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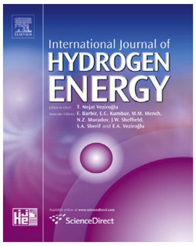

Combined effects of environmental vibrations and hygrothermal fatigue on mechanical damage in PEM fuel cells

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ABSTRACT

Automotive polymer electrolyte membrane (PEM) fuel cells are exposed to high magnitude road-induced impact loads and vibrations as well as high-level cyclic stresses due to humidity and temperature (hygrothermal) variations. The consequent plastic strain can exacerbate defects and may result in operational failure. In this study, a two-dimensional finite element model based on cohesive zone theory was employed to investigate the combined effects of hygrothermal cycle amplitude and amplitude and frequency of external vibrations on damage propagation. The simultaneous presence of hygrothermal cycles and vibrations severely intensified damage propagation within the expected fuel cell lifetime. Compared with applied vibrations, hygrothermal cycles produced a dominating effect on degradation. Under hygrothermal cycling, membrane cracks experienced more severe propagation compared to delaminations, while vibrations had a more significant effect on delaminations compared to cracks. The presence of a channel offset led to a 2.5-fold increase in delamination length compared to a case with no channel offset.

Introduction

The utilization of polymer electrolyte membrane (PEM) fuel cells in transportation applications has become a focus of attention due to their high power density, high overall efficiency, fast start-up and shut-down, and low emissions of greenhouse gasses and noise [1]. The combination of these characteristics makes the PEM fuel cell a promising candidate to be used as the engine and/or for auxiliary power in transportation applications. However, prohibitive cost, poor durability, and mechanical degradations are still the major challenges that limit their commercial success. While 2015 is a commercialization goal for fuel cell cars, dynamic conditions present during automobile operation have made it challenging to meet the 5000-h fuel cell life targeted by the U.S. Department of Energy [2].

PEM fuel cells are generally exposed to high magnitude road-induced vibrations and impact loads in the range of

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0.9–40 Hz when employed in transportation applications. These vibrations result in shear stresses between the layers of the PEM fuel cell that may initiate or exacerbate defects [3]. PEM fuel cells also experience a considerable amount of plastic strain due to humidity and temperature (hygrothermal) cycles during operation. The combination of these sources of mechanical stress can play an important role in the initiation and evolution of mechanical defects in the membrane electrode assembly (MEA) [4–10]. However, mechanical stress impacts on MEA mechanical degradation have yet to be fully investigated. Although performance degradation is inevitable, an improved understanding of damage initiation and propagation mechanisms can be used to effectively control and minimize the rate of degradation within PEM fuel cells [2].

The effects of vibrations on fuel cell damage has been mainly investigated with a focus on the fuel cell power performance [11–14]. In the experimental studies by Rouss et al. [13,14], Rajalakshmi et al. [12], and Betournay et al. [11] a fuel cell stack was exposed to multi-direction vibration tests. No visually detectable damage (cracks) or significant degradation in the power curves were observed during the test period of the above mentioned studies. However, longer test times with start-up and shut-down considerations will provide valuable insight for PEM fuel cell lifetime estimations. Also, an understanding of damage generation at the microscale necessitates high resolution imaging that could be provided by microscopy techniques, such as scanning electron [15] and X-ray microscopy [16–18]. More importantly, because the tested fuel cells were not in operation during the test period in Refs. [11–14], a considerable amount of plastic strain generated by humidity and temperature loading cycles may have been outside the scope of those investigations. A recent experimental study by Diloyan et al. [3] has shown that vibrations can considerably reduce the growth of platinum (Pt) particle agglomerations in the catalyst layer (CL). Loss of compression, thinning of the membrane, and degradations in PEM fuel cell components were also reported. Furthermore, in our previous work [19], it was observed that external vibrations, particularly at larger amplitude and frequencies, can significantly exacerbate damage in PEM fuel cells.

MEA fatigue and aging due to hydrothermal cycles have been widely investigated by several researchers [5,7,8,10,20–29]. However, damage evolution mechanisms in the MEA under these conditions still required deeper investigations. Rong et al. [6] used a microstructure model to study the damage propagation between Nafion and a carbon (C)/Pt agglomerate. They found that the delamination between the two phases initiated more readily under a higher frequency of start-ups and shut-downs (shorter cycles), while crack initiation in the Nafion phase occurred more rapidly under long cycles. Poornesh et al. [4] investigated the crack propagation in CLs using a sandwich model consisting of an interlayer embedded between two CLs. They found that the damage propagation in the CL was highly dependent on the vicinity of the crack. Ma et al. [9] investigated the capillary forces at an interface between a Nafion thin-film and two C/Pt particles. They showed that the capillary stresses can be large enough to induce interfacial delaminations. These studies [4,6,9] have provided valuable insight into the evolution of PEM fuel cell mechanical defects due to hygrothermal cycles; however, there is a significant need to predict the damage from realistic loading regimes of working PEM fuel cells. The mechanical damage evolution in the MEA requires a careful consideration of the vibrations and dynamic operating conditions in transportation applications, effects which have not yet been reported in combination in the literature.

In this paper, we present the combined effects of hygrothermal cycles and external vibrations on micro-scale defect (cracks and delaminations) propagation in automotive PEM fuel cells. A finite element (FE) model based on cohesive zone theory [30,31] was developed to study the defect propagation in PEM fuel cells under realistic working conditions. We also performed a parametric study to investigate the effects of the hygrothermal cycle amplitude, amplitude and frequency of external vibrations, location of the defect, and presence of channel offset on damage propagation in the MEA.

Modeling of damage in PEM fuel cells

Theory for damage propagation

The cohesive zone modeling (CZM) approach introduced by Turon et al. [30,31] was employed to simulate the damage evolution in the PEM fuel cell. The CZM assumes a cohesive damage zone near the tip of the defect (crack or delamination) and incorporates a softening relationship between the interface traction (stress) vector, τ, and interfacial separation displacement, δ, such that.

$$\begin{Bmatrix}\tau_s\\ \tau_t\\ \tau_n\end{Bmatrix} = \begin{bmatrix}(1-d)K & 0 & 0\\ 0 & (1-d)K & 0\\ 0 & 0 & (1-d)K+dKH(-\delta_n)\end{bmatrix}\begin{Bmatrix}\delta_s\\ \delta_t\\ \delta_n\end{Bmatrix} \text{ with } H(\delta) = \begin{cases}1 & \delta>0\\ 0 & \delta\le 0\end{cases} \tag{1}$$

where K is the initial stiffness of the interface prior to damage initiation, and d is the damage parameter which increases from 0 (no damage) to 1 (complete separation) under varying loading conditions. The Heaviside function, $H(\delta)$, is used to prevent the interpenetration of interface surfaces. Subscripts s and t correspond to the in-plane shear directions, while subscript n represents the normal direction to the interface.

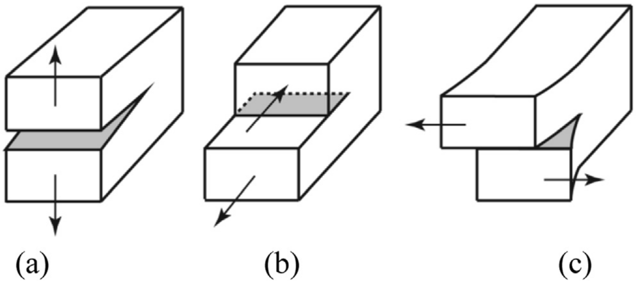

Fig. 1 – Schematic of damage growth modes: (a) opening (mode I), (b) in-plane shearing (mode II), and (c) out-of-plane shearing (mode III).