directions for titanium alloy cutting technologies, aiming to provide guidance for enhancing the cutting efficiency and surface integrity of titanium alloy components and to lay a theoretical foundation for subsequent relevant research.

**Key words:** titanium alloys; cutting technology; chip characteristics; cutting parameters; tools

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## 0 引言

钛合金以其卓越的低密度、高比强度、优异的高温力学性能、耐腐蚀性以及良好的生物相容性, 在航空航天、石油化工、海洋工程、汽车制造、生物医药等领域得到广泛应用<sup>[1-5]</sup>。近年来, 随着航空航天飞行器服役性能要求的日益严苛, 关键零部件及飞行器结构中钛合金的用量显著增加<sup>[6-9]</sup>。作为全球第二大民机市场, 中国对钛加工材的需求量巨大, 尤其是在大型客机制造方面<sup>[6]</sup>。2024 年全球钛加工材产量约为  $26 \times 10^4$  t, 其中航空航天、医疗和新兴领域的需求占比高达 58%<sup>[10]</sup>。同年, 我国在航空航天、电力和船舶领域的钛材用量持续快速增长, 全年占比约为 30.2%; 尤其值得注意的是, 3C 行业(计算机、通信和消费电子)异军突起, 年用钛量超过  $1.1 \times 10^4$  t<sup>[10-11]</sup>。然而, 钛合金固有的低导热性、高化学活性等特性使其切削加工难度大<sup>[12-17]</sup>, 采用传统切削方法难以保证零件的尺寸精度和表面质量, 导致生产成本居高不下, 并限制了新型钛合金的应用。这些瓶颈具体表现在以下方面: ①低导热系数导致切削温度过高; ②小变形系数加剧前刀面磨损; ③前刀面单位面积切削力较大; ④小弹性模量导致后刀面易磨损; ⑤化学活性高。为了突破传统切削技术的局限性, 国内外学者积极探索新型切削加工技术, 但相关研究仍存在不足。针对上述问题, 笔者系统总结了近年来国内外研究人员在钛合金切削加工技术、切削加工研究方法、切屑特征、切削工艺、切削刀具等方面的研究进展, 并对各种方法的优缺点进行了分析。最后, 指出了当前钛合金切削加工研究的不足和未来发展趋势, 旨在为相关领域的研究提供参考。

## 1 钛合金新型切削加工技术

随着我国航空航天与深海工程等领域的快速发展, 相关装备的核心零部件逐渐呈现结构复杂化、尺寸大型化趋势, 对机械加工工件表面完整性、加工精度及生产效率提出了更高要求。如图 1 所示, 某大型飞机起落架结构特征表现为: 总长跨度达 2~6 m、大长径比、回转曲面与非对称空间构型, 需经过 160 余道精密工序协同完成<sup>[18]</sup>。此类高难度加工场景已明显暴露出传统切削技术的局限性, 工艺效率低、制造成本高、工序衔接重复性差等问题日

益凸显, 越来越难以满足现代钛合金构件制造需求。近年来, 为了突破传统钛合金切削加工技术瓶颈, 国内外研究人员尝试开发出一系列新型切削加工技术, 主要包括高速切削技术<sup>[19-21]</sup>、超声振动辅助切削技术(一维超声振动辅助切削<sup>[22]</sup>、二维超声振动辅助切削<sup>[12,23-24]</sup>、超声椭圆振动辅助切削<sup>[25-26]</sup>、并行超声振动辅助切削<sup>[27]</sup>、高压冷却超声振动辅助切削<sup>[28]</sup>等)、车铣加工技术<sup>[16,29-30]</sup>、低温切削加工技术<sup>[31]</sup>、绿色湿式切削加工技术<sup>[32]</sup>、热氢处理辅助切削技术<sup>[33]</sup>等, 其关键特性如表 1 所示。



(a) 起落架外筒; (b) 起落架组装件

图 1 某大型飞机起落架<sup>[18]</sup>

Fig. 1 Landing gear of a certain large aircraft<sup>[18]</sup>

高速切削是一种高效、经济制备高质量、高精度工件的先进加工技术, 其切削速度通常高于传统切削速度 5~10 倍<sup>[34]</sup>。对钛合金而言, 切削速度大于 150 m/min 时即可认定为高速切削<sup>[35]</sup>。与传统切削过程不同的是, 高速切削过程是一种剧烈应变、大应变速率、高温及复杂应力状态下的热力耦合行为, 其切削加工机制发生了本质变化。研究证实<sup>[36]</sup>, 采用高速切削加工时可以有效减少切削热及低阶切削振动产生, 使得切削力降低约 30%、刀具寿命提高 70%。超声振动辅助切削技术作为一种新兴切削加工技术可以有效降低切削力及切削热、改善工件表面质量、细化表面微观组织, 提高工件加工质量<sup>[26,37]</sup>。切削加工过程中, 刀具受高频振动作用产生间歇式切削运动, 从而使得刀具与工件周期性接触和分离<sup>[22]</sup>。与常规切削加工过程相比, 超声振动辅助切削过程受高应变速率、动态应力及局部热-力耦合综合作用, 诱使工件亚表面组织和基体组织发生明显变化<sup>[38]</sup>。典型超声振动辅助切削技术包括一维、二维超声振动辅助切削。特别地, 超声椭圆振动辅助切削技术作为二维超声振动辅助切削的一种特殊方式, 其椭圆轨迹是通过控制相位差而在单一平面内产生的, 且切削过程需要严格同步两方向振动才能实现椭圆轨迹稳定形成<sup>[25,39]</sup>。这种微米级、超声频率的椭圆振动更有利于降低切削力及刀具磨损、促进散热、增强断屑或排屑能力, 进一步改善工件表面质量<sup>[26,40]</sup>。车铣加工技术是基于工件和铣刀

之间的复合旋转运动对工件进行切削加工的一种先进加工技术,其与数控技术条件充分适应<sup>[16,29-30]</sup>。根据铣刀与工件相对位置的差异,可分为正交车铣、正切车铣和轴向车铣。正交车铣加工技术可以通过工件低速旋转与铣刀高速旋转实现高速或超高速切削,并有效突破高速车削技术瓶颈,即卡盘和工件转速过高时导致的加工工艺难以保证<sup>[16]</sup>。此外,正交车铣加工过程可以促使切屑自动排除,显著抑制了“缠屑”现象的发生。低温切削加工技术是采用液氮、液态 CO<sub>2</sub> 或冷风等冷却介质对切削区域进行冷却的先进绿色加工技术,其核心原理是利用低温环境降低切削温度及材料的塑性<sup>[31,34,41]</sup>。按照冷却方式差异<sup>[34]</sup>,可以分为内冷低温切削加工和外冷切削加工。随着低温切削加工技术迅速发展,研究人员

