Effect of acid attack on thermal degradation and complex electromagnetic parameters of CF/Ni veil used in wind turbine rotor blades

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Abstract: Increase in energy global demand and environmental awareness push boundaries for the use of renewable resources. Wind turbine rotor blades, while in rotation, present large radar cross section, interfering in radar signals and depreciating the quality of navigation and communication in airspace. Aiming to eliminate such impacts, wind turbine rotor blades are developed using radar absorbing structures (RAS). Beyond structural properties, RAS may convert electromagnetic energy into heat, reducing spurious radiation and associated interference. In this work, carbon fiber nonwoven veil metallized with nickel (CF/Ni), possible precursor material used in RAS applied in wind turbine rotor blades, was submitted to acid attacks aiming reducing its reflector behavior in the X-band region of microwaves. Effects of acid attack on thermal degradation and electromagnetic properties of the CF/Ni veil were evaluated. Thermogravimetric analyses (TGA) in dynamic mode were performed in oxidative (air) and nitrogen atmospheres. Complex permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$) and permeability ($\mu_r = \mu' - j\mu''$) of CF/Ni veil were measured by means of a vector network analyzer in X-band (8.2 to 12.4 GHz). Results show that thermal degradation profiles of the veil are maintained after acid attack, with equal number of major degradative events. However, changes in DTG peaks are observed in both atmospheres, associated with different weight loss rates. Already, the acid attack caused minor changes in electromagnetic behavior of CF/Ni veil, with a slight reduction of reflector behavior. High values of permittivity and close to unity average permeability ($\mu < 1$) confirm the dielectric behavior of veil with reduced interaction with the magnetic field of microwaves (X-band). Electromagnetic results indicate necessity of aerial weight (g/m^2) reduction and/or application of frequency selective surface (FSS) technique on the CF/Ni veil, enabling application of the studied material as absorbing layer in wind turbine rotor blade manufacturing.

Keywords: Thermal degradation, CF/Ni nonwoven, Permittivity, Permeability, Wind turbine rotor blades.

Introduction

Global increase in energy consumption, growing concern with sustainability and awareness of environmental preservation direct efforts for application of renewable energies and use of eco-friendly resources [1]. Wind energy goes towards the aspects presented above, with reduced impact on the environment compared with fossil fuel based energy [2]. According to the report from Global Wind Energy Council, 2014, wind power generation increased 50 GW in a single year, yet another record-breaking were experienced in 2015, reaching 63 GW annual installations, a 22% global increase and with China leading with 30.8 GW of new installed capacity. Also, according to the same report, in the end of 2014 the global wind power generation capacity was 433 GW. Nowadays, the wind electric power generation approaches 500 GW on global installed capacity [3].

While working the rotation of wind turbines rotor blades (WTRB) impacts aeronautical radars, distorting positioning and navigation in airspace, mainly due to the large radar cross section (RCS) of wind turbines and the Doppler shift effects on the radar signals [1]. In this sense, Richardson [4] estimates that while the development of WTRB with low radar signature and radar interference technologies may appear somewhat tangent to the power generation industry, about 20 GW of wind power is not installed due to interference in radar signals.

WTRB are key structural parts in wind power generation and considering their cited impact on radar signals, as described above, their manufacture need to be equipped with radar absorbing materials (RAM). The intrinsic combination between RAM and structural materials is properly addressed as radar absorbing structures (RAS), each time more employed in WTRB of great dimensions [5].

Such class of structures (RAS) converts the radar microwave energy impinged on the WTRB into heat, via Joule effect, depreciating the reflected electromagnetic energy after incidence on the rotor blade surface. Thus, decreasing spurious radiation and minimizing the interference in radar signals [6].

