

超声冲击强化焊接接头及金属表面强化研究进展

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摘要: 工程机械零件及焊接结构在服役过程中常常因为表面发生磨损、腐蚀和疲劳断裂而失效, 而失效形式与其表面加工质量、应力分布状态和表面性能等因素密切相关。超声冲击是一种利用超声波振动驱动冲击针高速撞击工件表面, 使工件表面产生塑性变形和残余压应力的表面强化技术, 具有效率高、加工精度高以及加工范围广等优势。概述了超声冲击处理技术在焊接接头处理、金属材料表面强化、激光熔覆-超声冲击复合处理以及超声冲击-化学处理复合强化等方面的研究现状及进展。在此基础上, 重点综述了超声冲击处理 Al、Mg 合金及合金钢焊接接头残余应力、力学性能及抗疲劳性能的变化, 归纳了传统金属材料以及新兴高熵合金表面超声冲击处理后的组织、微观亚结构及性能变化, 总结了超声冲击对激光改性层组织性能的影响规律以及超声冲击预处理对离子渗氮/渗硫层形成及其性能的影响等。超声冲击处理明显降低了焊接接头的残余拉应力, 有效提高其疲劳强度, 使金属和涂层表面产生纳米化组织, 显著提升材料的表面硬度、耐磨性能、耐蚀性能以及耐高温性能, 从而延长工程构件的服役寿命。显然, 超声冲击处理技术与表面涂层技术相结合, 为工程零部件表面强化提供了新的思路。对于表面涂层, 超声冲击能够在兼顾其塑韧性的前提下提升表面性能, 获得更高的表面质量、更优异的耐蚀性能和耐磨性能, 广泛应用于关键零部件的强化、修复、再制造等领域。另外, 超声冲击层内细化的组织和大量的微观亚结构为后续化学处理提供了更多的扩散通道, 起到了积极的促进作用。最后展望了超声冲击处理技术在工程结构件中的应用前景及发展方向, 为其推广应用提供参考。

关键词: 超声冲击; 焊接接头; 高熵合金; 表面强化

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Research Progress of Ultrasonic Impact Treatment for Welded Joint and Metal Surface

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ABSTRACT: In engineering fields the construction machinery parts and the welded structures usually fail in practice due to surface wear, corrosion phenomenon and fatigue fracture phenomenon during their services, which makes a large amount of lost in industry production. It has been shown that the failure mechanism of metal surfaces is closely related to surface processing quality, stress distribution status and surface properties, and so on. As we know, ultrasonic impact treatment is a kind of surface strengthening technology, in which ultrasonic vibration are generated with a ultrasonic generator to drive the impact needle to impact the surface of work-piece at high speed, resulting in obvious plastic deformation as well as the generation of residual compressive stress. In addition, this technology possesses many advantages, such as high efficiency, high machining accuracy and wide machining range. In this paper, the research status and progress of ultrasonic impact treatment technology applied in welding joint treatment, surface strengthening of metal materials, laser cladding-ultrasonic impact composite treatment technology and ultrasonic impact-chemical treatment composite strengthening technology were summarized in general. On this basis, the change trend of residual stress distribution, mechanical properties and fatigue resistance of Al, Mg alloys and welded joints of alloy steels by ultrasonic impact treatment were summarized. In addition, the changes in the microstructures, substructures (such as dislocations, twins, and so on) and surface properties of traditional metal materials as well as new types of high entropy alloys after ultrasonic impact treatment were reviewed. Furthermore, the influence of ultrasonic impact treatment on microstructures and surface properties of laser surface modified layers was summarized and the effect of ultrasonic impact pre-treatment on the formation and surface properties of ion nitriding layer and ion sulphurizing layer was discussed. The results showed that ultrasonic impact treatment significantly reduced the residual tensile stress of the welded joints, effectively improved their fatigue strength, brought out nano-structures on the surfaces of metal and coatings, and significantly improved the surface hardness, wear resistance and corrosion resistance as well as high temperature resistance, so as to prolong the service life of engineering components. Obviously, the combination of ultrasonic impact treatment technology and surface coating technology provided a new idea for surface strengthening of engineering parts. For the surface strengthened layers, ultrasonic impact treatment was able to improve the surface properties dramatically on the premise of taking into account its plasticity and toughness, and bring out higher surface quality, better corrosion resistance and wear resistance. It was widely used in the fields of strengthening, repairing and re-manufacturing of key engineering parts in the engineering fields. Additionally, after ultrasonic impact treatment the refined structures in the ultrasonic impacted layer as well as a large number of microstructures provided more and more diffusion channels for subsequent chemical treatment, which played a positive role in promoting chemical treatment. Finally, the application prospect of ultrasonic impact treatment technology in engineering structural parts was prospected and the development direction of this technology was pointed in this article, all of which provided a reference for its popularization and application.

