

高熵化与纳米化热防护涂层在航空发动机中应用的研究进展

张晓东, 葛云洋, 李国强

(哈尔滨工业大学 材料科学与工程学院, 哈尔滨 150001)

摘要: 陶瓷涂层具有优异的抗腐蚀性能、抗高温性能以及较低的热导率, 将其覆盖在航空发动机热端部件表面可以起到热防护作用。其中, 最具代表性的为热障涂层和环境障涂层。热障涂层针对高温合金热端部件(主要是涡轮叶片)进行隔热防护, 环境障涂层针对陶瓷基复合材料进行防护。围绕力学、热物理和抗腐蚀性能对比了传统热障涂层与高熵化、纳米化热障涂层之间的差异; 综述了环境障涂层中两种稀土硅酸盐及其常见失效方式; 展望了高熵化、纳米化热障涂层未来在航空发动机上应用的发展方向。

关键词: 陶瓷涂层; 航空发动机; 高熵陶瓷; 纳米陶瓷; 热导率; 热膨胀系数

中图分类号: TG213; V255⁺5 **文献标识码:** A **文章编号:** 1672-2620(2026)01-0065-20

DOI: 10.3724/j.GTER.20250084

Progress on high-entropy and nanostructured thermal protective coatings for aero-engines

ZHANG Xiaodong, GE Yunyang, LI Guoqiang

(School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China)

Abstract: Because of excellent corrosion resistance, high temperature resistance, and low thermal conductivity, ceramic coating can play a protective role on the surface of hot end parts of aero-engines. The most representative ones are thermal barrier coatings (TBCs) and environmental barrier coatings (EBCs). The TBCs are used for thermal insulation protection of high-temperature alloy hot-end components (mainly turbine blades), while EBCs are used for protection against ceramic matrix composites. The differences between traditional thermal barrier ceramic coatings and high entropy and nano-sized thermal barrier ceramic coatings were compared in the aspects of the mechanical, thermophysical, and corrosion resistance properties, and two rare earth silicates in EBC and their common failure modes were reviewed; the future development direction of high entropy and nano-ceramic coatings in aero-engines was prospected.

Key words: ceramic coatings; aero-engine; high-entropy ceramic; nanostructured ceramic; thermal conductivity; coefficient of thermal expansion

0 引言

航空发动机的研发水平是衡量一个国家科技实力与工业基础的综合性标志^[1-3]。研究表明, 在维

持发动机基本布局与常规金属材料不变的前提下, 借助零部件优化设计与结构减重等手段, 可有效提升发动机的推重比^[4]。相应地, 为实现这一目标,

收稿日期: 2025-04-16

基金项目: 国家自然科学基金(52371062); 国家重点实验室开放基金; 中国国家重点研发计划(2020YFB2007900); 国家级科研项目

作者简介: 张晓东(1980-), 男, 江苏宿迁人, 教授, 博士生导师, 博士, 主要研究方向为面向极端服役环境的纳米结构陶瓷涂层材料与技术。

引用格式: 张晓东, 葛云洋, 李国强. 高熵化与纳米化热防护涂层在航空发动机中应用的研究进展[J]. 燃气轮机试验与研究, 2026, 39(1): 65-84. ZHANG Xiaodong, GE Yunyang, LI Guoqiang. Progress on high-entropy and nanostructured thermal protective coatings for aero-engines[J]. Gas Turbine Experiment and Research, 2026, 39(1): 65-84.

需进一步提高涡轮前温度,从而对航空发动机燃烧室与涡轮叶片的耐高温性能提出了更高要求^[5]。

1980s初,设计叶片结构是提高发动机工作温度的主要手段,使用先进的气膜冷却技术可以将叶片的工作温度提高400 K^[6]。但是这会造成一个较为严重的问题,即降低叶片温度会带来巨大的能量损耗,并随之加剧发动机的运行负担。为此,采用热障涂层(TBCs)来降低航空发动机的环境工作温度被认为是行之有效的方法^[7-8]。热障涂层是能够隔绝外部高温,从而确保基体高温合金在较低温度下工作的高隔热陶瓷材料^[9]。常用的航空发动机热障涂层结构包括梯度结构、多层结构以及双层结构3种^[10]。在高温极端服役环境下,顶部陶瓷层与黏结层之间通常会生成热生长氧化物(TGO),黏结层可以充当陶瓷层与基体之间的“黏结剂”^[11-14]。到目前为止,应用效果最好且最广泛的热障涂层是由氧化钇稳定氧化锆(YSZ)所构成的体系。其中,氧化钇的质量分数通常控制在6%~8%^[5]。

随着现代航空发动机对高效率与大功率性能要求的日益提升,其工作温度也相应增高。然而,传统YSZ涂层最高耐受温度仅为1 473 K,已难以满足这一日益严苛的服役条件。国内外相关研究表明,在YSZ热障涂层中掺杂稀土氧化物可有效提升其防护性能,这主要归因于稀土元素所具有的强吸附能力及其在ZrO₂晶格中引入的畸变效应^[2]。制备涂层常用的方法包括大气等离子喷涂(APS)、悬浮液等离子喷涂(PSP)、电子束物理气相沉积(EB-PVD)和等离子喷涂-物理气相沉积(PS-PVD)^[15-19]。

高熵稀土氧化物陶瓷材料是一种多组元固溶体,通常由5种或更多的稀土元素以近似等摩尔质量的比例构成^[20-21]。高熵稀土氧化物陶瓷材料具有以下3个优点:①优异的隔热性,通过晶格畸变效应增强了材料的声子散射,减小了原子扩散速率,降低了材料的热导率^[22-23];②良好的稳定性以及抗烧蚀性能,通过高熵效应提高了材料的混乱度,稳定了体系,增强了材料的抗烧蚀性能^[24];③灵活的可调性,通过各种元素的鸡尾酒式掺杂,使得材料的性能易随元素的添加而发生改变。但这类材料也有一定的缺陷,如脆性大、热循环寿命严重不足等。利用纳米材料通过表面涂层技术制备纳米结构陶瓷涂层,成为解决上述缺陷的方法之一^[25]。例如,王铀^[26]开发了TiO₂/Al₂O₃纳米结构热障涂层,该涂层具有良

好的耐磨性、耐腐蚀性、抗弯性能及较长的疲劳寿命。

与高温合金相比,陶瓷基复合材料(CMC)具有耐高温(1 723 K)、低密度(2.8 g/cm³)、抗氧化、强韧性等优点。实践表明,采用CMC代替传统高温合金能够减轻50%~70%的发动机质量,同时减少20%~50%的空气冷却量,大幅提高发动机工作效率^[27-29]。但是当处于高温环境时,表面保护性SiO₂会与大气中的水蒸气(质量分数为10%)反应生成Si(OH)₄,使材料性能快速下降^[30]。针对这一难题,NASA提出了环境障涂层(EBCs)的概念,并将其分为3代^[31]。

第1代环境障涂层能够提高陶瓷基复合材料稳定性并延长其使用寿命^[32]。但是涂层在长期热循环后会产生微裂纹,并且快速脱落失效^[33-34]。第2代环境障涂层是在第1代涂层的基础上进行改良升级得到的,采用Si基底/莫来石/BSAS(BaO-SrO-Al₂O₃-SiO₂)的多层涂层体系。该涂层体系具有良好的热稳定性,能有效降低热失配应力,避免产生裂纹^[35-36]。但BSAS在高温下会挥发,且在1 573 K以上时会与Si黏结层发生反应,导致涂层过早失效^[37]。LEE^[35]对比了稀土硅酸盐与第2代环境障涂层的高温热稳定性,发现纳米结构稀土硅酸盐能够有效提高环境障涂层的工作温度。在此基础上,加入Y、Yb能够使涂层获得低的热膨胀系数、良好的耐腐蚀性以及高温热稳定性^[38-39]。为此,NASA对第3代环境障涂层提出了两点要求:首先,应具有良好的高温热稳定性;其次,在1 773 K以上时不与莫来石层产生化学反应^[40]。第3代环境障涂层体系主要由Si黏结层+莫来石层+纳米结构稀土硅酸盐组成^[41]。第3代环境障涂层解决了界面结合强度差、裂纹萌生、易挥发等问题,但尚未被应用于工业实践中。目前,研究最热门、最有应用前景的是硅酸锆体系,但其还存在界面结合强度需提高的问题。另外,在涂层喷涂过程中,喷砂预处理和喷涂过程中可喷涂粉体的机械冲击易造成CMC陶瓷基体裂纹萌生;在高温考核过程中出现裂纹扩展,造成服役寿命不足。此外,虽然碳化硅的耐高温性能优于金属合金,但其抗氧化性较差,当接触CMAS(CaO-MgO-Al₂O₃-SiO₂)火山灰时其腐蚀速度加快,在含水蒸气条件下易发生水氧腐蚀。

本文介绍了航空发动机使用的传统/高熵化/纳米化热障涂层的发展概况,对比分析了各涂层的性

能差异,系统探讨了高熵稀土酸盐的力学和热物理性能,总结了传统/高熵化/纳米化热障涂层的优缺点,展望了热障涂层未来的发展趋势。

1 热障涂层材料研究进展

1.1 传统热障涂层材料

热障涂层作为高温合金的表面防护涂层,其陶瓷面层具备高熔点(2 973 K)、低热导率($2.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)、高热膨胀系数($1.1 \times 10^{-5} \text{ K}^{-1}$)、抗烧结及优异力学性能^[42],可通过低导热特性降低基材温度,同时显著提升合金的抗高温氧化、抗热腐蚀及抗热震性能,实现对基体的有效防护^[43-45]。在航空发动机领域,热障涂层技术不仅能减少约20%的燃油消耗,还可延长部件使用寿命;在船舶、汽车等领域,该技术也得到了广泛的应用^[46-48]。在较高的环境温度下,涂层的传热主要依靠晶格振动和辐射进行。该过程与声子的平均自由程密切相关,而平均自由程由声子间的碰撞散射,以及声子与晶界、缺陷、杂质之间的散射共同决定。研究表明,当涂层材料拥有较大的分子量、复杂的晶体结构、无方向性的键合时,其热导率更低,从而降低基材温度,提高其服役寿命^[49-50]。

研究表明,添加Pt、Hf、Dy等元素能有效提升热障涂层的抗热冲击性能与使用寿命^[51],然而,目前在航空发动机高温部件上得到成功应用的实例仍仅限于YSZ体系^[52]。虽然纯 ZrO_2 同样具有高熔点、低热导率特性以及优异的力学性能,但在热循环过程中,纯 ZrO_2 的亚稳态四方相会转变为单斜相,如图1所示。这种相变会使涂层体积变化4%~6%,从而增加热障涂层中的内应力,导致纯 ZrO_2 涂层脱落失效^[6]。

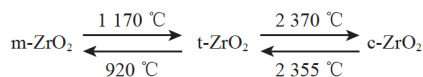


图1 纯 ZrO_2 在升温过程中的相转变^[53]

Fig.1 Phase transition of pure ZrO_2 during heating

为解决这一问题,研究人员在纯 ZrO_2 体系中加入少量的 Y_2O_3 、 CeO_2 等,将其作为稳定剂来抑制纯 ZrO_2 在热循环过程中的相变^[2]。这就使得当温度超过1 473 K时,YSZ体系中能够存在大量亚稳态四方相 t' ,并且在晶格畸变时, t' 晶胞被拉伸为长方形。低温相变增韧与高温铁弹增韧构成的双重增韧

机制,显著提升了热障涂层的韧性及其抗热震性能^[54]。随着研究的深入,STECURA^[55]对不同含量的YSZ体系进行了长期热循环实验,发现在纯 ZrO_2 体系中添加6%~8%(质量分数)的 Y_2O_3 ,可以获得相对较好的抗热震性能。 Y_2O_3 稳定剂添加量对涂层热循环寿命的影响如图2所示。

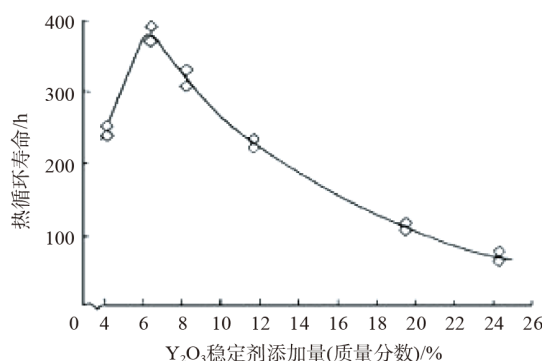


图2 不同 Y_2O_3 稳定剂添加量对涂层热循环寿命的影响^[55]

Fig.2 Effect of different Y_2O_3 stabilizer addition on thermal cycle life of coating

YSZ虽具备优异的隔热性能,但在高温服役中仍存在显著缺陷。①当工作温度超过1 473 K时,YSZ中纳米 t' 相会逐步分解为稳态 t 相和立方 c 相,随后 t 相向单斜 m 相转变,伴随4%~5%的体积膨胀,导致涂层内部应力累积并诱发裂纹扩展,最终引发涂层剥落失效^[5];同时,高温烧结会降低YSZ孔隙率,削弱声子散射效应,使其热导率升高^[2],且弹性模量增加会导致裂纹稳定性恶化^[56-57]。②发动机吸入的CMAS硅酸盐熔体通过毛细作用渗入涂层孔隙,会与 Y_2O_3 反应加速YSZ的相变,进一步加剧涂层开裂^[58-60]。③陶瓷层/TGO层/黏结层间的热膨胀系数差异显著,在热循环过程中界面处将产生应变失配应力;尽管黏结层可通过塑性变形释放TGO层/黏结层界面应力,但陶瓷层的低应变能力导致TGO层蠕变成为主要的应力释放途径;随着TGO层增厚蠕变能力下降,界面热应力迅速上升,最终引发YSZ涂层整体剥落^[61-62]。因此,亟待开发兼具高相稳定性、低热导率、强抗CMAS侵蚀能力及优异热匹配性的新型热障涂层材料。

