

## 固体氧化物燃料电池阴极接触组件研究进展

朱腾龙, 何 启, 吕秋秋, 钟 秦

(南京理工大学化学与化工学院, 南京 210094)

**摘 要:** 固体氧化物燃料电池(SOFC)的能量转换效率高, 其中, 平板式电堆具有功率密度大、模块化设计和装配灵活的特点。但是, 平板式电堆结构紧凑, 对装配工艺要求高, 普遍存在陶瓷单电池和金属连接体之间“固-固”界面接触差的问题, 导致电堆内阻大、输出性能低和稳定性差等问题。因此, 在平板式电堆组装过程中, 经常在单电池与连接体之间添加接触材料, 以改善界面接触效果。为此, 本文基于平板式 SOFC 电堆对阴极接触组件的需求, 论述了阴极接触组件在电堆中的作用, 阐述了阴极接触材料选择和结构设计, 总结了目前常见接触材料的研究进展, 包括贵金属、钙钛矿、尖晶石、复合材料等, 分析了接触电阻的影响因素, 探讨了阴极接触组件制备工艺和性能调控手段。

**关键词:** 固体氧化物燃料电池; 阴极接触组件; 接触电阻; 制备工艺; 数值模拟

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固体氧化物燃料电池(SOFC)作为一种高效能量转化设备, 可以将燃料中的化学能直接转化为电能, 一次发电效率 40%~60%, 热电联产效率可以达到 60%~90%<sup>[1]</sup>。根据结构形状不同, SOFC 单电池主要分为管式、平板式和板管式等类型, 其中, 平板式结构单电池的制备工艺简单, 易于批量化生产, 具备单电池与连接体之间的电子流动路径短、功率密度较高等优势, 是商业化应用前景最广的单电池构型<sup>[2]</sup>。

一般情况下, 单电池的工作电压仅为 0.7~0.9 V, 因此, 需要将多个单电池串联组成电堆以满足其实际应用需求<sup>[3-4]</sup>。典型的平板式 SOFC 电堆内部结构如图 1a 所示, 连接体表面一般具有特定结构的气道以达到较均匀的气体分布, 因此, 对单电池与连接体之间的电子传导提出了较高要求。而单电池制备均一性及电堆装配精度等因素, 导致单电池和连接体之间界面接触差, 会产生较大的电堆内阻, 还容易导致电堆快速衰减等问题<sup>[5]</sup>。

通过在单电池和连接体之间加入接触组件, 可以在一定程度上改进单电池和连接体的界面接触, 提供相对稳定的电子传导路径, 从而减小电堆内的接触电阻<sup>[6]</sup>。接触组件还可以在一定程度上缓解电

堆内各组件之间的接触应力, 提高电堆装配质量, 延长服役寿命。

接触组件的材料选择和结构设计需要综合考虑各方因素, 如图 1b 所示, 应具有良好的导电性、化学稳定性, 与相邻组件匹配的热膨胀系数(TEC), 足够的孔隙率和机械强度, 较低的原料成本和制造成本等<sup>[7-9]</sup>。由于 SOFC 阳极处于还原性气氛下, 阳极与连接体之间一般可以使用多孔金属作为接触材料, 如镍网、泡沫镍等, 具有较高的电导率和较优的可压缩性, 因此, 阳极侧的接触电阻通常较小<sup>[10]</sup>。然而, SOFC 阴极通常为陶瓷氧化物, 其与金属连接体之间形成的“固-固”接触界面经常表现出较大的接触电阻, 是电堆内接触电阻的主要来源; 此外, 在高温氧化性气氛中, 阴极接触组件的材料选择、结构设计和制备工艺等要求更苛刻<sup>[11-12]</sup>。

Zhu 等<sup>[13]</sup>针对阴极接触组件的材料选择进行了全面综述; Shen 等<sup>[14]</sup>介绍了阴极接触材料体系和相关制备工艺。本文在此基础上, 面向平板式 SOFC 电堆对阴极接触组件的需求, 阐述了阴极接触组件的材料选择和结构设计, 论述了接触组件在电堆中的作用, 总结了常见阴极接触材料的研究新进展, 探讨了阴极接触组件制备工艺和性能调控手段。

