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Charging Behavior of Chopped Carbon Fibers under High Intensity Electric Fields

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Abstract : In this study, we examined the charging behavior of chopped carbon fibers during electroflocking process, which is one of the key processes of the novel technique for fabricating conductive polymer composite films. Short carbon fibers (CF) during electroflocking were electrically charged by the combined effect of contact charging, corona charging and tribocharging. The specific charge built on CF surface was measured by using Faraday cup method. Specific charge increased not only with increasing electric field strength and potential impressed to mesh electrode as expected from theoretical considerations in literature, but with decreasing mesh opening size due to the improved contact charging condition. However, CF length was found unexpectedly to influence the amount of CF specific charge due to the agglomerated nature of CF flocks leading to the change in charging conditions.

Introduction

Recently so-called Electron Ion Technology (EIT),[1] which is based on charging, transport and deposition processes of materials under high intensity electric fields, has been finding increasing uses in the field of polymer composite technology.[2-5] Especially the fabrication of fiber-reinforced polymer films based on chopped fibers and powdered polymer is now being considered one of promising EIT applications. For example, it has been demonstrated to produce carbon fiber reinforced polymer (CFRP) films with high mechanical and electromagnetic interference (EMI) shielding properties using a novel method based on EIT.[6,7] Conductive CFRP films have attracted great attention in many applications such as EMI shielding materials of both interior and exterior wall of modern intelligent buildings, EMI shielding housing for notebook computers as well as self-regulated low temperature heaters.[8,9] The main advantage of EIT to produce conductive CFRP films is that fiber breakage during processing can be minimized or even eliminated due to the absence of severe fiber length reduction often encountered in extrusion-based processes. Moreover fiber alignment caused by rolling action may introduce beneficial anisotropy in mechanical properties. In this method combining electroflocking with polymer powder technology and thermoforming technique, the forming of CF layer normally aligned to adhesive polymer layer by electroflocking under the influence of high electric field is known to be one of the most important processes which determine the electrical and mechanical properties of the resulting films. In other words, the specific charge built on CF during electroflocking is the single most important parameter governing the movement and orientation of fibers through the interaction between CF and electric field. Though charging of

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dielectric fibers in electroflocking process was investigated,[10] to authors knowledge there has been no study on the charging behavior of conductive fibers like CF in spite of its scientific and practical importance in the fabrication of multifunctional composite films.

This paper presents the features of CF charging in electroflocking process, which is an important part of the EIT, enabling the fabrication of conductive CFRP films with EMI shielding properties.

Experimental

Materials and Procedure. CF of diameter of 8 μm (Grade TZ-307, Tae-Kwang Co., Korea) was used as a feedstock to a fiber feeding system. CF tow consisting of 3000 monofilaments was cut to CF flocks of length ranging from 1 to 5 mm using a precision fiber cutting machine (Dong Sung Engineering, Korea). An experimental fiber feeding system with three polyamide brush screws that facilitate the separation of CF monofilament from agglomerated chopped CF flocks was constructed and used for CF electroflocking.

Measurement of Specific Charge. Having been placed in a top part called fiber chamber of the fiber feeding system, lump of agglomerated CF flocks was separated to smaller ones and fed to a mesh electrode by the action of rotation of the screw brushes. Then, CF flocks were passing through the mesh electrode with the aid of mechanical vibration. The specific charge of CF was estimated using a Faraday cup method where Faraday cup was covered with grounded mesh electrode that permitted the passing of charged CF flocks smaller than mesh opening. The charge of Faraday cup containing charged CF flocks was measured using an electrometer (Keithley Model 6512, USA) with high input resistance. The electric circuit of fiber electroflocking and the scheme for charge measurement are shown in Figure 1. The direct current (DC) power source with output voltage up to 40 kV was used for this study. One of two types of electric circuit was employed in the experiment : one is with a top mesh grounded and the other with a top mesh to which a potential was impressed via the resistor R. All charge measurements have been carried out at relative humidity of 23 ± 5% and temperature of about 20 °C.

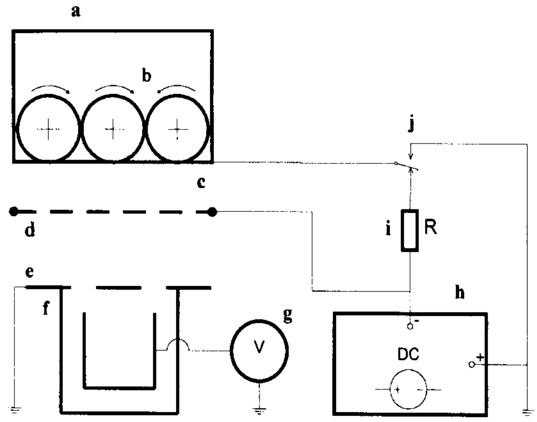

Figure 1. Electric circuit of CF electroflocking and charge measurement process (a: fiber chamber, b: brush rollers, c: ancillary mesh electrode, d: main mesh electrode, e: grounded mesh electrode, f: Faraday cup, g: electrometer, h: DC power source, i: resistor, j: divider).