选择更好的 ZrO_2 稳定剂,从而提高传统热障涂层的寿命成为未来研究的一个主要方向。已有文献表明,在 ZrO_2 中加入质量分数为8%的 Yb_2O_3 后,在相同的热冲击实验条件下,涂层的寿命比加入 Y_2O_3 的

ZrO₂涂层提高了近30%^[63]。BRANDON和TAYLOR^[64]在ZrO₂体系中加入质量分数为25%的CeO₂,发现在1 773 K下热循环100 h后,涂层物相仍为稳态t相;在1 873 K下热循环100 h后,仅有13%的单斜m相产生,大大提高了涂层使用寿命。

传统热障陶瓷材料的另一分支为焦绿石结构陶瓷材料(如La₂Zr₂O₇, LZ)。与YSZ体系相比,这种焦绿石涂层具有如下优点:①在温度升至熔点期间无相变产生;②抗烧结性能优异;③热导率极低;④氧离子扩散系数较低,能保护黏结层和基体金属不被氧化腐蚀^[65]。董智杰等^[66]研究表明,稀土锆酸盐的晶体结构与离子半径有关,当 $r(\text{RE}^{3+})/r(\text{Zr}^{4+})$ 比值处于1.46~1.61之间时为有序焦绿石结构,当比值处于1.35~1.44之间时为无序萤石结构,如图3所示。然而,LZ的热膨胀系数过低,通常与具有高热膨胀系数的黏结层和基体金属不匹配。因此,未来需要开发新型焦绿石结构的热障涂层材料。

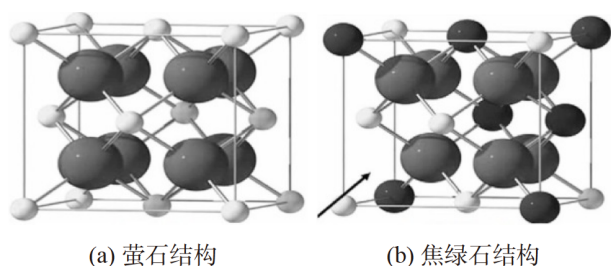


图3 稀土锆酸盐的两种晶体结构^[50]

Fig.3 Two crystal structures of rare earth zirconic acid

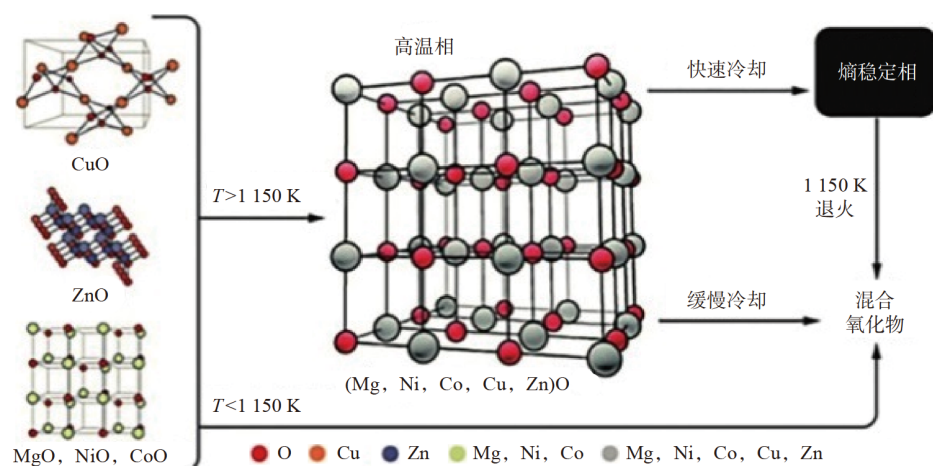


图4 (Mg,Co,Ni,Zn,Cu)O高熵陶瓷材料在高温下的相变^[70]

Fig.4 Phase transition of (Mg, Co, Ni, Zn, Cu)O high-entropy ceramic materials at high temperature

1.2 高熵热障涂层材料

近年来,高熵陶瓷材料成为材料领域的研究热点之一,其概念可追溯至21世纪初学者提出的高熵合金^[67-68]。该领域在航空用陶瓷材料方面取得了突破性进展。ROST等^[69]以多种氧化物为原料成功制备出具有面心立方结构的高熵陶瓷(Mg,Co,Ni,Cu,Zn)O材料,该材料在1 200 K时会发生高熵相至普通相的转变(图4^[70]),这是高熵陶瓷材料在航空陶瓷领域的首次应用。高熵陶瓷材料具备高熵效应、晶格畸变效应、迟滞扩散效应及“鸡尾酒”效应4大核心效应^[71],使其热学、力学及磁学性能优于传统陶瓷^[72]。

高熵陶瓷材料因其晶格被多种元素离子占据而产生强烈畸变,增强了声子散射并导致热导率降低,同时具备较高的热膨胀系数和由迟滞扩散效应带来的较低的扩散系数。高熵陶瓷材料优异的综合性能完全符合热障涂层对高隔热的选材要求,也使其成为新一代热障涂层的重点研究方向。已有研究通过APS技术制备了具有萤石相结构的高熵稀土热障涂层(La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})₂Zr₂O₇^[73],并对其在1 373 K下开展了长期热循环实验,发现相较于传统热障涂层,其耐久性大幅度提升。原因在于,迟滞扩散效应抑制了实验过程中涂层的收缩;与此同时,高熵热障涂层的热膨胀系数也出现了显著提升。目前,对于这种材料的研究仍处于初始阶段,未来需要进一步开展实验并形成完备的研究体系。

随着航空航天材料技术的不断发展,高熵陶瓷

材料在热障涂层领域中的研究也得到了不断深入。目前,高熵稀土锆酸盐^[74]、高熵稀土钽酸盐^[75]、高熵稀土钨酸盐^[76]、高熵稀土钼酸盐^[77]、高熵稀土铌酸盐^[78]等材料体系为热障涂层材料的主要研究对象。为探讨高熵稀土氧化物在航空发动机热障涂层中的应用,将主要从力学性能、热物理性能等方面对高熵陶瓷材料进行对比分析。

稀土氧化物作为热障涂层材料应用的可行性主要由维氏硬度(HV)、杨氏模量(E)、断裂韧性(K_{IC}) 3个因素决定。表1示出了高、中熵稀土氧化物的力学性能指标。可以看出, $(La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$ 的杨氏模量大于高熵稀土锆酸盐 $(Yb_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$, 但是其断裂韧性明显低于后者。该结果表明,高熵稀土锆酸盐能够承受更强的热冲击伤害,有利于减小热失配应力,从而避免发生脆性断裂。中熵稀土锆酸盐 $(Sm_{1/3}Eu_{1/3}Dy_{1/3})_2Zr_2O_7$ 的3项指标均小于 $(Sm_{0.2}Eu_{0.2}Tb_{0.2}Dy_{0.2}Lu_{0.2})_2Zr_2O_7$, 再次证明了高熵稀土锆酸盐 $(Sm_{0.2}Eu_{0.2}Tb_{0.2}Dy_{0.2}Lu_{0.2})_2Zr_2O_7$ 具有更高的损伤上限,能够防止热障涂层因高温裂纹扩散而脱落失效^[87]。

对比传统8YSZ涂层体系,高熵稀土钽酸盐的杨氏模量更低,表明其能够承受更长时间的热冲击伤害,并且其硬度同样低于7YSZ。在材料设计中,需平衡显微硬度与断裂韧性。降低硬度虽有助于阻碍裂纹扩展和消除残余应力,但硬度过低会削弱强度。目前,高熵稀土钽酸盐面临的关键问题在于其断裂韧性远低于7YSZ,因此提升其韧性是实现其在热障

涂层中应用的前提。

研究表明,高熵稀土钽/铌酸盐具有较高的断裂韧性与硬度。以HE-RETa₃O₉为例^[88],该材料具有稳定的晶体结构和良好的成分均匀性,其维氏硬度为140~180 GPa,杨氏模量为7~10 GPa,通过脆-韧性转变可使其断裂韧性达到1.8~2.5 MPa·m^{1/2}。ZHAO等^[89]测试了高熵稀土钽/铌酸盐的热学性能及力学性能。结果表明,HE-RE₃TaO₇、RE₃(Nb_{1/2}Ta_{1/2})O₇等高熵陶瓷材料的维氏硬度均在11~12 GPa之间,明显高于RE₃TaO₇和RE₃NbO₇,并与YSZ的硬度接近。HE-RE₃TaO₇、RE₃(Nb_{1/2}Ta_{1/2})O₇具有较高的硬度、优异的高温相稳定性、良好的化学相容性以及TGO稳定,表明高熵稀土氧化物陶瓷材料是极具发展前景的热障涂层材料。LI等^[90]通过常规烧结工艺在1 773 K下保温10 h,成功制备了平均晶粒尺寸为3.77~4.46 μm的(5RE_{0.2})Ta₃O₉材料。得益于高熵陶瓷材料特有的迟滞扩散效应,该材料呈现出缓慢的晶粒生长速率与细化的晶粒结构。其维氏硬度为6.90~7.93 GPa,断裂韧性高达3.09~6.98 MPa·m^{1/2},显著优于传统陶瓷材料。研究发现,6RETaO₄材料存在单斜-四方二级铁弹相转变的铁弹畴,使其维氏硬度达到较好的9.97 GPa^[86]。通过改变RETaO₄的晶界数与晶粒尺寸,其硬度有所降低,进而减缓了裂纹扩散,并减少了热应力损伤,最终提高了RETaO₄材料的热容和断裂韧性^[91]。ZHU等^[92]采用颗粒发泡法和固相法制备了高熵稀土铌酸盐材料,其断裂韧性和维氏硬度分别达到2.09~

表1 稀土氧化物力学性能指标
Table 1 Mechanical properties of rare earth oxides

材料	E/GPa	HV/GPa	$K_{IC}/(MPa \cdot m^{1/2})$	数据来源
$(Sm_{1/3}Eu_{1/3}Dy_{1/3})_2Zr_2O_7$	245.00	11.85	1.80	[79]
$(Sm_{0.2}Eu_{0.2}Tb_{0.2}Dy_{0.2}Lu_{0.2})_2Zr_2O_7$	257.00	12.42	2.24	[79]
$(Yb_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$	171.55	9.63	1.80	[80]
$(La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$	197.51	13.50	1.38	[80]
LNYS	166.84	8.32	1.94	[81]
LNLC	151.98	8.67	2.06	[81]
LNLC	181.36	7.44	1.90	[82]
EuTaO ₄	175.00	4.38	—	[83]
GdTbO ₄	154.00	6.10	—	[83]
(5RE _{0.2})TaO ₄	141.36	8.00	3.05	[84]
HE-RETa ₃ O ₉	—	5.90	3.57	[85]
4RETaO ₄	—	7.92	—	[86]
5RETaO ₄	—	6.15	—	[86]
6RETaO ₄	—	9.97	—	[86]

6.78 MPa·m^{1/2}和11~12 GPa。此外,受4大效应影响,高熵稀土氧化物陶瓷材料通常具有高孔隙率与低密度等特点,使其拥有更好的抗热震性能。
高温下部分单组分稀土酸盐及高熵稀土酸盐的

热物理性能如表2所示。REN等^[79]研究表明,高熵稀土锆酸盐的热导率低于La₂ZrO₇,但其热膨胀系数更高。图5展示了5RE₂Zr₂O₇的热物理性能和高温相稳定性。由于极端的成分无序,高熵稀土酸盐存在

表2 高温下部分高熵稀土酸盐及单组分稀土酸盐的热物理性能^[79]
Table 2 Thermophysical performance parameters of partially high entropy rare earth salts and single component rare earth salts at high temperature

材料	热导率/(W·m ⁻¹ ·K ⁻¹)	热膨胀系数/(10 ⁻⁶ K ⁻¹)	数据来源
La ₂ ZrO ₇	1.56 (1 000 ℃)	9.10 (1 000 ℃)	[45]
Nd ₂ ZrO ₇	1.25 (800 ℃)	9.50 (800 ℃)	[93]
Gd ₂ ZrO ₇	1.91 (1 200 ℃)	10.50 (1 000 ℃)	[93]
(La _{0.2} Ce _{0.2} Nd _{0.2} Sm _{0.2} Eu _{0.2}) ₂ Zr ₂ O ₇	0.76 (25 ℃)	—	[94]
(Sm _{0.2} Eu _{0.2} Tb _{0.2} Dy _{0.2} Lu _{0.2}) ₂ Zr ₂ O ₇	0.86 (1 000 ℃)	11.00 (1 000 ℃)	[87]
LNYS	1.55 (1 000 ℃)	12.40 (1 200 ℃)	[81]
LNLYC	1.04 (1 000 ℃)	12.60 (1 200 ℃)	[81]
Ln ₂ Ce ₂ O ₇	0.45 (1 000 ℃)	11.00 (1 000 ℃)	[82]
(Dy _{0.25} Er _{0.25} Y _{0.25} Yb _{0.25}) ₃ NbO ₇	0.86 (25 ℃)	9.70 (1 200 ℃)	[95]
(Dy _{0.2} Ho _{0.2} Er _{0.2} Y _{0.2} Yb _{0.2}) ₃ NbO ₇	0.72 (25 ℃)	10.20 (1 200 ℃)	[95]
(Y _{0.2} Ce _{0.2} Sm _{0.2} Gd _{0.2} Dy _{0.2})TaO ₄	1.20 (900 ℃)	10.30 (1 200 ℃)	[84]
(Y _{0.2} La _{0.2} Ce _{0.2} Nd _{0.2} Gd _{0.2})Ta ₃ O ₉	1.69 (800 ℃)	6.84 (1 500 K)	[85]
(Nd _{1/4} Sm _{1/4} Eu _{1/4} Gd _{1/4})TaO ₄	1.24 (1 000 ℃)	8.96 (1 200 ℃)	[86]
(Nd _{1/5} Sm _{1/5} Eu _{1/5} Gd _{1/5} Dy _{1/5})TaO ₄	1.29 (1 000 ℃)	9.05 (1 200 ℃)	[86]