In this work, carbon fiber nonwoven metallized with nickel (CF/Ni) (named in this text as CF/Ni veil), precursor material employed in WTRB, was submitted to nitric acid attack aiming to decrease the reflector characteristic of the studied sample. The effects of such treatment on thermal behavior and on the electromagnetic properties were investigated. Thermogravimetric analyzes (TGA) were performed in dynamic mode, in oxidative (air) and nitrogen atmospheres. Complex electromagnetic parameters, intrinsic permittivity (ε' and ε") and permeability (μ' and μ") were characterized in the frequency range between 8.2 and 12.4 GHz (X-band). This frequency range is widely used in aeronautical sector for navigation and communication [7].

Materials and Methods

CF/Ni veil

The carbon fiber veil metalized with nickel is produced by Advanced Fiber Nonwovens (AFN®), a group of Hollingsworth & Vose Company (HV®). Polyester is used as binder to keep the carbon fibers in random position. This veil is characterized by 25.4 g/m^2, 0.18 mm thickness and surface resistivity equals to 0.25 DC Ω/square.

Acid treatments were performed on the CF/Ni veil surface, intended to decrease or withdraw nickel content, aiming the reduction of reflection and increase of absorption of microwaves. In this sense, 7.0 cm x 7.0 cm samples of CF/Ni veil were separately immersed in HNO_3 5 mol/L solution during 2 different times, 45 and 120 min. Moderate manual agitation were applied every 5 min of acid attack. In the sequence, the veil samples were washed in deionized water with careful agitation and dried during 270 min in an oven at 60 °C.

Electromagnetic characterization

The electromagnetic characterization of the CF/Ni veil were conducted in a vector network analyzer (VNA) from Agilent Technologies, model PNA-L N5230C, with 4 ports and capability of frequency generation between 300 kHz and 20 GHz. The characterizations were performed using 2 of the 4 ports available and with rectangular waveguide, also from Agilent Technologies. The scattering parameters were determined in the frequency range of 8.2 to 12.4 GHz. Complex permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$) and permeability ($\mu_r = \mu' - j\mu''$) of CF/Ni veil were calculated via Nicolson-Ross algorithm and based on scattering parameters measured for each veil condition, with and without treatment in acid solutions.

Results and Discussions

Fig. 1 presents images obtained in scanning electron microscopy (SEM) analyzes of the CF/Ni veil in the original condition (Fig. 1a) and after acid attack (Fig. 1b).

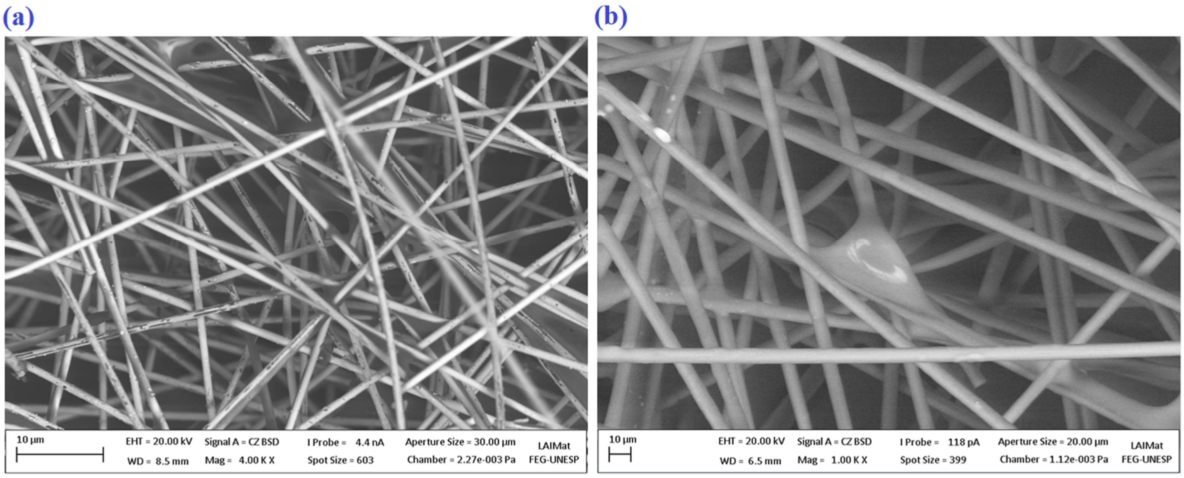

Figure 1: SEM of CF/Ni veil. (a) original sample; (b) after acid attack.

