

激光熔覆镍基合金摩擦磨损性能的研究进展

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摘要: 金属零部件表面因摩擦磨损导致金属零部件失效, 激光熔覆是有效的表面改性技术, 可提高金属零部件表面的摩擦磨损性能, 从而延长金属零部件的使用寿命。镍基合金粉末由于其与金属基体具有良好的湿润性、优异的性能提升、适宜的价格等优势, 成为激光熔覆材料中的研究重点。熔覆层成分调控是影响镍基合金熔覆层性能的根本原因, 通过利用不同物质的特殊性能细化晶粒调控涂层组织等, 从而提升涂层的耐磨性。通过对激光熔覆镍基合金熔覆层中不同的元素添加、自润滑相添加、陶瓷相添加、稀土添加产生的固溶强化、细晶强化和第二相强化等来调控熔覆层微观组织并减少内部缺陷, 优化熔覆层摩擦磨损性能的影响研究现状进行介绍, 并对未来镍基合金熔覆层发展方向进行总结与展望, 加深对镍基合金熔覆层摩擦磨损发展现状的了解。

关键词: 激光熔覆; 摩擦磨损; 镍基合金; 表面改性; 研究现状

Research progress on friction and wear properties of laser cladding nickel based alloys

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Abstract: The failure of metal components often results from surface wear caused by friction. Laser cladding is an effective surface modification technology that can enhance the friction and wear resistance of metal component surfaces, thereby extending the service life of metal parts. Nickel-based alloy powder has become a focal point of research in laser cladding materials due to its good wettability with metal substrates, excellent performance enhancement capabilities, and reasonable cost. Composition regulation of the cladding layer is a fundamental factor affecting the properties of nickel-based alloy cladding. By utilizing the unique properties of different substances to refine grain structure and control the coating's microstructure, the wear resistance of the coating can be improved. Therefore, this paper reviews the current research on the effects of adding various elements, self-lubricating phases, ceramic phases, and rare earth elements to the nickel-based alloy cladding layer in laser cladding. These additions contribute to solution strengthening, fine grain strengthening, and second phase strengthening, thus refining the microstructure and reducing internal defects of the cladding layer to optimize its friction and wear performance. The paper also provides a summary and outlook on the future development direction of nickel-based alloy cladding layers, serving as a reference for understanding the current state of research on the friction and wear properties of nickel-based alloy cladding layers.

Keywords: laser cladding; friction and wear; nickel-based alloy; surface modification; research status

1 序言

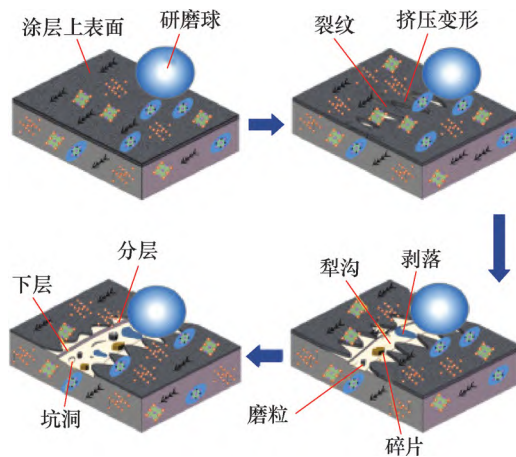
在复杂恶劣的工况下,金属零部件表面由于摩擦磨损导致金属零部件表面失效和使用寿命下降,造成不可挽回的经济损失,严重的还会导致一系列安全事故的产生^[1]。随着科学技术的发展,等离子喷涂^[2]、物理气相沉积(PVD)^[3]、化学气相沉积(CVD)^[4]、堆焊^[5]、渗碳^[6]、渗氮^[7]与激光熔覆^[8]等表面改性技术已被广泛应用,用来增强金属零部件的表面硬度和摩擦磨损性能。激光熔覆技术是通过高能激光束对粉末或丝材进行熔化后沉积到金属基体表面进行修复和强化的一种表面改性技术,相比于传统的表面改性技术,激光熔覆具有熔覆材料来源广泛,金属、合金、陶瓷和复合材料都可作为熔覆材料使用,通过对参数的控制,可实现对熔覆层形貌和性能的精确控制,以制备高质量的熔覆层,通过制备高性能熔覆层,延长金属零部件的使用寿命,对损坏的金属零部件进行修复,降低更换成本,成为现代工业中最为重要的表面改性技术之一,具有广阔的应用前景^[9-12]。