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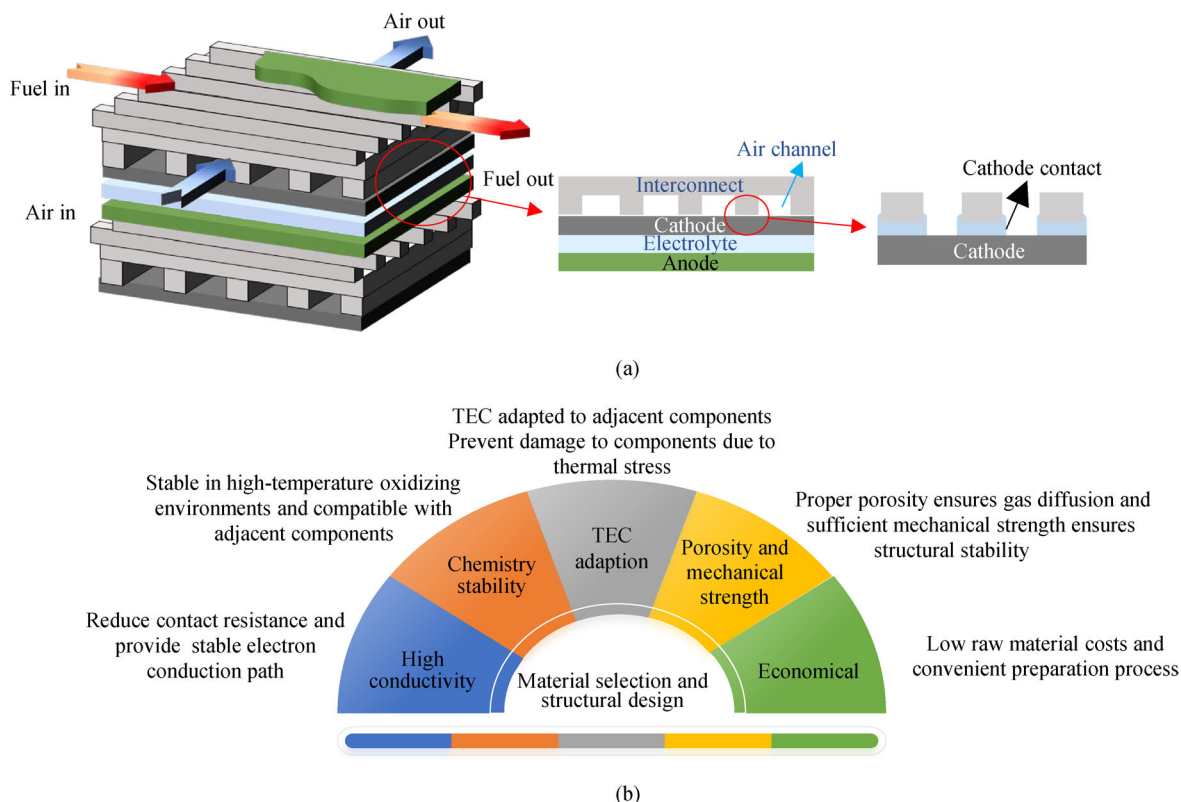
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第一作者: 朱腾龙(1988 ), 男, 博士, 副教授。

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First author: ZHU Tenglong (1988-), male, Ph.D., Associate Professor.

E-mail: zhutenglong@njjust.edu.cn



TEC is thermal expansion coefficient.

图 1 (a) 电堆及接触组件 (依附于阴极上, 通过压紧力与连接体接触) 示意图; (b) 接触组件材料选择与结构设计要求  
Fig. 1 (a) Schematic diagram of the stack and contact components; (b) contact component material selection and structural design requirements

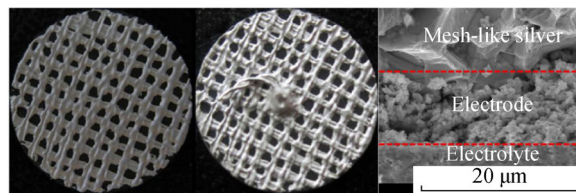
## 1 阴极接触材料选择

### 1.1 贵金属

Ag、Au、Pd 和 Pt 等贵金属在高温下具有优异的抗氧化性、高导电性以及一定的烧结活性, 并且具有较好的延展性, 可以通过自身形变缓解由于 TEC 失配而产生的电堆内应力<sup>[15]</sup>。但是, 从材料成本角度考虑, Au、Pd、Pt<sup>[16–18]</sup>这 3 种材料无法应用于大规模生产, 相较而言, 只有 Ag 有可能应用于阴极接触材料或者集电材料。

Ag 作为接触材料, 通常以银浆和银网 2 种形式使用。银浆的组成和烧结温度等因素会显著影响接触层的质量。因此, 优化银浆的配方和烧结工艺对提高接触层的性能至关重要。Gong 等<sup>[19]</sup>研究了使用银浆的烧结温度对阴极接触电阻的影响, 发现 800 °C 下烧结的银浆具有最低的面比电阻, 但是 Ag 的挥发现象较为严重。Lu 等<sup>[20]</sup>研究发现气流量越大、运行温度越高, Ag 的挥发速率越快。Guo 等<sup>[21]</sup>研究了 5 种不同的电流收集技术, 发现以稀释的银浆作为集电层获得了最高的峰值功率密度。Chen 等<sup>[22]</sup>对比了稀释浆料涂覆和浓缩银浆网格集电层的性能

和稳定性, 如图 2 所示, 使用浓缩银浆的网状集电层结构更加稳定。Kim 等<sup>[23]</sup>通过在银浆中添加石墨使得集电层在烧结过程中形成所需孔隙率, 显著降低了接触电阻, 提高了长期运行稳定性。



(a) Before sintering (b) After sintering (c) Microscopic topography of cross-section

图 2 网格状集电层实验前后对比图<sup>[22]</sup>

Fig. 2 Comparison before and after the grid collector experiment

此外也可以直接使用银网作为阴极接触组件, 相较于使用银浆, 银网结构稳定且在电堆装配中的操作更加方便。银作为阴极接触材料, 有优异的导电性和烧结活性等优点, 但在成本和稳定性方面存在挑战。

### 1.2 钙钛矿氧化物

掺杂的钙钛矿氧化物在高温下通常表现出较高的电子电导率, 并且在阴极氧化环境中表现出

较好的化学稳定性和热稳定性, 因此具有作为接触材料的应用前景。目前, 常用于阴极接触材料研究的典型钙钛矿氧化物有  $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ 、

$\text{La}_{0.8}\text{Sr}_{0.2}\text{CoO}_3$ 、 $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_3$ 、 $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$ 、 $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ 、 $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$  等, 其 TEC 和导电性能如表 1 所示<sup>[24-30]</sup>。

