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FRICTION AND WEAR OF POLYMERIC MATERIALS REINFORCED BY CARBON NANOTUBES

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ABSTRACT
The present work studies friction coefficient and wear of polymeric materials such as high density polyethylene (HDPE), low density polyethylene (LDPE) and polystyrene (PS). The polymers are filled by carbon nanotubes (CNTs) in concentration up to 1.0 wt. % as well as paraffin oil in concentration of 5.0 wt. %. The frictional behavior of the proposed composites is investigated at different values of applied load at dry sliding.

It was observed that friction coefficient slightly increased with increasing NCTs content. The reason of friction increase is attributed to the abrasive action of CNTs. Besides, CNTs strengthened the polymeric matrix and increased its shear strength and consequently friction increased. Wear drastically decreases down to minimum then significantly increased with increasing CNTs content. Minimum wear values were observed at 0.6 wt. % CNTs. The reduction of wear can be explained on the basis that reinforcing the tested polymers by CNTs makes the micro-cracks propagation more difficult and increases tensile strength. As CNTs content increases the tubes will agglomerate and decrease the interfacial adhesion between the CNTs and polymer, so that CNTs will be simply pull-out and will not contribute towards decreasing wear resistance of the composites. Friction displayed by the tested polymers filled by 5.0 wt. % paraffin oils and reinforced by CNTs showed lower values than that observed for composites free of oil. Friction coefficient slightly decreased with increasing CNTs content. It seems that, oil impregnated in the matrix enhances the release of NCTs from the matrix during sliding, where they work as rollers on the contact surface. HDPE composites displayed minimum friction coefficient and wear, while PS showed the highest values.

KEYWORDS
Friction, wear, high density polyethylene, low density polyethylene, polystyrene, carbon nanotubes.

INTRODUCTION
Due to their versatile properties combined with a favorable strength-to-weight ratio, polymer composites find numerous applications in industry, [1]. To further improve their performance, new matrix and reinforcing materials are required. The control of the nanostructure and the addition of nanoparticles to polymers have led to structural

and functional property enhancements in a number of polymeric systems as a material answer to continuous requirements from advanced industrial sectors, [2]. Ultra high molecular weight polyethylene (UHMWPE) is widely used for articulating surfaces in total hip and knee replacements. UHMWPE based polymer composites were synthesized by synergistic reinforcing of bioactive hydroxyapatite (HA), bioinert aluminum oxide (Al_2O_3), and carbon nanotubes (CNTs) using compression molding, [3].

An analysis has been made of the literature on friction and wear of polymer nanocomposites prepared by compounding nanofillers with molten thermoplastics, [4]. The structure-properties-processing relationship of poly(butylene terephthalate) (PBT) nanocomposites, [5]. It is known that graphite has excellent lubricant properties due to the 2D graphene layers bonded via van der Waals forces, [6]. Thus, graphite nanoplatelets (GNPs) should have high lubricating efficiency during contact frictional movement of sliding parts. Microstructure and tribological properties of copper-based hybrid nanocomposites reinforced with copper coated multiwalled carbon nanotubes (MWCNTs) and silicon carbide (SiC) were studied, [7].

The effect of the ionic liquids (ILs) with respect to their anion type and the length of alkyl chain as dispersing and coupling agent in carbon nanotube (CNT) filled styrene butadiene rubber (SBR)/natural rubber (NR) blends, [8]. Carbon nanotubes (CNTs) were embedded in aluminum carbide coating in desired vertical/horizontal direction in order to fabricate a nanocomposite layer with unidirectional enhanced mechanical properties, [9]. Carbon fiber reinforcements with an excellent mechanical performance to weight ratio are primarily preferred for advanced composite applications, [10]. The poor interfacial adhesion between carbon fiber surfaces and polymer molecules caused intrinsically by hydrophobicity and chemical inertness of carbon is a long existing issue to overcome. Provide a description of the recent advances in the preparation of polymer nanocomposites via mechanical milling, [11].

An assessment of possible future scenarios that could be created by the utilization of improved experimental methodologies and a deeper understanding of structure-property relationship is also provided. Polymeric nanocomposites are promising tribological materials. However, the wear debris generated on the sliding surface of composite materials is highly affected by the nanofillers used (types, surfaces, etc.), [12]. Multi-walled carbon nanotubes (MWCNTs) are commonly used in polymer formulations to improve strength, conductivity, and other attributes, [13]. A developing concern is the potential for carbon nanotube polymer nanocomposites to release nanoparticles into the environment as the polymer matrix degrades or is mechanically stressed. The majority of artificial joints incorporate biomedical grade ultrahigh molecular weight poly ethylene (UHMWPE), whose wear is considered most important in controlling service time of the whole joint, [14].