镍基合金具有良好的润湿性、抗氧化性、摩擦磨损性能、耐腐蚀性和自溶性等综合性能,以及合适的价格,是激光熔覆的首选材料^[13, 14]。随着社会工业的发展和应用环境对金属零部件表面摩擦磨损性能的要求增加,单一的镍基合金熔覆层,在应对不同恶劣工况时,性能有限,为提高镍基合金熔覆层应对不同恶劣环境摩擦磨损的适应能力,可以通过在镍基合金熔覆层的基础上添加不同的物质来进一步提高熔覆层的摩擦磨损性能。因此,通过对镍基合金熔覆层中引入不同的元素、陶瓷相、自润滑相和稀土,通过不同物质的第二相强化、固溶强化、细晶强化等特殊性能对微观组织进行改善和内部缺陷的减少优化,从而对镍基合金熔覆层摩擦磨损性能进行优化提升的现状进行介绍,并对未来镍基合金熔覆层摩擦磨损性能的发展方向进行展望和总结。

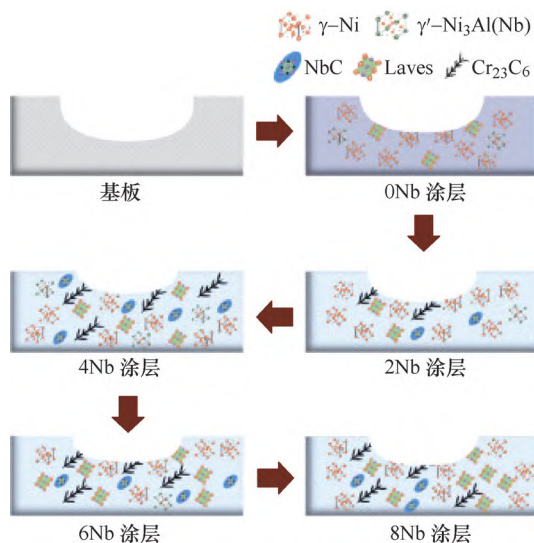
2 元素添加对熔覆层摩擦磨损性能的影响

不同元素可利用其不同性能作用于熔覆层从而改善其摩擦磨损性能。WANG等^[15]为提高Inconel 625熔覆层的性能,以0.5%SiC添加量为定值,改变Nb元素的添加量来进一步提升熔覆层的性能,相

比于Inconel 625熔覆层,随着Nb元素的提升,促进了NbC和Cr₂₃C₆硬质相的析出,晶粒得到了细化,磨损机制由基体严重的磨粒磨损、黏着磨损和氧化磨损转变为涂层轻微的磨粒磨损和氧化磨损。图1所示为涂层在摩擦磨损中生成氧化膜,硬质相分散在晶间和晶界,在摩擦磨损过程中疲劳应力的作用下,硬质相脱落,产生磨粒磨损和氧化磨损现象。但过多的Nb元素添加不利于析出相的均匀分布,使摩擦磨损性能下降。HUANG等^[16]研究了Ta元素添加对Ni60A/WC熔覆层性能的影响,发现随着Ta元素的添加,TaC含量提升,在熔覆过程中促进了WC的分解,Ta是强碳化物元素,易于C元素结合,降低了WC含量,降低了裂纹敏感性,细化了晶粒,促进碳化物的均匀分布,当Ta元素添加量为10%



a) 摩擦过程示意



b) 不同涂层的耐磨性机制

图1 涂层的摩擦和磨损原理^[15]

时具有最优的摩擦磨损性能。YAN等^[17]在Ni60AA粉末基础上添加不同元素,制备Ni60AACu、Ni60AACuMo、Ni60AACuMoW三种熔覆层,以研究元素添加对Ni60AA熔覆层性能的影响规律,元素的添加导致熔覆层硬度下降,但Ni60AACu在室温和600℃下拥有最优的摩擦磨损性能,在摩擦磨损过程中Cu取代部分Ni形成CuMo固溶体具有良好的减摩性能,导致在硬度下降的情况下具有比Ni60AA熔覆层更优异的常温和高温摩擦磨损性能。