表 1 用于阴极接触材料的典型钙钛矿氧化物热膨胀和导电性能

Table 1 Typical perovskite oxide thermal expansion and conductivity properties for cathode contact materials

| Perovskite                                                                        | TEC(0–1000 °C)/K <sup>-1</sup> | Electrical conductivity (800 °C)/(S·cm <sup>-1</sup> ) | Ref.    |
|-----------------------------------------------------------------------------------|--------------------------------|--------------------------------------------------------|---------|
| $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$                                      | $11.7 \times 10^{-6}$          | 170                                                    | [27–28] |
| $\text{La}_{0.8}\text{Sr}_{0.2}\text{CoO}_3$                                      | $19.1 \times 10^{-6}$          | 1220                                                   | [24]    |
| $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_3$                                      | $17.2 \times 10^{-6}$          | 1270                                                   | [30]    |
| $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$                                      | $11.4 \times 10^{-6}$          | 580                                                    | [25]    |
| $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ | $19.3 \times 10^{-6}$          | 1000                                                   | [26]    |
| $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ | $17.3 \times 10^{-6}$          | 426                                                    | [29]    |

钙钛矿阴极接触材料面临的问题是难以同时兼顾高电导率、适配 TEC 和适当的烧结活性。Tietz 等<sup>[31]</sup>在控制相同的制备和测量条件下, 对比了  $\text{La}_{0.8}\text{Sr}_{0.2}\text{Mn}_{1-x}\text{Co}_x\text{O}_{3-y}$ 、 $\text{La}_{0.8}\text{Sr}_{0.2}\text{Fe}_{1-x}\text{Co}_x\text{O}_{3-y}$  和  $\text{La}_{0.8}\text{Sr}_{0.2}\text{Mn}_{1-x/2}\text{Fe}_{1-x/2}\text{Co}_x\text{O}_{3-y}$  的性质, 结果表明,  $\text{La}_{0.8}\text{Sr}_{0.2}\text{Mn}_{1-x}\text{Co}_x\text{O}_{3-y}$  在 Co 掺杂达到 0.25 时的电导率约为 100 S/cm, TEC 约为  $13 \times 10^{-6} \sim 15.5 \times 10^{-6} \text{ K}^{-1}$ , 烧结程度约为 30%~40%, 并且具有一定的孔隙率, 被认为是较好的材料组成折中选择。Agarkova 等<sup>[32]</sup>优化了  $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$  (LSM) 的预处理条件, 在不使用无机烧结助剂的情况下, 制备出了具有足够附着力和性能的稳定接触层。

$\text{La}_{0.6}\text{Sr}_{0.4}\text{CoO}_{3-\delta}$  (LSC) 的电导率高, 但是化学活性高、热膨胀系数大, 在长期和变工况运行中容易产生多种界面问题。Chou 等<sup>[33]</sup>将 LSC 与惰性材料(如莫来石)进行混合, 降低了阴极接触组件的热膨胀, 在长期测试过程中表现出了较高的化学稳定性。

$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$  (LSCF) 具有较为合适的电导率和 TEC, 是研究较多的阴极接触材料之一<sup>[29-34]</sup>。LSCF 作为阴极接触材料, 需要在较低温度(700~800 °C)下实现初步烧结, 使其具有一定的机械强度。Stevenson 等<sup>[35]</sup>研究了不同烧结助剂(Cu、Bi、B、Mo、Co)的效果, 结果显示氧化铜的助烧效果最佳。Naumovich 等<sup>[36]</sup>通过引入 A 位阳离子空位和 B 位铜的部分取代两种方法对 LSCF 材料进行优化, 在 800 °C 以下获得了较高的电导率, 25~700 °C 的 TEC 为  $13.5 \times 10^{-6} \sim 14.8 \times 10^{-6} \text{ K}^{-1}$ 。

$\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_{3-\delta}$  (LNF) 具有较高的电导率、较好的 TEC 适配性以及一定的耐 Cr 侵蚀等特点, 是一种很有前景的阴极材料, 同时具有作为阴极接触材料的潜力<sup>[29,37-38]</sup>。Morán-Ruizd 等<sup>[39]</sup>和 Jimenez-Villegas 等<sup>[40]</sup>研究了 LNF 基钙钛矿氧化物材料作为

接触材料的性能, 获得了较好的化学相容性和较小的面电阻。

作者所在课题组 Lyu 等<sup>[41-43]</sup>采用 LNF 作为阴极接触组件, 研究了其导电特性、稳定性、元素迁移等基本性能, 发现了长期电流负载过程中 LNF 中 Ni 元素迁移和面电阻减小现象, 并进行了机理解析。进一步在纽扣尺寸电池和工业尺寸单电池中开展了电化学性能研究, 解析了 LNF 接触层对单电池性能的影响机制。研究了 LNF 接触组件厚度和煅烧温度对阳极支撑 SOFC 单电池电化学性能的影响, 结果如图 3 所示, LNF 接触材料能够降低单电池的欧姆阻抗和极化阻抗, 提高单电池电化学性能, 但在低氧分压下也会阻碍阴极侧氧气的扩散。进一步地, 采用干压造粒和高温煅烧预处理等对 LNF 颗粒尺寸进行调控, 提高了单电池在宽氧分压下的电化学性能, 结果表明: 采用大粒径 LNF 接触组件能够显著提高单电池输出性能, 经过高温烧结处理的 LNF 接触材料表现出更好的热稳定性, 单电池在 21 次热循环中表现出高稳定性, 为 LNF 接触材料在 SOFC 电堆中的实际应用提供了参考。

