

影响固体氧化物电池堆输出性能的界面因素研究进展

裴梓翔¹, 张 洁¹, 韩丽增¹, 范天成¹, 张 旻²

(1. 宁波市电力设计院有限公司, 浙江 宁波 315020; 2. 中国科学院宁波材料技术与工程研究所, 全省先进燃料电池与电解池技术重点实验室, 浙江 宁波 315201)

摘 要: 固体氧化物燃料电池堆是固体氧化物燃料电池(SOFC)发电系统的核心部件, 也是 SOFC 能否商业化应用的关键。当电池与密封材料性能满足要求时, 电池电极与连接体间的接触界面成为影响电池堆性能的直接因素。本文对 SOFC 电池堆的结构与界面进行分析, 同时对界面接触改善方法的研究现状进行综述, 如增大界面接触面积、提高电池堆外部载荷、改进集流层材料与优化集流体表面涂层等, 为研制高效、稳定运行的电池堆提供参考。

关键词: 固体氧化物燃料电池; 界面; 电池堆; 运行寿命

中图分类号: TM911 文献标志码: A 文章编号: 0454-5648(2026)07-2524-10

网络出版时间: 2026-04-13



固体氧化物燃料电池(Solid oxide fuel cell, SOFC)以高温(600~1000 °C)下的氧离子导体为电解质, 直接将燃料化学能转化为电能, 兼具高效、清洁与燃料普适性 3 大优势, 被视为分布式供能、重型交通及便携式电源的理想方案^[1-2]。不同于传统热力循环, SOFC 基于电化学反应, 其效率不受卡诺限制; 电池堆的电效率即可达 40%~60%, 若辅以余热回收实现热电联供, 系统综合效率可跃升至 85% 以上^[3]。SOFC 的核心部件包括阳极、阴极和电解质, 然而, 单电池的工作电压仅不到 1 V, 且输出功率有限, 必须将数十至上百片单体串并联成电池堆才能达到实际应用需求。因此, 电池堆是 SOFC 系统的“心脏”, 也是性能、寿命与成本的决定性部件。

全球 SOFC 商业化进程不断提速, 国际上已接近商业化应用状态。美国 Bloom Energy 公司于 2018 年登陆纽约证券交易所, 累计装机量 1.2 GW, 其中, 2024 年出货量为 318 MW^[4-5]。对于大型固定式发电系统, 耐久性和可靠性极其重要, 美国能源部设定 60 000 h 耐久目标^[6], 日本新能源产业技术综合开发机构(NEDO)提出 40 000 h 的运行时间/250 次启停指标^[7-8], 德国于利希研究中心以短堆 100 000 h 连续

运行刷新世界纪录^[9-10]。

SOFC 电池堆由单电池、金属连接体和高温密封件构成, 其性能瓶颈已从“材料本身”转向“界面耦合”^[11]。SOFC 电池堆中的关键界面包括电解质与阴阳极界面(电荷转移与离子输运)、阴阳极与连接体界面(电子收集、气密与热应力管理)。这些界面同时承载电流传导、气体分配、热交换及机械约束, 是 SOFC 内部多个物理化学过程的交汇点, 其结构、化学组成和稳定性直接决定了单电池的 electrochemical 性能、稳定性和寿命, 任何微观缺陷(氧化皮增厚、界面反应层、应力开裂或密封泄漏)都会以欧姆损耗、极化阻抗或热机械失配的形式放大, 最终降低电池堆输出并缩短寿命。

为了使电池堆性能满足要求, 研究人员首先想到的是尽可能提升单电池性能, 通过开发双钙钛矿、Ruddlesden-Popper 等新型电极材料^[12-13], 采用表面浸渍、原位析出修饰^[14-16]、构建异质界面^[17-18]的方式来提高电极催化活性, 或通过电极结构设计(如梯度孔隙)^[19-20]提高气体扩散能力, 从而提高单电池输出性能。目前, 实验室纽扣电池的功率密度推高至 2~3 W/cm², 但当尺寸放大到 10 cm × 10 cm 时, 受

收稿日期: 2025-08-01。 修订日期: 2025-09-04。

基金项目: 国家自然科学基金(U24A2062); 浙江省自然科学基金白马湖实验室区域创新发展联合基金资助项目(LBMHY24B060003); 宁波市重点研发计划(2023Z155)。

第一作者: 裴梓翔(1990—), 男, 本科, 高级工程师。

通信作者: 张 旻(1991—), 男, 博士, 助理研究员。

Received date: 2025-08-01. Revised date: 2025-09-04.

First author: PEI Zixiang (1990—), Male, Undergraduate, Senior Engineer.

E-mail: 759734093@qq.com

Correspondent author: ZHANG Yang (1991—), male, Ph.D., Assistant Researcher.

E-mail: zhangyang@nimte.ac.cn

限于气体分布不均、电流路径拉长及界面接触不良,功率密度普遍回落至 $0.4\sim 0.8\text{ W/cm}^2$, 远低于现有报道的纽扣电池功率密度^[21-22]。

当前, 电池堆中的电极与密封材料性能研究已趋于成熟, 能够满足性能要求, 电极与连接体间的接触界面成为影响电池堆性能的直接因素。本文将系统回顾 SOFC 电池堆中“电极-连接体”界面的研究进展, 从界面微观结构演变、接触电阻的耦合机制, 到增大接触界面、提高电池堆外部载荷、改进集流层材料与优化集流体表面涂层等优化策略, 旨在为下一代高功率、长寿命、低成本 SOFC 电池堆界面工程研究提供参考。

1 电池堆的结构与界面

SOFC 电池堆可视为“三明治”式重复单元的多层叠加, 每个重复单元由单电池、金属连接体(Interconnect)以及环绕四周的高温密封材料组成, 其对应的结构如图 1 所示^[23]。单电池中包括阴极(Cathode)、电解质(Electrolyte)与阳极(Anode), 三者通过多层煅烧工艺形成复合陶瓷片。SOFC 基本工作原理为燃料气(如 H_2 、 CH_4 等)在阳极的三相界面处失去电子, 被氧化成离子, 例如, 氢气氧化为质子(H^+); 失去的电子通过外电路对外做功输送至阴极; 氧气在阴极三相界面处得到电子, 被还原为氧离子(O^{2-}); 氧离子在电解质两侧氧分压梯度驱动下, 从阴极侧穿过电解质传输至阳极, 与阳极侧的 H^+ 发生反应生成水(H_2O)^[24]。

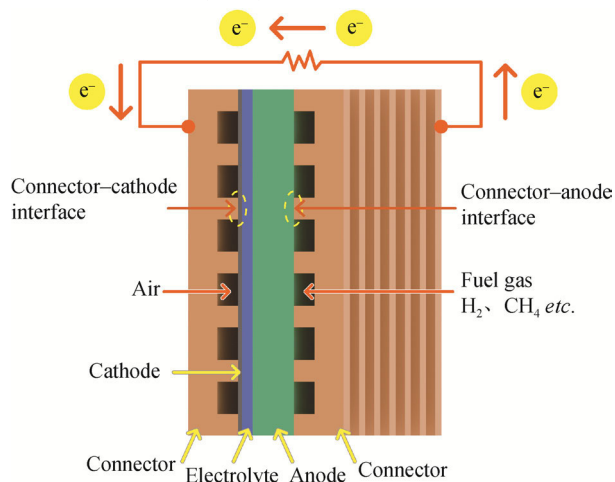


图 1 固体氧化物燃料电池堆结构示意图

Fig. 1 Schematic diagram of the solid oxide fuel cell stack structure

从电池堆尺度看, SOFC 的电化学反应链在宏观上必须跨越 2 个关键界面, 即阳极与连接体间的界面, 以及阴极与连接体间的界面。这两个界面既

是电流传输的“高速通道”, 也是热-机械-化学三重耦合的“脆弱地带”, 其几何精度、表面氧化层厚度、接触压力及热膨胀匹配程度直接决定电池堆的欧姆损耗、极化阻抗与长期可靠性。为量化界面质量, 通常引入面比电阻或界面电阻 2 个指标进行比较。其中, 面比电阻是“整体”指标, 表示沿电流方向的单位面积上所表现出的总阻抗, 涵盖电极阻抗与界面接触电阻; 而界面电阻衡量接触质量的“局部”参数, 仅反映两个接触界面之间的附加阻抗, 可由总面比电阻减去各部件电阻后获得^[25, 26]。

