

激光熔覆在高速列车上的应用研究现状

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摘要: 高速列车轮轨、制动盘、车轴是易发生磨损的部件, 采用激光熔覆技术能有效改善磨损或对损伤部件进行修复。综述了激光熔覆应用于高速列车轮轨、制动盘、车轴的研究现状。归纳了现有研究中各部件所采用的熔覆材料。总结了不同部件所关注的性能, 针对不同部件的特性, 分析了其对激光熔覆层性能的需求和应采用的熔覆层性能测试方法。对于列车轮轨, 旨在通过激光熔覆涂层提高其接触面抗磨损和抗滚动接触疲劳性能; 对于制动盘, 旨在通过涂层减小其摩擦磨损和热疲劳; 对于车轴可采用激光熔覆技术对已损伤的部位进行修复, 并应重点关注车轴修复后的疲劳性能。此外, 提出了激光熔覆实际应用于高速列车部件上现存的几个关键问题, 包括: 激光熔覆热影响区组织对部件服役性能的影响; 激光熔覆残余应力的影响; 激光熔覆低效率和高稀释率的问题; 激光熔覆组件热损伤问题。目前的研究主要集中于激光熔覆材料的选择和性能评价, 而从组织演变、残余应力及服役性能三者综合考虑的轨道交通理论基础有待构建。

关键词: 激光熔覆; 高速列车; 熔覆材料; 残余应力; 服役性能

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Application Status of Laser Cladding in High-speed Trains

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ABSTRACT: The components of high-speed trains, such as wheels, rails, brake discs, and axles, are prone to wear. Laser cladding is an effective way to reduce wear and repair damaged parts. The application status of laser cladding in such components was reviewed. The cladding materials used for various components in the current study were summarized. The performance of different components was summarized. According to the characteristics of different components, the requirements of components for laser cladding performance and the testing methods of cladding performance were analyzed. As for wheels and rails, the cladding layer aimed to improve the wear resistance and anti-rolling contact fatigue performance of the contact surface. As for brake discs, the cladding layer aimed to reduce friction, wear and thermal fatigue. Finally, laser cladding was used to repair the damaged parts of the axle, and the fatigue performance of the repaired axle was emphasized. Several key issues of the practical application of laser cladding in high-speed train components were put forward, including effect of heat-affected zone on the service performance of components, effect of residual stress, low efficiency and high dilution rate of laser cladding and thermal damage of laser clad components. The current research mainly focuses on the material selection

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and performance testing of the cladding layer. The theoretical basis for each component considering the structure evolution, residual stress and service performance needs to be established.

KEY WORDS: laser cladding; high-speed trains; cladding materials; residual stress; service performance

近年来,世界范围内的轨道交通产业发展迅速。至 2018 年,高速列车已在 16 个国家和地区运营,在全球范围内的轨道长度超过 40 000 公里,已经成为各地区之间沟通的重要纽带^[1-2]。列车在行驶过程中,钢轨和列车零部件难免发生磨损失效,如最为常见的车轮与钢轨之间的磨损^[3]、制动盘在制动过程中的磨损^[4]以及车轴的磨损^[5]。如何利用表面技术保护或提升钢轨及零部件性能,以减小磨损,或对已损零部件进行修复再制造,是当前轨道交通领域值得研究的问题。

激光熔覆技术是 20 世纪 70 年代随大功率激光器的发展而兴起的表面技术,其原理为利用激光辐照使被熔覆的基材表面薄层和加入的涂层材料一同熔化,并快速凝固,使涂层材料与基体表面形成牢固的冶金结合^[6]。激光熔覆的特点主要包括熔覆层组织致密、晶粒细小、与基体结合强度高、稀释率低、对基体的热输入量低、热影响区面积小等^[7-8]。当前可用于激光熔覆的材料体系主要包括自熔合金(Fe 基、Co 基、Ni 基、Cu 基等)^[9-12]、陶瓷材料^[13]和复合材料^[14]。

激光熔覆技术主要应用于功能涂层制备以及零部件的再制造和直接成形。通过在零件表面制备涂层,使零件具有耐磨、耐蚀等性能^[15]。利用该技术,一方面可对表面受损的零部件进行修复^[16],另一方面还可使材料或零部件直接成形^[17]。由于激光熔覆技术相较于传统用于轨道交通的表面技术(堆焊、电镀、热喷涂等),具有稀释率、熔覆层孔隙率低、与基体结合强度高等优点^[18],早在 20 世纪 90 年代,Olofsson^[19]提出激光熔覆技术是解决车轮面临列车提速和轴重增加的问题的潜力技术手段。近年来,我国高速列车从以快速制造为主,逐步转变为以维修为主(大修期),激光熔覆技术引起了轨道交通领域的关注,相关研究及应用日益增多。本文将对激光熔覆技术在轨道交通领域的研究现状进行归纳及总结。

