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A Review of Materials used for Solid Oxide Fuel Cell

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Abstract: To have the benefits of clean electric power with out engines, solar panels and wind farms which are familiar sources of alternative energy were a dream of the engineers and environmentalists. Even though they are effective sources of electric energy, there are problems with the stability of their energy sources at all times. Extracting electricity from a device called as "solid electrolyte fuel cell" were demonstrated by the scientists and since then there has been an intense research and development effort on alternative energy technology known as fuel cells. Now, as energy issues are at the forefront of current events, fuel cell technology is ripening and on the verge of being ready for large scale commercial implementation.

This paper briefly reviews materials currently used in the solid oxide fuel cells ,merits and demerits of the various materials used in SOFC such as Electrolytes, Anode, Cathode and Interconnects are discussed and in addition various fabrication processes and structural supports are reviewed. Materials are to be developed for all components of SOFC, in order to reduce operating temperature and overall cost.

1.Introduction

Production and distribution of energy affects all sectors of the global economy. The increasing industrialization of the world requires sustainable, highly efficient energy production. Without major technological developments, energy demand cannot be satisfied.The application of the fuel cell technologies may be one of the most important technological developments during the next decades. A fuel cell operating as a sort of continuously replenished battery provides an alternative, where by electrical energy can be made available with small losses. If the fuel is clean, the effluents are in principle only water, heat and CO_2. Fuel cell plants can be modular in design, and the energy production can be adjusted to meet the actual demand, which is a convenient feature for a power source in a technological society.

2.Fuel Cell

A fuel cell is an electrochemical device that directly converts chemical energy, from a reaction between a fuel and an oxidant, into electrical energy and it offers a clean, pollution free technology and, electrochemically generate electricity at high efficiencies. The basic elements of a typical fuel cell, as depicted in fig.1, consist of an electrolyte in intimate contact with a porous anode (negative electrode) and a porous cathode (positive electrode). The fuel and oxidant gases flow along the surface of the anode and cathode, respectively, and they react electrochemically in the three-phase-boundary (TPB) region established at the gas-electrolyte-electrode interface. A fuel cell can theoretically produce electrical energy for as long as fuel and oxidant are fed to the porous electrodes. Different fuels can be used, such as hydrogen, ethanol, methanol, or gaseous fossil fuels like natural gas. Solid or liquid fossil fuels need to be gasified first before they can be used as fuel. Oxygen or air can be used as oxidant[15].
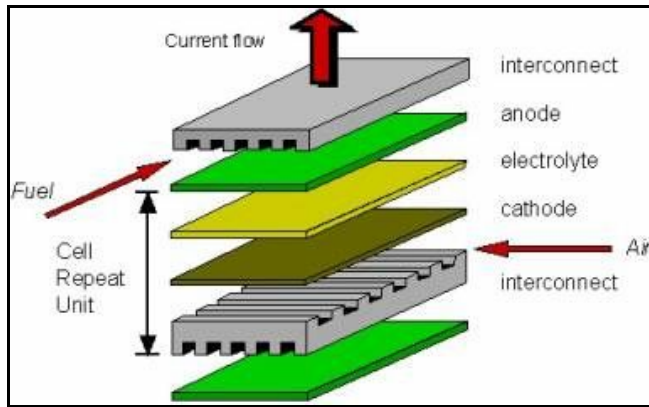
Fig.1. Schematic representation of a Planar Fuel Cell

2.1.History

The history of fuel cell dates back to 1839 when Sir William Grove first described its principle and demonstrated a fuel cell at room temperature using a liquid electrolyte. In 1899, Nernst discovered the solid oxide electrolyte by using stabilized zirconia. In the middle of the 20th century further developments occured. Several types of fuel cells were developed in the race for conquering the space. In the eighties focus on pollution and the demand for higher efficiency in the exploitation of fossil resources initiated a new wave of fuel cell developments. At present several types of fuel cells are being developed and reach the consumer market within a few years.The primary challenges are cost and durability, to be solved by materials selection and design engineering[15].

2.2.Types of fuel cells

Today the following types of fuel cells are commonly known, all named after the employed electrolyte material.