LI等^[18]研究了添加Mo元素在Ni60AA/WC中对熔覆层的性能改善,在摩擦过程中熔覆层表面形成致密的氧化膜,氧化膜凭借自身硬度作为球与熔覆层之间的接触介质,进而优化熔覆层耐磨性,随着Mo元素添加量的提升,裂纹呈现先升后降趋势,高熔点Mo元素与其他元素生成碳化物,析出作为成核点,细化了晶粒,抑制了裂纹的产生,过量的Mo元素增加了熔覆层与O元素的亲和力,引入杂质和氧化物,引起裂纹数量的提升,提升了熔覆层中 $M_{23}(C, B)_6$ 相的强度,促进 Mo_2C 新相的产生,当Mo元素添加量为1%时,具有最小的摩擦系数和磨损量,提升了熔覆层的摩擦磨损性能。FENG等^[19]通过在Inconel 625中添加Al元素改善熔覆层的性能,Al元素的添加促进BCC含量的提高,与固溶强化效应协同作用,提升了熔覆层的硬度和摩擦磨损性能。HONG等^[20]以20%WC陶瓷颗粒为添加定量,改变Nb元素的添加量,来进一步优化Q550钢表面Ni60熔覆层的性能,Nb元素的添加促进了沉积到熔覆层底部的WC残留颗粒的分解,抑制了 Cr_7C_3 相的产生,促进了NbC相的析出,但熔覆层的硬度随Nb元素的添加逐渐下降,适量的Nb元素添加有利于熔覆层性能的提高,NbC由粗条状转化为细针状,组织分布更加均匀,强化了熔覆层与基体的结合,当添加3%Nb时,有效防止摩擦过程中硬质相的脱落,进一步提升了熔覆层的摩擦磨损性能。在镍基熔覆层中控制元素的含量和比例,通过硬质相的引入、固溶强化和晶粒细化等,使熔覆层耐磨性能达到理想效果。

3 陶瓷相添加对熔覆层摩擦磨损性能的影响

镍基合金粉末具有良好的韧性和湿润性,单一镍基合金粉末对熔覆层性能的提升具有局限性,陶

瓷相具有高硬度、耐磨性、耐高温等优良性能,但与基体热物理性能差距较大,易出现裂纹、剥落等现象,将陶瓷相添加到镍基合金粉末中,可结合两者优点,制备高性能的金属陶瓷复合熔覆层,通过陶瓷相的生成方式可分为直接添加和原位生成。LI等^[21]以Ti粉和镍包石墨粉作为TiC原位合成的元素来源,增强U71Mn钢上Ni45熔覆层的性能,随着Ti粉和镍包石墨粉含量的提高,熔覆层中TiC衍射峰增强,熔覆层显微硬度相较于Ni45熔覆层得到显著提高,摩擦磨损性能呈现先提高后减少的趋势,过量的添加导致熔覆层脆性提高,韧性下降,摩擦过程中产生大面积剥离,不利于摩擦磨损性能的提升,当Ti+C含量为15%时,具有最优的摩擦磨损性能。HU等^[22]在304上熔覆不同WC含量的镍基合金熔覆层,图2所示为不同WC含量的磨损机理示意。由图2可知,WC的添加抑制了枝晶长大,溶解产生的W和C元素固溶并促进增强相的生成,在第二相强化、固溶强化和细晶强化的综合作用下,随着WC含量的提升,摩擦磨损性能呈线性关系得到提升。LIU等^[23]研究了在Ni50涂层中添加WC陶瓷颗粒增强镍基合金熔覆层的摩擦磨损性能,WC的添加有助于熔覆层微观组织的细化,显微硬度得到提高,残存的WC镶嵌在熔覆层中,可有效提升熔覆层的摩擦磨损性能,当WC添加量为20%时具有最优的摩擦磨损性能。ZHAO等^[24]以不同比例的TiC-TiN-B4C作为增强相添加在Ni204中制备熔覆层,添加10%TiC-10%TiN-10%B4C的镍基合金熔覆层,具有最高的显微硬度,最低的摩擦系数,在陶瓷相和其促进生成的增强相的共同作用下,熔覆层摩擦磨损性能得到增强。NING等^[25]通过有限元仿真分析发现Inconel 625/SiC熔覆层与基体结合处,出现应力集中,影响熔覆层的成形质量,通过进行试验对熔覆层性能进一步分析,试验表明,随着SiC含量的增加,熔覆层残余应力呈现先减后增的趋势,微观组织得到了细化,碳化物析出变多,对熔覆层硬度和摩擦磨损性能的提高具有积极作用。原位合成碳化物相比于直接添加,有利于减少陶瓷相与基体粉末之间的热物性能差距,提升陶瓷相在熔覆层中的结合强度,但陶瓷相不同的引入方式仍不可避免的带来裂纹等内部缺陷,从而影响熔覆层耐磨性的进一步提升。