1 轮轨激光熔覆材料及性能

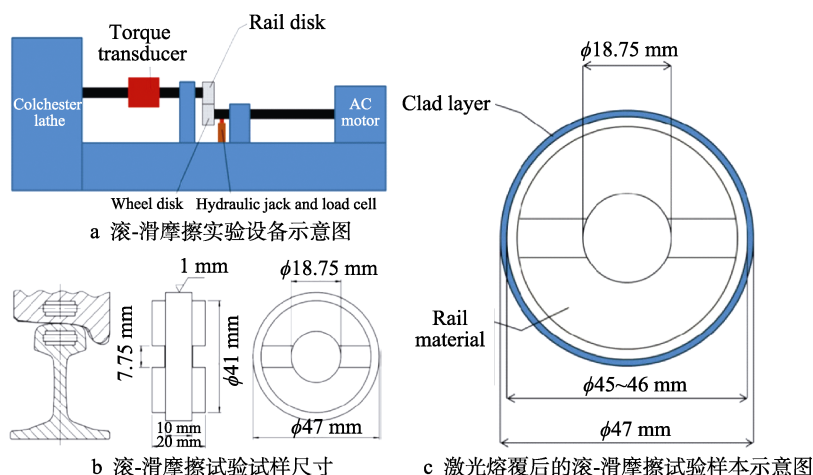
轮轨接触面磨损和滚动接触疲劳(RCF)是影响列车车轮和轨道寿命的两个最重要的因素,直接影响列车的动力学、行驶安全和维修,是轨道交通领域一直致力解决的问题^[20-21]。激光熔覆技术可用于修复受损轮轨表面,也可在车轮踏面和轮缘表面制备涂层,以减小磨损和改善抗 RCF 性能。目前,针对轮轨激光熔覆的研究已有较多的文献报道。

目前车轮所使用的材料多为中碳低合金钢,钢轨大多为高碳低合金钢^[22-23]。对于车轮和钢轨,已有的

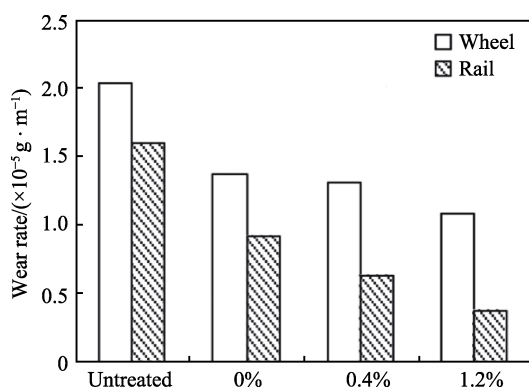
研究表明,自熔性合金粉末是最常被使用的熔覆材料。考虑到熔覆材料与钢基体的亲和力(其中 Fe 基合金粉末最为常用,如 316、410、420 不锈钢都已被用作轮轨的激光熔覆材料),为进一步提高熔覆层的硬度和耐磨性,Cr、Co 等合金粉末也常被添加于 Fe 基合金粉末中^[24]。优质的陶瓷材料也可被用于钢轨的激光熔覆。Aladesanmi 等^[25]使用 Ti+TiB₂ 复合陶瓷粉末在钢轨表面进行了激光熔覆,并对比了不同 Ti 和 TiB₂ 配比下涂层的变化。研究发现,在 Ti 和 TiB₂ 质量配比为 1:1 时,涂层的硬度和显微组织最佳。

评价轮轨表面激光熔覆层性能时,为了更接近列车行驶时轮轨之间的实际摩擦情况,常用滚-滑摩擦试验装置(图 1)来评定熔覆层的使用效果,例如 Lewis 等^[26]采用了此试验装置进行测试。在对轮轨熔覆层进行可靠性评价中,耐磨性能和抗 RFC 性能是两个重要的评价指标。耐磨性能常用试样试验过程中的失重率/磨损率来表征,通过涡流裂纹检测器可监测试验中疲劳裂纹的产生。Lewis 等^[27]在标准 R260 钢轨材料表面熔覆了六种不同材料的涂层,包括多相锰钢变体(MMV)、马氏体不锈钢(MSS)、TWIP 钢、NiCrBSi 合金、Stellite 12 和 Stellite 6,并对熔覆层的性能进行了测试和评价。与未经过熔覆的钢轨相比,涂覆 MSS、Stellite 12 和 Stellite 6 涂层的质量磨损率减小,并且对偶车轮钢的磨损率也降低。其中 MSS 和 Stellite 12 使磨损率减小了 50%,但二者的涂层都表现出较高的孔隙率。Stellite 6 使磨损率降低了 70%,并且涂层中基本未见孔隙。此外,在试验中,所有样品均未产生 RFC 裂纹,比基体表现出更好的抗 RFC 性能。Fu 等^[28]在车轮和车轴材料上分别熔覆了 Fe 基合金涂层,关注了氧化镧对激光熔覆层性能的影响,通过轮轨材料的对磨来测试涂层的性能。发现氧化镧的加入能够使涂层的显微组织细化,大大减轻了轮轨表面的磨损,磨损率与氧化镧含量的关系如图 2 所示。相较于无熔覆层轮轨磨损,由于所制备的激光熔覆层一般具有较高的强度和硬度,磨损形式会由粘着磨损+剥层磨损向犁削磨损+剥层磨损转变^[29]。