Fig. 2 presents TGA of the CF/Ni veil in original condition (Fig. 2a) and after acid attack in solution 5 mol/L during 45 min (Fig. 2b). Both curves are related with thermal degradation in N_2 atmosphere. Fig. 2a shows that at the temperature of ~72 °C the weight losses are of ~0.1%. As the temperature increases, the TGA shows losses of ~1% until 292 °C. However, the highest rate of weight loss (174.4 μg/min) for the original CF/Ni veil occurs at 403.6 °C, as can be seen in DTG curve (blue). The residual mass after 880 °C is 70.3%, with a total weight loss of 29.6% over the entire temperature range analyzed during the test.

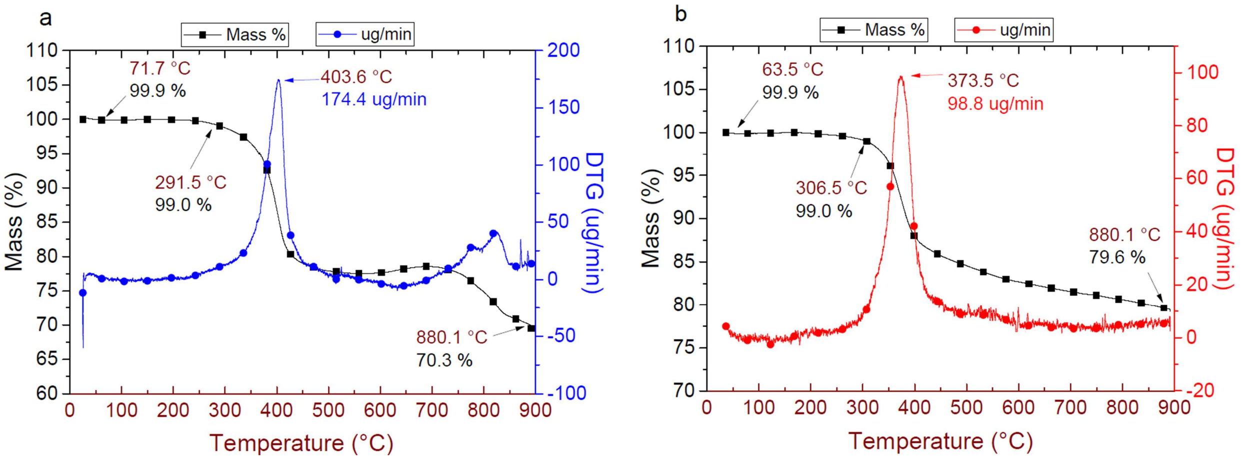

Figure 2: TGA of CF/Ni veil in N_2 atmosphere. (a) original sample; (b) after acid attack.

Fig. 3 presents TGA of the CF/Ni veil in original condition (Fig. 3a) and after acid attack in solution 5 mol/L during 45 min (Fig. 3b). Both curves are related with thermal degradation in oxidative atmosphere. Fig. 3 show that at the temperature of ~40 °C the weight losses are of ~1%. The TGA shows 3 main events of mass losses in both conditions, original and after acid attack samples. However, the highest rate of weight loss (279.1 µg/min) for the CF/Ni veil after acid attack occurs at 699 °C, as can be seen in DTG curve (red). The residual mass is 1.5% for the CF/Ni samples after acid attack at temperatures above ~750 °C. On the other hand, the residual mass for the original CF/Ni veil in oxidative atmosphere is equal to 47.7% at 811.3 °C.