华中科技大学课题组 Wang 等<sup>[30,44-51]</sup>采用  $\text{LaCo}_{0.6}\text{Ni}_{0.4}\text{O}_3$  (LCN) 作为阴极接触组件, 探究了粉体的合成方法、煅烧温度对粉体电导率以及粒径大小的影响, 发现在 800 °C 制备的 LCN 阴极接触组件及预处理后的 SUS430 不锈钢为连接体的组合表现出最优的性能。采用粗粉/细粉/粗粉搭配涂刷的方式制备了 LCN 接触组件, 在短期测试中保持了细粉的优势, 在长期测试中, 细粉之间添加活性较小的粗粉层, 能有效释放热循环产生的热应力。随后分别采用 Ag 和 YSZ 与 LCN 进行复合, 研究发现加入摩尔分数为 15% Ag 粉的 LCN 接触组件, 界面之间存在的微烧结能够增强与金属连接体的良好接触, 使其面积比

电阻(ASR)在长期测试过程中稳定在  $110 \text{ m}\Omega\cdot\text{cm}^2$ 。YSZ、LCN、空气组成三相反应区,提高了反应活性,

减小了极化阻抗。当 YSZ 含量为 10% 时, 电池输出性能最好, 最大功率密度达到  $668 \text{ mW}\cdot\text{cm}^{-2}$ 。

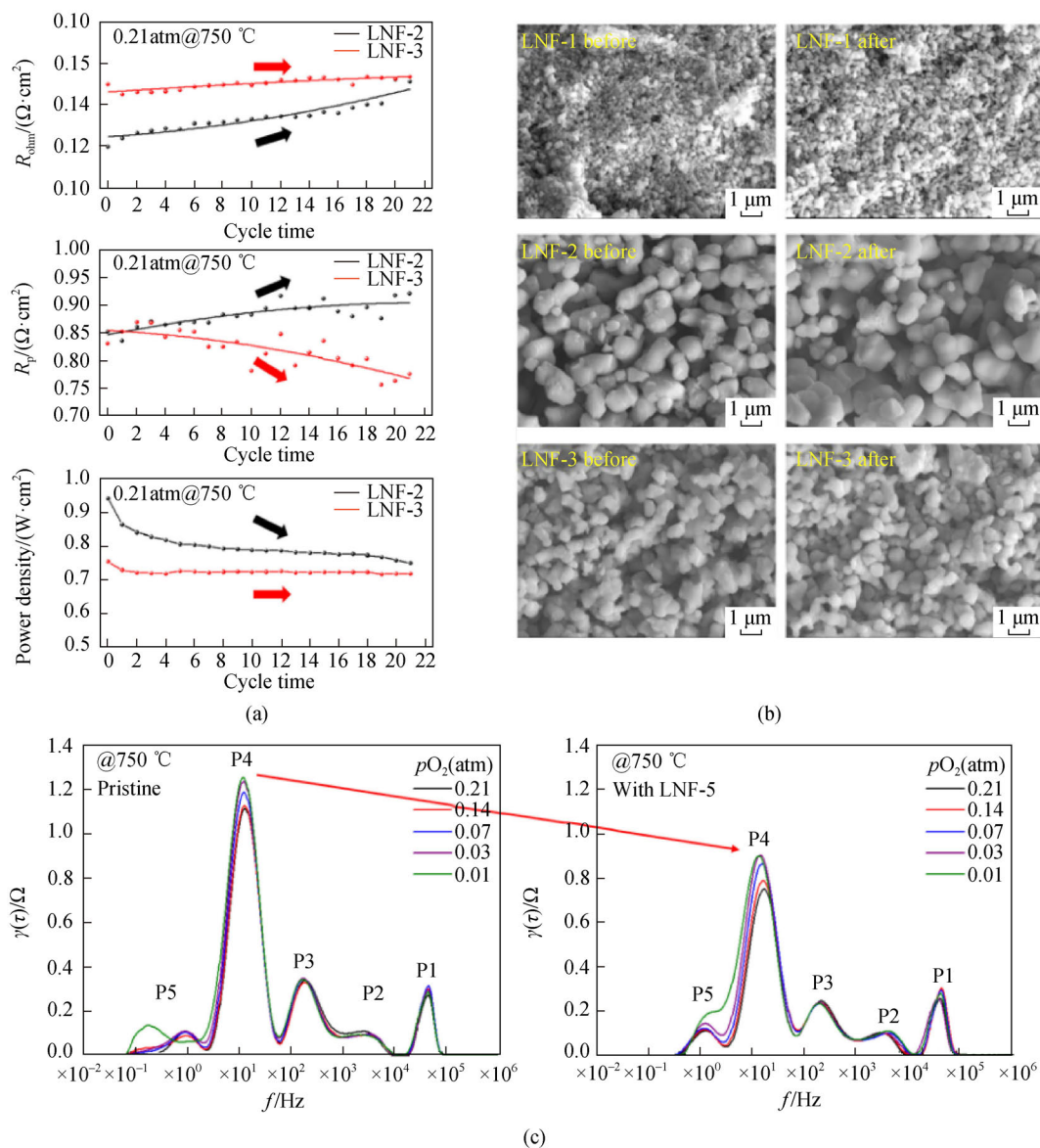


图3 (a)不同粒径 LNF 接触层热循环测试结果<sup>[43]</sup>; (b)直流电流负载前后 LNF 接触层断面微观形貌对比<sup>[43]</sup>; (c)DRT 分析结果<sup>[42]</sup>  
Fig. 3 (a) Thermal cycling test results of LNF contact layer with different particle sizes<sup>[43]</sup>; (b) comparison of the microscopic morphology of LNF contact layer sections before and after DC current load<sup>[43]</sup>; (c) DRT analysis results<sup>[42]</sup>