Results and Discussion

Generally charging of fibers or powder is produced by the combination of several processes : i) contact charging, ii) charging in corona discharge, iii) static electrification (or tribocharging) and iv) electric polarization in electric field.[1,10,11] Among these only the first three processes are responsible for the excess charge of conductive fibers or particles.

In the case of electroflocking of fiber, the contact charging of fibers is the process of charge transfer from mesh electrode connected with DC power source to uncharged fibers contacted with it. As a result the fibers will acquire some charge. According to theoretical consideration of fiber contact charging the charge value of fibers should increase in proportion to the strength of electric field.[10] The charging in corona discharge is by means of a transport followed by an injection of charge carriers (electrons and ions) onto fiber surface in the electric field of corona discharge occurring near mesh electrodes and is known to exhibit linear dependence on electric field strength.[1,11] Static electrification or tribocharging of fibers depends on many parameters including physicochemical nature and dimension of fibers, type of mesh material, design and speed of brush screws. It is known that the dependence of fiber tribocharging on outside electric field strength is linear: it may increase or decrease according to the nature of fibers and counter materials.[12,13] Therefore, excess charge that fibers acquire during electroflocking is expected, in principle, to linearly increase with the imposed electric field strength. Experimental results obtained for dielectric fibers basically agree with these theoretical considerations.[10]

Experimental dependences of specific charge of CF on electric field strength for conductive CF are shown in Figure 2~4. The analysis of these results leads to the following conclusions. First, specific charge of CF increased with electric field strength in all cases and the dependence can be either linear or parabolic. Probably nonlinear dependence of specific charge on electric field strength is due to combined effect of the change of contact charging conditions and discharge effects. Second, specific charge value depends on both mesh size (Figure 2) and the potential of charging electrode (Figure 3, 4). The decrease of mesh size (and wire diameter) mainly leads to the increase of CF specific charge as shown in Figure 2. This is due to the improvement of contact charging conditions resulting from the increase of both total contact area and the contact duration of fibers as opening size of mesh electrodes decreases. Figure 3 shows that, under given electric field strength, specific charge of CF accumulated for shorter distance between electrodes is larger than that for

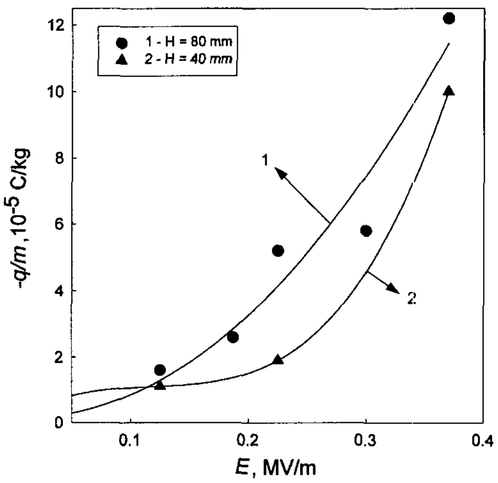

Figure 3. Dependence of specific charge, q/m, of CF with length of 3 mm on electric field strength, E at the distance between electrodes 80 mm (curve 1) and 40 mm (curve 2).

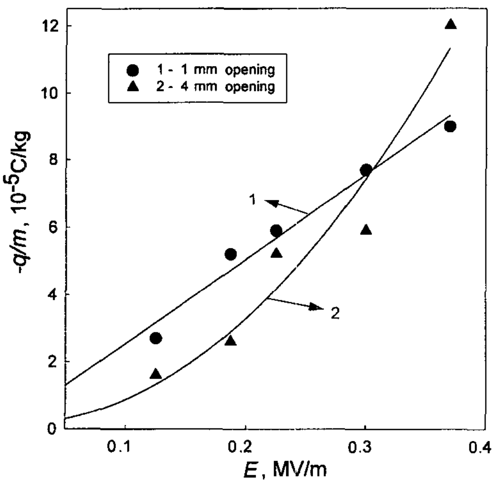

Figure 2. Dependence of specific charge, q/m, of CF with length of 3 mm on electric field strength, E, for mesh electrodes with mesh size 1 mm (curve 1) and 4 mm (curve 2) at constant distance between electrodes of 80 mm.