2 阳极与连接体的界面

SOFC 阳极既是燃料电化学氧化的反应场所, 也是电子的产生来源, 因此, 需同时具备高离子-电子混合导电性、适当的催化活性以及耐高温强还原气氛下的化学稳定性等^[27]。目前工业化阳极普遍采用金属-陶瓷复合体系, 以 Ni 为电子导电相, 氧化钇稳定的氧化锆 (YSZ)或氧化钆掺杂的氧化锆(GDC)为离子导电骨架, 形成 Ni-YSZ、Ni-GDC 等金属-陶瓷复合阳极^[28]。通过调控 Ni 含量与孔隙率, 可同时获得低极化阻抗与低欧姆阻抗的阳极材料。随着 SOFC 工作温度从传统 $800\text{ }^\circ\text{C}$ 以上降至 $600\sim 750\text{ }^\circ\text{C}$, 连接体材料亦由 LaCrO_3 系陶瓷^[29]过渡到低成本铁素体不锈钢(Fe-16Cr ^[30]、 Fe-22Cr ^[31]等), 以兼顾抗氧化性、热膨胀匹配与可加工性。

在此温度区间, 阳极侧始终处于强还原气氛, 界面本质为“金属-金属”接触, 即 Ni 与金属连接体间接触, 而金属同质界面理论上可获得极低的接触电阻。本团队研究表明, $10\text{ cm} \times 10\text{ cm}$ 短堆在初始阶段的阳极-连接体界面接触电阻仅为 $4.8\text{ }\mu\Omega\cdot\text{cm}^2$, 在恒定电流条件下运行 600 h , 界面接触电阻增大到 $8.5\text{ }\mu\Omega\cdot\text{cm}^2$ 左右并趋于稳定(图 2)。连接体电阻随时间变化的曲线表明, 这一电阻增大并非由连接体氧化引起。然而, 当采用甲烷等碳氢燃料时, 不锈钢

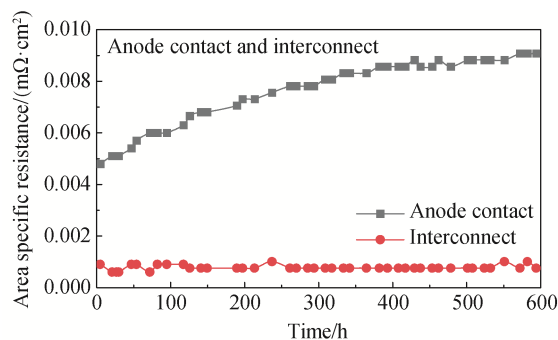


图 2 SOFC 阳极侧界面接触电阻

Fig. 2 Contact resistance at the anode side interface of SOFC

表面易发生碳沉积, 导致石墨化或金属碳化物层的形成, 显著增大界面阻抗^[32–33]。此外, 燃料的湿度对电极微结构也有很大影响, 干燥工况下, 面比电阻随运行时间显著增加^[34]。

3 阴极与连接体的界面

在 SOFC 运行期间, 阴极持续通入空气, 阴极及其接触的连接体所处的环境始终保持氧化气氛。为兼顾高电催化活性与化学稳定性, 阴极普遍采用具有混合离子–电子导电(MIEC)特性的钙钛矿氧化物^[35–36], 如 $\text{La}_{0.6}\text{Sr}_{0.4}\text{MnO}_3$ ^[37]、 $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ ^[38] 或 $\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.5}\text{Fe}_{1.5}\text{O}_{5+\delta}$ ^[39] 等。与此同时, 为了满足电池在高温氧化气氛下正常运行, 金属连接体表面通常也需要沉积 20~40 μm 的防护涂层(如钙钛矿或尖晶石氧化物)以抑制 Cr 挥发与高温氧化^[40]。因此, 阴极侧界面本质上是“氧化物–氧化物”非金属接触, 其导电路径依赖烧结颈、涂层微裂纹及接触点的隧穿/跃迁机制, 界面电阻远高于阳极侧“金属–金属”接触。

本团队通过对前述同一个 10 cm × 10 cm 电池堆关键部件进行监测, 结果发现初始阴极–连接体界面电阻接近 200 $\text{m}\Omega\cdot\text{cm}^2$ 。在恒流运行时, 界面电阻缓慢下降至 180 $\text{m}\Omega\cdot\text{cm}^2$, 随后趋于稳定(图 3)。显然, 阴极侧界面接触电阻比阳极侧大 5 个数量级, 因此, 阳极侧界面电阻几乎可忽略不计。

此外, 对于阳极支撑电池, 阴极侧接触质量直接关联电池堆寿命, 其内在机制可归结为电–热–化学–机械耦合效应: 首先, 界面接触质量差会导致界面微间隙增大, 离子/电子的传输路径随之延长, 欧姆阻抗显著增大; 同时, 局部阻抗差异在电流作用下诱发非均匀欧姆热, 局部热应力循环驱动材料蠕变并造成不可逆变形, 最终导致性能劣化; 此外, 界面温度升高还会驱动阴极中 Sr 等元素向电解质扩散, 生成 SrZrO_3 等绝缘相, 进一步加剧性能衰减^[41–42]。

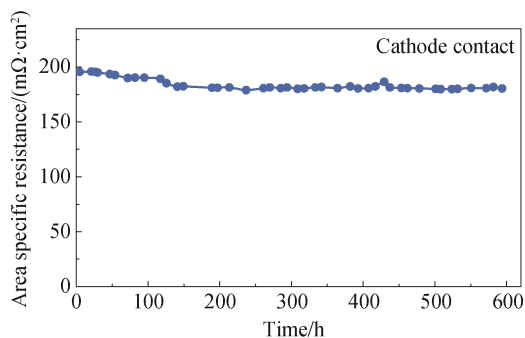


图 3 SOFC 阴极侧界面接触电阻

Fig. 3 Contact resistance at the cathode side interface of SOFC

阴极侧界面接触质量可以通过测试后的阴极宏观形貌观察得到。Jin 等^[43]拆解大量电池堆后发现, 阴极表面保持清晰、连续接触痕迹的单元 1(图 4a), 初期虽出现短暂电压陡降, 随后迅速趋于平稳, 功率衰减速率仅为 2.50%/kh; 而几乎无任何可见接触痕迹的单元 2(图 4b), 前 335 h 电压保持稳定, 之后急剧下滑, 衰减速率高达 22.68%/kh。2 个单元的电压监测曲线如图 4c 所示。由此可见, 阴极–连接体界面电阻既是制约瞬时输出功率的瓶颈, 也是长期性能衰减的主因, 后续研究有必要进一步降低阴极–连接体界面电阻。

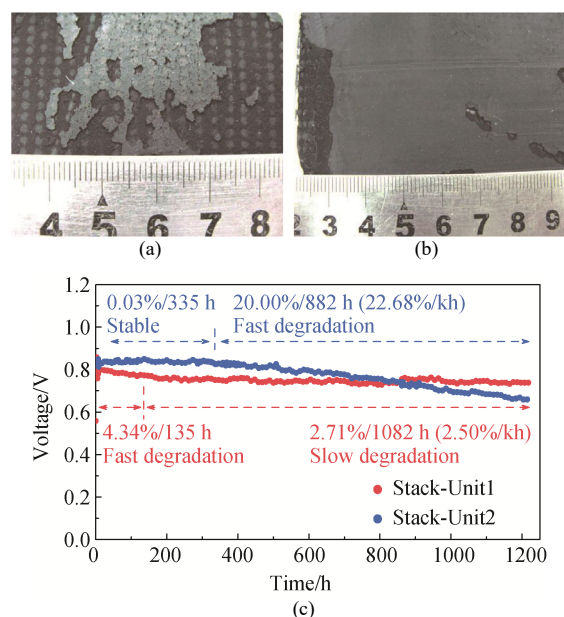


图 4 (a, b) 测试后 SOFC 阴极界面接触痕迹形貌; (c) 长期测试电池堆单体电压监测曲线

Fig. 4 (a, b) Contact morphology at the cathode interface of SOFC after testing; (c) voltage monitoring curve of the long-term tested stack unit