The main parameters acting on the characteristics of thermoplastic composites: matrix nature and reinforcement: material, loading level, form, and arrangement without forgetting some basic design principles, [15].The effect of carbon nanotube (CNT) reinforcement on the sliding wear behavior of epoxy (EP) and ultra-high molecular weight polyethylene (UHMWPE) was studied under uniform sliding against martensitic bearing steel (100Cr6) and austenitic stainless steel (X5CrNi18-10) in a ball-on-prism arrangement, [16].The field of material surface modification with the aim of biomaterial construction involves several approaches of treatments that allow the preparation of

materials, which positively influence adhesion of cells and their proliferation and thus aid and improve tissue formation, [17].

An analysis has been made of the literature on friction and wear of polymer nanocomposites prepared by compounding nanofillers with molten thermoplastics, [18]. Zirconia-based ceramics have been introduced in biomedical applications, for example, in hip implants, [19]. Certain zirconia composites are prone to spontaneously transform from the tetragonal phase to the monoclinic phase during long-term storage in the presence of moisture at low temperatures.

The structure-properties-processing relationship of poly(butylene terephthalate) (PBT) nanocomposites. The chapter first reviews PBT binary nanocomposites and PBT ternary nanocomposites, [20]. It is known that graphite has excellent lubricant properties due to the 2D graphene layers bonded via van der Waals forces, [21]. Thus, graphite nanoplatelets (GNPs) should have high lubricating efficiency during contact frictional movement of sliding parts. Microstructure and tribological properties of copper-based hybrid nanocomposites reinforced with copper coated multiwalled carbon nanotubes (MWCNTs) and silicon carbide (SiC) were studied, [22]. The effect of the ionic liquids (ILs) with respect to their anion type and the length of alkyl chain as dispersing and coupling agent in carbon nanotube (CNT) filled styrene butadiene rubber (SBR)/natural rubber (NR) blends, [23]. The development of bioceramic materials is at the forefront of health-related issues in many countries. Arguably, research into ceramic biomaterials has reached a level of involvement and sophistication comparable only to electronic ceramics, [24].

The aim of the present work is to study friction of new polymeric nanocomposite material which consist of HDPE, LDPE and PS and filled with CNTs as well as paraffin oil. The frictional behavior of the proposed composites is investigated at different values of applied load.

EXPERIMENTAL

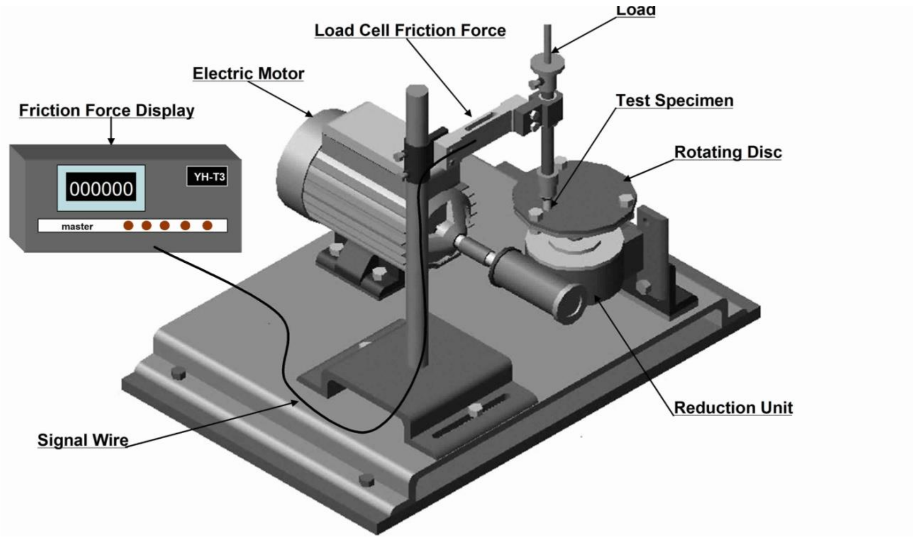

Fig.1. Arrangement of test rig.

