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Electrical resistivity prediction of dry carbon fiber media as a function of thickness and fiber volume fraction combining empirical and analytical formulas

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ABSTRACT

The transverse electrical resistivity of the dry unidirectional carbon fiber preforms was studied experimentally taking into consideration various parameters. The dependency of the electrical resistivity transverse to the fibers was thoroughly experimentally studied as a function of the preform thickness and the fiber volume fraction. Empirical mathematical relations were extracted and combined with a non-linear compaction semi-analytical formula. The extracted formula consolidates the compressibility of the preform material, the preform thickness and the fiber volume fraction or the applied pressure in order to calculate the electrical resistivity of the unidirectional preform material transverse to the fibers. Two electrical resistance measurements, at two different thicknesses and two electrical resistance measurements, at two different pressure levels, are necessary to obtained, in order to predict the full range of the electrical resistivity values of the preform material transverse to the fibers as a function of thickness and fiber volume fraction. Very good agreement between the proposed formulas and the experiments has been obtained.

1. Introduction

The electrical conductivity of two phase composite media has been studied by various researchers [1–10]. More specifically, the electrical resistivity of the continuous dry carbon fiber (CF) preforms and carbon fiber reinforced plastics (CFRPs) is dependent on the CF electrical resistivity, direction [4–8], fiber's diameter, thickness [9,10] and the fiber volume fraction [10]. Regarding the thickness-pressure curves of the deformable fibrous media, three different regimes can be observed during compaction [11,12]: (1) a first linear regime, (2) a non-linear regime and (3) a second linear regime, Fig. 1. During the first regime, the fibrous layers are compacted considerably with small amount of pressure. The deformation of the preform comes almost entirely from the apparent compressibility of the interstitial space, and not from the compressibility of the fiber solid itself. During the second (2) regime, the compression of the solid fibers and the voids are deformed simultaneously due to the preform's structure being more stable. In the final regime (3), the porosity approaches a constant value and the compression of the solid fibers is dominant [11,12].

It is widely known that the fiber volume fraction as a function of the applied pressure can be expressed by the following, well known, empirical formula Eq. (1) [11–18].

$$v = aP^b \tag{1}$$

On the other hand, an analytical formulation by Chen et al. describes the thickness of the preform as a function of the applied pressure or as a function of fiber volume fraction [11]. According to Athanasopoulos and Kostopoulos, the electrical conductivity of the dry unidirectional CF preforms is related to the thickness of the preform [9]. Similar results have been obtained by Tse et al. [8] regarding the electrical conductivity of CFRP laminates. Increasing the thickness of the unidirectional preform, the density of the carbon fiber contacts increases, creating a material with higher electrical conductivity. As a consequence the electrical resistivity decreases reaching a steady value. The electrical resistivity can be

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Nomenclature

R	Resistance (Ω)
ρ	Electrical resistivity (Ωm)
h	Thickness per layer (m)
H	Total Thickness (m)
N	Number of Layers
N_{cr}	Critical number of layers
P	Applied Pressure (Pa)
P_{max}	Max applied pressure (Pa)
v	Fiber Volume Fraction
v_f	Final fiber volume fraction
v_o	Initial fiber volume fraction
A_f	Areal weight (kg/m^2)
d_f	Fiber Diameter (m)
ρ_f	Carbon fiber density (kg/m^3)
k	Experimental fitting parameter
a,b	Power Curve Coefficients
α,β	Power Curve Coefficient
C_b	Bulk compressibility (MPa^{-1})
C_{b0}	Initial Bulk compressibility (MPa^{-1})
C_s	Fibers compressibility (MPa^{-1})
λ	Dimensionless pressure
φ	Porosity
φ_o	Initial porosity
f	Final
o	Initial