- The Phosphoric Acid Fuel Cell (PAFC),
- The Molten Carbonate Fuel Cell (MCFC),
- The Solid Oxide Fuel Cell (SOFC),
- The Proton Exchange Member Fuel Cell (PEMFC).

Each type of fuel cell has certain characteristics, some of which are listed in the Table.

	PAFC	**MCFC**	**SOFC**	**PEMFC**
ELECTROLYTE	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
OPERATING TEMPERATURE	375^0F (190^0C)	1200^0F (650^0C)	1830^0F (1000^0C)	175^0F (80^0C)
FUELS	Hydrogen(H_2) Reformate	H_2/CO Reformate	H_2/CO/CH_4 Reformate	H_2 Reformate
REFORMING	External	External/Internal	External/Internal	External
OXIDANT	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
ELECTRICAL EFFICIENCY(HHV)	40-50 %	50-60 %	45-55 %	40-50 %

3.The solid oxide fuel cell

Solid oxide fuel cells (SOFCs) represent one of the most environmentally clean and versatile means of efficiently converting chemical energy to electrical energy. High temperature solid oxide fuel cells provide many advantages over traditional energy conversion systems with high efficiency, reliability, modularity, fuel adaptability, and very low levels of NO_x and SO_x emissions. Furthermore, because of their high temperature of operation (~1000°C), natural gas can be reformed within the cell stack eliminating the need of an expensive, external reformer.

3.1.Principle of operation

The operating principle of the solid oxide fuel cell is illustrated in fig.2. A SOFC essentially consists of two porous electrodes separated by a dense oxygen ion conducting electrolyte. Oxidant is reduced at the cathode side and fuel is oxidized at the anode. The difference in oxygen activity of the two gases at the electrodes provides a driving force for motion of the oxide ions in the electrolyte. Oxide ions formed by dissociation of oxygen at the cathode under electron consumption migrate through the electrolyte to the anode where they react with hydrogen to form water and release electrons creating current flow through an external circuit, or load, as depicted in figure[15]
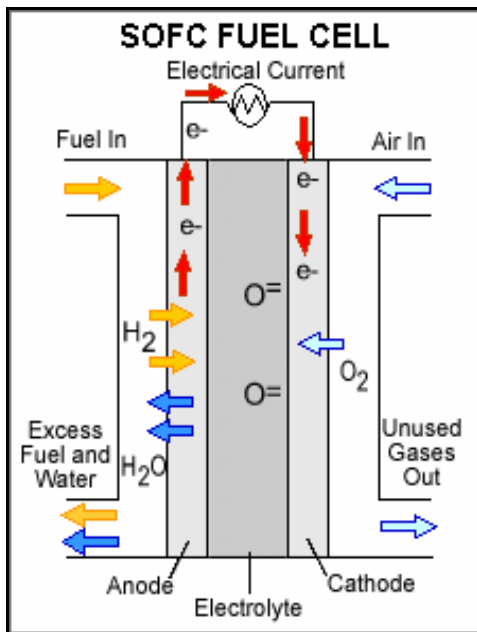

Fig.2. A Solid Oxide Fuel Cell

3.2.Advantages

The advantages of SOFC with respect to other fuel cells are,

- They present high efficiency ~50%) with hydrocarbon fuels such as natural gas, liquefied petroleum gas, diesel and biogas., which avoids expensive and difficult fuel reforming process to generate pure hydrogen. As result of their high operating temperatures, SOFCs can be effectively combined with micro turbines to enable the development of electricity generation products with ~60% efficiency. Efficiencies of this level have not been obtained by any other combination of technologies,

- SOFCs are made from commonly available ceramic materials which do not have moving parts or corrosive liquid electrolytes. Therefore they lead to highly reliable electricity generation systems which require low maintenance,

The manufacturing process for SOFCs is based on well-known equipment that is widely available and well proven in the manufacture of electronic ceramic components.

Leading companies in SOFC commercialization are Siemens-Westinghouse (Germany / USA), Sulzer (Switzerland), Global Thermoelectric (Canada), Ceramic Fuel Cells Ltd. (Australia) and Mitsubishi Heavy Industries (Japan)[15].