Experiments were carried out using pin-on-disc wear tester. It consists of a rotary horizontal steel disc driven by variable speed motor. The details of the wear tester are shown in Fig. 1. The test specimen made of the proposed polymeric composites is held in the specimen holder that fastened to the loading lever. Friction force is measured by means of the load cell. The steel disc is fastened to the rotating disc. Its surface roughness was about 3. 2 µm, R_a. Test specimens are in the form of cylindrical pins of 6 mm diameter. Tests are carried out under constant sliding velocity of 2.0 m/s and 1.2, 1.8 and 2.4 N applied load. Every experiment lasted 5 minutes. All measurements were performed at 30 °C and 10 % humidity.

The test specimen in the form of a cylinder is 10 mm diameter and 70 mm height. This diameter was reduced to 6 mm to be in contact to the steel disc. The tested polymeric materials were HDPE, HDPE and PS. Those polymers were reinforced by CNTs and filled by paraffin oil. All these constituents were molded in a die at 150 °C temperature by using hydraulic press. CNTs were added to polymer in different contents (0.2, 0.4, 0.6, 0.8 and 1 wt. %) while oil contents were 1, 2, 3, 4 and 5 wt. %.

RESULTS AND DISCUSSION

The effect of reinforcing the tested composites by CNTs on friction coefficient is shown in Figs. 2 – 4, where friction coefficient slightly increased with increasing NCTs content. Friction coefficient of PS composites gave the highest values followed by LDPE and HDPE, Fig. 2. The same trend was observed at 1.8 and 2.4 N load, Figs. 3 and 4 respectively. The reason of friction increase is attributed to the abrasive action of CNTs. Besides, CNTs strengthened the polymeric matrix and increased its shear strength and consequently friction force increased.

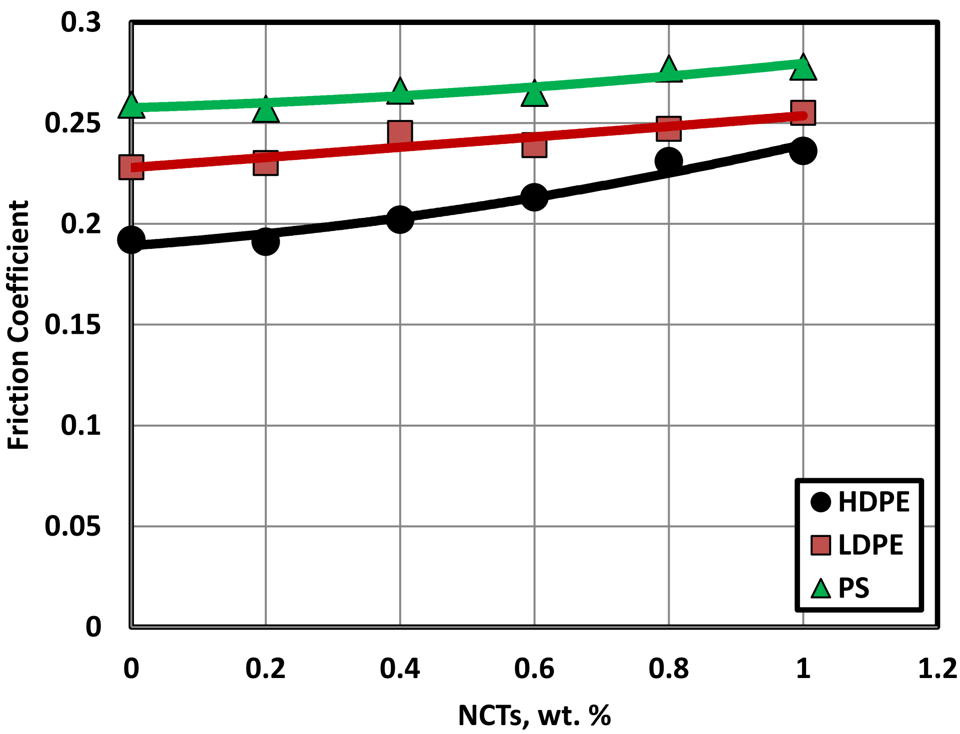

Fig. 2 Friction coefficient displayed by polymers sliding against steel at 1.2 N load.

