Wear and Indentation Resistance of Polyethylene Nanocomposites at High Temperatures

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Abstract-The presence of nanofillers in the polyethylene matrix can play an important role in changing their behavior during mechanical testing. Moreover, high ambient temperature can seriously affect the properties of polyethylene and cause softening, which leads to a decrease in stiffness, strength, hardness, and wear resistance. In the current work, carbon nanotubes (CNTs) and nanoclays with 0.5wt.% are embedded into polyethylene blend matrix to enhance its mechanical properties, mainly wear and indentation resistance at different ambient temperatures. The results show that the processing method used resulted in homogenous distribution and good dispersion of nanofillers. The addition of 0.5 wt.% CNT or nanoclays increased the indentation and wear resistance at both room and high temperatures. At high temperatures, the presence of nanofillers caused an increase in wear resistance by 32.2% at maximum depth.

Keywords-polyethylene; wear; indentation; temperature; nanotube; mechanical properies

I. INTRODUCTION

Nanoindentation testing is an alternative method that can be used to assess the near-surface properties of polymeric materials like wear and penetration resistance [1]. This type of near-surface property testing has been widely applied for polymeric materials loaded with nanoparticles to investigate the correlation between properties and volume of fraction of nanoparticles [2-8]. However, up to date, most nanoindentation experiments are limited to evaluating near-surface properties of polymeric materials at room temperature, whereas, elevated temperatures have remarkable effects on the properties of polymeric materials within their operating environments. Therefore, instrumented indentation techniques have been developed to perform testing under various environmental conditions including high temperatures and moisture to meet the commercial requirements [9-15]. Polyethylene-based nanocomposites are attractive to researchers due to their wide range of applications and types [16-18]. Moreover, they have ease machinability, competitive cost, and various processing methods in addition to good properties like corrosion resistance, flexibility, ductility, and impact resistance. However, it is known that temperature has severe effects on the properties of polymeric materials, which cause softening and lower their properties.

This work is carried out to evaluate the effects of nanoparticle addition on the penetration and wear resistance of polyethylene at different temperatures (22.8 and 40°C). A low volume of fractions of carbon nanotubes and nanoclays (0.5wt.%) were embedded separately into the blend of polymeric materials to improve their mechanical properties, mainly wear and penetration resistance.

II. EXPERIMENTAL METHODS

A. Materials

Nanoclay and CNTs were added separately to blended polymers of ultra-high molecular weight polyethylene and high-density polyethylene. The ultra-high molecular weight polyethylene powder has an average molecular weight of 3×10^6g/mol, and was provided by SABIC Company, Saudi Arabia. The high-density polyethylene pellets were purchased from ExxonMobil Chemical Europe, Belgium. Nanoclay was provided by Elementis specialties, USA and Multi-wall Nanotubes (MWNT) with an average diameter of 25nm were purchased from Nanocyl, Belgium.

B. Processing

A twin-screw extruder was used to blend 75wt.% of ultra-high molecular weight polyethylene with 25wt.% of high-density polyethylene. Then, two types of nanoparticles were embedded separately into the polymeric matrix using similar conditions. These types are CNTs and nanoclay with a constant volume fraction of 0.5wt.% to form polyethylene nanocomposites. The mini twin-screw extruder consists of five controlled zones from the feeding port to the die. The processing parameters used in this work are shown in Table I. The extruder produces small pellets which are then compressed using a hot press with 190ºC to form a square mould (100×100×1.65mm). Various moulding pressure and holding times were applied to find the optimal one which was 309MPa moulding pressure and 15min holding time. Then, water was used to cool the mould to room temperature.