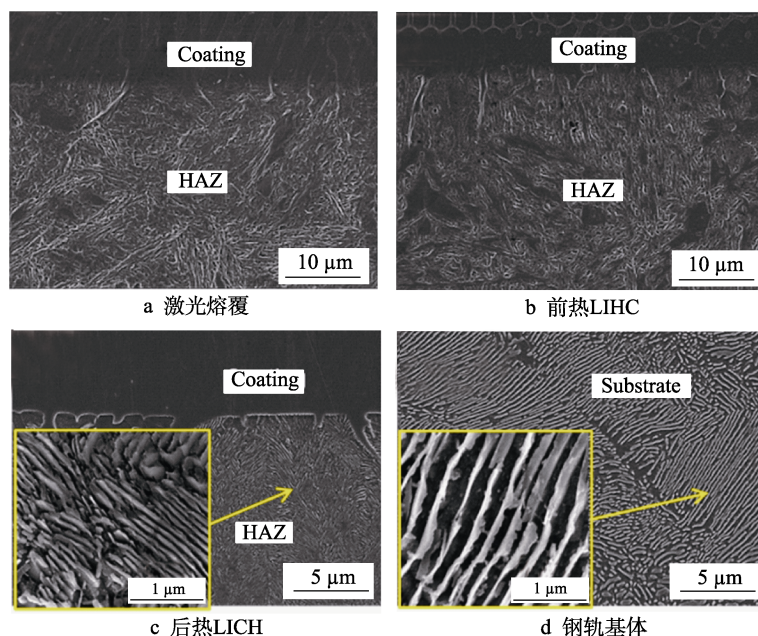
传统的激光熔覆技术在钢轨的应用上存在两大障碍:一是如何避免激光快速加热和冷却作用下熔覆层的开裂;二是如何消除热影响区中高硬度、低韧性的马氏体组织^[30]。有学者对此进行了有针对性的研究。Li 等^[30]尝试采用新型激光-感应复合熔覆(LIHC)技术解决修复钢轨中遇到的此类问题。他们分别采用传统激光熔覆、前热 LIHC 技术、后热 LIHC 技术进行了试验。结果表明,后热 LIHC 技术能有效地防止

图1 模拟实际轮轨摩擦试验装置及试样图^[26]Fig.1 Simulated actual wheel-rail friction equipment and sample dimensions^[26]:

a) schematic diagram of rolling-sliding friction test equipment; b) dimensions of rolling-sliding friction test sample; c) schematic diagram of rolling-sliding friction test sample after laser cladding

图2 基体和不同氧化镧含量的车轮/轨道涂层的磨损率^[28]Fig.2 Wear rates of the substrate and the wheel/rail coatings with different lanthanum contents^[28]

热影响区的开裂和马氏体相变的发生。采取后热 LICH 时, 热影响区在 500~800 °C 间的转变过程近似等温转变过程, 冷却速度满足获得单一珠光体组织的条件。如图 3 所示, 采用后热 LICH 技术的热影响区组织为珠光体组织, 且基本不改变熔覆层的组织特征和性能。Lai 等^[31-32]在研究中发现, 350 °C 预热能有效抑制激光熔覆过共析钢钢轨热影响区马氏体的形成, 而采用熔覆后加热和缓冷的方法会导致 410L 不锈钢熔覆层的软化。此外, 对于钢轨的激光熔覆工艺, 还探究了不同熔覆方向对熔覆层的影响。由于冷却速率和基体稀释的作用, 熔覆方向会显著影响熔覆层的组织特征, 沿着钢轨的纵向进行熔覆, 可使熔覆层具有更好的力学性能。

图3 不同覆层工艺单道熔覆试样热影响区微观组织及基体微观组织^[30]Fig.3 Microstructures of the HAZs in the single-track samples by different cladding ways and the rail substrate^[30]: a) laser cladding; b) pre-LIHC; c) post-LIHC; d) rail substrate

激光熔覆的残余应力是学者关注的问题之一, 激光熔覆的内应力可能会导致熔覆层的开裂和构件变形^[33]。Narayanan 等^[34]针对 UIC 900A/grade 260 钢轨激光熔覆马氏体不锈钢涂层后的残余应力进行了测量, 结果显示熔覆层和结合区处的残余应力为压应力, 基体处的残余应力为拉应力, 并指出结合区的三

