Multifunctional material design for strain sensing: carbon black effect on mechanical and electrical properties of polyamides

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Multifunctional material design for strain sensing: carbon black effect on mechanical and electrical properties of polyamides

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Abstract

This work investigates the coupled effect on the mechanical and electrical properties of carbon black (CB) dispersed in polyamide 6,6 matrix. The amount of CB added to the polymer matrix was varied between c.a. 5 and c.a. 25 wt %. The presented results reveal the capability of conductive carbon nanostructured particles, known as carbon black, to functionalize the thermoplastic polymers by activating conductive percolation networks, as obtained over the percolation threshold. The electrical resistivity of the composite compounds under static and dynamic conditions was determined. In this domain, the variation of the electrical properties with the applied stress, is assessed through mechanical tests with in-situ electrical measurements. The conductivity sensitivity of reinforced composites to the applied strain is analyzed within direct (DC) and alternate current (AC) regime, revealing the effect of frequency on the composite strain sensitivity. An investigation on the morphology of particle dispersion at the microscopic level highlights the role played by microstructural arrangements on the homogenized bulk properties of composites. Mean field homogenization models for the estimation of composite stiffness are compared to the experimental results.

1 Introduction

Polymeric matrix composite (PMC) materials are gaining high interest in the industry and scientific community: their unique properties have paved the way to their usage for numerous applications. However, polymers are insulating, meaning that cannot conduct current. During the last decade, researchers have proved the capability of carbon nanoparticles of modifying the properties of PMC even at the macro-scale. In this regard, great accomplishment can be found in several characteristics, including stiffness enhancement(1–4), strength increase(5), induced plasticity(6), toughening mechanism(7,8), electrical conductivity(9–11), strain sensing (12–23). The evolution of the micro-mechanic alongside with material science knowledge has opened the doors to a boundless portfolio of materials, which properties can be tailored on the design specification by properly defining material constituents and architecture from the nano to the micro scale. The spread of these “smart materials” has not dispensed industrial sectors such as aerospace(24) or automotive(25,26), where functional material can help designers cutting costs, producing lighter structures, and adding new functionalities as structural health monitoring(27–30) (SHM). SHM is an inverse technique aiming at assessing the health state of a structure by processing signals from sensors mounted on the monitored part. The adoption of innovative materials (fiber-reinforced composites, sandwich structures, multi-material laminates), for which the study on fatigue response and damage tolerant design have not been consolidated yet, put the requirement for a reliable, but affordable and lightweight SHM. In accomplishing this, smart self-sensing materials are ideal candidates. Indeed, self-sensing materials shows a change in the electrical conductivity when a stress (or strain) is applied; this phenomenon is usually activated by highly conductive particles (e.g., carbon nanotube, carbon fibers) dispersed into the polymer(31).

The adoption of such materials in SHM allows monitoring large structures without any sensor: every point of the smart material structure is monitorable and the cost increase only relies on the functionalizing particle addition to the neat polymer. The goal of this work is to comprehensively study the effect of Carbon Black (CB) particles loading on the mechanical, electrical and strain sensing properties of polyamide 6 and polyamide 66 (PA6 and PA66, respectively). First, we manufactured CB-PA composites with injection molding as described in Section 2.1. In Section 2.2 particles concentration and morphology are analyzed with Scanned Electron Microscopy (SEM) and Thermogravimetric Analysis (TGA), while the percolation threshold of CB reinforced PA is established; in Section 3.1, the effect of particles concentration on the stiffness and strength of composites is experimentally investigated through tensile tests and correlated with different homogenization models. In Section 3.3, we present the results of tensile tests with in-situ resistance and impedance measurements on conductive and propose a novel model for the estimation of the material Gauge Factor (GF) variation with the applied electric frequency. At the best of authors knowledge, this work is the first revealing the effect of the excitation current frequency on the self-sensing material gauge factor.

2 Materials and methods

2.1 Materials

Composite specimens were manufactured starting from commercial PA6/CB masterbatch (Cabelec CA3178, polyamide 6 with 27,5 wt.% of CB, MFI= 10 g/10 min at 275°C) with addition of PA6 (polyamide 6 TECHNYL C 206, Solvay) or PA66 (polyamide 66 TECHNYL A 205F, Solvay). Polymers and the compound were melt-compounded by using a Babyplast 6/10P micro injection molding machine (Rambaldi srl, Italy) having a type-V tensile test specimen mold (ASTM D638). Prior to use, the polymers and masterbatch were dried at 80°C for 4 h, while barrel, injection, nozzle, and mold temperatures were set at 255, 250, 245, and 60°C for PA6, or 280, 275, 270 and 70°C for PA66 compositions, respectively.

2.2 Experimental tests

2.2.1 TGA

Thermogravimetric measurements were performed with a TA Q500 instrument, TA Instruments, by using c.a. 8-10 mg of sample. The temperature was increased from 50 °C to 700 °C under nitrogen (N_2) gas flow, then to 800 °C in air (heating rate: 10 °C/min in both steps). This method was adopted to determine the polymer and CB contents after compounding.

2.2.2 SEM

Field-emission Scanning Electron Microscopy (FeSEM), Tescan Mira 3 (Tescan, Brno, Czech Republic) was used to assess the particle distribution of the specimens and the corresponding fracture surfaces. An accelerating voltage of 5 kV was used together with a secondary emission signal. The specimen surfaces were not coated with metals since the specimens were electrically conductive and to avoid possible contaminations.

2.2.3 DC electrical properties

DC electrical properties were obtained under static conditions by using a conventional two-point probe technique with the specimen connected with a Keithley 2420 source meter. Compounds were cut to obtain smaller specimens c.a. 20 × 14 × 2 mm in size. Both faces of specimens were polished to eliminate the outermost surface and Ag conductive paste was used to make round shaped electrodes with an average diameter of 2mm. Electrical resistivity (ρ) was obtained by using the equation: $\rho = R \times (A/d)$, where R is the measured resistance, A is the sample cross-section, and d is the distance between electrodes. Hence, obtained values were referred to as volume resistivity. Measurements were obtained by placing the specimens in a homemade sample holder consisting of a fixed side and a spring-loaded electrode.

2.2.4 Tensile test with in-situ conductivity measure

The tensile tests have been conducted with the universal test machine Zwick/Roell Z5.0 with a maximum load of 5kN in the displacement control mode with a crosshead rate of 5 mm/min. The strain is then computed as the ratio of the crosshead displacement over the initial grip distance.

To measure the in-situ electrical response, the Hioki 3538 impedance meter is connected to the silver epoxy electrodes on the specimen's surface through a 4-point probe connector. Four-terminal sensing is an electrical impedance measuring technique using separate pairs of current and voltage sensing electrodes, eliminating the contact resistance from the measurements. The electrical frequency response in the range of 0-10 kHz is measured at each displacement increment of 50 μm, while keeping the crosshead position fixed. The dynamic range is sampled within evenly logarithmic spaced frequency intervals. Due to the visco-elasto-plastic nature of the polymer, a stress relaxation can be observed while the strain is fixed, resulting in a decrease of the measured force during the measurement window. The effect has been attenuated by applying a low displacement rate of 5mm/min.