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TABLE I. PROCESSING METHOD PARAMETERS

Extruder speed (rpm)	**Processing temperature (ºC)**					
	Zone 1	Zone 2	Zone 3	Zone 4	Die	Cooling
400	180	190	200	210	220	water

C. Material Testing and Characterization

Various characterization techniques were applied to evaluate the dispersion and distribution of nanoparticles in the matrix of polyethylene nanocomposites. They were investigated using two experimental techniques, which are Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM). A NanoTest Machine 600 from Micro Materials Ltd (Wrexham, UK) was used to perform the wear test on the specimens using a controlled chamber at temperatures of 22.8 and 40°C. A diamond Rockwell tip, with a 200µm radius, 2mN load, 10µm/s speed, and 10 scratches was applied. The surface morphology of the polymer nanocomposite was investigated using a sharp tip (in the range of 5-10nm) of an Atomic Force Microscope manufactured by Veeco Instruments Inc. (Cambridge, UK). Then, the Nanoscope software was used to analyze the data. An instrumented indentation machine with a controlled chamber Micro Materials Ltd (Wrexham, UK) was used to perform the experiments under temperatures of 22.8 and 40ºC. At least 10 indents were made using a Berkovich indenter, with a face angle of 65.3° with 10mN maximum load, 600s dwell period, and 2mN/s loading and unloading rates. Oliver and Pharr method [19] was applied to analyze the results. In this method, the initial portion of the unloading curve is described by the power low relation:

$$P = \alpha\,(h - hr)m \quad (1)$$

where P is the load, α and m are constants determined by curve fitting, h is penetration depth and hr is the depth of the residual impression. The contact stiffness (S) can be obtained by:

$$S = \frac{dP}{dh}(h = h_{max}) = m \propto (h_{max} - h_r)^{m-1} \quad (2)$$

The contact depth (h_c) at maximum load (P_{max}) can be estimated using:

$$h_c = h_{max} - \varepsilon \frac{\mathrm{P}_{max}}{\mathrm{S}} \quad (3)$$

where ε is a constant related to the geometry of the indenter, which is 0.75 for the Berkovich indenter and h_{max} is the maximum penetration depth. Thus, the projected contact area (A_c) is determined from h_c by the following relation:

$$A_c \approx 24.5\, h_c^2 \quad (4)$$

and hence the indentation hardness (H) is:

$$H = \frac{P_{max}}{A_c} = \frac{P_{max}}{24.5 h_c^2} \quad (5)$$

The reduced modulus can be calculated from stiffness (S) using the relation:

$$S = \frac{dP}{dh} = \beta \frac{2}{\sqrt{\pi}}\, E_r \sqrt{A} \quad (6)$$

where $A = 24.5\, h_p^{\,2}$, E_r is the reduced modulus, and β is a correction factor that depends on the type of indenter (1.034 for Berkovich indenter). Consequently, the elastic modulus (E_s) for the specimen can be calculated using the equation:

$$\frac{1}{E_r} = \frac{(1-\nu_s)^2}{\mathrm{E_s}} + \frac{(1-\nu_i)^2}{\mathrm{E_i}} \quad (7)$$

where E_s, ν_s and E_i, ν_i are the elastic modulus and the Poisson's ratios of the specimen and the indenter respectively, (E_i = 1141GPa, ν_i=0.07).

A dwell period of 600s was applied at maximum load to minimize the effect of viscoelastic behavior (nose).

III. RESULTS AND DISCUSSION

A. Nanoparticle Dispersion and Distribution

Dispersion and distribution of nanoparticles into the matrix are very important factors that significantly affect the mechanical properties of the processed polymer-based nanocomposite. Figures 1 and 2 show that CNTs and nanoclays were dispersed very well into the polyethylene blend. Figure 3 shows the surface morphology of the three materials investigated in the current paper. Figure 3(a) shows the blend without any additions, whereas Figures 3(b)-(c) indicate the presence of nanoclays and CNTs on the surface of the tested materials. Moreover, it can be seen that the nanoparticles are distributed homogeneously on the surface of polyethylene nanocomposite, which indicates the effectiveness of the applied processing technique.