4.Materials for SOFC

SOFC power systems are not yet cost-effective to merit large-scale deployment in the power generation industry. Among the approaches currently being investigated to decrease the cost of SOFCs, improving power density while decreasing operating temperature is perhaps the most promising option. However, decreasing operating temperature has the effect of increasing all types of performance losses in the cell. Thus the simultaneous goals of improving power density while lowering the operating temperature are at odds with each

other. Therefore, the focus of recent research is aimed at development of more active electrodes and more conductive electrolyte materials that can efficiently operate at lower temperatures (600-800°C).

The main focus of investigation has been the optimization of SOFC cell performance at a relatively low (<800°C) operation temperature to enable the use of less-costly materials for system components. The optimization has been carried out to reduce internal resistances of SOFC by two methods: 1) the reduction of electrolyte layer thicknesses to 5-10um and 2) the use of electrolyte materials with high ionic and electrical conductivities. Additional research has been carried out by investigating anode and cathode layer thickness variation, material characterization and component porosity on the performance below 800 ^{o}C [16].

The basic components of a ceramic fuel cell stack are electrolyte, anode, cathode and interconnect. The materials for different cell components are to be selected based on the following criteria:

- Suitable electrical conductivity is required for different cell components to perform their intended cell functions,
- Adequate chemical and structural stability at high temperatures are required during cell fabrication as well as during cell operation,
- There should be thermal expansion matching among different cell components.

4.1.Selection of Electrolyte Material

Solid oxide fuel cells are based on the concept of an oxygen ion-conducting electrolyte through which the oxide ions (O^{2-}) migrate from the air electrode (cathode) side to the fuel electrode (anode) side where they react with the fuel (H_2, CO, etc.) to generate an electrical voltage. For optimum cell performance, the electrolyte must be free from porosity to avoid gas permeation from one side to the other. It should also be uniformly thin to minimize ohmic loss, and it should have high oxygen ion conductivity with transport number for oxygen ions close to unit and a transport number for electrons as close to zero as possible[15].

Oxide materials with fluorite crystal structure such as yttria stabilized zirconia (YSZ), rare earth doped ceria and rare earth doped bismuth oxide have been widely investigated as electrolytes for fuel cells . Of these materials, YSZ has been most successfully employed as the electrolyte material for SOFCs operated at a temperature of ~1000°C.[8,15]

For more than 90 years, zirconia has been well known as an oxygen conductor at temperatures above 800°C. Additionally, zirconia's extremely low electronic conductivity has made this material especially suitable for a solid electrolyte for oxygen sensors and for fuel cells. Cubic Zirconia (ZrO_3), stabilized with 8-9 mol% Y_2O_3 (YSZ) is a proven solid electrolyte, exhibiting predominantly ionic conductivity over a wide range of oxygen partial pressures. The most commonly used composition for the YSZ electrolyte in SOFCs is (Y_2O_3)0.08-(ZrO_3)0.92 because the material possesses an adequate level of oxygen ion conductivity and exhibits desirable stability in oxidizing and reducing atmospheres. The ionic conductivity of YSZ (.02 S/cm at 800°C and .1S/cm at 100°C) is comparable with that of liquid electrolytes, and it can be made very thin (25-50 um). A small amount of alumina may be added to the YSZ to improve its mechanical stability. Tetragonal phase zirconia has also been added to YSZ to strengthen the electrolyte structure so that thinner materials can be produced.

Other electrolyte materials such as scandium doped zirconia (SDZ), Gadolinium doped Ceria (GDC) and Bismuth Yttrium Oxide (BYO) have also been investigated. These materials exhibit ionic conductivities that are 3-5 times higher than YSZ material, enhancing device performance at operating temperatures below 700 ^{o}C and enabling thicker electrolyte layers. However, these alternate materials exhibit poor stability at low oxygen partial pressures, reducing their suitability for use in a variety of SOFC applications[16].