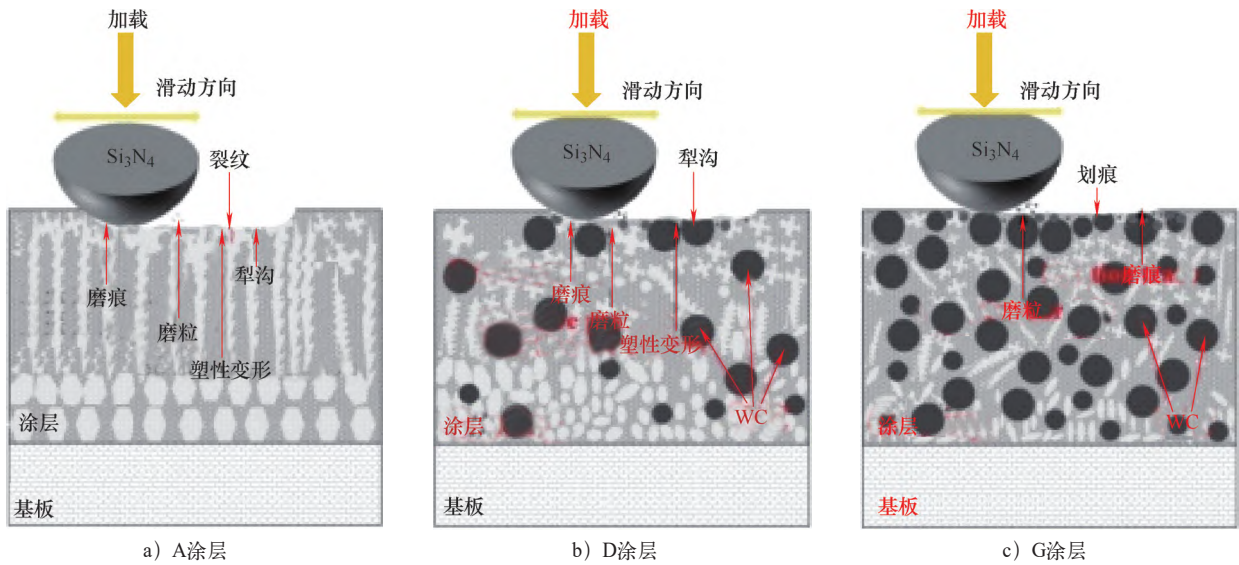


图2 Ni/WC复合涂层的磨损机理^[22]

注：柱状晶 等轴晶 胞晶

4 稀土添加对熔覆层摩擦磨损性能的影响

稀土元素的添加可通过细化晶粒，净化组织、促进硬质相析出、产生固溶强化等提升镍基合金熔覆层的成形质量和摩擦磨损性能。SHI等^[26]通过在65Mn钢表面Ni60A/SiC熔覆层中添加稀土氧化物 La_2O_3 来进一步改善熔覆层的性能， La_2O_3 的加入促进了熔池的流动，促进了硬质相的生成，使元素和硬质相分布更加均匀，细化了熔覆层组织晶粒，使