2.3 Homogenization models

2.3.1 Voigt model

Due to the heterogeneous nature of the composites under study, the effect of CB loading in the polyamide matrix can be analyzed by mean-field homogenization theories. Under the assumptions of constant strain in the Representative Volume Element (RVE), negligible interaction between inclusions and homogeneously dispersed particles - the Voigt model(32) can estimate the composite elastic modulus E_c from the volume fraction of particles:

$$E_c = Em \cdot v_m + E_p \cdot v_p$$

Where E_m and E_p are the Young's Modulus of the matrix and the particles respectively, and v_m and v_p the volume fractions. Since the particle content has only been measured as weight percentage, the volume fraction is computed by means of the density ratio between matrix and inclusions. The density of PA6, PA66 and Carbon Black(4) are assumed to be 1.1, 1.1 and 1.8 g/cm^3, respectively.

2.3.2 Strain gradient elasticity theories

The classical estimates (bounds) of the Hashin-Shtrikman type for materials with an isotropic distribution of the phases(33) read:

$$\underline{\mu} = \mu^{(1)} + \frac{c_2(\mu^{(2)}-\mu^{(1)})}{1+c_1\frac{\mu^{(2)}-\mu^{(1)}}{\mu^*+\mu^{(1)}}} \quad \text{and} \quad \underline{k} = k^{(1)} + \frac{c_2(k^{(2)}-k^{(1)})}{1+c_1\frac{k^{(2)}-k^{(1)}}{k^*+k^{(1)}}} \qquad (3)$$

with μ^* and k^* the shear and bulk moduli of the Hill constraint tensor:

$$\mu^* = \frac{\mu^0(9k^0+\mu^0)}{6(k^0+2\mu^0)} \quad \text{and} \quad k^* = \frac{4}{3}\mu^0 \tag{4}$$

The choice $\mu^0 = \mu^{(1)}$ *and* $k^0 = k^{(1)}$ corresponds to the lower Hashin-Shtrikman bound which coincides with the Mori Tanaka (MT) model (34) while the choice $\mu^0 = \mu^*$ and $k^0 = k^*$ defines the self-consistent (SC) estimate (35).

Homogenization methods utilizing classical elasticity-based Eshelby tensors cannot capture the particle size effect experimentally observed in particle–matrix composites at the micron and nanometer scales. A simplified strain gradient elasticity theory (SSGET) for spherical inclusion has been proposed by Gao and Ma(36), that introduced one material length scale parameter instead of two classical elastic constants.

Equation 4 is rearranged as follows:

$$\underline{k} = k^{(1)} + k^{(1)}\frac{c_2(k^{(2)}-k^{(1)})}{k^{(1)}+c_1(k^{(2)}-k^{(1)})S_p} \quad \text{and} \quad \underline{\mu} = \mu^{(1)} + \mu^{(1)}\frac{c_2(\mu^{(2)}-\mu^{(1)})}{k^{(1)}+c_1(k^{(2)}-\mu^{(1)})S_s} \tag{5}$$

where S_p ad S_s are the Eshelby tensor components:

$$S_p = \frac{\nu+1}{3(1-\nu)}\left\{1 + \frac{3}{2}\left(\frac{L^{(0)}}{R}\right)^3\left[1 - \left(\frac{R}{L^{(0)}}\right)^2 - \left(1 + \frac{R}{L^{(0)}}\right)^2 e^{-\frac{2R}{L^{(0)}}}\right]\right\} \tag{6}$$

$$S_s = \frac{8-10\nu}{15(1-\nu)}\left\{1+\frac{3}{2}\left(\frac{L^{(0)}}{R}\right)^3\left[1-\left(\frac{R}{L^{(0)}}\right)^2-\left(1+\frac{R}{L^{(0)}}\right)^2 e^{-\frac{2R}{L^{(0)}}}\right]\right\} \quad (7)$$

$L^{(0)}$ and R are the material length scale parameter and the inclusion radius, respectively.

3 Results and discussion

3.1 Particle dispersion and morphology analysis

3.1.1 TGA

TGA plots of PA6-based compounds are shown in Figure 1. Due to the thermogram similarities, they are to be considered as representative of both, PA6 and PA66 compositions.

From the weight loss of the TGA curves, the percentage of polymer inside each composite in the same temperature range (c.a. 320-700°C) can be evaluated and by difference, the percentage of filler (37). The real compositions of the compounds are summarized in Table 1. Besides PA66_25, which contains 22.6 wt.% of CB, from the other compositions it can be concluded that they are close to the predicted compositions.

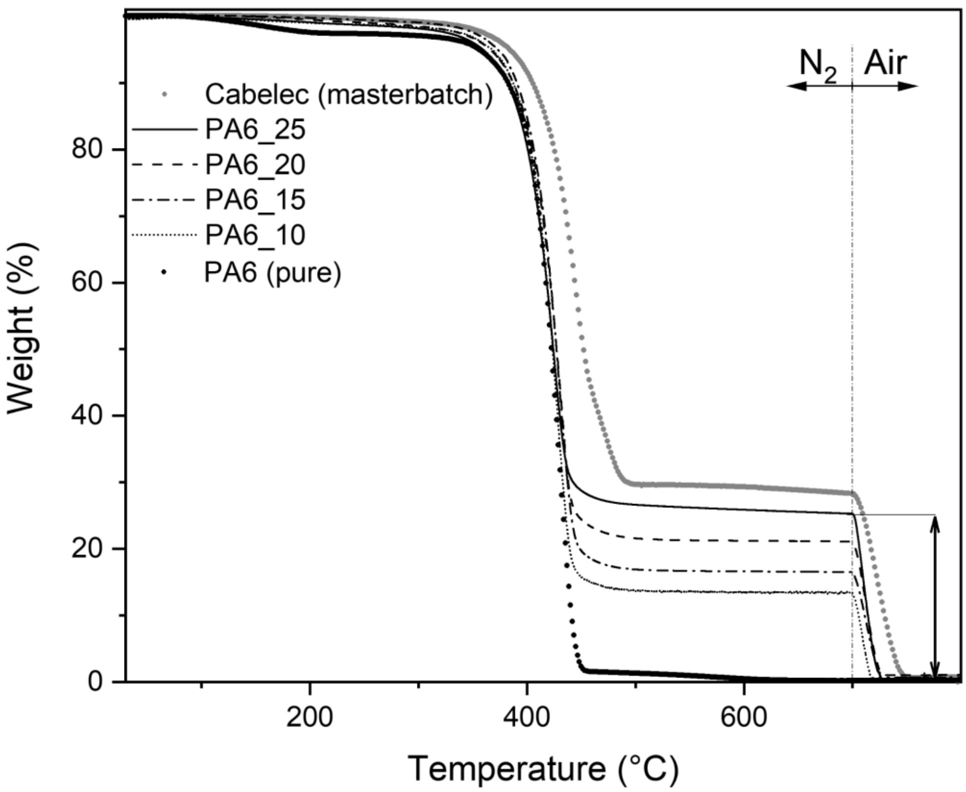


Figure 1 - TGA plots of the PA6-based compounds (gray circles: Cabelec; black solid line: PA6_25, black dashed line: PA6_20; black dotted dashed line: PA6_15; black dotted line: PA6_10, black circles: PA6, respectively) obtained under N2 (up to 700 °C) and air flow (from 700 °C up to 800 °C).

