RELAXATION OF THERMAL STRESSES IN PLANAR SOFC STACKS

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ABSTRACT

A new stack structure was discussed for reducing the thermal stresses in planar SOFC stacks including alloy separators. The stresses investigated originate in the difference in thermal expansion between the separators and electrolytes. We show that the use of YSZ support rings protecting thin electrolyte films reduces the thermal stresses in the cell stack. The use of alloy wires for the connection of electrodes and separators is also investigated to prevent the mechanical failure of the electrodes, which is caused by the thermal stresses.

INTRODUCTION

Solid oxide fuel cells have potential for creating new energy conservation systems, however, because of the insufficient durability for thermal cycles, the applications of SOFCs are considerably limited. The damages which occur during the thermal cycles, arise from the low thermal conductivity and the lack of toughness in the ceramic materials. It is effective for increasing the thermal conductivity and mechanical strength to adopt alloy components in the cell stacks, however, it causes thermal stresses in the stack due to the difference in thermal expansion between the alloy and ceramic materials.

We have pointed out that the thermal stresses are reduced when slips occur between a separator and adjacent single cells in a cell stack (1). Figure 1 shows a schematic drawing of a planar SOFC stack which has the slide planes and wire interconnections. We call the stack Soft Stack. In the figure the electrolyte film is sandwiched by YSZ support rings which protect the thin YSZ electrolyte film. The separators slide on the support rings during the heating up and the cooling down processes. The wire interconnection in the figure was investigated previously (2). The experimental assembly of the wire interconnection which was tested at 900°C is shown in Figure 2.
CALCULATION OF THE THERMAL STRESSES

The thickness of the support ring should be determined by the calculation of friction forces between the separator and support ring. We cannot proceed the calculations equally for the heating and cooling processes, because adhesion proceeds at operating temperature.

Calculation for a heating process

When a cell stack is heated from room temperature to operating temperature, radial friction forces are applied uniformly to a support ring as shown in Figure 3, therefore the forces at sides AD and BC of a minute part ABCD in the ring are balanced as shown in Figure 4 (3). The equation of the force balance is

\[-\sigma_u t d\theta dr + prd\theta dr = 0\]  

where \(t\) is the thickness of the ring, \(p\) is frictional force per unit surface area of the ring and \(\sigma_u\) is the stress in the ring along \(\theta\) direction. The subscript \(U\) denotes a heating process. From Equation 1, we have

\[\sigma_u = \frac{pr}{t}\]  

The stress for heating process \(\sigma_u\) increase with \(r\), therefore it has a maximum for \(r = R\), where \(R\) is the radius of the support ring.

Calculation for a cooling process

In the cooling process, we must consider the adhesion between the separator and the electrolyte, because of the high operating temperature and high stack pressures. Figure 5 shows adhering and not adhering areas in the surface of a support ring. It is expected that the bending stress in the support ring has a maximum when half of the surface area is adhering to the separator as shown in Figure 5. The forces applied to the adhering areas A and B are combined in both areas, and they are represented by the arrows \(P_A\) and \(P_B\) respectively. Figure 6 shows the bending of the support ring by \(P_A\) and \(P_B\) (\(= P\)). The bending moment \(M\) applied on the ring at angle \(\phi\) is

\[M = PR_c\left\{ \frac{1}{\pi(1+\kappa)} - \frac{\cos\phi}{2} \right\}\]  

where \(R_c\) is the radius of the centroidal axis of the ring (4).
The coefficient $\kappa$ is

$$\kappa = -1 + \frac{R_c}{2h} \ln\left\{ \frac{R_c + h}{R_c - h} \right\}$$  \hspace{1cm} (4)$$

where $h$ denotes half of the width of the ring.

The stress $\sigma_D$ applied on the cross section $CC'$ is

$$\sigma_D = \frac{M}{AR_c} \left\{ -\frac{z}{\kappa(R_c-z)} - 1 \right\} - \frac{P}{2A} \cos \phi$$  \hspace{1cm} (5)$$

where subscription $D$ denotes a cooling process, $A$ is the cross-sectional area of $CC'$ and $z$ is the distance from the centroidal axis and taken positive in the direction towards the center of the support ring. The stress in the ring for cooling process $\sigma_D$ has a maximum at $\phi = \pm 90^\circ$ and $z = h$.

**Calculation of the thickness of support rings**

We can estimate the thicknesses of the support rings required for the heating and cooling processes by using Equations 2 and 5. The results of the tensile test of YSZ reported by Matsusue (5) and the results of the measurements of the friction forces between YSZ and heat resistance alloy at 900 and 1000°C (1) are used for the calculation. Figure 7 shows the result for a heating process. The thickness of the ring is determined for a given value of the diameter of the ring. The calculation was made for different stack pressures $P_s$. It is obvious from the results that thick (more than 1mm thick) support rings are not necessary for withstanding the frictions applied on the ring in the heating process.

Figure 8 shows the results calculated for cooling processes. The minimum values for the thickness of support ring are determined for a given inner radius $R_i$ and outer radius $R$ of the ring. It is roughly predicted from Figure 8 that 2mm thick support rings having the inner radius of 180mm and outer radius of 200mm are necessary for a stack cooled from 1000°C with a stack pressure of 0.092kg/cm². From these analyses on the size of support rings, it can be concluded that thick support rings are not necessary for 400mm diameter cells operated at 900°C when the stack pressure is less than 0.1kg/cm². This value of stack pressure is about 1/10 of that of conventional planar SOFC stacks.