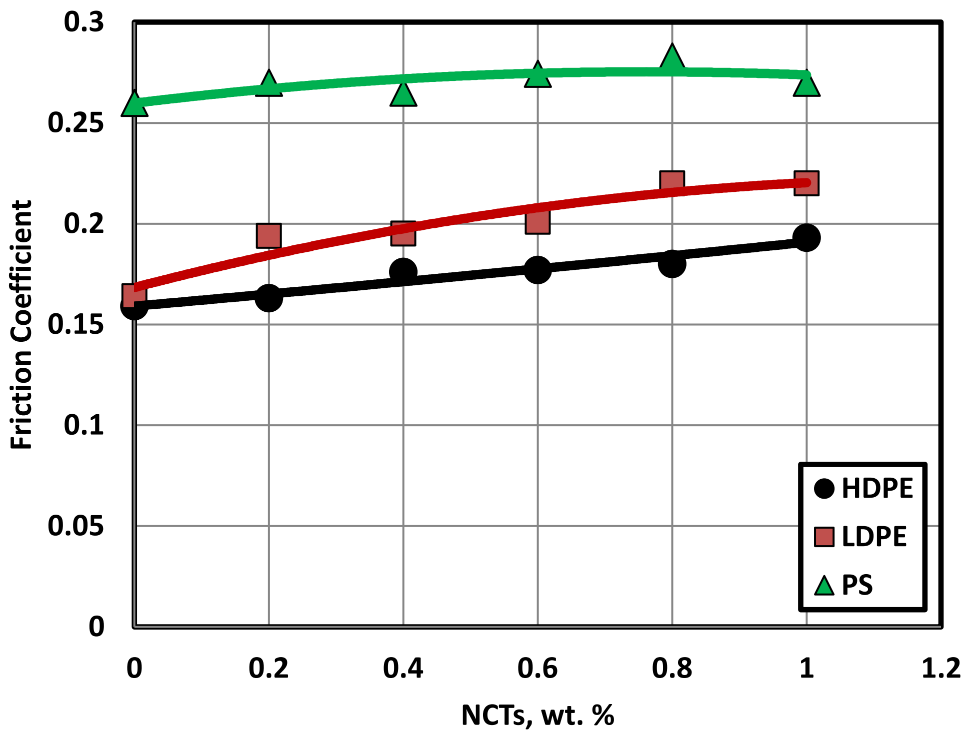

Fig. 3 Friction coefficient displayed by polymers sliding against steel at 1.8 N load.

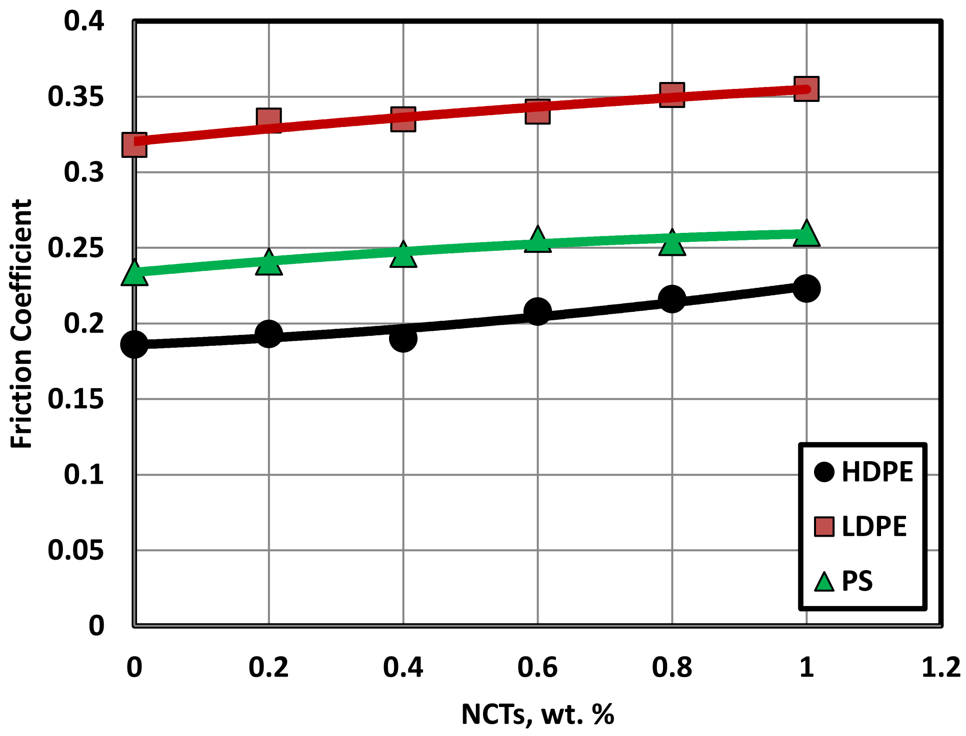

Fig. 4 Friction coefficient displayed by polymers sliding against steel at 2.4 N load.