Ni60A/SiC熔覆层硬度和摩擦磨损性能得到进一步的提升。ZHANG等^[27]通过添加 CeO_2 对Ni60/WC熔覆层性能进行改善， CeO_2 的添加减少了熔覆层的内部缺陷，晶粒尺寸得到细化，促进了组织和元素的均匀分布，当 CeO_2 含量为2%时硬度和摩擦磨损性能达到最优。LIANG等^[28]在Ni60中添加4% CeO_2 、5% Y_2O_3 和5% La_2O_3 制备熔覆层与Ni60对比，如图3所示，稀土改性熔覆层气孔和裂纹含量下降，韧

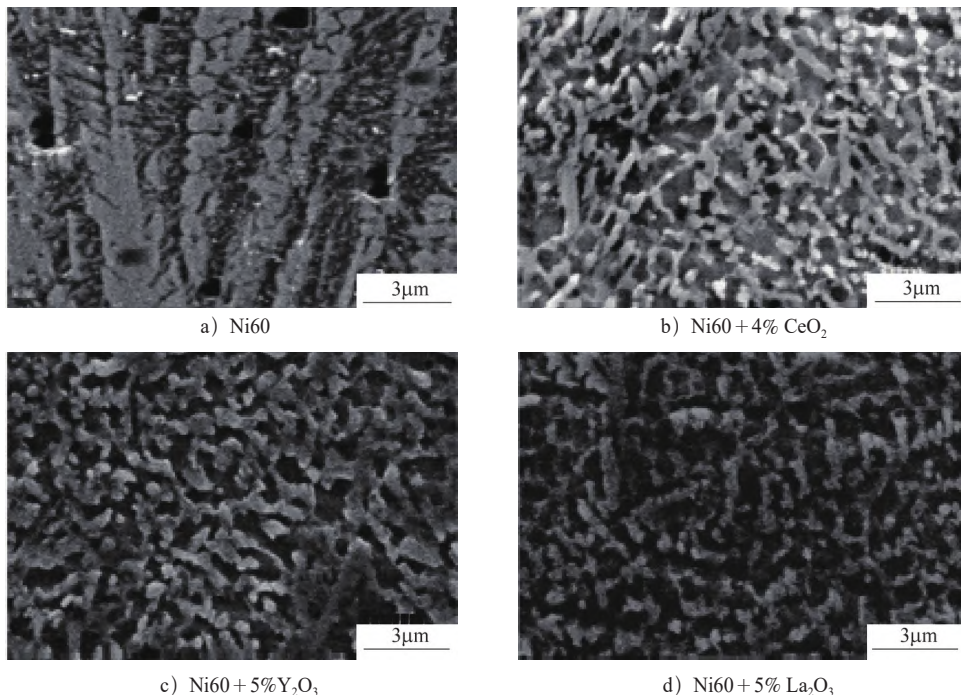


图3 上部强化层的SEM形貌^[28]

性提高,晶粒得到细化,元素分布均匀,有利于摩擦磨损性能的提升。SU等^[29]在60Si2Mn表面Ni60A/Cr₂C₃熔覆层中添加不同含量Y₂O₃,探究稀土氧化物对熔覆层性能的影响,随着Y₂O₃的添加,Ni60A/Cr₂C₃熔覆层裂纹和孔隙等内部缺陷得到有效减少,熔覆层和基体具有更好的冶金结合,提高熔覆层的韧性,使复合涂层不易脱落,促进了硬质相的析出和均匀分布,当Y₂O₃添加量为1.5%时(见图4中M5样品),具有最低摩擦系数,摩擦系数曲线更加平滑,磨损量低,表现出最优的综合摩擦磨损性能。

GAO等^[30]通过添加不同含量La₂O₃来改善Ni60熔覆层的性能,随着La₂O₃的添加,熔覆层表面裂纹减少,XRD衍射峰产生偏移,产生晶格畸变,熔覆层中硬质相析出减少,显微硬度降低,但元素组织分布更加均匀,当La₂O₃含量为1.6%时,硬度曲线最为平缓,具有最低的摩擦系数,磨损深度最低,相比于Ni60熔覆层展现出优异的摩擦磨损性能。稀土元素的添加对物相的组成无显著改变,提升熔池的对流作用,通过吸附夹杂物净化组织,细化晶粒来提升熔覆层的耐磨性能。