In the following sections, authors will refer to different composites by the following nomenclature: PL_wt. Where *PL* indicates the neat polymer (PA6 or PA66) and *wt* the weight percentage of carbon black (e.g., PA6_10 and PA66_10 refer to polyamide 6 and polyamide 66 loaded with CB 10 wt.%, respectively).

Table 1 - Composition of samples as obtained from TGA measurements

Label	CB (wt.%) [1]	Polymer (wt%)
Cabelec	27,5	72,5
PA6_10	12,1	87,9
PA66_10	9,7	90,5
PA6_15	15,5	84,6
PA66_15	13,7	86,3

PA6_20	19,5	80,5
PA66_20	20,0	80,0
PA6_25	23,6	76,4
PA66_25	22,6	78,4

[1] As obtained from weight loss between 800°C (air flow) and 700°C (N_2 gas flow).

3.1.2 SEM

The particle distribution was assessed for both PA6 and PA66 with the three different particle concentrations (c.a. 15%, 20% and 25% wt.). All the samples reported a uniform particle distribution. SEM images of PA6 with 25% wt. of CB are reported in Figure 2 at different magnifications: 40kX (Figure 2a), 80kX (Figure 2b) and 120kX (Figure 2c). Figures 2a, 2b and 2c are representative of the particle distribution of the whole specimen. At least 5 different zones of the specimen were analysed that reported the same distribution of the particles. Figure 2a and 2b are at lower magnification and show that the particle distribution is homogeneous and there are no areas with a lower presence of particles or agglomerates. Figure 2c shows the 120 kX magnification that highlights the particle shape and size of the carbon black particles. Figure 2c displays the presence of both spherical and elliptical shapes that are typical of CB particles. A digital image correlation software, Tescan Mira Software (Tescan, Brno, Czech Republic), has been used to study the sizes of the particles. 30 different particles were measured to assess the sizes of the elliptical and spherical shapes. The elliptical particles present an average major axis of 113 nm (±18 nm) while the minor axis is 74 nm (±15 nm). The average area of the elliptical particles is 6600 nm^2. On the other hand, the spherical particles present an average diameter of 83 nm (±16 nm) and an average area of 5400 nm^2.

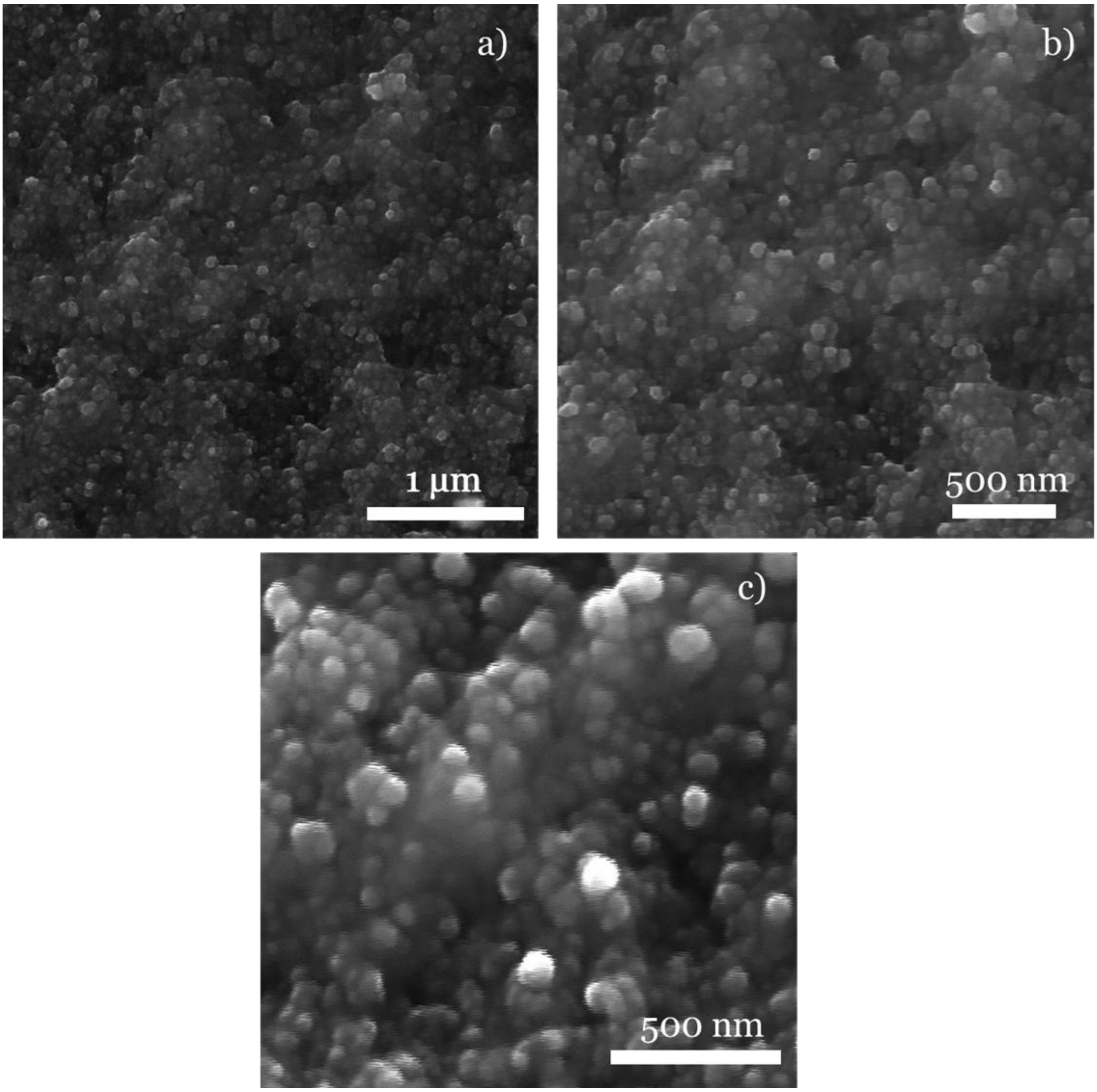


Figure 2 - SEM images of the sample PA6_25% wt. at 40 kX magnification (a), 80 kX magnification (b) and 120 kX magnification (c)Figure 3 presents SEM images of PA6_15% (3a and 3b), PA6_20% (3c and 3d) and PA6_25% (3e and 3f) at two different magnifications, 50 kX (3a, 3c and 3e) and 100 kX (3b, 3d and 3f).