轴残余压应力可能会导致涂层-基体的分离。此外, 还探究了钢轨受循环四点弯曲载荷和磨损后的残余应力变化, 如图 4 所示, 研究发现残余应力会因载荷而重新分布, 但在 10 次左右循环后便会达到稳定, 并且磨损只会对试样表面的残余应力产生影响。

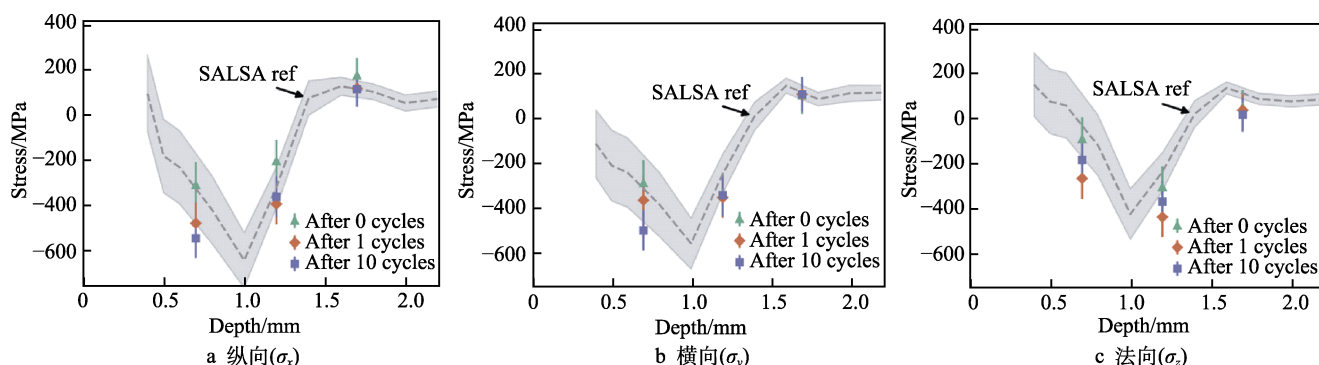


图 4 四点弯曲试验对熔覆钢轨残余应力的影响^[34]

Fig.4 Effect of applying 4-point bending on the residual stresses in the cladding rail: a) longitudinal direction (σ_x); b) transverse direction (σ_y); c) normal direction (σ_z)^[34]

目前针对轮轨激光熔覆的研究已相对全面, 但高速列车轮轨附加值相对较低。考虑到激光熔覆的成本和效率问题, 相比于在表面制备涂层, 对受损的轮轨进行修复是更为高效和经济的手段。此外, 如何有效地改善熔覆后轮轨内部残余应力场, 以提升轮轨服役安全性, 是值得探究的问题。

2 制动盘激光熔覆材料现状

列车的制动盘在制动过程中需要把动能转化为热能, 除受到剧烈的摩擦外, 还会经历温度急剧升高和迅速下降的过程, 摩擦磨损失效和热疲劳失效是制动盘最主要的两种失效形式^[35], 因此在测试制动盘熔覆层性能时, 应考虑高温的影响。制动盘材料常采用低碳或中碳合金钢。目前对于制动盘激光熔覆的研究主要集中在材料匹配上。在常用的自熔合金中, Ni 基合金和 Co 基合金相较于 Fe 基具有更好的耐热性。为保证制动盘的高强度和高硬度, 以及良好的耐高温性能, 所选用的制动盘激光熔覆材料一般为含 Cr 较多的 Ni 基或 Co 基合金粉末。Liu 等^[36]采用激光熔覆技术在制动盘材料 30CrNiMo 表面制备了 Co06 涂层, 并在室温及 200、400、600 °C 的条件下进行了摩擦磨损试验, 以测试涂层耐磨性能。测试结果如图 5 所示, 涂层的耐磨性明显优于基体, 且当温度升高时, 涂层和基体的磨损形式都会发生改变。在室温下, 基体的磨损机制以磨粒磨损为主; 200、400、600 °C 的磨损机制以粘着磨损为主。对于 Co06 涂层, 在室温和 200 °C 时以磨粒磨损为主, 200 °C 时会发生轻微的粘着磨损, 而 400、600 °C 时则以粘着磨损为主。王玉乔等^[37]为避免涂层与基体间硬度差距过大而发生开裂, 向 Ni 基自熔合金粉末之中加入 V、Ti、B、Si 等微量合金元