4 界面接触的改善方法

4.1 增大界面接触面积

在 SOFC 中, 界面接触电阻与真实接触面积近似成反比, 因此, 增加实际接触面积成为降低损耗、提升功率的首要策略。Jiang 等^[44]在 5 cm × 5 cm 的阳极支撑电池系统中研究了阴极集流银网投影面积覆盖率对性能的影响。结果发现, 当银网与 $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ (LSCF) 的阴极投影面积覆盖率从 4.6% 提升至 27.2% 时, 单电池电阻从 1.43 $\Omega\cdot\text{cm}^2$ 骤降至 0.19 $\Omega\cdot\text{cm}^2$, 对应功率密度从 125 mW/cm^2 跃升至 520 mW/cm^2 (图 5)。因此, 适度扩大接触面积可显著改善电子收集效率, 从而提高单电池的输出性能。

然而, 集流接触面积并非越大越好, 其上限受到电子收集与质量传输的约束。阴极接触面积增加可提高电子收集效率, 但会压缩氧气的有效扩散截面积, 当投影面积覆盖率 $>40\%$ 时, 有效扩散系数可下降 20%~30%, 浓差极化快速升高。此外, 银的弹性模量(83 GPa)^[45]远低于 LSCF(140~180 GPa)^[46], 热循环时界面局部应力集中导致微裂纹, 实际接触面积较理论值低 15%~25%。

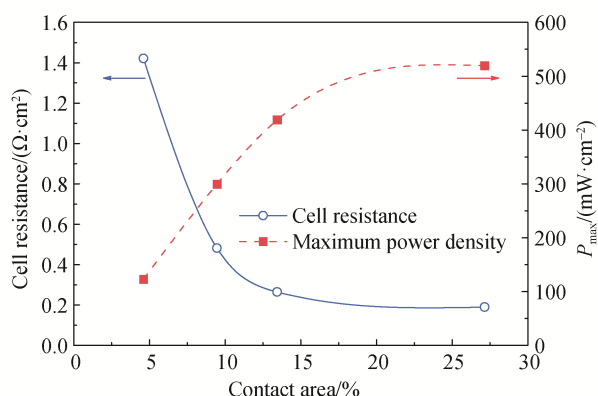


图 5 电池总电阻与最大功率密度随阴极界面接触面积的函数图^[44]

Fig. 5 Cell resistance and maximum power density of anode-supported cells as a function of contact area at the cathode interface^[44]

Guan 等^[47]进一步在 $10\text{ cm} \times 10\text{ cm}$ 尺寸的单电池上验证了这一“最优覆盖率”概念。当理论投影面积覆盖率增至 60%时, 单电池实测最大输出功率密度仅为 0.1 W/cm^2 , 远低于理论的输出功率, 证明单纯增加覆盖率已失效。为解决该矛盾, 采用阴极粉体-银复合浆料取代传统银网。经二次煅烧后, 浆料中的 LSCF 与基底形成烧结颈, 银相则在孔壁析出并构筑三维多孔导电网络。当设计覆盖率由 28%增至 40%时, 功率密度呈单调上升; 继续增至 45%后, 因扩散受阻功率略有回落(图 6)。

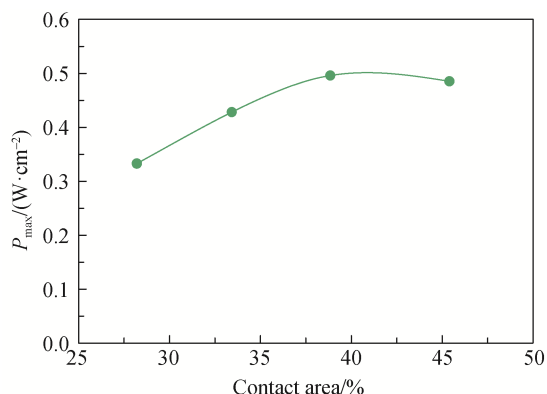


图 6 SOFC 最大功率密度与阴极界面接触面积关系

Fig. 6 Relationship between maximum power density and contact area at the cathode interface of anode-supported cells

4.2 提高电池堆外部载荷

在 SOFC 中, 功能层之间并非理想平面, 而是微米级粗糙度的“峰-谷”结构。常温装配时, 峰顶会与连接体先行接触, 升温后由于各层热膨胀差异, 间隙会进一步放大, 导致接触电阻骤增, 严重时甚至导致电极剥落或密封开裂。因此, 在电池堆组装阶段引入可控的外部机械载荷, 成为同步降低接触电阻、保证平面度与气密性的必要手段^[48]。德国于利希研究中心^[49]通过多物理场耦合模拟, 系统研究了外部载荷对 SOFC 接触电阻的影响规律, 发现接触电阻随压力增加呈现非线性下降趋势。当接触压力从零增大时, 界面微凸体发生弹塑性变形, 界面电阻呈指数下降; 继续加压时, 界面电阻下降趋缓, 内部应力开始累积; 外部载荷过大时, 电解质或阴极层出现横向裂纹, 界面电阻反而回升, 功率密度骤降。因此, 需要兼顾低接触电阻与结构完整性, 既要确保足够接触点, 又要避免构件损伤^[50]。

Murata 等^[51]采用直流四探针法对直径为 2.5 cm 的圆形 $(\text{La}_{0.85}\text{Sr}_{0.15})_{0.85}\text{MnO}_3$ (LSM)与连接体界面进行原位测试, 结果显示外部压力从 20 kPa 增大至 98 kPa 时, 界面电阻由 $6.7\text{ m}\Omega\cdot\text{cm}^2$ 降低至 $1.1\text{ m}\Omega\cdot\text{cm}^2$ 。Zhou 等^[52]针对 $10\text{ cm} \times 10\text{ cm}$ 的 36 片平板型电池堆开展数值模拟仿真, 结果表明, 在 5844.16 N 的加载压力下, 阳极、电解质及阴极的最大压应力依次为 76.66、33.31、30.65 MPa, 对应最大拉应力分别为 12.64、55.81、30.22 MPa。此外, 受压力传递损失影响, 应力自端板向中心逐步递减。Chen 等^[53]指出, 增加连接体厚度会在内部产生更多高应力区, 进而削弱电池堆的界面接触。Zhang 等^[54]以有效面积为 100 cm^2 的单电池为对象, 通过对比不同装配压力下的输出功率, 确定最优值为 7 MPa, 并将所得结果推广至由 120 片 0.2 m^2 单电池构成的电池堆, 最终将该电池堆的装配压力设定为 $150\text{ kg}\cdot\text{cm}^{-2}$ ($\sim 14.7\text{ MPa}$)。Guan 等^[55]进一步提出利用阴极表面压痕面积与压入深度作为量化指标, 在 $10\text{ cm} \times 10\text{ cm}$ 单池实验中通过调节装配压力使压痕深度由 $50\text{ }\mu\text{m}$ 增至 $100\text{ }\mu\text{m}$ 时功率密度由 0.32 W/cm^2 增大至 0.5 W/cm^2 , 继续加深至 $150\text{ }\mu\text{m}$ 则因过压产生裂纹而略微下降(图 7)。由此, 确立了“数据驱动的精准加压”替代“经验压紧”的新思路, 即借助在线压力传感、接触痕迹反演与寿命预测模型, 在装配阶段即可锁定最优压力窗口, 实现电池堆高功率与长寿命的协同优化。值得注意的是, 外部载荷须结合电池构型、电池堆片数、投影面积及整体结构等关键参数, 同时还需考虑