### 1.3 尖晶石氧化物

在 SOFC 电堆中, 尖晶石常被用于金属连接体表面涂层<sup>[52]</sup>。尖晶石是良好的电子导体, 与电堆中其他组件有较好的 TEC 匹配, 也可以作为阴极接触材料。金属连接体涂层和接触组件的作用不同, 涂层是覆盖在连接体表面的致密保护薄膜, 而接触组件则位于电极与连接体之间, 用于优化电子传导、减少接触电阻, 此外还需要足够的孔隙率来保证气体扩散<sup>[53]</sup>。近年来用于阴极接触材料研究的尖晶石氧化物包括  $(\text{Mn}, \text{Co})_3\text{O}_4$ 、 $\text{Mn}_2\text{CuO}_4$ 、 $\text{NiFe}_2\text{O}_4$  等, 如表 2 所示<sup>[54–62]</sup>。

尖晶石材料的烧结温度较高, 将其作为接触材料存在一定困难<sup>[55]</sup>。Yu 等<sup>[63–64]</sup>利用气体雾化的 Co–Mn 基合金前驱体来降低尖晶石接触层烧结温度, 研究了金属前驱体反应烧结制得的  $\text{MnCo}_2\text{O}_4$  基接触层微观结构和性能, 在  $800^\circ\text{C}$  的长期测试中表现出优异的性能。与 Co–Mn 基尖晶石相比, Ni–Fe 基尖晶石成本较低, 但电导率也较低, 并且需要较高的烧结温度。Yu 等<sup>[65]</sup>探究了不同前驱体对  $\text{NiFe}_2\text{O}_4$  基尖晶石接触层微观结构和性能的影响, 结果表明, 尖晶石层与金属前驱体具有独特的反应性烧结, 在持续 1000 h 的测试中, ASR 显著降低。

Hayes 等<sup>[66]</sup>通过反应烧结制备了  $\text{Mn}_{1.25}\text{Co}_{1.75}\text{O}_4$  (MCO)作为阴极侧接触组件, 获得了显著减小的面电阻, 并且在 2000 h 的测试中表现出较高的稳定性。Cu-Mn 基尖晶石也可以用于阴极接触材料。Zielke 等<sup>[67]</sup>探究了一种金属铜锰泡沫材料, 其在运行条件下被氧化为导电的  $\text{Cu}_{1+x}\text{Mn}_{2-x}\text{O}_4$  尖晶石, 与使用金箔作为接触材料的单电池测试相比, 铜锰泡沫具有相近的初始电阻, 表现出一定的应用前景。

表 2 常见尖晶石接触材料的热膨胀系数和电导率

Table 2 The coefficient of thermal expansion and electrical conductivity of common spinel contact materials

| Spinel                               | TEC(0–800 °C)/K <sup>-1</sup> | Electrical conductivity<br>(800 °C)/(S·cm <sup>-1</sup> ) | Ref.        |
|--------------------------------------|-------------------------------|-----------------------------------------------------------|-------------|
| $\text{Mn}_2\text{CoO}_4$            | $6.9 \times 10^{-6}$          | 21                                                        | [57, 59]    |
| $(\text{Mn}, \text{Co})_3\text{O}_4$ | $10.8 \times 10^{-6}$         | 60                                                        | [54, 56–57] |
| $\text{MnCo}_2\text{O}_4$            | $14.1 \times 10^{-6}$         | 30                                                        | [57]        |
| $\text{NiFe}_2\text{O}_4$            | $10.8 \times 10^{-6}$         | 0.26                                                      | [55]        |
| $\text{Mn}_2\text{CuO}_4$            | $10.0 \times 10^{-6}$         | 100                                                       | [55, 61]    |

## 1.4 复合材料

除了上文提到的单相材料外, 复合材料也是研究热点之一。复合材料综合了不同材料的优势性能, 其中贵金属和其他材料的复合是目前的较优选择。

Shong 等<sup>[68]</sup>研究了 Ag 和 NiO 混合物作为阴极接触材料, 由 20% Ag 和 80% NiO (摩尔分数)组成的微球状混合物在 800 °C 下的 ASR 值为  $2.24 \text{ m}\Omega \cdot \text{cm}^2$ , 同时 NiO 的引入减轻了 Ag 挥发问题。

Huang 等<sup>[69]</sup>对比了 LSCF、LSCF+10%Ag、Ag 3 种组件的界面接触电阻, 结果显示 LSCF+10%Ag 的接触电阻最小, 长期稳定性最好。

Wang 等<sup>[70]</sup>采用改进的溶胶凝胶法制备了  $(\text{La}_{0.8}\text{Sr}_{0.2})_{1-x}\text{Ag}_x\text{MnO}_{3+\delta}$  (LSAM)作为集流材料, 在掺杂 15% (摩尔分数)的 Ag 后, 起始烧结温度从 1150 °C 降低到 800 °C; 在 750 °C 下 ASR 值约为  $12 \text{ m}\Omega \cdot \text{cm}^2$ , 集电效果与 Pt 相近。