The SEM images are representative of the two different materials adopted PA6 and PA66 and of the three different adopted concentrations. The lower magnifications, 3a, 3c and 3e of Figure 3 show that the particle distribution is homogeneous. The higher magnifications show that the particles are very close and there are no areas with a lower presence of particles because all the analysed compounds are higher than the percolation point. This verification was the aim of this analysis.

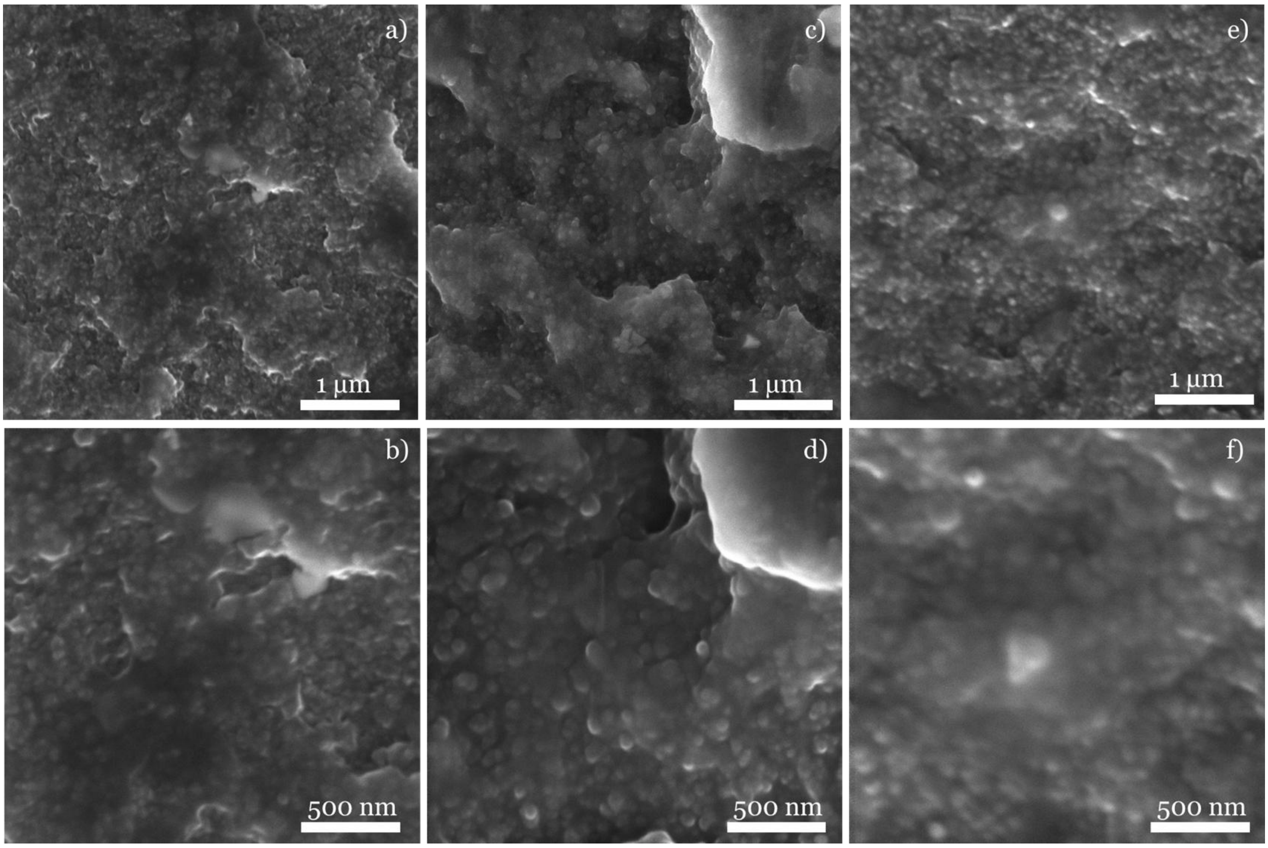


Figure 3 - SEM images at two different magnifications 50 kX (2a, 2c and 2e) and 100 kX 2b, 2d and 2f) of the samples PA6_15% (1a and 1b), PA6_20% and PA6_25%.

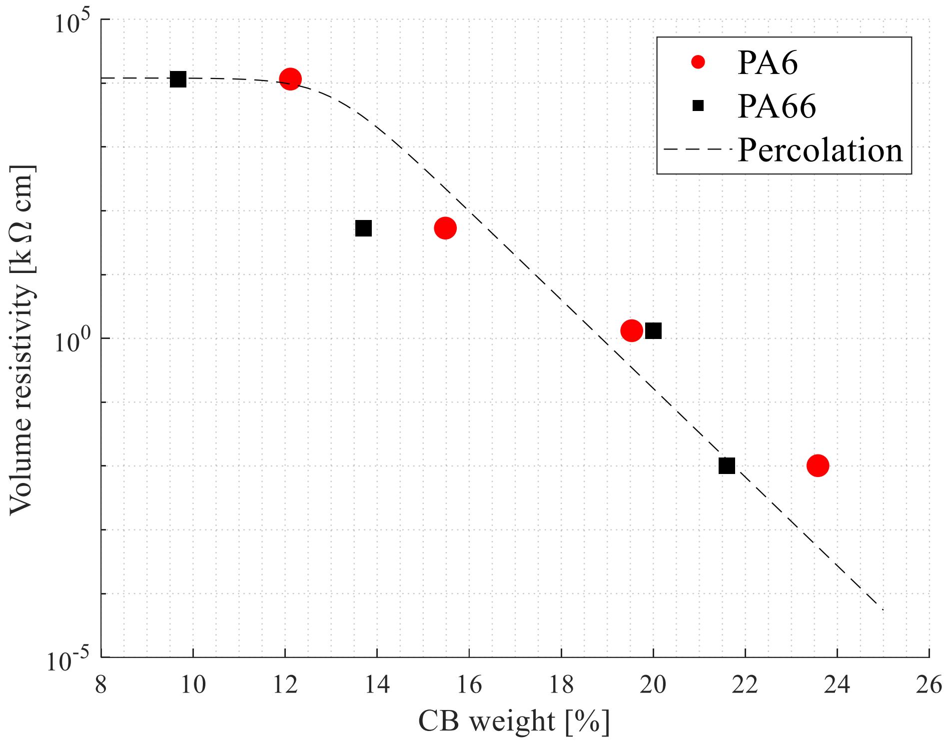
3.2 Percolation threshold

DC electrical resistivity of the CB-filled PA6 and PA66 composites (10-28 wt.%), measured at room temperature are shown in **Errore. L'origine riferimento non è stata trovata.**. In this figure, electrical resistivity increases with the decreasing CB loading. Notwithstanding the different injection process temperatures, the two types of polymer composites exhibit a similar electrical behavior. Both Pa6 and PA66 based composites exhibits a resistivity increase by 7 orders of magnitude from 3,9 to $1,2\times10^5$ and 5,2×105 $k\Omega\ cm$, respectively.