密封材料特性, 经实测后予以确定与优化^[56]。

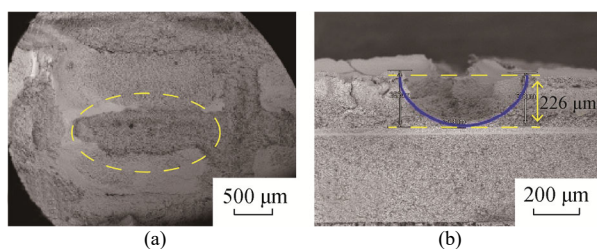


图7 测试后 SOFC 阴极集流层形貌^[55]; (a)表面; (b)断面
Fig. 7 Morphology of SOFC cathode current collector layer after testing^[55]: (a) surface; (b) cross-section

4.3 改进集流层材料

增大接触面积与提高接触深度是改善界面接触的两大措施, 但都离不开集流层材料的添加。SOFC 电池堆运行环境复杂, 阴极侧既有高温又有氧化气氛, 集流层材料同时扮演“高速电子公路”与“缓冲垫”双重角色, 其本征电导率、高温抗氧化性、与相邻层的热-机械匹配度直接决定界面电阻与长期稳定性^[57]。黄红艳^[58]通过数值模拟计算指出, 当阴极集流层的电导率从 200 S/cm 提高至 1000 S/cm 时, 阴极接触电阻从 130 mΩ·cm² 降低至 28.65 mΩ·cm², 但电导率继续提升至 5000 S/cm 时, 接触电阻仅降低 3%, 表明数千西门子级的电导率即可满足需求。

考虑到电池在空气中的稳定性以及高电导率, 研究者们首先想到的是选择贵金属作为阴极侧的集流层材料, 如 Pt^[59]或 Ag^[60]等。但不同金属的热膨胀系数、弹性模量、化学相容性以及稳定性均有所不同, 导致其作为集流层展现出的接触电阻并不一致。Simner 等^[61]研究了 Pt、Ag 与 Au 作为 La(Sr)FeO₃ 阴极集流层浆料的差异, 结果表明, Ag 和 Au 因高温挥发/扩散快、与 Cr 形成高阻相, 导致功率快速衰减, Pt 浆则表现出较好的稳定性, 单电池性能甚至略有提高。Huang 等^[62]采用 Pt 浆作为 Sr₂MgMoO₆ 阳极的集流层, 展现出较高的功率密度与长期稳定性。但 Bi 等^[63]研究发现, 该材料展现出较好的输出功率与稳定性可能是集流层材料导致的, 采用 Pt 浆作为集流层材料的单电池输出功率是使用 Ag 浆的 6.4 倍, 且具有更为优异的稳定性。因此, 选用合适的集流层材料也是提高单电池的输出功率与稳定性的关键因素。

除贵金属外, 一些钙钛矿和尖晶石氧化物也可作为集流层材料使用。LaCo_{0.6}Ni_{0.4}O₃ (LCN) 是一种具有潜力的阴极材料, 也可以作为集流层材料使用^[64–65]。LCN 中 Co 含量较多, 导致其热膨胀

系数较高($17.2 \times 10^{-6} \text{ K}^{-1}$), 易与目前常用的 LSCF 阴极以及连接体材料失配。Yang 等^[66]将 10%(质量分数)纳米 Ag 掺入 LCN, 既利用 Ag 的高导电桥接裂纹, 又通过纳米尺度分散抑制团聚, 面比电阻降至 65 mΩ·cm², 但过多的银粉引入会团聚并破坏 LCN 结构。为防止银粉团聚, Shin 等^[67]在银粉中引入 1.4 倍石墨粉进行造孔, 与没有孔的传统银浆相比, 孔隙率增加了 61.2%, 750 °C 时的输出功率提高了 25%, 达到 1328 mW/cm²。

LaNi_{0.6}Fe_{0.4}O₃(LNF)在 800 °C 时电导率达到 580 S/cm, 且热膨胀系数($11.4 \times 10^{-6} \text{ K}^{-1}$)与常用连接体材料匹配, 因此, LNF 具有作为集流层材料的潜力^[68]。Wang 等^[69]通过丝网印刷 LNF 层, 使得电池最大功率密度提高约 15%, 接触电阻仅为 86 mΩ·cm²。但在低氧分压情况下, LNF 的引入会阻碍氧气的扩散。朱腾龙等^[70]通过高温烧结预处理对 LNF 颗粒尺寸进行调控, 使 750 °C 时最大功率密度由 0.66 W/cm² 提升至 0.94 W/cm²。

为了使氧化物集流层材料能够达到与贵金属相似的调控效果, 同时兼顾成本与性能, 研究人员采用向氧化物集流层材料中添加贵金属形成复合集流层材料的方法, 取得了显著进展, 例如 LSM+Ag^[71–72]、LSM+Pd^[73]等。LSCF 是目前 SOFC 常用的阴极材料, Spotorno 等^[74]利用交流阻抗谱定量分析了 Crofer22 APU、铂网、Crofer22 APU + LSCF、铂网 + LSCF 四种集流层材料的欧姆阻抗与极化阻抗, 结果显示, 铂网 + LSCF 的组合展现出最为优异的性能, 在 750 °C、0.7 V 下的输出功率为 1.22 W/cm²。为了完全避开贵金属, Tucker 等^[75–76]在传统 LSM 集流层中添加具有低软化点的玻璃材料或无机黏结剂, 其烧结后形成玻璃-陶瓷互穿网络, 以提高集流层黏附强度, 阻抗值仅为 Pt 的一半(图 8), 而成本下降 90% 以上。

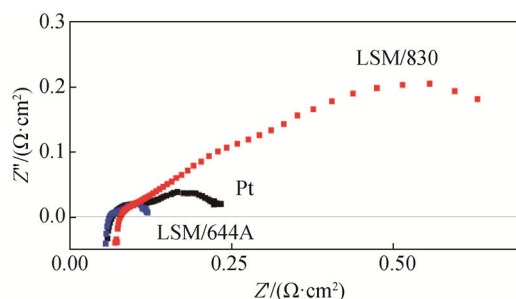


图8 不同阴极接触材料层单电池在 800 °C 时的电化学阻抗谱^[76]

Fig. 8 Electrochemical impedance spectra of anode-supported cells with various cathode contact material layers at 800 °C^[76]

4.4 优化集流体表面涂层

考虑到电池堆的实际应用，金属连接板在高温空气侧服役时仍存在氧化问题，导致其面比电阻显著增大，成为影响电池堆寿命的重要因素之一^[77]。在金属连接体表面构筑一层兼具“抗氧化”与“低电阻”双重功能的涂层，可将氧化抑制与界面损耗控制合二为一^[78]。

早期研究将钙钛矿阴极直接作为防护涂层。Morán-Ruiz 等^[79]在 Crofer22 APU 上沉积 $\text{LaNi}_{0.6}\text{Co}_{0.4}\text{O}_3$ 钙钛矿氧化物作为连接体涂层，使阴极与连接体间的接触电阻仅为 $5.4 \text{ m}\Omega\cdot\text{cm}^2$ 。Pyo 等^[80]采用湿法喷涂的方式在 Crofer22 APU 表面制备了 LSM 防护层，并在还原气氛下致密化，8000 h 运行后面比电阻稳定在 $20 \text{ m}\Omega\cdot\text{cm}^2$ ，仅为未防护样品的 1/5。然而，钙钛矿涂层致密化温度过高，采用普通煅烧方法难以制备，限制了其作为保护涂层的规模化应用^[81]。