Ceria (CeO_2) doped with either Gd_2O_3(GDC)[2,8,13] or Sm_2O_3(SDC)[10] has power densities approaching 0.4 W/cm2 at temperatures as low as 773 K. While it has been known for many years that ceria has an ionic conductivity roughly ten times that of YSZ, but, ceria is reducible, particularly at higher temperatures. When reduced, ceria becomes electronically conductive. Its reducibility also makes it brittle and more difficult to work with, although recent work with supported ceria films on porous stainless steel may solve this problem[6]. Ceria based electrolytes are often used as additives to enhance the performance of SOFC cathodes and anodes[16].

Scandium doped zirconia (SDZ) has a conductivity that is roughly three times that of YSZ and it has better mechanical properties than YSZ [7]. Strontium doped lanthanum cobalt iron oxide (LSCF) or Lanthanum strontium manganite (LSM) cathodes may be used for SDZ electrolyte[6,8].Unfortunately, scandium is rare and expensive.

Strontium and magnesium doped lanthanum gallate (LSGM) was discovered more recently and has an ionic conductivity similar to that of doped ceria[8] and it has higher oxygen-ion conductivity than conventional YSZ between 600-800^{0}C and negligible electronic conductivity[9,14]. While it is not reducible like ceria, the fact that it is a stoichiometric compound implies that the composition must be precise. The most commonly used composition for the LSGM electrolyte in SOFCs is La0.8Sr0.2Ga0.8Mg0.2O2.8. LSGM is currently considered as one of the most promising electrolyte materials for intermediate temperature SOFCs[14] .

The high operating temperatures of SOFC are required in part for high ionic conductivity in the electrolyte. However, conductivity can be calculated and controlled by using thin electrolytes[7].

4.2.Selection of Cathode Material

The choice of cathode material depends on the target application, the specific ceramic electrolyte material, the desired operating temperature, and the electrochemical cell design and fabrication methods used. Cathodes are manufactured as a porous structure to allow rapid mass transport of reactant and product gases[16]. The air electrode operates in an oxidizing environment of air or oxygen at ~1000°C and participates in the oxygen reduction reaction, i.e., oxygen in the gas phase is reduced to oxygen ion consuming two electrons in the process. SOFC Cathodes have to show high electronic and ionic conductivity, sufficient thermal and chemical stability at high temperature in air as well as good compatibility with the electrolyte. It should have sufficient porosity to facilitate transport of molecular oxygen from the gas phase to the air electrode/electrolyte interface.

To satisfy the requirements of cathode material, lanthanum manganite(La MnO$_3$) suitably doped with alkaline earth elements is used[10]. The defect chemistry, electrical conduction and cathodic polarization behavior of doped lanthanum manganite with alkaline earth elements has been found to satisfy all the requirements to be an effective air electrode. The electronic conductivity of lanthanum manganite is due to hopping of an electron hole between +3 and +4 valence states of Manganese(Mn). This conductivity is enhanced by doping with a divalent ion such as calcium or strontium[15]. Perovskite structured lanthanum strontium manganite (LSM) and lanthanum calcium manganite (LCM) are the most often used cathode materials as they offer excellent thermal expansion matches with zirconia electrolytes and provide good performance at operating temperatures above 800°C[16]. Furthermore, the reactivity and inter diffusion between doped lanthanum manganite and yttria stabilized zirconia electrolyte have shown minimal interactions between these two materials at 1000°C.

Additions of Oxygen-ion conductive electrolyte material mostly Yttria stabilized Zirconia (YSZ) or Cerium Gadolinium Oxide(CGO) to the Perovskite leads to the formation of a composite cathode and this can improve the cathodic performance further[12]. A composite of YSZ and Strontium doped LaMnO$_3$ (LSM), is a compromise between performance, stability, and ease of fabrication[1,4,5]. LSM is a reasonably good electronic conductor and has a good CTE match for YSZ, but it has a very low ionic

conductivity. The YSZ within the composite electrode provides connectivity with the electrolyte and allows conduction of ions from the electrolyte into the electrode[6]. One can increase the performance of LSM based cathodes significantly by engineering the cathode-electrolyte interface to increase the length of the TPB.