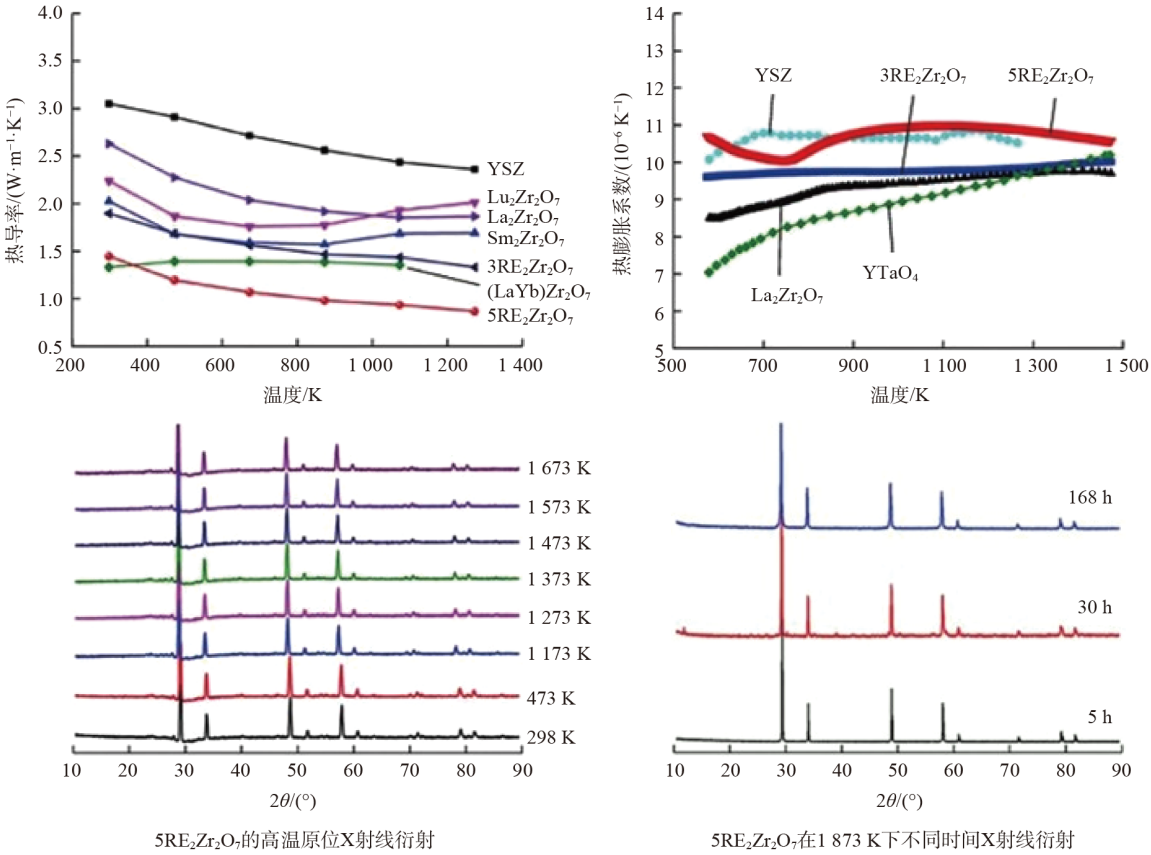


图5 5RE₂Zr₂O₇的热物理性能^[2]
Fig.5 Thermophysical performance of 5RE₂Zr₂O₇

化学键波动、局部晶格畸变和原子半径失配。复杂的晶体结构与极端的成分无序性增强了声子散射,使得致密的高熵多组分陶瓷材料在具备较高热膨胀系数的同时,保持了较低的热导率;此外,局部离子电荷无序性的加剧与构型熵的存在,被认为是高熵稀土酸盐热导率进一步下降的关键原因。

LI等^[96]在1 273 K下将 ZrO_2 与 La_2O_3 、 Eu_2O_3 、 Nd_2O_3 、 Sm_2O_3 、 Gd_2O_3 、 Y_2O_3 混合反应,最终制备出高熵稀土钨酸盐 $\text{HE}(\text{5RE}_{1/5})_2\text{Zr}_2\text{O}_7$ 。在573~1 473 K温度范围内,其热导率均低于 $1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$,较同等孔隙度的YSZ体系降低了约50%^[97]。LUO等^[80]在1 773 K下合成了热导率为 $1.003 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ 的高熵陶瓷材料 $(\text{Yb}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$,较同等温度下单组分 $\text{La}_2\text{Zr}_2\text{O}_7$ 的热导率低42%。上述结果表明,高熵稀土钨酸盐陶瓷材料具有优良的综合性能,可作为热障涂层的潜在材料。

晶格畸变导致高熵稀土钨酸盐的原子扩散速率较小,因此高熵稀土钨酸盐的晶格尺寸无序参数与热导率呈负相关。XUE等^[98]在1 673 K下制备了 $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Ce}_2\text{O}_7$ 高熵陶瓷材料,在该温度下其热导率达到 $0.92 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$,降低了热传输。ZHANG等^[99]制备了 $(\text{La}_{0.25}\text{Dy}_{0.25}\text{Yb}_{0.25}\text{Y}_{0.25})_2\text{Ce}_2\text{O}_7$ 和 $(\text{La}_{0.25}\text{Nd}_{0.25}\text{Yb}_{0.25}\text{Y}_{0.25})_2\text{Ce}_2\text{O}_7$ 两种高熵稀土钨酸盐材料,这两种新型材料的热导率明显低于YSZ和 $\text{Sm}_2\text{Ce}_2\text{O}_7$,具有更好的保温能力。这主要归因于晶格畸变、氧空位声子散射以及复杂的元素组成等因素的共同作用^[81]。此外,受“鸡尾酒”效应影响,高熵陶瓷材料大量的氧空位和多组分稀土离子极大地增强了声子散射能力,导致 $(\text{La}_{0.25}\text{Dy}_{0.25}\text{Yb}_{0.25}\text{Y}_{0.25})_2\text{Ce}_2\text{O}_7$ 的热导率低于 $(\text{La}_{0.25}\text{Nd}_{0.25}\text{Yb}_{0.25}\text{Y}_{0.25})_2\text{Ce}_2\text{O}_7$ 。

相较于单组分钨酸盐,高熵稀土钨酸盐的热导率和热膨胀系数均较高。胡万鹏等^[100]通过固相烧结和热压烧结制备了 $(\text{Yb}_{0.2}\text{Lu}_{0.2}\text{Ho}_{0.2}\text{Er}_{0.2}\text{Tm}_{0.2})_4\text{Hf}_3\text{O}_{12}$ 和 $(\text{La}_{0.2}\text{Gd}_{0.2}\text{Ho}_{0.2}\text{Er}_{0.2}\text{Tm}_{0.2})_4\text{Hf}_3\text{O}_{12}$ 两种高熵稀土钨酸盐。相较于单组分钨酸盐,其具有较高的弹性模量、更低的热膨胀系数和热导率。这是因为高熵稀土钨酸盐的无序性和晶格畸变造成了声子散射,最终降低了热导率。研究表明,焦绿石结构的钨酸盐(如 $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Pr}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_2\text{Hf}_2\text{O}_7$)的热导率($1.00\sim 1.24 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)极低,且高温综合性能优异^[101]。相较于无序萤石结构钨酸盐,焦绿石结构

的钨酸盐具有热导率更低和离子导电性更高的优势。国外研究也证实,在1 073 K时 $\text{Eu}_2\text{Hf}_2\text{O}_7$ 的热导率可达 $1.30 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ^[102]。与此同时,YE等^[103]利用萤石结构高熵钨酸盐 $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Pr}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_2\text{Hf}_2\text{O}_7$ 的严重晶格畸变,同样实现了低热导率($0.93 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)与超高显微硬度($1\ 089\text{HV}_{0.3}$)的结合。

高熵稀土钨酸盐拥有不次于上述高熵稀土钨酸盐的综合性能。陈琳和冯晶^[104]通过高温固相法制备了 RE_3TaO_7 ($\text{RE}=\text{La}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}, \text{Dy}$)和 RETa_3O_9 ($\text{RE}=\text{Ce}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}, \text{Dy}, \text{Er}$)材料。上述两种材料具有高熔点、低热导率、高热膨胀系数和良好的高温相稳定性,符合热障涂层材料的选材标准。WANG等^[105]制备了含有m和m'相的 RETaO_4 材料。实验表明,该材料的比热容随温度升高而逐渐增大,可能是在加热期间陶瓷体积膨胀和声子激发作用所导致。图6为 RETaO_4 和YSZ材料的热导率,可以看出 RETaO_4 的热导率随孔隙率增大而降低,并且低于8YSZ。据此,可以推断 RETaO_4 有作为热障涂层材料的潜力,且具有更好的热性能。

RETaO_4 的热导率主要受 RE^{3+} 的离子半径和孔隙率影响,后者为主要影响因素。楼志豪等^[86]制备了3种新型单相单斜 RETaO_4 材料,其气孔率均小于3%,晶粒结构紧密且稀土元素在晶格中均匀分布,同时均具有良好的相稳定性。此外, RETaO_4 材料还具有较低的热导率,这是因为高熵陶瓷材料存在严重的晶格畸变效应,导致声子散射增加。退火也会对高熵稀土钨酸盐产生显著影响。LI等^[90]将 $(\text{5RE}_{0.2})\text{Ta}_3\text{O}_9$ ($\text{RE}=\text{La}, \text{Ce}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}$ 中的5种元素)在1 723 K下进行长时间退火,发现随着时间的增加,其晶粒尺寸由 $3.76 \mu\text{m}$ 逐渐增大为 $9.05 \mu\text{m}$ 。在室温至773 K内,其热导率仅为YSZ材料的50%($1.14\sim 1.98 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$);热膨胀系数在1 073 K时为 $(5.60\sim 7.80)\times 10^{-6} \text{ K}^{-1}$ 。

MIYAZAKI等^[87]在298~1 673 K温度范围内测试了 $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{Zr}_2\text{O}_7$ 的原位高温X射线衍射(XRD)图谱,发现当温度从298 K升至1 673 K时,其晶体结构仍为缺陷萤石单相结构;同时在1 873 K下测试了这种高熵稀土钨酸盐的长期热稳定性,发现热处理后的晶体结构与原始烧结体保持一致,表明 $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{Zr}_2\text{O}_7$ 具有良好的高温相稳定性。CMAS主要由 CaO-MgO-

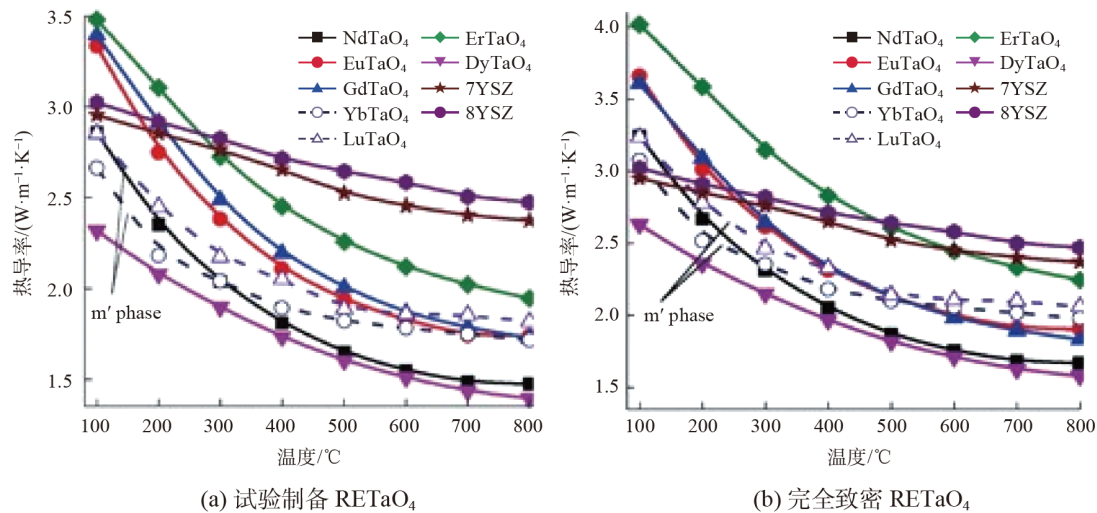


图6 YSZ和 RETaO_4 的热导率^[2]
Fig.6 Thermal conductivities of YSZ and RETaO_4

Al_2O_3 - SiO_2 硅酸盐组成,当航空发动机工作温度超过1 473 K时,CMAS会渗入涂层并腐蚀,严重缩短涂层热循环寿命。TU等^[106]对比了 $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$ -1材料与单组分锆酸盐 $\text{La}_2\text{Zr}_2\text{O}_7$ 的抗CMAS腐蚀性能。结果表明,前者的抗CMAS腐蚀性能明显优于后者。这是因为 $\text{La}_2\text{Zr}_2\text{O}_7$ 材料存在晶界腐蚀现象,而 $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$ -1具备高熵陶瓷材料特有的迟滞扩散效应,形成了晶粒细密的反应层,使得在陶瓷面层和反应层均未出现水平或垂直裂纹,仅通过溶解后再沉淀形成CMAS腐蚀。除上述原因外, $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$ -1材料稳定性较强,能够抑制陶瓷涂层在冷却期间的开裂。因此, $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$ -1可作为热障涂层的优质候选材料。

REN等^[107]在1 673 K下将 $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{Ce}_2\text{O}_7$ 和 $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{ZrCeO}_7$ 两种高熵稀土铈酸盐长时间烧结(0~168 h),并测试了相对密度,发现短时间内(0~5 h)两者的相对密度迅速增加。在烧结168 h后, $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{Ce}_2\text{O}_7$ 的断口XRD检测没有发现第二相,但是表面XRD检测出第二相,这可能是部分表面 CeO_2 高温挥发所致。 $(\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Tb}_{0.2}\text{Dy}_{0.2}\text{Lu}_{0.2})_2\text{ZrCeO}_7$ 经表面、断口XRD检测均未发现第二相,表明 Zr^{4+} 的加入能够提升高熵陶瓷材料的高温相稳定性和抗烧结性能。TANG等^[81]对LNYLC和LNYSC高熵稀土铈酸盐进行了差示扫描量热(DSC)测试以及热重分析(TGA),发现在1 473 K以下,DSC曲线