尖晶石因其高导电性、强抗氧化性以及较低的致密化温度，被认为是理想的连接体涂层，尤其以锰钴尖晶石 $[(\text{Mn}, \text{Co})_3\text{O}_4]$ 应用最为广泛^[82-83]。锰钴尖晶石涂层在长期高温氧化条件下对连接体有很好的防护作用，Dayaghi 等^[84]报道，锰钴尖晶石涂层保护后的 430 不锈钢在 750°C 连续氧化 750 h 后，氧化膜厚度仅 $4 \mu\text{m}$ 且致密无裂纹，未保护的样品表面氧化层则出现局部脱落现象。王碧辉等^[85]通过电泳沉积的方式在 430 不锈钢上制备了 $\text{Mn}_{1.5}\text{Co}_{1.5}\text{O}_4$ 尖晶石涂层，长期运行后面比电阻稳定在 $16.5 \text{ m}\Omega\cdot\text{cm}^2$ 左右。冯仰光等^[86]通过喷涂的方式在 441 不锈钢表面制备了锰钴尖晶石涂层，其与 LSCF 阴极之间的界面电阻从最初的 $20.78 \text{ m}\Omega\cdot\text{cm}^2$ 缓慢下降至 $7.99 \text{ m}\Omega\cdot\text{cm}^2$ 。Zhang 等^[87]通过预氧化方式电镀了 CeO_2 掺杂的 Co-Fe-Ni 尖晶石涂层，面比电阻稳定在 $14.6 \text{ m}\Omega\cdot\text{cm}^2$ ，显著提升 430 不锈钢的高温抗氧化与导电性能。

5 结论与展望

随着 SOFC 商业化程度的不断推进，SOFC 的研究重心已从单电池材料转向电池堆级系统集成。大量实验结果表明，电池堆内部各关键部件间的界面接触已成为制约输出功率与寿命的核心瓶颈。阴极侧为氧化物-氧化物接触，界面电阻高达约 $200 \text{ m}\Omega\cdot\text{cm}^2$ ，而阳极侧处于不含碳氢燃料的强还原气氛，呈现金属-金属接触，界面电阻仅约 $9 \mu\Omega\cdot\text{cm}^2$ ，相差 5 个数量级，故可忽略其对总阻抗的贡献。因

此，阴极侧必须依赖集流层/涂层体系同时完成电子收集、应力缓冲与抗氧化保护。未来，界面优化的主线将围绕“集流层材料-连接体涂层-界面粗糙度”三维协同设计展开。表 1 汇总了提升固体氧化物燃料电池堆界面接触性能的策略，包括增大界面接触面积、提高外部载荷、改进集流层材料及优化集流体表面涂层等，为研制高效、稳定运行的电堆提供参考。

表 1 提升固体氧化物燃料电池堆界面接触性能的策略
Table 1 Strategies for enhancing interfacial contact performanc in solid oxide fuel cell stacks

No.	Category	Strategies
1	Interface contact area	Increased the projection area coverage of the silver mesh current collector
2	Assembly load of the stack	Precise load regulation via cathode surface indentation area and depth
3	Current collection contact material	Adopting cathode and precious metal composite current collector contact material
4	Current collector surface coating	Spinel oxide as a coating; Establish the relationship between surface roughness and power degradation

集流层材料开发趋势正从贵金属走向氧化物，再迈向双相复合的梯度体系，在满足千西门子电导率要求的同时，通过组分、微观结构以及孔隙率协同调控，实现与阴极及连接体的热-机械-化学三重匹配。

与此同时，界面电阻的精准定量表征仍是亟待突破的难点。传统四探针法受电池堆气密性限制，只能测得总电阻，难以剥离真实界面接触贡献。下一步需要在电池堆内部预埋超薄导线，耦合交流阻抗谱与电压监测，实时跟踪每一重复单元的界面状态；同时借助后位激光共聚焦显微镜、原子力显微镜等工具，建立表面粗糙度-接触深度-功率衰减的定量关联模型，为可预测的界面调控提供数据闭环。

总体而言，目前研究者对界面调控仍存在盲目性，调控结果难以预知。唯有彻底掌握界面机制，SOFC 电池堆才能在设计阶段锁定最优装配压力、粗糙度窗口和材料组合，进而实现对 SOFC 电池堆性能的调控，从而支撑数万小时耐久性的商业化目标，为分布式发电等大规模应用奠定基础。

参考文献:

- [1] NIKIFORAKIS I, MAMALIS S, ASSANIS D. Understanding solid oxide fuel cell hybridization: A critical review[J]. Appl Energy, 2025, 377: 124277.
- [2] QASEM N A A, ABDULRAHMAN G A Q. A recent comprehensive