Studies have indicated that excess (>10%) Mn in the LSM material improves device performance for layers formed at high sintering temperatures (>1200°C). XRD investigation at the LSM/electrolyte interface for YSZ electrolytes indicates Mn is effective in decreasing the pyrochlore (La$_2$Zr$_2$O$_7$) phase at the LSM/YSZ interface, reducing resistance at that interface[16].

The factors that limit the performance of LSM-based cathodes continue to be debated, but it is certain that much better electrode performance can be achieved with other conductive oxides such as Strontium doped LaFeO$_3$ (LSF), Strontium doped LaCoO$_3$ (LSCo), and related materials.These oxides have good electronic conductivity as well as ionic conductivity.Unfortunately, there is a problem with CTE matching with these alternative cathode materials (The CTE of LSCo is more than double that of LSM and YSZ.). More important, the temperatures required for sintering the electrodes to the electrolyte are high enough to cause solid-state

reactions between YSZ and both LSF and LSCo. A product of the reactions with YSZ is the insulating phase, $La_2Zr_2O_7$. Solid-state reactions occur also between LSM and YSZ above approximately 1500 K, but this temperature is just sufficient to adequately sinter the cathode to the electrolyte[6].

Significant effort has gone into trying to take advantage of the excellent cathode properties of LSF and LSCo. One method for doing this is to insert a barrier layer, such as doped ceria, between the YSZ and the cathode. The ceria layer is essentially part of the electrolyte and prevents contact between the YSZ and the cathode material. The approach has been shown to provide excellent cathode performance; however, it requires an additional processing step and the mechanical properties of these electrodes tend to be poor. An alternative approach to using LSF and LSCo, involves producing a porous YSZ layer in contact with the YSZ electrolyte, then impregnating the porous layer with salt solutions to fabricate the perovskites inside the porous YSZ layer. This procedure decouples the calcinations of the YSZ in the electrode to the YSZ electrolyte from the calcinations of the perovskite within the electrode, so that high sintering temperatures can be used without causing solid-state reactions[6].

In case the electrolyte used is of LSGM, the cathode used may be of LSM ($LaSrMnO_3$) and in order to lower the interfacial polarization it is well known that the electrode needs to be a mixed conductor (have both electronic and oxygen ion conductivities). Since, LSM is a p-type semi-conductor, it is advantageous to mix it with LSGM which will enhance oxygen-ion conductivity [11].

Strontium doped lanthanum cobalt iron oxide (LSCF) is also used as electrode material with LSGM electrolyte for application in micro-solid oxide fuel cells(μ-SOFC) [3]. Since the LSCF is already a mixed conductor, mixing it with LSGM is not expected to significantly lower the interfacial polarization. However, it is to be noted that there is a 50% mismatch in thermal expansion coefficient between the LSCF electrode material and LSGM electrolyte material. Therefore from the point of view of lowering the interfacial thermal stresses it is desirable to have a LSCF-LSGM composite electrode as the cathode. Several cathode materials, LSM- LSCF, LSM-LSGM and LSCF-LSGM composite electrodes were also being used for possible application in Intermediate Temperature SOFCs based on the LSGM electrolyte. LSM or LSCF cathodes are also used for SOFCs using YSZ electrolytes[9].LSCF-CGO composites are used as cathode material where the electrolyte is CGO[8]. At lower operating temperature in the $600-800^0C$,alternate perovskite structured ceramic electrode materials like Lanthanum Strontium Manganese Ferrite(LSMF),Praseodymium Strontium Manganite (PSM) and Praseodymium Strontium Manganese Ferrite(PSMF)can be used[16].

4.3.Selection of Anode Material

The anode must be stable in the reducing environment of the fuel, should be electronically conducting, and must have sufficient porosity to allow the transport of the products of fuel oxidation away from the electrolyte/fuel electrode interface[15].

SOFC anodes are fabricated from composite powder mixtures of electrolyte material (i.e. YSZ, GDC or SDC) and nickel oxide (the nickel oxide subsequently will be reduced to nickel metal prior to operation)[10,16]. Nickel is a well-known SOFC anode material, and acts as the fuel side electro catalyst and current collector. Nickel-based cermets with the electrolyte YSZ is the most widely used anode at present[4].

