

表面摩擦磨损与润滑

缸套-活塞环摩擦副表面性能强化研究进展

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摘要: 缸套-活塞环是内燃机中最重要的摩擦副, 该配副的磨损失效占内燃机摩擦磨损故障的 40%左右。表面性能强化是提高缸套-活塞环摩擦副服役寿命和可靠性的重要方法。简要分析了内燃机缸套-活塞环服役工况与磨损失效机理, 总结了影响缸套-活塞环摩擦磨损行为的重要因素。详细综述了表面改性、表面涂覆和表面复合处理技术在缸套-活塞环表面强化中的研究和应用现状, 其中化学热处理、离子注入和表面淬火等表面改性技术, 通过改变缸套-活塞环表面化学成分和组织结构, 而改善其摩擦学性能, 表面织构可起到贮存润滑油、容纳磨屑等重要作用。表面复合镀铬、气相沉积薄膜、热喷涂金属和金属陶瓷涂层等技术, 也常用于缸套-活塞环的表面强化改性。同时, 通过多种表面强化技术复合处理, 如激光淬火和低温离子硫化复合、磁控溅射与渗氮复合、堆焊与表面滚压复合等, 多种技术优势互补, 可以实现缸套-活塞环摩擦副表面综合性能的协同提升。最后简要总结了各项表面强化技术的优缺点和亟待解决的问题。

关键词: 缸套; 活塞环; 减摩耐磨; 表面强化; 表面改性; 表面涂覆

中图分类号: TG174.4; TH117 **文献标识码:** A **文章编号:** 1001-3660(2019)08-0185-14

DOI: 10.16490/j.cnki.issn.1001-3660.2019.08.025

Research Progress in Surface Performance Reinforcement of Cylinder Liner and Piston Ring Friction Pair

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ABSTRACT: Cylinder liner-piston ring is the most important friction pair in the internal combustion engine and its wear failure accounts for about 40% of the friction and wear failure in the internal combustion engine. Surface performance reinforcement is an important method to improve the service life and reliability of the cylinder liner-piston ring friction pair. The service condition and failure mechanism of the internal combustion engine cylinder liner-piston ring were briefly analyzed. The important factors influencing the friction and wear behaviors of cylinder liner-piston ring pair were summarized. Then, the research and applications of surface modification, surface coating and composite surface treatments on the cylinder liner and

收稿日期: 2018-12-30; 修订日期: 2019-02-23

Received: 2018-12-30; Revised: 2019-02-23

基金项目: 国家自然科学基金(51535011, 51675531); 北京市自然科学基金(3172038)

Fund: Supported by National Natural Science Foundation of China (51535011, 51675531); Beijing Municipal Natural Science Foundation (3172038)

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piston ring surface reinforcement were reviewed in detail. Surface modification technologies such as chemical heat treatment, ion implantation and surface quenching could promote the tribological properties by improving the surface chemical composition and structure of cylinder liner and piston ring. The surface texturing had great importance in the storage of lubricating oil and abrasive debris. Composite chromium plating, vapor deposition of thin films and thermal spraying of metal and metal-ceramic coatings technologies were also suitable for cylinder liner-piston ring surface reinforcement and modification. Simultaneously, synergetic improvements of the surface comprehensive performance of the cylinder liner-piston ring friction pair and can be accomplished via various surface strengthening technologies, such as laser quenching and low temperature ionic sulfurizing, magnetron sputtering and nitriding, surfacing and surface rolling etc. and multiple complementary advantages. Finally, the advantages and disadvantages of these surface performance reinforcement technologies and problems to be solved were briefly summarized.

KEY WORDS: cylinderliner; piston ring; anti-friction and wear-resistance; surface strengthening; surface treatment; surface coating

随着机械和动力系统的发展,内燃机在车辆、船舶、航空以及工农业生产中广泛应用,其节能减排问题和摩擦运动部件失效问题受到越来越多的关注^[1-2]。据报道,缸套与活塞环的磨损失效量占整机摩擦学故障的 40%左右,能量损耗达总机械能损耗的 60%^[3-4]。节能减排政策正围绕汽车等行业展开,而内燃机效率与主要温室气体二氧化碳的产生直接相关,严格控制排放迫使研究人员寻找更好的解决方案来提高内燃机的效率,包括改进燃烧系统和废热回收系统及组件系统优化和小型化等。在这些方法中,改善摩擦系统、减少内燃机摩擦损耗是一个关键且效益显著的方法^[5-6]。因此,通过缸套-活塞环表面强化来实现节能减排具有广阔前景。

由于内燃机性能不断提高,并向高功率、高效率、低油耗、低排放、长寿命的方向发展,这对缸套和活塞环的抗高温氧化性能、抗腐蚀性能和耐磨性能等提出了更高的要求^[7]。内燃机气缸服役工况复杂,影响因素较多,由于制造和装配精度、摩擦磨损和高温燃气压力等影响,内燃机缸套容易产生形变,这会导致活塞环与缸套之间周向间隙不均匀,从而导致气密性和润滑条件变差。尤其是在活塞运动的上止点,活塞环和缸套表面温度大于 300 °C,压力达到最大值,润滑油膜容易流失或被烧毁,导致摩擦副处于临界润滑状态,活塞环极易发生磨损加剧、粘环、断环等。活塞环开口处更容易漏气,油膜更容易被破坏,因此其开口附近与缸套接触表面的磨损量更大。活塞环直接承受缸内高温高压燃烧气体作用,弹性和耐磨性降低,上下端面因油内残渣和混进的灰尘等发生磨粒磨损。一般来说,摩擦副滑动接触表面的磨损量比活塞环上下端面大,决定着最大磨损量及活塞环的使用寿命。国内外学者对其摩擦状态进行了大量研究。Gangopadhyay 等^[8]对某型缸套内壁润滑油膜最小厚度和润滑状态进行分析,如图 1 所示,发现转速为 1500 r/min 时,活塞环长期处于不良润滑状态,不利于减摩。同时,随着温度和负荷的增加及供油速率的

下降,摩擦系数不稳定,摩擦初期的摩擦系数高于正常水平^[9]。此外,高温燃气中的燃烧产物对金属有腐蚀作用,活塞环往复运动过程中,速度变化快、压力变化大且与缸套表面相互撞击和振动,使得摩擦磨损进一步加剧。

缸套-活塞环表面磨损会直接导致内燃机功率下降、油耗增加及排放超标等,此外还可能导致高压燃气泄露、破坏正常润滑、摩擦面粘着致活塞环卡死等严重故障。缸套-活塞环表面质量很大程度上决定了内燃机的性能、能耗和使用寿命,因此其表面性能强化尤为重要。本文详细介绍了缸套-活塞环表面改性、表面处理和表面涂覆等表面强化技术,分析了各种技术应用优势和缺点,为从事缸套-活塞环表面强化的科研人员和工程技术人员提供参考。