KEY WORDS: ultrasonic impact treatment; welded joint; high entropy alloys; surface modification

当材料性能无法满足服役时的力学、化学和热学等外界条件时就会发生失效。工程构件的失效多是由磨损、腐蚀和疲劳断裂引起的,这些失效形式均与表面加工质量、应力状态、表面强度等具有密切联系^[1]。为了提高机械零部件的可靠性,延长其使用寿命,确保设备高效安全稳定运行,亟需对其表面进行强化处理。超声冲击技术(UIT)作为新兴的机械加工方法之一,是利用超声波振动驱动冲击针高速撞击工件表面,使工件表面产生塑性变形和残余压应力^[2],具有效率高、加工精度高、加工范围广等优势,在焊接接头消应力处理、金属材料表面强化、表面预处理及复合强化等方面发挥着重要作用。

本文总结了焊接接头、钢铁材料、有色金属、高

熵合金、激光熔覆层表面超声冲击处理以及超声冲击-化学处理复合改性的研究现状,分析了不同基体组织超声冲击处理后的组织、力学性能以及表面性能的演变特点,有助于深入理解超声冲击处理技术在工程结构中的应用前景及适用范围。

1 超声冲击处理焊接接头研究现状

焊接接头组织不均匀、应力集中以及较高的残余拉应力等因素严重影响结构的承载能力和服役寿命^[3-4]。超声冲击处理是一种有效的焊后改善焊接接头力学性能的工艺措施,其借助机械撞击和超声振动的共同作用,使焊趾表面产生塑性变形从而引入有益的残余

压应力。20 世纪 70 年代苏联著名的 Paton 焊接研究所自制超声冲击设备并运用于消除军舰焊缝的残余应力, 尤其在工作环境温度较低的情况下, 取得了显著成效^[5]。随后, 超声冲击技术在改善焊接接头力学性能方面得到了极为广泛的应用。

1.1 超声冲击处理 Al 及 Mg 合金焊接接头

Al 合金因其具有优良的力学性能和高的比强度, 被广泛应用在飞机、舰艇、装甲车、高速动车等领域^[6-7], 但 Al 合金熔化焊时热裂纹敏感性较大、焊缝强度降低等弊端对其性能发挥非常不利。超声冲击技术的出现, 为铝合金焊接结构的性能提升以及推广应用提供了重要的技术支撑。首先, 超声冲击能够细化表层晶粒, 提高其强度及塑韧性。何柏林等^[8]对 6082 铝合金熔化极惰性气体保护焊 (MIG) 焊接接头进行超声冲击处理后, 冲击电流和冲击时间分别为 1.5 A、2 min 时, 最小晶粒尺寸可达 200 nm 左右。此外, 2A12 铝合金非熔化极惰性气体保护电弧焊 (TIG) 焊接接头经过超声冲击处理后, 气孔和缩松等缺陷明显降低, 抗拉强度提高了 17.4%, 伸长率增加了 28%^[2]。其次, 经过超声冲击处理后, 铝合金焊接接头的应力状态得以改善。双丝 MIG 焊接 7A52 铝合金后, 对其接头进行超声冲击全覆盖处理, 焊趾处形成相对连续、均匀、光滑的过渡圆弧, 有效缓解焊接接头的应力集中; 焊接接头表面形成一层致密的塑性变形层, 晶粒细化, 焊接区的拉应力转变成压应力, 硬度和疲劳强度均显著提高^[9-10]。

超声冲击处理后, 应力状态的改变能够有效改善 Al 合金焊接结构的抗疲劳性能。动车车体用 A7N01P-T4 铝合金焊接接头经过超声冲击处理后, 在循环周次为 2×10^6 周次时, 接头疲劳强度提升 41%^[11], 接头的应力腐蚀性能得到有效改善^[12]。

Mg 合金作为工程应用中最轻的结构材料, 具有密度小、比强度高、加工性好以及承受冲击载荷能力强等特点, 在航空航天、汽车及电子信息技术等领域具有广阔的应用前景^[13-15]。然而, Mg 合金焊接接头在循环载荷作用下极易在焊缝缺陷处发生疲劳断裂。研究表明, MB8 镁合金焊接接头经超声冲击处理后, 表面获得纳米晶组织, 在循环寿命为 2×10^6 和 1.0×10^8 周次的条件下, 疲劳强度分别提高了约 32.07%^[13]和 26%^[14]。超声冲击不仅显著降低了焊趾处的应力集中, 还改变了接头疲劳断裂位置, 焊态试样在焊缝缺陷处断裂转变为在热影响区断裂^[13-14]。

1.2 合金钢焊接接头超声冲击处理

合金钢焊接结构在工程中得到了极为广泛的应用, 然而十字接头中焊缝过于密集, 焊接区应力分布极不合理, 严重影响焊接结构的服役性能^[16-17]。有研究表明^[18], 16MnR 十字接头经过超声冲击处理后,

焊趾处过渡半径增大, 母材与焊缝过渡趋于平缓, 焊趾表面组织明显细化, 由焊态的拉应力状态转变为压应力状态, 残余压应力最大可达 269.8 MPa, 表面显微硬度最高达 340.5 HV。但如果超声冲击参数选择不当, 将导致接头表层出现不同类型的缺陷, 影响焊接接头整体的表面质量。由此可见, 采用超声冲击处理焊接接头应重视工艺参数的选择及优化, 以确保获得高质量焊接接头表面质量。