素, 以对熔覆粉末进行优化。研究表明, Ti 相较于 V 有更优异的细化晶粒效果, 最佳的添加量为 1%, B 和 Si 的最优添加量分别为 3.5% 和 4.5%。陶瓷材料由于耐热性好、强度高和硬度高的特点, 可作为增强相加入制动盘表面涂层中, 以进一步提高涂层的性能。赵龙志等^[38]在 45# 钢表面采用激光熔覆技术制备了不同 SiC 含量的 SiC/Ni60A 复合涂层, 以探究碳化硅含量对涂层性能的影响。结果表明, SiC 能细化涂层的晶粒, 且当 SiC 含量为 20% 时, 涂层具有最高的硬度 (1039.9HV_{0.2}) 和最佳的耐磨性能, 磨损量仅为基体的 1/36.3。但当 SiC 含量达到 25% 时, 会存在 SiC 颗粒过剩, 并在磨损的过程中剥落, 使涂层耐磨性能下降, 如图 6 所示。此外, 高熵合金具有优异的耐磨性和耐蚀性^[39], 同样适用于制动盘熔覆材料。曹振飞^[40]采用 CrMnFeCoNi 高熵合金粉末对制动盘进行激光熔覆修复, 熔覆层磨损量较基体减小了 24.7%, 且具有更优秀的耐蚀性能。

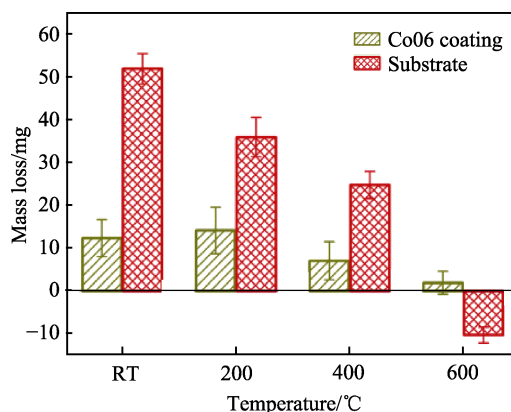
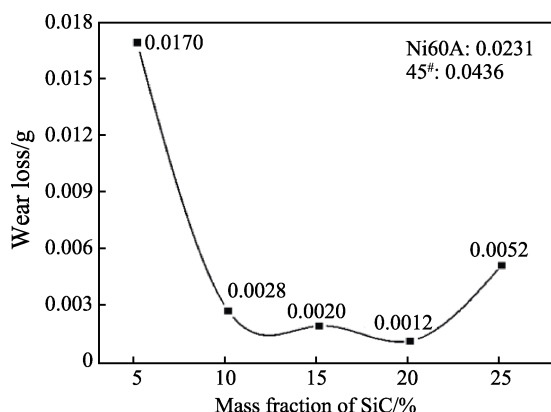


图 5 不同温度下 Co60 涂层和基体的磨损量^[36]

Fig.5 Wear loss of Co60 coating and substrate at different temperature^[36]

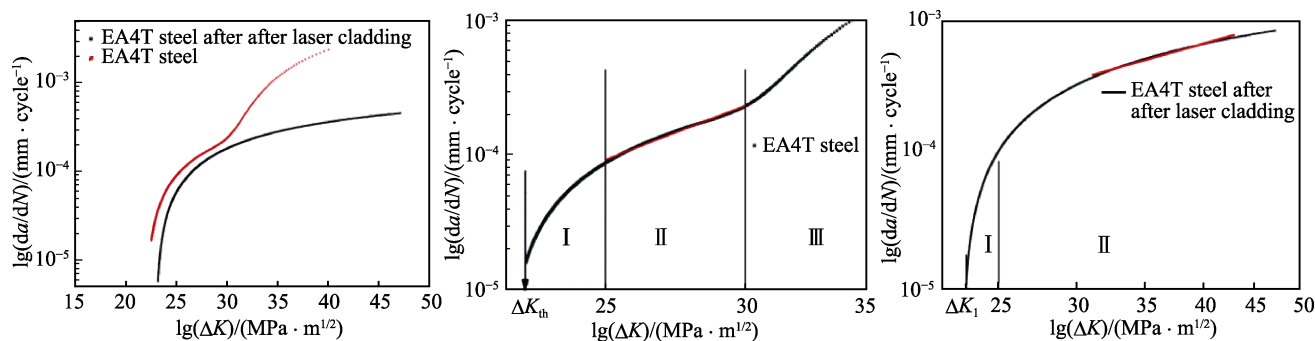
图6 不同SiC含量下涂层的磨损性能^[38]Fig.6 Wear resistance of laser cladding layer with different SiC contents^[38]

目前,对于制动盘激光熔覆涂层的研究主要集中在材料优化方面,且性能测试基本采用传统的室温或高温摩擦磨损试验。而在实际制动过程中,制动盘温度迅速变化的影响考虑尚不充分,更接近于实际制动情况的涂层的性能有待进一步的研究。

3 车轴激光熔覆材料及组织调控现状

高速列车的车轴作为非常重要的部件,其造价昂贵。在服役、组装、退卸或检修过程中,车轴与轮座、集电环座、齿轮座等配合部位易发生划伤、磕碰和微动磨损等^[41]。目前对于划伤深度小于0.1 mm的车轴,