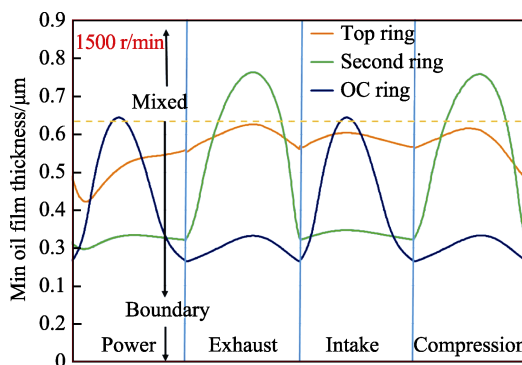


图 1 某型发动机 1500 r/min 时
最小油膜厚度及润滑状态^[8]

Fig.1 Minimum oil film thickness and lubrication
state at 1500 r/min for a type of engine^[8]

1 表面改性技术

表面改性技术通过改变基体表面化学成分、组织结构或表面形貌,成为提高缸套-活塞环表面硬度、耐磨性和疲劳强度等性能的有效途径,主要包括化学热处理、离子注入、表面淬火和表面织构。

1.1 化学热处理

化学热处理主要包括渗碳、渗氮、渗硫、渗铬、渗硼等,渗入元素通过“钉扎效应”使晶体位错密度增加,降低裂纹拓展速率并阻止位错移动,同时形成摩擦性能良好的化合物层。缸套和活塞环常采用渗氮强化,因为渗氮温度较低,零件变形量较小,缸套和活塞环的耐磨性好且疲劳寿命高。气体渗氮活塞环目前应用较多,主要利用氨气分解扩渗氮原子到金属晶体结构,但对活塞环气体渗氮影响的因素较多,且存在钝化、无选择性氮化和形成裂纹等问题。等离子渗氮则能有效改善这些缺陷,并进一步提高活塞环表面硬度。通过等离子溅射可以去除表面钝化膜并活化表面,而且还能避免扩散区晶界氮化物的复合层形成和析出,渗氮层的硬度达到 1100HV^[10-11]。

传统热处理工艺存在诸多缺点,如渗碳高温导致缸套应力大且易变形、渗氮设备复杂、周期长等。研究人员开发了多元共渗和复合渗等工艺,对缸套表面进行等离子多元共渗,复合硬化层的显微组织为隐针马氏体、硼硅化合物和片状石墨。在硬化层和基体之间存在过渡层,厚度为 35~60 μm ,其主要成分为隐针马氏体和片状石墨。由于细晶强化、多元共渗强化和马氏体相变硬化作用,缸套表面能够获得很高的硬度和耐磨性^[12]。此外,对铸铁活塞环进行多元共渗复合处理能够有效提高氮化层厚度,有效改善活塞环耐磨耐蚀性能^[13]。

1.2 离子注入

离子注入技术通常是将高能离子在常温下强行挤入基材表面,材料表面获得过饱和固溶体、亚稳相和非晶态等组织结构,且不产生热变形,能有效保证工件的几何形状和尺寸精度不变。离子注入技术可控性好,但其设备系统复杂、注入深度较小。20 世纪 90 年代以来,研究人员通过离子注入技术有效提高了缸套和活塞环寿命^[14]。Shen 等^[15]通过离子注入在缸套表层产生晶格缺陷抑制位错,并生成了高硬度的固溶硬化相及合金化合物,使高铬铸铁缸套使用寿命提高 3~4 倍,活塞环寿命提高 2 倍。Budzyński 等^[16]通过注入氮离子使活塞环主要磨损形式由粘着和磨粒磨损转化为氧化磨损,摩擦系数和磨损深度分别降低 64%和 36%,证明了离子注入可以大幅度改善活塞环表面摩擦学性能。

1.3 表面淬火

对缸套-活塞环进行表面淬火可以在摩擦表面获得微细的马氏体组织,从而提高表面硬度和耐磨性,常用方法有高频感应淬火、等离子淬火和激光淬火。

高频感应淬火利用交流电的集肤效应使工件表

面迅速升温后迅速冷却,在工件表面获得淬火组织,达到相应的硬度要求。缸套整个内表面都得到硬化,但变形量较大且容易产生裂纹,采用油冷却缸套内应力较小,可以获得比水冷却更高的硬度和更少的裂纹^[17]。此外,缸套经过高频淬火后需进行回火处理,以进一步降低残余应力,避免产生裂纹。为了有效克服螺旋线圈加热的缸套内外温差和应力大的缺点,Sun 等^[18-19]设计出新型矩形线圈(如图 2)对大型缸套进行感应加热,相对于电阻炉加热,其效率更高。通过在缸套末端焊接热处理环,在线圈末端加入磁化剂,可以消除感应加热大型缸套过程中的锐角效应,避免了缸套末端过热,在缩短加热时间的同时,能得到与传统热处理工艺相似的晶粒(图 3)。

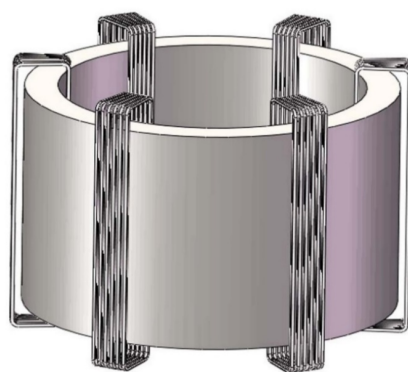


图 2 矩形线圈缸套感应加热示意图^[18]
Fig.2 Induction heating of rectangular coil on cylinder liner^[18]

等离子淬火设备简单,前处理工艺简单,生产效率高,具有较高的经济实用性。该工艺对工件热影响小,使缸套表面组织转化为莱氏体和马氏体而内部无明显变化,可以获得高硬度和强度的同时保持缸套韧性。对缸套进行等离子淬火的研究较少且工艺基本相同,对缸套内孔表面进行等离子淬火,被加热的气缸套表层迅速冷却,气缸套表层的金相组织由奥氏体转变成莱氏体及隐针马氏体硬化组织,从而大大提高了缸套表层的硬度及耐磨性^[20]。

激光淬火功率密度大,可以在保证缸套耐磨性的同时节省加工时间,提高工作效率,但目前设备成本相对较高^[21]。激光淬火缸套变形小且可获得极细马氏体组织,使其硬度与耐磨性优于渗氮处理缸套。然而,随着服役时间的增加,缸套磨损量随各部分温差变化而不均匀变化,容易形成喇叭口形状,导致密封性降低。由于金属材料对激光的吸收率较低,在进行激光淬火之前,需要对材料进行表面磷化处理,以提高激光淬火效率。杨国成等^[22]对缸套进行激光淬火并探究了不同磷化方法和淬火轨迹对激光淬火强化效果的影响,在优化工艺条件下,缸套寿命提高了 2~3 倍。