Wear of the tested composites is illustrated in Figs. 4, 5 and 6 at 1.2, 1.8 and 2.4 N load respectively. It can be seen that wear drastically decreases down to minimum then significantly increased with increasing CNTs content. Minimum wear values were observed at 0.6 wt. % CNTs. The reduction of wear can be explained on the basis that reinforcing the tested polymers by CNTs makes the micro-cracks propagation more difficult, allowing an increase in tensile strength. This may be regarded to the strong interfacial property between the CNTs and polymer, where the stress is efficiently transferred from the reinforcement to the matrix through the excellent interface during compressive loading. As CNTs content increases the tubes will agglomerate and separate the layers of the polymer to be well bonded to each other. In the absence of sufficient interfacial adhesion between the CNTs and polymer, the tubes will be simply pull-out and will not contribute towards decreasing wear resistance of the composites.

An investigation of the tribology of three thermoplastic polymer composites based on polytetrafluorethylene, polyethylene terephthalate and polyamide, that are considered to be used as sliding bearings in nanopositioning, was carried out, [25]. It was observed that, the high Young's modulus was found to be beneficial for the formation of a thin transfer film responsible of a low and stable friction coefficient. The low yield strength resulted in a thick transfer film, which caused large fluctuations in the friction coefficient. This behavior can influence both wear and friction, where CNTs are able to increase the mechanical properties of the composites providing a relatively high Young's modulus. Besides, CNTs could reduce the adherence of the polymer transfer film onto the steel counterface by forming a layer of the tubes separating the two sliding surfaces.

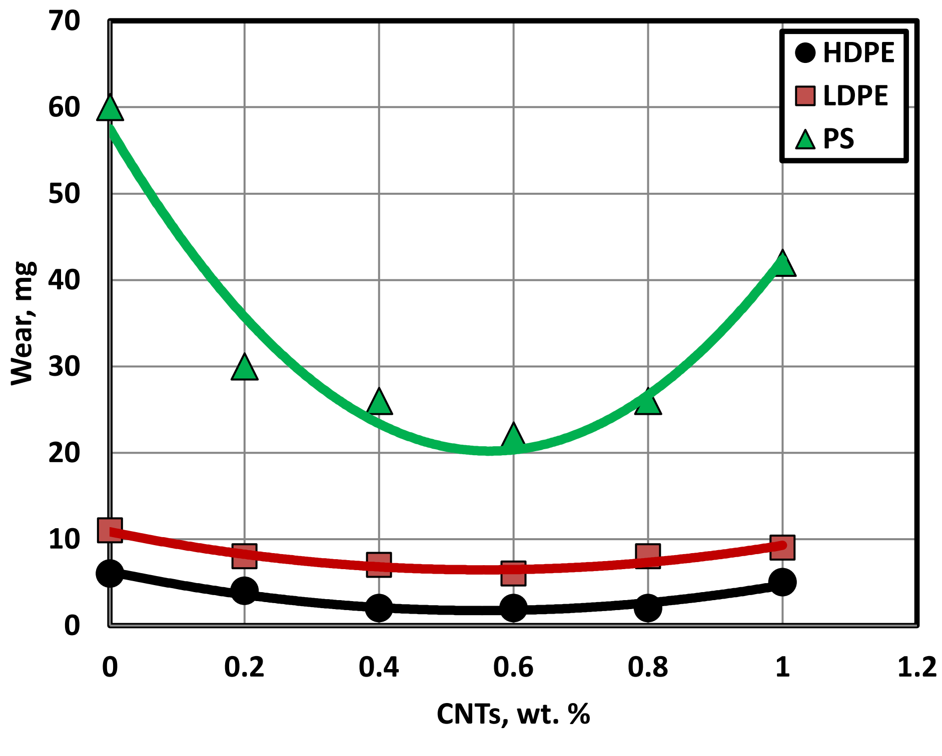

Fig. 5 Wear of polymers sliding against steel at 1.2 N load.

