

# 超声滚压表面复合强化研究综述

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**摘要:** 超声滚压技术通过位错的湮灭和产生将晶粒细化至纳米级, 提高了材料硬度和耐磨损等性能。探讨了如何进一步提升材料的服役性能, 通过将超声滚压与其他处理技术相结合形成复合加工工艺, 克服单一超声滚压处理工艺的局限性, 如超过塑性变形的极限或过度强化带来的起皱、开裂和压溃等。超声滚压表面复合强化技术作为特种复合加工工艺, 在零件高性能表面制造中具有明显优势。根据超声滚压在复合工艺中的位置顺序, 分别介绍了超声滚压前端强化、同步强化和后续强化 3 种加工类型。超声滚压前端复合加工技术主要包括超声滚压复合物理气相沉积技术和超声滚压复合离子注入技术等。在超声滚压同步强化方面, 讨论了声电耦合和温度场辅助超声滚压对变形层厚度和摩擦磨损性能的影响。在超声滚压后续强化方面, 介绍了涂层复合超声滚压技术, 讨论了它对涂层裂纹、孔隙以及表面粗糙度的影响。此外, 分析了超声滚压对复合强化过程中材料微观组织演化和塑性变形的作用机制, 总结了这些技术在改善表面强化效果和满足复杂服役要求方面的研究现状。最后, 展望了超声滚压复合强化技术的应用前景和发展方向, 强调了它在提高材料服役性能方面的研究价值和目标。

**关键词:** 超声滚压; 复合强化; 微观组织演化; 表面强化

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## Review of Research on Ultrasonic Surface Rolling Composite Strengthening Technology

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**ABSTRACT:** The ultrasonic surface rolling process (USRP) refines the grain to nanometer level through the annihilation and generation of dislocation, which improves the hardness and wear resistance of the material. The strengthening mechanism of USRP technology mainly includes dislocation strengthening and fine grain strengthening. By applying ultrasonic frequency mechanical vibration with a certain amplitude along the normal direction of the surface of the component with a rolling head, the static pressure and ultrasonic shock vibration of the rolling head are transmitted to the rotating or static surface of the mechanical component under a certain feeding condition, which results in periodic extrusion and obvious plastic deformation of the metal

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material surface. Besides, dislocation is easy to occur on the metal material surface under the action of USRP, and the dislocation density increases with dislocation initiation and entanglement. The continuous annihilation and generation of dislocation refine the surface to the nanometer level, and then form a gradient nanolayer. This can reduce the surface roughness of the material and improve the surface properties such as hardness, wear resistance and corrosion resistance, which is beneficial to the surface properties of the material. The work aims to explore how to further improve the serviceability of the material by combining USRP with other processing technologies to form a composite processing technology to overcome some of the limitations of a single USRP technology, such as the limit of plastic deformation or the defects of crushing caused by excessive strengthening. After USRP treatment, shear deformation and local fatigue damage will occur on the surface of the material, resulting in reduced deformation resistance. In addition, the severe plastic deformation will cause the hardness of the surface strengthening layer to increase, which can not be significantly improved in the subsequent process. The strengthening effect of USRP is also limited by the material itself. Therefore, the combination of USRP and other processing technologies to form a composite processing technology is an effective way to further improve the properties of materials. USRP composite strengthening technology, as a special composite processing technology, has obvious advantages in the high-performance manufacturing of parts. According to the position sequence of USRP in the composite process, three processing types are introduced, including USRP front-end strengthening, synchronous strengthening and follow-up strengthening respectively. USRP front-end composite machining technology includes USRP composite vapor deposition technology and USRP composite ion implantation technology. The effects of acoustic and electric coupling and temperature field assisted USRP on the thickness and friction and wear properties of the deformed layer are discussed. In the follow-up strengthening of USRP, the composite USRP technology of the coating is introduced, and its effects on crack healing, pore reduction and surface roughness reduction are discussed. USRP, as a front-end strengthening technology, can accelerate the ion diffusion rate. The electrical pulse and temperature promote the movement of the dislocation, and the energy input enhances the ability of the dislocation to cross the barrier, increases the number of dislocations, and thus improves the plastic deformation ability of the metal surface. USRP as a follow-up strengthening technology can enhance the adhesion between the coating and the substrate, eliminate the pores in the coating, repair cracks and reduce the surface roughness of the material. In addition, the mechanism of USRP on the microstructure evolution and plastic deformation of materials during the composite strengthening process is analyzed, and the current research status of these technologies in improving the surface strengthening effect and meeting the complex service requirements is summarized. Finally, the application prospect and development direction of USRP composite strengthening technology in the future are prospected, and its research value and goal in improving the serviceability of materials are emphasized.

**KEY WORDS:** ultrasonic rolling; composite strengthening; evolution of microstructure; surface strengthening

机械零件的损坏多数是由工作表面的疲劳断裂、磨损、腐蚀等造成的。因磨损、腐蚀而损坏的机械零件数量占损坏零件总数的 90% 左右<sup>[1]</sup>, 因此而损坏的机械设备占机械设备总数的 30% 左右, 零件磨损消耗的能量占有所有设备消耗能量的 1/3<sup>[2]</sup>。金属材料的硬度、耐磨损、耐冲蚀、抗腐蚀、抗氧化以及表层残余应力都是影响零部件使用性能的关键因素<sup>[3]</sup>。所以, 如何提高零部件的使用性能和疲劳寿命是当今先进制造技术领域的重大课题。金属材料的机械、物理、化学性质, 如硬度、耐磨、耐腐蚀、抗氧化以及表面残余应力等主要取决于材料表面完整性。

超声滚压技术是在传统的滚压加工基础上加入超声振动的一种表面自纳化技术, 利用滚压头在工件表面进行强化提高表面完整性。超声波的振动作用会加速材料内部原子和分子的运动<sup>[4]</sup>, 从而降低材料的强度和硬度。超声波传播过程中产生的界面摩擦会导

致局部升温<sup>[5]</sup>, 促进分子的扩散和位移, 使材料分子排列更加松散。此外, 超声波的周期性应力加载能够引起材料的塑性流动<sup>[6]</sup>, 改变其晶体结构, 从而可以对材料起软化作用, 使材料的屈服应力减小, 塑性流动性增强。随着对超声滚压表面强化技术的研究不断深入, 其应用范围已由单一的金属材料扩展到涂层材料和复合材料<sup>[7]</sup>, 甚至从传统的机械加工领域扩展到了轮船汽车和生物医疗等制造领域。

超声滚压技术相比于其他表面强化技术具有如下优势<sup>[8]</sup>: 与涂层相比, 超声滚压后不会产生新物质, 不会产生分层, 材料在服役过程中不会产生剥落; 能与数控机床集成, 可以根据零件实际的磨损情况对局部区域进行重点强化; 与车削、喷丸强化相比, 超声滚压技术可以对材料进行光整强化一体加工。