将其与微量润滑技术结合并开发出了一种低温微量润滑切削加工技术。该技术将低温冷却介质与微量切削液混合后的低温气雾喷射到切削区域,同时发挥强冷却和润滑效应,表现出广阔的工程应用前景<sup>[42]</sup>。绿色湿式切削加工技术是指切削加工过程通过采用低污染、可降解、高性能切削液减少废液排放、延长刀具寿命、提升加工效率,从而实现绿色环保与资源节约的加工方式<sup>[43]</sup>。热氢处理辅助切削技术是一种基于氢元素在钛合金中的可逆合金化特性,将氢作为过渡合金化元素,达到改善钛合金切削性能目的一种新型加工技术,具体流程包含三个阶段<sup>[33-44]</sup>:置氢处理、对含氢材料的热效应、真空脱氢。目前,该技术已在铸造钛合金、钛基复合材料、残钛处理及钛合金机械性能改善方面获得工程应用。

表 1 新型切削加工技术关键特性<sup>[12,16,19-33]</sup>  
Table 1 Key characteristics of new cutting technology<sup>[12,16,19-33]</sup>

Machining technology	Characteristics or principle	Advantages	Disadvantages
High-speed cutting	Speed is 5-10 times higher than traditional, Thermo-mechanical coupling occurs, and a critical speed threshold exists.	Reduce cutting heat and low-order vibration, reduce cutting force, extend tool life	High requirements for tool materials and equipment, challenges in parameter optimization, high initial investment and maintenance costs
Ultrasonic vibration-assisted cutting	The tool is subjected to high-frequency vibration, and is comprehensively acted by high strain rate, dynamic stress, and local thermo-mechanical coupling	Reduce cutting force and cutting heat, improve surface quality and chip evacuation, improve machining accuracy, extend tool life	Limited machining efficiency, challenges in tool life prediction, complex equipment and high cost, low technology maturity
Turn-milling machining	Composite rotational motion of workpiece and milling cutter, capable of high-speed/ultra-high-speed cutting, breaking through the centrifugal force bottleneck	Suitable for high-speed machining and micro parts, reduce surface roughness, automatic chip evacuation	Limited machining efficiency and applicability, high environmental requirements, lack of systematic market and industrial support, complex operation, high cost
Cryogenic cutting	Cool the cutting area using cooling media such as liquid nitrogen, liquid CO <sub>2</sub> , cold air, etc.	Reduce cutting temperature, extend tool life, improve workpiece surface integrity	High parameter sensitivity, challenges in chip control, high cost
Green wet cutting	Low-pollution, degradable, and high-performance cutting fluid	Reduce waste liquid emissions, extend tool life, improve machining efficiency; environmentally friendly	The lubricating fluid has a “double-edged sword” effect, high parameter sensitivity, challenges in chip control, increased workshop safety risks
Thermohydrogen treatment assisted cutting	Based on the reversible alloying characteristics of hydrogen in titanium alloys, hydrogen is used as a transitional alloying element	Improve cutting performance, but there is a threshold for the beneficial effect of hydrogen on cutting.	Narrow hydrogen content control window, challenges in tool life prediction, complex process, high cost, potential hazards to subsequent welding

## 2 钛合金切削加工研究方法

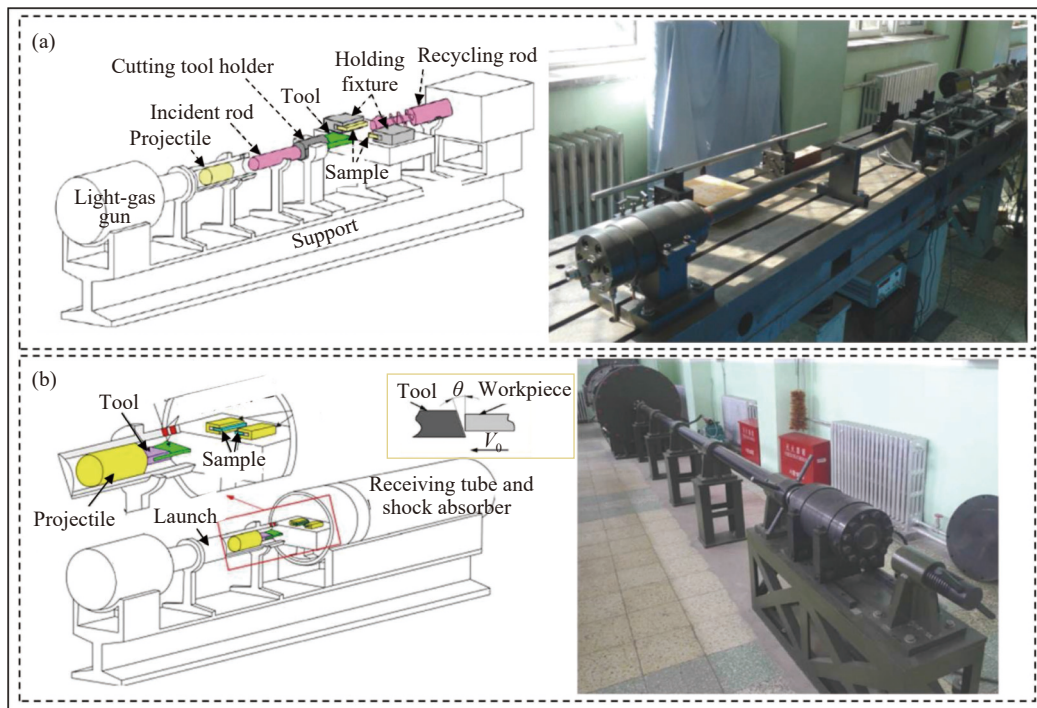
金属材料切削加工过程的本质是工件材料在高温、高加载率、反复热-力耦合冲击条件下的复杂弹性变形<sup>[18]</sup>。目前,常用研究方式主要包括传统实验法、霍普金森压杆实验法、本构模型解析法及数值模拟等<sup>[45-51]</sup>。随着先进切削技术的快速发展,传统实验法在高应变速率测试、小尺寸试样力学行为分析、瞬态高应变速率效应模拟与热力耦合效应研究方面面临一系列限制。同时,较大的经济成本与时间成本也是传统实验法关键制约性因素。与传统实验法相比,低成本且易操作的霍普金森技术逐渐成

为研究材料切削性能的重要方式,其核心装置为分离式霍普金森压杆。目前,进行速度为 5~30 m/s 时的切削实验主要基于霍普金森压杆进行,实验装置如图 2(a) 所示;进行速度为 30~250 m/s 时的切削实验主要基于轻气炮实验装置进行,如图 2(b) 所示<sup>[52]</sup>。