采用打磨的方式进行修复。而对于划伤深度大于0.1 mm的车轴,则对其进行封存处理,待技术成熟时再对其进行修复^[42]。激光熔覆技术被认为是一种前景较好的车轴修复方法。车轴材料多选用优质的碳素结构钢或合金结构钢^[43]。目前对于车轴修复所选用的激光熔覆材料基本为Fe基或Ni基合金粉末,为保证熔覆层强度,常在粉末中加入Cr或陶瓷材料^[44-46]。在熔覆粉末中加入La和Ce等稀土元素可与O、C、S元素等形成稀土夹杂物,作为非均质形核质点,起到细化熔覆层晶粒的作用^[47]。由于车轴受力状态复杂且受循环载荷作用,在对车轴熔覆层进行性能测试时,除强度、韧性等性能外,抗疲劳性能也是一个非常重要的指标。Chen等^[48]采用kf311铁基合金粉末在EA4T车轴钢基体上进行了熔覆,熔覆层的硬度高于基体。采用三点弯曲试验测试了基体和熔覆试样的疲劳裂纹扩展速率。如图7所示,基体试样的疲劳裂纹扩展速率高于带有熔覆层的试样,说明激光熔覆提高了EA4T钢的疲劳寿命。Kang等^[49]在熔覆42CrMo钢时,提出了向NiCrBSi合金粉末中加入负热膨胀系数材料 ZrW_2O_8 的方法,来解决涂层与基体间热膨胀系数不匹配导致的熔覆层易开裂的问题,使裂纹得到了有效的控制。陈林等^[50]在对EA4T车轴钢进行熔覆时引入了超声振动,将原本方向性明显的枝晶打碎,降低了枝晶的偏析程度。此外,超声振动还可细化熔覆层晶粒,在不改变熔覆层的物相组成情况下,使熔覆层硬度分布更为均匀。

图7 EA4T钢熔覆前后的裂纹扩展速率与应力强度因子之间的关系^[48]Fig.7 Relationship between crack propagation rate and stress intensity factor for EA4T steel and laser clad EA4T steel^[48]

车轴用钢对于材料的各项性能要求较高。Huang等^[51]提出了采用激光固态成形技术(LSF)和淬火-回火(QT)工艺制备高强度、高韧性的34CrNiMo6钢的方法。LSF材料的组织由铁素体和细小碳化物组成,热处理后,组织转变为回火索氏体。试样的抗拉强度、屈服强度、断面收缩率和延伸率分别为980 MPa、916 MPa、58.9%和13.9%,均高于锻造标准,且屈服强度相较锻造试样提高了27%。

对于激光熔覆用于车轴的修复,目前的研究手段基本是在车轴材料表面制备熔覆层,并进行性能的测试,而在实际的修复应用中,往往需要对车轴缺口进行填补。车轴服役时所受载荷复杂,缺口经过激光熔

覆修复后,车轴上载荷和应力的分布情况以及实际的疲劳性能值得引起关注,有待通过数值模拟与实验相结合的方法对其进行进一步研究和分析。

4 激光熔覆应用于高速列车可能的几个关键问题

尽管当前学术界成果^[52-54]逐步支撑激光熔覆是具有较好潜力的修复及性能提升技术方法这一结论,但有关激光熔覆实际用于轨道交通轮轨、车轴、制动盘等部件的性能提升和修复再制造还未见报道。这可能的主要原因在于激光热源对原始基体的热影响,正

如行话所说的“下火”问题仍存在疑虑,且轨道交通对安全性要求较高,必须要求实施台架试验或实车试验,但这一系列试验费用昂贵,需要得到国家大力扶持,才能将科学研究结果落地实际应用。

4.1 热影响区 (HAZ) 组织及对服役性能的影响

所谓的“下火”问题主要为激光熔覆热影响区 (HAZ) 的马氏体转变。基体中的马氏体组织具有低的塑性和断裂韧性,因而多年来被各国铁路标准协会所禁止 (如美国铁路工程和道路维护协会、欧洲铁路标准和中国铁路标准协会^[55-57])。此外, Lai 等^[31]还指出,除了 HAZ 区的脆性行为,存在于此区的残余拉应力也可能是激光熔覆钢轨早期失效的原因。因此,对于轨道交通而言,对 HAZ 组织、应力及其整体性的相关研究显得尤为重要。Niederhauser 等^[58]通过对钢轨材料 Co-Cr 激光熔覆层的拉-压疲劳 ($R=-1$) 性能进行研究,发现疲劳裂纹源从 B82 车轮钢基体萌生,在 HAZ 处停止,在 HAZ 处未见规则裂纹。针对具有不同厚度和硬度的两种熔覆层,因两者的 HAZ 厚度和硬度相差不大,导致疲劳性能相差不大,因此作者提出 HAZ 是影响激光熔覆钢板疲劳性能的关键因素。Lewis 等^[59]对钢轨激光熔覆 stellite 6 熔覆层的