不同于感应淬火,等离子和激光淬火都不是淬硬

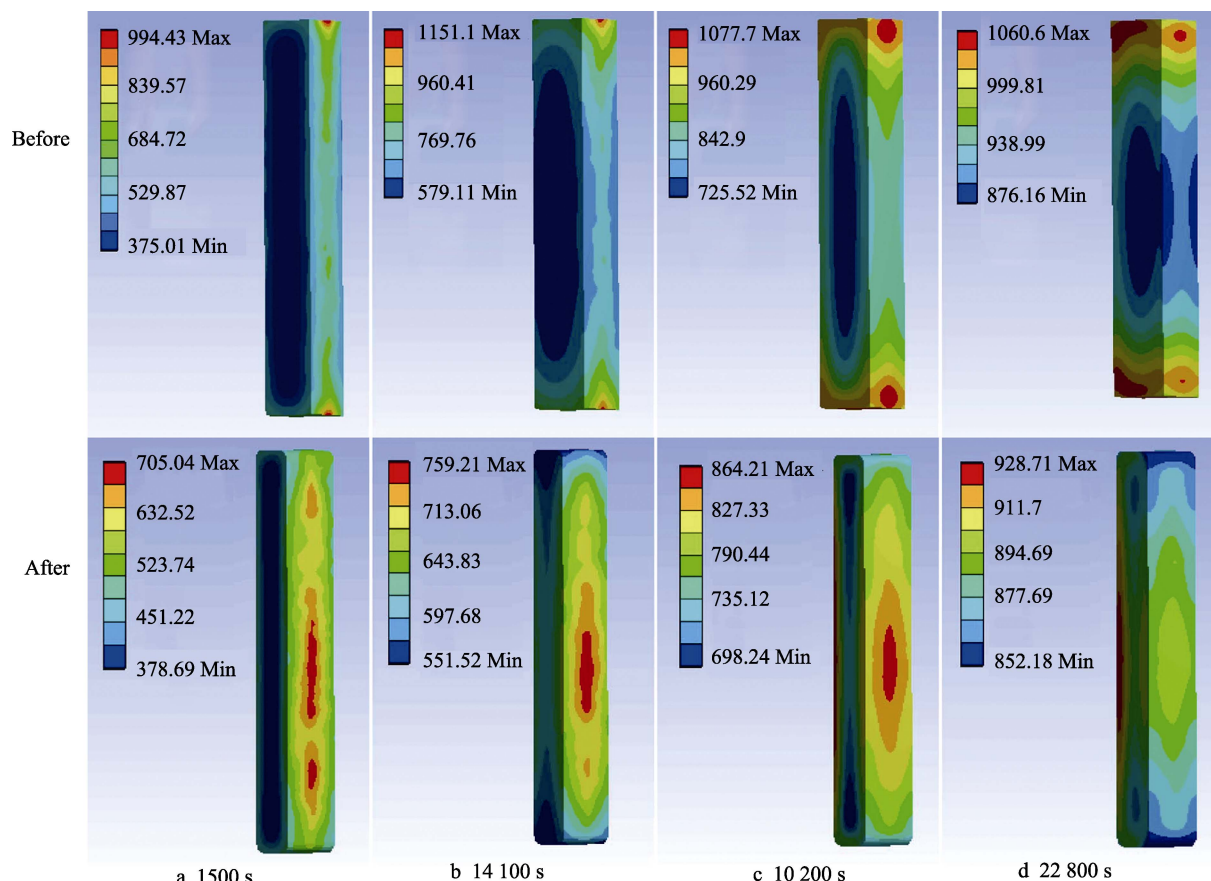


图3 添加磁化剂和焊接热处理环前后缸套在不同加热时间的温度曲线对比^[18]

Fig.3 Contrast of temperature curves of the cylinder liner at different time before and after the addition of the magnetizer and the welding heat treatment ring (the figure above shows the condition the magnetizer and the heat treatment ring are added)^[18]

整个缸套内壁，而是形成一定规则轨迹的连续硬化带。等离子和激光网纹淬火可以在缸套表面形成连续规则的硬化带为骨架的储油结构，在提高耐磨性的同时还保证了缸套与活塞环间储油润滑^[23]。另外，等离子和激光淬火还可以通过程序控制实现不同区域变密度扫描，使缸套各部分硬度和磨损均衡，延长缸套使用寿命。然而，上述几种热处理工艺都难以避免地产生残余应力，由于内外温差和金属热膨胀系数较大，表面残余压应力明显高于其内部应力，了解其大小对于结构设计、材料选择和加工工艺的优化具有重要意义^[24]。

1.4 表面织构

表面织构是提高摩擦机械部件承载能力、耐磨性和摩擦系数的一种常用方法，表面上微米级织构有利于润滑油膜的生成，其协同润滑效应有助于改善缸套-活塞环的摩擦学性能^[25]。一般认为表面粗糙度越小，摩擦系数和磨损量越小，然而摩擦副表面粗糙度降到原子量级时，摩擦力反而会增加^[26]。Hamilton等^[27]在20世纪60年代提出了利用摩擦副表面楔形间隙和流体动压承载，开始探索表面织构改善摩擦性能。由于缸套与活塞环表面并非理想光滑的，表面光滑的理

论模型无法解释上下行程止点摩擦力较大的现象，人们开始关注粗糙度对缸套-活塞环摩擦磨损性能的影响^[28]。将缸套和活塞环表面微孔隙视为微小液体动压润滑轴承，在流体动压润滑条件下能够有效增加摩擦副表面承载能力^[29-31]。但由于加工条件等因素制约，这项研究最初未受到广泛关注。随着微加工技术的迅速发展，多种织构技术被广泛研究和应用，如机械加工、超声加工、光刻、等离子刻蚀和激光织构等。近年来，有学者通过激光增材制备表面织构（图4），新增材料和织构油润滑协同减摩，显示出利用减摩耐磨材料增材制造来制备表面织构的巨大潜力^[32]。

目前，内燃机行业主要通过平顶珩磨来改善缸套内壁摩擦学性能，对于缸套常用的珩磨斜纹，随着珩磨角度的增大，摩擦阻力不断增大，珩磨角度小于55°时，摩擦系数较低^[33]。Mezghani等^[34]则对比分析了混合润滑条件下平顶珩磨和螺旋滑动珩磨（珩磨角分别为50°和130°），发现相对于平顶珩磨，螺旋滑动珩磨增加了油膜厚度并降低了摩擦系数，且其加工工艺简单，更适于批量生产。大量理论和实验研究表明，在摩擦副表面加工出具有一定形状的微织构图案，承载的润滑油膜可以有效减少摩擦副表面微凸体接触，在流体润滑条件下具有明显的减摩效果^[35-37]。

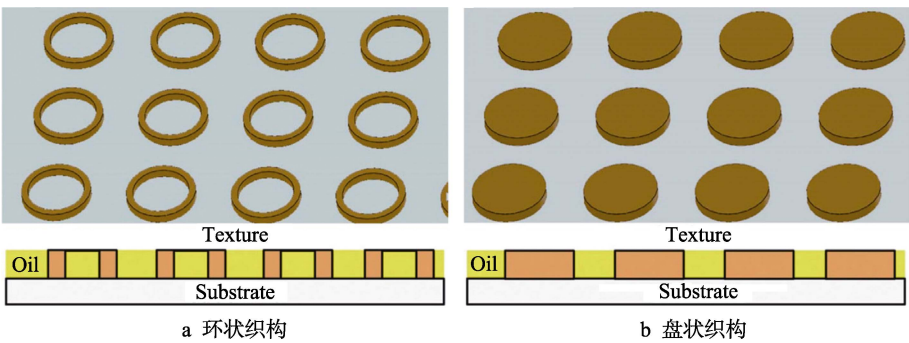


图 4 激光增材结构示意图^[32]
Fig.4 Schematic diagram of laser additive texture: (a) ring texture; (b) disc-shaped texture^[32]