在高科技领域, 单一的涂层、离子注入等表面强化工艺无法满足环境的摩擦磨损和腐蚀性能要求, 容

易造成分层脱落,另外还存在一些气孔、裂纹等缺陷。结合超声滚压表面强化技术,能够有效消除材料表面加工后产生的缺陷,将残余拉应力转化为残余压应力,从而进一步提高材料性能。超声滚压复合强化主要包括超声滚压复合涂层强化技术<sup>[9]</sup>、超声滚压复合离子注入<sup>[10]</sup>、声电耦合<sup>[11]</sup>、温度场辅助超声滚压<sup>[12]</sup>。因此,本文阐述了超声滚压表面强化技术的加工原理、超声滚压复合加工工艺,并对其进行了展望。

## 1 超声滚压表面强化技术的加工原理

超声滚压表面强化技术 (Ultrasonic Surface Rolling Process, USRP) 是一种以超声波 (18~30 kHz) 为能量,通过静载滚动的工作模式,对金属零件进行往复滚动的动态冲击式压力光整加工工艺。该工艺通过滚压头沿零部件表面法线方向施加一定幅度的超声频机械振动,在一定进给条件下,滚压头的静压力和超声波冲击振动传递到旋转或静止的机械零部件表面,产生周期性的冲挤作用,使金属材料表面产生大幅度塑性变形。USRP 加工材料表面示意图及原理如图 1 所示<sup>[13]</sup>。这种工艺使工件表面获得一定的弹性回复,产生的塑性流动使其表面“低谷”被“高峰”填充,

从而使其表面粗糙度降至纳米级,显著提升零件表面硬度,并在其表层形成了深层的梯度纳米晶粒层及残余压应力区域。因此,零件的疲劳强度、耐磨性和耐腐蚀性等综合性能得到显著提升。与传统滚压相比,USRP 可以在较小的静压力条件下形成更深的表面残余压应力层<sup>[14]</sup>。USRP 装置<sup>[15]</sup>主要由超声波发射器、预紧弹簧、超声换能器、超声变幅杆、滚珠等构成。

在 USRP 的静压力和超声冲击作用下,金属表层晶粒会产生严重的塑性变形,促进位错的滑移和增殖,从而导致位错密度增大,并且逐渐形成位错墙和位错缠结。在滚压头连续的冲击作用下,位错墙和位错缠结变为小角度亚晶界,由于位错的不断湮灭和产生,导致晶界两侧晶粒取向不同,晶界成为位错运动的阻碍<sup>[16]</sup>。晶粒或晶界在连续应力作用下不断碎化,直到位错的湮灭和产生达到平衡,晶粒尺寸趋于稳定<sup>[17]</sup>,从而在材料表层形成梯度纳米结构。USRP 在微观组织纳米化和加工硬化的共同作用下,显著提高了零件的强度、表面显微硬度,增强了摩擦磨损性能。这是由于在 USRP 强化过程中,会将残余拉应力转化为残余压应力,因此可以延缓疲劳裂纹的扩展,延长零件的使用寿命<sup>[18]</sup>。

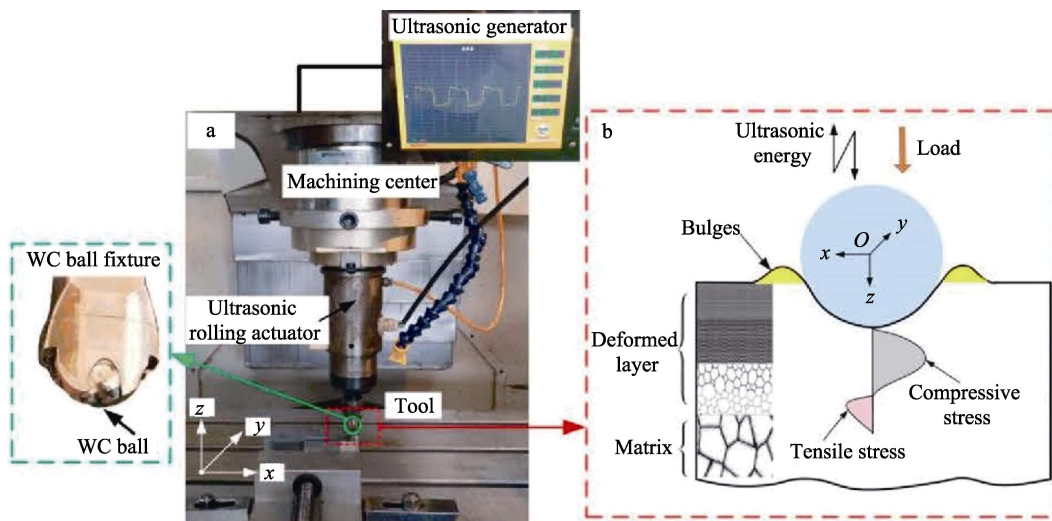


图 1 USRP 加工实验 (a) 及加工原理 (b) <sup>[13]</sup>

Fig.1 USRP processing experiment (a) and schematic diagram of processing (b) <sup>[13]</sup>

## 2 USRP 复合工艺

### 2.1 单一 USRP 的局限性

轮船汽车、生物医疗等领域对零件的表面性能提出了更高的要求。然而,单一的 USRP 存在一些局限性,如当静压力和滚压次数等参数超过材料的塑性变形极限时,材料表面会出现起皱、开裂和压溃等表面缺陷,并且滚压处理后的表面也会出现剪切变形和局部疲劳损伤,从而降低变形抵抗力,严重的塑性变形会引起表

面强化层硬度过高,使后续工艺无法持续改善材料性能。另外,材料本身的特性也会对 USRP 强化效果产生影响,例如高硬度的合金难以通过超声滚压在其材料表面加工出较深的强化层,从而无法达到理想的效果<sup>[19]</sup>。因此,为了弥补单一 USRP 的局限性,在现有 USRP 的基础上,通过结合其他表面强化工艺和物理场技术 (温度、电脉冲等),形成复合超声滚压表面强化技术。根据在复合工艺中超声滚压技术应用的前后顺序,可以将 USRP 复合工艺划分为 USRP 前端强化、USRP 同步强化、USRP 后续强化,如图 2 所示。

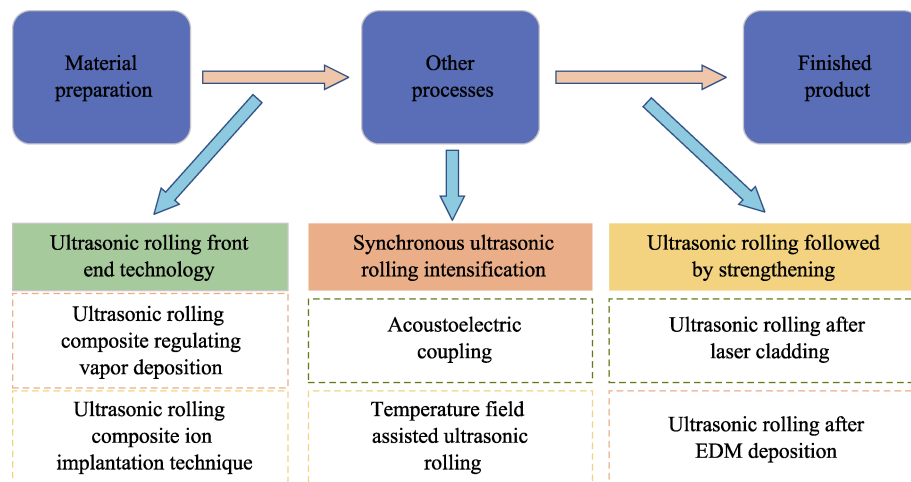


图 2 超声滚压复合工艺分类  
Fig.2 Classification of USRP composite process

## 2.2 USRP 前端强化

前端强化可以作为复合技术的一项基础工作,通过对待加工材料和构件进行前端强化处理,可以增强结构的稳定性,提供更好的性能和特性,为复合材料的制备奠定更好的基础。超声滚压前端强化是一种通过 USRP 对材料表面进行预处理的方法。它可以增大涂层与基体的接触面积,并提高表层晶粒的纳米化程度,从而增大离子扩散速率。

