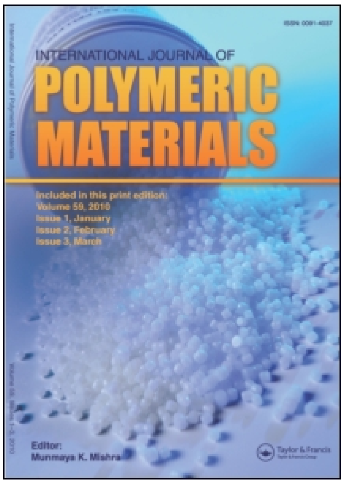

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Mechanical Properties of Nylon 66/Nickel-Coated-Carbon Fibers Composite

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Yielding and Fracture Properties of Nylon 66-based Composites reinforced with nickel-coated carbon fibers are studied at different filler levels over a range of temperatures and strain rates. Tensile elastic modulus showed an increase whereas the yield stress decreased with increasing filler content. The yield stress of this composite showed strain rate and temperature dependence. Activation stress volume and activation energy of yielding process, at relatively high strain rates, are determined. The fracture toughness parameters, G_c and K_c, are also enhanced with filler content. The observed fracture morphology could account for the measured mechanical properties.

KEY WORDS Nylon composite, yielding, fracture, yield stress, toughness, morphology.

1. INTRODUCTION

The importance of advanced composites of high mechanical and electrical performance as replacements for metals in commercial and military aerospace purposes has been long time recognized. The technology of polymer-base composite components is nowadays considered as crucial necessity for most industrial aspects. The ultimate mechanical properties of a polymeric composite may be strongly influenced by the degree of interfacial interaction between the filler and matrix. Thus the behavior of a fiber-reinforced polymers is governed to a certain degree by the properties of the reinforcing fiber, resin matrix, and the efficiency of the matrix-fiber interface. Considerable research and technological efforts have been devoted in the last two decades to develop advanced composite materials and improve their physical reinforcement through modification of the used matrix resins (thermosets, thermoplastics) and fillers (fibers, particulates). Fiber-reinforced polymer-matrix are extensively used in automotive and aerospace industries. Most of the aerospace and industrial components of composites contain graphite (carbon) fibers as the reinforcement, and the epoxy or thermoplastic resins as the matrix.[1-3]

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This article is one part of a series studies concerned with the electrical and mechanical of reinforced thermosets and thermoplastic composites.[4–8] In the present paper, we report the results of a study concerning with the tensile properties and fracture behavior of nylon 66-nickel-coated carbon fiber composite investigated over a wide range of temperatures and strain rates to have better understanding to the role played by the interfacial adhesion between filler and matrix. Finally, the correlation among the fracture behavior and morphology of these composites are discussed.

2. EXPERIMENTAL DETAILS

2.1 Material and Specimen Preparation

The materials used in the present work were polyamide 66 provided by RAPRA (Rubber and Plastics Research Association of Great Britain) with $Mn = 16.4 \times 10^3$, $Mw = 38.5 \times 10^3$, $w/Mn = 4$, and nickel-coated carbon fibers of average measured diameter 10 μm, Young's modulus 80 GPa and tensile strength 1.5 Gpa. Fiber stands were provided by Marbo S.p.A. (Milan, Italy). They were chopped into single filaments of average length 1 mm and mixed with the polyamide 66 using a brabender-like apparatus (Rheocord EC of Haake Inc.) at a temperature of 260°C with a mixing time of 10 minutes and at a roller speed of 32 r.p.m. The composites coming from the mixer were then compression molded in a heated press at a temperature of 260°C and a pressure of 100 Bar, to obtain sheets of 1.3 mm thick. The carbon fiber contents in these composites were 5, 10, 20, and 30 wt %.

2.2 Tensile Tests

To study the deformation behavior of these composite materials, dumb-bell shaped specimens were cut from the sheets. Tensile tests were performed by means of an Instron testing machine equipped with an environmental chamber for work at different temperatures and over a range of strain rates. Temperature readings were taken by placing a thermometer near the test specimen. Prior to testing the specimens were dried under vacuum at 90°C for 10 hours.

2.3 Impact Fracture Tests

Fracture tests were carried out on a charpy Instrument Pendulum (Ceast Autographic Pendulum MK2), at an impact speed of 1 m/sec. Sample with a notch depth to width ratio of 0.3 and a test span of 48 mm were fractured at room temperature for all composite concentrations. The relative curves of energy and load against time as displacement were recorded at each temperature.