对缸套-活塞环摩擦表面结构的研究，则主要集中在结构形貌、尺寸和工况等因素对摩擦学性能的影响^[38-39]。

对于激光表面结构，凹坑结构由于其可控性好、代表性强而研究较多（表 1），凹坑直径和深径比两种因素协同竞争，共同影响润滑油膜厚度，进而影响表面摩擦学性能，直径最佳值与润滑油黏度和温度有关，目前广泛认为结构表面凹坑最佳深径比为 0.1，摩擦副相对滑动速度也会影响其摩擦学性能，摩擦系

数随着相对速度的增加而减小（图 5）^[40-41]。研究发现，凹坑面积占比也会明显影响表面摩擦磨损性能（图 6），由于 5%面积比例的凹坑所产生的流体动压最大，其减摩耐磨性能最佳，摩擦系数和磨损量分别减少 38%和 72%^[42]。沟槽结构和凹坑结构（图 7）常用于内燃机缸套与活塞环，Usman 等^[43]研究发现与滑动方向垂直的沟槽结构液体动压载荷最大而导致减摩性能最好，并且较浅的结构深度更有利于减小摩擦，较深则不利于减摩。

表 1 不同凹坑结构对比
Tab.1 Contrast of different dimple textures

Reference	Diameter / μm	Depth / μm	Full/Partial texture	Dimpled. ensity/%	Lubrication conditions	Findings
[29]	10~100	1~10	Full/Partial	10~35	Mixed lubrication	Smaller dimple dimension, especially with partial texturing shows significant hydrodynamic effects.
[40]	15~800		Full	10	Mixed lubrication	The depth-to-diameter ratio and diameter of the dimple both have significant influence on the possibility to build up pressure with the dimples. In case of the optimum texture over 80% of friction reduction can be achieved.
[42]	300~700	50	Full	0, 2, 5, 10	Lubricated sliding contact	The change in the dimple area fraction dramatically reduce friction and wear, and 5% is the optimal value.
[44]	100	25	Full	20	Starved lubrication	The cylinder liner wear scar depth was decreased by 21.7% compared to non-laser processing, and it's strongly related to the dimple distribution angle.
[45]	150~200	5	Full	13	Full fluid/starved lubrication	The dimple causes smaller friction force up to 15% for the highest speed and applied load. The beneficial oil pockets influence was especially evident in conditions of better lubrication, where the friction force decreased almost twice.
[46]	88.5~93.5	16~35	Full		Dry friction, solid lubrication, oil lubrication	Lubricants combined with appropriate laser surface texture and solid lubricants can effectively reduce friction and wear.
[47]	70	5~25	Full	0~40	Boundary and mixed lubrication	In the LST process, the laser beam increases the local regions' hardness 2~3 times by the remelting process. The textured specimen having a dimple density of about 10% and a dimple depth of about 8 μm showed a promotion in lubrication.
[48]	400~2000	46~60	Full	0~0.26	Mixed lubrication	The dimple size affects its load-carrying capacity and help to lower the COF between the frictional surfaces, but the dimples decrease the surfaces' resistant to wear in this experiment.

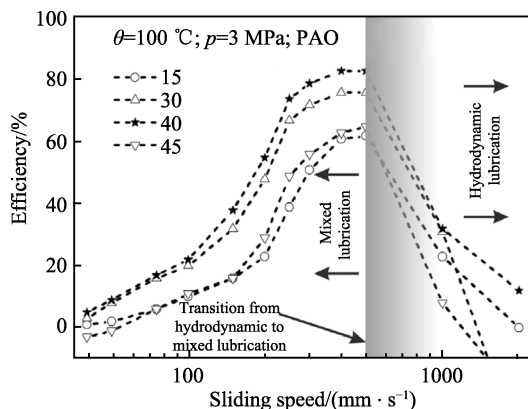
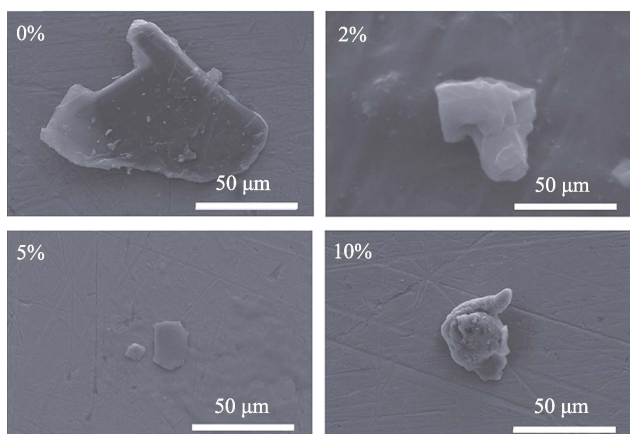
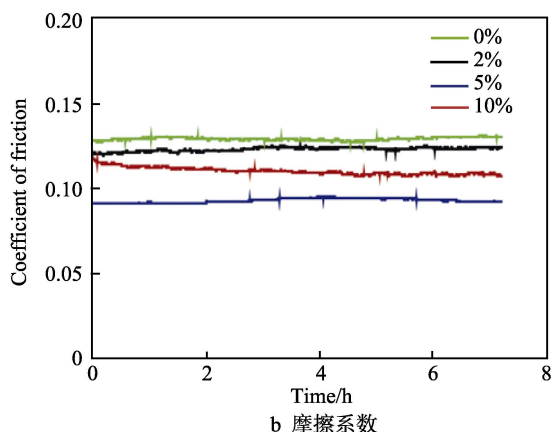


图5 不同直径凹坑的织构摩擦系数随摩擦副相对滑动速度的变化曲线^[40]

Fig.5 Change curves of friction coefficients of dimple texture with diameters of 15, 30, 40 and 45 mm along with the relative sliding speed of friction pairs^[40]



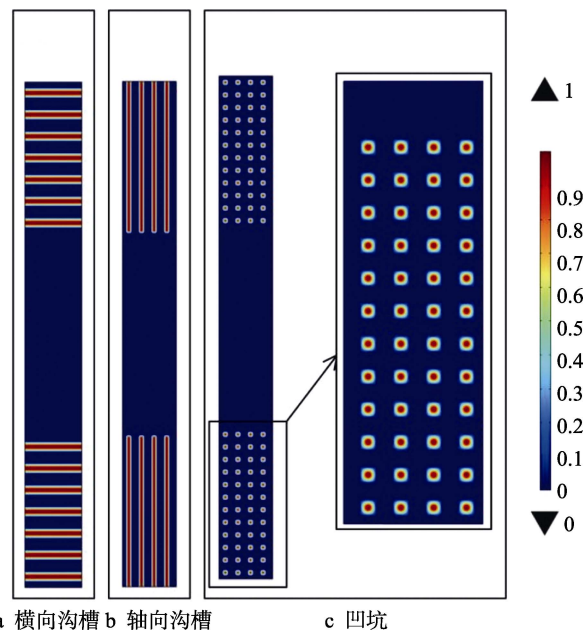
a 磨屑



b 摩擦系数

图6 不同面积比例凹坑的织构产生的磨屑和摩擦系数^[42]
Fig.6 Debris (a) and friction coefficient (b) generated by textures with different dimple area fraction^[42]