四点弯曲疲劳断口的研究表明,裂纹起裂于熔覆层中的夹杂和熔覆层与 HAZ 区的界面,并向基体扩展。作者提出脆性特征的 HAZ 区可能不足以抵抗此区承受的高疲劳强度而成为裂纹源。对于激光熔覆层的轴向静拉伸性能而言,熔覆试样是以脆断形式发生失效,且裂纹起源于熔覆层,向 HAZ 和基体扩展^[60]。

近年来,研究者借助各类技术与激光熔覆技术复合,以改变 HAZ 马氏体组织。如 Lai 等^[32]在钢轨激光熔覆前,通过氧焊枪预热钢轨避免了马氏体转变。前述文献^[30]中,采用感应后热处理,在 HAZ 区获得了间距更小的珠光体组织。HAZ 的轴向拉伸通过韧性断裂形式提升了试样拉伸性能。

4.2 激光熔覆对残余应力的影响

激光熔覆过程中不可避免产生残余应力,而残余应力对激光熔覆部件服役性能有较大影响。Lewis 等^[59]采用激光熔覆在 R260 钢轨上熔覆马氏体不锈钢,其四点弯曲疲劳性能远远优于熔覆的 stellite 6,达到了 NR/SP/TRK111 要求疲劳强度超过 230 MPa 的标准。作者认为马氏体不锈钢熔覆层的残余压应力 (stellite 6 为残余拉应力) 是其获得与基体同等疲劳强度的原因。ROY 等^[61]采用中子衍射法测试了激光熔覆重载钢轨残余应力分布,如图 8 所示。激光熔覆 410L 钢

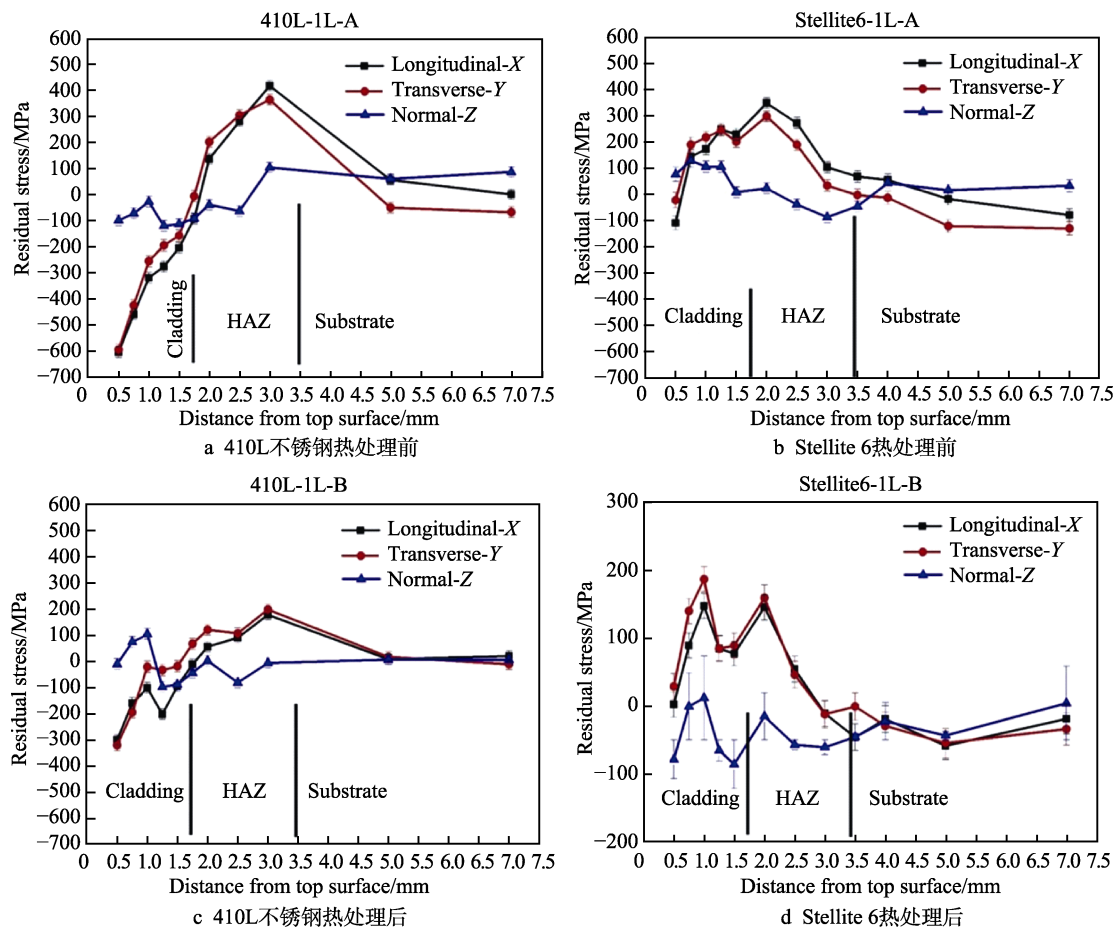


图 8 钢轨激光熔覆不同材料后的残余应力分布^[61]