- review of fuel cells: History, types, and applications[J]. *Int J Energy Res*, 2024, 2024: 7271748.
- [3] HUANG S L, YANG C, CHEN H, et al. Coupling impacts of SOFC operating temperature and fuel utilization on system net efficiency in natural gas hybrid SOFC/GT system[J]. *Case Stud Therm Eng*, 2022, 31: 101868.
- [4] WANG B W, WANG R X, LU R H, et al. Development and industrialization progress of solid oxide cell in China[J]. *Int J Green Energy*, 2025, 22(2): 334–342.
- [5] AL BULUSHI F, SARAVANAN A M, PATIL G, et al. Studies on bloom energy server[J]. *Recent Innov Chem Eng Former Recent Pat Chem Eng*, 2022, 15(3): 214–225.
- [6] WHISTON M M, AZEVEDO I M L, LITSTER S, et al. Meeting U.S. solid oxide fuel cell targets[J]. *Joule*, 2019, 3(9): 2060–2065.
- [7] HOSOI K, NAKABARU M. Status of national project for SOFC development in Japan[J]. *ECS Trans*, 2009, 25(2): 11–20.
- [8] KUNZ F, PETERS R, SCHÄFER D, et al. Progress in research and development of solid oxide cells, stacks and systems at forschungszentrum jülich[J]. *ECS Trans*, 2023, 111(6): 1667–1676.
- [9] SUZUKI M, TAKUWA Y, INOUE S, et al. Durability verification of residential SOFC CHP system[J]. *ECS Trans*, 2013, 57(1): 309–314.
- [10] FANG Q P, BLUM L, STOLTEN D. Electrochemical performance and degradation analysis of an SOFC short stack following operation of more than 100, 000 hours[J]. *J Electrochem Soc*, 2019, 166(16): F1320–F1325.
- [11] LEE W, LANG M, COSTA R, et al. Enhancing uniformity and performance in solid oxide fuel cells with double symmetry interconnect design[J]. *Appl Energy*, 2025, 381: 125178.
- [12] FAN L D, LUO W Y, FAN Q X, et al. Status and outlook of solid electrolyte membrane reactors for energy, chemical, and environmental applications[J]. *Chem Sci*, 2025, 16(16): 6620–6687.
- [13] HUMAYUN M, LI Z S, ISRAR M, et al. Perovskite type ABO_3 oxides in photocatalysis, electrocatalysis, and solid oxide fuel cells: State of the art and future prospects[J]. *Chem Rev*, 2025, 125(6): 3165–3241.
- [14] SHIN H, SEO J, JEON S, et al. Enhanced catalytic activity and stability of SOFC electrodes through plasma-driven surface modification[J]. *J Mater Chem A*, 2024, 12(18): 10695–10703.
- [15] CHEN S G, ZHANG H X, YAO C G, et al. Review of SOFC cathode performance enhancement by surface modifications: Recent advances and future directions[J]. *Energy Fuels*, 2023, 37(5): 3470–3487.
- [16] DING D, LI X X, LAI S Y, et al. Enhancing SOFC cathode performance by surface modification through infiltration[J]. *Energy Environ Sci*, 2014, 7(2): 552.
- [17] ZHAO C H, LI Y F, ZHANG W Q, et al. Heterointerface engineering for enhancing the electrochemical performance of solid oxide cells[J]. *Energy Environ Sci*, 2020, 13(1): 53–85.
- [18] GAO Y, LIU K C, LI Q, et al. The approaches to conducting *in-situ* heterostructure electrodes for SOCs: A mini review[J]. *Sustain Mater Technol*, 2024, 41: e01107.
- [19] CONNOR P A, YUE X L, SAVANIU C D, et al. Tailoring SOFC electrode microstructures for improved performance[J]. *Adv Energy Mater*, 2018, 8(23): 1800120.
- [20] HUANG C C, HU J H, HUANG J H, et al. All-ceramic solid oxide fuel cells utilizing phase-inversion derived scaffolds and impregnated nanoparticles as cathodes[J]. *J Eur Ceram Soc*, 2025, 45(11): 117399.
- [21] SUMI H, SHIMADA H, YAMAGUCHI Y, et al. Why is the performance different between small- and large-scale SOFCs?[J]. *Electrochim Acta*, 2023, 443: 141965.
- [22] PIROU S, TALIC B, BRODERSEN K, et al. Production of a monolithic fuel cell stack with high power density[J]. *Nat Commun*, 2022, 13: 1263.
- [23] 王显玉, 杜志鸿, 王捷, 等. 平板式固体氧化物燃料电池密封材料研究进展[J]. *硅酸盐学报*, 2025, 53(7): 2066–2078.
- WANG Xianyu, DU Zhihong, WANG Jie, et al. *J Chin Ceram Soc*, 2025, 53(7): 2066–2078.
- [24] RAZA T, YANG J J, WANG R M, et al. Recent advance in physical description and material development for single component SOFC: A mini-review[J]. *Chem Eng J*, 2022, 444: 136533.
- [25] SHONG W J, LIU C K, KAO W X, et al. Effect of electric current on cathode-side contact resistance in SOFC stacks[J]. *Int J Hydrog Energy*, 2025, 100: 863–869.
- [26] WU W, GUAN W B, WANG W G. Contribution of properties of composite cathode and cathode/electrolyte interface to cell performance in a planar solid oxide fuel cell stack[J]. *J Power Sources*, 2015, 279: 540–548.
- [27] ZAINON A N, SOMALU M R, KAMARUL BAHRAIN A M, et al. Challenges in using perovskite-based anode materials for solid oxide fuel cells with various fuels: A review[J]. *Int J Hydrog Energy*, 2023, 48(53): 20441–20464.
- [28] AHMED N, DEVI S, DAR M A, et al. Anode material for solid oxide fuel cell: A review[J]. *Indian J Phys*, 2024, 98(3): 877–888.
- [29] BRODNIKOVSKIY D M. Materials for connecting solid oxide fuel cells (overview)[J]. *Powder Metall Met Ceram*, 2024, 63(3–4): 184–193.
- [30] ZHOU J W, CHEN Q F, SANG J K, et al. Conductivity and oxidation behavior of Fe-16Cr alloy as solid oxide fuel cell interconnect under long-stability and thermal cycles[J]. *Acta Metall Sin (Engl Lett)*, 2021, 34(5): 668–674.
- [31] MORÁN-RUIZ A, VIDAL K, LARRAÑAGA A, et al. Evaluation of using protective/conductive coating on Fe-22Cr mesh as a composite cathode contact material for intermediate solid oxide fuel cells[J]. *Int J Hydrog Energy*, 2015, 40(14): 4804–4818.
- [32] ZENG Z, NATESAN K. Corrosion of metallic interconnects for SOFC in fuel gases[J]. *Solid State Ion*, 2004, 167(1–2): 9–16.
- [33] YAN M, FU P, CHEN Q Y, et al. Electrical performance and carbon deposition differences between the bi-layer interconnector and conventional straight interconnector solid oxide fuel cell[J]. *Energies*, 2014, 7(7): 4601–4613.
- [34] SOURKOUNI G, ARGIRUSIS C. Study on the degradation of SOFC anodes induced by chemical and electrochemical sintering using EIS and μ -CT[J]. *Appl Sci*, 2023, 13(23): 12785.
- [35] SAMREEN A, ALI M S, HUZAIFA M, et al. Advancements in perovskite-based cathode materials for solid oxide fuel cells: A comprehensive review[J]. *Chem Rec*, 2024, 24: e202300247.
- [36] DESTA H G, GEBRESLASSIE G, ZHANG J J, et al. Enhancing performance of lower-temperature solid oxide fuel cell cathodes through surface engineering[J]. *Prog Mater Sci*, 2025, 147: 101353.
- [37] SANNA C, SQUIZZATO E, COSTAMAGNA P, et al. Electrochemical study of symmetrical intermediate temperature-solid oxide fuel cells based on $\text{La}_{0.6}\text{Sr}_{0.4}\text{MnO}_3/\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_{1.95}$ for operation in direct methane/air[J]. *Electrochim Acta*, 2022, 409: 139939.
- [38] ZENG D P, XU K, ZHU F, et al. Enhancing the oxygen reduction reaction activity and durability of a solid oxide fuel cell cathode by surface modification of a hybrid coating[J]. *Int J Hydrog Energy*, 2023, 48(62): 23992–24001.