### 2.2.1 超声滚压复合物理气相沉积技术

AISI 1045 钢广泛应用于模具、传动齿轮、轴类及其他需要承受载荷的机械零件上,但其受力部分容易发生磨损或断裂故障。为了适应复杂的工况,常通过在钢材表面制备涂层来提高材料的摩擦磨损性能,高硬度涂层在一定程度上提高了钢基板的抗磨性能,但若不进行表面预处理,涂层与基板之间的界面结合强度一般不足以承受实际应用的较高外载荷,导致涂层

严重分层,降低了涂层的使用寿命。为增强涂层与基体的附着力<sup>[20]</sup>,采用 USRP 在材料表面形成微结构。

AlTiN 涂层是目前应用广泛的耐磨硬质涂层之一,要求其涂层和基体体系具有足够的界面结合强度。然而,由于硬 AlTiN 涂层和软钢基板的力学和热性能不匹配,在实际使用条件下,AlTiN 涂层经常遇到涂层黏附强度不足的问题<sup>[21]</sup>。Meng 等<sup>[22]</sup>首先在 AISI 1045 钢表面进行了往复 USRP,形成了规则的沟槽织构,并通过超声滚压复合物理气相沉积(PVD)技术制备出优质的 AlTiN 涂层(如图 3 所示<sup>[23]</sup>)。这种方法解决了涂层与基体黏附强度不足的问题,并且显著提高了 AlTiN 涂层的抗磨性能。通过 USRP 制备的沟槽织构将界面结合从传统的二维结构转变为三维结构,从而增大了涂层与材料的空间黏附面积,提高了涂层-织构钢体系的界面结合力,同时基板表面形成了纳米梯度,提高了复合体系的抗裂性能,并且微织构对磨损屑的储存和润滑膜的转移有积极作用。

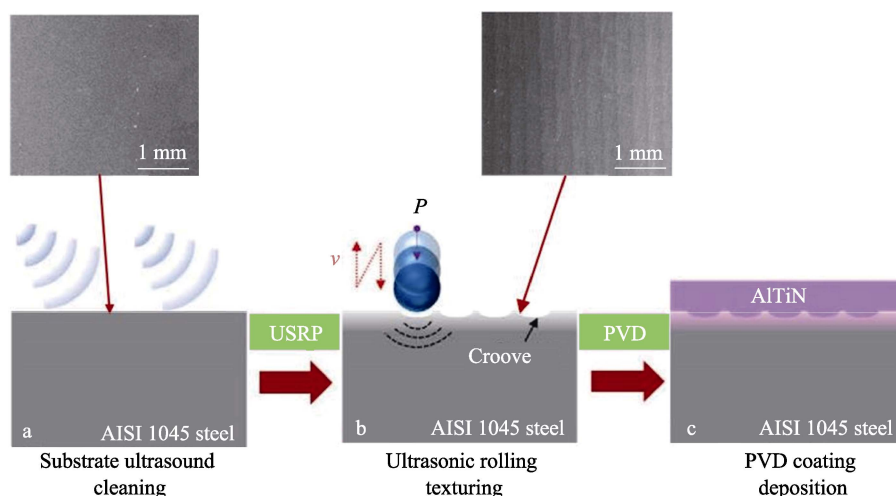


图 3 USRP 微织构表面沉积 AlTiN 涂层的制备过程<sup>[23]</sup>  
Fig.3 Preparation process of AlTiN coating deposited on USRP textured surface<sup>[23]</sup>





预处理工艺降低了渗氮温度,这是因为晶界和位错等微观结构缺陷可以提高渗氮的扩散速度和化学反应速率。研究发现,相比于单一的等离子渗氮技术,通过 USRP 预处理可以将渗碳温度从 850 °C 降到 750 °C,并且晶粒纳米化使氮化层的硬度和厚度显著提高,有效改善了钛合金在真空中的抗磨性能(如图 6 所示)。

## 2.3 USRP 同步强化

### 2.3.1 声电耦合

USRP 可以降低表面粗糙度,提高显微硬度。然而,经过加工后的表面会出现剪切变形和局部疲

劳损伤,从而导致变形抵抗力降低<sup>[36]</sup>。此外,严重的塑性变形产生的表面强化层硬度较高,难以在后续工艺中进一步改善。为避免 USRP 处理后出现不可逆转的损伤,可以引入电脉冲<sup>[37-38]</sup>来解决该问题,电脉冲处理通过输入瞬时高能脉冲电流,显著影响了金属材料的塑性、再结晶、相变、组织演化<sup>[39]</sup>、铸件组织和疲劳寿命。利用电脉冲处理材料可以增强材料表面层位错迁移、原子迁移和塑性变形能力,增大相变的速度,促进微裂纹愈合,并减少缺陷的数量,从而改善表面质量。该工艺的原理如图 7 所示<sup>[40]</sup>。

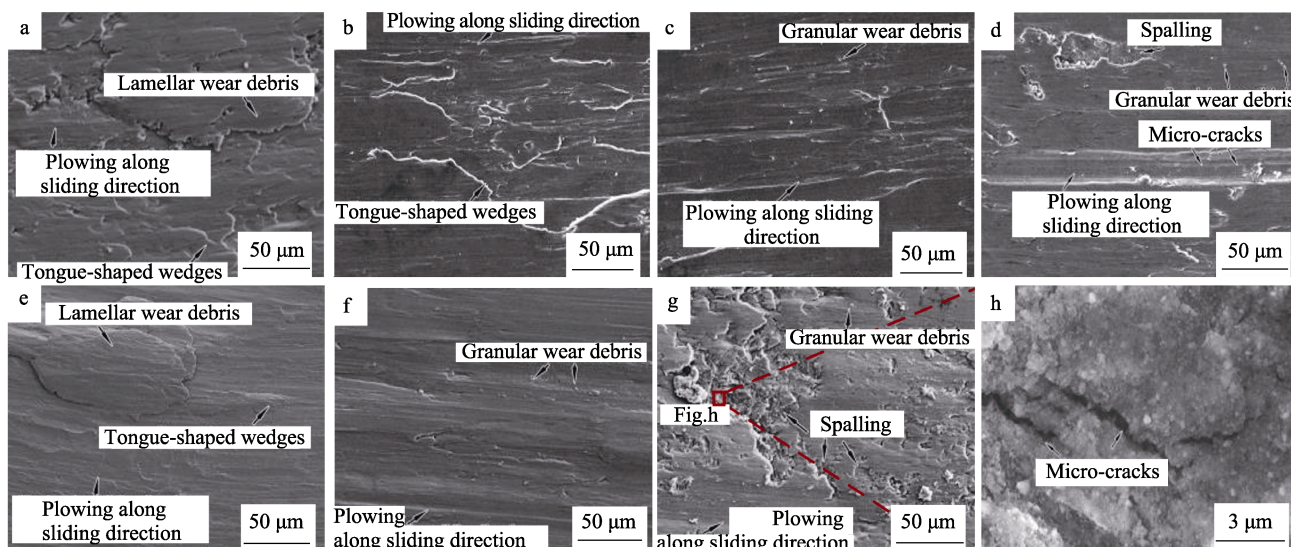


图 6 未 USRP 处理 (a-d) 和 USRP 处理 (e-g) 钛合金<sup>[35]</sup>  
Fig.6 Titanium alloy without USRP treatment (a-d) and with USRP treatment (e-g)<sup>[35]</sup>