单一密度和形状的织构在缸套部分区域可以降低摩擦系数,而在某些区域正好相反^[49]。在活塞环中心部分制备凹坑织构,与全织构和边缘局部织构活塞环相比,具有更低的摩擦力和更高的负载能力,改变凹坑排列方式和密度也会明显影响润滑性能,缸套表



a 横向沟槽 b 轴向沟槽

c 凹坑

图7 三种织构图案^[43]

Fig.7 Three texture schemes: (a) horizontal groove; (b) axial grooves; (c) dimples^[43]

面间距均匀的凹坑协同润滑能力强于凹坑间距变化的缸套^[31]。凹坑织构分布角度会明显影响缸套磨损性能指标。Zhan 等^[44]发现缸套表面凹坑分布角度为 60° 时,磨痕深度最小。Chen 等^[50]验证了该观点并得到新的结论,即分布角为 45° 时,摩擦系数最小,90° 时磨痕磨损最严重。Noutary 等^[51]则基于流体动力学模型分析了缸套-活塞环织构表面承载力,发现沟槽深度和面积密度对提高摩擦磨损性能的影响明显优于其几何形状。Hua 等^[52]对缸套内壁进行分区并设计了 3 种织构方案,发现在缸套内壁活塞行程上止点和裙部接触区采用较大的深度和面积占有率,中间行程和下止点区域采用较小值,有利于改善缸套-活塞环的润滑性能并减少耗油量,最多能降低 45.5% 油耗。同时,人们开始关注并探索复合织构来进一步改善摩擦磨损性能,根据缸套不同区域润滑状态和磨损特征制备密度合理变化的微织构,可以更好地产生润滑油膜以减小摩擦阻力和内燃机油耗,计算结果表明,织构面积比例对承载力的影响大于深径比的影响,且织构最佳面积比例随摩擦副相对运动速度的增加而减小^[41]。此外,不同形状的织构混合也可以有效降低摩擦系数,比如椭圆与圆形凹坑、网状与凹坑复合织构表面的摩擦系数都比单一织构的更低,这说明适当密度和形状组合的织构比均匀单一密度织构更加容易产生润滑油膜^[53]。

在干摩擦条件下的织构研究相对较少,但也能一定程度上减少磨损,尤其是粘着磨损明显减少。这主要是由于织构可以减小应力集中和摩擦系数,形成的微槽、微坑可以储存磨屑,激光织构局部重熔还有利于提高织构区域的硬度和耐磨性^[47]。大量实验证明,

缸套磨损可能是滑动触点入口区域的润滑膜破裂所致^[54-55]。在缺油润滑条件下, 织构对减摩性能的改善程度明显降低且摩擦系数不稳定, 这主要是由于缸套与活塞环的接触面积 (图 8) 和流体压力不稳定变化造成的^[45,56-57]。

目前, 由于织构图案和尺寸的多样性以及摩擦学性能的评价方法差异, 尚未形成规范统一的标准, 研究成果对比参考性较低且存在不少争议, 需进一步实验分析寻找最优方案。此外, 未经优化或应用不当的表面织构不利于改善摩擦学性能, 并可能得出错误的结论^[58]。

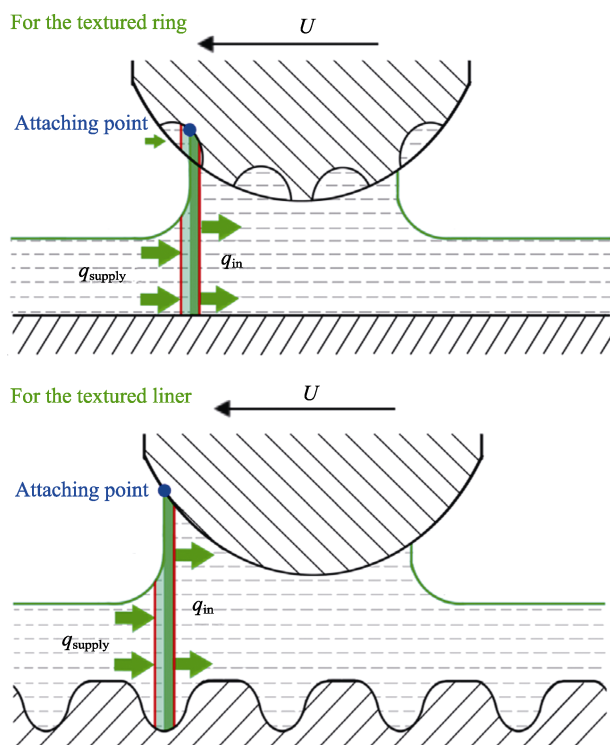


图 8 缸套与活塞环织构接触点润滑示意图^[57]
Fig.8 Lubrication of contact point between cylinder liner and piston ring texture^[57]

2 表面涂覆技术

表面涂覆技术作为一种重要的表面强化技术, 通过功能多样的材料选择与灵活设计涂覆层, 为缸套-活塞环提供了减摩耐磨、耐腐蚀等许多特性, 适用于不同服役工况, 在工业尤其是汽车行业应用较多。涂覆技术能够有效减轻内燃机重量并延长使用寿命, 为实现节能减排和有效提高燃油经济性提供了一种新思路, 主要包括表面镀层、气相沉积、表面熔覆和热喷涂。