- [39] ABDALLA A M, ZHE W, SUN Y W, et al. Enhanced performance in SOFC cathodes via B-site co-dopant switching in PBSCF0.25 and PBSFC0.25 layered perovskites[J]. *Int J Appl Ceram Technol*, 2025, 22(4): e15088.
- [40] 董子烨, 吴毅恒, 卢冲, 等. 电泳沉积制备 MnCo 尖晶石涂层的高温长期稳定性研究[J]. *中国腐蚀与防护学报*, 2025, 45(1): 46–60.
DONG Ziye, WU Yiheng, LU Chong, et al. *J Chin Soc Corros Prot*, 2025, 45(1): 46–60.
- [41] KENNOUCHE D, FANG Q, BLUM L, et al. Analysis of the cathode electrical contact in SOFC stacks[J]. *J Electrochem Soc*, 2018, 165(9): F677–F683.
- [42] CHEN K F, JIANG S P. Surface segregation in solid oxide cell oxygen electrodes: Phenomena, mitigation strategies and electrochemical properties[J]. *Electrochem Energy Rev*, 2020, 3(4): 730–765.
- [43] JIN L, GUAN W B, NIU J Q, et al. Effect of contact area and depth between cell cathode and interconnect on stack performance for planar solid oxide fuel cells[J]. *J Power Sources*, 2013, 240: 796–805.
- [44] JIANG S P, LOVE J G, APATEANU L. Effect of contact between electrode and current collector on the performance of solid oxide fuel cells[J]. *Solid State Ion*, 2003, 160(1–2): 15–26.
- [45] JIANG Y J, LU M Y, WANG S L, et al. Temperature coefficient of Young's modulus of silver microwhiskers determined by a laser Doppler vibration measurement[J]. *Mod Phys Lett B*, 2021, 35(21): 2150350.
- [46] HU C, DUAN L, PAN Z H, et al. Improving the stability of $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ electrode for solid oxide fuel cells by introducing sintering inhibitors[J]. *Ceram Int*, 2024, 50(19): 37419–37429.
- [47] GUAN W B, ZHAI H J, JIN L, et al. Effect of contact between electrode and interconnect on performance of SOFC stacks[J]. *Fuel Cells*, 2011, 11(3): 445–450.
- [48] GOHAR O, KHAN M Z, SALEEM M, et al. Navigating the future of solid oxide fuel cell: Comprehensive insights into fuel electrode related degradation mechanisms and mitigation strategies[J]. *Adv Colloid Interface Sci*, 2024, 331: 103241.
- [49] PEKSEN M. A coupled 3D thermo-fluid–thermomechanical analysis of a planar type production scale SOFC stack[J]. *Int J Hydrog Energy*, 2011, 36(18): 11914–11928.
- [50] LIM H T, VIRKAR A V. A study of solid oxide fuel cell stack failure by inducing abnormal behavior in a single cell test[J]. *J Power Sources*, 2008, 185(2): 790–800.
- [51] MURATA K, SHIMOTSU M. Reduction of electrical contact resistance between components solid oxide fuel cell[J]. *J Ceram Soc Japan*, 2003, 111(1292): 222–226.
- [52] ZHOU R D, CAI W Q, SUN K H, et al. Analysis of assembly and thermal stress in kW scaled SOFC stacks[J]. *Int Commun Heat Mass Transf*, 2025, 163: 108702.
- [53] CHEN X D, JI Y T, YAN D, et al. Thermal stress and contact analysis utilizing tested temperature data in a kW-class external-manifold solid oxide fuel cell stack[J]. *Appl Energy*, 2024, 370: 123635.
- [54] ZHANG R Y, HAN M F, XU S S, et al. Analysis of the assembly pressure of a high-power molten carbonate fuel cell stack during initial roasting[J]. *Fuel*, 2024, 378: 132895.
- [55] GUAN W B, JIN L, WU W, et al. Effect and mechanism of Cr deposition in cathode current collecting layer on cell performance inside stack for planar solid oxide fuel cells[J]. *J Power Sources*, 2014, 245: 119–128.
- [56] FITZPATRICK J, MEINHARDT K, KARRI N, et al. Finite element modeling of the glass sealing process for solid oxide cell stacks[J]. *Chem Eng J*, 2024, 498: 155452.
- [57] 朱腾龙, 何启, 吕秋秋, 等. 固体氧化物燃料电池阴极接触组件研究进展[J]. *硅酸盐学报*, 2025, 53(10): 3031–3040.
ZHU Tenglong, HE Qi, (LÜ/LV/LU/LYU) Qiuqiu, et al. *J Chin Ceram Soc*, 2025, 53(10): 3031–3040.
- [58] 黄红艳. 固体氧化物燃料电池阴极接触电阻数值模拟研究[D]. 镇江: 江苏科技大学, 2020.
HUANG Hongyan. Numerical simulation study of cathode contact resistance in planar solid oxide fuel cell[D]. Zhenjiang: Jiangsu University of Science and Technology, 2020.
- [59] BOUKAMP B A, HILDENBRAND N, BOUWMEESTER H J M, et al. Impedance of thin film cathodes: Thickness and current collector dependence[J]. *Solid State Ion*, 2015, 283: 81–90.
- [60] KIM M C, YULDASHEV R, KWON S, et al. Solid oxide fuel cell stack with enhanced performance and durability utilizing a porous Ag coating layer as the current collector[J]. *Int J Hydrog Energy*, 2024, 71: 797–803.
- [61] SIMNER S P, ANDERSON M D, PEDERSON L R, et al. Performance variability of $\text{La}(\text{Sr})\text{FeO}_3$ SOFC cathode with Pt, Ag, and Au current collectors[J]. *J Electrochem Soc*, 2005, 152(9): A1851.
- [62] HUANG Y H, DASS R I, XING Z L, et al. Double perovskites as anode materials for solid-oxide fuel cells[J]. *Science*, 2006, 312(5771): 254–257.
- [63] BI Z H, ZHU J H. Effect of current collecting materials on the performance of the double-perovskite $\text{Sr}_2\text{MgMoO}_{6-\delta}$ anode[J]. *J Electrochem Soc*, 2011, 158(6): B605.
- [64] WANG F Z, YAN D, ZHANG W Y, et al. $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_{3-\delta}$ as cathode contact material for intermediate temperature solid oxide fuel cells[J]. *Int J Hydrog Energy*, 2013, 38(1): 646–651.
- [65] DUAN N Q, YANG J J, GAO M R, et al. Multi-functionalities enabled fivefold applications of $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_{3-\delta}$ in intermediate temperature symmetrical solid oxide fuel/electrolysis cells[J]. *Nano Energy*, 2020, 77: 105207.
- [66] YANG J J, LI Z, YAN D, et al. The investigation of Ag & $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_{3-\delta}$ composites as cathode contact material for intermediate temperature solid oxide fuel cells[J]. *Int J Hydrog Energy*, 2018, 43(28): 12705–12712.
- [67] SHIN J W, LEE D Y, HUSSAIN A, et al. Highly robust and porous cathode current collecting layer for flat-tubular solid oxide fuel cell stack applications[J]. *Ceram Int*, 2024, 50(21): 41016–41027.
- [68] MORÁN-RUIZ A, VIDAL K, LAGUNA-BERCERO M Á, et al. Effects of using $(\text{La}_{0.8}\text{Sr}_{0.2})_{0.95}\text{Fe}_{0.6}\text{Mn}_{0.3}\text{Co}_{0.1}\text{O}_3$ (LSFMC), $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_{3-\delta}$ (LNF) and $\text{LaNi}_{0.6}\text{Co}_{0.4}\text{O}_{3-\delta}$ (LNC) as contact materials on solid oxide fuel cells[J]. *J Power Sources*, 2014, 248: 1067–1076.
- [69] WANG Y, LYU Q Q, ZHU T L, et al. Electrical and electrochemical performances evaluation of $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$ Cathode contact and current collecting layer in SOFCs[J]. *J Electrochem Soc*, 2022, 169(4): 044531.
- [70] 张琨, 王宇, 朱腾龙, 等. $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$ 阴极接触材料导电特性调控及其对 SOFC 电化学性能的影响[J]. *无机材料学报*, 2024, 39(4): 367–373.
ZHANG Kun, WANG Yu, ZHU Tenglong, et al. *J Inorg Mater*, 2024, 39(4): 367–373.
- [71] WILKINSON L T, ZHU J H. Ag-perovskite composite materials for SOFC cathode–interconnect contact[J]. *J Electrochem Soc*, 2009, 156(8): B905.
- [72] ZHAO C H, LIU R Z, SHAO L, et al. Effect of $\text{Ag}-(\text{La}_{0.8}\text{Sr}_{0.2})_{0.95}\text{MnO}_3$

- current-collecting layer on the stability of anode-supported solid oxide fuel cell[J]. *J Alloys Compd*, 2010, 496(1–2): 433–435.
- [73] WANG C, XIN X S, XU Y J, et al. Performance of a novel La(Sr)MnO₃-Pd composite current collector for solid oxide fuel cell cathode[J]. *J Power Sources*, 2011, 196(8): 3841–3845.
- [74] SPOTORNO R, PICCARDO P, SCHILLER G. Effect of cathode contacting on anode supported cell performances[J]. *J Electrochem Soc*, 2016, 163(8): F872–F876.
- [75] TUCKER M C, CHENG L, DEJONGHE L C. Glass-containing composite cathode contact materials for solid oxide fuel cells[J]. *J Power Sources*, 2011, 196(20): 8435–8443.
- [76] TUCKER M C, CHENG L, DEJONGHE L C. Inorganic binder-containing composite cathode contact materials for solid oxide fuel cells[J]. *J Power Sources*, 2013, 224: 174–179.
- [77] EBRAHIMIFAR H, ZANDRAHIMI M. Oxidation and electrical behavior of a ferritic stainless steel with a Mn–Co-based coating for SOFC interconnect applications[J]. *Oxid Met*, 2015, 84(3–4): 329–344.
- [78] ZHU W Z, DEEVI S C. Opportunity of metallic interconnects for solid oxide fuel cells: A status on contact resistance[J]. *Mater Res Bull*, 2003, 38(6): 957–972.
- [79] MORÁN-RUIZ A, VIDAL K, LARRAÑAGA A, et al. Laser machining of LaNi_{0.6}M_{0.4}O_{3-δ} (M: Co, Fe) dip-coated on a Fe–22Cr mesh material to obtain a new contact coating for SOFC: Interaction between Crofer22APU interconnect and La_{0.6}Sr_{0.4}FeO₃ cathode[J]. *Int J Hydrog Energy*, 2015, 40(26): 8407–8418.
- [80] PYO S S, LEE S B, LIM T H, et al. Characteristic of (La_{0.8}Sr_{0.2})_{0.98}MnO₃ coating on Crofer22APU used as metallic interconnects for solid oxide fuel cell[J]. *Int J Hydrog Energy*, 2011, 36(2): 1868–1881.
- [81] BRYLEWSKI T, DABEK J, PRZYBYLSKI K, et al. Screen-printed (La, Sr)CrO₃ coatings on ferritic stainless steel interconnects for solid oxide fuel cells using nanopowders prepared by means of ultrasonic spray pyrolysis[J]. *J Power Sources*, 2012, 208: 86–95.
- [82] ZHU J H, CHESSON D A, YU Y T. Review: (Mn, co)₃O₄-based spinels for SOFC interconnect coating application[J]. *J Electrochem Soc*, 2021, 168(11): 114519.
- [83] 吴诗静, 陈霖, 刘佳乐, 等. Mn–Co 基尖晶石涂层在固体氧化物燃料电池连接体合金中的研究进展[J]. *陶瓷学报*, 2022, 43(5): 733–741.
- WU Shijing, CHEN Lin, LIU (Jia)(Le)Yue, et al. *J Ceram*, 2022, 43(5): 733–741.
- [84] DAYAGHI A M, ASKARI M, RASHTCHI H, et al. Fabrication and high-temperature corrosion of sol–gel Mn/Co oxide spinel coating on AISI 430[J]. *Surf Coat Technol*, 2013, 223: 110–114.
- [85] 王碧辉, 刘聚, 崔志翔, 等. 电泳沉积制备 MnCo 尖晶石涂层的高温长期稳定性研究[J]. *中国腐蚀与防护学报*, 2024, 44(4): 972–978.
- WANG Bihui, LIU Ju, CUI Zhixiang, et al. *J Chin Soc Corros Prot*, 2024, 44(4): 972–978.
- [86] 冯仰光, 林科迪, 张旸, 等. Mn-Co 涂层对 SUS441 不锈钢面比电阻及其阴极侧界面电阻的影响[J]. *硅酸盐学报*, 2025, 53(10): 3013–3021.
- FENG Yangguang, LIN Kedi, ZHANG Yang, et al. *J Chin Ceram Soc*, 2025, 53(10): 3013–3021.
- [87] ZHANG Y, LIU Q Y, LI Q, et al. Microstructure, oxidation resistance, and electrical conductivity of CeO₂-doped Co-Fe-Ni spinel coatings on SUS 430 SOFC interconnects[J]. *Jom*, 2025, 77(8): 6154–6165.

