CFRPS WITH EMBEDDED CARBON FIBER TEG MODULE AS ENERGY HARVESTER DEVICE

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Abstract

In the present work, a carbon fiber (CF) based thermoelectric device was constructed for a possible self-powered advanced composite application. A parametric study of the electric and thermoelectric response of carbon fiber structures was carried out aiming to optimize the thermoelectric performance of advanced composites. Single carbon fiber's thermoelectric properties were performed and followed by a scale-up to the measurement of the response of a longitudinal CF Thermoelectric Element Generator (TEG) module. The CF-based TEG with 10 p-type thermocouples depicted a total voltage output of 22.4 mV upon being exposed to a temperature gradient (ΔT) of 75°C.

1. Introduction

Polymer-matrix composites containing a high proportion of continuous aligned carbon fibers as the reinforcement are the dominant advanced lightweight structural materials for aircraft, satellites, sporting goods, etc. Although their structural performance is well established, the multifunctionality of these materials is a topic of active research. Multifunctionality means the ability to provide both structural and nonstructural functions [1].

FRP composite are currently employed for automotive, wind turbine blade, and compressed gas storage applications. The ability of purposefuly designing FRPs makes them ideal as platforms for the architecture of structural components that include clean energy alternatives. This would demand the exploitation of energy flow during operation and could be expanded to other application fields i.e. industrial equipment and components such as heat exchangers and pipelines, geothermal energy production, structural materials for buildings, fly-wheels for electricity grid stability, support structures for solar systems, shipping containers and other systems which can also benefit from lower cost, high strength and stiffness, corrosion resistant and lightweight composite materials to impact national energy goals [2].

Multifunctional structures are an extremely interesting section of composite science and technology, due to their potential implementation in structural health monitoring, temperature control, strain or damage sensing, energy harvesting, storage and generation. Research on multifunctional composites has been focused on exploiting multifunctionality for providing energy saving, actuation abilities and other smart functions either intrinsically or via the integration of innovative "devices" [3]. The attainment of these functions requires the exploitation of thermoelectric, thermal conduction, electrical conduction and piezoresistive properties, which are aspects that have received relatively little attention in relation to structural materials. Moreover, in structural components the multiplicity of mechanical, thermal, and electrical fields that are potentially present using operation could provide a suitable environment for energy harvesting. Energy harvesting technologies may even render a structure self-powered in relation to targeted functionalities.

The technologies that facilitate the conversion of heat to electricity (e.g. thermoelectricity) are a good candidate for energy harvesting in the aforementioned applications. Thermoelectric (TE) materials generate electricity even from small temperature gradients often created by insufficient power sources (e.g. combustion engines or power plants). TE materials obey the well-known thermoelectric or Seebeck effect (opposite to Peltier effect) described by the thermoelectric power (TEP) or thermopower or Seebeck coefficient (S), which is the direct solid state conversion of thermal energy to electrical [4]. An electric current is created through the diffusion of charge carriers, either electrons or holes from the hot side of the material to the cold. The Seebeck coefficient is defined then as: $S=\Delta V/\Delta T$ (1), where ΔV is the electric potential difference created by a temperature gradient ΔT. The Seebeck coefficient value is used for the calculation of the power factor ($PF=\sigma\times S^2$). It is an intrinsic material property related to the electronic properties of the materials, independent of their geometry and it can be positive for p-type and negative for n-type semiconducting behaviour. The dimensionless figure of merit (ZT) $ZT=(\sigma\times S^2/k)T$, where k is the thermal conductivity and T is the absolute temperature, is also used to compare the thermoelectric efficiency. Therefore, it can be realised that the combination of high electrical conductivity and Seebeck coefficient, coupled with low thermal conductivity leads to an optimum thermoelectric efficiency [5].

Conventional thermoelectric materials and thermoelectric generators (TEGs) devices are based on low band gap semiconductors e.g. Bi_2Te_3, PbTe, etc. However, they are expensive to mass production, non- flexible, they cannot be deposited on large surfaces for potential large-scale energy harvesting, they are often toxic and consist of rare and expensive elements [6]. On the other hand, organic thermoelectric TE materials are very attractive due to easy processing, material abundance and environmentally friendly characteristics, but their potential is significantly restricted by the inferior thermoelectric properties [7,8].

Initial efforts for exploitation of these functionalities used glass and polymer fibers, which are less expensive than carbon fibers, but they are not electrically conductive and consequently are less suitable for thermoelectric applications [9]. Regarding carbon fiber reinforced composites (CFRCs), the thermoelectric voltage of a continuous CFRC in the longitudinal direction is low, as a result of the intrinsic low value of the epoxy-fiber interfaces. Current research has been focused on the thermoelectric and conduction behavior in the through-thickness direction [10,11]. There has been reported through the use of combinations of interlaminar fillers, thermoelectric power increase, thermal conductivity decrease and electrical conductivity increase, so that the dimensionless thermoelectric figure of merit is increased by four orders of magnitude. By using interlaminar filler and increasing the curing pressure during composite fabrication, the thermal conductivity is increased significantly [12].