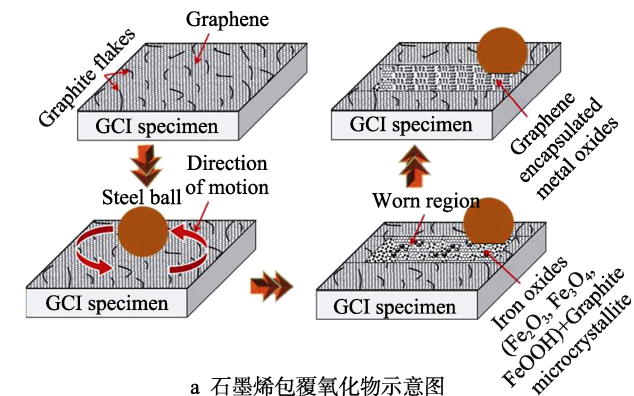
2.1 表面镀层

典型的缸套-活塞环表面镀层制备技术包括电镀、电刷镀^[59]、化学镀^[60]等, 目前工业领域常采用

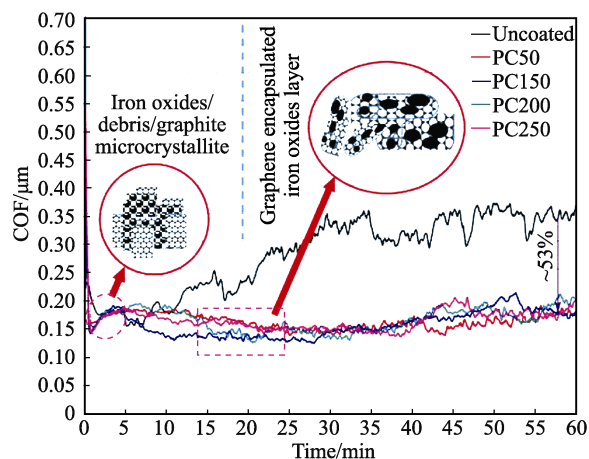
电镀铬和喷钼工艺^[61]来强化缸套和活塞环的耐磨耐蚀性能。电镀铬工艺技术成熟且在国内外被广泛应用, 研究表明, 由于铬硬度高且耐蚀性好, 镀铬缸套相对于普通缸套, 其使用寿命延长 50%^[62]。目前国内厂商广泛采用的松孔镀铬可以在工件表面获得网状结构孔隙, 具有更轻的质量且有利于内燃机储油润滑, 使用寿命较普通硬铬提高 5~7 倍^[63]。此外, 还能通过优化工艺和材料, 制备出功能梯度镀铬涂层、陶瓷增强复合镀铬涂层、自润滑耐磨复合镀铬涂层等, 以适应各种不同润滑及载荷条件, 显著增强缸套-活塞环表面摩擦学性能。比如, Soares 等^[64]利用纳米立方氮化硼对常规镀铬层进行强化, 使涂层摩擦系数降低 20%, 且活塞环和缸套磨损量明显减少。目前沿用多年的电镀铬工艺相对复杂, 能耗高且污染严重, 已难以满足日益增长的减摩耐磨需要且受到各国限制, 开发新工艺迫在眉睫。

2.2 气相沉积

气相沉积主要有化学气相沉积 (Chemical Vapor Deposition, CVD) 和物理气相沉积 (Physical Vapor Deposition, PVD), 沉积薄膜杂质少, 结构致密, 结合强度高。Tripathi 等^[65]采用 CVD 在灰铸铁缸套表面沉积了石墨烯薄膜, 摩擦过程中在试件表面产生了石墨烯及其包覆的金属碎片和氧化物, 增强了试样的润滑性并降低了剪切力 (图 9), 使基体摩擦系数减少 53%, 耐磨性增强 2 倍。CrN、DLC 等典型的 PVD 薄膜已被开发出来, 由于它们具有优异的耐磨性、耐腐蚀性和抗氧化性, 摩擦系数低, 硬度高且在基体上具有良好的粘接性能, 越来越多地用于缸套-活塞环减摩耐磨。采用 PVD-CrN 还能有效改善铸铁缸套表面油膜失效问题, 有助于实现流体动压润滑和减少磨损^[66]。此外, 由于其涂层致密, 硬度较高, 也常用于活塞环表面强化。Bruno 等^[67-68]对比研究了几种常见活塞环涂层的摩擦系数和耐磨性能 (图 10), 发现 PVD-CrN 活塞环的摩擦系数和磨损量最低。PVD-WCN 薄膜能使活塞表面硬度提高近 30 倍, 至 33.3 GPa, 由于其极高的硬度, 磨损量降低为无涂层活塞磨损量的 1/90^[69]。同时, PVD 薄膜可以兼备高硬度与低摩擦系数。Di 等^[70]采用磁控溅射技术在活塞环上制备了 CrMoN/MoS₂ 固体润滑涂层, 其结构致密 (图 11), 耐磨润滑相 MoS₂ 在硬质相 CrN、Mo₂N 的支撑下, 使整体硬度高于 Cr 涂层, 且减摩耐磨性能都优于 Cr 涂层。采用等离子增强磁控溅射技术在活塞环和缸套上制备 TiSiCN 涂层, 能使活塞环和缸套的磨损量分别降低 29% 和 50%^[71]。优异的减摩耐磨性能为气相沉积应用于缸套-活塞环表面涂覆提供了可能, 此外, 物理气相沉积工艺对基体热影响较小, 能有效保证工件尺寸精度。然而, 目前气相沉积薄膜偏薄、成本较



a 石墨烯包覆氧化物示意图



b 摩擦系数对比

图9 石墨烯包覆氧化物示意图及摩擦系数对比^[65]
Fig.9 Schematic diagram of graphene coated oxide (a) and comparison of friction coefficient (b)^[65]

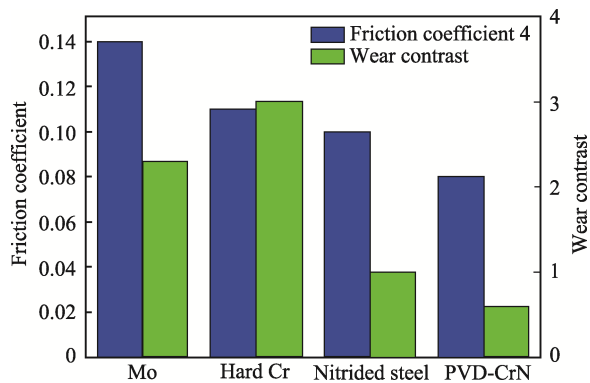
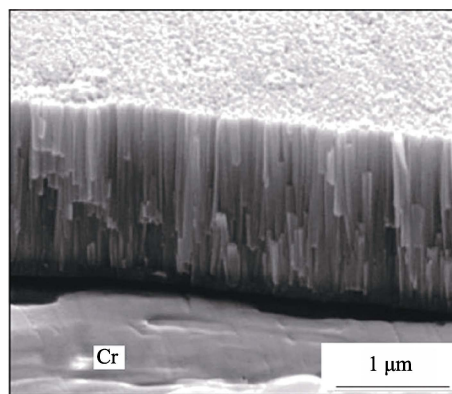
图10 常见活塞环涂层摩擦系数和磨损量排序^[68]

Fig.10 Friction coefficient and wear of common piston ring coatings^[68]

高,不利于大型重载气缸表面强化,其生产效率亟待提高。

2.3 表面熔覆

对内燃机缸套的熔覆工艺按热源分类,主要有感应、激光和等离子熔覆。感应熔覆加热快,但可能导致涂层中间不完全熔化;激光熔覆的功率密度高,冷却速度快,导致熔覆层致密且性能稳定,但成本高;等离子熔覆功率大,成本低,但热影响较大,容易产生气孔和裂纹等缺陷。此外,热喷涂涂层尤其是一些



a Cr涂层

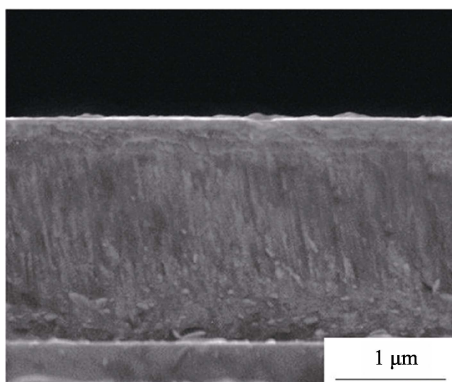
b CrMoN/MoS₂涂层图11 活塞环 Cr 涂层和 CrMoN/MoS₂ 涂层截面形貌^[70]