2.4 Microscopy and X-Ray Diffraction

Adhesion and morphological investigations were carried out using a Philips 501 SEM on fracture surfaces obtained by tensile and impact tests. The samples for SEM observations were metal-coated using a Polaron sputtering apparatus with

Au-Pd alloy. Optical examinations were carried out using a Wild M420 Stereomicroscope. The obtained X-ray diffraction patterns from the nylon 66 matrix were concentric rings indicating isotropy. Thus no orientation of the matrix takes place during compression moldings.

3. RESULTS AND DISCUSSION

3.1 Tensile Results

The stress-strain curves obtained at a strain rate $\varepsilon = 7.4 \times 10^{-3}\ S^{-1}$ for various prepared composites show a ductile plastic deformation behavior. It was noticed that by increasing the content of the nickel coated carbon fibers, the degree of brittleness increases. This is accounted for by the presence of relatively brittle carbon fibers embedded in a ductile nylon matrix. The dependence of the Young's modulus (*E*) on the fiber concentration in composites is shown in Figure 1. It can be seen that the stiffness of the material increases linearly with the weight fracture of the carbon fibers. This modulus enhancement is normally expected for reinforcing-fiber composites. The yield stress was determined from the intersection of two tangents on the stress-strain curve for a ductile behavior and from the maximum point for the brittle one.[9] Figure 1 shows the variations of the yield stress (σ_y) as a function of the carbon fiber content. This quantity decreases linearly with filler

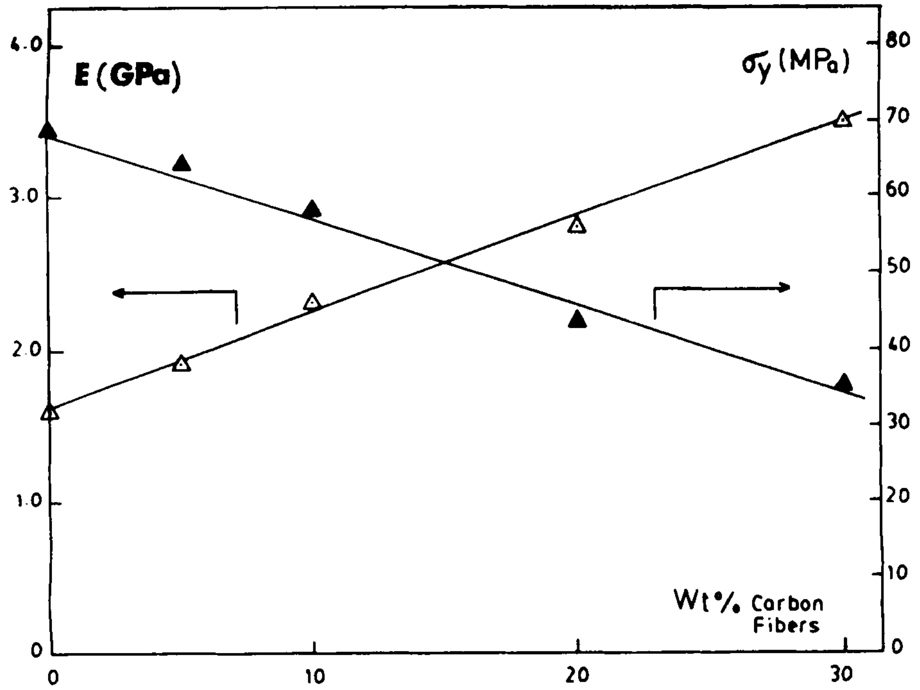

FIGURE 1 Young modulus and yield stress reinforced nylon 66 as a function of carbon-fiber content, $\dot{\varepsilon} = 7.6 \times 10^{-3}$.