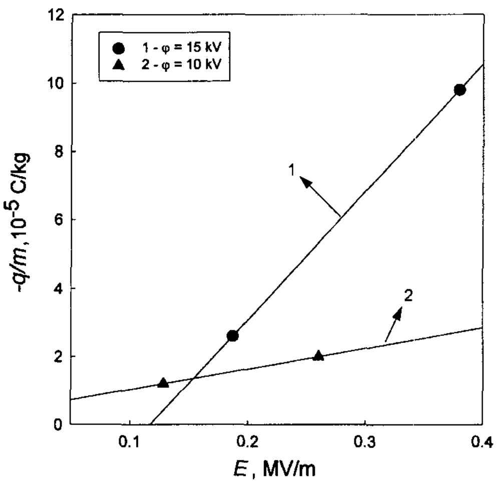

Figure 4. Dependence of specific electric charge, q/m, of CF with length of 3 mm on electric field strength, E, at the electric potential impressed on charging mesh electrode ϕ = -15 kV (curve 1) and ϕ = -10 kV (curve 2).

longer distance.

Because electric field strength is the ratio of electric potential impressed to main mesh electrode to the distance between two electrodes, impression of higher potential in case of longer distance would be necessary to yield the same electric field strength. Figure 4 also shows that the value of specific charge of CF with higher electric potential is lager than that with lower impressed electric potential. The corona charging effect due to the non-uniform electric field near mesh electrode at high electric potential can be attributed to large value of CF specific charge even for the same electric field strength. These data are also in agreement with theoretical considerations.

It is interesting to compare the specific charge of bundles of dielectric fibers (polyamide) found in literature and that of conductive CF in this study obtained during electroflocking at the similar conditions (fiber length of about 3 mm, flock diameter of 0.05 mm ; electric field strength of 0.37 MV/m, and charging electrode potential of 30 kV). The average initial charge value of CF corresponding to specific charge of 90 μC/kg is about $q_i \approx 1 \times 10^{-12}\ C$, whereas for polyamide fibers it is $q_i \approx (1{\sim}3) \times 10^{-13}\ C$.[10] From this it is obvious that conductive fibers like CF achieve higher charge level than dielectric polyamide fibers by contact charging in electroflocking process.

It is noted that sometimes at low values of electric field strength and the electric potential impressed on mesh electrode the specific charge of CF accumulated in Faraday cup exhibits positive polarity, despite negative contact charging condition was employed. Especially, significant positive charging of CF was observed for the case of electroflocking circuit with additionally impressed potential on top mesh of fiber feeder by using a divider (see Figure 1). The dependence of specific charge of CF on electric field strength obtained at this circuit is shown in Figure 5. The comparison of Figure 5 with Figure 2 (curve 1) obtained at the same mesh size (mesh opening size of 1 mm) reveals that the latter circuit provides higher values of specific charge of CF. In case without imposed outside electric field (potential is zero) deposited CF have positive charge

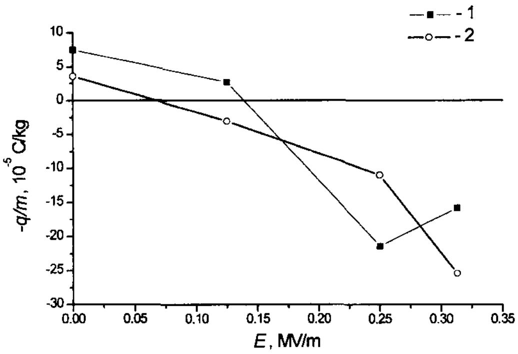

Figure 5. Dependence of CF specific charge, q/m, on electric field strength, E, for electrodeposited fibers with CF length of 5 mm (curve 1) and 2 mm (curve 2) at mesh opening size of 1 mm.

due to tribocharging effect through frictional contacts of CF with polyamide brush screws and metal meshes. More tribocharging effect can be expected for longer fibers because at the same conditions the feeder productivity would be less for longer fibers and the contact time for friction increases in this case. For CF electroflocking at low values of electric field strength, the contact and negative charging by corona discharging would not be able to compensate for positive tribocharging, hence resulting in specific charge of CF with positive polarity (Figure 5, curve 1). For shorter CF, the extent of this tribocharging effect on fiber specific charge would be less. In real electroflocking processes, however, the electric field strength over 0.2 - 0.3 MV/m is employed so that fiber tribocharging effect can be neglected.