作者贡献声明:

裴梓翔: 撰写初稿、获取资金支持

张 洁: 数据管理、数据分析、绘制图表

韩丽增: 执行文献调研、修订论文

范天成: 验证结果、参与数据分析

张 旸: 设计论文框架、审阅与修订论文、监督和指导

Interfacial Factors Affecting Output Performance of Solid Oxide Cells: A Brief Review

PEI Zixiang¹, ZHANG Jie¹, HAN Lizeng¹, FAN Tiancheng¹, ZHANG Yang²

(1. Ningbo Elect Power Design Inst Co. Ltd, Ningbo 315020, Zhejiang, China; 2. Zhejiang Key Laboratory of Advanced Fuel Cells and Electrolyzers Technology, Ningbo Institute of Material Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, Zhejiang, China)

Extended Abstract

Solid oxide fuel cells (SOFCs) can convert the chemical energy of fuels directly into electricity. This endows them with high efficiency, clean operation and fuel flexibility, positioning SOFCs as an attractive solution for distributed generation, heavy-duty transport and portable power. The commercialization is accelerating, and the performance bottlenecks shift from materials to interface. The existing electrodes and seals meet most requirements, the electrode-interconnect contact becomes the immediate determinant of stack performance. This review represents recent progress on the electrode-interconnect interface in SOFC stacks, covering microstructural evolution, contact-resistance mechanisms and optimization strategies, enlarging the contact region, tuning stack clamping pressure, improving current-collector materials and refining protective coatings to inform the design of next-generation, high-power, long-life and low-cost stacks.

The anode side is always in a strongly reducing atmosphere, so the interface is essentially metal-to-metal (Ni versus metallic interconnect) and can, in principle, yield an extremely low contact resistance. The cathode side is an oxide-to-oxide non-metallic contact with much higher resistance. In a previous work, the anode-interconnect contact resistance was only 6 $\mu\Omega\cdot\text{cm}^2$, whereas the cathode-interconnect value approached 200 $\text{m}\Omega\cdot\text{cm}^2$ —five orders of magnitude higher—rendering the anodic contribution negligible.

Contact resistance is approximately inversely proportional to the real contact area. Increasing the contact area is thus a primary route to lower losses and higher power. Moderate enlargement improves electron collection, but an excessive coverage shrinks the

oxygen diffusion cross-section and rapidly raises concentration polarization.

Current collector layers are not flat. Micron-scale “peaks and valleys” contact at room temperature, and mismatched thermal expansion during heat-up widens these gaps, sharply increasing resistance or even causing electrode spalling. A controlled external clamping load introduced during stack assembly therefore becomes essential to reduce contact resistance, while maintaining flatness and gas-tightness. Resistance decreases nonlinearly with pressure. It is therefore critical to balance low contact resistance with structural integrity. It is demonstrated that cathode imprint area and penetration depth can serve as quantitative indicators.

Enlarging contact area or penetration depth both require an added current-collector layer that simultaneously acts as a “high-speed electron highway” and a “stress cushion”. Its intrinsic conductivity, high-temperature oxidation resistance and thermo-mechanical compatibility govern interface resistance and long-term stability. Noble metals (*i.e.*, Pt, Ag) are first considered for the cathode side due to their stability and conductivity. Perovskites and spinels are also viable alternatives. To marry the performance of noble metals with cost-effective oxides, composite collectors such as LSM+Ag and LSM+Pd are fabricated. Completely noble-metal-free routes employ low-softening glass or inorganic binders that sinter into glass-ceramic interpenetrating networks to enhance adhesion.

For practical stacks, metallic interconnects inevitably oxidize in high-temperature air, causing the increase of ASR and threatening lifetime. A single coating that suppresses oxidation and maintains a low interfacial resistance is therefore highly desirable. Previous studies used perovskite cathodes directly as protective layers, but their high densification temperature hindered large-scale application. Spinel coatings—especially Mn-Co spinel are preferred because they combine high electronic conductivity, excellent oxidation resistance and moderate sintering temperatures.

Summary and prospects SOFC research shifts from single-cell materials to stack-level system integration. The experimental evidence shows that the contact between critical stack components is a dominant bottleneck governing both power output and lifetime. The anode side, operating in a reducing atmosphere and forming a metal-to-metal contact, exhibits a contact resistance, which is five orders of magnitude lower than the oxide-to-oxide interface on the cathode side and can be therefore neglected. The cathode side, in contrast, must rely on a current-collector/coating system that simultaneously ensures electron collection, stress buffering and oxidation protection. Consequently, future interface optimization will revolve around a three-dimensional, “current-collector material, interconnect coating and surface roughness” synergistic design framework.

Current-collector development evolves from noble metals to oxides and onward to graded, dual-phase composites. These systems aim to deliver conductivities on the order of kilosiemens/cm, while achieving triple matching—thermal, mechanical and chemical—with both the cathode and the interconnect through coordinated control of composition, microstructure and porosity.

Meanwhile, an accurate quantification of interfacial resistance remains a critical challenge. Conventional four-point measurements are limited by stack hermeticity, yielding only the total resistance, making it impossible to isolate the true interfacial contribution. The next step involves embedding ultrathin leads within the stack to couple AC impedance spectroscopy with *in-situ* voltage monitoring, thereby tracking the interfacial state of every repeating unit in real time. Post-mortem laser confocal microscopy and atomic force microscopy will be employed to establish quantitative correlations among surface roughness, contact depth and power degradation, creating a data-closed loop for predictive interface engineering.

The existing interface tuning still relies heavily on trial and error, and outcomes remain unpredictable. Understanding interfacial mechanisms can favor the design of SOFC stacks to lock in optimal clamping pressures, roughness windows and material combinations, thereby achieving a precise performance control. This mastery is essential to realizing commercial durability targets of tens of thousands of hours and laying the foundation for large-scale deployment in distributed generation.

Keywords solid oxide fuel cell; interface; stack; lifespan