Fig.11 Cross section morphology of Cr (a) and CrMoN/MoS₂ (b) coated piston ring^[70]

自熔合金涂层,可以通过激光重熔、电弧重熔等消除孔隙、裂纹和未熔颗粒,以提高涂层致密性、结合强度和耐磨性等^[72-73]。表面熔覆与热喷涂技术具有相似性,最主要的特点在于熔覆功率和能量密度大,熔覆层完全熔化,组织致密且与基体形成冶金结合。例如,Yu等^[74]利用感应熔覆使Ni基涂层与灰铸铁实现了冶金结合,并且无明显缺陷或裂纹,表面硬度比基体高2倍。通过等离子转移弧离心熔覆在缸套表面制备铁基涂层,并使缸套旋转,在离心力作用下,由于材料完全熔融而具有较好的流动性,气孔因为密度较低被甩向涂层边缘,使涂层更加致密且无孔隙,同时Cr、C、B等元素向涂层表面迁移,涂层成分呈梯度变化,使涂层的耐磨性比基体提高18倍^[75]。激光重熔由于其能量很高,能够在缸套内壁制备出性能良好的高熔点陶瓷纳米涂层,有效提高了缸套的硬度、耐磨性和耐腐蚀性,并使缸套在极端恶劣的工作环境下,更好地保持其物理化学性质的稳定性^[76]。

2.4 热喷涂

热喷涂技术是表面强化和修复的重要技术,工艺方法多,涂层适用广,经济性高,主要包括火焰喷涂、电弧喷涂和等离子喷涂。

火焰喷涂容易导致粉末、丝材或涂层氧化,迫使科研人员不断优化工艺、改进设备并发展出超音速火

焰喷涂。Celik 等^[77]采用超音速火焰喷涂在 316 不锈钢缸套表面以 NiAl 为粘接层制备了 WC 基涂层, 涂层基体接触良好, 结构致密且氧化物含量低。在边界润滑条件下, 火焰喷涂 WC/CrC 涂层与陶瓷增强镀铬、渗氮及 CrN-PVD 活塞环相比, 具有更低的摩擦系数和更高的耐磨性, 在类似活塞做功的准流体动压润滑条件下, 也表现出最佳摩擦磨损性能^[78]。20 世纪 90 年代初, 通用汽车公司率先研制出旋转 HVOF 丝材喷涂系统, 并在铝合金汽车发动机缸体内壁制备了铝青铜耐磨涂层, 成功替换了传统嵌套灰铸铁缸套的方式^[79]。同时该公司研制出低碳钢合金丝材, 研究发现涂层内部孔隙和喷涂时生成的高含量 FeO 固体润滑相, 有助于提高涂层在边界润滑条件下的减摩耐磨性能, 但形成的 FeAlO_3 相会在涂层中引起裂纹萌生^[80-81]。美国 Kermetico 公司研制出旋转式内孔超音速空气助燃 (HVAF) 粉末喷涂系统, 采用空气助燃, 使混合燃气中氧含量较 HVOF 低 5 倍, 能有效防止金属氧化和硬质碳化物脱碳, 并使粉末在形成涂层后仍保持其原始力学性能^[82]。这些内孔喷涂新工艺的研究将进一步推动内燃机缸套的修复与再制造发展, 经济实用的表面技术有望进一步提高内燃机性能。

电弧喷涂功率和效率较高, 成本低且安全性高, 操作简便, 在缸套涂层制备应用较多。目前技术较为成熟的是双丝电弧喷涂。Kim 等^[83]采用双丝电弧喷涂在铝合金缸套制备 Fe 基涂层, 并在油润滑和干摩擦条件下进行摩擦学实验, 发现即使在苛刻的工况下也能表现出良好的摩擦性能, 有助于实现铝合金替换铸铁缸套, 并优化铝合金缸套减摩性能。Yao 等^[84]采用电弧喷涂在缸套表面制备了 FeCrB 涂层, B 元素的添加显著提高了涂层显微硬度, 有效改善了缸套的导热性和耐磨性。为使设备轻便化, 并提高送丝稳定性, 沈阳工业大学设计出一种单丝内孔喷涂装置并应用于小直径缸套喷涂, 但目前该工艺和设备还需进一步优化^[85]。

等离子喷涂对基体的热影响小, 尤其适合缸套等薄壁件表面强化, 由于具有较高的喷涂和沉积效率, 它成为汽车工业中最常应用的热喷涂方法。等离子热源温度极高, 可以熔化陶瓷、高熔点金属等难熔材料, 制备出孔隙率低、硬度高的耐磨涂层。徐滨士课题组^[86-87]于 2000 年研制成功获得国家科技进步二等奖的高效能超音速等离子喷涂系统 (HEPJet), 并在 2016 年利用内孔等离子喷涂系统, 在航空发动机缸套内壁制备了 TiO_2 基涂层, 由于陶瓷相光滑、化学稳定性好且硬度高, 涂层在润滑条件和干摩擦条件下的减摩耐磨性能都优于珩磨缸套。等离子喷涂也适用于在活塞环上制备耐磨合金涂层, Davis 等^[88]利用大气等离子喷涂制备了 Ni-Mo-Al 合金涂层, 并添加 Cr_2AlC 使其与空气反应生成坚硬耐蚀的 Cr_7C_3 , 显著提高了活塞环的硬度和耐磨性。此外, 美国 Flame-Spray Industries (FSI) 公司开发了等离子转移弧喷涂工艺 (PTWA), 具有很高的沉积效率, 涂层孔隙率较低。由于其特殊的设计, 使得喷枪体积较小, 能适用于更小直径的缸套, 具有光明的工业应用前景, FSI 公司和 Ford 汽车公司已在全球推广了近十套 PTWA 设备^[89-90]。

为了更好地优化摩擦系统, 缸套-活塞环表面涂层硬度及磨损性能也需要相互匹配, 否则可能会导致对磨副磨损失效。Zhu 等^[91]研究了三种不同表面涂层 ($\text{Cr-Al}_2\text{O}_3$ 、CrN、Mo) 活塞环与镀铬缸套配副的摩擦磨损性能, 发现 $\text{Cr-Al}_2\text{O}_3$ 环极易磨损, CrN 活塞环具有较高的硬度和密度, 其磨损量最小, 但摩擦系数高于 Mo 涂层。同样, 虽然 DLC 涂层在活塞环上表现出优异的耐磨性能, 但其较高的硬度也可能造成缸套表面加速磨损^[92-93]。 $\text{Cr}_3\text{C}_2/\text{NiCr}$ 具有很高的硬度和耐磨性, 在活塞环上制备该涂层并进行摩擦实验, 发现与镀铬活塞环相比, 活塞环磨损量减少了 1/6, 缸套磨损量却增加了 3 倍^[94]。此外, 涂层质量的影响因素较多 (图 12), 对其进行进一步优化可以显著提升缸套-