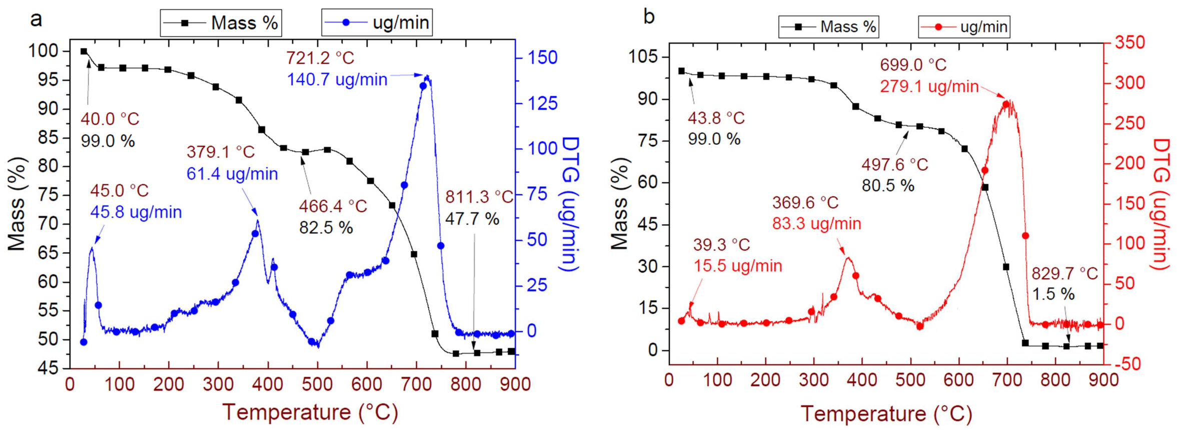

Figure 3: TGA of CF/Ni veil oxidative atmosphere. (a) original sample; (b) after acid attack.

The electromagnetic parameters were measured in a vector network analyzer (VNA) equipped with a rectangular wave guide, in the X-band. From the scattering parameters (Par_S) were calculated the complex parameters of permittivity and permeability through Nicolson-Ross method [8]. The real and imaginary parts of intrinsic electromagnetic parameters, relative permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$) and permeability ($\mu_r = \mu' - j\mu''$), of the CF/Ni veil, as received and after acid attack, are presented in Fig. 4. The configuration of CF veil metallized with Ni (Fig. 1a), intrinsically good electrical conductor, bonded with polyester resin, favors the presence of voids along the 0.18 mm thickness. Such configuration contributes for the polarization effect, determining high values of real part of permittivity

(Fig. 4a). Thus, the CF arrangement in the veil confers to this material dielectric behavior, in both conditions. The average real permittivity for the CF/Ni veil decreased from 158.5 to 139.9 due to the acid attack, reducing the reflector behavior for the incident microwaves.

The average values for the permeability, presented in Fig. 4b and Fig. 4d, under the unity ($\mu_r < 1$), indicate diamagnetic behavior, in both conditions (original and after acid attack). In this sense, the material does not present interaction with the magnetic field of the incident microwaves. Based on the results presented, the decreasing of interference of radar signals on the CF/Ni veil can be obtained by the reduction of weight per area or by using frequency selective surface technique on the studied veil [1, 7].