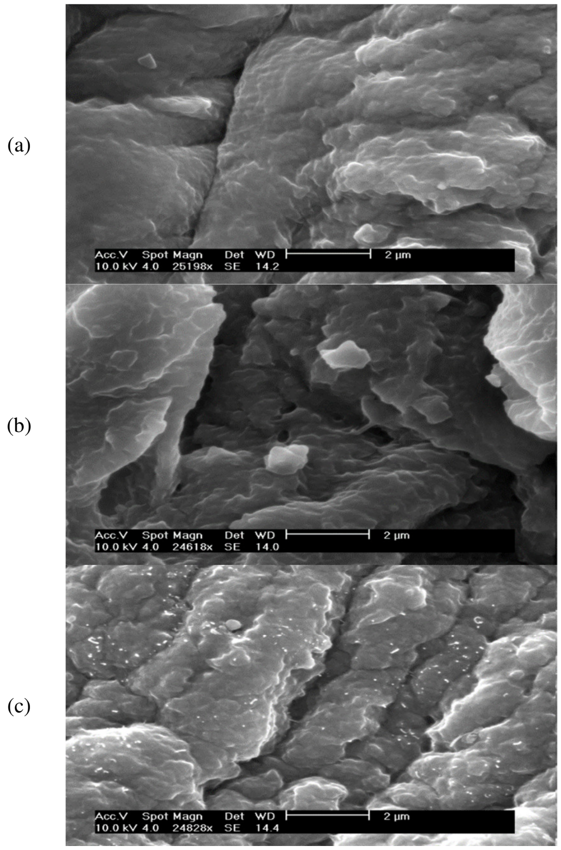


Fig. 1. SEM images showing the dispersion of nanoparticles into the blend matrix: (a) blend, (b) blend with 0.5wt.% clay, and (c) blend with 0.5wt.% CNT.

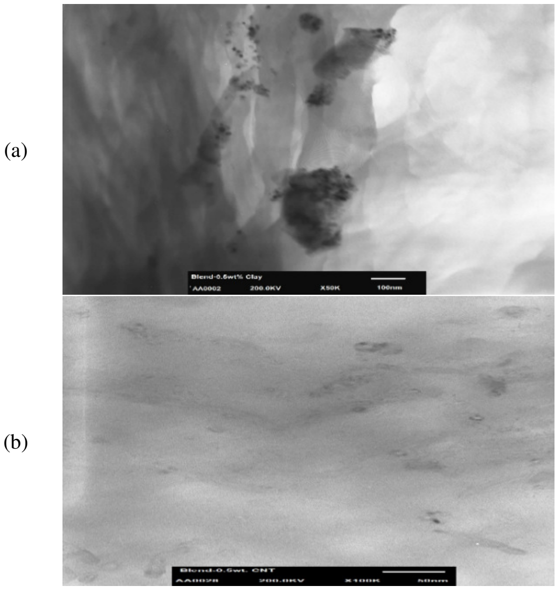
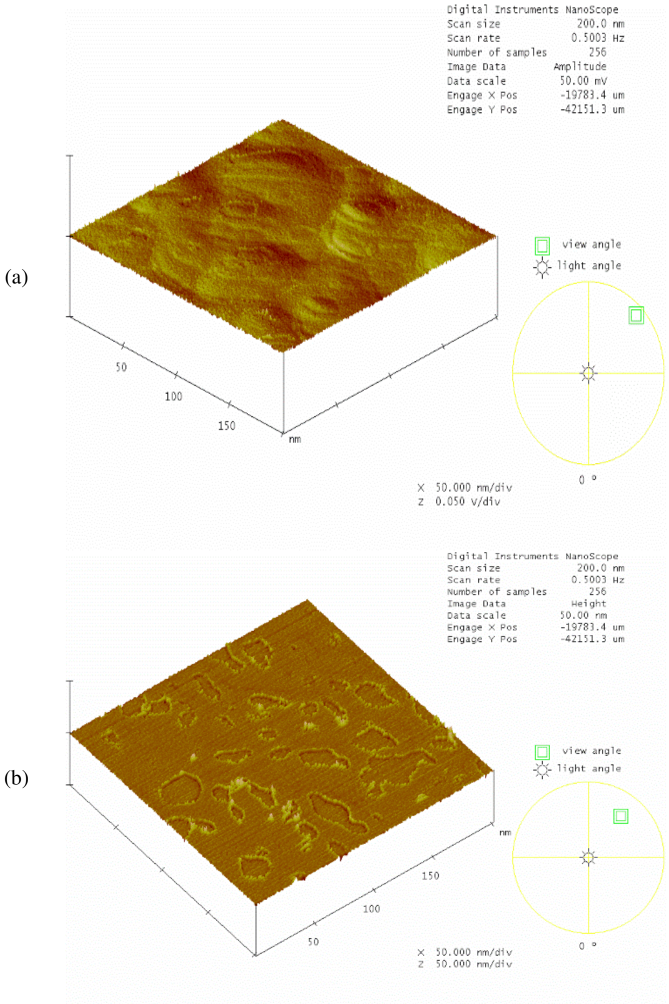