Fig.8 Residual stress distribution of rail after laser cladding with different materials^[61]: a) 410L stainless steel before heat treatment; b) stellite 6 before heat treatment; c) 410L stainless steel after heat treatment; d) stellite 6 after heat treatment

轨在XYZ方向均为残余压应力,HAZ区为残余拉应力,最大残余拉应力位于距离熔覆层表面3mm处,约为413MPa。而激光熔覆stellite 6的熔覆层和HAZ均表现为残余拉应力,最大残余应力位于距离熔覆层上表面2mm处,约为379MPa。覆层后热处理是一种有效提高激光熔覆组件材料完整性的方法。Roy等^[62]指出覆层后热处理有效改善了激光熔覆钢轨的滚动接触疲劳行为。后热处理对熔覆钢轨的影响因材料而异,如图8c、d所示,410L激光熔覆层经后热处理后,残余应力降低,熔覆层最大压应力降为约319MPa,HAZ最大拉应力降为195MPa。Stellite 6熔覆层后热处理后,熔覆层以拉应力为主,HAZ是拉应力和压应力混合,且残余压应力在熔覆层/HAZ和HAZ/基体界面表现明显。一般而言,高的残余压应力有利于提高轮轨的滚动接触疲劳,但熔覆层高的残余压应力需要HAZ/基体拉应力的平衡,因而熔覆后处理可用于降低应力水平,提升轮轨熔覆组件的综合性能。

4.3 激光熔覆低效率及高稀释率问题

常规激光熔覆一般采用的线速度为0.3~1.8m/min,激光能量主要作用在基体上,熔池较大,粉末颗粒的熔化主要靠熔池提供热量,熔覆层具有熔深较大、熔宽较宽的特点。而轨道交通零部件尺寸较大,采用传统激光熔覆技术面临效率低等问题。近年来,德国弗朗恩霍夫激光技术研究所^[63]发明了一种超高速激光熔覆技术,其熔覆速度可达25~200m/min,加工过程中激光聚焦于工件上方,使能量大部分作用于工件上方的粉末上。采用这种技术进行熔覆时,基体的热输入虽然极小,但却能保证粉末与基体发生充分的冶金结合,涂层的稀释率一般仅为2%~4%^[64]。高速激光熔覆可有效提高零部件的熔覆效率,在轨道交通领域拥有良好潜力。

4.4 激光熔覆组件热损伤问题

廖文和等^[65]总结当前关于热损伤的研究发现,机械制造领域的热损伤一般是将其视为材料出现了非连续性破坏(孔洞的产生、微裂纹的形成等),导致热应力产生,材料局部发生均匀性变化(HAZ形成)。激光熔覆引入的残余应力和熔覆材料本身的脆性可能是热损伤的源头,一般体现在静拉伸强度起裂于熔覆层,而疲劳破坏多发生在熔覆层与基体衔接部分。激光熔覆引入的材料非连续性也属于热损伤范围。廖文和等^[65]在总结前期研究基础上,基于非连续性、显微硬度、残余应力损伤因子,提出热损伤程度量化评定综合模型。对于特定轨道交通部件,其性能评价各有侧重。例如,轮轨主要是磨损及滚动接触疲劳,制动盘主要为磨损及热疲劳,而车轴主要为旋转弯曲疲劳。因而未来的工作是需要建立各典型部件的热损伤程度量化评价综合模型。

5 结语

高速列车的轮轨、制动盘、车轴等部件经常发生磨损,表面技术是修复或提升其性能,以减小磨损的有效手段。激光熔覆技术在轨道交通领域具有十分广阔的应用前景。目前对于高速列车部件激光熔覆的研究主要集中在熔覆材料方面,熔覆试样的各项性能测试结果基本能满足需求。但当前缺乏全面地从组织演变、残余应力及服役性能三者综合的角度构建轨道交通的理论基础,对于轨道交通领域零部件修复的热损伤定量评估模型也相对缺乏。通过热损伤定量评估模型综合以上部分的熔覆层组织、残余应力及服役性能,是搭建科学研究与实际应用的桥梁。此外,将超声振动辅助激光熔覆、电磁辅助激光熔覆、超高速激光熔覆等新技术应用在高速列车激光熔覆领域,以进一步提升熔覆层的性能,可能是未来的研究方向。

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