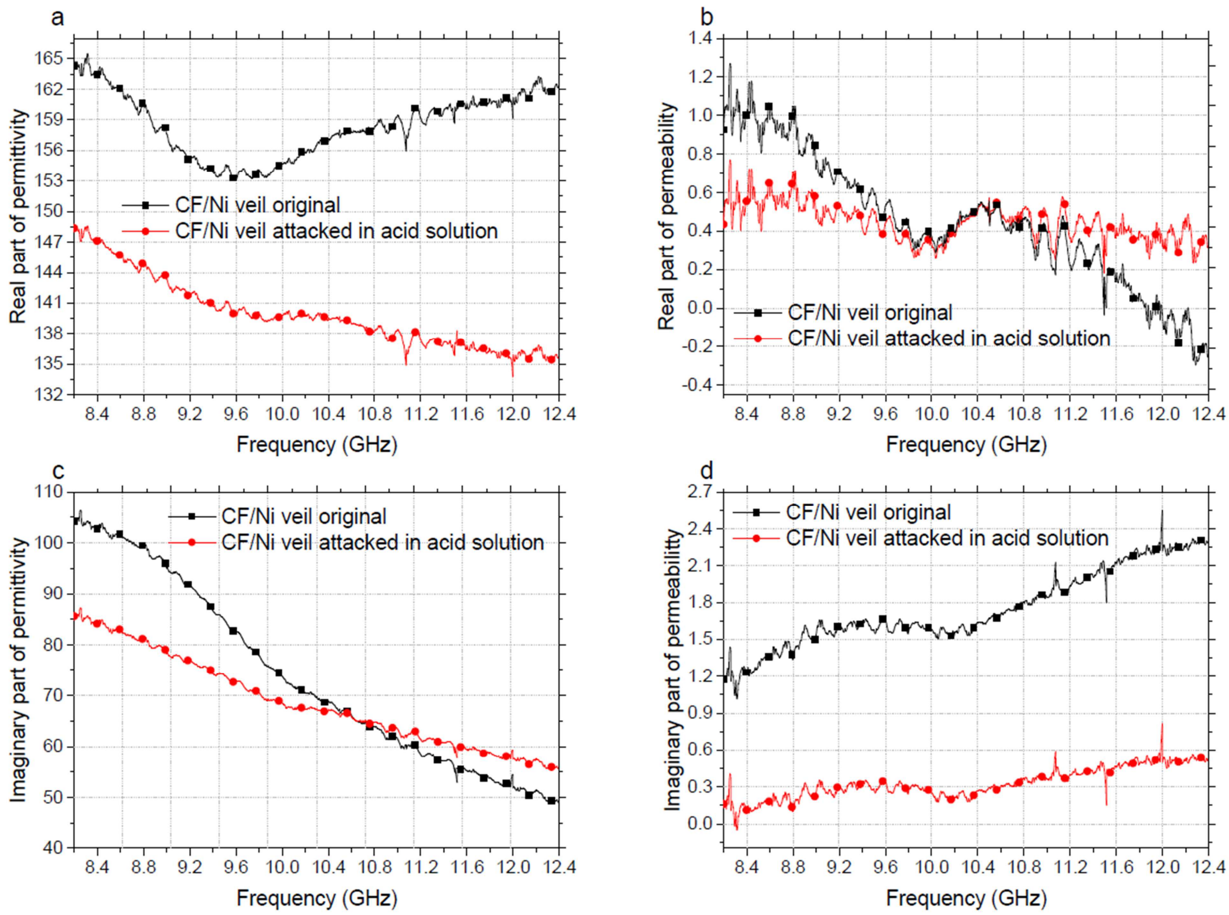

Figure 4: Complex parameters of CF/Ni veil as received and after acid attack. (a) real part of permittivity; (b) real part of permeability; (c) imaginary part of permittivity and (d) imaginary part of permeability.

Conclusions

Thermal degradation behavior and complex electromagnetic parameters of CF/Ni veil, applied as a microwave absorbing layer in the wind turbine rotor blades manufacture, were characterized. From TGA analyzes, in dynamic mode, the acid attacked samples do not show changes in TGA curves, maintaining the number of main degradative events, in both atmospheres: nitrogen (1 main event) and oxidative (3 main events). However, the temperatures and weight loss rates associated with DTG peaks, for the same atmospheres, show changes for the acid attacked samples. Further, the onset degradation temperature and the residual mass change with the acid attack and, as expected, with the different atmospheres. The complex electromagnetic parameters show that the CF/Ni veil behaves as dielectric material, even after acid attack. High values for real part of permittivity (*ε'*) indicate polarization effect, which combined with conductive characteristics of the CF veil increase the reflector behavior for incident microwaves. Also, relative permeability values under de unity ($\mu_r < 1$) characterize a diamagnetic material, with no interaction with magnetic fields of microwaves. From the presented discussion and identified reflector behavior of the studied CF/Ni veil, it is suggested to reduce the weight/area of veil or to use the FSS technique on this sample for increasing its microwave absorbing characteristic.

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Oral presentation