众所周知, 大厚度高强钢焊接接头中应力分布更复杂, 服役过程中发生断裂的危险性较大^[19-20]。有研究表明^[21], 大厚度 EQ47 高强钢焊接结构经覆盖焊缝及母材局部超声冲击处理后, 焊接残余应力显著降低, 冲击区域的拉应力全部转化为压应力, 且分布较均匀。针对高速列车转向架在实际运用中出现的疲劳问题, 对转向架用 SMA490BW 钢十字焊接接头进行超声冲击处理, 有效降低了焊趾处的应力集中系数, 降低了裂纹萌生概率^[22-23]。此外, 超声冲击处理细化了晶粒, 裂纹在塑性变形区的扩展路径变长, 超声冲击处理试样的疲劳强度相比于未处理试样提高了 25%。

对于耐候钢和不锈钢等特殊性能用钢, 焊接接头的残余拉应力极易导致应力腐蚀开裂, 缩短构件的使用寿命^[24-25]。超声冲击处理能够显著降低焊接拉应力, 从而有效延长其使用寿命。其次, 拉应力是导致焊接结构产生腐蚀疲劳断裂的重要因素。超声冲击处理不仅能够降低拉应力, 同时还能够有效提升构件表面的耐腐蚀性能, 因此其对抗腐蚀疲劳起到积极作用。A106-B 碳钢焊条电弧焊焊接接头焊趾处经超声冲击处理后, 残余拉应力明显降低, 其腐蚀疲劳寿命显著提升^[26]。

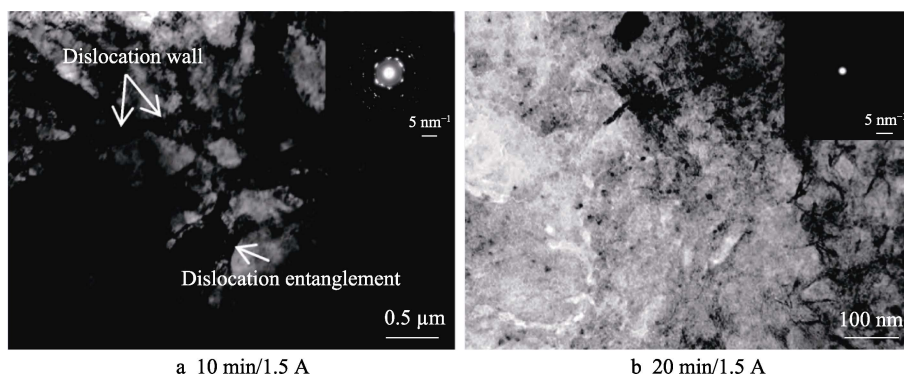
2 金属材料表面超声冲击处理研究现状

金属材料表面性能无法满足日益苛刻的工况条件需求, 超声冲击强化技术为提高工件服役性能、延长使用寿命提供了新的思路。吕宗敏等^[27]借助超声冲击诱发 SMA 490BW 钢表面产生等轴纳米晶以及大量的位错墙、位错缠结 (图 1), 造成加工硬化, 产生了沿深度方向呈梯度分布的硬度, 对改善其疲劳性能有益。同时, 通过优化超声冲击工艺参数, 能够有效避免叠形裂纹等缺陷, 优化表面质量及完整性。7225 钢表面超声冲击处理后, 屈服强度由原始试样的 520 MPa 提高至 610 MPa, 疲劳寿命增加了约 4 倍。当冲击次数越多且冲击道次越少时, 可获得最佳的表面平滑度^[28]。此外, 低碳钢超声冲击处理后, 得益于梯度纳米组织结构以及晶界渗碳体相的存在, 有效延缓裂纹的萌生, 使其在 300~500 °C 下的高温磨损性能得到提高^[29]。

Al、Cu 和 Ni 等有色金属也可通过超声冲击获得优异的表面性能。Kahraman^[30]采用超声冲击技术对 AA7075 铝合金表面进行不同冲击次数处理, 冲击层厚度随着冲击次数和变形量的增加而增大, 且冲击处理未改变铝合金基体的相结构。由于晶粒细化和加工硬化的共同作用, 表面纳米层硬度显著提高。Yin 等^[31]研究发现, 690Ni 基合金表面超声冲击处理后, 晶粒尺寸由 44.63 μm 降至 38.48 μm , 近表层~0.45 mm 范围内应力明显降低, 摩擦因数由 0.42 降至 0.34, 磨痕宽度和深度减小, 耐磨性能提升约 1 倍。纯铜表面超声冲击处理后, 晶粒尺寸约 10 nm, 冲击硬化层深度