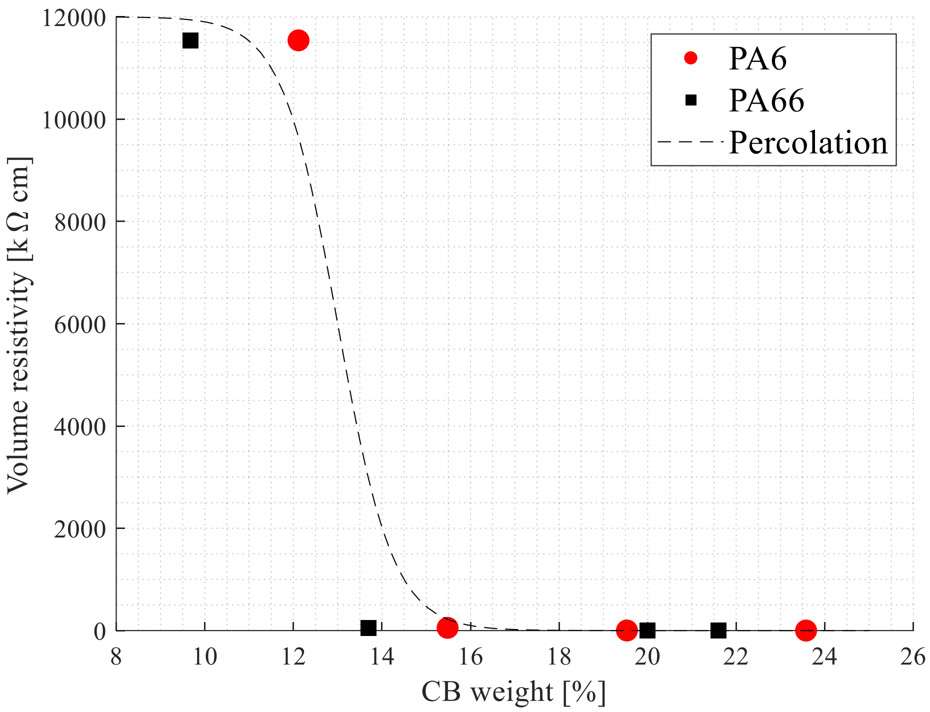
The percolation threshold, defined as the particle concentration above which the composite goes from being a perfect insulator to a conductive, can be described by a sigmoid function in the form:

$$R = R^0 \cdot \frac{1}{1+e^{a(x-\bar{x})}} \qquad \text{(xx)}$$

Being R^0 the resistance of the insulating composite, a the coefficient describing the resistance variation with the filler loading and $\bar{x}$ the percolation threshold. Figure 4 shows the results of volumetric resistance measurements.



10^5
10^0
10^{-5}
8
10
12
14
16
18
20
22
24
26
CB weight [%]
Volume resistivity [k Ω cm]
PA6
PA66
Percolation



12000
10000
8000
6000
4000
2000
0
8
10
12
14
16
18
20
22
24
26
CB weight [%]
Volume resistivity [k Ω cm]
PA6
PA66
Percolation

Figure 4. Change in volume resistivity of CB reinforced PA6 and PA66

The sigmoid function that best approximates the resistance variation with the particle concentration has a percolation threshold of 13% with an R^0 of 12^5 $k\Omega cm$ and a coefficient α equal to 1.8.

3.3 The effect of carbon black on mechanical properties

Although the main goal of the present study is to analyze the effect of CB particles on the strain sensitivity of conductive PA/CB composites, it is fundamental to assess the composite mechanical response at first. In fact, any modification to the material composition with the goal of functionalization, should not degrade the stiffness and strength of the material itself. On the assumption of material response symmetry in tension and compression, only tensile tests are performed to evaluate the elastic modulus of composites. Experiments have been performed following the ISO D638 standards, adopting the specimen shape of type V with a minimum section of 3x3 mm and grip distance of 50 mm.

The Young Modulus and Ultimate Tensile Strength (UTS) of neat PA6 are experimentally measured as 2.4±0.1 GPa and 42±4 MPa, respectively; the bulk Young's modulus for the PA66 is found in literature as 2.5 GPa(38).

The bulk modulus of CB reinforced PA66 is monotonically increasing in the range of 10–25% weight percentage, showing a small deviation from the average value among different repetitions Figure 5 shows the measured values, the error bar and the linear trend approximating the experimental results.

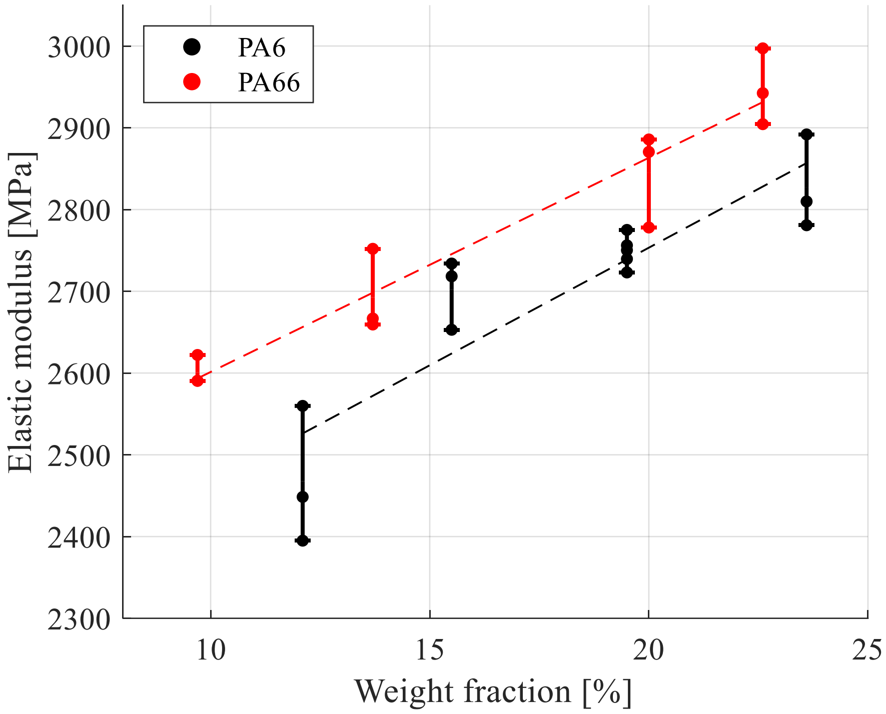


Figure 5 - Young's modulus of composites with different neat polymer and CB concentration.