没有产生显著吸热或放热峰,表明其在升温过程中没有发生相转变,具有良好的高温相稳定性;TGA曲线平缓,说明在升温过程中无物质质量的变化。ZHANG等^[108]对LNYSLC同样进行了DSC测试和TGA,实验结果与TANG等^[81]的相似,表明材料具有较强的晶格稳定性。XUE等^[98]在298~1 673 K温度范围内,对 $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Ce}_2\text{O}_7$ 进行了原位XRD物相检测。结果表明,1 673 K下的物相结构与298 K下的一致,均为萤石结构,表明其具有良好的高温相稳定性。研究进一步发现,随着烧结温度升高,晶格膨胀造成衍射角偏移至低角度,使得晶格常数有所增加。

对高熵稀土钽酸盐 $\text{HE-RETa}_3\text{O}_9$ 在298~973 K温度范围内进行XRD物相检测发现,其始终保持四方结构,在升温期间并无相变发生^[90],表明高熵稀土钽酸盐具有良好的相稳定性。WANG等^[84]通过第一性原理计算了 $(5\text{RE}_{0.2})\text{TaO}_4$ 扩胞之后的混合焓,发现可以通过改变混合焓来降低体系吉布斯自由能,最终达到稳定陶瓷体系的目的。将氧化铝和 $\text{HE-RETa}_3\text{O}_9$ 在1 573~1 773 K短时间保温并进行XRD物相表征发现,仅存在 $\text{HE-RETa}_3\text{O}_9$ 和 $\alpha\text{-Al}_2\text{O}_3$ 峰,证明这种陶瓷材料与TGO层具有良好的相容性。

综上所述,相较于传统的YSZ涂层,高熵稀土酸盐具有较低的热导率、较高的热膨胀系数、优异的高温相稳定性以及良好的力学性能,能够延长基材服役寿命。其中,高熵稀土锆酸盐性能最优,目前相关

研究也最多。然而,相较于针对热物理、力学性能的研究,目前关于高熵稀土酸盐抗CMAS和水-氧腐蚀的研究较少。为此,未来需开展更多研究,以确保高熵稀土材料成为传统YSZ的可靠替代品。

1.3 纳米陶瓷涂层材料

由于结合纳米材料与表面工程技术的纳米涂层能够有效解决航空发动机、舰船在极端服役环境下由腐蚀、磨损、高温导致的寿命下降问题,因此纳米涂层一直备受国内外研究人员的重视。作为第4代防护涂层的代表,纳米结构的热障涂层因其优异的性能而备受瞩目。KEAR和SKANDAN^[109]对YSZ纳米涂层进行了热循环实验,发现YSZ纳米涂层能够提高热障涂层服役寿命的根本原因主要在于:①降低了涂层裂纹数量和长度,增加了其断裂韧性;②增加了涂层光电子散射,降低了整体热导率;③引入气孔,增加了声子散射,以及涂层本身具有良好的力学性能。综上所述,与传统热障涂层相比,纳米涂层具有更优异的力学性能、更低的热导率、较高的断裂韧性以及与基体间良好的结合强度,这些优势使其拥有更好的高温相稳定性,从而延长了其服役寿命^[110-112]。

LIMA等^[113]采用APS技术制备了纳米氧化锆涂层,测量了其弹性模量、表面粗糙度和显微硬度。结果表明,该纳米涂层表面较为光滑,且随着表面粗糙度的增加,显微硬度与弹性模量逐渐降低。CHEN和DING^[114]采用APS技术将纳米氧化锆涂层喷涂在不锈钢表面,并对两者间的结合强度进行了测定。结果表明,其结合强度(45 MPa)明显高于传统氧化锆涂层与不锈钢之间的结合强度;且该纳米涂层结构致密,气孔率仅为7%。CHEN等^[115]研究表明,利用APS技术制备的纳米氧化锆涂层的显微硬度(8.6 GPa)为常规氧化锆涂层的1.6倍。

黏结层氧化速率增大会降低热障涂层的使用寿命。ZHOU等^[116]通过液相等离子法制备了NiCrAlY黏结层,随后采用APS技术在黏结层上喷涂制备了8YSZ涂层,得到了纳米结构热障涂层。研究表明,纳米结构涂层具有良好的抗热循环氧化性能,在1 323 K下进行300次热循环后,纳米涂层的质量增益仅为1.200 mg/cm²。WANG等^[117]采用APS技术制备了100、300、500 μm的纳米YSZ涂层与传统YSZ涂层,并在1 473 K下进行了热循环实验。结果表明,在同一热循环次数经110 h后,300 μm的两种涂

层的质量增益分别为2.885 mg/cm²和3.222 mg/cm²。

吕艳红等^[118]采用APS技术获得了8YSZ纳米涂层,在298~1 173 K温度范围内,其热导率仅为0.556 5~0.647 9 W·m⁻¹·K⁻¹。原因在于,8YSZ涂层中存在大量未熔化的纳米颗粒和微小孔隙,导致声子散射增加,热导率降低。研究进一步表明,随着纳米涂层晶粒度的增加,其热导率将有所升高^[119]。经过多年研究,现已成功开发出纳米结构双层热障涂层技术。该技术通过将纳米陶瓷材料LZ与YSZ送粉,采用等离子喷涂技术制备出纳米结构的LZ/YSZ热障涂层。结果表明,这种纳米结构双层热障涂层的隔热性能显著优于传统YSZ涂层和纳米结果单层陶瓷YSZ涂层,在同等厚度下隔热效果提升了70%;且LZ/YSZ热障涂层具有更好的抗热震性能和抗氧化性能^[120],如图7、图8所示^[121-123]。这项技术为解决航空发动机热障涂层材料在1 473 K以上难以使用的问题提供了支持。

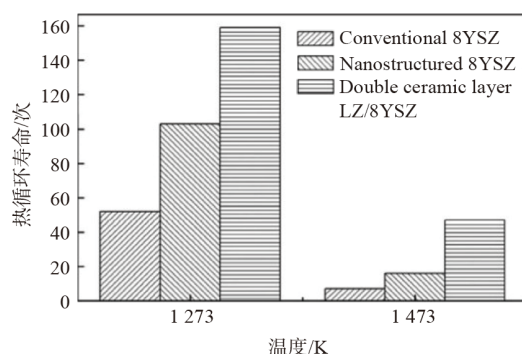


图7 3种涂层的热震实验结果^[121-123]

Fig.7 Cycles of thermal shock for three coatings

另一种热喷涂纳米氧化物陶瓷涂层为Al₂O₃/TiO₂体系^[120,124-125]。Al₂O₃/TiO₂纳米涂层的晶粒尺寸为10~40 nm,仅为传统涂层晶粒尺寸的1%;且其韧性强,拥有良好的耐磨性、抗腐蚀性、抗热震性以及优异的加工性能;该纳米氧化物陶瓷涂层技术曾获得“世界研究开发百项奖”^[126]和美国国防部“军民两用先进技术奖”^[127-128]。关于纳米稀土合金化的研究揭示出,纳米稀土的引入促使Al₂O₃/TiO₂涂层形成三维网状结构,这一结构演变带来了性能的飞跃:与微米涂层相比,其韧性、结合强度、耐磨性和疲劳性能分别提高了1倍、2倍、4~8倍和10倍^[129]。表3对比了Al₂O₃/TiO₂纳米涂层与传统涂层的抗腐蚀性能和力学性能。可以看出,纳米涂层的各方面

性能均优于传统涂层,特别是耐磨性、耐腐蚀性、抗弯性以及结合强度。

1.4 硅基陶瓷涂层材料

稀土硅酸盐种类繁多,按照化学式可分为稀土单硅酸盐(RE_2SiO_5)和稀土焦硅酸盐($\text{RE}_2\text{Si}_2\text{O}_7$)两类。稀土单硅酸盐中的 RE_2O_3 与 SiO_2 的比例为1:1,不同的RE其晶体结构不同^[130],如图9所示。当RE离子半径较大时,通常形成X1- RE_2SiO_5 ,可称其为低温相;当RE离子半径较小时,通常形成X2- RE_2SiO_5 ,可称其为高温相。两种晶体之间的转变温度约为1 473 K^[131]。稀土焦硅酸盐中的 RE_2O_3 与 SiO_2 比例为1:2,由于RE离子半径和烧结温度的不

同,稀土焦硅酸盐存在7种晶体结构,分别为:A、B(或 α)、C(或 β)、D(或 γ)、E(或 δ)、F、G型^[132]。 $\text{RE}_2\text{Si}_2\text{O}_7$ 多晶型结构均可视为由 REO_x ($x=6,7,8$)多面体和 SiO_4 四面体构成,如表4所示。

为提高环境障涂层的高温稳定性,需着重研究以上两类稀土硅酸盐与CMC基体之间的热膨胀系数适配性问题。FERNÁNDEZ-CARRIÓN等^[133]在高温下通过XRD测量了不同晶体结构的 $\text{RE}_2\text{Si}_2\text{O}_7$ 的热膨胀系数。实验表明,A- $\text{RE}_2\text{Si}_2\text{O}_7$ 的热膨胀系数最大,并且具有各向同性的热膨胀行为,其余晶体结构的 $\text{RE}_2\text{Si}_2\text{O}_7$ 则具有各向异性的热膨胀行为。ZHAO等^[134]采用溶胶-凝胶法制备了 $\text{Yb}_2\text{Si}_2\text{O}_7$ 粉

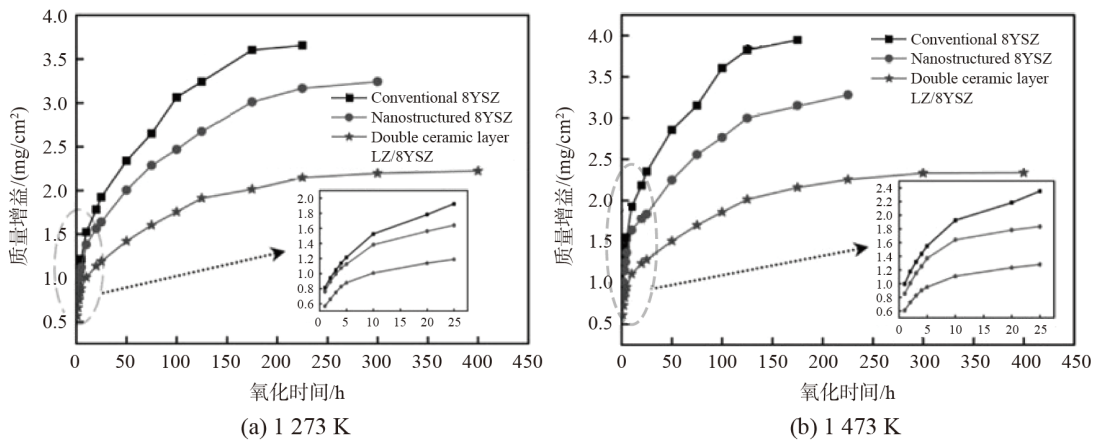


图8 不同时间和温度下3种涂层的质量增益^[121-123]
Fig.8 Weight gain of three coatings at different time and temperatures

表3 纳米结构 $\text{Al}_2\text{O}_3/\text{TiO}_2$ 涂层性能^[124]
Table 3 The properties of nanostructured $\text{Al}_2\text{O}_3/\text{TiO}_2$ coating

涂层	强度	硬度/GPa	耐磨性/($\text{N}\cdot\text{m}\cdot\text{mm}^{-3}$)	耐腐蚀性	可磨削性	疲劳寿命/次	抗弯性	结合强度/kPa
传统涂层	较差	1 000	7.5×10^3	良	较差	$<10^5$	涂层剥落	13 091
纳米涂层	优良	1 000	4×10^4	优异	优异	$>10^6$	弯曲180°无剥落	约55 120

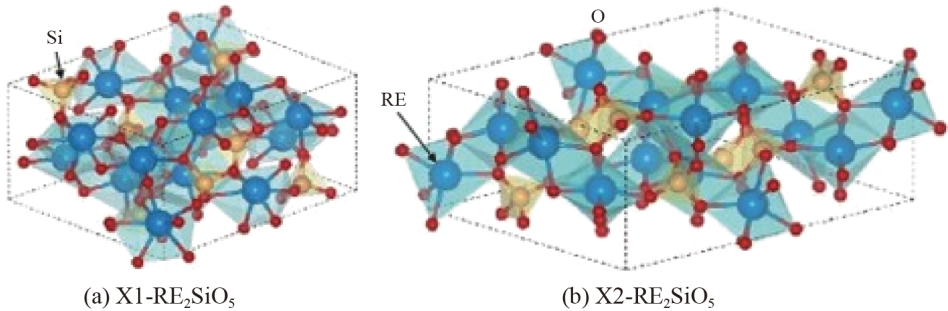


图9 RE_2SiO_5 的两种晶体结构^[130]
Fig.9 Two crystal structures of RE_2SiO_5

末,最终在1 773 K下通过热压烧结工艺制备了Yb₂Si₂O₇块体。采用第一性原理计算其弹性模量、硬度、断裂韧性和弯曲强度,发现在1 073~1 873 K温度之间,该材料的热膨胀系数范围为(3.7~4.5)×10⁻⁶ K⁻¹。表5总结了两类稀土硅酸盐的热物理性能。可以看出,稀土焦硅酸盐的热膨胀系数更适配于CMC基体,稀土单硅酸盐的抗水氧腐蚀性更好,但是其热膨胀系数较大。

环境障涂层可保护硅基复合材料免受高温水蒸气腐蚀,但由于其具有陶瓷材料的脆性大等问题,在极端环境下服役容易损伤失效——主要失效形式为高温水氧腐蚀、CMAS腐蚀以及热冲击失效等^[135],如图10所示。

1.4.1 高温水氧腐蚀

环境障涂层在高温下服役时,主要通过陶瓷面层发生氧化生成保护膜来保护航空发动机免受侵蚀。但由于陶瓷材料脆性大,在长期热循环过程中,易导致涂层中萌生裂纹并扩展。随着裂纹的出现,大气中的水蒸气通过裂纹与Si黏结层发生反应,生成Si(OH)₄等高温挥发化合物,引起环境障涂层尺