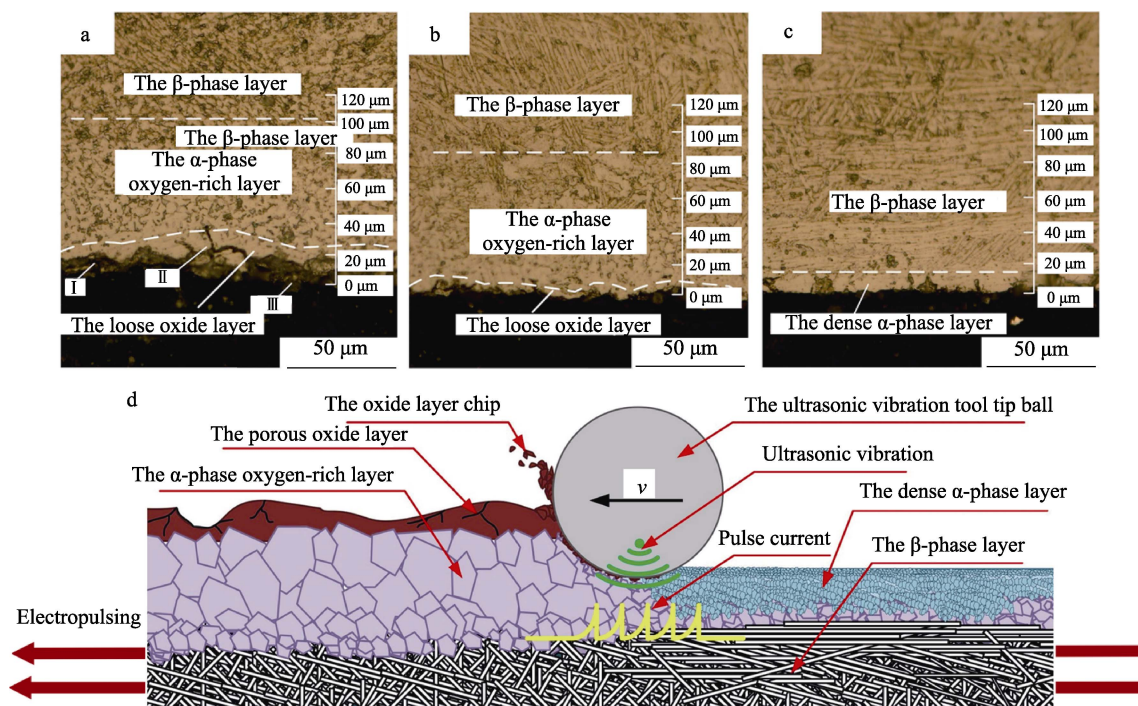


图 7 声电耦合原理和处理前后微观形貌<sup>[40]</sup>  
Fig.7 Principle of acoustoelectric coupling and microscopic morphology before and after treatment<sup>[40]</sup>



Sun 等<sup>[41]</sup>对镍铝青铜 (NAB) 进行了电脉冲辅助超声滚压 (EP-USRP) 强化, 并探究了它对加工表面的影响。研究表明, 经 EP-USRP 处理的试样表面质量明显优于仅使用 USRP 处理的试样表面质量。此外, 在 NAB 的表面还形成了一层强化梯度层, 使其表面硬度大幅提高。由于电脉冲可以增强金属的塑性流变, 促进位错的扩散和移动, 所以 EP-USRP 处理后, NAB 的抗空化腐蚀能力显著增强, 如图 8 所示。这主要是由于 EP-USRP 工艺改善了表面质量, 削弱了空化泡的坍塌。同时, 表面预置压应力和加工硬化可抵抗空化泡的冲击, 表层结构的变形改变了裂纹的扩展方向, 从而改善了电化学性能, 大大提高了 NAB 材料的抗空蚀性能。Ye 等<sup>[42]</sup>也通过 EP-USRP 诱导了商业纯钛的梯度纳米结晶, 并提升了表面的力学性能。结果表明, EP-USRP 处理后的纯钛材料具有更低的摩擦因数和更少的磨损损失。EP-USRP 还可以将最大磨痕深度减小约 2/3, 如图 9 所示。相较于单一 USRP 处理, EP-USRP 技术使硬化层厚度仅为其 0.5 倍, 表面粗糙度降低至 0.026  $\mu\text{m}$ 。在纯钛基体中, EP-USRP 处理能够产生较大的残余压应力, 并产生热-非热效应, 增大位错的迁移率和密度, 从而促进

纯钛基体中纳米微晶的形成。

综上所述, 传统的 USRP 处理可以改善试样的表面粗糙度和硬度, 提高试样的耐磨性, 但试样表面还存在少量的裂纹缺陷<sup>[43]</sup>。采用 EP-USRP 技术可以进一步提高滚压后试样的性能, 使基体硬度更高、表面更加光滑且具有更好的耐磨性。这是由于引入电脉冲后, 在处理过程中产生了高温的热效应, 增强了试样表面的塑性流动性, 加速了相变和再结晶过程, 并促进了裂纹的愈合。EP-USRP 技术赋予了试样更平滑的表面和纳米级的组织结构, 同时也提高了试样的力学性能。

2.3.2 温度场辅助超声滚压

温度场辅助超声滚压是在 USRP 过程中引入温度场, 利用温度场对材料微观结构和力学性能的影响, 从而获得更好表面性能的材料。其原理是通过高温加热软化材料或涂层, 降低其塑性变形抵抗力<sup>[44]</sup>, 从而促进材料在 USRP 过程中的塑性变形<sup>[45]</sup>。软化的材料在动态冲击和高频冲击作用下被挤压并填充到孔隙和裂缝中, 从而提高了材料的表面形貌和粗糙度。此外, 在温度场和 USRP 作用下, 残余压应力更