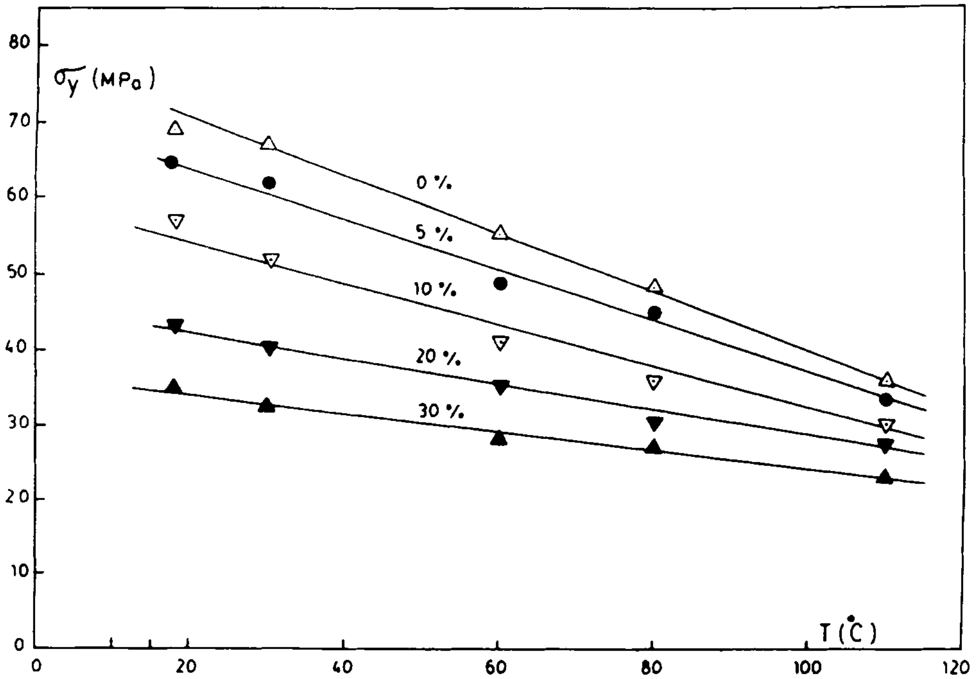

FIGURE 2 Variation of the yield stress of composite with temperature.

content and most likely due to weak interfacial bonding of the fibers with the nylon matrix.

Stress-strain curves were also obtained at different temperatures and strain rates. The tensile yield stress for pure nylon, and 5, 10, 20, 30 wt% fiber composites measured over a temperature to 110°C are shown in Figure 2. It was found that the yield stress decreases also linearly with temperature. The tensile yield stress for composite specimens measured at room temperature is plotted as a function of log strain rate in Figure 3. The data show a linear relationship between the yield stress and the strain rate for the nylon 66 polymer and the composites, but the straight lines are not parallel which indicates the occurrence of more than a single activated-rate process. This departure from parallelity is accounted for by the existence of the coated carbon fibers. However, the data still show that the yield stress increases as a function of strain rate for the given composite. The equivalence in increasing yield stress by increasing strain rate and decreasing temperature can be drawn from Figures 2 and 3. The overall effect of the strain rate on yielding behavior, shown in Figure 3, can be described by the Eyring theory.[10,11] The values of activation energy and stress activation volume are calculated using the Eyring equation for an activated-rate process, which can be written in terms of the strain rate, $\dot{\varepsilon}$, and absolute temperature, T, as

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp[-(E_a - \sigma_y V^*)]/kT \qquad (1)$$

where $\dot{\varepsilon}_0$ is constant, E_a is the activation energy for an activated-rate process, σ_y

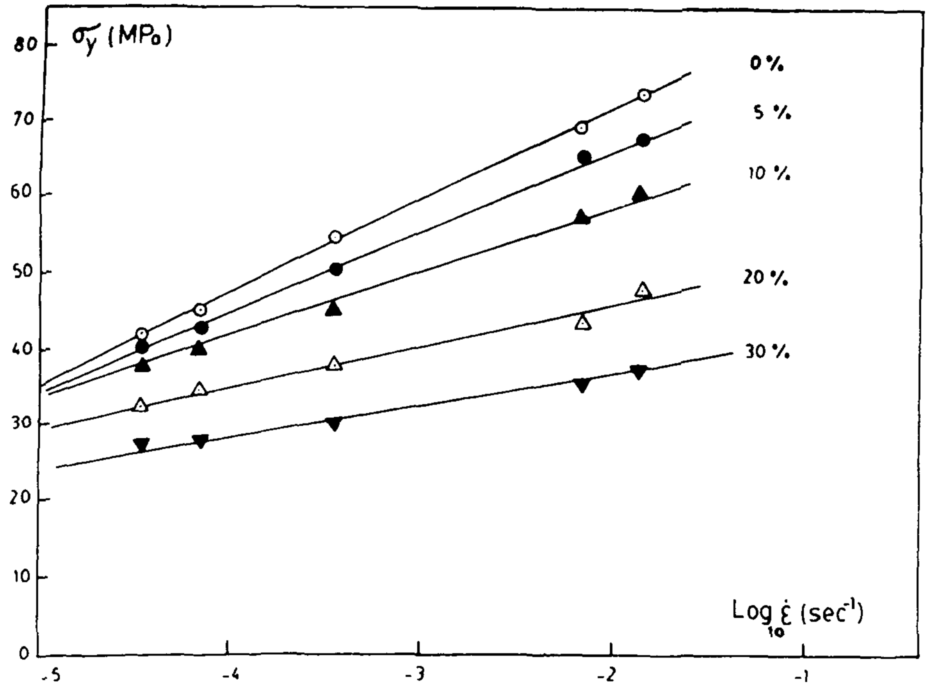

FIGURE 3 Dependence of the yield stress of composite on strain rate.