Xin 等<sup>[71]</sup>开发了一种钙钛矿-尖晶石复合导电陶瓷。前驱体由被还原的纳米  $\text{Mn}_{0.9}\text{Y}_{0.1}\text{Co}_2\text{O}_4$  (MYC)尖晶石材料包覆的微米级 LSCF 钙钛矿颗粒组成。采用还原尖晶石粉末有助于提高复合材料的烧结活性, 而利用钙钛矿 LSCF 颗粒的高导电率则有效提高了复合材料的导电性能。

Shong 等<sup>[72–73]</sup>研究表明, 使用锰、钴和 10%(质量分数)LSC 粉末混合作为阴极接触材料的 AISI 441 不锈钢, 在 800 °C 下老化 10 000 h 后, 表现出较低的 ASR 增长。

## 2 接触组件的设计和制备

### 2.1 接触组件的保护涂层制备

在 SOFC 电堆中, 含 Cr 金属连接体在高温下易产生挥发性的 Cr 物质, 从而引起阴极毒化<sup>[74–75]</sup>。因此, 需要寻找能够减少或阻止 Cr 物质挥发的材料或方法, 以提高电堆的长期稳定性。接触组件可以有效减轻 Cr 元素对阴极的毒性作用, 减缓阴极性能的降解。Pan 等<sup>[51]</sup>选择了 LCN 作为接触材料, 通过丝网印刷在 Fe-16Cr 合金基板上制备了多孔的原位保护涂层, 成功阻碍了 Cr 的扩散, 减少了氧化物的生长, 并提高了金属的抗氧化能力。接触材料与连接体中的 Cr 元素发生反应并形成保护膜, 从而阻碍 Cr 元素向阴极的迁移, 这也是防止阴极 Cr 中毒的有效策略。

此外, 接触组件与连接体的直接接触可能导致接触组件自身性能的退化, 包括导电性和机械稳定性。因此, 研究中也可通过在金属连接体表面制备致密的保护涂层来防止 Cr 的扩散<sup>[76–77]</sup>。

### 2.2 接触面积的影响

在电堆中, 如果单电池层面的性能和效率一定, 则电堆能达到的实际性能和效率就取决于电堆的电阻损失, 其中阴极接触电阻的影响最大<sup>[29]</sup>。除了接触材料自身导电性以外, 接触面积、界面形式、载荷强度等都是重要的影响因素。

其中, 阴极/连接体之间的接触面积直接影响电荷的传输效率。增加接触面积可以减小电荷传输电阻。Wang 等<sup>[78]</sup>研究发现, 接触面积取决于接触组件与阴极表面粗糙度的匹配性, 较高的匹配度可以显著增加有效接触面积并提高电池性能。

接触面积对单电池在实际工况下的性能影响较复杂。笔者课题组 Wang 等<sup>[41–43]</sup>研究发现, 在氧分压较低的工况下, 接触面积较小的单电池表现出更好的电化学反应性能, 这主要是由于在低氧分压工况下, 阴极表面的气体扩散/吸附成了主要控速步骤; 较大的接触面积虽然增加了电荷传输路径, 但在一定程度上阻碍了氧气的扩散和吸附。因此, 在电堆的生产制造过程中, 需要综合考虑多种实际工况下阴极接触组件的设计和制造, 选择合适的接触面积。

### 2.3 数值模拟在阴极接触电阻方面的应用

SOFC 工作温度高、结构复杂, 采用实验方法开展研究受到了很多限制, 数值模拟在相关研究中发挥了关键作用<sup>[79]</sup>。

黄红艳<sup>[80]</sup>利用有限元软件建立了含阴极接触层的平板式 SOFC 三维模型, 研究了阴极接触层的杨氏模量、外界施压载荷对 SOFC 输出功率密度的影响。结果如图 4a 所示, 随着杨氏模量的增大, 电池的功率密度在逐渐减小, 随着施压载荷的增加, 电池的功率密度逐渐增大。张纪豪等<sup>[81]</sup>模拟了特定输出电压或平均电流密度时沿流道方向电池电极处

的电压与电流密度分布, 发现银网面积的减小将放大水平电流的累积效应, 使得电池性能迅速恶化。Dey 等<sup>[82]</sup>探究了接触电阻在不同载荷和温度下的变化规律, 发现阴极接触电阻随温度的升高而减小, 阳极侧相反, 并且都随着载荷的增大而减小。Ewald 等<sup>[83]</sup>研究发现在施加 1 MPa 的夹紧压力时, 相对于在干燥状态下安装的接触层, 接触电阻显著降低。