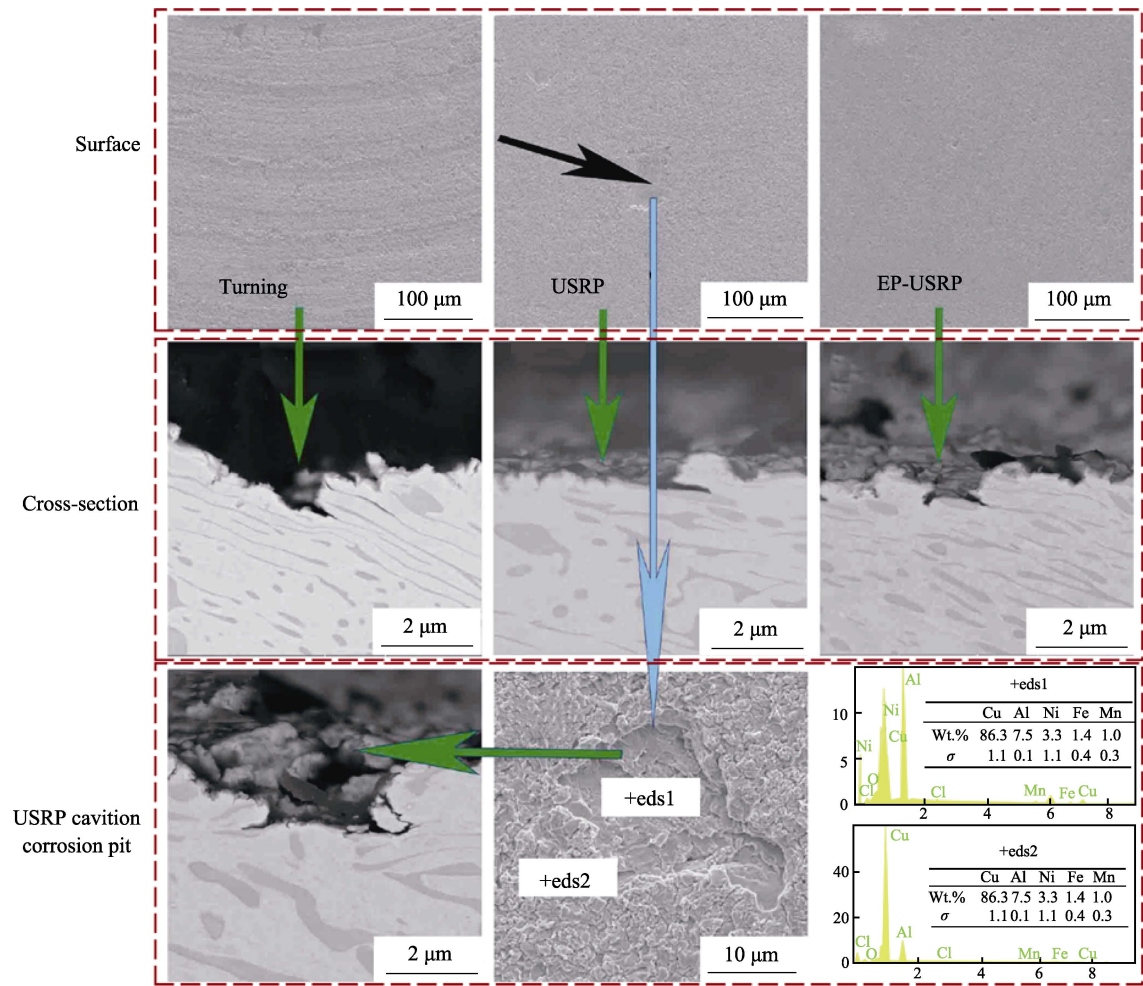


图 8 NAB 不同强化表面空化腐蚀微观结构<sup>[41]</sup>

Fig.8 Microstructure of cavitation corrosion on NAB with different strengthening surfaces<sup>[41]</sup>

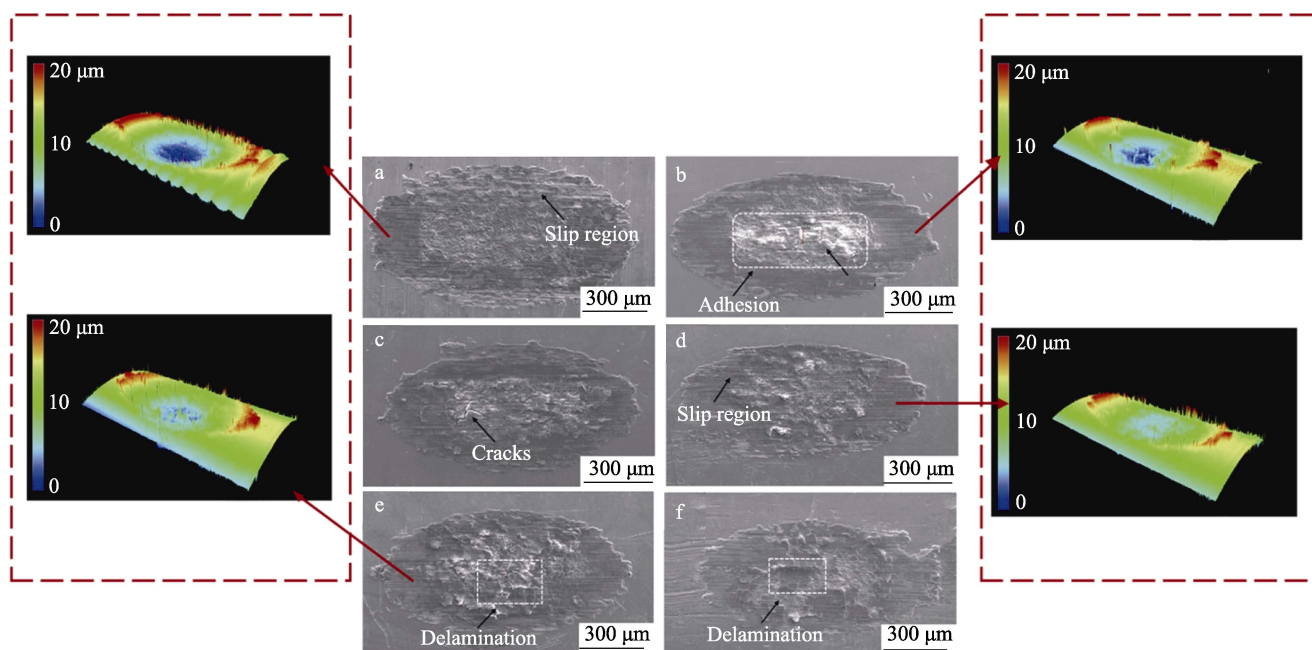


图9 车削 (a)、USRP (b) 以及 EP-USRP 在 450 Hz (c)、500 Hz (d)、550 Hz (e)、600 Hz (f) 下试样的磨损痕迹及磨损轨迹的 3D 形态<sup>[42]</sup>

Fig.9 3D morphology of sample wear traces and wear trajectories under turning (a), USRP (b) and EP-USRP at 450 Hz (c), 500 Hz (d), 550 Hz (e) and 600 Hz (f)<sup>[42]</sup>

容易引入材料表层<sup>[46]</sup>。此外,温度辅助超声滚压可以更好地实现晶粒细化效果,增大位错密度,并有效促进碳化物的沉淀<sup>[47]</sup>。因此,该材料的韧性和强度得到了进一步的提高。现在研究阶段主要采用高频感应的U形感应线圈、包裹电热丝的铜套以及电脉冲加热等方法来实现温度场的引入。

