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Stress and plastic deformation of MEA in fuel cells Stresses generated during cell assembly

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Abstract

A linear elastic–plastic 2D model of fuel cell with hardening is developed for analysis of mechanical stresses in MEA arising in cell assembly procedure. The model includes the main components of real fuel cell (membrane, gas diffusion layers, graphite plates, and seal joints) and clamping elements (steel plates, bolts, nuts). The stress and plastic deformation in MEA are simulated with ABAQUS code taking into account the realistic clamping conditions. The stress distributions are obtained on the local and the global scales. The first one corresponds to the single tooth/channel structure. The global scale deals with features of the entire cell (the seal joint and the bolts). Experimental measurements of the residual membrane deformations have been provided at different bolts torques. The experimental data are in a good agreement with numerical predictions concerning the beginning of the plastic deformation.

Keywords: Fuel cell design; Proton exchange membrane (PEM); Nafion; Mechanical response; ABAQUS

1. Introduction

Proton exchange membrane fuel cell (PEMFC) is a possible substitute of combustion engine owing to its high efficiency and low level of pollutions. The PEMFC's operating characteristics, specifically durability, necessitate significant improvements [1]. The required lifetime of PEMFC exceeds 5000 h for automotive applications [2]. The PEMFC lifetime limitations can be caused by different factors. One of the reasons concerns with the loss of the conductivity properties of proton exchange membrane or degradation of catalyst layers [3]. Another reason deals with the thermo-mechanical deformation of membrane electrode assembly (MEA) which is the heart of PEMFC. Today Nafion® (Nafion® is registered trademark of sulfonated tetrafluorethylene copolymer by DuPont) is used usually as a material for membrane in fabrication of MEA. This polymer provides the protons transport from anode catalyst layer to cathode one and has unique thermal and mechanical stability. The membrane operates in chemical hostile environment with changes in temperature and humidity and under mechanical stresses. Today it is accepted that lifetime limitations of MEA are caused by chemical and thermo-mechanical factors. The general chemical factors are the decrease of electrochemical activity of catalytic layers and inter diffusion of platinum into membrane during fuel cell running.

Mechanical stresses which also limit durability of MEA have two origins. The first is the technology of fuel cell and stack assembly (bolt assembling). The function of the bolts deals with the necessity to assure the tightness and the electrical conductivity of contact elements. The contact pressure is one of the parameters which determine the performance of fuel cells [4,5]. Additional mechanical stresses arise during fuel cell running, because PEMFC consists of the materials with different thermal expansion and swelling coefficients. The temperature and the concentration gradients, which are associated with the gradients of material properties, generate mechanical stresses within fuel cell. In order to improve the durability of fuel cells, it is necessary to understand the phenomena which govern the arising

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of pinholes and delamination between membrane and gas diffusion layer [6]. It is difficult to separate the mechanical, the thermal and the chemical effects in this problem. Besides, specific mechanical properties of Nafion®, as well as complexity and coupling of physical phenomena, compose a real scientific challenge to understand stresses and mechanical deformation arising in fuel cell during running.

The goal of several papers was an improvement of knowledge about mechanical stresses and plastic deformation within fuel cell. Regarding the physico-mechanical properties of Nafion®, it is possible to find sufficient information for predictive numerical simulations [7–10]. The problem of mechanical behavior of PEMFC has been studied in the review [11], where unavoidable difficulties of the multi-physical coupling have been considered. The possibility of mechanical failures of the membrane in fuel cell was discussed in [12]. Many works concern the mechanical behavior of the membrane [10–19]. Three recent works should be marked especially [17–19]. The membrane behavior under static hydro-thermal loading was investigated in [17]; the second work [18] was devoted to the mechanical stress evolution during the duty cycle (increasing/decreasing of the temperature and humidity). In the third one [19] the mechanical stress evolution was studied under humidity cycles at a constant working temperature (85 °C). The perfect plastic–elastic model of the membrane was assumed in [17,18] and the isotropic hardening model was used in [19]. The two modes of the fuel cell assembly were investigated in these works, namely *fixed force mode* corresponding to a case of fixed external stress, and *fixed displacement* mode corresponding to a case of initial compression and then a fixed displacement. The mechanical parameters of the membrane considering the temperature and humidity dependence are based on the work [10] data.

