



## Short communication

## Interface strength analysis of the corrugated anode-electrolyte interface in solid oxide fuel cell characterized by peel force

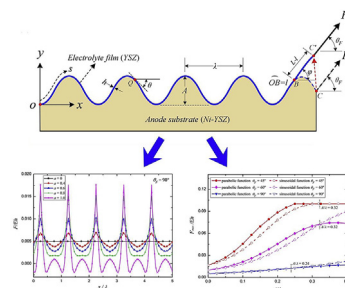
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## HIGHLIGHTS

- A novel corrugated interface theory model is used to analyze the interface strength.
- The corrugated interface with the parabolic function is introduced.
- The analytical solution agrees well with the previous research.
- Ultimate/allowable peel strengths of the two shape functions are compared.
- Critical peel angle and amplitude-wavelength ratio are determined.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The interface delamination will directly lead to mechanical failure of solid oxide fuel cells (SOFCs), so improving interface strength is essential to ensure the stability of cell. A novel fundamental theoretical model for half-cell of corrugated SOFC is employed to analyze the interface strength of corrugated anode-electrolyte interface of which interfacial morphology is characterized by parabolic function. Based on potential energy principle and first variation theory of half-cell system, the analytical solution of peel force under different peel angles is derived and agrees well with the previous research result. The results show that introducing the corrugated interface can improve the interface strength. The extreme values of peel force described by parabolic function are compared with that by sinusoidal function under different peel angles. The ultimate peel strength and allowable peel strength corresponding to two shape functions are preferable in different ranges of amplitude-wavelength ratio. In addition, the corresponding peel angle and amplitude-wavelength ratio are also determined and discussed for when peel angle is less than inclination angle of corrugated film. The research provides guidance for optimizing the interfacial morphology and enhancing the interface strength.

## 1. Introduction

The solid oxide fuel cells (SOFCs) have received considerable attention as new energy sources for transforming chemical energy into electrical energy directly. Compared with traditional fossil fuels, SOFCs have several important advantages such as high specific energy, high power generating efficiency and environment-friendly property [1,2]. In recent years, corrugated SOFCs have received a lot of attention

because they have higher fuel utilization, lower temperature difference and higher current density [3–8] by enlarging triple phase boundary length of the cell compared with traditional planar SOFC [9,10]. Similar to typical planar SOFC, the anode-supported corrugated SOFC consists of three components, i.e., anode, cathode and electrolyte which is a dense film of only a few tens of microns thick or even thinner, but the interfaces between electrodes and electrolyte are corrugated rather than flat.

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The research on corrugated SOFCs mainly focuses on the analysis of their electrochemical performance [3–8,11–13]. For example, Ce-bollero et al. [11], Su et al. [12] and Chao et al. [13] prepared corrugated SOFC by pulsed laser method or atomic layer deposition to improve the power density. But many mechanical problems, such as delamination, crack et al., also need to be solved before commercialization. As is well-known, delamination has a significant influence on durability and stability of the cell and its formation mechanism can be described as follow [14–16]. The thin electrolyte subjected to residual stress is expected to fail by traversing cracking through the thickness direction then it delaminates from electrodes. Upon the occurrence of delamination, it may cause the failure of SOFCs ultimately [17,18], so the interface strength of SOFCs needs to be guaranteed. The interface strength of planar SOFCs has been investigated by other researchers through indentation [19,20], but the method is not suitable for corrugated interface. The peeling behavior can be used for analyzing the interface strength of both flat [21–23] and corrugated [24–30] film-substrate system. Because electrolyte is thin, so half anode-supported corrugated SOFC including electrolyte and anode belongs to film-substrate system and its interface strength can also be investigated by peeling behavior.

At present, the theoretical researches about interface strength of SOFCs with different corrugated interfacial morphology are limited. To understand interface strength of half anode-supported corrugated SOFC, peeling behavior is employed in this paper. The peel force acting on electrolyte film is used to characterize interface strength between electrolyte film and anode substrate. Based on potential energy principle and first variation theory of half-cell system, the corrugated interfacial morphology is characterized by parabolic function and corresponding analytical solution of peel force under different peel angles is analyzed. In addition, the variation tendencies and extreme values of peel forces which the corresponding interfacial morphologies are described by sinusoidal and parabolic shape functions are compared. Within a certain range of geometrical parameter, the preferable corrugated interfacial morphology is also confirmed for improving the interface strength.

## 2. Theoretical model

A typical half anode-supported corrugated SOFC consists of anode and electrolyte. The usual materials which employed for anode and electrolyte are nickel yttria-stabilized zirconia composites (Ni-YSZ) and yttria-stabilization zirconia (YSZ) respectively. The anode substrate and electrolyte film are prepared together and electrolyte film adheres on anode substrate perfectly. It is assumed that the materials used in SOFC are homogeneous, isotropic and the linear elastic model is defined for all materials [31–33].