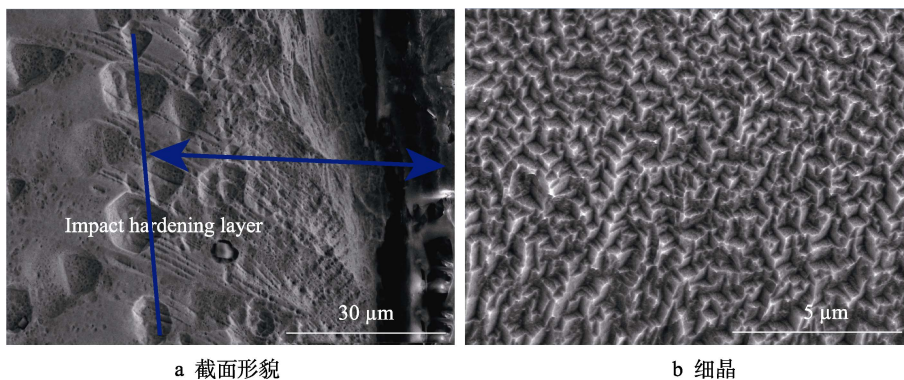
达 338 μm , 表面硬度提升 233.5%, 抗拉强度由 263 MPa 提升至 308 MPa^[32]。

近年来, 高熵合金因其高混合熵、晶格畸变、原子迟滞扩散及鸡尾酒效应, 展现了良好的塑韧性和优异的耐磨抗蚀性能^[33-35]。Li 等^[36]采用超声冲击强化技术处理 $\text{Al}_{1.0}\text{CoCrFeMnNi}$ 高熵合金, 结果发现, 随着 Al 含量的增加, 高熵合金结构从单相 FCC 向 FCC+BCC 和单相 BCC 结构转变, 硬度随之增加。经超声冲击处理后, 近表层发生塑性变形, 产生细晶结构(图 2 和图 3), 且硬度和耐磨性能均提高(图 4)。但随硬度升高, 超声冲击硬化效果减弱, 硬化层较薄(图 4c), 在高速重



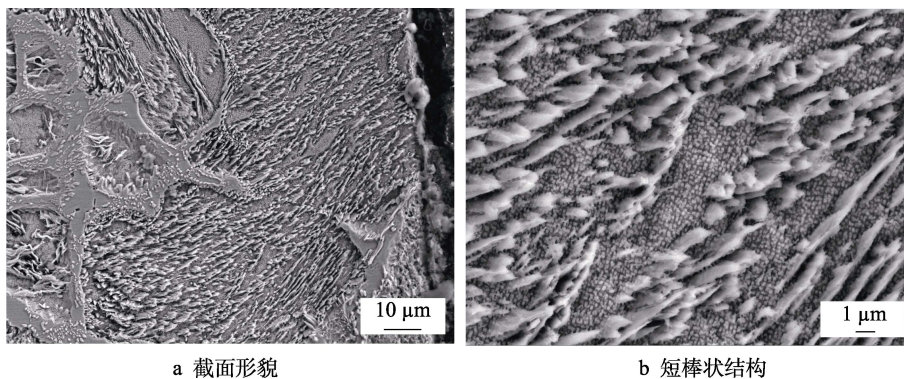
a 10 min/1.5 A

b 20 min/1.5 A

图 1 SMA 490BW 钢超声冲击硬化层 TEM 分析^[27]Fig.1 TEM images taken from ultrasonic impact treated SMA 490BW steel^[27]

a 截面形貌

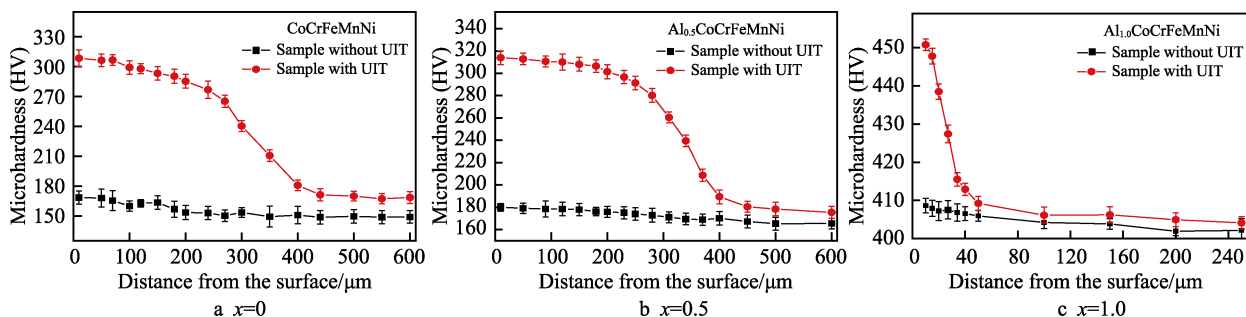
b 细晶

图 2 $\text{Al}_{0.5}\text{CoCrFeMnNi}$ 高熵合金超声冲击截面组织^[36]Fig.2 Cross-sectional microstructures of $\text{Al}_{0.5}\text{CoCrFeMnNi}$ HEAs by ultrasonic impact treatment^[36]: a) cross-sectional morphology; b) refined grains

a 截面形貌

b 短棒状结构

图 3 $\text{Al}_{1.0}\text{CoCrFeMnNi}$ 高熵合金超声冲击截面组织^[36]Fig.3 Microstructure of $\text{Al}_{1.0}\text{CoCrFeMnNi}$ HEA by ultrasonic impact treatment^[36]: a) cross-sectional morphology; b) short rod-like structures