为了进一步分析金属材料的切削加工行为,研究人员基于动态力学性能数据构建了相应的本构模型。例如,经典 Johnson-Cook 模型和改进 Johnson-Cook 模型<sup>[51,53-57]</sup>、Zerilli-Armstrong 模型和力学阈值应力 MTS 模型<sup>[58-59]</sup>、Khan-Huang 模型<sup>[60-61]</sup>、Bodner-Patom 模型<sup>[62]</sup> 和 Campbell 模型<sup>[63]</sup> 等。其中,John-

son-Cook 模型形式简单、便于拟合, 已被广泛应用于不同金属材料切削加工过程本构模型构建<sup>[64]</sup>。WU 等<sup>[51]</sup> 根据霍普金森压杆实验数据构建了 TC21 合金的 Johnson-Cook 模型, 预测了其高速切削变形行为。近年来, 随着钛合金切削加工场景向特殊化和复杂化发展, 研究人员开发了多种改进型 Johnson-Cook 模型以更精准地预测材料切削加工

过程。CALAMAZ 等<sup>[57]</sup> 通过在 Johnson-Cook 模型中增加表征应变软化作用的项, 开发出了一种 TANH 模型(双曲正切模型), 并将其与传统 Johnson-Cook 模型的预测效果进行了比较。结果表明, 传统 Johnson-Cook 模型预测获得的切削参数约为实验值的 2 倍, 而 TANH 模型可以较为准确的预测切削屑中的应变状态及切削屑形态。



(a) 霍普金森压杆实验平台; (b) 基于轻气炮的高速切削模拟实验平台

图 2 基于霍普金森技术的正交切削实验系统<sup>[52]</sup>

Fig. 2 Orthogonal cutting experimental system based on Hopkinson technique<sup>[52]</sup>

近年来, 有限元法、有限体积法、有限差分法和边界元法等数值模拟技术的突破性发展显著降低了切削加工研究的时间、空间和经济成本。通过多物理场耦合仿真和动态过程可视化技术, 能够精确再现切屑形成、刀具磨损等微观细节, 为建立切削参数优化模型、改善加工表面完整性提供了科学化路径<sup>[65]</sup>。1974 年, TAY 等<sup>[66]</sup> 首次将有限元法应用于金属材料切削加工, 并基于有限元模型系统分析了正交切削过程切削区域的温度状态。随着国内外钛合金工程应用需求急剧上升, 数值模拟技术在其切削加工研究中的重要作用日益凸显。ÖZEL 等<sup>[67]</sup> 利用三维有限元模型比较了不同涂层材料(无涂层、TiAlN、TiAlN+cBN)刀具对 Ti-6Al-4V 合金切削过程切削力、切削温度、切削屑形态及刀具磨损状态的影响, 并由此开发出一种考虑应变软化效应的改

进材料加工预测模型。SHAH 等<sup>[68]</sup> 将有限元法与本构模型分析相结合并考虑了材料的韧性失效机制, 获得了 Ti-6Al-4V 合金的切削温度与应变分布, 阐明了韧性材料切削加工过程材料失效、损伤萌生与演变对锯齿状切削屑形成具有重要作用。MIAO 等<sup>[69]</sup> 采用数值模拟技术有效验证了其新设计的硬质合金 WC/Co 刀具(增加了沟槽, 图 3)在 Ti-6Al-4V 合金加工过程的显著优势, 即降低切削力和切削温度、减轻切削刃处的应力集中。HUANG 等<sup>[70]</sup> 利用有限元方法研究了刀具的直接传导问题, 精准预测了 Ti-6Al-4V 合金加工过程刀具与切削屑界面处的温度分布状态及其变化情况。值得注意的是, 受模型精度、切削加工过程高度复杂、高精度仿真耗时长、工艺参数优化方法单一等方面限制, 切削加工的高效、快速、精准数值模拟预测仍面临诸多难题。

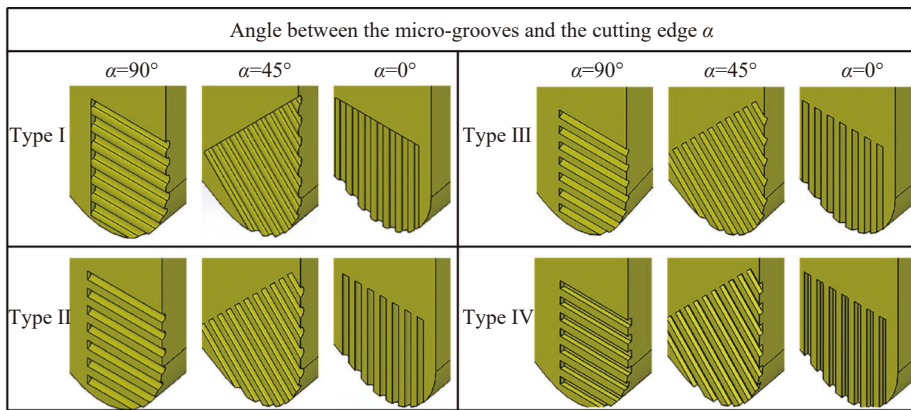


图 3 不同类型沟槽刀具设计<sup>[69]</sup>  
 Fig. 3 Design of different types of micro-grooved cutting tools<sup>[69]</sup>

### 3 钛合金切屑特征

金属材料切削过程中,工件与刀具之间的相互作用促使切屑形成,工件、刀具与切屑之间存在三个关键变形区,如图 4 所示<sup>[55,71]</sup>。第一变形区为剪切滑移变形区(工件材料的主要变形区),切削层材料在该区域内发生塑性变形和剪切滑移,并促使切屑形成,切屑与前刀面之间的相互摩擦或挤压作用诱使切屑变形加剧及温度升高。第二变形区为切屑与刀具前刀面的摩擦接触区域,大量靠近刀具前刀面的切屑在该区域内逐渐纤维化,这会导致切屑流动速度降低并呈卷曲状,从而进一步促进摩擦热产生。第三变形区为刀具后刀面与工件已加工表面的摩擦区域,该区域内切削热与切削力直接作用在工件材料表面,这种相互作用与第一区域相同,但与第二区域存在明显差异。需要说明的是,切削过程产生的切削热主要源于以下三个方面:克服金属材料塑性变形所做的功、前刀面与切屑之间的摩擦、工件已加工表面与后刀面之间的摩擦<sup>[70-71]</sup>。相应地,这些热量在三个关键变形区内的变化主要由以下环节控制:与工件材料、切屑、刀具之间的热传导或随周围介质包括切削冷却液流失。切屑作为金属材料切削加工过程不可忽视的产物,其形状特征对切削力、切削温度、切削效率甚至刀具寿命及工件加工质量等均可产生重要影响<sup>[52]</sup>。对金属材料而言,常见切屑形状主要包括带状切屑、锯齿状切屑、C 形切屑、粒状切屑、螺旋切屑及宝塔状卷屑等。其中,锯齿状切屑形成是钛合金切削加工过程的典型特征<sup>[72-73]</sup>。