is the yield stress, V^* is the stress activation volume, k is Boltzmann constant, and T is the absolute temperature. This equation implies that the stress at yield and the logarithm of strain rate have a linear relationship with the slope given by

$$\partial\sigma_y/(\partial \ln \dot{\varepsilon})_T = kT/V^* \qquad (2)$$

Values for the activation energy and the activation volume are calculated from the observed linear dependence of Figure 3 for nylon 66 polymer and the prepared composites. Figure 4 shows the variations of activation energy, E_a, and the volume, V^*, as a function of weight fraction of coated carbon fibers. The V^* increases rapidly with the filler content. This behavior is not unique, it differs from composite to another as we seen in our recent investigations[4,5] and other reported studies.[12,15] Certainly, there is no straightforward concept or mechanism to predict the E_a behavior as a function of filler content. To account for this behavior few factors must be taken into consideration. For instance, the yielding phenomenon is strongly dependent on the type of filler as well as on the matrix structure. The reinforcing fibers have influence on the interphase morphology where the transcrystalline region between the fiber and matrix may be quite different from the matrix. Also, the surface fiber history (coated, uncoated, treated) will affect the whole interfacial mechanism. All these factors certainly will affect, in a peculiar fashion, the E_a behavior as a function of filler content in composites. Finally, it does not appear to have a well defined mechanism that controls the activation energy with increasing

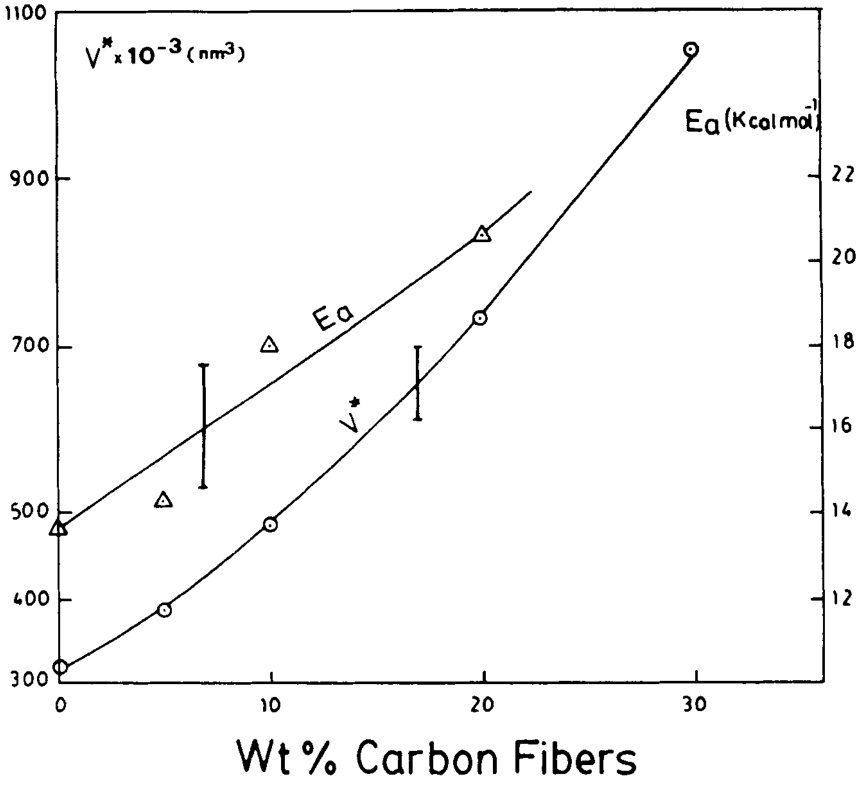

FIGURE 4 Variation of the activation volume and activation energy as a function of carbon-fiber content.

the filler content. More decent research work should be devoted to clear the context dealing with the above mentioned structural effects.