寸与形状的改变,最终造成涂层脱落失效,如图11所示。为提高环境障涂层使用寿命,应尽量避免Si黏结层与水蒸气在高温下发生反应^[136]。JIAN等^[137]通过调整APS参数在硅基复合材料(SiC_f)上制备了双层环境障涂层(Yb₂Si₂O₇+Si)体系,研究了其耐热性和耐水氧腐蚀性能。结果表明,在热循环期间,陶瓷面层表面产生了气孔和裂纹,在Si黏结层与Yb₂Si₂O₇面层之间发生了氧化反应,使得TGO层产生过多,生长应力逐渐增大,最终使涂层脱落失效。UENO等^[138]通过反应烧结与等离子喷涂在SiN基材表面制备了Lu₂Si₂O₇/Lu₂Si₂O₇+莫来石/Lu₂Si₂O₇多层体系,并在1 573 K下使用高温蒸汽装置进行了腐蚀实验。结果表明,在腐蚀过程中该环境障涂层具备较好的抗腐蚀性能,但由于Lu₂Si₂O₇被水汽腐蚀而产生了孔隙,导致剩余的水蒸气扩散至Si黏结层,并与Si黏结层发生化学反应生成了TGO。

1.4.2 CMAS腐蚀

在高温环境中,跑道灰尘、沙漠灰尘等会生成熔融玻璃态沉积物——CMAS相。航空发动机工作时,这些熔融玻璃态沉积物会通过环境障涂层中的

表4 RE₂Si₂O₇的晶体结构、空间群和晶系^[130]
Table 4 Crystal structures, spatial groups, and crystal systems of RE₂Si₂O₇

晶体结构	元素	空间群	晶系
A	La, Pr, Nd, Sm, Eu	<i>P</i> 4 ₁ 22- <i>P</i> 4 ₁	四方晶系
B(α)	Eu, Gd, Tb, Dy, Ho, Er	<i>P</i> 1- <i>P</i> 1	三斜晶系
C(β)	Ho, Er, Tm, Yb, Lu	<i>C</i> 2/ <i>m</i> - <i>C</i> 2- <i>C</i> <i>m</i>	单斜晶系
D(γ)	Ho, Er	<i>P</i> 2 ₁ / <i>a</i>	单斜晶系
E(δ)	Eu, Gd, Tb, Dy, Ho	<i>P</i> _{nam} - <i>P</i> _{na} 2 ₁	正交晶系
F	Sm, Eu	<i>P</i> 1- <i>P</i> 1	三斜晶系
G	La, Ce, Pr, Nd, Sm	<i>P</i> 2 ₁ / <i>n</i>	伪正交晶系

表5 稀土硅酸盐材料的热物理性能^[130]
Table 5 Thermophysical properties of rare earth silicate materials

材料	熔点/℃	热膨胀系数/(10 ⁻⁶ K ⁻¹)	热导率/(W·m ⁻¹ ·K ⁻¹)	<i>E</i> /GPa
Yb ₂ SiO ₅	1 950	7~8	2.3~1.5 (300~1 400 K)	149
Yb ₂ Si ₂ O ₇	1 850	3.7~4.5 (800~1 600 K)	4.6~2.0 (300~1 400 K)	168
Y ₂ SiO ₅	1 980	6.9 (473~1 623 K)	1.6~1.9 (473~1 673 K)	124
Y ₂ Si ₂ O ₇	1 775	3.9 (300~1 527 K)	4.9~1.9 (300~1 400 K)	155
Lu ₂ SiO ₅	2 010	5.92 (473~1 623 K)	3.3~1.7 (300~1 073 K)	176
Lu ₂ Si ₂ O ₇	—	3.8	4.5~1.7 (300~1 300 K)	—
Er ₂ SiO ₅	1 980	5.9 (473~1 623 K)	1.4~1.5 (473~1 673 K)	157
Gd ₂ SiO ₅	1 900	10.3 (473~1 623 K)	1.45 (273~1 573 K)	—
Sc ₂ SiO ₅	—	5.0~6.0	2.3~3.5 (473~1 673 K)	—
Sc ₂ Si ₂ O ₇ +Sc ₂ O ₃	1 860	5.0~6.0	—	—

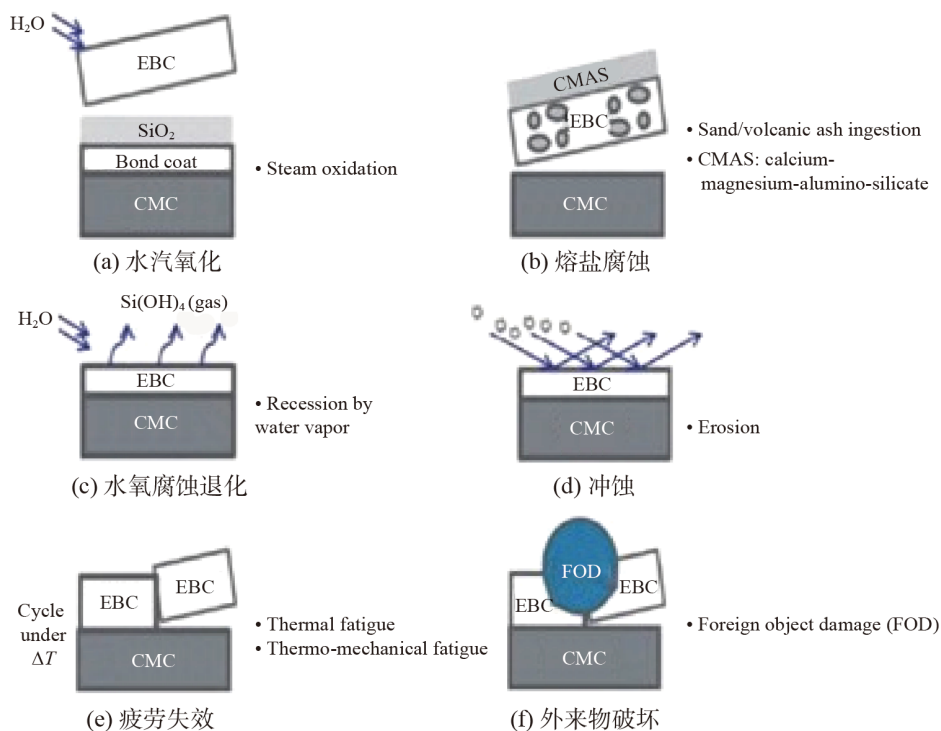
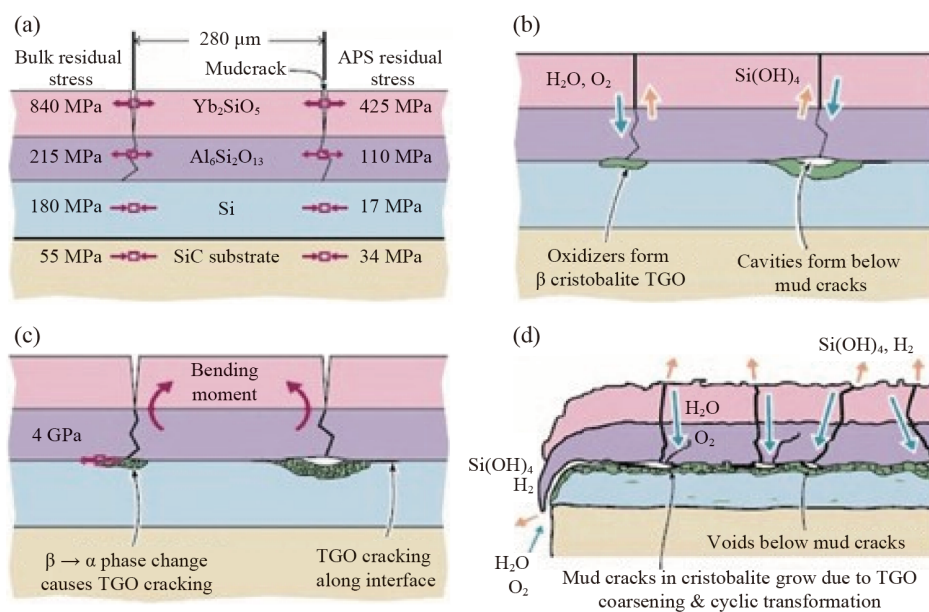
图10 环境障涂层不同失效形式^[135]

Fig.10 Different failure modes of EBCs

图11 Yb₂SiO₅/莫来石/Si涂层失效示意图^[139]Fig.11 Schematic diagram of failure mechanisms of Yb₂SiO₅/mullite/Si coatings

孔隙流入涂层,冷却时堵塞孔隙,增大堵塞区与未堵塞区的热膨胀系数,产生过多残余应力,导致涂层失效^[140]。此外,CMAS还会与环境障涂层发生化学反应,改变涂层结构,严重影响其性能。WIESNER等^[141]在1 473、1 573、1 673、1 773 K下将CMAS相

与Yb₂Si₂O₇相分别热处理1、10、50 h,研究了两者之间的化学反应。结果表明,Yb₂Si₂O₇逐渐溶解于熔融CMAS中,为CMAS晶界侵蚀扩散拓宽了通道。NIEAI等^[142]通过无压烧结制备了3种Yb₂Si₂O₇-YSZ和1种Yb₂Si₂O₇陶瓷材料,并在1 673 K下分别进行

了4、8、24、48 h的热腐蚀实验。结果表明,多层体系涂层的反应层深度小于单一体系涂层的,并通过XRD物相表征检测到2种致密 $\text{Al}_5\text{Y}_3\text{O}_{12}$ 和 $\text{Al}_5\text{Yb}_3\text{O}_{12}$ 相,其减少了CMAS渗入深度。该结果表明, $\text{Yb}_2\text{Si}_2\text{O}_7$ -YSZ体系的抗CMAS腐蚀性能更优,原因在于大量的 Y^{3+} 溶入CMAS中,导致致密氧化物相生成。TIAN等^[143]研究了稀土单硅酸盐($\text{X1-RE}_2\text{SiO}_5$)在1 573 K下的CMAS腐蚀机制。研究发现,CMAS与硅酸盐相反应生成致密 $\text{Ca}_2\text{RE}_8(\text{SiO}_4)_8\text{O}_2$ 相,且随着稀土元素离子半径增大, $\text{X1-RE}_2\text{SiO}_5$ 腐蚀层深度逐渐减小,表明其具有较好的抗CMAS腐蚀性。

1.4.3 热冲击失效

航空发动机在服役期间会经历多次升降温过程,这就要求环境障涂层应具备良好的热冲击性能。影响材料热冲击性能的主要因素包括材料的弹性模量、热导率以及热膨胀系数等。RICHARDS等^[144]通过APS技术在SiC基体上沉积了 $\text{Yb}_2\text{Si}_2\text{O}_7$ /莫来石/Si黏结层3层环境障涂层体系,研究了该体系在热冲击过程中的涂层脱落现象。实验表明,在降温过程中,由于环境障涂层与基体的热膨胀系数不同, $\text{Yb}_2\text{Si}_2\text{O}_7$ 层产生了拉应力,导致裂纹萌生;然后将涂层置于90% H_2O +10% O_2 环境中,在383~1 589 K温度范围内开展长期热循环,发现裂纹通过 $\text{Al}_6\text{Si}_2\text{O}_{13}$ 氧化物层扩散至Si黏结层中并横向扩展,长期循环后导致涂层脱落失效。SEO等^[145]在硅基复合材料表面沉积了自愈合 $\text{Yb}_2\text{Si}_2\text{O}_7$ /Si黏结层双层体系。研究发现,仅开展几次热循环后,涂层中即产生了贯穿性垂直裂纹;然而,在1 623 K下该涂层能够承受300次热循环并保持稳定,且裂纹密度随着热循环次数的增加而降低。随后对涂层进行5 000次热循环后发现,裂纹中包覆 SiO_2 致密相,并且促进了莫来石中 Al_2O_3 相析出,表明 $\text{Yb}_2\text{Si}_2\text{O}_7$ /Si黏结层双层体系具备良好的抗热冲击性能。

2 结论

(1) 多层结构涂层能够提高陶瓷基复合材料热端部件的工作温度与使用寿命,第3代Si黏结层+莫来石+纳米结构稀土硅酸盐多层体系是目前实践效果最好的环境障涂层。极端服役环境(高温水氧腐蚀、热冲击腐蚀、CMAS腐蚀)会导致涂层脱落失效,多功能耦合环境障涂层将是未来该领域的研究热点。此外,航空发动机真实服役环境难以准确模拟,

建立更为精准完善的航空发动机用环境障涂层的评判体系也是当前研究的重点。

(2) 高熵稀土酸盐具有较低的热导率和高于YSZ陶瓷的热膨胀系数。相较于传统陶瓷涂层(YSZ),高熵稀土涂层能够使热导率降低50%,高熵稀土酸盐是优异的热障涂层潜在选材。此外,高熵稀土酸盐中的稀土元素组合较为随机,可通过第一性原理计算得出热导率更低、热膨胀系数与基体更匹配以及力学性能更好的稀土元素掺杂组合。同时,需制备出样品开展实验验证,以节约时间和经济成本;优化喷涂工艺,使高熵稀土涂层拥有更长的服役寿命。

(3) 相较于传统陶瓷涂层,纳米结构陶瓷涂层具有更优异的韧性、抗热震性能、力学性能和更低的热导率,能够大幅度延长涂层使用寿命,在工业实践中具有更广阔的应用前景。鉴于纳米结构陶瓷涂层的研究时间相对较短,未来还需从以下4个方面进行深层次探索:①从纳米粉的制备到喷涂工艺的选择再到涂层的设计、制备、表征,均需进一步研究与讨论;②推动自动控制系统在纳米热喷涂工艺中的应用;③促进热喷涂纳米涂层技术与先进表面工程技术的深入融合;④通过精准的结构与成分设计,确保纳米结构陶瓷涂层在长期服役环境下的稳定性。

参考文献:

- [1] 晋小超,侯成,吉新阔,等. 热障涂层系统损伤与断裂研究进展[J]. 中国材料进展,2020,39(11):897-910. JIN Xiaochao, HOU Cheng, JI Xinkuo, et al. Advances in damage and fracture of thermal barrier coatings[J]. Materials China, 2020, 39(11): 897-910. (in Chinese)
- [2] 张晓东,梁逸帆,宋艺,等. 高熵稀土氧化物热障涂层材料研究进展[J]. 材料保护,2024,57(3):15-27. ZHANG Xiaodong, LIANG Yifan, SONG Yi, et al. Research progress of high entropy rare earth oxide thermal barrier coating materials[J]. Materials Protection, 2024, 57(3): 15-27. (in Chinese)
- [3] 陶顺衍,杨加胜,邵芳,等. 航机CMC热端部件用热喷涂涂层的机遇与挑战[J]. 无机材料学报,2024,39(10):1077-1083. TAO Shunyan, YANG Jiasheng, SHAO Fang, et al. Thermal spray coatings for aircraft CMC hot-end components: opportunities and challenges[J]. Journal of Inorganic Materials, 2024, 39(10): 1077-1083. (in Chinese)

- [4] 刘巧沐,黄顺洲,何爱杰. 碳化硅陶瓷基复合材料在航空发动机上的应用需求及挑战[J]. 材料工程, 2019,47(2):1-10.
LIU Qiaomu, HUANG Shunzhou, HE Aijie, Application requirements and challenges of CMC-SiC composites on aero-engine[J]. Journal of Materials Engineering, 2019, 47(2): 1-10. (in Chinese)
- [5] 朱晨,于建海,郭亚飞,等. 航空发动机热障涂层存在的问题及其发展方向[J]. 表面技术, 2016, 45(1): 13-19.
ZHU Chen, YU Jianhai, GUO Yafei, et al. Problems of aircraft engine thermal barrier coating and its developing direction[J]. Surface Technology, 2016, 45(1): 13-19. (in Chinese)
- [6] 徐惠彬,宫声凯,刘福顺. 航空发动机热障涂层材料体系的研究[J]. 航空学报, 2000, 21(1): 7-12.
XU Huibin, GONG Shengkai, LIU Fushun. Recent development in materials design of thermal barrier coatings for gas turbine[J]. 2000, 21(1): 7-12. (in Chinese)
- [7] GOWARD G W. Recent development in high temperature coatings for gas turbine air foils[C]//High temperature corrosion. Los Angeles: National Association of Corrosion Engineers, 1983: 553-560.
- [8] SIMS C T. Niobium in superalloys: a perspective[J]. High Temperature Technology, 1984, 2(4): 185-201.
- [9] 杨晓光,耿瑞,熊昌炳. 航空发动机热端部件隔热陶瓷涂层应用研究[J]. 航空动力学报, 1997, 12(2): 183-188.
YANG Xiaoguang, GENG Rui, XIONG Changbin. A survey on application of TBC for aeroengine hot sections[J]. Journal of Aerospace Power, 1997, 12(2): 183-188. (in Chinese)
- [10] 唐治虎. 航空发动机热障涂层材料体系的研究[J]. 新型工业化, 2022, 12(1): 172-173.
TANG Zhihu. Research on thermal barrier coating material systems for aero-engine[J]. The Journal of New Industrialization, 2022, 12(1): 172-173. (in Chinese)
- [11] 王飞,董会,伊静,等. 双层结构粘结层热生长氧化物近指数生长机理研究[J/OL]. 表面技术, 2025. <https://link.cnki.net/urlid/50.1083.TG.20251017.1609.008>.
WANG Fei, DONG Hui, YI Jing, et al. The near-exponential growth mechanism of thermally grown oxide in double bond coat[J/OL]. Surface Technology, 2025. <https://link.cnki.net/urlid/50.1083.TG.20251017.1609.008>. (in Chinese)
- [12] MILLER R A. Thermal barrier coatings for aircraft engines: history and directions[J]. Journal of Thermal Spray Technology, 1997, 6(1): 35-42.
- [13] BOSE S, DEMASI-MARCIN J. Thermal barrier coating experience in gas turbine engines at Pratt & Whitney[J]. Journal of Thermal Spray Technology, 1997, 6(1): 99-104.
- [14] STECURA S. Optimization of the Ni-Cr-Al-Y/ZrO₂-Y₂O₃ thermal barrier system[J]. Advanced Ceramic Materials, 1986, 1: 68-76.
- [15] KUMAR A, NAYAK S K, BIJALWAN P, et al. Optimization of mechanical and corrosion properties of plasma sprayed low-chromium containing Fe-based amorphous/nanocrystalline composite coating[J]. Surface and Coatings Technology, 2019, 370: 255-268.
- [16] LAN Y L, LI J Q, CHEN Q Z, et al. Mechanical properties and thermal conductivity of dense β -SiAlON ceramics fabricated by two-stage spark plasma sintering with Al₂O₃-AlN-Y₂O₃ additives[J]. Journal of the European Ceramic Society, 2020, 40(1): 12-18.
- [17] USTINOV A I, POLISHCHUK S S, DEMCHENKOV S A, et al. Formation of thin foils of high-entropy CrFeCoNiCu alloys by EB-PVD process[J]. Surface and Coatings Technology, 2020, 403: 126440.
- [18] LI Chenyi, GUO Hongbo, GAO Lihua, et al. Microstructures of yttria-stabilized zirconia coatings by plasma spray-physical vapor deposition[J]. Journal of Thermal Spray Technology, 2015, 24: 534-541.
- [19] GUO Lei, HE Wenting, CHEN Wenbo, et al. Progress on high-temperature protective coatings for aero-engines[J]. Surface Science and Technology, 2023, 1(1): 6.
- [20] ZHAO Zifan, CHEN Heng, XIANG Huimin, et al. (Y_{0.25}Yb_{0.25}Er_{0.25}Lu_{0.25})₂(Zr_{0.5}Hf_{0.5})₂O₇: a defective fluorite structured high entropy ceramic with low thermal conductivity and close thermal expansion coefficient to Al₂O₃[J]. Journal of Materials Science & Technology, 2020, 39: 167-172.
- [21] ROST C M. Entropy-stabilized oxides: explorations of a novel class of multicomponent materials[Z]. 2016.
- [22] 赵鹏森,曹新鹏,郑海忠,等. 稀土掺杂热障涂层的研究进展[J]. 航空材料学报, 2021, 41(4): 83-95.
ZHAO Pengsen, CAO Xinpeng, ZHENG Haizhong, et al. Research progress of rare earth doped thermal barrier coatings[J]. Journal of Aeronautical Materials, 2021, 41(4): 83-95. (in Chinese)
- [23] OSES C, TOHER C, CURTAROLO S. High-entropy ceramics[J]. Nature Reviews Materials, 2020, 5(4): 295-309.
- [24] YAN Xueliang, CONSTANTIN L, LU Yongfeng, et al. (Hf_{0.2}Zr_{0.2}Ta_{0.2}Nb_{0.2}Ti_{0.2})C high-entropy ceramics with

- low thermal conductivity[J]. *Journal of the American Ceramic Society*, 2018, 101(10):4486–4491.
- [25] WU Qiong, MIAO Weishou, ZHANG Yidu, et al. Mechanical properties of nanomaterials: a review[J]. *Nanotechnology Reviews*, 2020, 9(1):259–273.
- [26] 王 铀. 纳米结构涂层与纳米改性材料[J]. *金属热处理*, 2010, 35(1):9–14.
- WANG You. Nano-Structured coatings and nano-modified materials[J]. *Heat Treatment of Metals*, 2010, 35(1):9–14. (in Chinese)
- [27] REN Zhaowen, ZHOU Wancheng, QING Yuchang, et al. Improved mechanical and microwave absorption properties of SiC_r/SiC composites with SiO₂ filler[J]. *Ceramics International*, 2021, 47(10):14455–14463.
- [28] WANG Xiulei, GAO Xiaodong, ZHANG Zhenghe, et al. Advances in modifications and high-temperature applications of silicon carbide ceramic matrix composites in aerospace: a focused review[J]. *Journal of the European Ceramic Society*, 2021, 41(9):4671–4688.
- [29] HEREDIA F E, HE Mingyuan, EVANS A G. Mechanical performance of ceramic matrix composite I-beams [J]. *Composites Part A: Applied Science and Manufacturing*, 1996, 27(12):1157–1167.
- [30] MENON M N, FANG H T, WU D C, et al. Creep and stress rupture behavior of an advanced silicon nitride: part III, stress rupture and the monkman–grant relationship[J]. *Journal of the American Ceramic Society*, 1994, 77(5):1235–1241.
- [31] 陈 旭, 洪智亮, 鲁琳静, 等. 环境障碍涂层研究综述 [J]. *材料导报*, 2011, 25(19):32–38.
- CHEN Xu, HONG Zhiliang, LU Linjing, et al. Overview on the development of environment barrier coating[J]. *Materials Reports*, 2011, 25(19):32–38. (in Chinese)
- [32] PRICE J R, VAN ROODE M, STALA C. Ceramic oxide-coated silicon carbide for high temperature corrosive environments[J]. *Key Engineering Materials*, 1992, 72:71–84.
- [33] LEE K N, MILLER R A, JACOBSON N S, et al. Environmental durability of mullite coating/SiC and mullite-YSZ coating/SiC systems[C]//*Proceedings of the 19th Annual Conference on Composites, Advanced Ceramics, Materials, and Structures—B: Ceramic Engineering and Science Proceedings*. Hoboken, USA:1995.
- [34] LEE K N. Key durability issues with mullite-based environmental barrier coatings for Si-based ceramics [J]. *Journal of Engineering for Gas Turbines Power*, 2000, 122(4):632–636.
- [35] LEE K N. Current status of environmental barrier coatings for Si-based ceramics[J]. *Surface and Coatings Technology*, 2000, 133:1–7.
- [36] LEE K N, FOX D S, ELDRIDGE J I, et al. Upper temperature limit of environmental barrier coatings based on mullite and BSAS[J]. *Journal of the American Ceramic Society*, 2003, 86(8):1299–1306.
- [37] KIMMEL J, MIRIYALA N, PRICE J, et al. Evaluation of CFCC liners with EBC after field testing in a gas turbine[J]. *Journal of the European Ceramic Society*, 2002, 22(14–15):2769–2775.
- [38] MAIER N, RIXECKER G, NICKEL K G. Formation and stability of Gd, Y, Yb and Lu disilicates and their solid solutions[J]. *Journal of Solid State Chemistry*, 2006, 179(6):1630–1635.
- [39] TSARENKO I, DU H H, LEE W Y. Effects of thin mullite coating on the environmental stability of sintered Si₃N₄[J]. *Journal of the American Ceramic Society*, 2004, 87(3):417–420.
- [40] LEE K N, FOX D S, BANSAL N P. Rare earth silicate environmental barrier coatings for SiC/SiC composites and Si₃N₄ ceramics[J]. *Journal of the European Ceramic Society*, 2005, 25(10):1705–1715.
- [41] KHAN Z S, ZOU B, HUANG W, et al. Synthesis and characterization of Yb and Er based monosilicate powders and durability of plasma sprayed Yb₂SiO₅ coatings on C/C–SiC composites[J]. *Materials Science and Engineering: B*, 2012, 177(2):184–189.
- [42] WEI Zhiyuan, MENG Guohui, CHEN Lin, et al. Progress in ceramic materials and structure design toward advanced thermal barrier coatings[J]. *Journal of Advanced Ceramics*, 2022, 11(7):985–1068.
- [43] BECK T, TRUNOVA O, HERZOG R, et al. TBCs for gas turbines under thermomechanical loadings: failure behaviour and life prediction[J]. *EPJ Web of Conferences*, 2012, 33:02001.
- [44] BUSO E P, QIAN Z Q, TAYLOR M P, et al. The influence of bondcoat and topcoat mechanical properties on stress development in thermal barrier coating systems[J]. *Acta Materialia*, 2009, 57(8):2349–2361.
- [45] CAO Xueqiang, VASSEN R, STOEVEER D. Ceramic materials for thermal barrier coatings[J]. *Journal of the European Ceramic Society*, 2004, 24(1):1–10.
- [46] VINCENZINI P. High tech ceramics: World Congress Proceedings: parts A, B and C[M]. New York: Elsevier, 1987.
- [47] LACKEY W J, STINTON D P, CERNY G A, et al. Ceramic coatings for advanced heat engines—a review and projection[J]. *Advanced Ceramic Materials*,