目前,关于钛合金锯齿状切屑的形成机制仍存在一定争议,典型理论主要包括绝热剪切理论和周期性断裂理论,如图 5 所示<sup>[50,74]</sup>。绝热剪切理论认为,在钛合金切削加工过程中高应变率区域会因应变集中和热软化效应形成绝热剪切带(Adiabatic

shear band, ASB),这种不均匀的局部化塑性变形最终诱使锯齿状切屑形成<sup>[27]</sup>。ZENER 等<sup>[75]</sup>最早研究了绝热剪切带形成机制并将其归因于金属材料变形过程中的热塑性失稳。RITTEL 等<sup>[76]</sup>采用分离式霍普金森压杆技术确定了 Ti-6Al-4V 合金剪切压缩试样中绝热剪切带的萌生及完全发育状态。LÜ 等<sup>[77]</sup>通过研究不同切削速度对 Ti-25V-15Cr 合金切屑特征的影响,发现该合金切削加工后切屑呈典型锯齿状特征,且  $\beta$  晶粒内部形成了大量剪切带;同时,随着切削速度提高,绝热剪切带的形成频率增加且剪切带之间亚晶粒尺寸更为细小,锯齿状特征更为明显。ZAN 等<sup>[78]</sup>采用电子背散射衍射技术(Electron Backscatter Diffraction, EBSD)深入分析了不同厚度 Ti-6Al-4V 合金切屑形成机制,发现切屑厚度较小时(未变形切屑厚度为 50  $\mu\text{m}$ ,图 6(a)(b))切削变形较为均匀,且初生  $\alpha$  相变形程度较低,锯齿状切屑主要出现在相界面或  $(\alpha+\beta)$  片层集束内部等低强度区域;切屑厚度较大时(未变形切屑厚度为 100  $\mu\text{m}$  或 150  $\mu\text{m}$ ,图 6(c)~(f))初生  $\alpha$  相可以被切割,规则的锯齿状切屑主要由绝热剪切带或裂纹萌生诱发。

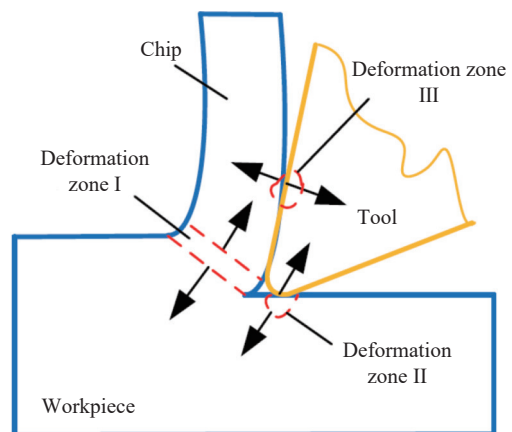
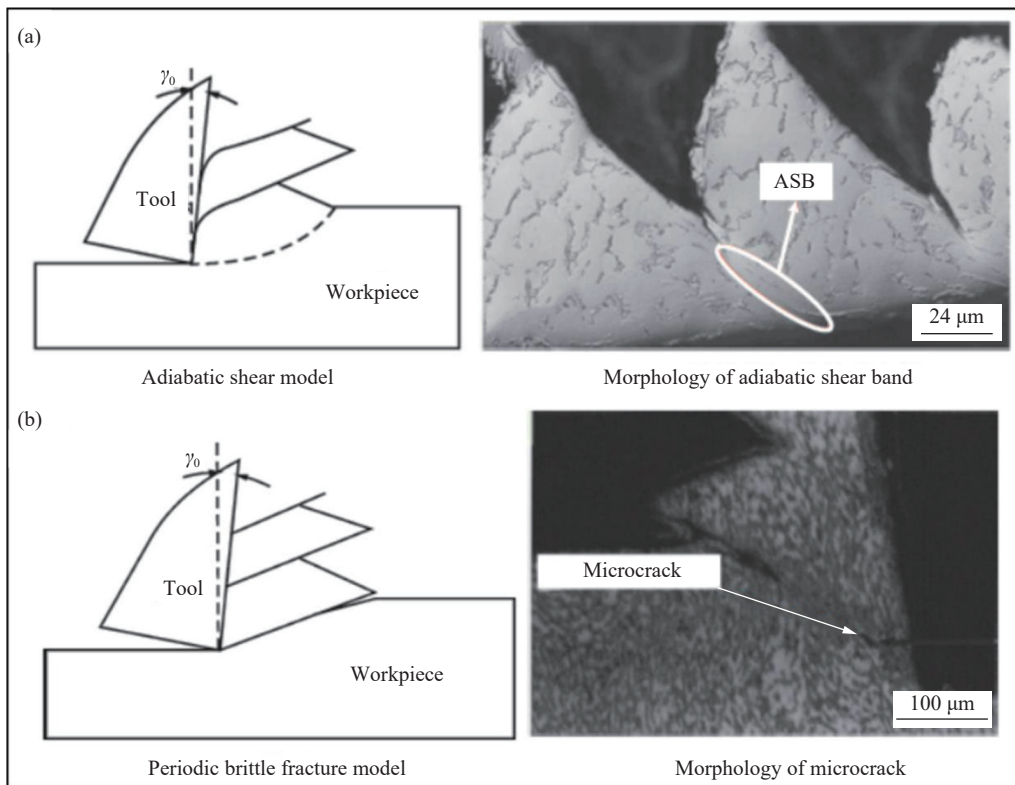


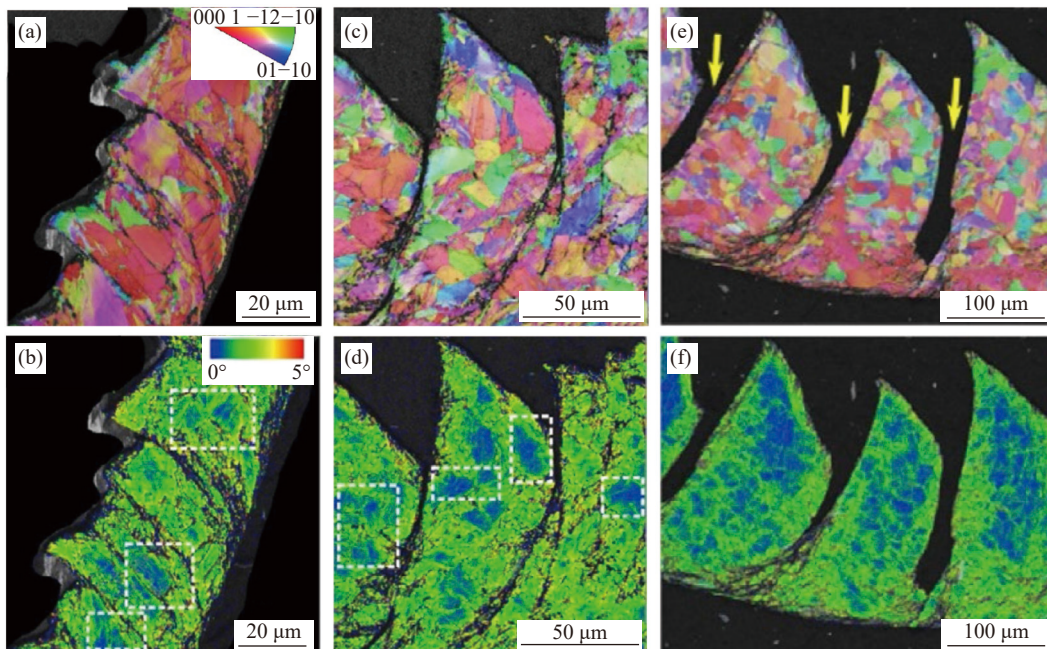
图 4 金属材料切削区域示意<sup>[65,71]</sup>  
 Fig. 4 Schematic of metal material cutting zone<sup>[65,71]</sup>