Ni has also been chosen as an anodic material due to its high electrical conductivity and stability under chemically reducing and part reducing conditions. The presence of nickel can be used with advantage as an internal reforming catalyst, and provides a mechanism for internal fuel reforming directly on the anode. The NiO/YSZ anode material is most often used with YSZ electrolyte material[1], whereas NiO/SDC and NiO/GDC anode materials are best suited for ceria based electrolyte materials[10,16]. Anode material in high temperature SOFCs is Ni/YSZ cermets, whereas in intermediate temperature SOFCs it is Ni/CeO_2 (Sm, Gd)[10]. Standard anode materials are formulated with nickel contents equivalent to 43 volume % nickel metal (after reduction of nickel oxide to nickel metal). The composite powders are produced with surface areas matched to the requirements of the specific fabrication method used in making the SOFCs. For example, composite anode powders can be provided with surface areas of 15-20 m^2/gram for screen printing, 5-10 m^2/gram for tape casting .The anode is manufactured with high porosity (20-40%) so that mass transport of reactant and product gases is not inhibited. Some anodic polarization loss occurs at the interface between the anode and the electrolyte and bi-layer anodes are being investigated in an attempt to reduce this effect[16].

Ceria doped with Gadolinium or Lanthanum (GDC or LDC) is an excellent oxygen-ion conductor and is also chemically and mechanically compatible with the LSGM electrolyte and has electronic conductivity

under reducing conditions. Therefore, Ni-GDC or Ni-LDC cermet is expected to be an effective anode if its reaction with the LSGM electrolyte can be prevented. The reactivity of the Ni-GDC or Ni-LDC cermet anode with the LSGM electrolyte was studied by using the Ni-GDC / LSGM / Ni-GDC or Ni-LDC / LSGM / Ni-LDC symmetrical cell at 800°C under a reducing atmosphere. Ni reacts with the LSGM and forms insulating phases (lanthanum nickelates) at elevated temperatures. Therefore the use of a layer of doped ceria between the LSGM electrolyte and Ni-GDC or Ni-LDC anode to prevent direct contact between the Ni in the anode with the lanthanum in the LSGM electrolyte was explored. Since the doped ceria has sufficiently high oxygen-ion conductivity and the buffer layer will be thin (< 5μm), it is not expected to increase the ohmic polarization resistance of the cell.A cathode with a thickness of 40μm is sufficient to minimize the interfacial polarization resistance[9].

Usually the SOFC anodes are prepared by mixing and sintering NiO and an oxygen-ion-conducting oxide in air, followed by reducing the NiO to Ni under reducing conditions. Use of gadolinium or lanthanum doped ceria (GDC or LDC) as the oxygen-ion-conducting oxide in the anode would buffer the thermal expansion mismatch between the anode and the electrolyte and also result in lowering the charge-transfer polarization due to its mixed-conducting property[9].

Cermets like Ni-ceria or Cu-ceria[8] are used as anode materials where SOFCs directly utilize hydrocarbon fuels. But it is found that they have considerable limitations. Ni-ceria is not well suited for use with hydrocarbon fuels because the high Ni content (~50 vol%) promotes coking. Thus Ni-ceria was successfully used only with methane and at relatively low temperatures (~500°C)[15]. Another solution to avoid the coking problems associated with Ni-based anodes is to replace the Ni with a metal that is not a catalyst for carbon formation. Some researchers have focused on Cu-based cermets, since Cu does not catalyze carbon formation and remains metallic in the range of $P(O_2)$ experienced in the anode. Because Cu is not a good oxidation catalyst, a separate material, ceria, is added to achieve this function. Preparation of Cu-based anodes required the development of new fabrication procedures. The biggest problem with Cu anodes is the fact that Cu tends to sinter at temperatures above 1073 K, limiting its use to lower operating temperatures. Recent results with Cu-Co bimetallic anodes suggest that thermally stable materials are possible by using mixed-metal composites[6]. Cu-ceria is better suited for hydrocarbons because Cu does not promote coking. However Cu is not as good electro catalyst as Ni. Furthermore, Cu has a relatively low melting point, and thus not compatible with many standard high temperature SOFC fabrication techniques. A composition consisting of a mixture of $La_{0.8}Sr_{0.2}Cr_{0.8}Mn_{0.2}O_{3-}$, which is an electronic conductor, $Ce_{0.9}Gd_{0.1}O1.95$ which is an ionically conducting oxide, and ~4wt% Ni is also used as anode material. In this anode composition, the metallic component is mostly replaced by an electronically conducting ceramic that does not promote coking. With an oxide taking the role of electronic conductor, the amount of metal catalyst can be reduced low enough to eliminate coking. This composition shows performances comparable to Ni-GDC with hydrogen and methane, and can be also used with propane and butane[15].