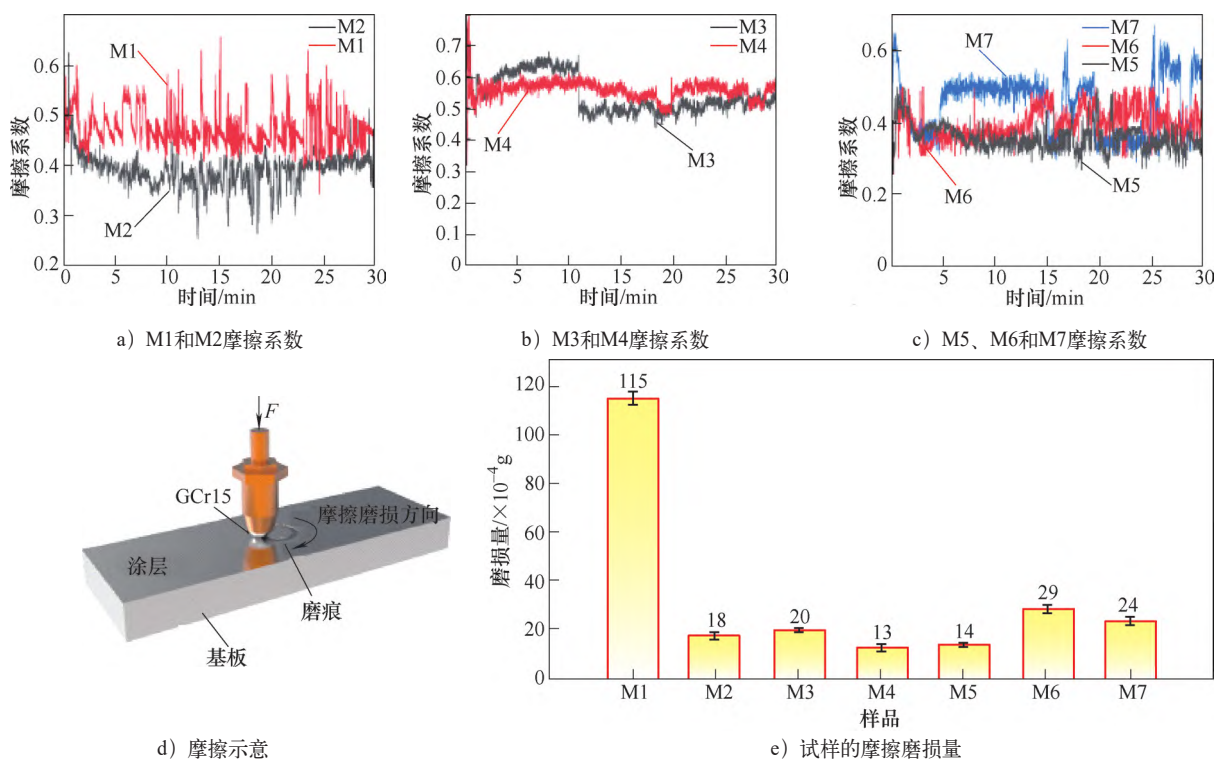


图4 试样的摩擦磨损性能^[29]

5 自润滑相添加对熔覆层摩擦磨损性能的影响

在镍基合金熔覆层中添加固体润滑剂h-BN、石墨、WS₂等,可通过在摩擦过程中减少摩擦过程中的摩擦系数,提升熔覆层的摩擦磨损性能。LUO等^[31]对激光熔覆制备Ni60/CNTs与Ni60作对比(见图5),CNTs在高能激光束的作用下分解,生成的C元素与Ni60中其他元素形成的碳化物,使Ni60/CNTs熔覆层硬度得到提高,CNTs具有良好的自润滑性能,且细化了晶粒尺寸,与碳化物协同作用,使Ni60/CNTs熔覆层摩擦磨损性能得到提高。ZHAO等^[32]制备h-BN/Ni60和Nano-Cu/h-BN/Ni60两种自