Liu 等<sup>[48]</sup>采用感应加热辅助 USRP 技术对 Ti6Al4V 材料的表面进行了强化研究。研究发现,温度场辅助超声滚压能够进一步提高材料的表面质量,随着温度的升高,材料表面变形层的厚度增大(如图 10 所示)。当样品在 650 °C 下处理时,表面和亚表面的缺陷被修复,与未加工表面相比,其表面粗糙度降低了 96%,表面硬度提高了 33%。由于钛合金在常温下难以发生塑性变形,提高温度可以增强材料的塑性变形能力。Luan 等<sup>[49]</sup>也对超高强度钢进行了加热 USRP 研究,探究了材料的表面完整性,实验装置如图 11 所示。研究发现,随着温度的升高,残余压应力明显降低,这是由加热引起的严重过时效效应和快速静态/动态恢复引起的,适当的加热温度有助于提高材料的疲劳寿命。在 100~300 °C 范围内,材料的流变应力明显下降,并表现出由新晶粒和晶界的迁移引起的软化作用,屈服强度、极限强度和弹性模量均呈现随温度升高而降低的趋势。

## 2.4 USRP 后续强化

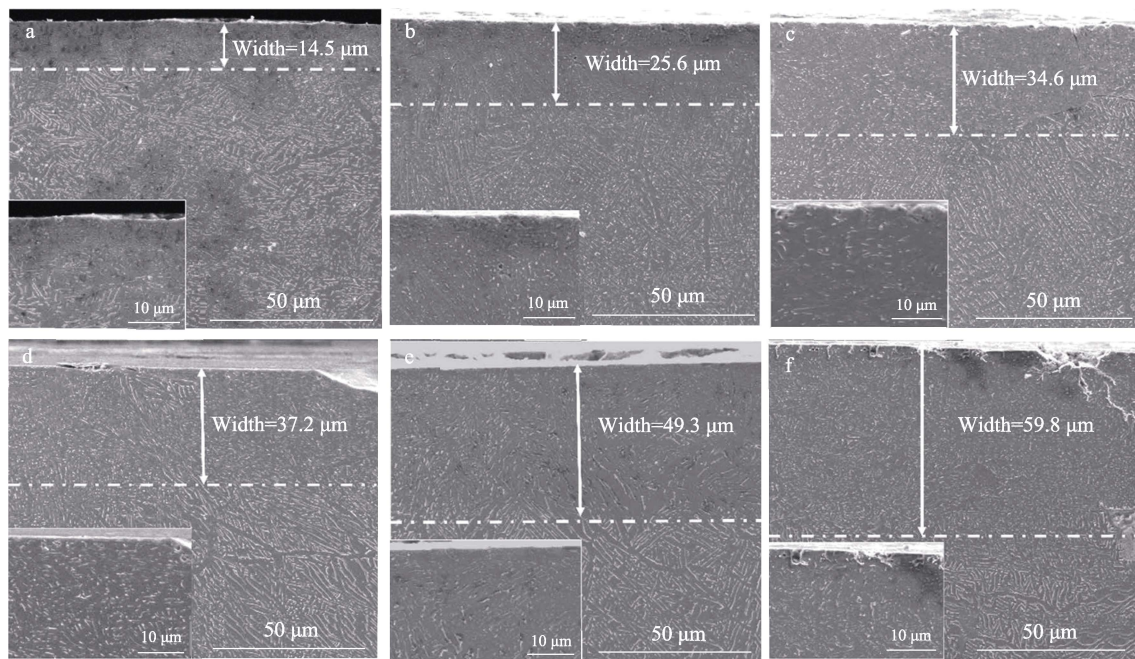
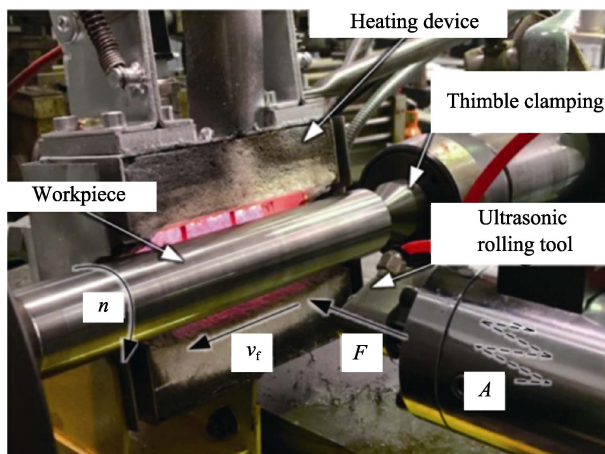
在海洋、石油天然气等领域以及钻井设备等长期服役在各种苛刻和复杂的环境中,表面腐蚀和磨损会导致装备受损<sup>[50]</sup>,从而影响其正常运行。为了保护、

强化或实现其他特殊功能,可以在某些金属或非金属材料表面形成具有一定厚度的涂层<sup>[51-52]</sup>。然而,由于涂层与基体结合力不强,涂层容易发生分层或剥落,而且材料表面可能存在气孔、裂纹和凹坑等缺陷,导致涂层过早失效<sup>[53]</sup>。

为了消除涂层表面气孔、裂纹等缺陷,Zhao 等<sup>[54]</sup>对 Ni/WC 涂层进行了 USRP 处理,并研究了不同主轴速度下横截面形貌,如图 12 所示。图 12a 为未进行 USRP 处理的等离子喷涂 Ni/WC 涂层,可以观察到涂层呈层状堆叠结构,层状结构之间不够紧凑,且存在着很多缺陷,如裂纹、孔隙等,这不能满足零件高速、重载的工作条件要求<sup>[55]</sup>。通过 USRP 处理,涂层组织得到了不同程度的改善,涂层更加紧密。表面的粗糙度由 1.24 μm 降低至 0.58 μm,如图 12b~d 所示。同时,涂层表面和亚表面的裂纹愈合和孔隙明显减少,层状堆叠结构得到消除。然而,涂层表面依然存在一些缺陷。

Zhang 等<sup>[56]</sup>通过电火花沉积法在铝青铜基体上制备了铝青铜涂层(ESD),然后通过 USRP 对表面进行了强化处理。研究表明,经过 USRP 处理后,稳定磨损阶段的平均摩擦因数(COF)由 0.36 下降到 0.303,磨损量下降约一半,ESD 涂层的耐磨性随着孔洞的愈合而显著提升,应力状态由残余拉应力向残余压应力转变,且硬度随着深度的增大而提高(如图 13 所示)。肖锦初<sup>[57]</sup>也对 3Cr13 涂层进行了 USRP 强化处理,并研究了处理后的涂层显微硬度。研究发现,经过 USRP 处理后,涂层表面形貌更加平整。3Cr13 涂层在 USRP 处理前后的显微硬度变化如图 14



图 10 不同温度下材料表面变形层厚度<sup>[48]</sup>Fig.10 Thickness of surface deformation layer of materials at different temperature<sup>[48]</sup>图 11 加热辅助 USRP 加工装置<sup>[49]</sup>Fig.11 Heating assisted ultrasonic rolling processing device<sup>[49]</sup>

所示。可知,随着涂层深度的增大,显微硬度逐渐降低,USRP 处理影响深度约为  $260\ \mu\text{m}$ ,距离表面  $50\ \mu\text{m}$  时显微硬度达到峰值,约为  $548\text{HV}$ 。研究表明,与未经 USRP 处理的 3Cr13 涂层相比,经过 USRP 处理的涂层峰值显微硬度提高了 33% 左右,孔隙率从原来的 2.9% 降低至 1.5%。