This work addresses the materials science of the multifunctionality, particularly in relation to the thermoelectric power in the longitudinal direction of the CFRP laminates, with encapsulation of a thermoelectric generator (TEG) device by exploiting the carbon fiber yarns as thermocouples, as they exposed electrically in series and thermally parallel to temperature gradients.

2. Results and Discussion

2.1. Materials

The CFs used in this study were the unsized M40 and the sized M40B high modulus PAN fibers-12k (Torayca) with a tensile strength of 2.74 GPa and a modulus of 392 GPa, the sized M40J high modulus PAN fibers-12k (Torayca) with a tensile strength of 4.41 GPa and a modulus of 377 GPa and the A-38 PAN fibers-6k (Aksaca) with a tensile strength of 3.8 GPa and a modulus of 240 GPa, as stated by the manufacturer.

2.2 Thermoelectrical characterization of carbon fibers

Carbon fibers present a large variety of characteristics such as different mechanical and electrical properties. More specifically, the thermoelectric response of 4 carbon fiber types was evaluated on single fiber level. The DC electrical resistance (R) of CF was represented by measuring the resistance on a single fiber level by a standard two-probe method using an Agilent34401A6½ digital multimeter. Single filaments were thoroughly detached from the CF yarns and resistance measurements were carried out at 25 mm electrode-electrode distances and glued with silver paste to stabilize them. The distance between the two electrodes defines the fiber's length and used further for the resistivity (ρ) and electrical conductivity (σ) calculations. The single fiber diameters from the 4 different categories were determined through SEM imaging modes.

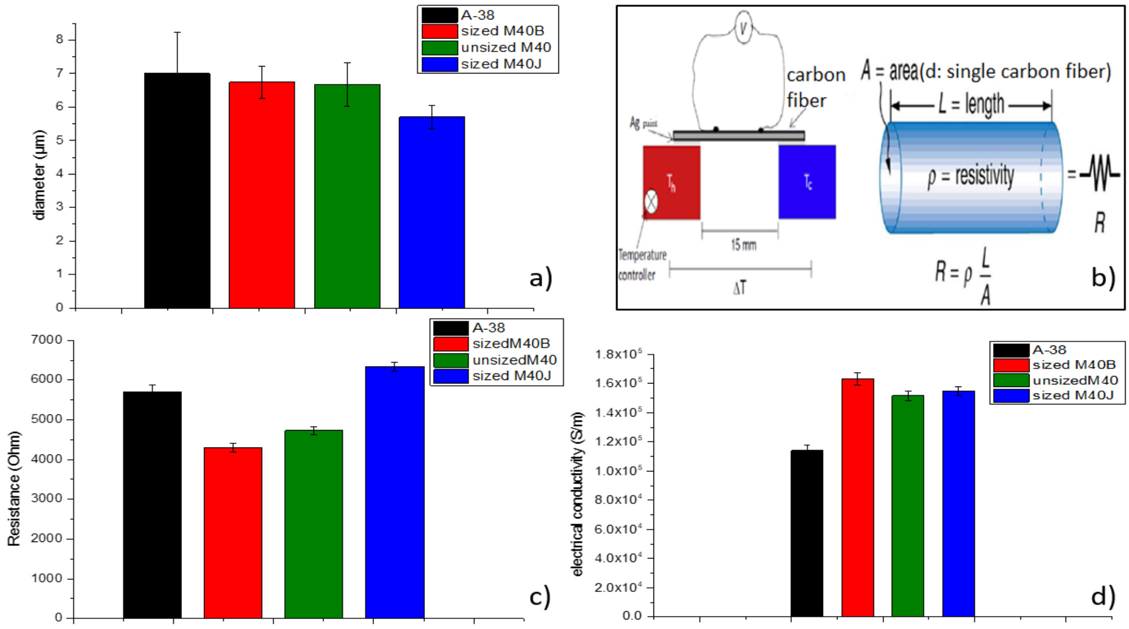

Figure 1. a) the mean diameter of CF types investigated in this study, b) graphical representation of thermoelectric measurements, c) resistance and d) electrical conductivity of CFs on single fiber level.

For the thermoelectric measurements a custom made set-up was developed to obtain the Seebeck voltages. Single CFs were mounted on two metal blocks, which enabled the thermopower generation on account of temperature gradients.