Compared to the neat polymer, the bulk modulus of CB composite increases up to 20%. In PA6 composites, the particle weight percent increase from 10% to 25% lead to a 13% increase in the elastic modulus. In the case of PA66, the stiffness increases of 13% within the investigated weight percentage range. This demonstrates that the effect of the CB on the two polymers, PA6 and PA66, is consistent.

3.3.1 Mean-field homogenization models

Results from tensile tests are compared with homogenization theories described in Section 2.3. The Voigt model predicts an elastic modulus increase on average twice larger than that observed experimentally. The limit of this theory relies in the assumption of perfectly dispersed inclusions, neglecting any interaction between particles, and any clustering carbon black spheres. Microscopies of CB morphology of the tested specimens shows a clear agglomeration formation in composite with particle weight concentration higher than 10%, yielding to the non-conformity of the Voigt hypothesis with the case under study.

As showed in Figure 6, both the Mori-Tanaka and Reuss models correctly predicts the effect of carbon black spherical inclusions on the elastic modulus increase, with a maximum error of 4% respect to the mean value. The SSGET based homogenization model is fitted with a size radius of 83 μm, as observed in SEM image in Section 2, and a material length parameter of 8.3 μm for the PA66 and 5 μm for the Nylon. Figure 6 shows that the SSGET do not correctly accounts for the particle size on the stiffening effect of CB particles for PA66 based composites. In can be concluded that the Mori-Tanaka and Reuss models can be adopted to effectively predict the elastic modulus of polyamides composites loaded with carbon black particles.

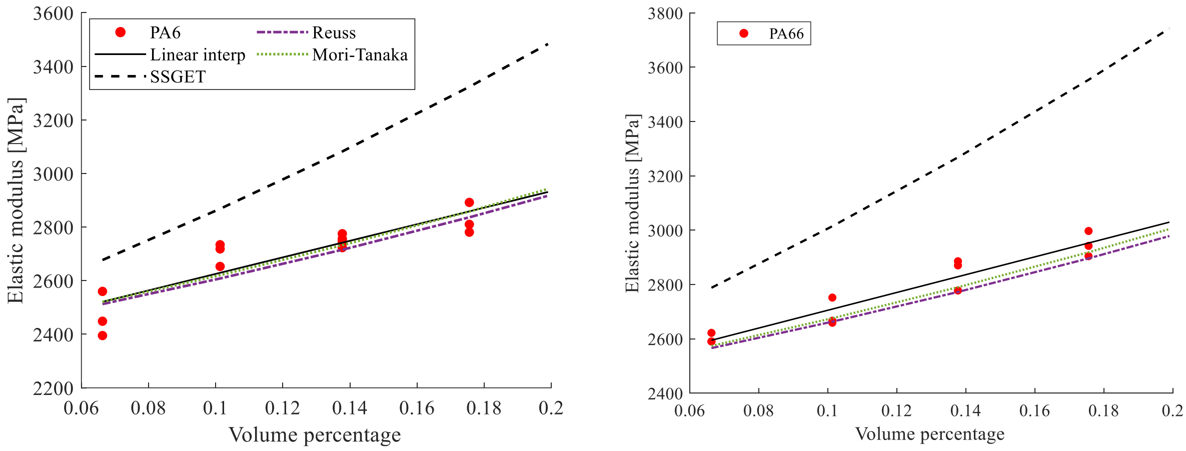


Figure 6 - Comparison of homogenization theories prediction with experimental measurements for PA6 and PA66 with different CB mass fraction

3.3.2 Fracture surfaces (SEM)

Figure 6 shows representative cryofractured surfaces of the PA6 (6a, 6b and 6c) and PA66 (6d, 6e, and 6f) for the three different concentrations, 15%, 20% and 25%, respectively. All the fracture surfaces are very similar and display a reproducible failure surface. There is a central area where the crack starts to propagate and appears quite smooth. Besides this area, the fracture is irregular with the presence of clear and large cracks. These two peculiar areas are more evident in Figure 6g that reports a higher magnification of the fracture surface of the specimen PA66 with 20% wt. of CB. As it is well visible in all the subfigures of Figure 6, the crack starts to propagate in the darker point of the smoother circular area. The higher magnification of Figure 6g reports the presence of one defect that was found in that area. These defects trigger the crack propagation initiation. The microscope analysis conducted on all the specimens showed that one or two defects were detected in the darker area for the two polymers prepared with the three particle concentrations. Twelve voids were measured using a digital image correlation software. These voids present a circular shape and an average diameter of 26 µm with a standard deviation of 6 µm.