H13 钢经淬火、回火处理后其淬透性、韧性、抗热裂能力等性能得到了显著的提升,在热作模具和压铸模具中得到了广泛的应用。在长期的冷热交替作用下,零件表面经常会产生热磨损、高温氧化、腐蚀等缺陷<sup>[58]</sup>,为修复 H13 钢,提高钢材的利用率,纪皓文等<sup>[59]</sup>采用激光熔覆制备 GH5188 高温合金涂层的方法来修复 H13 钢零件,提高了零件的摩擦磨损性能。研究发现,经过 USRP 处理后,修复涂层中的柱

状晶和胞状等轴晶经高频循环挤压和滚压塑性变形后破碎成了细小的等轴晶(如图 15 所示),表层晶粒尺寸为  $100\sim 500\ \text{nm}$ ,随着深度的增大,涂层的塑性变形能力逐渐减小,呈现出梯度变形组织结构。研究表明,USRP 处理后涂层表面粗糙度降低了 58%,显微硬度提高了 70%。这是由于经 USRP 处理后涂层位错增加,屈服强度提高,其表层晶粒细化,作用机理如图 16 所示<sup>[60]</sup>。

为了探究 USRP 对模具钢熔覆层硬度的影响,在处理过程中采用不同的下压量对熔覆层进行处理<sup>[61]</sup>。结果发现,随着下压量的增加,熔覆层表层硬度呈现出先升高后降低的趋势,最大硬度值达到了  $59.18\text{HRC}$ 。熔覆层表层硬度下降的原因可能是,当下压量超过一定值时,滚压头与熔覆层接触面积较大,导致超声振动的强化效果减弱,并且滚压头的阻尼增加,加工过程中产生的温度进一步软化了熔覆层,降低了滚压强化效果。另外,激光熔覆后进行 USRP 处理还会产生超声波空化效应、热效应和声流效应<sup>[62-63]</sup>。空化气泡的形成和破裂在金属液中产生了一定范围的高温、高压、高速的微射流,从而使晶粒破碎和细化<sup>[64]</sup>。

USRP 处理可以修复涂层中的孔洞缺陷,减少裂纹源,并降低材料表面粗糙度。通过改变涂层中的残余拉应力为有利的残余压应力,可以有效控制涂层中的裂纹萌生和扩展,从而减少涂层的剥落<sup>[65]</sup>。经过 USRP 处理后,涂层的硬度升高,使脱落的层状结构难以镶嵌到材料表面,因此涂层的磨损量降低,使材料性能更优越。

综上所述,在 3 种复合加工技术中,USRP 技术



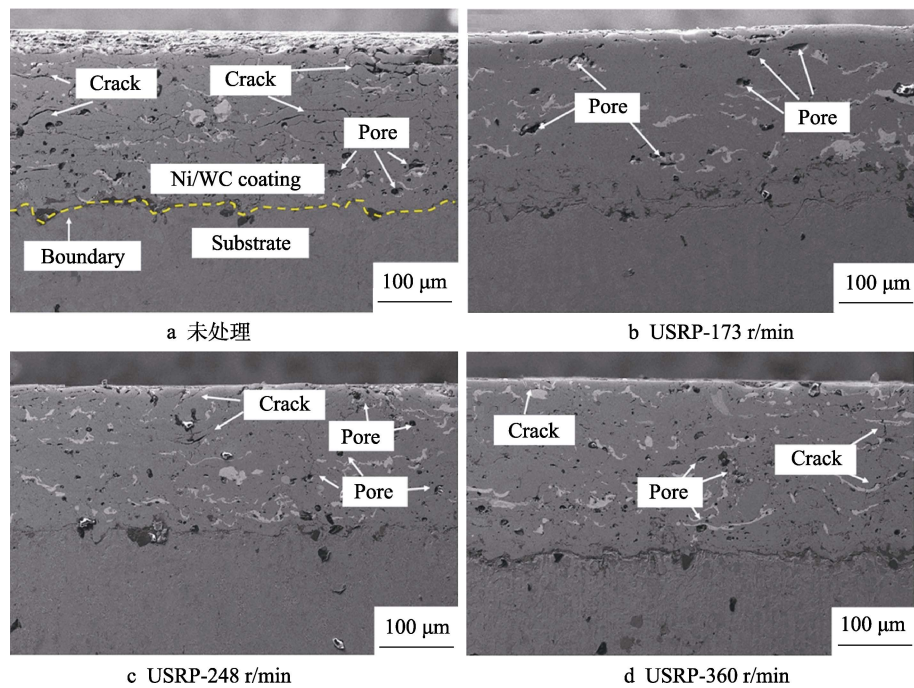


图 12 未处理和 USRP 处理样品的微观结构<sup>[54]</sup>

Fig.12 Microstructure of untreated and USRP treated samples: a) untreated; b) USRP-173 r/min; c) USRP-248 r/min; d) USRP-360 r/min<sup>[54]</sup>

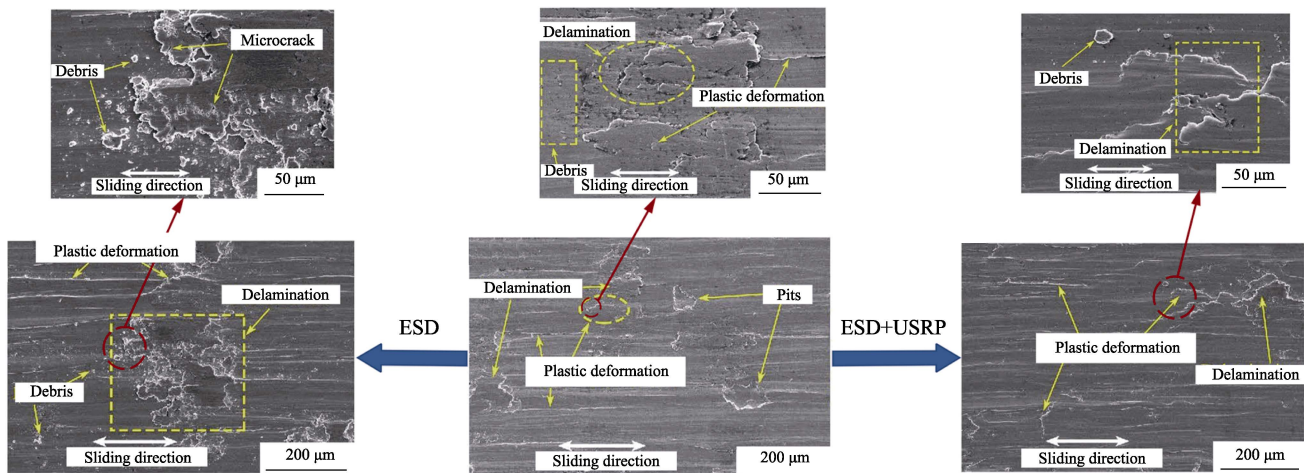


图 13 不同加工方法下 ESD 涂层的磨损形态对比<sup>[56]</sup>

Fig.13 Comparison of wear morphology of ESD coatings under different processing methods<sup>[56]</sup>