3.2 Impact Fracture Results

3.2.1 Fracture toughness parameters. The critical stress intensity factor, K_c is calculated using the fracture mechanics approach[16–18] from the equation

$$K_c = \sigma Y(a)^{1/2} \quad (3)$$

where σ is the nominal stress at the onset of crack propagation, a is the initial crack length, and Y is a calibration factor depending on the specimen geometry.

For the determination of the critical strain energy release rate, G_c, the following equation is used

$$G_c = U/BW\phi \quad (4)$$

where U is the fracture energy corrected from the kinetic energy contribution, B and W are the thickness and the width of the specimen, respectively, and ϕ is a calibration factor which depends on the lengths of crack and size of the sample. The values were taken from Plati and Williams.[19]

3.2.2 Fracture toughness results. The critical strain energy release rate (G_c) as a function of coated carbon-fiber content at room temperature is shown in Figure 5. The relationship between G_c and fiber content is a linear one, where the critical strain energy release rate increases with increasing fiber content. The enhancement of G_c observed at room temperature is mainly attributed to the occurrence of stiff localized aggregates of carbon fibers interacted with magnetic forces and to the existence of entanglement network between the fibers themselves and the nylon matrix. These features of carbon fibers are able to toughen the composites structure. A similar behavior is observed for the critical stress intensity factor, K_c.

4. MORPHOLOGICAL STUDY

Optical examination of the molded composites showed relatively smooth surfaces without pores or voids and almost even fiber distribution upon the surfaces. The tensile deformation behavior of tested composite specimens was characterized by a yielding phenomenon with crazes and shear banding, and finally a failure with relatively straight edge transverse cracks. Figure 6 shows scanning electron micrographs of fractured surfaces of specimens of 5, 10, 20, and 30 wt% nickel-coated-

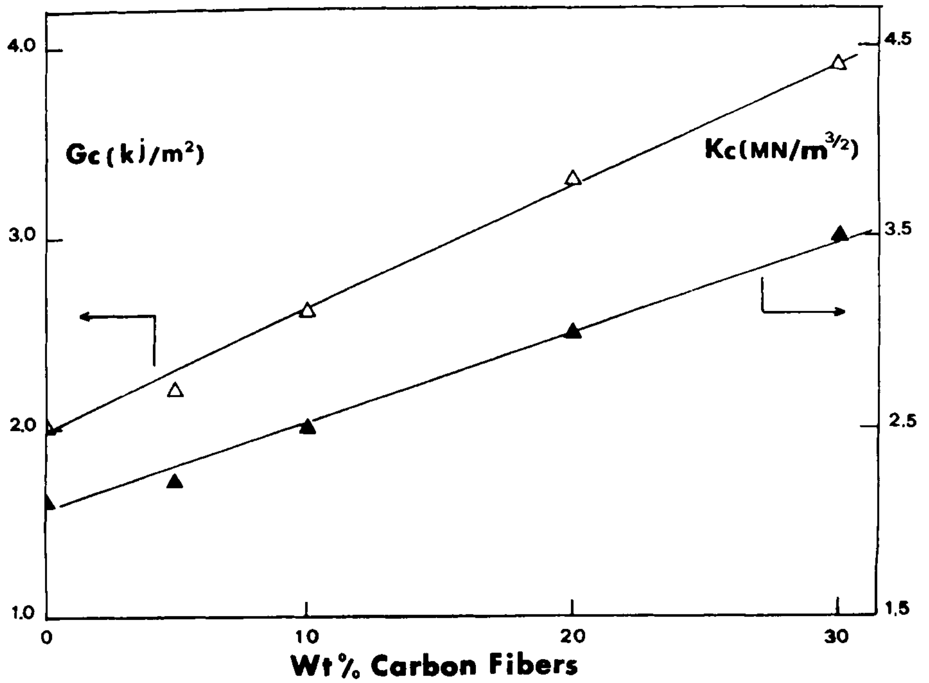

FIGURE 5 Critical stress intensity factor (K_c) and critical strain energy release rate (G_c) as a function of carbon fiber content.