- 1986,2(1):24-30.
- [48] KVERNES I,LUGSCHEIDERT E. Thick thermal barrier coatings for diesel engines[J]. Surface Engineering,1995,11(4):296-300.
- [49] CLARKE D R. Materials selection guidelines for low thermal conductivity thermal barrier coatings[J]. Surface and Coatings Technology,2003,163-164:67-74.
- [50] 王青,王亚平,丁秉钧. 热障涂层隔热性能研究进展[J]. 功能材料,2013,44(23):3363-3367.
WANG Qing,WANG Yaping,DING Bingjun. Progress on heat insulation performance of thermal barrier coatings[J]. Journal of Functional Materials,2013,44(23):3363-3367. (in Chinese)
- [51] 华佳捷,张丽鹏,刘紫薇,等. 热障涂层失效机理研究进展[J]. 无机材料学报,2012,27(7):680-686.
HUA Jiajie,ZHANG Lipeng,LIU Ziwei,et al. Progress of research on the failure mechanism of thermal barrier coatings[J]. Journal of Inorganic Materials,2012,27(7):680-686. (in Chinese)
- [52] XU Zhenhua,HE Limin,MU Rende,et al. Double-ceramic-layer thermal barrier coatings of $\text{La}_2\text{Zr}_2\text{O}_7/\text{YSZ}$ deposited by electron beam-physical vapor deposition[J]. Journal of Alloys and Compounds,2009,473(1-2):509-515.
- [53] 倪嘉,闫平,史昆,等. 热障涂层陶瓷材料的研究进展[C]//2020中国铸造活动周论文集. 合肥,中国:2020.
NI Jia,YAN Ping,SHI Kun,et al. Research progress of thermal barrier coating ceramic materials[C]//2020 China Foundry Week Discussion Collection. Hefei,China:2020. (in Chinese)
- [54] 张洪博,段文皓,张涛,等. 热障涂层材料研究概述[J]. 材料保护,2022,55(7):177-186.
ZHANG Hongbo,DUAN Wenhao,ZHANG Tao,et al. Research overview of thermal barrier coating materials[J]. Materials Protection,2022,55(7):177-186. (in Chinese)
- [55] STECURA S. Optimization of the $\text{NiCrAl-Y/ZrO}_2\text{-Y}_2\text{O}_3$ thermal barrier system[R]. NASA-TM-86905,1985.
- [56] ZHANG Hongye,LIU Zhanwei,YANG Xiaobo,et al. Interface failure behavior of YSZ thermal barrier coatings during thermal shock[J]. Journal of Alloys and Compounds,2019,779:686-697.
- [57] 王进双. 氧化锆热障涂层失效机理研究[D]. 武汉:武汉理工大学,2018.
WANG Jinshuang. Failure mechanism of zirconia thermal barrier coating[D]. Wuhan:Wuhan University of Technology,2018. (in Chinese)
- [58] MOHAN P,PATTERSON T,YAO Bo,et al. Degradation of thermal barrier coatings by fuel impurities and CMAS: thermochemical interactions and mitigation approaches[J]. Journal of Thermal Spray Technology,2010,19(1-2):156-167.
- [59] 王昆,邹兰欣,郭磊,等. 航空发动机及燃气轮机热障涂层高温腐蚀与防护[J]. 中国腐蚀与防护学报,2025,45(1):1-19.
WANG Kun,ZOU Lanxin,GUO Lei,et al. High-temperature corrosion and protection of thermal barrier coatings for aeroengines and gas turbines[J]. Journal of Chinese Society for Corrosion and Protection,2025,45(1):1-19. (in Chinese)
- [60] 郑蕾,郭洪波,郭磊,等. 新一代超高温热障涂层研究[J]. 航空材料学报,2012,32(6):14-24.
ZHENG Lei,GUO Hongbo,GUO Lei,et al. New generation thermal barrier coatings for ultrahigh temperature applications[J]. Journal of Aeronautical Materials,2012,32(6):14-24. (in Chinese)
- [61] LEE M J,LEE B C,LIM J G,et al. Residual stress analysis of the thermal barrier coating system by considering the plasma spraying process[J]. Journal of Mechanical Science and Technology,2014,28(6):2161-2168.
- [62] HEVERAN C M,XU Jiapeng,SARIN V K,et al. Simulation of stresses in TBC-EBC coating systems for ceramic components in gas turbines[J]. Surface and Coatings Technology,2013,235:354-360.
- [63] STECURA S. New $\text{ZrO}_2\text{-Yb}_2\text{O}_3$ plasma-sprayed coatings for thermal barrier applications[J]. Thin Solid Films,1987,150(1):15-40.
- [64] BRANDON J R,TAYLOR R. Phase stability of zirconia-based thermal barrier coatings part II. Zirconia-yttria alloys[J]. Surface and Coatings Technology,1991,46(1):91-101.
- [65] VASSEN R,CAO Xueqiang,TIETZ F,et al. Zirconates as new materials for thermal barrier coatings[J]. Journal of the American Ceramic Society,2000,83(8):2023-2028.
- [66] 董智杰,付前刚,胡逗. 稀土锆酸盐热障涂层的合金化改性研究进展[J]. 稀有金属材料与工程,2024,53(6):1770-1780.
DONG Zhijie,FU Qiangang,HU Dou. Review on alloying modification of rare earth zirconate for thermal barrier coatings[J]. Rare Metal Materials and Engineering,2024,53(6):1770-1780. (in Chinese)
- [67] YE H J W,CHEN S K,LIN S J,et al. Nanostructured high-entropy alloys with multiple principal elements: novel alloy design concepts and outcomes[J]. Ad-

- vanced Engineering Materials, 2004, 6(5):299–303.
- [68] XIANG Huimin, XING Yan, DAI Fuzhi, et al. High-entropy ceramics: present status, challenges, and a look forward[J]. Journal of Advanced Ceramics, 2021, 10: 385–441.
- [69] ROST C M, SACHET E, BORMAN T, et al. Entropy-stabilized oxides[J]. Nature Communications, 2015, 6: 8485.
- [70] DRAGOE N, BÉRARDAN D. Order emerging from disorder[J]. Science, 2019, 366(6465): 573–574.
- [71] 栾亨伟, 赵威, 姚可夫. 高熵合金的力学性能及功能性能研究进展[J]. 材料热处理学报, 2020, 41(1): 1–11.
- LUAN Hengwei, ZHAO Wei, YAO Kefu. Recent developments on mechanical and functional properties of high entropy alloys[J]. Transactions of Materials and Heat Treatment, 2020, 41(1): 1–11. (in Chinese)
- [72] 谢鸿翔, 项厚政, 马瑞奇, 等. 高熵陶瓷材料的研究进展[J]. 材料导报, 2022, 36(6): 61–68.
- XIE Hongxiang, XIANG Houzheng, MA Ruiqi, et al. Research progress of high-entropy ceramic materials[J]. Materials Reports, 2022, 36(6): 61–68. (in Chinese)
- [73] ZHOU Lin, LI Fei, LIU Jixuan, et al. High-entropy thermal barrier coating of rare-earth zirconate: a case study on $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Zr}_2\text{O}_7$ prepared by atmospheric plasma spraying[J]. Journal of the European Ceramic Society, 2020, 40(15): 5731–5739.
- [74] 蒋浩然, 林硕, 张康飞, 等. $\text{ZrO}_2/\text{Al}_2\text{O}_3$ 多孔陶瓷的制备与力学性能[J]. 材料工程, 2021, 49(5): 157–162.
- JIANG Haoran, LIN Shuo, ZHANG Kangfei, et al. Preparation and mechanical properties of $\text{ZrO}_2/\text{Al}_2\text{O}_3$ porous ceramics[J]. Journal of Materials Engineering, 2021, 49(5): 157–162. (in Chinese)
- [75] PING Xinyu, MENG Bin, LI Chen, et al. Thermophysical and electrical properties of rare-earth-cerate high-entropy ceramics[J]. Journal of the American Ceramic Society, 2022, 105(7): 4910–4920.
- [76] 喻晓峰, 史平平, 赵丹阳, 等. 热/环境障涂层用稀土钪酸盐的抗腐蚀性能研究现状[J]. 粉末冶金材料科学与工程, 2025, 30(4): 261–271.
- YU Xiaofeng, SHI Pingping, ZHAO Danyang, et al. Research status on the corrosion resistance of rare earth hafnates used in thermal/environmental barrier coatings[J]. Materials Science and Engineering of Powder Metallurgy, 2025, 30(4): 261–271. (in Chinese)
- [77] 桑玮玮, 张红松, 陈华辉, 等. $(\text{Sm}_{0.2}\text{Gd}_{0.2}\text{Dy}_{0.2}\text{Y}_{0.2}\text{Yb}_{0.2})_3\text{TaO}_7$ 高熵陶瓷的制备及热物理性能[J]. 无机材料学报, 2021, 36(4): 405–410.
- SANG Weiwei, ZHANG Hongsong, CHEN Huahui, et al. Preparation and thermophysical properties of $(\text{Sm}_{0.2}\text{Gd}_{0.2}\text{Dy}_{0.2}\text{Y}_{0.2}\text{Yb}_{0.2})_3\text{TaO}_7$ high-entropy ceramic[J]. Journal of Inorganic Materials, 2021, 36(4): 405–410. (in Chinese)
- [78] 张奕雄, 王盼盼, 何君杰, 等. 一种作为潜在热障涂层材料的新型高熵铌酸盐氧化物热物理性能研究[J]. 中国稀土学报, 2024, 42(3): 522–527.
- ZHANG Yixiong, WANG Panpan, HE Junjie, et al. Thermophysical properties of a novel high-entropy niobate oxide as a potential thermal barrier coating material[J]. Journal of the Chinese Society of Rare Earths, 2024, 42(3): 522–527. (in Chinese)
- [79] REN Ke, WANG Qiankun, SHAO Gang, et al. Multi-component high-entropy zirconates with comprehensive properties for advanced thermal barrier coating[J]. Scripta Materialia, 2020, 178: 382–386.
- [80] LUO Xuewei, LUO Lirong, ZHAO Xiaofeng, et al. Single-phase rare-earth high-entropy zirconates with superior thermal and mechanical properties[J]. Journal of the European Ceramic Society, 2022, 42(5): 2391–2399.
- [81] TANG An, LI Bin, SANG Weiwei, et al. Thermophysical performances of high-entropy $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Yb}_{0.2}\text{Y}_{0.2}\text{Sm}_{0.2})_2\text{Ce}_2\text{O}_7$ and $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Yb}_{0.2}\text{Y}_{0.2}\text{Lu}_{0.2})_2\text{Ce}_2\text{O}_7$ oxides[J]. Ceramics International, 2022, 48(4): 5574–5580.
- [82] ZHANG Hongsong, LV Jianguo, LI Gang, et al. Investigation about thermophysical properties of $\text{Ln}_2\text{Ce}_2\text{O}_7$ ($\text{Ln}=\text{Sm}, \text{Er}$ and Yb) oxides for thermal barrier coatings[J]. Materials Research Bulletin, 2012, 47(12): 4181–4186.
- [83] CHEN Lin, HU Mingyu, WU Peng, et al. Thermal expansion performance and intrinsic lattice thermal conductivity of ferroelastic RETaO_4 ceramics[J]. Journal of the American Ceramic Society, 2019, 102(8): 4809–4821.
- [84] WANG Jun, WU Fushuo, ZOU Ruohan, et al. High-entropy ferroelastic rare-earth tantalite ceramic: $(\text{Y}_{0.2}\text{Ce}_{0.2}\text{Sm}_{0.2}\text{Gd}_{0.2}\text{Dy}_{0.2})\text{TaO}_4$ [J]. Journal of the American Ceramic Society, 2021, 104(11): 5873–5882.
- [85] LIU Hanwen, LIU Ling, XIANG Huimin, et al. Orthorhombic to tetragonal polymorphic transformation of YT_2O_9 and its inhibition through the design of high-entropy $(\text{Y}_{0.2}\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Gd}_{0.2})\text{Ta}_3\text{O}_9$ [J]. Journal of the European Ceramic Society, 2022, 42(8): 3559–3569.
- [86] 朱嘉桐, 楼志豪, 张萍, 等. 稀土钽酸盐(RETaO_4)高熵陶瓷的制备与热学性能研究[J]. 无机材料学报, 2021, 36(4): 411–417.
- ZHU Jiatong, LOU Zhihao, ZHANG Ping, et al. Pre-

- paration and thermal properties of rare earth tantalates (RETaO_4) high-entropy ceramics[J]. *Journal of Inorganic Materials*, 2021, 36(4): 411–417. (in Chinese)
- [87] MIYAZAKI A, KINOSHITA T, TATEBAYASHI T, et al. Thermal stability and proton conductivity of densely proton injected phosphate glasses containing rare-earth elements[J]. *Journal of Non-Crystalline Solids*, 2020, 541: 120064.
- [88] CHEN Lin, LI Baihui, GUO Jun, et al. High-entropy perovskite RETa_3O_9 ceramics for high-temperature environmental/thermal barrier coatings[J]. *Journal of Advanced Ceramics*, 2022, 11(4): 556–569.
- [89] ZHAO Zifan, CHEN Heng, XIANG Huimin, et al. High entropy defective fluorite structured rare-earth niobates and tantalates for thermal barrier applications [J]. *Journal of Advanced Ceramics*, 2020, 9: 303–311.
- [90] LI Chen, MENG Bin, FAN Sining, et al. Rare-earth-tantalate high-entropy ceramics with sluggish grain growth and low thermal conductivity[J]. *Ceramics International*, 2022, 48(8): 11124–11133.
- [91] 桑玮玮. 掺杂稀土钽酸盐热障陶瓷的热物理及腐蚀性能研究[D]. 北京: 中国矿业大学(北京), 2022.
- SANG Weiwei. Thermophysical and corrosion properties of doped rare earth tantalate thermal barrier ceramics[D]. Beijing: China University of Mining and Technology-Beijing, 2022. (in Chinese)
- [92] ZHU Jiatong, XU Jie, ZHANG Ping, et al. Enhanced mechanical and thermal properties of ferroelastic high-entropy rare-earth-niobates[J]. *Scripta Materialia*, 2021, 200: 113912.
- [93] LEHMANN H, PITZER D, PRACHT G, et al. Thermal conductivity and thermal expansion coefficients of the lanthanum rare-earth-element zirconate system[J]. *Journal of the American Ceramic Society*, 2003, 86(8): 1338–1344.
- [94] ZHAO Zifan, XIANG Huimin, DAI Fuzhi, et al. $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_2\text{Zr}_2\text{O}_7$: a novel high-entropy ceramic with low thermal conductivity and sluggish grain growth rate[J]. *Journal of Materials Science & Technology*, 2019, 35(11): 2647–2651.
- [95] ZHU Jiatong, MENG Xuanyu, XU Jie, et al. Ultra-low thermal conductivity and enhanced mechanical properties of high-entropy rare earth niobates (RE_3NbO_7 , RE = Dy, Y, Ho, Er, Yb)[J]. *Journal of the European Ceramic Society*, 2021, 41(1): 1052–1057.
- [96] LI Fei, ZHOU Lin, LIU Jixuan, et al. High-entropy pyrochlores with low thermal conductivity for thermal barrier coating materials[J]. *Journal of Advanced Ceramics*, 2019, 8: 576–582.
- [97] ZHAO Meng, PAN Wei, WAN Chunlei, et al. Defect engineering in development of low thermal conductivity materials: a review[J]. *Journal of the European Ceramic Society*, 2017, 37(1): 1–13.
- [98] XUE Yun, ZHAO Xiaoqi, AN Yulong, et al. High-entropy $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})_2\text{Ce}_2\text{O}_7$: a potential thermal barrier material with improved thermo-physical properties[J]. *Journal of Advanced Ceramics*, 2022, 11(4): 615–628.
- [99] ZHANG Haoming, SONG Yan, SANG Weiwei, et al. Thermophysical performances of novel high entropy $(\text{La}_{0.25}\text{RE}_{0.25}\text{Yb}_{0.25}\text{Y}_{0.25})_2\text{Ce}_2\text{O}_7$ (RE=Nd and Dy) oxides[J]. *Ceramics International*, 2022, 48(6): 8380–8386.
- [100] 胡万鹏, 张广珩, 张洁, 等. 高熵稀土钨酸盐热障/环境障涂层材料的制备与性能研究[J]. *航空制造技术*, 2023, 66(1–2): 53–60.
- HU Wanpeng, ZHANG Guangheng, ZHANG Jie, et al. Synthesis and property of high-entropy rare earth hafnate as thermal/environmental barrier coating material[J]. *Aeronautical Manufacturing Technology*, 2023, 66(1–2): 53–60. (in Chinese)
- [101] CONG Longkang, ZHANG Shouyang, GU Shengyue. Thermophysical properties of a novel high entropy hafnate ceramic[J]. *Journal of Materials Science & Technology*, 2021, 85: 152–157.
- [102] LÓPEZ-COTA F A, CEPEDA-SÁNCHEZ N M, DÍAZ-GUILLÉN J A, et al. Electrical and thermophysical properties of mechanochemically obtained lanthanide hafnates[J]. *Journal of the American Ceramic Society*, 2017, 100(5): 1994–2004.
- [103] YE Fuxing, MENG Fanwei, LUO Tianyuan, et al. Ultrafast high-temperature sintering of $(\text{Y}_{0.2}\text{Dy}_{0.2}\text{Er}_{0.2}\text{Tm}_{0.2}\text{Yb}_{0.2})_4\text{Hf}_3\text{O}_{12}$ high-entropy ceramics with defective fluorite structure[J]. *Journal of the European Ceramic Society*, 2022, 42(11): 4686–4691.
- [104] 陈琳, 冯晶. 稀土钽酸盐 RE_3TaO_7 和 RETa_3O_9 陶瓷热-力学性质研究进展[J]. *现代技术陶瓷*, 2019, 40(6): 367–397.
- CHEN Lin, FENG Jing. Research progress of thermomechanical properties of rare earth tantalates RE_3TaO_7 and RETa_3O_9 ceramics[J]. *Advanced Ceramics*, 2019, 40(6): 367–397. (in Chinese)
- [105] WANG Jun, CHONG Xiaoyu, ZHOU Rong, et al. Microstructure and thermal properties of RETaO_4 (RE = Nd, Eu, Gd, Dy, Er, Yb, Lu) as promising thermal barrier coating materials[J]. *Scripta Materialia*, 2017, 126: 24–28.
- [106] TU Tianzhe, LIU Jixuan, ZHOU Lin, et al. Graceful behavior during CMAS corrosion of a high-entropy