(a) 绝热剪切理论模型及绝热剪切带微观形貌; (b) 周期断裂理论模型及微裂纹形貌

图 5 钛合金锯齿状切屑形成理论<sup>[50,74]</sup>

Fig. 5 Serrated chip formation theory for titanium alloy<sup>[50,74]</sup>



未变形切屑厚度为 50  $\mu\text{m}$  时: (a) 反极图, (b) 局部取向差图; 未变形切屑厚度为 100  $\mu\text{m}$  时: (c) 反极图, (d) 局部取向差图; 未变形切屑厚度为 150  $\mu\text{m}$  时: (e) 反极图, (f) 局部取向差图

图 6 不同厚度 Ti-6Al-4V 合金切屑 EBSD 分析<sup>[78]</sup>

Fig. 6 EBSD analysis of Ti-6Al-4V alloy chips with different thicknesses<sup>[78]</sup>

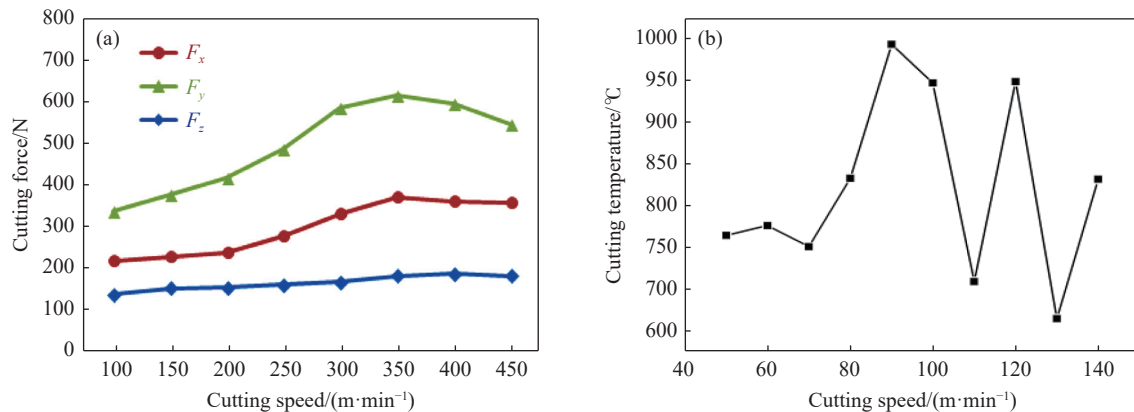
周期性断裂理论认为钛合金锯齿状切屑的形成是裂纹引发几何失稳而导致的周期性断裂, 单一切

屑单元在切屑宽度上存在不连续分布的微裂纹区和连续的粗裂纹(整体脆性断裂区)<sup>[52,74]</sup>。VYAS 等<sup>[74]</sup>

研究了钛合金锯齿状切屑的特征并将其形成归因于循环裂纹,且锯齿状切屑的形成趋势随切削速度增加逐渐降低。GENTE等<sup>[79]</sup>基于空气炮技术系统研究了Ti-6Al-4V合金切屑根部的特征,指出锯齿状切屑的形成主要与表面裂纹扩展有关。除了上述两种典型理论外,研究人员还尝试从晶体结构、切削条件等方面解释锯齿状切屑形成机制。例如,MO-TONISHI等<sup>[80]</sup>通过分析纯钛、 $\alpha+\beta$ 钛合金、 $\beta$ 钛合金切削加工过程,尝试将锯齿状切屑的特征与其晶体结构建立内在关系。基于当前大量研究结果,研究人员更倾向于采用绝热剪切理论解释钛合金锯齿状切屑形成机制。

#### 4 切削参数对钛合金切削行为的影响

作为反映金属材料切削加工特性的重要物理量,切削力和切削温度备受研究人员关注。切削力是指切削加工过程中金属材料抵抗刀具切削而产生的力<sup>[18]</sup>;切削温度通常是指刀具前刀面与切削屑接触区域的平均温度<sup>[81]</sup>。过大的切削力、过高的切削温度及二者耦合作用均会对工件加工表面质量、刀具寿命等造成不利影响,导致相关零部件服役过程存在安全隐患。切削速度、切削深度和进给量/进给速度作为金属材料切削过程的核心工艺参数,其多因素耦合作用对切削力和切削温度的动态演化具有决定性影响。



(a) 切削速度对切削力的影响; (b) 切削速度对切削温度的影响

图7 切削速度对切削力、切削温度的影响<sup>[18,82]</sup>

Fig. 7 Effects of cutting speed on cutting force and cutting temperature of the workpiece<sup>[18,82]</sup>

#### 4.2 切削深度

SATYANARAYANA等<sup>[85]</sup>基于Taguchi-grey法分析了切削速度、切削深度等参数对Ti-6Al-4V合金加工性能的影响,优化获得了适宜的加工参数,并指出切削深度对切削力的影响程度低于切削速度。黄蓓等<sup>[86]</sup>采用传统实验法研究了切削