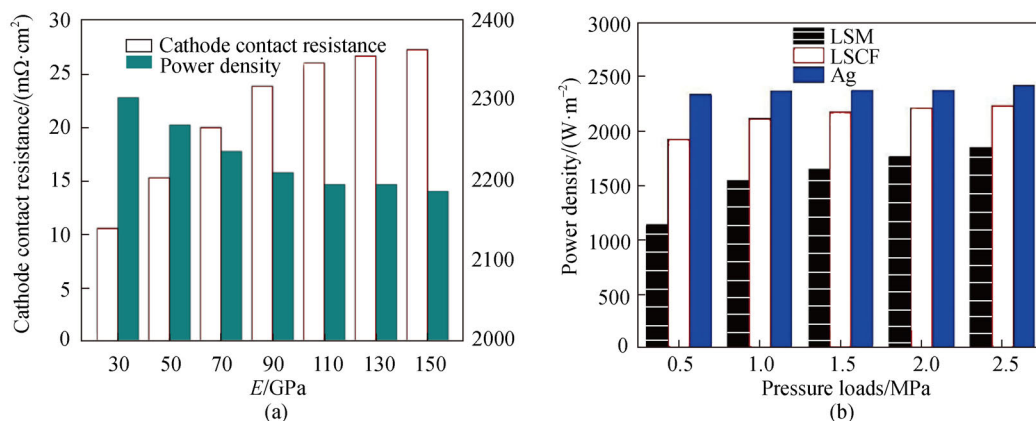


图 4 (a)杨氏模量和(b)载荷强度对接触材料功率密度的影响<sup>[80]</sup>

Fig. 4 (a) Effect of Young's modulus and (b) load strength on the power density of contact materials<sup>[80]</sup>

## 2.4 接触组件的制备及装配

由于电堆装配特点的不同, 并且为了满足不同的结构、性能要求, 接触组件所采用的制备工艺也不同, 主要包括丝网印刷、喷涂、流延等。

Sick 等<sup>[84]</sup>利用丝网印刷的工艺在阴极表面制备了 200 μm 厚的多孔 LSCF 接触层, 获得的粗糙界面减少了空气扩散阻力, 有效减少了接触电阻。

Wain-Martin 等<sup>[85]</sup>利用喷涂技术阴极层 LSF 表面制

备了 15 μm 厚的 LNF 接触层, 有效降低了接触电阻。

笔者所在课题组 Zhang 等<sup>[86]</sup>针对现有电堆中接触组件强度差、易断裂等问题, 通过流延法制备了一种新型柔性自支撑 LNF 接触组件, 该接触组件表现出优异的韧性、延展性和可压缩性, 如图 5a 所示。Lei 等<sup>[86]</sup>采用水基流延制备了  $\text{Cu}_{1.5}\text{Mn}_{1.5}\text{O}_4$ 、 $\text{Co}_3\text{O}_4$  和  $\text{Al}_2\text{O}_3$  组成的柔性接触组件, 表现出明显的低接触电阻和高稳定性, 如图 5b 所示。

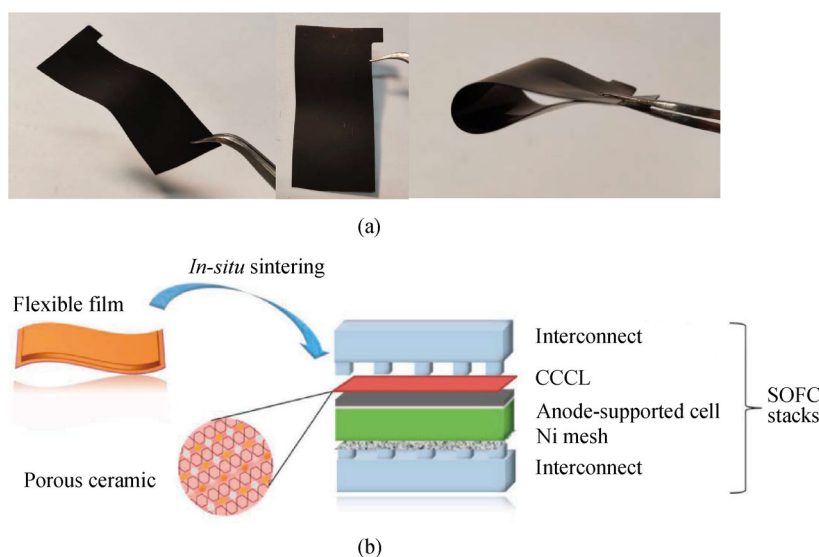


图 5 (a) 柔性 LNF 接触组件实物图<sup>[86]</sup>; (b) 柔性阴极集电层(CCCL)结构示意图<sup>[87]</sup>

Fig. 5 (a) Physical diagram of flexible  $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_{3-\delta}$  (LNF) contact assembly<sup>[86]</sup>; (b) schematic diagram of flexible cathode current collector layer (CCCL) structure<sup>[87]</sup>

此外, Chen 等<sup>[88]</sup>采用相转换和激光扫描技术, 制备了一种具有独特微观结构的集电层, 显著降低了电子的迁移距离, 应用该集电层的对称电池极化电阻仅为银集电极的 20%。Yu 等<sup>[89]</sup>采用共烧结法制备了涂层/接触双层结构, 在 800 °C 进行 1500 h 的测试中表现为较低的面积比电阻(ASR)和衰减率。Ni 等<sup>[90]</sup>开发了一种基于  $\text{Sm}_{0.5}\text{Sr}_{0.5}\text{CoO}_3$  的新型阴极电流收集元件, 显著提高了电池的电流收集效率和气体扩散速率。

实际研究中需根据对接触组件的需要来选择合适的方法, 虽然已经有较多方法可以用于制备接触组件, 但电堆运行具有复杂性, 单种制备方法或许不能满足所有需求, 还需开发更多的新方法。

### 3 总结与展望

接触组件在 SOFC 电堆中扮演着至关重要的角色, 显著影响了电堆的性能、可靠性和稳定性。本文围绕平板式 SOFC 电堆阴极接触组件, 综述了接触材料的选择, 分析了接触电阻的影响因素, 介绍了相关制备工艺。