Ti doped YSZ has also been extensively studied as anode material for SOFC. In combination with nickel this material shows improved anode behavior with respect to the thermal expansion coefficient and a better electrical conductivity than that of the YSZ, as well as a lower degradation rate at 1000°C. This degradation has been attributed to the lower agglomeration tendency of the nickel particles of the Ti containing cermets compared to the regular Ni/YSZ cermets[15].

Several perovskite materials based on lanthanum chromite and strontium titanate[14] have also been investigated with regard to their potential application as anodes in SOFCs. These show excellent materials for interconnects. Strontium substituted lanthanum chromites (LSC) have been intensively studied as interconnects and these are stable at high temperatures and under reducing conditions. With 5 wt% ruthenium, LSC presented no carbon deposition when used as anode and when methane was used as fuel. Its catalytic activity was stable for more than 200h under reducing conditions[15].

4.4.Selection of Interconnect

The ceramic cell made of anode, electrolyte and cathode is held between metal inter connecting plates that act as air and gas flow plates as well as the electrical connection between each cell. Interconnection also protects the air electrode material from the reducing environment of the fuel on the fuel electrode side. The requirements of the interconnection are most severe of all cell components and include the following:

- Nearly 100% electronic conductivity,
- Stability in both oxidizing and reducing atmospheres at the cell operating temperature since it is exposed to

air (or oxygen) on one side and fuel on the other side,

- Low permeability for oxygen and hydrogen to minimize direct combination of oxidant and fuel during cell operation
- A thermal expansion close to that of the air electrode and electrolyte,
- Non-reactivity with the air electrode and the electric contact material (e.g.nickel).

To satisfy these requirements, doped lanthanum chromite is used as the interconnection material. Lanthanum chromite is a p-type conductor; its conductivity is due to small polaron hopping from room temperature to 1400°C at oxygen pressures as low as 10^{-18} atm. The conductivity is enhanced as lower valence ions (e.g., Ca, Mg, Sr, etc) are substituted on either the La^{3+} or the Cr^{3+} sites[15]. Interconnects for stacks operating in reduced temperatures are often constructed from less expensive stainless steel.The interconnects are also made of Ferritic Stainless Steel[8]. Most intermediate temperature SOFC developers are using metallic bipolar plates. Often a ferritic stainless steel is specified because of low(12.5×10^{-6} K^{-1}) thermal expansion coefficients of these alloys. More over by using compositions with Nb and Ti, excellent electronic interfacial contacts can be maintained between the cell components for extended periods[7].

5. Fabrication Processes

In addition to the above materials selection criteria, the fabrication processes have to be chosen in such a way that every sequential component fabrication process does not affect the components already fabricated and to minimize the cell fabrication cost. New SOFC designs and production processes can help to improve SOFCs and bring down materials and manufacturing costs. Different processes have been suggested to enable cost-effective, high volume manufacturing of SOFCs. These techniques, include screen-printing[1], slip casting, tape casting[4,8], colloidal deposition, spray pyrolysis[1,3,8],vacuum plasma spraying(VPS)[8] Flame or thermal spraying[12], RF sputtering [16], sol - gel deposition [13], polymer spin coating [4,13], physical vapor deposition (PVD)[4], reactive magnetron sputtering[4], electrochemical vapor deposition(EVD)[4], electrophoretic deposition and laser reactive deposition (LRD)[4,5,16]. It is important to note that each of these processes has been reported to produce at least one operating cell in a laboratory setting. Control of parameters such as material thickness, in-film defect levels, material dopant concentrations and porosity, becomes critical to ensure cell performance within end of line specifications.