图 4 $\text{Al}_x\text{CoCrFeMnNi}$ 高熵合金超声冲击显微硬度^[36]Fig.4 Microhardness curves of $\text{Al}_x\text{CoCrFeMnNi}$ HEAs samples by ultrasonic impact treatment^[36]

载摩擦条件下硬化层的存在时间短,对性能的提升程度有限,限制了该技术在表面强化领域的应用。将超声冲击技术与电火花熔凝技术相结合,能够有效增加强化层深度,提升其表面性能^[37-38]。李晓刚等^[37]采用超声冲击与电火花熔凝复合处理 DH36 钢表面,其塑性变形区深度大幅增加,形成约 25 μm 厚的细晶熔凝组织,硬化层深度约为 55 μm ,表面硬度提高 65.1%,表面粗糙度降低约 79.6%。复合处理后 DH36 钢表面的耐磨性较单纯超声冲击处理明显提高。

3 激光-超声冲击复合处理研究

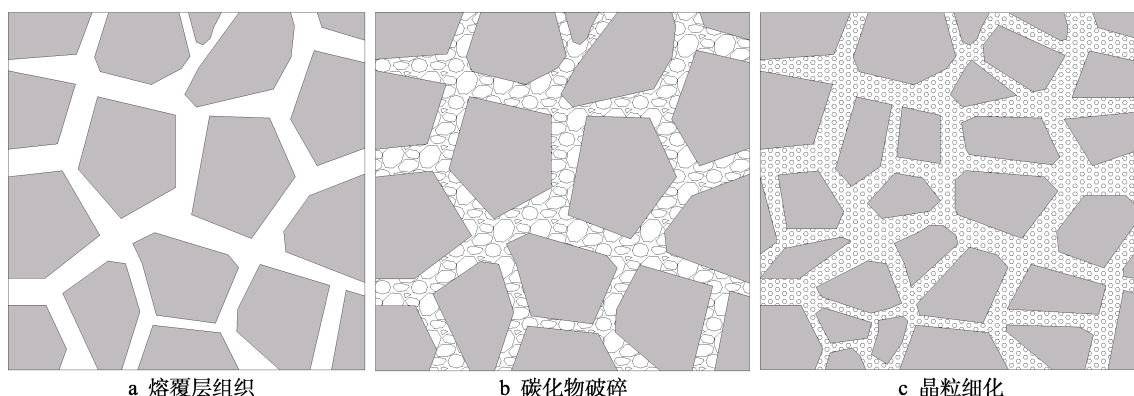
表面涂层技术能够克服铸造材料的组织缺陷和尺寸形状限制,更好地发挥合金性能^[39-41]。激光表面改性技术具有热影响区小、结合强度高等优势,在关键零部件表面强化领域得到广泛应用^[42-44]。将其与超声冲击技术相结合,能够解决激光改性层组织不均匀、残余应力大及成形质量差等问题,以满足应用表面对精度和性能的要求。

激光相变硬化 (LHT) 具有加工速度快、效率高、热影响区小且成本低等优势。Lesyk 等^[45-46]将激光相变硬化与超声冲击 (UIT) 复合处理技术应用于 AISI 1045 钢表面强化中,结果显示,相比于 UIT 和 UIT+LHT, LHT+UIT 复合处理后 AISI 1045 钢表面粗糙度

最小且硬度最高 (约 1100HV0.05); 与未处理试样相比,由于细小马氏体的生成,表面磨损量降低了 84%。

激光熔覆技术是利用高能束激光和合金粉末共同作用,实现对工件表面进行强化及修复。将激光熔覆处理与超声冲击相结合能够进一步提升熔覆层的组织及性能。戚永爱等^[47]采用超声冲击技术对 FGH95 镍基高温合金熔覆层进行处理发现,强塑性变形区内位错塞积现象显著,熔覆层组织形成细化的小晶块;次塑性变形区深度为 0.1~0.25 mm,微塑性变形区内等轴晶细化至 5.4 μm ,细化深度达 0.7 mm,表面显微硬度高达 594.25HV,比未经冲击熔覆层提高了 1.3 倍。李美艳等^[48]开展了 Ni 基熔覆层超声冲击处理,结果显示,超声冲击高速应变速率下, Ni 基熔覆层表面晶界碳化物被破碎成细小颗粒,呈弥散分布 (图 5),同时形成了约 5 μm 厚的细晶层,在细晶强化和弥散强化共同作用下冲击硬化层硬度提升 50%以上,耐蚀性能也明显提高。