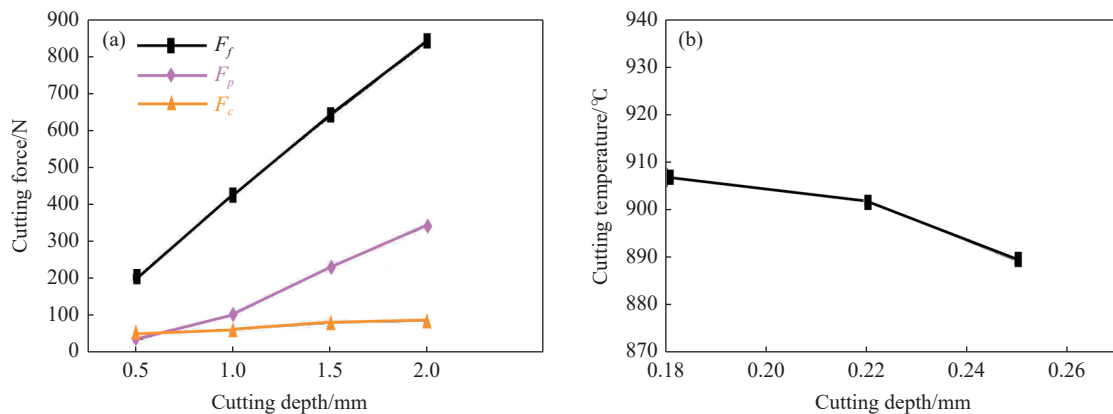
#### 4.1 切削速度

WU等<sup>[82]</sup>基于有限元数值模拟技术系统研究了切削速度(150~450  $m \cdot min^{-1}$ )对Ti-6Al-4V合金切削过程的影响规律,发现切削力随切削速度增大呈现先升高后降低的趋势(图7(a)),切削速度对切削力的影响存在阈值。张昌明等<sup>[18]</sup>采用传统实验法分析了铣削速度(50~140  $m \cdot min^{-1}$ )对TC18合金切削温度的影响,发现切削温度随铣削速度的增大而提高,且温度提高速率与铣削速度密切相关(图7(b)):铣削速度较低时(<70  $m \cdot min^{-1}$ ),切削温度提升十分缓慢;铣削速度提高至70~100  $m \cdot min^{-1}$ 时,切削功消耗及由此产生的总切削热显著增加,导致切削温度快速提升;铣削速度较高时(>100  $m \cdot min^{-1}$ ),切削屑带走的热量显著增多,即传入工件材料或刀具的热量降低,切削温度在650~1000  $^{\circ}C$ 波动。BROWN等<sup>[83]</sup>系统评估了切削速度对Ti-6Al-4V合金正交铣削工件表面完整性的影响,发现在较低铣削速度下更容易获得大表面应变和塑性变形深度的工件。薛超义等<sup>[84]</sup>通过研究切削速度对Ti-6Al-4V合金加工表面残余应力的影响,发现切削表面的残余压应力与切削速度正相关。一方面,工件表面塑性变形程度随切削速度增加而增大,残余应力在热力耦合作用下随之增大;另一方面,切削加工过程工件材料表面相变诱使相比例发生变化,从而导致晶格畸变并产生残余应力。

深度对Ti-6Al-4V合金切削力的影响,发现切削力随切削深度增加而增大(图8(a)),这主要是由于切削深度增加可以促使切削面积增大,从而导致摩擦力和变形力显著提高。韩京辉等<sup>[87]</sup>采用近红外光纤传感的多光谱切削温度测量方法对不同切削深度下Ti-6Al-4V合金切削过程刀具温

度进行了测量,发现刀具温度随切削深度增加而提高。不同的是,吴东等<sup>[88]</sup>通过研究切削深度对 Ti-6Al-4V 合金高速加工过程切削温度的影响,发现切削温度随切削深度增加而降低(图 8(b)),这主要是由于工件、刀具、切屑之间的接触区域随切削深度增加而增大,即三者之间的散热面积增大,从而促进断屑排出并促使温度降低。LI 等<sup>[89]</sup>通过研究切削深度对 TC17 合金高速铣削过程工

件表面微观结构的影响,指出切削深度对表面微观组织无明显影响,且未观察到明显冶金相变现象。CORDUAN 等<sup>[90]</sup>研究了切削深度对 Ti-6Al-4V 合金车削过程 PCD 刀具磨损的影响,发现当切削深度大于 1 mm 时将导致刀具寿命显著降低。王晓琴等<sup>[91]</sup>以刀具前刀面月牙洼磨损深度为判断系统分析了切削深度对刀具寿命的影响,发现刀具寿命与切削深度呈负相关。



(a) 切削深度对切削力的影响; (b) 切削深度对切削温度的影响

图 8 切削深度对切削力和切削温度的影响<sup>[86,88]</sup>

Fig. 8 Effects of cutting depth on cutting force and cutting temperature<sup>[86,88]</sup>

#### 4.3 进给量/进给速度

对金属切削加工过程而言,进给量是指刀具在进给方向上相对于工件的位移量,进给速度是指刀具和工件在单位时间内在进给方向上的相对位移。ALI 等<sup>[92]</sup>系统研究了进给速度对 Ti-6Al-4V 合金进给切削力和主切削力的影响。结果表明,在给定进给速度范围内(80、120、160 mm/min),进给切削力随进给速度增加呈现出先降低后增大的趋势(图 9(a)),而主切削力则呈现逐渐增大的趋势;特别地,进给速度对主切削力的影响程度显著大于进给切削力。SULAIMAN 等<sup>[93]</sup>采用有限元模拟技术研究了进给量(0.1~0.25 mm/r)对 Ti-6Al-4V 合金切削温度的影响,发现切削温度随进给量增加而增大,这与切削厚度增加、摩擦力增大,导致剪切区域热量增多密切相关。相似地,吕偿等<sup>[94]</sup>基于 ABAQUS 数值模拟软件系统分析了每齿进给量对 Ti-6Al-4V 合金铣削温度的影响,也获得了相同结论,即进给量由 0.025 mm/r 提高至 0.038 mm/r,铣削温度随之提高(图 9(b))。YANG 等<sup>[95]</sup>通过研究进给量对 Ti-6Al-4V 合金铣削工件表面粗糙度的影响,发现进给方向上工件表面粗糙度随每齿进给量增加逐渐增大,但垂直进给方向上工件表面粗糙度几乎无变化

(图 9(c))。YUAN 等<sup>[96]</sup>采用实验法研究了进给量对 Ti-6Al-4V 切削过程 KW10 刀具寿命的影响,发现进给量增大可以导致刀具寿命显著降低:进给量由 0.08 mm/r 提高至 0.13 mm/r 时导致刀具寿命由 ~55 min 降低至 20 min 以下。

需要说明的是,切削速度、切削深度和进给量/进给速度等切削参数对金属材料切削行为的影响并不是孤立的。例如,RASHID 等<sup>[97]</sup>在研究 Ti-6Cr-5Mo-5V-4Al 合金激光辅助切削过程中,综合考虑了切削速度与进给量对切削力、切削温度的影响。姜怡君等<sup>[98]</sup>针对 TB18 合金实际切削加工过程中的突出问题,系统研究了切削速度、切削深度、进给速度等参数与不同材质刀具寿命之间的交互影响规律。因此,针对钛合金切削加工过程,系统阐明切削参数对材料切削特性及刀具服役状态的影响规律,对实现高效优质工件制备及刀具寿命延长具有重要的工程价值。