2.3. Carbon fiber based TEG fabrication

The intrinsic functionality of CFs to act as TEGs, provides the possibility of producing architectured structural components which will convert thermal energy to electricity. This may be performed via single or multiple interconnections in the reinforcements that bridge thermal gradients. This strategy converts the structure to a smart device that generates electricity that may be employed either passively (e.g. for cooling or actively e.g. for powering other functionalities).
In the current work, via serial inteconnetction of up to 10 p-type CF yarns a total voltage output of 22.4 mV was achieved over a thermal gradient of 75°C (Fig. 3).

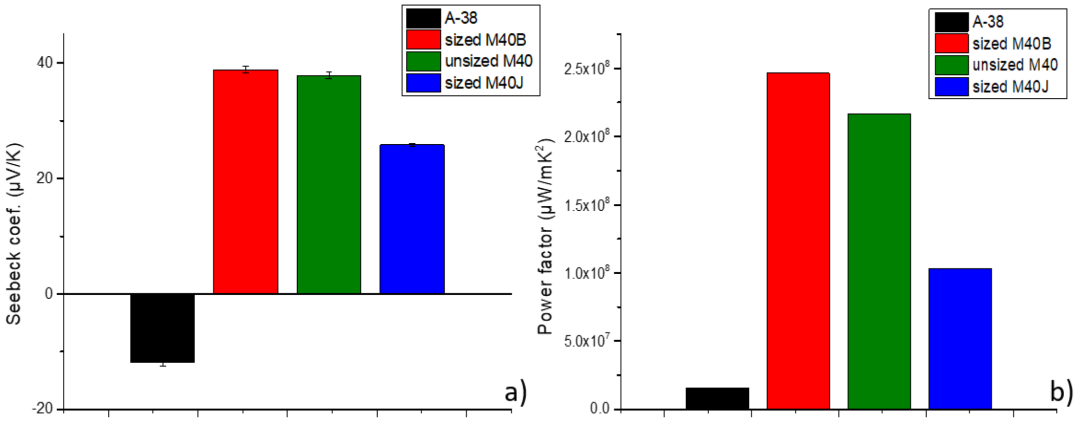

Figure 2. a) Seebeck coefficient and b) power factor of CFs on single fiber level.

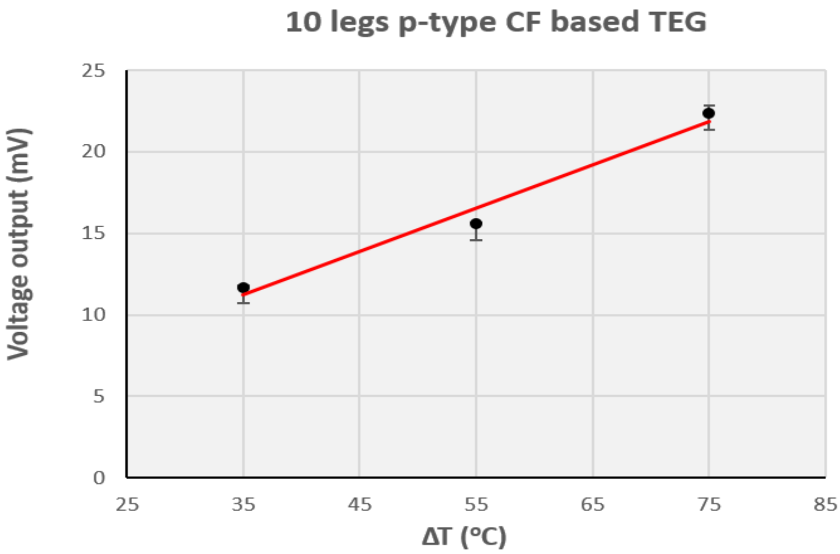

Figure 3. TEG voltage output of arctictured CF TEGs.

3. Conclusions

Composite materials are exposed in several cases to environments where there exists a temperature difference e.g. composite parts of airplanes, automotive, etc. Thus, their potential to function as thermoelectric materials is a very intriguing field of research. Thermoelectric materials are emerging candidates for thermal energy harvesting (such as waste heat) due to their ability to generate voltage upon exposure to a temperature gradient. An alternative route to enhance the thermoelectric response for structural large scale advanced composites was suggested via the expoitation of the intrinsic capability of CFs to act as TEG. It was shown, that via controlled architecture, the proposed CF based TEG was evaluated for its thermoelectric performance. The output voltage of the fabricated device was 22.4 mV when applied to 75ºC temperature difference. This novel approach with embedded thermoelectric modules opens up many opportunities in applications such as autonomous power generation powering low energy portable electronics and distributed sensors for various functions.

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