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FLEXIBLE INTERCONNECTION

Reduction in the stack pressure by flexible interconnection

It is effective for reducing the stack pressure to adopt the flexible interconnection. Figure 9 shows the schematic cross section of a conventional planar cell stack. The separators press the electrodes to reduce the electric resistivity in the contact between the electrode and the ribs of the separators. Considerable pressures are required to reduce the resistivity because of the hard structure of the separators. The stack pressure is also used for the close contacts between the electrolyte sheets and separators to prevent the leakage of the fuel gas and air. It is difficult to divide the stack pressure properly between the two parts in this structure because the compliances of the separator and electrolyte are low and the electrode materials are brittle.

Deformation of the interconnecting wire

Figure 10 schematically shows an alloy wire connecting the alloy separator and electrode. The ends of the wire are fixed to the separator and electrode. The wire moves from the position AB to A'B', as the displacements of the separator and electrode occur during a heating process. There must be a small amount of deflection $\delta$ in the form of the wire at low temperature, so that it can be stretched at high temperature as shown in the figure. A calculation was made to estimate $\delta$ for the conditions that the distance between the separator and electrodes was 5mm, and the cell radius was 100mm, and the separator material was Inconel 600. It was concluded from the calculation that the deflection $\delta$ of 0.24mm was required for an operating temperature of 900°C.

Calculation of the conductance of wire interconnection

It is desirable to use thinner alloy wires for high compliance interconnections, however, there must be a minimum diameter for the alloy wires to increase durability for oxidation and corrosion at operating temperatures. By assuming the resistivity of La(Sr)CrO$_3$ as $2.5 \times 10^{-9}\Omega\text{cm}$ (6) and Inconel 600 as $1.2 \times 10^{-4}\Omega\text{cm}$ (7), We can estimate that the conductance of 0.11mm diameter Inconel wires which connect the separator and electrode with the density of 0.25 wires/mm$^2$ (Figure 11a), is equal to the La(Sr)CrO$_3$ interconnection where the thickness and gap of the ribs are 2mm (Figure 11b). We must correct the estimated diameter of the alloy wires to be a larger value because of the requirement of the formation of the protective oxide layers on the surfaces of the wires, however, it is expected that a flexible interconnection between the cathode and separator can be made of heat resistant alloy wires.
A single planar stack for cycle tests

A single planar stack made of flexible interconnections is being prepared. Figure 12 shows a schematic cross-sectional view of the single stack, and a photograph of the alloy foil current collectors for thermal cycle tests. The separators are made from Inconel 600. Ni-Cr alloy foil is used instead of wires for the current collectors, because the foil current collectors can be replaced easily by new ones after a cycle test. The diameter of the stack is 80mm and the distance from electrode to separator wall is 15mm. The thickness of the foil ranges from 100 to 200μm. The thickness and inner diameter of the support rings are 2mm and 60mm, respectively. The stack pressure is 0.1kg/cm². The temperature is cycled between room temperature and operating temperature, and the cell performance is monitored.

SUMMARY

Tubular cell stacks which release thermal stresses with the nickel felt are in advance of conventional planar cell stacks, therefore relaxation mechanisms must be introduced in advanced planar cell stacks. In this report a new design of planar cell stack is proposed, in which a sliding mechanism between the separator and electrolyte relaxes the stresses. It is also pointed out that a flexible interconnection between the electrodes and separators is necessary to relax the stresses applied to the electrodes.

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Figure 1 Schematic cross-sectional view of a planar stack showing the concept of Soft Stack.

Figure 2 Experimental apparatus for testing a flexible wire interconnection between Inconel 600 plate and air electrode prepared on a 0.25 mm thick, 25×25 mm 8YSZ sheet (2).
Figure 3  Stress pattern applied to a support ring during the heating process.

Figure 4  Balance of the forces in the support ring for the heating process.

Figure 5  Force distribution pattern used for the calculation of the maximum stress in a support ring at the beginning of the cooling processes.

Figure 6  The bending moment applied on the ring in the cooling process.
Figure 7 The minimum thicknesses of the support ring calculated for the heating processes at 900 and 1000°C, as a function of the diameter of the ring. Ps: stack pressure.

Figure 8 The minimum thicknesses of the support ring calculated for the beginning of the cooling processes at 900 and 1000°C, as a function of the diameter of the ring.

Figure 9 Schematic of a conventional planar cell stack.

Figure 10 Schematic diagram showing a wire interconnection (A'B') which is stretched at operating temperature due to the difference in thermal expansion between the separator and electrolyte.
Figure 11 An alloy wire type (a) and a ceramic rib type (b) interconnections having equal electric conductance; the resistivity data for the calculation are $1.2 \times 10^4 \Omega \text{cm}$ for Inconel 600 and $2.5 \times 10^2 \Omega \text{cm}$ for LaCrO$_3$, respectively.

Figure 12 Photograph of Ni-Cr alloy foil current collectors (a), and cross-sectional view of a planar single stack designed for the cycle test of the flexible interconnection (b).