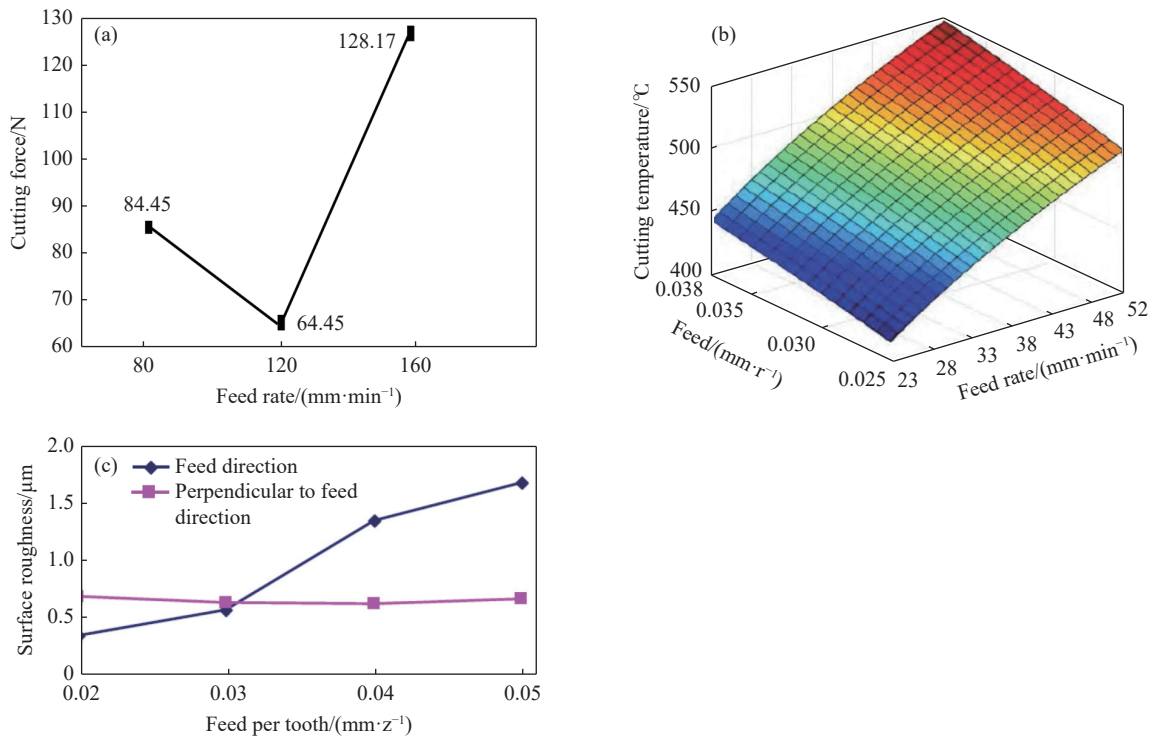
## 5 钛合金切削刀具

### 5.1 刀具磨损机理

目前,典型刀具磨损方式主要包括粘结磨损、磨粒磨损、氧化磨损、扩散磨损、涂层破损/剥落

及微崩刃等<sup>[18]</sup>。粘结磨损是指工件、刀具、切屑在高温高压作用下发生粘结且粘结点处产生相对运动,导致刀具材料被撕裂,如图 10(a) 所示。姜增辉等<sup>[99]</sup>通过研究 Ti-6Al-4V 合金低速切削加工过程中刀具磨损机理,发现 YG8、YW2、YT15 三种硬质合金刀具的主要磨损形式为粘结磨损。分析认为,这主要是由于 Ti-6Al-4V 合金与硬质合金刀具之间的化学亲和力较高,从而导致切削过程切屑易粘结在刀具上,切屑等粘结颗粒脱离刀具过程诱使粘结磨损发生。特别地,当刀具切出过程中伴有切屑粘结时,粘结物在再次切入过程中会诱发微崩刃,即切削刃处产生许多微小缺口,如图 10(b) 所示。磨粒磨损是指切削加工过程中硬质颗粒进入刀具-工件或刀具-切屑接触面,从而导致工件表面产生大量划痕等缺陷。毫无疑问,钛合金自身硬度及刀具材料的特性将会对该类型缺陷产生直接影响。张昌明等<sup>[18]</sup>在研究 TC18 合金切削加工过程中刀具磨损状态时发现,合金中 Fe、Al、Cr、Mo 元素为碳化物等硬质颗粒的形成提供了成分基础,导致刀具磨损初期便

发生了磨粒磨损,如图 10(c) 所示。进一步,刀具涂层将随着切削过程的进行逐渐脱落,从而加剧磨粒磨损。氧化磨损是指刀具材料中的亲氧元素在高温切削过程中与氧元素反应生成氧化膜,当氧化膜的强度、硬度均较低时十分容易破损甚至剥落,并重新形成一层新的氧化膜。姜增辉等<sup>[99]</sup>在研究 Ti-6Al-4V 合金高速切削加工过程中硬质合金刀具磨损机理时发现,随着切削速度提高,氧化磨损逐渐成为主要磨损形式之一。扩散磨损是指切屑、刀具与工件之间的元素扩散诱使刀具化学成分发生变化,对刀具的切削加工能力造成不利影响,如刀具表面强度和硬度降低,从而导致刀具磨损<sup>[18,91]</sup>。对涂层刀具,当切削刃处的涂层与刀具基体的结合强度低于复杂交变应力时,切削刃处的涂层逐渐发生破损;进一步,在该应力持续作用下,涂层破损区域向前刀面扩展,造成严重的刀具磨损,如图 10(d) 所示。值得注意的是,钛合金切削加工过程中,刀具磨损通常具有非单一性特征,表现为多种磨损形式共存的复合现象。



(a) 进给速度对切削力的影响; (b) 进给速度和进给量对切削温度的影响; (c) 每齿进给量对工件表面粗糙度的影响

图 9 进给量或进给速度对切削力、切削温度和工件表面粗糙度的影响<sup>[92,94-95]</sup>

Fig. 9 Effects of feed or feed rate on cutting force, cutting temperature and surface roughness of the workpiece<sup>[92,94-95]</sup>