阴极接触组件的未来发展可能集中在以下几个方面: 首先, 研发新材料, 比如一些新型阴极材料不仅可用于阴极本身, 还可作为阴极接触组件的候选材料。其次, 创新制备工艺, 虽然实验室研究可以探索多种新颖或成熟的技术, 但工业生产中制备工艺的选择则更多地受到样品稳定性和成本的限制; 因此, 通过制备工艺创新, 例如 3D 打印技术、低温烧结与纳米技术等来弥补材料性能的不足是一个值得研究的方向。最后, 考虑电堆的实际工况及变动(如流场、温度和电流分布), 在结构设计方面, 通过采用梯度配置和变结构等设计, 以提高匹配性和长期运行稳定性。然而, 大规模生产和成本控制仍是商业化成功的关键。未来的研发还需注重环保和可持续性, 确保材料选择与生产过程符合绿色发展理念。

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## Research Progress on Cathode Contact Components for Solid Oxide Fuel Cell

ZHU Tenglong, HE Qi, LYU Qiuqiu, ZHONG Qin

(School of Chemistry and Chemical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China)

### Extended Abstract

Solid oxide fuel cells (SOFCs) represent a highly efficient energy conversion technology capable of directly transforming chemical energy from fuels into electricity, with single-cycle efficiencies ranging from 40% to 60% and combined heat-and-power efficiencies reaching up to 60%–90%. Among various SOFCs configurations, planar SOFCs stacks become popular due to their high-power density, modular design, and flexible assembly. However, the compact structure of planar stacks imposes stringent requirements on assembly precision, often leading to a poor "solid-solid" interfacial contact between ceramic single cells and metallic interconnects. This issue results in high internal resistance, reduced output performance, and compromised long-term stability. To address these challenges, cathode contact components are introduced between the single cell and interconnect to optimize interfacial contact, ensuring stable electron transport pathways and mitigating mechanical stress during operation.

The selection and design of cathode contact materials are critical, requiring a balance of high electrical conductivity, chemical stability, thermal expansion coefficient (TEC) compatibility with adjacent components, sufficient porosity for gas diffusion, mechanical strength, and cost-effectiveness. While anode-side contact materials (*e.g.*, nickel mesh or foam) perform well under reducing atmospheres, cathode-side materials face harsher conditions due to high-temperature oxidative environments and the inherent brittleness of ceramic oxides. Consequently, cathode contact materials must meet more rigorous criteria to minimize contact resistance and ensure durability.

This review represents the selection of contact materials, analyzes the influencing factors of contact resistance, and introduces the relevant preparation processes. In terms of material selection, precious metals possess excellent electrical conductivity and sintering activity. However, aside from silver, the material costs are relatively high. Silver itself also faces some issues such as volatility at high temperatures. Perovskite materials have low cost and high stability in cathodic environment, and material systems such as  $\text{La}_{0.8}\text{Sr}_{0.2}\text{CoO}_3$  (LSC),  $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$  (LSCF),  $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$  (LSM),  $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_{3-\delta}$  (LNF), and  $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$  (LCN) are used as contact materials for research, and the research goal is how to achieve the trade-off between conductivity, TEC, and sintering activity, and the ASR change during long-term isothermal and thermal cycling is also a key issue. Spinel material is more used in the coating of the linker, which is important in preventing the migration of Cr and protecting the blocker against oxidation. The development of composite materials combines the excellent properties of different materials. For instance, LSCF-Ag composites exhibit a reduced interfacial resistance and an enhanced long-term stability.

Contact resistance is an important factor that affects the overall performance of the battery stack, and the factors influencing contact resistance mainly include interface contact effects, contact area, load strength, elastic modulus, and temperature. Balancing electronic transport and gas diffusion is crucial as excessive contact area under low oxygen conditions may hinder the diffusion of oxygen. The existing research focuses on studying the effects of various factors on contact resistance and battery performance through the combination of experiments and numerical simulations. This integration serves as a mutual validation, enhancing the reliability of the results, saving time and costs, as well as providing a deeper understanding of the underlying physical mechanisms. In terms of the preparation process, in addition to the commonly used methods such as screen printing, spraying, and casting, some novel forming techniques are also applied in the preparation of contact components, such as laser scanning technology, electrophoretic deposition, physical vapor deposition, and magnetron sputtering, each with its own advantages and disadvantages.

**Summary and Prospects** Cathode contact components play a pivotal role in determining the efficiency, reliability, and longevity of SOFC stacks. The future development of cathode contact components may focus on several aspects, the first of which is the development of new materials. Innovative cathode materials can be used for the cathode itself and served as candidate materials for the cathode contact layer. It is important to optimize the preparation process. Lab-scale studies can explore various novel or established preparation techniques. However, in industrial production, the choice of preparation processes is constrained by sample stability and cost. Therefore, optimizing the preparation process to compensate for some inherent shortcomings of the materials is a direction worthy of research. Furthermore, the study of contact components will become more complex when considering the actual operating conditions within the stack, such as flow field distribution, temperature distribution, and current distribution. In terms of structural design, concepts such as gradient configuration and asymmetric structures can be applied to achieve the overall performance and structural stability.

In summary, some challenges remain in achieving large-scale commercialization while significant progress is made in cathode contact materials and components. Collaborative efforts integrating material science, engineering, and computational modeling will be a key to advancing SOFCs technology toward widespread adoption in clean energy systems.

**Keywords** solid oxide fuel cell; cathode contact assembly; contact resistance; preparation process; numerical simulation