In the papers [17–19] the numerical simulations have been performed for the single tooth/channel configurations using 2D schematization. Thus, the obtained results reflect the local effects on the scale of only one channel. The gradients on the scale of entire fuel cell, in particular, the temperature and the mass fraction variation with respect to the distance from the entrance are not taken into account. So, the results cannot be used for the prediction of the edging effects near the seal joints. Moreover, the classical boundary conditions (displacement or force) do not reflect reality of the fuel cell assembling. Indeed, the bolts act as flexible elements which impose the different stress depending on their elongation and their stiffness.

The aim of the present paper is to fill up some gaps of the previous works [17–19]. This paper treats the numerical calculations of mechanical stresses arising in a single fuel cell during the assembling (cold model). The physical model of fuel cell, the numerical procedure and all parameters necessary for mechanical stresses calculation are presented with respect to the previous works. The calculations have been provided for a fuel cell geometry which is similar to the one used in the papers [17–19]. Nevertheless, a single tooth/channel configuration of the works [17–19] has been generalized in order to obtain the mechanical stresses in the entire fuel cell. More precisely, all the channels and the joints are taken into account in this model. Thus, the proposed configuration allows understanding of the border effects in the fuel cell. The stresses arising during cell assembling are discussed on the scale of one channel and on the scale of the entire cell.

2. Model definition

2.1. Geometry

The fuel cell has a complicated three-dimensional structure Fig. 1a and b; nevertheless, in this article a two-dimensional approach is used. Contrary to the previously proposed mod-

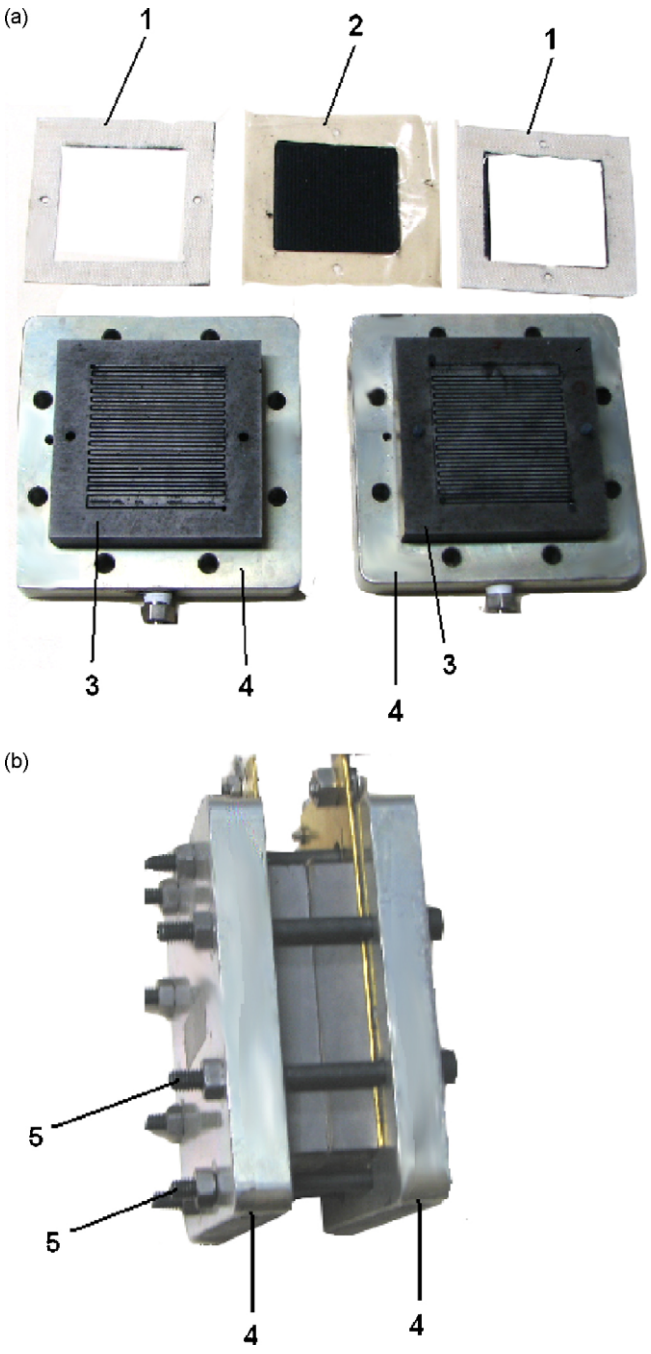

Fig. 1. (a) Fuel cell components and (b) fuel cell after assembly. (1) Seal joints, (2) MEA, (3) graphite plates, (4) steel plates and (5) bolts.