Fig. 2. TEM images showing the presence of nanoparticles in the blend: (a) blend with 0.5wt.% clay and (b) blend with 0.5wt.% CNT.



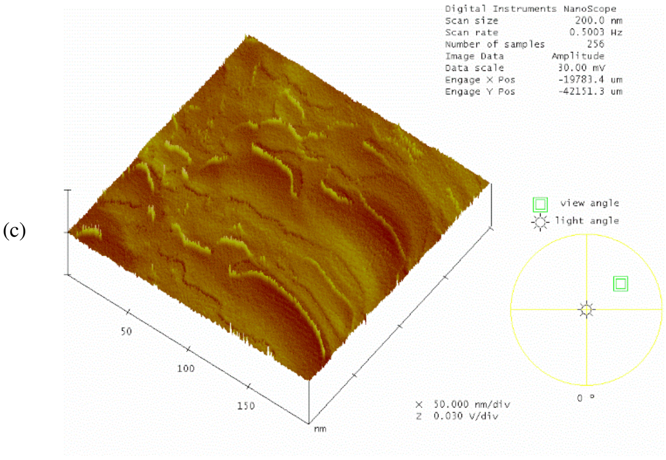


Fig. 3. AFM images showing the surface morphology of: (a) blend, (b) blend with 0.5wt.% clay, and (c) blend with 0.5wt.% CNT.

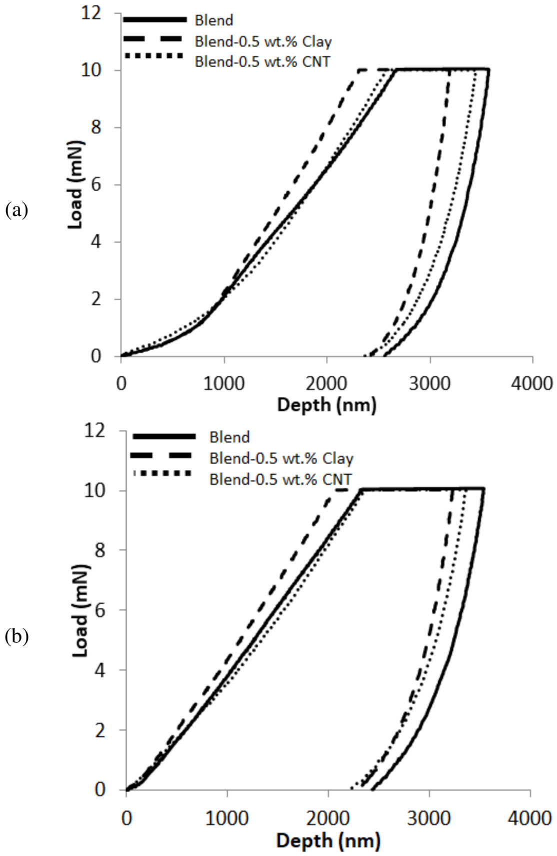


Fig. 4. Indentation behavior of polyethylene nanocomposites at different ambient temperatures: (a) 22.8°C, (b) 40°C.