润滑熔覆层与Ni60对比,固体润滑剂的添加,使自润滑熔覆层在25~600℃下发生高温软化,显微硬度均低于Ni60熔覆层,h-BN具有优良润滑性能,Cu包h-BN可减少熔覆过程中高能激光束对h-BN的烧损,Cu具有一定的润滑效能,高温可生成CuO固体润滑剂,与h-BN共同作用,使熔覆层在25~600℃下摩擦系数得到明显下降,提升熔覆层的摩擦磨损性能。ZHANG等^[33]探究了不同含量NbC对Ni60/NbC熔覆层性能的影响,在最优NbC含量熔覆层的基础上,通过添加固体润滑剂石墨烯来进一步提升熔覆层的质量,当石墨烯添加量为10%时,熔覆层

与基体呈现良好的冶金结合,未发现明显裂纹和孔洞,石墨烯提高了熔覆层中C元素含量,促进了硬质相的析出,石墨烯的高导热性提高了熔池的流动性,细小NbC颗粒熔化重新凝结形成花瓣和棒状大颗粒,和熔覆层其他硬质相共同作用抑制了晶粒的生长,提高了熔覆层的显微硬度,有利于熔覆层摩擦磨损性能的提升。FENG等^[34]制备NiCrBSi、单层NiCrBSi-30%WS₂,双层NiCrBSi-30%WS₂三种熔覆层,WS₂的添加,使熔覆层硬度得到下降,但在摩擦过程中形成硫化物润滑膜,有效减少了摩擦系数,摩擦磨损性能得到提升,双层NiCrBSi-30%WS₂具有最优的摩擦磨损性能。固体润滑剂的添加可均匀分布于熔覆层中,在摩擦磨损中起润滑介质作用,也形成润滑保护膜以减少摩擦过程中的磨损减少,激光熔覆过程中固体润滑剂受热分解,一方面分解后元素与熔覆层一系列反应有助于性能的提升,另一方面导致润滑相含量的减少,可通过在固体润滑相表面镀Ni、Cu等减少和激光的直接接触进而减少润滑相的损失,因此在高温条件下自润滑性能有待进一步研究。

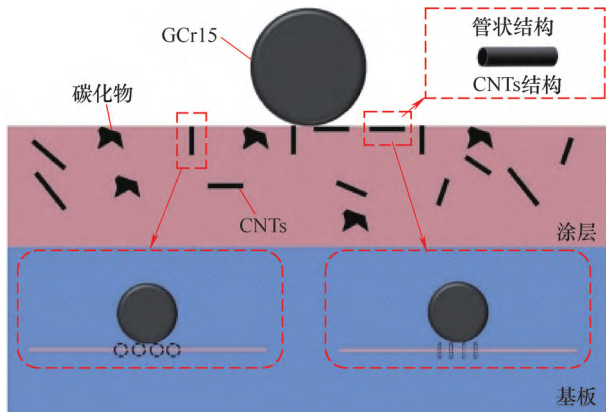


图5 Ni60/CNTs 涂层磨损机理^[31]

6 结束语

对于镍基合金熔覆层成分调控,通过添加稀土、自润滑相、元素、陶瓷相来改善熔覆层摩擦磨损性能,但当前镍基合金体系不够丰富,集中于常见的添加物,未来可进一步拓展不同添加物质的研究范围。对金属零部件表面激光熔覆镍基合金熔覆层局限于零部件形状,金属基体形状多为平面或圆轴基体,缺乏对于曲面、弧形等不规则形状表面镍基合金熔覆层摩擦磨损性能的研究,且对于镍基涂

层摩擦磨损性能应用环境的研究,多集中于干摩擦方面,实际镍基合金耐磨熔覆层,应用在更为恶劣复杂的环境中,缺乏对于高温高压环境,强酸腐蚀等极端环境下的摩擦磨损性能研究,且研究成果转换率低。不同的物质添加对镍基涂层的摩擦磨损性能的影响具有差异性,当前对各类常见镍基合金熔覆层体系摩擦磨损性能的提升具有大量的研究,但缺乏相应的数据库和相关软件对其进行归纳总结,为激光熔覆镍基合金的进一步研究和实际工业修复使用提供方便的查询支持,从而进一步推动镍基合金熔覆层的标准化进程。

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