Early investigations[10] carried out for dielectric fibers have shown that the charge of fibers linearly increases in the range of fiber length from 1 to 20 mm and that the extent of dependence of fiber charge on fiber length increases with electric field strength. From the following expression relating fiber specific charge and charge of each fiber

$$\frac{q}{m} = \sum_i \frac{q_i}{m_i} = \frac{4}{\pi d^2 \gamma_f} \sum_i \frac{q_i}{l_i}$$

(d and γ_f are the diameter and the density of fibers, respectively), it is evident that specific charge of fibers is not dependent on fiber length. Experimental data obtained for dielectric fibers was also in good agreement with this.[10]

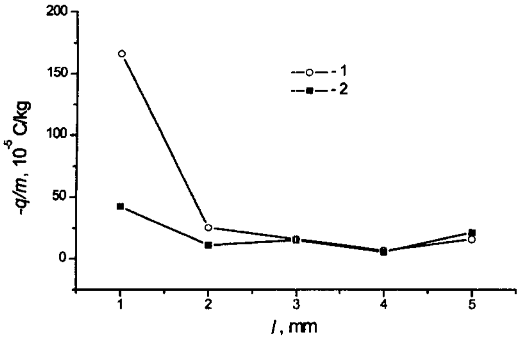

Figure 6. Dependence of CF specific charge, *q/m*, on CF length, *l*, under electric field strength of 0.313 MV/m (curve 1) and 0.25 MV/m (curve 2) for CF length ranging from 1 to 5 mm.

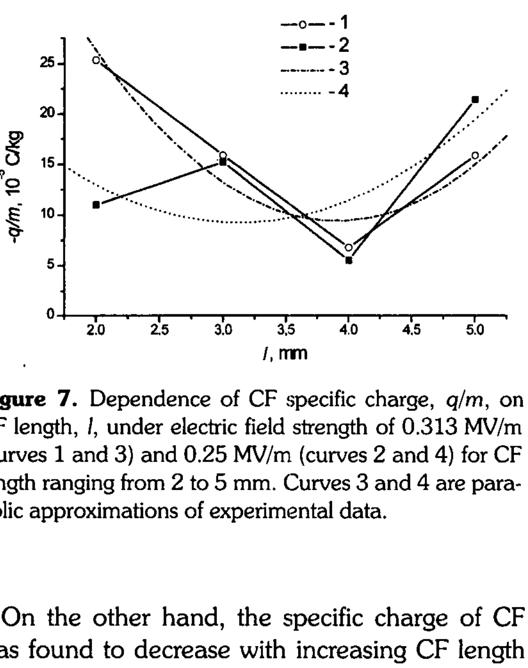

Figure 7. Dependence of CF specific charge, *q/m*, on CF length, *l*, under electric field strength of 0.313 MV/m (curves 1 and 3) and 0.25 MV/m (curves 2 and 4) for CF length ranging from 2 to 5 mm. Curves 3 and 4 are parabolic approximations of experimental data.

On the other hand, the specific charge of CF was found to decrease with increasing CF length from 1 to 5 mm as shown in Figure 5 and 6. The decrease is most conspicuous in CF length region from 1 up to 3 mm. It appears from Figure 6 that the increase of electric field strength amplifies the dependence of CF specific charge on CF length with more noted effect for shorter CF. More detailed analysis of the dependence of specific charge on CF length over 2 mm reveals that the dependence has a parabolic character with minimum specific charge at the CF length of 4 mm (Figure 7). Experimental data seem well fitted to the second order parabolic equation (Figure 7, curves 3 and 4). According to the extrapolated values from parabolic equations, the increase of CF length from 3 to 10 mm would lead to 19.2 times increase of specific charge. In particular, specific charge of CF increases from 9.42×10^{-5} up to 181.68×10^{-5} C/kg for electric field strength of 0.313 MV/m as CF length increases from 4 to 10 mm. This complex experimental dependence of specific charge on CF length is thought to be due to the agglomerated nature of CF flocks resulting from incomplete fiber separation in a fiber feeder. Also this can be attributed to the tribocharging effects exhibiting CF length de-pendence.

Summary

The charging behavior of discontinuous CF during electroflocking process under high intensity electric fields was experimentally studied. Specific charge of CF during electroflocking was found to depend on various experimental parameters including electric field strength, charging electrode potential, mesh opening size of charging electrode and CF length. The specific charge of CF increased with increasing field strength and electrode potential as expected from theoretical consideration but decreased with increasing mesh openings size probably due to the change of contact charging condition. Specific charge of CF exhibited unexpected dependence on CF length: it decreased with increasing CF length up to 3 mm and increased for CF length of more than 4 mm. This complex dependence of CF specific charge on CF length can possibly be associated with the agglomerated nature of CF flocks and the tribocharging effect.

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