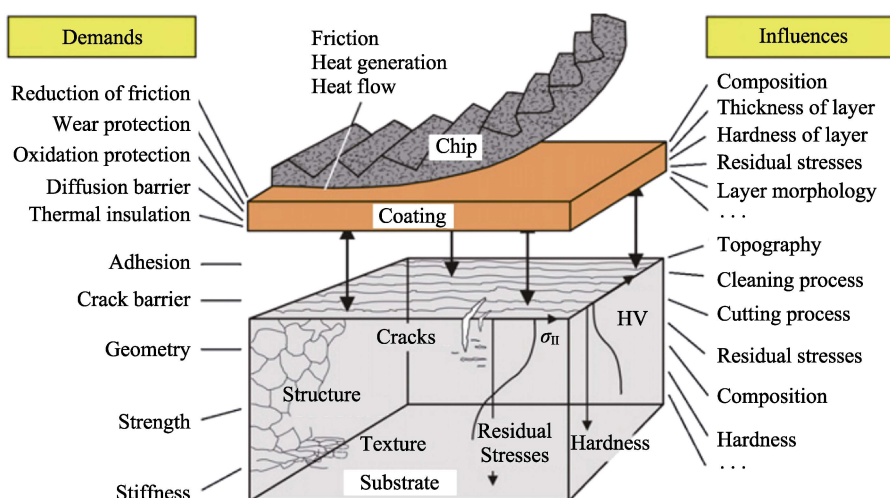


图 12 涂层性能与涂层质量影响因素^[96]

Fig.12 Influence factors of coating performance and coating quality^[96]

活塞环表面性能和摩擦学性能。例如,改变复合涂层成分对其摩擦学性能和接触疲劳强度有很大影响,Carvalho 等^[95]在活塞环 AISi 涂层中加入碳纳米管(CNTs),发现改变 CNTs 含量可以有效调控其耐磨性和机械性能,精确调控复合涂层各组分比例,可以适应不同的工况条件,CNTs 含量为 6%时,涂层获得了最佳耐磨性能;CNTs 含量为 2%时,涂层获得了最佳力学性能。因此,缸套和活塞环表面材料的选择和配合,应该作为改善内燃机摩擦学性能的重要考虑因素。

3 表面复合处理

缸套-活塞环减磨耐磨需要其表面具有较低摩擦系数、高耐磨性、较高硬度和疲劳强度,且耐高温、防腐蚀性能好等特点,单一表面技术难以满足其所需的多种性能,复合表面技术则可以克服单一表面技术的局限性,使多种表面技术协同优化、发挥各自优势^[97]。比如,在内燃机缸套表面制备 DLC 涂层,结构化后进行台架考核,发现缸套表面织构可以提高内燃机的有效功率,最多提高 5.8%^[98]。但目前缸套内壁涂层/薄膜表面的织构性价比不够高,织构与涂层的搭配需进一步研究,尤其要寻求两者的优化参数和提高生产效率。金梅^[99]在缸套内壁刻蚀微坑织构,并用球磨法填充固体润滑剂 MoS_2 ,以制备复合润滑结构,该结构能有效提高缸套的承载性能且降低了其摩擦系数。Cai 等^[100]对 42MnCr52 钢进行了激光淬火和低温离子硫化复合表面处理工艺,结果表明,复合层由软表面硫化物层和次表面激光淬火硬化层组成,具有良好的高温减磨耐磨性能,激光淬火硫化物层的协同作用使缸套硬度提高了 20%,摩擦系数降低了 10%,磨损量降低了 50%。Ma 等^[101]采用微弧氧化(MAO)和电泳沉积(EPD)相结合的方法,在 ZL109 铝合金活塞环基体上,制备了 MoS_2 增强氧化铝新型陶瓷基复合材料,与高硅铝合金基体相比,陶瓷基复合材料在干滑动下对缸套的摩擦系数降低了 35%,磨损损失降低了 95%。为了解决柴油机气缸磨损失效的问题,马亚军等^[102]利用磁控溅射方法在渗氮活塞环上沉积 MoN 涂层,由于涂层具有较高硬度,表现出比渗氮活塞环更好的摩擦学性能。李占明等^[103]采用精密脉冲等离子粉末堆焊+滚压强化复合处理工艺修复与强化内孔,在修复层表面形成较大残余压应力,实现了损伤内壁修复的控型与控性有效结合,解决了堆焊修复层表面组织性能不均匀的难题,并有效提高了涂覆层的疲劳寿命。目前国内外应用于缸套-活塞环的复合技术还不够多,工艺成本和受限空间很大程度上限制了它们在缸套内的应用,高效合理的新型复合技术仍有待发掘和进一步发展。各种表面技术科学合理协同应用,相得益彰,但不合理的工艺搭配则难以实现或改善表面性能。因此,制定复合工艺前应充

分了解各工艺原理和性能,互相弥补不足,避免不利影响。

4 结论与展望

1) 化学热处理和离子注入技术不仅可以降低缸套-活塞环表面摩擦系数,还可以通过位错强化和固溶强化等途径,有效地提高缸套-活塞环表面强度并增强耐磨性。元素进入基材表面后,表面改性层和基体不会出现断层和界面,能有效提高该摩擦副的安全可靠性,但改性层较薄且工艺周期较长。另外,热处理温度较高会导致工件变形,需要合理控制温度和形变,可以注入不同直径离子,较大直径离子轰击基材表面以便较小离子进行扩散强化。

2) 表面淬火能够有效提高缸套-活塞环表面的硬度和耐磨性,如何减少零件变形量和降低残余应力需进一步深入研究。表面织构能有效改善缸套-活塞环的摩擦学性能,但各种表面织构参数较多且缺乏通用的理论模型,还需进一步研究、总结并制定一些通用标准和模型,尤其是浩如烟海的织构几何模型需要利用模拟软件辅助分析。

3) 表面涂覆技术具有通用性、灵活性、实用性和经济性等显著优势,但涂层质量和结合强度仍需进一步优化提高,尤其是在缸套内表面由于热膨胀系数不匹配、粉尘夹杂和残余热应力的作用,涂覆层与缸套结合强度不够高。目前很多学者通过表面织构、表面改性及优化涂覆材料与喷涂工艺,来提高涂覆层与平面基体的结合强度^[104-107],但在缸套等曲面上的相关研究报道较少。希望能够通过改善表面形貌、界面应力状态等提高涂覆层结合强度,优化工艺参数实现小孔径缸套的涂覆,并提高内孔涂覆层质量。

4) 通过不同表面强化技术复合应用,并不断拓宽材料种类,高效科学地寻求最优工艺和材料组合,实现缸套-活塞环表面硬度、强度、韧性、减摩、耐磨性能的协同提升。

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