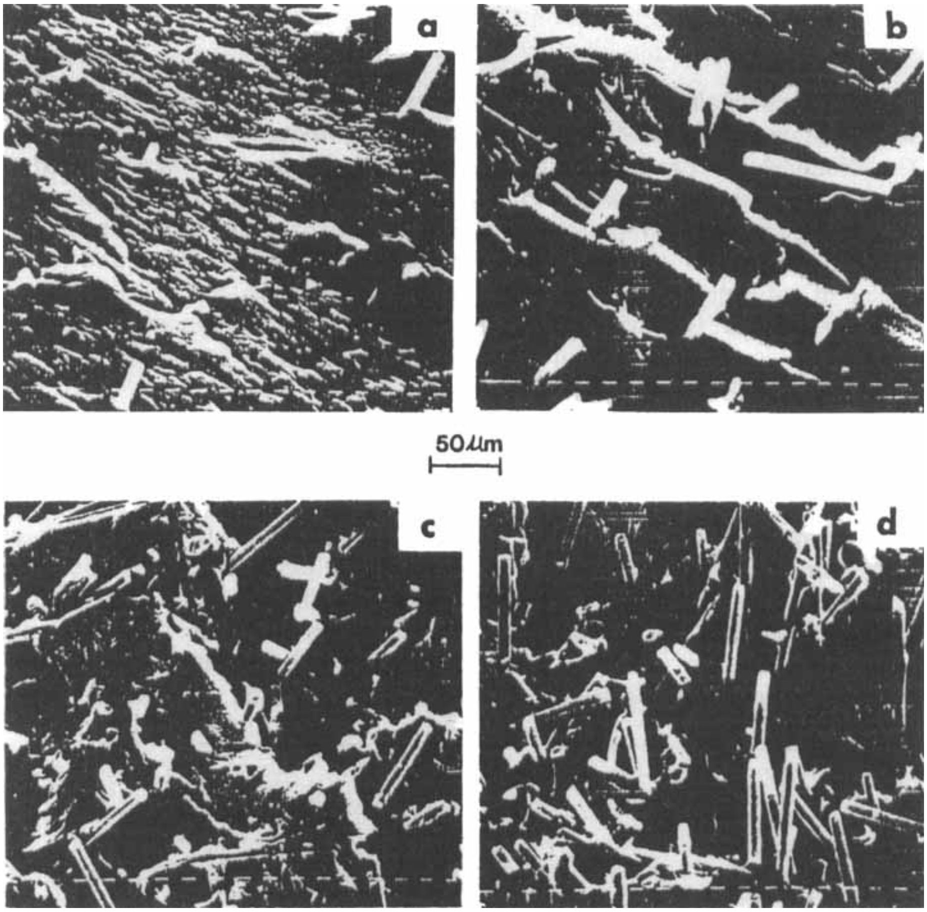

FIGURE 6 Scanning electron micrographs of composites fractured under impact tests. (a) 5 wt% carbon fibers, (b) 10 wt% carbon fibers, (c) 20 wt% carbon fibers and (d) 30 wt% carbon fibers.

carbon fibers concentration obtained during the fracture tests. It can be seen that the fracture surfaces of low fiber content, 5 and 10 wt% composites, the fibers are more or less in good adhesion to nylon 66 matrix. The fracture surfaces of the highly fiber content specimens, 20 and 30 wt% show that large number of fibers are not covered by the nylon matrix and are pulled out during the fracture process. This indicates that coated-fibers are not bound very well to the matrix because nickel coating particles may prevent good contact or interaction with the nylon matrix.

This observed morphology can explain the overall behavior of the measured mechanical parameters. The stiffness enhancement is mainly attributed to the carbon fibers of high modulus with respect to the polymer matrix. The decrease of the yield stress with increasing of the fiber concentration is due to weak interfacial bonding between the fibers and nylon matrix. The matrix deformation is characterized by a ductile behavior with shear banding and microcracks as shown from the SEM micrographs. The toughness enhancement with fiber content can be attributed to composite lamination where the applied stress is suddenly accommodated and the impact energy is dispersed through the composite bulk. Thus, during fracture, the amount of energy required to form voids and cracks at the fiber-matrix interface increases with increasing carbon fiber network supporting the applied loads, particularly in the crack-tip zone characterized by a large amount of plastic deformation.[18]

5. CONCLUSION

Nylon 66-based composites reinforced with nickel-coated-carbon fibers were prepared to study their mechanical properties as a function of fiber content, temperature and strain rate. The following conclusions can be drawn from the results obtained:

1. The stiffness of composites is increased and the yield stress decreased with increasing the fiber content.
2. The yield stress showed temperature and strain rate dependence.
3. The activation volume and activation vary with the carbon fiber concentration.
4. The fracture toughness is enhanced with the fiber content.
5. The observed morphology could correlate with the measured mechanical parameters.

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