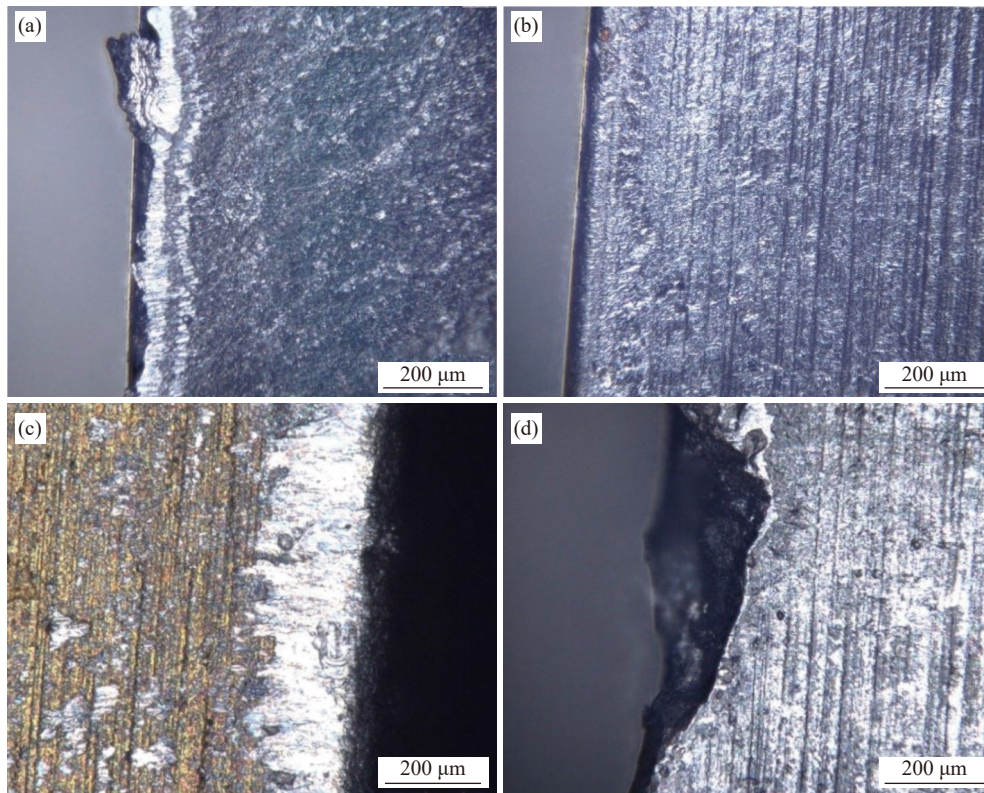
### 5.2 刀具材料及涂层材料

基于上述磨损机理,刀具材料的选择通常需考虑以下因素:①刀具材料具有较高的硬度、强度、韧性;②刀具材料与工件材料之间具有良好的化学稳

定性<sup>[18]</sup>。目前,常用刀具材料主要包括高速钢、硬质合金、涂层刀具、陶瓷刀具与超硬材料,各类材料的特点如表 2 所示<sup>[6,93,98-101]</sup>。随着钛合金切削加工技术飞速发展,切削速度和切削精度显著提高,对刀具

材料及涂层技术提出了更高要求。ZHOU 等<sup>[6,102-103]</sup>研制了一种钛合金高速切削用超细晶梯度硬质合金 Co10Ti3, 并采用 TiAlCrN(ACT)作为涂层材料。研究证实, 该涂层刀具(Co10Ti3-ACT)的耐磨性达到了国际领先水平: Co10Ti3-ACT 刀具的磨损量与 GC1105 涂层刀具(瑞典 Sandvik 公司)基本一致, 仅

为 GC4225 涂层刀具(瑞典 Sandvik 公司)的 30%、国产 YBG202 涂层车刀(株洲钻石公司)的 50%。为了有效抑制钛合金切削加工过程刀具快速磨损, 苏永生等<sup>[101]</sup>设计了一种含有微沟槽的 YG8 和 PCD 刀具, 并将其用于 Ti-6Al-4V 低温切削加工, 发现微沟槽设计有利于降低刀具与切屑之间的摩擦力。



(a) 粘结磨损; (b) 微崩刃; (c) 磨粒磨损; (d) 涂层破损

图 10 典型刀具磨损形式<sup>[18]</sup>

Fig. 10 Typical wear modes of cutting tools<sup>[18]</sup>

表 2 不同刀具材料比较<sup>[6,93,98-101]</sup>

Table 2 Comparison of different cutting tool materials<sup>[6,93,98-101]</sup>

Tool materials	Composition or classification	Advantages	Disadvantages
High-speed steel	Elements such as W, Mo, Cr, V	Good comprehensive performance, low cost; suitable for complex tools; used for machining non-ferrous and ferrous materials	Heat resistance temperature is only 600 °C, and serious wear occurs during high-speed cutting
Hard metal	Tungsten-cobalt type (YG), tungsten-titanium-cobalt type (YT), tungsten-titanium-tantalum-niobium type (YW)	YG has good toughness; YT has high hardness; YW has excellent comprehensive performance	Large brittleness and insufficient impact toughness; YT is prone to chemical wear
Coated tool	Cemented carbide/high-speed steel substrate + coatings such as TiC/TiN/Al <sub>2</sub> O <sub>3</sub>	High hardness, high wear resistance, high chemical stability, heat resistance, oxidation resistance, and low friction coefficient	Low bonding strength of conventional coatings; the substrate has poor impact resistance and is prone to microcracks
Ceramic tool	With Al <sub>2</sub> O <sub>3</sub> or Si <sub>3</sub> N <sub>4</sub> as the matrix, with a small amount of other alloying elements added	High hardness, high wear resistance and heat resistance, high chemical stability, and low friction coefficient	Large brittleness; poor thermal conductivity; rarely used for titanium alloys
Superhard material	Diamond (PCD), cubic boron nitride (cBN)	High hardness, high wear resistance and heat resistance, high chemical stability, low friction coefficient, and excellent thermal conductivity	Diamond is extremely costly and reacts with iron-group elements; cBN is expensive

## 6 面临的挑战及未来发展方向

随着钛合金切削加工趋于高速化与精密化、先进钛合金材料迅速发展,当前切削加工技术面临诸多挑战。

1)当前仅极少数企业具备准高速切削能力,主流工艺切削速度集中于50~100 m/min,与未来高速切削需求存在显著差距;

2)钛合金切削加工行为本构模型构建需融合实验验证与数值模拟等多种研究方法,系统考虑宏-微观参量耦合关系,从多尺度、多维度进一步提升模型合理性与预测精度;

3)工件表面质量作为切削加工性能的核心评价指标,现有评价体系难全面覆盖各影响因素,构建系统化表面质量评价体系仍是未来研究重点方向之一。

## 7 结语

钛合金具有低导热性、高化学活性等特征,这使得切削加工难度显著增大,导致零件的尺寸精度和表面质量难以控制。近年来,国内外学者开发了高速切削、超声振动辅助切削、车铣加工、低温切削加工等系列新型切削加工技术,在改善加工精度、提高加工效率或降低刀具磨损等方面表现出显著优势。为了进一步改进切削加工工艺、优化切削性能,研究人员采用传统实验法、霍普金森压杆实验法、本构模型解析法及数值模拟等方法系统研究了钛合金切削加工行为:①钛合金切削加工过程通常形成锯齿状切屑,关于该类型切屑形成的典型理论主要包括绝热剪切理论和周期性断裂理论;②切削参数对金属材料切削行为的影响并非孤立的,复杂的多因素耦合作用对切削力和切削温度的动态演化、工件加工表面质量、刀具寿命具有决定性影响;③钛合金切削加工过程中,刀具磨损通常具有非单一性特征,表现为多种磨损形式共存的复合现象。

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