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Full Length Article

Thermomechanical characterisation of commercial Gas Diffusion Layers of a Proton Exchange Membrane Fuel Cell for high compressive pre-loads under dynamic excitation

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HIGHLIGHTS

- Three industrial GDLs are tested under thermomechanical excitations.
- The pseudo-static mechanical response is strongly nonlinear versus pressure.
- The dynamical mechanical response is linear versus pressure at room temperature.
- The PTFE and MPL additions to the GDLs reduce the dynamic compression modulus.
- The dynamic compression modulus increases linearly until 280 °C.

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ABSTRACT

A Proton Exchange Membrane Fuel Cell (PEMFC) is a mechanically constrained stack composed of several heterogeneous elements. The internal mechanical stress and the mechanical heterogeneity strongly influence the overall PEMFC performances and have to be known and mastered. One of the core components of the PEMFCs is the Gas Diffusion Layer (GDL). In general, this element is composed of non-woven carbon fibre paper or woven carbon cloth. Consequently, the mechanical properties necessary to develop an optimal fuel cell are complicated to extract. Moreover, the mechanical properties of the GDL, and in particular the compression modulus, have to be accurately characterised with respect to various excitation types related to the transportation applications. Consequently, it is essential to investigate, from experiments, the compression modulus of the GDL with respect to large static loads, dynamic loads, different excitation frequencies and temperature. The objective of this paper is to provide the results measured for three widely used commercial GDLs (SGL 24 AA, SGL 24 BA and SGL 24 BC) using an experimental characterisation method with high compressive pre-loads under dynamic excitation over a large temperature range. The experiments show that the stabilisation of the non-linear mechanical behaviour occurs after five loading/unloading cycles. The static pre-loads highly influence the dynamic compression modulus. However, the level of the excitation frequency does not appear to modify the mechanical behaviour. Temperature seems to linearly influence the dynamic compression modulus in two different temperature domains.

1. Introduction

A Proton Exchange Membrane Fuel Cell (PEMFC) is an electric generator based on a mechanically constrained stack composed of several heterogeneous elements [1]. One of the key components of the PEMFCs is the Gas Diffusion Layer (GDL) [2,3]. In general, this element is composed of non-woven carbon fibre paper or woven carbon cloth [4,5]. The mechanical material behaviour of these elements is anisotropic or can be assumed orthotropic [6]. Because of the high porosity of the GDL, all its physical properties are strongly related to its compressive behaviour [7]: water management [8], electrical properties [9], thermal properties [10], ... One of the fundamental mechanical properties of the GDL is the out-of-plane compression modulus [11,12]. Estimating the compression modulus is essential to perfectly knowing and mastering this mechanical parameter in order to develop optimal fuel cell systems [13].

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Nomenclature

K_m and K_c measured and corrected stiffness moduli (N m^{-1})
K_s and K_∞ sample and test machine stiffness moduli (N m^{-1})
F_d and F_s dynamic and static forces (N)
δ_m and δ_c measured and corrected loss factors (degree)
δ_s and δ_∞ sample and test machine loss factors (degree)
D_∞ test machine displacements (m)
$D_{c.d}$ and $D_{c.s}$ corrected dynamic and static displacements (m)
$D_{m.d}$ and $D_{m.s}$ measured dynamic and static displacements (m)
E_c dynamic compression modulus (N m^{-2})
e sample thickness (m)
S contact area (m^2)
$\underline{X}$ indicates X is a complex quantity with $j^2 = -1$

Indeed, scientists try to model the PEMFC behaviour by the finite element method [14,11] to link the mechanical properties of the constitutive components and the overall fuel cell system performances. But, the models are approximated because the mechanical properties of the GDL are generally considered as isotropic [15] and are not specifically known with respect to various excitation types [16]. This last point is particularly important for the embedded systems in transport applications.