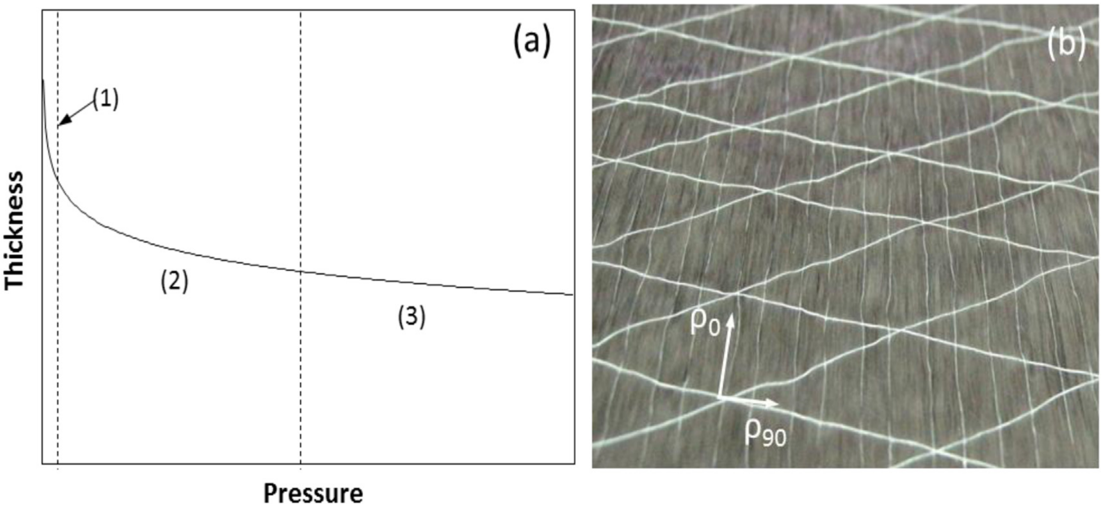

Fig. 1. (a) Typical compaction behavior of dry fibrous layered stricture, (b) 80 gr/m^2 T700SC UD preform.

calculated with a power law curve, between specific limits, with great accuracy [9]. The accurate prediction of the electrical resistivity transverse to the fibers as a function of various parameters is of great importance because of the fibrous conductive materials' applications [19–25].

The dependency of the electrical resistivity transverse to the fibers (ρ_{22}) as a function of the: a) CF preform thickness (H), b) fiber volume fraction (v_f) or the applied pressure (P), and the c) compressibility of the medium, was investigated thoroughly, incorporating the analytical formula of Chen et al. [11] to the extracted power law curves.

2. Experimental setup and materials

2.1. Electrical resistivity measurements

The electrical resistance of the dry carbon fiber unidirectional preform was measured using an apparatus ensuring uniform pressure distribution on the surface of the CF preform specimens. The effect of the contact resistance and the electrodes on the measurements was practically negligible compared to the measured electrical resistance values. Carbon fiber preforms were airtight sealed by using sealant tape and a vacuum bagging film. A vacuum pump extracts the air from the inside of the setup. The vacuum level was monitored using two vacuum gages. The vacuum meter was constant in all tests, and equal to (5 Pa).

At the edges of the preform specimens, two braided copper electrodes were placed as shown in Fig. 2. The pressure was applied on both the preform and braid copper electrodes. Copper cables were soldered on the braid electrodes, and were connected to a precision multimeter (KITHLEY 2002) through the airtight volume. We must note that the measurement of the electrical resistivity is not affected by the application of local extra pressure above the copper braid connections. This fact indicates that in higher pressure levels (>1 bar) the contact resistance remains at the same value, and the preform – braided copper contact interface affects less than 4% of the measurements.

The material tested was a unidirectional preform which consisted of T700SC carbon fiber inlay (fiber diameter $d_f = 7\ \mu m$). The areal density of the unidirectional material is equal to 80 gr/m^2. The weight content of the non-conductive stitches is less than 0.3% of the areal preform weight. Measurements were taken for each pressure level (0.1 MPa, 0.2 MPa, 0.4 MPa, 0.6 MPa, 0.8 MPa) applied to (2, 6, 9, 24) number of layers. For each specimen, the measurement was repeated three times. The electric resistivity measurements were not significantly different from each other. The experimental apparatus is consisted off a 1) vacuum bag, 2) flow medium (highly porous mesh, 3) a peel ply layer, 4) the CF unidirectional preform, 5) non-conductive rigid plate, 6) fibrous copper