Based on potential energy principle and first variation theory of half-cell system, the interface strength of corrugated interface between electrolyte and anode is investigated by peeling electrolyte film from anode substrate. The schematic diagram of half-cell and peeling progress are shown in Fig. 1(a) where  $h$  is the thickness of electrolyte film,  $s$  is the arc-length along the film with respect to origin  $O$  and  $\theta$  is the inclination angle between film tangent and horizontal axis. In initial stage, the electrolyte film with arc-length  $L$  is attached to substrate which is shown in  $OC$  arc segment of Fig. 1(a). Under the action of  $F$  with peel angle  $\theta_F$ , arbitrary arc segment  $BC$  with arc-length  $L-l$  is peeled off and point  $C$  moves to point  $C'$ . While the rest of film, i.e.  $OB$  arc segment, still adheres to substrate perfectly. The peel angle maintains  $\theta_F$  during the peeling process and inclination angle at point  $B$  is  $\varphi$ .

The corrugated interfacial morphology between electrolyte and anode can be described as different shape functions, such as sinusoidal, exponential, parabolic function and so on. In this theoretical model, the parabolic function is adopted and its shape function can be expressed as

$$Y(x) = \sum_{i=1}^n y_i(x) \tag{1}$$

$$y_i(x) = a^3 + (-1)^{i-1} \{ a [x_i - 2(i-1)a]^2 - a^3 \} \tag{2}$$

where  $a$  is geometric parameter of interface and the range of  $x_i$  is from  $(2i-3)a$  to  $(2i-1)a$  meanwhile  $x_i \geq 0$ . As shown in Fig. 1(b), the parabolic function  $Y(x)$  is a periodic function and the amplitude is  $A = 2a^3$ , wavelength is  $\lambda = 4a$ . When  $a = 0$ , the corrugated interface degenerates into flat interface. The arc-length of electrolyte film bonded to anode substrate is  $l$  and it can be expressed as

$$l = \int_0^a \sqrt{1 + y_1'^2} dx + \sum_{i=2}^{n-1} \int_{(2i-3)a}^{(2i-1)a} \sqrt{1 + y_i'^2} dx + \int_{(2n-3)a}^x \sqrt{1 + y_n'^2} dx \tag{3}$$

where  $n = 2.5T$ . Because the tangent value of inclination angle  $\theta$  equals to the first-order derivative of shape function of the film, so

$$\theta = \arctan y_i' = \arctan \{ (-1)^{i-1} 2a [x_i - 2(i-1)a] \} \tag{4}$$

For half-cell system, the potential energy can be described as

$$U = U_b + U_t - W_F - U_a \tag{5}$$

where  $U_b$  is the bending elastic energy of electrolyte film,  $U_t$  is the strain energy of electrolyte film,  $W_F$  is the work done by external force  $F$  and  $U_a$  is the interfacial adhesion energy between electrolyte and anode. The bending elastic energy of electrolyte film  $U_b$  can be expressed as

$$U_b = U_{b1} + U_{b2} = \int_0^l \frac{K}{2} \theta'^2 ds + \int_l^L \frac{K}{2} \theta'^2 ds \tag{6}$$

where  $K = Eh^3/12$  is the distribution of bending stiffness of film and. Because  $\theta'$  is the curvature of film, the relationship between curvature  $\theta'$  and parabolic function  $Y(x)$  is

$$\theta' = \frac{|Y''|}{(1 + Y'^2)^{\frac{3}{2}}} \tag{7}$$

The denominator of Eq. (7) is deduced by Taylor expansion and higher-order terms have been discarded. Therefore,

$$U_{b1} = \int_0^l \frac{K}{2} \theta'^2 ds = \int_0^x \frac{K}{2} Y''^2 dx = \int_0^a \frac{K}{2} y_1''^2 dx + \int_a^{3a} \frac{K}{2} y_2''^2 dx + \dots + \int_{(2n-3)a}^{(2n-1)a} \frac{K}{2} y_{n-1}''^2 dx + \int_{(2n-3)a}^x \frac{K}{2} y_n''^2 dx = \frac{Ea^2 h^3 x}{6} \tag{8}$$

The strain energy  $U_t$  of electrolyte film can be expressed as

$$U_t = \int_l^L \frac{1}{2} Eh \varepsilon^2 ds \tag{9}$$

where  $E$  and  $\varepsilon = F \cos(\theta - \theta_F)/(Eh)$  are the Young's modulus and elastic strain of electrolyte respectively. The work done  $W_F$  by external force  $F$  is

$$W_F = \vec{F} \cdot \vec{u}_F + \int_l^L F \varepsilon ds \tag{10}$$

where  $\vec{F}$  is a vector and  $\vec{F} = (F \cos \theta_F, F \sin \theta_F)$ .  $\vec{u}_F$  is the displacement of point  $C'$  which is the application point of force  $\vec{F}$  and

$$\vec{u}_F = \int_l^L (\cos \theta - \cos \theta_F, \sin \theta - \sin \theta_F)^T ds \tag{11}$$

The displacement is defined relative to reference point which has the coordinate of

$$(L \cos \theta_F, L \sin \theta_F) \tag{12}$$

The interfacial adhesion energy  $U_a$  between electrolyte and anode can be expressed as

$$U_a = \int_0^l \Delta \gamma ds = \Delta \gamma l \tag{13}$$

where  $\Delta \gamma$  is constant adhesion energy between film and substrate.

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