One of the major challenges in the SOFC design is the choice of the method of structural support. Four types of structural supports are provided, anode support, cathode support, electrolyte support and substrate support. The support structure refers to the thickest, and mechanically strongest layer, onto which the other layers are bonded. Each design has it benefits and shortcomings. Anode and cathode supported designs exhibit lower activation polarization at lower operating temperatures, but higher concentration polarization due to increased gas transport resistance. Electrolyte supported designs, while providing greater device reliability are favorable only at high operating temperatures (900-1100°C) due to the increased ohmic resistance of electrolyte materials at lower operating temperatures. In the substrate supported design, the substrate can be very thick and is non-electrochemically active, enabling very thin component layers, but requiring additional manufacturing process, increasing overall cell cost. Additionally, substrate supported designs continue to require gas transport through the substrate, compounding polarization losses at the electrode bonded to the substrate. The anode supported cell has been improved to give very high power density (up to 1.2 Wcm-2 at 770 °C) and reliable process for laboratory-scale manufacture, an important achievement for reducing stack cost. This optimized anode supported design has a thick (1mm) anode which acts as the supporting structure. The electrolyte and cathode are very thin in comparison, 10um and 50um respectively, reducing operation temperatures to within a range of 600 to 750 °C. The anode supported intermediate temperature SOFC design is the most widely studied by SOFC developers in recent years[8]. The anode, cathode and electrolyte are made from ceramic materials to withstand these operating temperatures[16].

Composite technology is a new approach to solid oxide fuel cell (SOFC) fabrication. It is based on the net shape processing, which uses a combination of colloidal suspension and polymer precursor techniques. Different elements of SOFC can be prepared and optimized using this approach[4].

6. Strategy for low temperature operation

There are two major obstacles that have to be solved to operate SOFCs at intermediate temperatures, including the performance of electrolyte and electrodes. Lowering the operating temperature is possible with the use of alternative materials, appropriate cell design and manufacturing routes. As the operating temperature

of an SOFC is reduced, the ohmic loss of the cell across the electrolyte can become a serious problem in an ordinary high temperature electrolyte material. This ohmic loss may be minimized through the use of higher ionic conductivity materials such as gadolinium- doped ceria or strontium and magnesium doped $LaGaO_3$. Reducing the thickness of the electrolyte membranes will obviously decrease the electrolyte ohmic loss. Another issue is the slow electrode reaction rates, which may result in polarization losses when the operating temperature is decreased. It is believed that the electrode reactions™ occur mainly at the triple points between oxygen ions / gas / electrons, so-called triple-phase-boundaries (TPBs). Therefore, both an extended reaction zone and a sufficient porous microstructure will enhance the electrode performance. Mixed ionic and electronic conductors (MIEC) offer a way to enlarge the TPBs over the entire particle surface, and are ideal electrode materials for both anode and cathode. In addition, nanomaterials, with dimensions down to the atomic scale (10^{-9} meters), represent a new generation of advanced materials with improved physical, chemical and mechanical properties. An important feature of such nanomaterials is the high fraction of atoms that reside at grains and grain boundaries, largely enhancing the chemical activity. Nanostructured materials provide opportunities for significantly improved materials performance[14].

7. Conclusion

While stable SOFC have been successfully demonstrated in large-scale systems, the present focus on smaller systems, operating at lower operating temperatures and with hydrocarbon fuels, requires a re-examination of the materials to be used in SOFC, especially for the cathodes and anodes. Because electrode performance depends strongly on both composition and structure and is not understood in detail on a fundamental level, opportunities remain for finding novel materials that exhibit better electrochemical activity with good mechanical properties and thermal stabilities. Materials development will certainly continue to make SOFCs increasingly affordable, efficient and reliable.

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