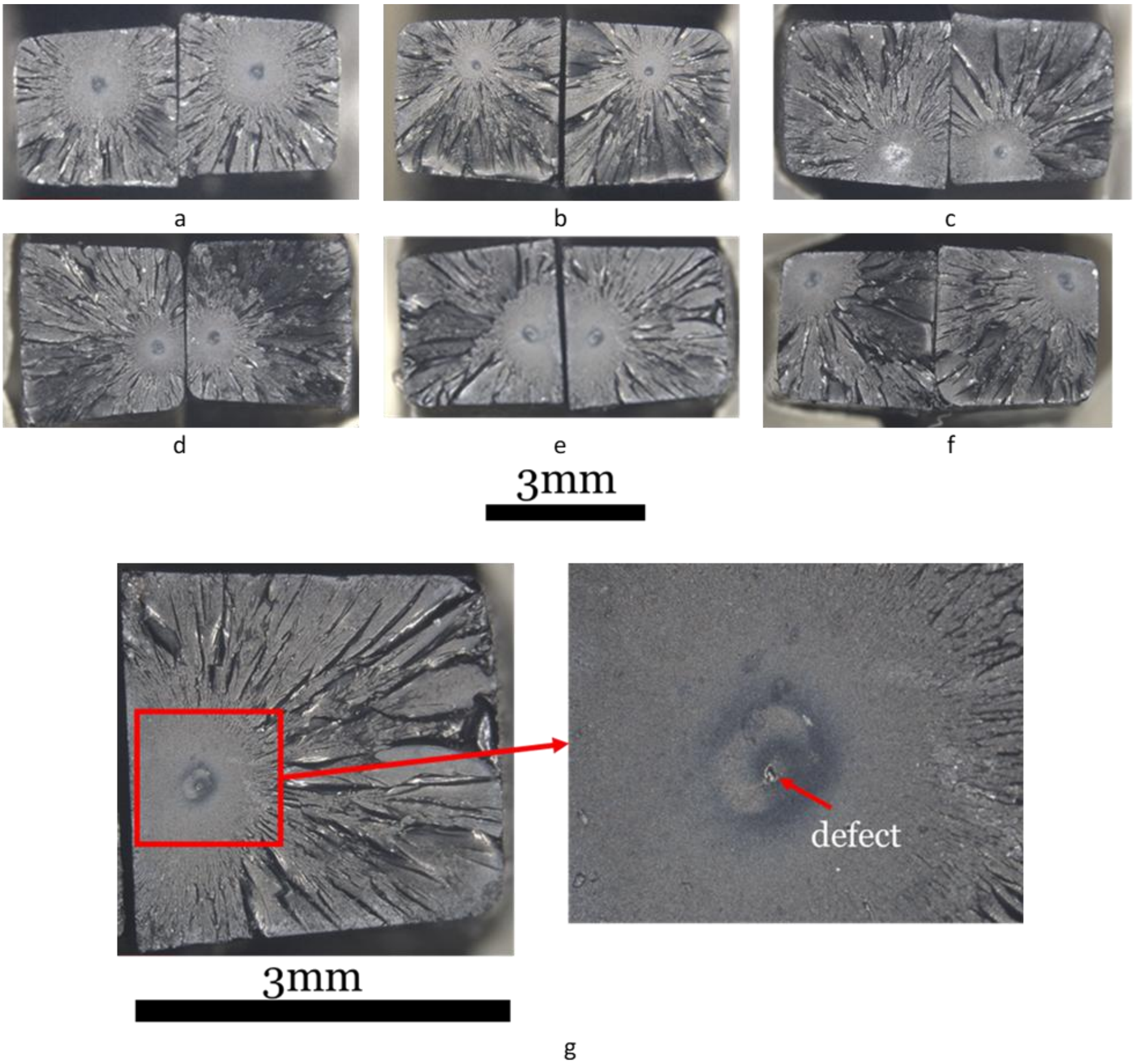


Figure 7 - Representative fracture surfaces of the PA6 and PA66 compounds

3.4 Strain sensitivity

The main goal of the present work is to study the variation of the electric passive properties induced by the mechanical strain in Carbon Black reinforced polyamides. The resistivity of composites is studied in direct current (DC) and alternate current (AC) regime within a frequency spectrum ranging from 0 to 10 kHz. The electrical frequency response of each coupon is measured at fixed displacement increments of 0.05 mm.

From the frequency response measured at each displacement increment, it is possible to reconstruct the strain variation with respect to the applied strain for each sampled excitation frequency. First, the direct current electrical response is compared with the stress- strain curve of the material (Figure 8a) and a linear equation with null offset is fitted with the experimental measurements with a least-squares method. Figure 8b shows a comparison of the linearized strain sensitivity of dynamic impedance Z versus strain curves at three different frequencies. It is clearly highlighted the fact that strain sensitivity of the conductivity changes with the excitation frequency.

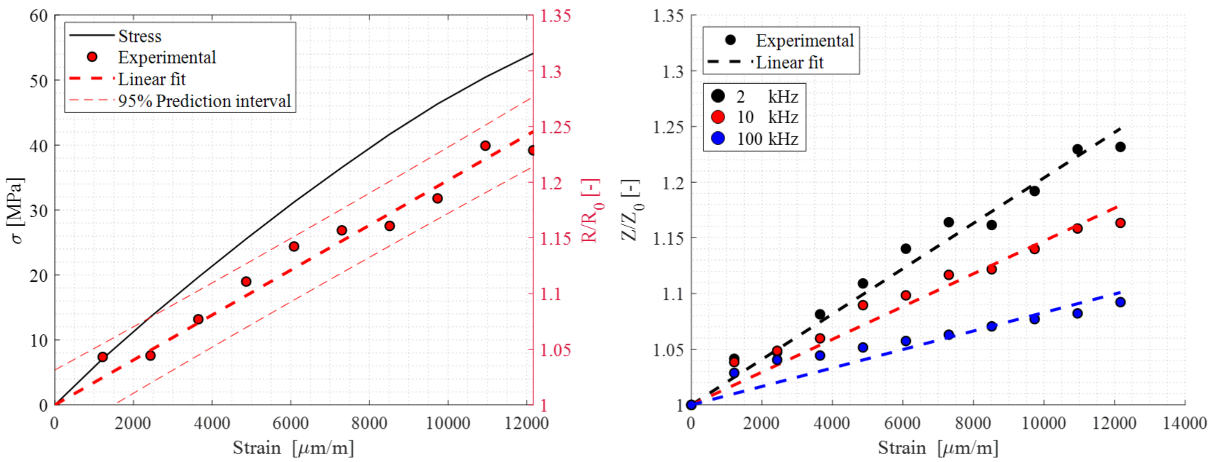


Figure 8 - a) Variation of electrical resistance compared with stress in the material, b) Variation of impedance for different frequencies. Results shown in figure are referred to PA6_20

The gauge factor GF is then computed at each excitation frequency $\bar{f}$ as:

$$GF^{\bar{f}} = \min_{G} \sum_{\varepsilon} \left(\Delta Z_{\varepsilon}^{\bar{f}} / Z_{\varepsilon=0}^{\bar{f}} - G * \varepsilon\right) \quad (8)$$

The conductivity of composites linearly varies with the logarithm of the current frequency, yielding to the equation:

$$GF = GF^{DC} + a \cdot log(f) \qquad (9)$$

where a is fitted with a least-square method. Figure 9 shows the accuracy of equation 9 in predicting the dynamic gauge factor for PA6_20.

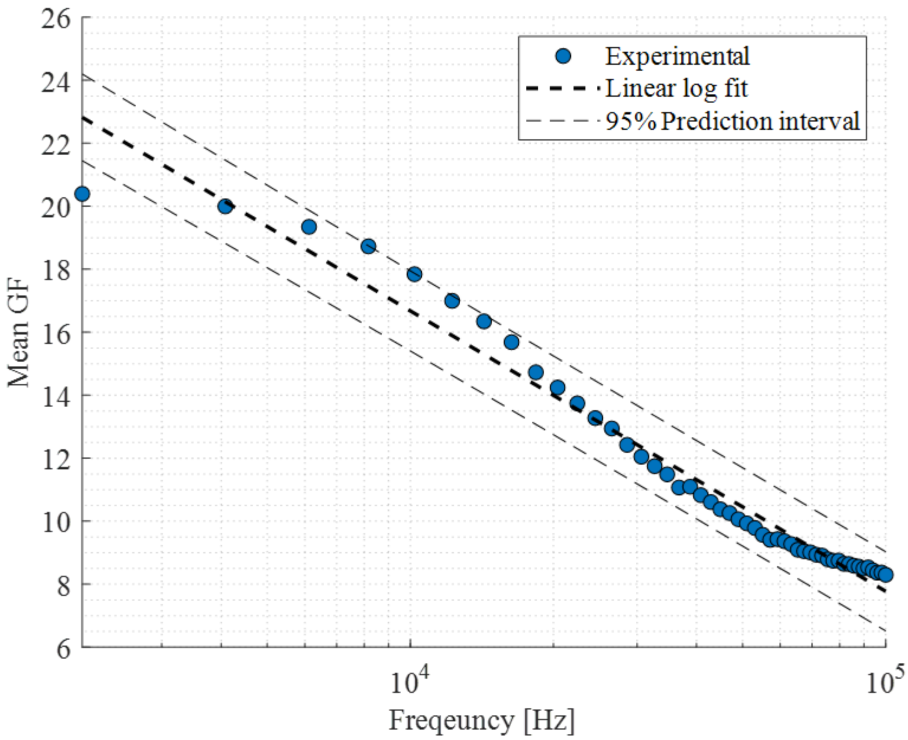


Figure 9 - Linearized Gauge Factor vs. excitation frequency for PA6_20 composite, with a=-3.9 and GF^{DC}= 23.