Basically, a fuel cell is under two major compressive stress states. During assembly, the GDL endures compressive stress of around 1 MPa. In operation, a fuel cell system endures some changes in relative humidity and temperature. Indeed, the membrane thickness is related to the water content [17]. Furthermore, temperature has a significant influence on the component dimensions due to the thermal expansion coefficients. The overall thickness of constitutive layers increases. The consequence is a large variation of the mechanical stress into the stack. The compressive stress can easily reach 10 MPa and more [18]. In the literature, the compressive stress–strain behaviour of the GDL is determined by placing it between two flat plates and measuring the deflection as a function of the static compressive force [19–24]. Thus, the characterisation methods developed are essentially for static stress conditions.

Furthermore, in transportation, fuel cell systems are also excited by vibrations and consequently the different components also endure these vibrations [25,26]. These vibrations have a significant influence on the overall PEMFC performances [27]. So, providing the compression modulus of the GDL with respect to dynamic excitations is a key point for optimal fuel cell design. To the authors' knowledge, few papers have considered the influence of dynamic excitation on the compression modulus of a GDL [28]. As already mentioned, temperature also plays a major role in the PEMFC performance [29]. Progress has been made on high temperature fuel cell systems (HT-PEMFC) which provide several advantages in overall fuel cell operation in terms of system compactness and heat management [30]. For instance, water management is facilitated with the only presence of water vapour. The background theory behind the HT-PEMFC commercialisation is given in [31] and the drawbacks of each component are highlighted. However, these studies do not cover the thermomechanical properties of the GDL for high pre-loadings and dynamic loadings although another numerical work [32] states the strong relationship between high temperature and mechanical behaviour of the GDL. Few papers have developed the coupling between temperature and compression modulus [7]. To the authors' knowledge, no author has provided a thermomechanical characterisation under dynamic excitation for commercial GDLs.

The objective of this paper is to provide a thermomechanical characterisation of three widely used commercial GDLs (SGL 24 AA, SGL 24 BA and SGL 24 BC) by using high compressive preloads under dynamic excitation and over a large temperature range. The purpose is to give fuel cell system designers some practical information and tools in order to clarify the relations between compression modulus, temperature, pre-loading and dynamic excitation.

This publication is organised as follows. Section 2 describes the experimental characterisation method. In Section 3, experimental results are shown and discussed. Finally, concluding comments are provided.

2. Experimental characterisation method

In this section, the experimental set-up is described. The characterisation procedure is provided in [28].

2.1. Mechanical measurement apparatus

The Dynamic Mechanical Analysis (DMA) test machine (Metravib VA2000) is used to characterise Gas Diffusion Layers. Basically, it consists of a displacement sensor, a temperature control system, a load sensor, a drive motor in order to apply the stress conditions, a drive shaft and a guidance system [33]. An oscillating force is applied to a sample of the GDL and an analysis is performed of the material's response to that force. Strain–stress diagrams can be plotted. A Dynamic Scanning Calorimetry (DSC) is also used to find out the characteristic temperatures. The mass variation with respect to temperature is determined with a ThermoGravimetric Analysis (TGA).

2.2. Technical specifications of the samples selected

The three commercial Gas Diffusion Layers selected and studied were provided by the SGL Group company. Table 1 details their technical specifications.

2.3. Sample holders

A careful attention was paid to design the sample holders. The aim of the proposed method is to determine the compression modulus of the GDLs with respect to large static loads of up to 10 MPa. As the DMA test machine can deliver a maximum force of 60 N during the dynamic test, the surface area in contact with the sample and the sample holder is calculated in order to attain at least 10 MPa. The sample holder is depicted in [24]. Due to the low sample thickness, the parallelism between the sample holder and the GDL has to be carefully managed. So, in addition to the parallel plates, a self-alignment device (a ball device) is added which

Table 1
Technical specifications of the GDLs selected.

GDL reference	PTFE rate (wt%)	MPL	Thickness (μm)
24 AA	0	No	190 ± 30
24 BA	5	No	190 ± 30
24 BC	5	Yes	235 ± 30