- rare-earth zirconate for thermal barrier coating material [J]. Journal of the European Ceramic Society, 2022, 42(2): 649–657.
- [107] REN Ke, WANG Qiankun, CAO Yejie, et al. Multi-component rare-earth cerate and zirconocerate ceramics for thermal barrier coating materials[J]. Journal of the European Ceramic Society, 2021, 41(2): 1720–1725.
- [108] ZHANG Hongsong, ZHAO Liming, SANG Weiwei, et al. Thermophysical performances of $(\text{La}_{1/6}\text{Nd}_{1/6}\text{Yb}_{1/6}\text{Y}_{1/6}\text{Sm}_{1/6}\text{Lu}_{1/6})_2\text{Ce}_2\text{O}_7$ high-entropy ceramics for thermal barrier coating applications[J]. Ceramics International, 2022, 48(2): 1512–1521.
- [109] KEAR B H, SKANDAN G. Thermal spray processing of nanoscale materials[J]. Nanostructured Materials, 1997, 8(6): 765–769.
- [110] 王 铀, 张晓东, 郝 佩, 等. 适用于掺氢燃气轮机的新型环境/热障涂层[J]. 发电技术, 2024, 45(5): 868–877.
WANG You, ZHANG Xiaodong, HAO Pei, et al. New environmental/thermal barrier coatings suitable for hydrogen doped gas turbines[J]. Power Generation Technology, 2024, 45(5): 868–877. (in Chinese)
- [111] 张晓东, 王 昊, 梁逸帆, 等. 基于热障涂层的 $\text{La}_2\text{Zr}_2\text{O}_7$ 材料改性研究进展[J]. 材料保护, 2024, 57(3): 50–62.
ZHANG Xiaodong, WANG Hao, LIANG Yifan, et al. Research progress of $\text{La}_2\text{Zr}_2\text{O}_7$ material modification based on thermal barrier coating[J]. Materials Protection, 2024, 57(3): 50–62. (in Chinese)
- [112] 耿洪滨, 宋 艺, 张晓东, 等. 面向先进热障涂层的陶瓷材料研究进展[J]. 航空制造技术, 2023, 66(20): 20–35.
GENG Hongbin, SONG Yi, ZHANG Xiaodong, et al. Research progress on ceramic materials toward advanced thermal barrier coatings[J]. Aeronautical Manufacturing Technology, 2023, 66(20): 20–35. (in Chinese)
- [113] LIMA R S, KUCUK A, BERNDT C C. Evaluation of microhardness and elastic modulus of thermally sprayed nanostructured zirconia coatings[J]. Surface and Coatings Technology, 2001, 135(2–3): 166–172.
- [114] CHEN Huang, DING Chuangxian. Nanostructured zirconia coating prepared by atmospheric plasma spraying[J]. Surface and Coatings Technology, 2002, 150: 31–36.
- [115] CHEN Huang, ZHOU Xiaming, DING Chuanxian. Investigation of the thermomechanical properties of a plasma-sprayed nanostructured zirconia coating[J]. Journal of the European Ceramic Society, 2003, 23(9): 1449–1455.
- [116] ZHOU Chungen, WANG Na, WANG Zhenbo, et al. Thermal cycling life and thermal diffusivity of a plasma-sprayed nanostructured thermal barrier coating [J]. Scripta Materialia, 2004, 51(10): 945–948.
- [117] WANG Wenquan, SHA C K, SUN Daqian, et al. Microstructural feature, thermal shock resistance and isothermal oxidation resistance of nanostructured zirconia coating[J]. Materials Science and Engineering: A, 2006, 424(1–2): 1–5.
- [118] 吕艳红, 吴子健, 唐建新, 等. 纳米YSZ热障涂层隔热行为研究[J]. 中国表面工程, 2006, 19(1): 24–27.
LV Yanhong, WU Zijian, TANG Jianxin, et al. Study on the heat insulating behavior of nanostructure YSZ thermal barrier coatings[J]. China Surface Engineering, 2006, 19(1): 24–27. (in Chinese)
- [119] 周 斌, 王全胜, 柳彦博, 等. 纳米氧化锆涂层晶粒度与隔热性能的关系[J]. 材料保护, 2006, (3): 1–3.
ZHOU Bin, WANG Quansheng, LIU Yanbo, et al. Grain size and thermal conductivity of nano-zirconia thermal barrier coating[J]. Materials Protection, 2006, (3): 1–3. (in Chinese)
- [120] 王 铀. 热喷涂纳米涂层20年回顾与展望[J]. 表面技术, 2016, 45(9): 1–9.
WANG You. Review and prospects for 20-year development of thermal sprayed nanocoatings[J]. Surface Technology, 2016, 45(9): 1–9. (in Chinese)
- [121] WANG Liang, WANG Yangqiu, SUN Xiaoguang, et al. A novel structure design towards extremely low thermal conductivity for thermal barrier coatings—experimental and mathematical study[J]. Materials & Design, 2012, 35: 505–517.
- [122] WANG Liang, WANG Youyuan, SUN Xiaoguang, et al. Preparation and characterization of nanostructured $\text{La}_2\text{Zr}_2\text{O}_7$ feedstock used for plasma spraying[J]. Powder Technology, 2011, 212(1): 267–277.
- [123] WANG Liang, WANG Yongzhe, SUN Xiaoguang, et al. Thermal shock behavior of 8YSZ and double-ceramic-layer $\text{La}_2\text{Zr}_2\text{O}_7$ /8YSZ thermal barrier coatings fabricated by atmospheric plasma spraying[J]. Ceramics International, 2012, 38(5): 3595–3606.
- [124] 王 铀, 杨 勇. 热喷涂纳米结构涂层的研究进展及在外军舰艇上的应用[J]. 中国表面工程, 2008, 21(1): 6–15.
WANG You, YANG Yong. Research progress of thermal sprayed nanostructured coatings and their application in foreign warships[J]. China Surface Engineering, 2008, 21(1): 6–15. (in Chinese)
- [125] 王 铀. 大力发展纳米表面工程[J]. 热喷涂技术,

- 2011,3(1):8–16.
- WANG You. To develop nano-surface engineering[J]. Thermal Spray Technology,2011,3(1):8–16. (in Chinese)
- [126] The prestigious list of the 100 Most Technologically Significant New Products of the Year[EB/OL]. [2025-04-11]. <http://www.rdmag.com/features/0109100mech.asp>.
- [127] KAVETSKY R. The navy's program in nanoscience and nanotechnology - a look ahead[EB/OL]. [2025-04-11]. <http://www.dtic.mil/dust/PDF/cgr.pdf>.
- [128] BRYANT R E. Management and introduction of technology-an OSD office of technology transition perspective for effects based support in the new security environment[EB/OL]. [2025-04-11]. <http://www.dodmantech.com/PUBS/MgrGuideToTechTrans-AppendC.pdf>.
- [129] WANG You,JIANG S,WANG Meidong,et al. Abrasive wear characteristics of plasma sprayed nanostructured alumina/titania coatings[J]. Wear,2000,237(2):176–185.
- [130] 钟 鑫. 等离子体喷涂硅酸锆涂层结构与性能研究[D]. 上海:上海大学,2018.
- ZHONG Xin. Microstructure and properties of ytterbium silicates coating deposited by atmospheric plasma spray[D]. Shanghai:Shanghai University, 2018. (in Chinese)
- [131] 罗颐秀. 稀土硅酸盐材料热学性能的理论研究及声子工程调控[D]. 合肥:中国科学技术大学,2019.
- LUO Yixiu. Theoretical investigation and phonon engineering on thermal properties of rare-earth silicates[D]. Hefei:University of Science and Technology of China,2019. (in Chinese)
- [132] AYYASAMY M V,DEJKERS J A,WADLEY H N G,et al. Density functional theory and machine learning guided search for $\text{RE}_2\text{Si}_2\text{O}_7$ with targeted coefficient of thermal expansion[J]. Journal of the American Ceramic Society,2020,103(8):4489–4497.
- [133] FERNÁNDEZ-CARRIÓN A J,ALLIX M,BECERRO A I. Thermal expansion of rare-earth pyrosilicates[J]. Journal of the American Ceramic Society,2013,96(7):2298–2305.
- [134] ZHOU Yanchun,ZHAO Cen,WANG Feng,et al. Theoretical prediction and experimental investigation on the thermal and mechanical properties of bulk $\beta\text{-Yb}_2\text{Si}_2\text{O}_7$ [J]. Journal of the American Ceramic Society,2013,96(12):3891–3900.
- [135] 周邦阳,崔永静,王长亮,等. 稀土硅酸盐环境障涂层研究进展[J]. 材料工程,2023,51(12):12–23.
- ZHOU Bangyang,CUI Yongjing,WANG Changliang, et al. Research progress in rare earth silicate environmental barrier coatings[J]. Journal of Materials Engineering,2023,51(12):12–23. (in Chinese)
- [136] EATON H E,LINSEY G D,MORE K L,et al. EBC protection of SiC/SiC composites in the gas turbine combustion environment[R]. ASME 2000-GT-0631, 2000.
- [137] JIAN Yingjie,WANG Yanfei,LIU Rongjun,et al. Oxidation performance of ytterbium disilicate/silicon environmental barrier coating via optimized air plasma spraying[J]. Journal of Materials Science and Chemical Engineering,2021,9(4):19–26.
- [138] UENO S,OHJI T,LIN H T. Recession behavior of a silicon nitride with multi-layered environmental barrier coating system[J]. Ceramics International,2007,33(5):859–862.
- [139] RICHARDS B T,BEGLEY M R,WADLEY H N G. Mechanisms of ytterbium monosilicate/mullite/silicon coating failure during thermal cycling in water vapor [J]. Journal of the American Ceramic Society,2015, 98(12):4066–4075.
- [140] WIESNER V L,BANSAL N P. Crystallization kinetics of calcium–magnesium aluminosilicate (CMAS) glass [J]. Surface and Coatings Technology,2014,259: 608–615.
- [141] WIESNER V L,SCALES D,JOHNSON N S,et al. Calcium–magnesium aluminosilicate (CMAS) interactions with ytterbium silicate environmental barrier coating material at elevated temperatures[J]. Ceramics International,2020,46(10):16733–16742.
- [142] NIEAI A A,MOHAMMADI M,SHOJAIE-BAHAA-BAD M. Hot corrosion behavior of calcium magnesium aluminosilicate (CMAS) on the $\text{Yb}_2\text{SiO}_5\text{-8YSZ}$ composite as a candidate for environmental barrier coatings[J]. Materials Chemistry and Physics,2020, 243:122596.
- [143] TIAN Zhilin,ZHANG Jie,ZHENG Liya,et al. General trend on the phase stability and corrosion resistance of rare earth monosilicates to molten calcium–magnesium–aluminosilicate at 1300 °C[J]. Corrosion Science,2019,148:281–292.
- [144] RICHARDS B T,SEHR S,DE FRANQUEVILLE F, et al. Fracture mechanisms of ytterbium monosilicate environmental barrier coatings during cyclic thermal exposure[J]. Acta Materialia,2016,103:448–460.
- [145] SEO H I,KIM D,LEE K S. Crack healing in mullite-based EBC during thermal shock cycle[J]. Coatings, 2019,9(9):585.