超声冲击技术与激光熔覆技术的结合,为高熵合金的应用及性能发挥提供了新的思路。已研究发现^[49],激光熔覆 $\text{Al}_{0.5}\text{CoCrFeMnNi}$ 高熵合金层内部存在明显的凝固边界,并伴有片状团簇和多边形沉淀,由单相 FCC 结构组成,超声冲击处理并未改变涂层的相结构。然而,经过一次超声冲击处理后,发生明显的塑性变形,形成了一层较薄的冲击层,沿凝固边界的原

图 5 激光熔覆层表面冲击强化示意图^[48]Fig.5 Diagram of impact hardening for laser cladding coating^[48]: a) structural characteristics of laser cladding coating; b) fragmentation of carbides; c) grain refinement

始析出物被破碎成细小的析出物。2次处理后,冲击层表面形成大量絮状物,随着冲击次数的增加,冲击层表面出现明显的塑性变形痕迹。对比可见,经一次超声冲击处理可获得最小表面粗糙度和最大表面硬度。在3.5%NaCl和1 mol/L NaOH溶液中,超声冲击层电流密度分别降低了69.6%和87%,说明超声冲击显著提高了高熵合金层的耐蚀性,但应注意选择优化冲击处理参数。Cui等^[50]对高速激光熔覆FeCoNiCrMn高熵合金层进行超声冲击处理后,表面形成了梯度组织结构,且由于细晶强化、晶界润湿相转变以及残余压应力的产生,硬化层在3.5%NaCl溶液中的耐蚀性提高了33.3%。

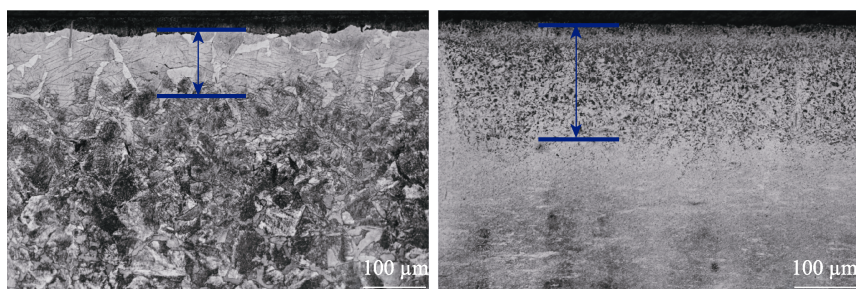
借助超声冲击技术处理激光增材制造成形件表面,所形成的塑性变形层在随后的熔覆过程中发生再结晶,减小或消除了残余应力且细化了晶粒,达到了减小各向异性、提高成形件综合力学性能的目的。激光增材制造TC4成形件经超声冲击处理后水平方向的塑性有效提高,水平和垂直方向的拉伸性能均达到锻件之上水平,且各向异性控制在5%以内^[51]。Donoghue等^[52]采用超声冲击处理激光增材制造Ti-6Al-4V沉积层,两种工艺交替进行,EBSD分析发现,超声冲

击将原始粗大柱状晶打断,塑性变形层内晶粒明显细化,为激光增材制造高性能钛合金的工业化实际应用奠定了成形技术基础。

4 超声冲击-化学处理复合改性研究

离子氮化作为一种有效的表面强化技术,具有氮势高、处理时间短、工件变形小且节能环保等优点,能够进一步提升合金及涂层表面耐磨性、耐蚀性及抗疲劳性能^[53]。离子渗氮过程中,氮原子扩散和氮化物的形成受组织及微观亚结构的影响,而超声冲击能够在工件表面获得大量的晶界和位错、沟槽等,这些缺陷和晶界有利于氮元素的深层扩散和氮化物的形核^[54],可以缩短渗氮所需的时间和降低渗氮工艺温度,获得优异的表面强化层。

低压螺杆泵用钢40Cr表面超声冲击处理后,离子渗氮层深度明显增加(图6),且组织更加细小致密,超声冲击-离子渗氮层的摩擦因数以及磨损量均显著降低(图7和图8)^[55]。显然,超声冲击诱导产生的细晶结构及大量微观缺陷,为氮原子扩散提供了快捷通道,加速了氮原子扩散的动力学过程,促进了



a 未经超声冲击

b 超声冲击处理

图6 超声冲击前后40Cr钢离子渗氮层的截面组织^[55]

Fig.6 Cross-sectional microstructures of ion nitriding layer of 40Cr steel^[55]:

a) without UIT; b) UIT

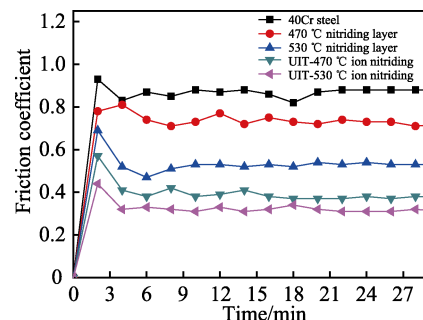
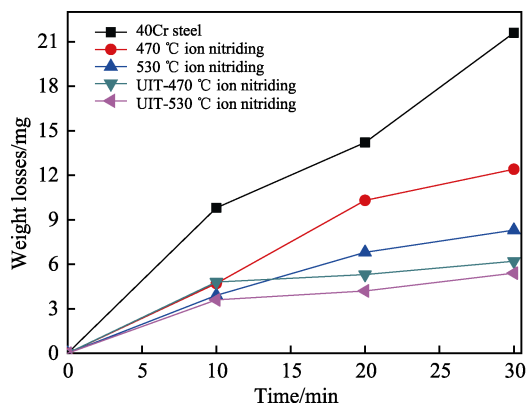
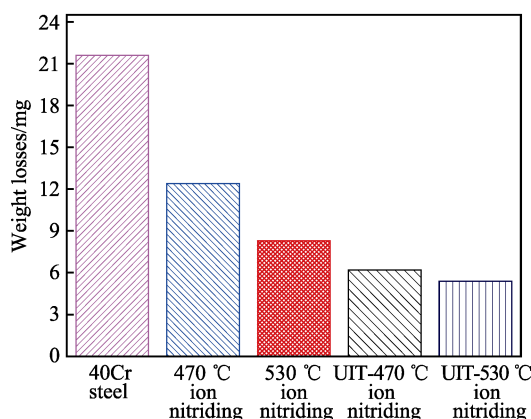


图7 超声冲击40Cr钢离子渗氮层的摩擦因数曲线^[55]

Fig.7 Friction coefficient curve of ion nitriding layer of 40Cr steel before and after ultrasonic impact^[55]



a 磨损量变化曲线



b 磨损量对比图

图8 不同处理工艺下渗氮层的磨损量^[55]

Fig.8 Weight losses of nitrided layer under different treatment processes^[55]:

a) weight losses curve; b) weight losses comparison chart

渗氮层厚度的增加,显著降低了渗氮温度,避免了高温长时渗氮带来的氮化层组织粗化以及渗氮件大变形问题^[56]。由于超声冲击处理后表面氮化物更加细小致密,其耐蚀性能也显著提升,如表 1 所示^[55]。此外,通过超声冲击-离子渗氮复合处理,能够有效解决 304 不锈钢硬度低、耐磨性差的问题,但渗氮温度过高,反而会恶化其表面耐磨性能,应综合各影响因素优化处理工艺^[57]。

表 1 不同工艺下渗氮层电化学测试结果^[55]
Tab.1 Electrochemical fitting parameters
of different nitride layers^[55]

Processing	$E_{\text{corr}}/\text{mV}$	$I_{\text{corr}}/\mu\text{A}$
40Cr	-812.4	59.9
470 °C ion nitriding	-670.5	38.6
530 °C ion nitriding	-646.6	31.7
UIT-470 °C ion nitriding	-204.7	1.93
UIT-530 °C ion nitriding	-334.6	0.89

超声冲击与离子渗氮进行复合处理能够提高耐磨性能,还可与低温离子渗硫处理相结合,制备自润滑涂层,起到耐磨减摩作用。王志^[58]采用激光熔覆制备的 Ni55 涂层经超声冲击处理后形成了约 350 μm 厚的细晶层(图 9b)。经 460 °C 保温 2.5 h 离子渗硫处理后, Ni55 熔覆层表面硫化物层疏松并形成大小不一的孔洞(图 10a),而冲击硬化层表面产生大量细小的硫化物颗粒(图 10b),摩擦因数明显降低(图 11),表面磨痕深度和宽度大幅度减小。同时,基于超声冲击处理后组织结构特征、硫化物层形貌、成分以及摩擦学性能评价,构建了超声冲击处理后的生长模型,如图 12 所示。

由此可见,超声冲击用于离子渗氮、离子渗硫等化学处理的预处理工序,所形成的细小组织结构及微观缺陷,为离子的吸附、扩散提供了有利条件,促进氮化物层和硫化物层的形成及生长,更有助于发挥涂层的耐磨、减摩性能。超声冲击-化学处理复合改性技术在接触摩擦构件中具有广阔的应用前景。