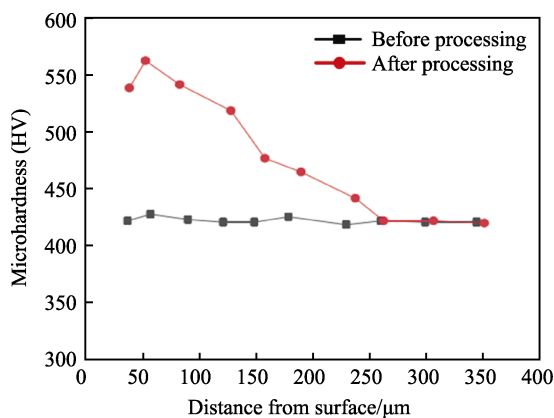


图 14 3Cr13 涂层 USRP 前后显微硬度分布<sup>[57]</sup>

Fig.14 Distribution of microhardness of 3Cr13 coating before and after USRP<sup>[57]</sup>

有不同的作用，在 USRP 前端强化中，USRP 技术作为辅助工艺提高了离子注入等工艺的加工效果；在 USRP 同步强化中，温度场等物理场辅助超声滚压技术防止了加工后出现的剪切变形和局部疲劳损伤；而在 USRP 后续强化中，USRP 技术作为激光熔覆等涂层工艺的后续处理，消除了涂层的气孔、裂纹等缺陷，降低了涂层表面粗糙度。前端强化是一种预处理方法，利用 USRP 技术制备微织构增大了涂层与基体的黏附面积，增强了涂层与材料表面的附着力<sup>[66]</sup>；纳米结构中大量的晶界缺陷可以作为原子的快速扩散通道，从而大大提高了原子扩散率。USRP 前端强化适用于需要改善材料表面性能的场景，如金属加工和模具制造。USRP 同步强化是通过电脉冲和温度场等物



表 1 USRP 复合强化技术应用及单一表面强化技术局限性

Tab.1 Application of USRP composite strengthening technology and limitations of single surface strengthening technology

Composite surface strengthening technology	Single processing limitations	Composite effect	Application areas
USRP composite coating	1) The surface of the material is rough 2) There are defects such as pores, pits, cracks 3) The coating is prone to peeling off during wear	1) The material's surface layer is nano-nanoized, and the microhardness is improved 2) The cracks heal and the microscopic morphology is smoother 3) The coating has stronger adhesion to the substrate and is not easy to fall off	Aerospace and manufacturing hammer forging dies and hot working dies, molds, transmission gears
USRP composite ion implantation	1) Nitriding parts are prone to embrittlement or peeling 2) The efficiency of ion diffusion is low 3) Nitriding temperature is high, and it is easy to change the microstructure	1) The ion diffusion efficiency is improved 2) The material peak hardness and hardening layer depth are increased 3) The thickness of the uniform carburized layer is increased	The manufacture of heat transfer pipe materials for fuel tanks, engine cylinder liners, steam generators
Electrical pulse-assisted USRP	1) There are still cracks on the surface of the material after single USRP 2) The deformation resistance is reduced 3) It limits case hardening and process impact depth	1) The material plasticity is reduced 2) The fluidity of the material is enhanced 3) The peak hardness and depth of reinforcement of the material are increased	Aerospace, marine engineering, such as marine propellers, pump shafts, valve stems
Temperature-assisted USRP	1) There are still cracks on the surface of the material after single USRP 2) Titanium alloy and other materials are difficult to plastic deformation at room temperature 3) The thickness of the deformation layer is small	1) The plasticity resistance of the material is reduced 2) The fluidity of the material is enhanced 3) The depth of the deformation layer is increased and defects are reduced such as porosity and cracks	The manufacture of drums for aero-engine blades, compressor discs and aero-engine rotors

3 结论与展望

1) USRP 技术依靠高频连续冲击,使工件表面发生塑性变形,改变原有应力场,实现冷作硬化,USRP 常用于常规金属材料性能提升,目前对合成纤维、陶瓷涂层等非金属材料的热辅助的 USRP 研究相对较少。如何调整 USRP 加工参数来提升不同材料的表面完整性、拓展 USRP 的应用范围还需深入研究。经 USRP 处理后,工件表层晶粒细化,形成了梯度纳米结晶层,提高了工件表面硬度、耐磨性和耐腐蚀性等性能,延长了疲劳寿命,但针对 USRP 工艺参数对材料性能提升的作用规律的研究还不够深入,材料抗疲劳性能与工艺参数选择之间的协同调控关系还需继续深入研究。

2) USRP 前端强化是对工件进行超声滚压预处理,形成沟槽微织构和梯度纳米层,增大沉积涂层与基体的接触面积,纳米晶粒晶界为离子提供了快速扩散通道,提高了离子的扩散速度,增大了渗透层的厚度,改善了材料摩擦和抗腐蚀性能。USRP 同步强化

利用电脉冲和加热使材料力学性能降低,增加了材料的滑移体系和机制,降低了材料的塑性变形抵抗力,促进了微裂纹愈合,从而获得了性能更好的材料表面改性层。USRP 后续强化可以消除涂层中气孔、裂纹等缺陷,增强涂层与基体的结合力,提高涂层的耐久性,防止出现分层和剥落。

3) 针对不同材料的特性和需求,可通过优化 USRP 参数和调控微观结构来实现最佳 USRP 工艺选择。该优化过程可以建立一个以不同 USRP 参数下材料的微观组织结构、力学性能等为主要内容的信息数据库,为其他工艺与 USRP 复合提供最佳选择,并为生产应用提供科学合理的技术支持。同时,还可以进一步研究一维或多维 USRP 复合工艺的动态响应模型和微观结构演变机理,以实现材料表面完整性和疲劳寿命的预测和控制。这样可以为制定更准确的工艺参数、优化产品性能以及提高材料加工过程的稳定性提供指导。

4) 推动 USRP 在涂层的后处理和再制造领域的应用,为深海勘探等领域的高性能材料的制备和受损零件的修复提供技术支持。USRP 复合工艺的强化过



程大多只有单一的物理场作用, 尚未充分发挥多场协作的潜力。因此, 未来可以集中研究多个物理场之间的相互作用, 探索多场协同作用下的 USRP 复合工艺、工具和设备的研发。这将提高 USRP 复合工艺的效率和质量, 为高性能材料的制备和修复提供更好的解决方案。为了提高 USRP 复合工艺的质量控制和应用可行性, 需要建立完善的表面完整性评估与检测体系。这将有助于准确评估不同 USRP 复合工艺下的表面完整性, 并指导优化工艺参数以实现更好的结果。在建立评估和检测体系时, 应考虑使用各种表面分析技术和非破坏性检测方法, 确保对 USRP 复合工艺的表面完整性进行准确评估。

5) 研制加工性能优异的 USRP 设备, 如将超声滚压装置与等离子注入装置集成, 可以做到 USRP 后立刻进行离子注入或 USRP 与离子注入叠加, 探究该方法对材料表面摩擦磨损和力学性能的影响, 与常规超声复合等离子注入技术相比是否进一步提高了原子扩散速率和渗透层厚度。减少外部因素的干扰, 实现对 USRP 的封闭控制, 并结合视觉检测技术, 对加工过程中的参数进行自动补偿, 提高加工的精度和稳定性。

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