B. Nanoindentation Behavior

Figure 4 shows the indentation behavior of the blend and its nanocomposites. It is clear that the addition of 0.5wt.% nanoclays enhanced the indentation resistance of the blend at both room and high temperatures. More enhancement in indentation resistance is achieved by the embedding of CNT into the blend's matrix at similar conditions. This can be attributed to the difference in geometry between CNT (one-dimensional shape) and clay (two-dimensional shape).

Moreover, the interaction between nanoparticles and the matrix is another important factor that depends on the bond strength between the two materials and the interface thickness and properties.

C. Wear Resistance

The incorporation of nanofillers into polymeric matrix can significantly affect the tribological performance of polymer nanocomposites [20]. This is achieved by improving the load bearing capacity and reducing the crack initiation in the surface. However, it is known that nanofiller geometry has a great influence on the mechanical behavior and the mobility of polymer chains. Therefore, investigating the effect of two types of nanofillers with different geometry on the wear resistance of polyethylene nanocomposites at different ambient temperatures is a novel work. It can be seen in Figure 5 that the addition of CNT and nanoclays has significant influence on the wear resistance of polyethylene-based nanocomposites.

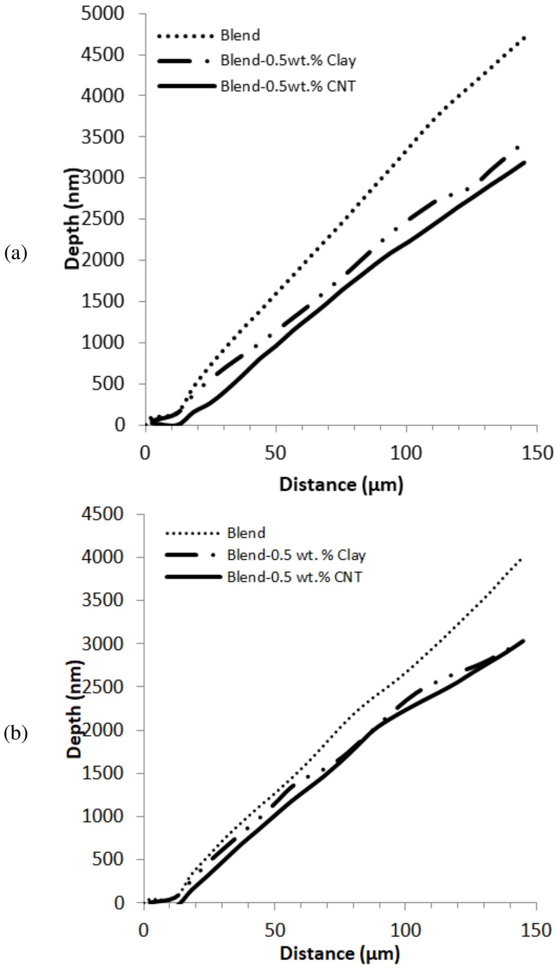


Fig. 5. Wear resistance of polyethylene nanocomposites at different ambient temperatures: (a) 22.8°C, (b) 40°C.

The addition of a low volume fraction of nanofillers resulted in a 25% increase in wear resistance and maximum depth at room temperature. At high temperatures, the presence of these nanofillers caused an increase in wear resistance by 32.2% at maximum depth. These results indicate that nanocomposites have higher wear resistance at different ambient temperatures. This can be attributed to the presence of nanofillers, which disrupted the movement of polymeric chains. Moreover, the application of high temperature on the blended material caused a reduction in wear resistance by 15%. On the other hand, only a 5% reduction in wear resistance is observed for nanocomposites at high temperatures. This indicated that the use of polymer-based nanocomposites increases wear resistance of blends at various ambient temperatures.

IV. CONCLUSIONS

In this study, homogeneous distribution and good dispersion of nanofillers were achieved using an in-house processing method. The addition of a low volume fraction of nanofillers caused an increase in indentation resistance of polymer-based nanocomposites at various ambient temperatures. Moreover, the presence of CNTs and nanoclays in the polymeric materials resulted in a significant improvement in wear resistance at both room and high temperatures, due to the chain movement mechanisms of the nanofillers, which work as obstacles for chain movements during the application of the load.

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