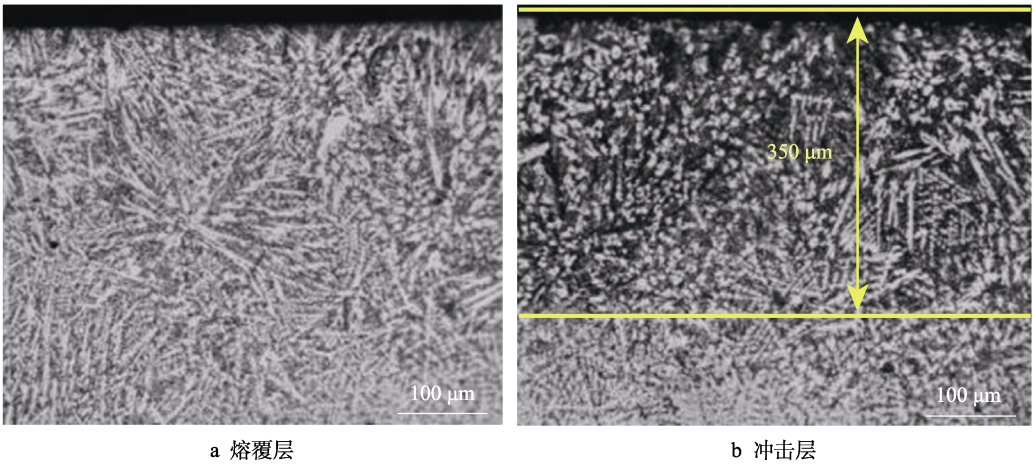


图 9 超声冲击前后 Ni55 熔覆层的截面形貌^[58]
Fig.9 Cross-sectional microstructures of Ni55 cladding coating before and after ultrasonic impact treatment^[58]: a) laser cladding coating; b) impacted layer

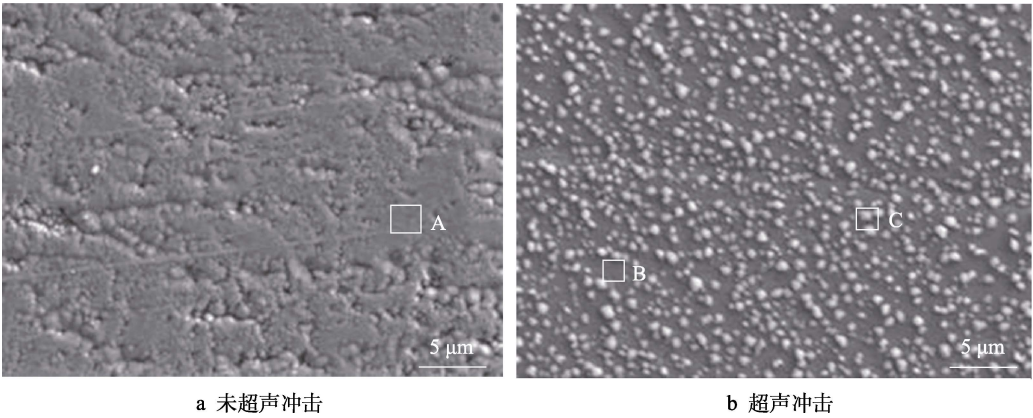
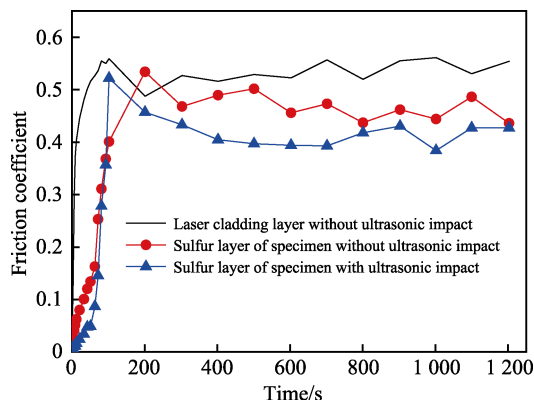
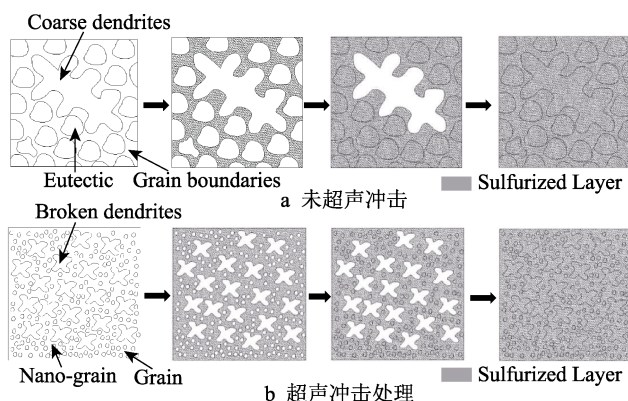


图 10 Ni55 熔覆层表面渗硫层的微观形貌对比^[58]
Fig.10 Comparison of microstructure of sulfide layer^[58]: a) specimen without UIT; b) specimen with UIT

图 11 不同渗硫层的摩擦因数曲线^[58]Fig.11 Friction coefficient curve of different layers^[58]图 12 熔覆层表面超声冲击处理后离子
渗硫层的生长模型^[58]Fig.12 Schematic diagram of the growth of sulfur layer^[58]:
a) specimen without UIT; b) specimen with UIT

5 结语

超声冲击处理技术作为一种表面强化技术,在改善表面组织结构、力学性能、应力状态等方面展现了独特的优势,已在焊接接头、金属材料、高熵合金表面强化等领域得到广泛应用。将激光表面改性技术、离子渗氮、离子渗硫等化学处理技术与超声冲击相结合的复合强化技术也越来越得到研究者的关注。借助超声冲击制备细晶组织能够为离子渗硫提供有利的扩散通道,有效提高渗硫速率,获得细小致密的渗硫层,在提高表面耐磨性能的同时,改善其减摩润滑性能,在关键摩擦副表面强化中具有广阔的应用前景。

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