To assess the effect of particle concentration on the strain sensitivity, the mean GF and its standard deviation can be computed for each composite composition at each excitation frequency. Eventually, the mean GF variation with excitation current frequency of different composites is compared in Figure 9. Every GF measured and computed across the analyzed frequency spectra, are predicted with an error lower than 5% by the linear logarithmic model. Figure 10 shows that there is a linear variation of the dynamic gauge factor with the logarithm of excitation current frequency for each of the conductive composites under study (PA66 with CB weight content of 15, 20 and 25 %). Since the GF dynamic law is linear, few dynamic measures are then necessary to fit the model and assess the frequency effect on the composite strain sensitivity. The slope of the model goes across a sign inversion when shifting from 20% to 25% of conductive particles weight content. The phenomena may be associated to the formation of inductive structures of CB particles that can activate a magnetic field enhancing the current flow in the composite material. This will be further investigated with experimental test for concentrations between 20% and 25%, and visual analysis for the reconstruction of the particles 3D arrangement at high concentrations.

At the best of authors knowledge, this is the first research revealing the relation between the gauge factor and the alternate current excitation frequency, evidencing that there is a clear influence of the AC frequency on the composite resistivity and that it is different at different filler content.

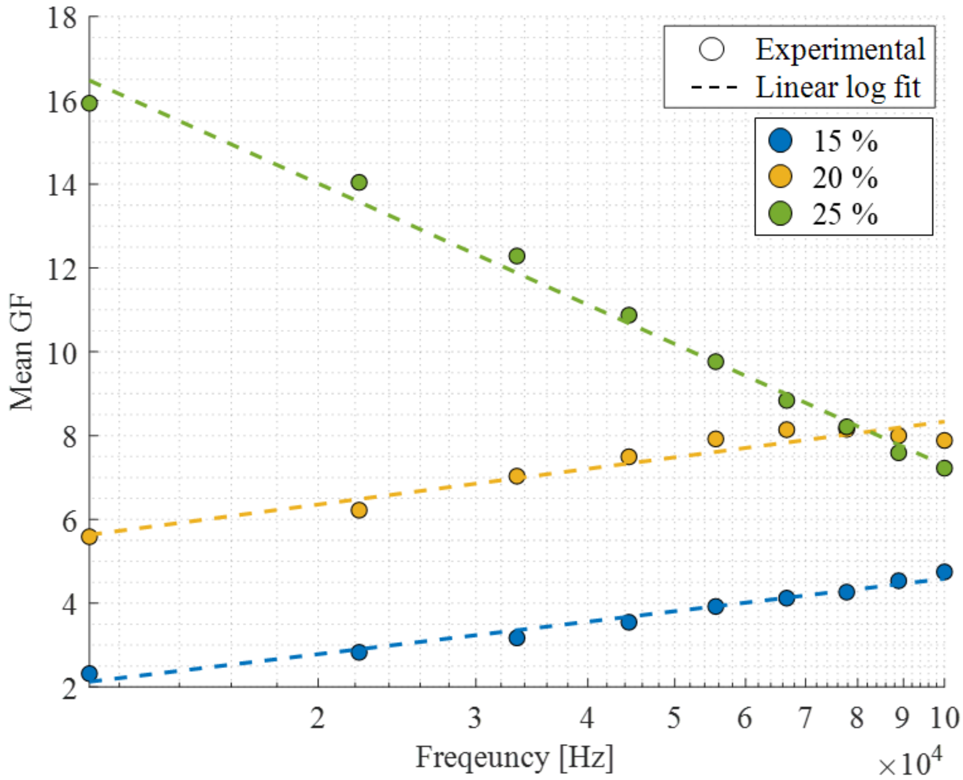


Figure 10 - Effect of carbon black particle dispersion on the strain sensitivity of PA66 in the frequency domain

Conclusions

The authors experimentally analyze the effect of carbon black on the mechanical and electrical properties of PA6 and PA66 polymers. Composite specimens are produced by injection molding, mixing the neat polymer with different weight fractions of PA6/CB compound. The evaluation of the quantity and the dispersion degree of carbon black is obtained from thermogravimetric analysis (TGA) and Field-emission Scanning Electron Microscopy (FeSEM). The effect of CB filler quantity on the elasto-plastic response is evaluated with quasi-static tensile tests and fracture surfaces are investigated with FeSEM to assess the influence of CB morphology on the composite strength. The percolation threshold of different compositions has been determined by conductivity measurements; conductive specimens have been tested under axial loading while in-situ measuring the strain-induced change in the composite resistivity and impedance. The gauge factor (GF) has been defined for different composites with different matrices at different volume fractions within an electrical frequency range up to 10kHz.

The presented results of the experimental study demonstrated that the dispersion of Carbon black particles within a PA6 and PA66 matrix enhances the stiffness and strength of composite when the volume fraction is up to 20%. Nevertheless, higher concentration could lead to CB agglomeration, yielding to the embrittlement of the composite. The percolation threshold of polyamide/CB composite is found at 13% volume fraction of carbon particles. Overall, the composite electric resistance exhibits high strain sensitivity (gauge factor from 15 to 25). By analyzing the strain sensitivity of PA6 and PA66 composite with different Carbon Black concentration excited with different current frequency, this study established that the current frequency does indeed have a significant effect on the composite gauge factor, with a strong correlation to the particle loading. This suggests that, while filler concentration does influence the overall conductivity of the composite, the interplay of CB dispersion and excitation current frequency defines the strain sensitivity of these materials. Carbon black is an ideal candidate for the functionalization of fiber reinforced polyamides since it activates self-sensing feature that can be enhanced by varying the current frequency, while enhancing its mechanical properties. Application can be found in Structural Health Monitoring of FRP parts, conductive plastic for HMI and others requiring an integrated strain sensor.

Acknowledgements

Authors sincerely thanks Luis Castellanos Molinas for his contribution on the set up of the experimental facilities and Alessandro Antonini for his contribution in the execution of experimental tests.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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