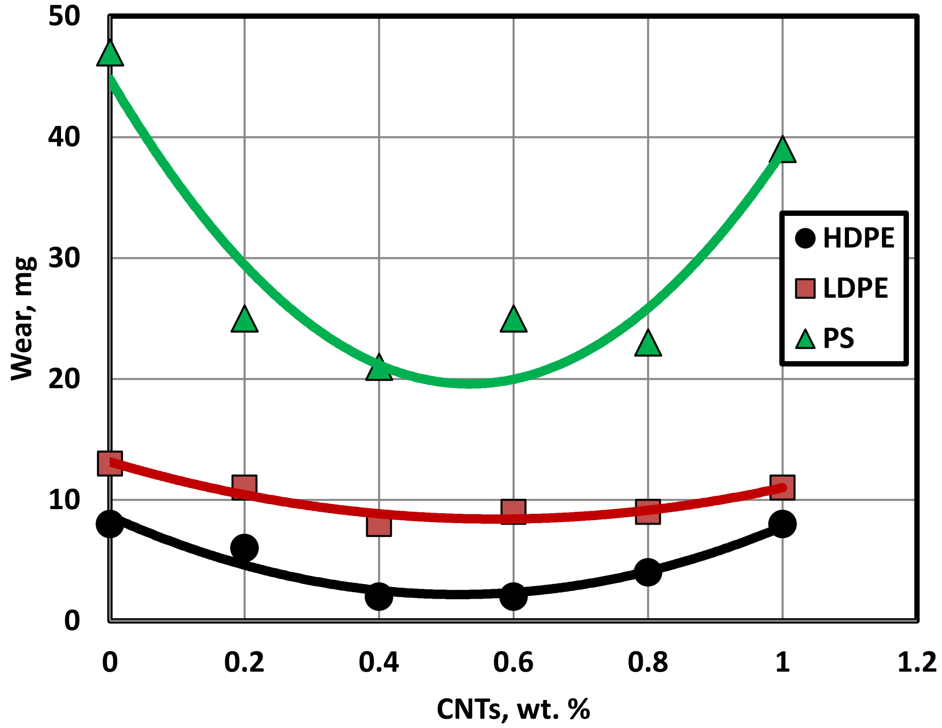

Fig. 6 Wear of polymers sliding against steel at 1.8 N load.

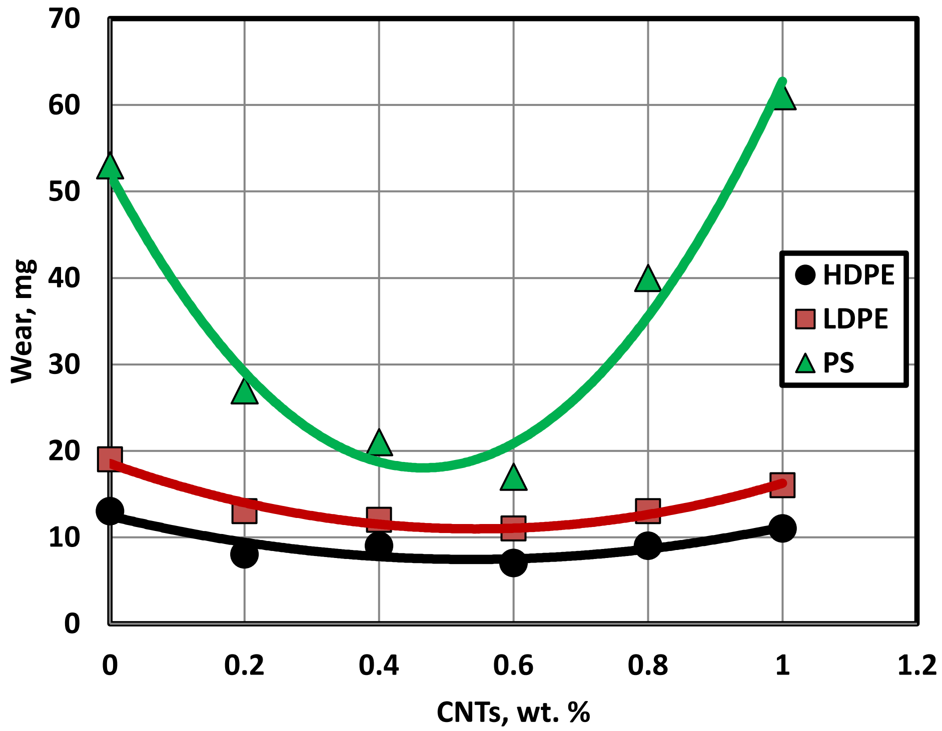

Fig. 7 Wear of polymers sliding against steel at 2.4 N load.

The followings are the results of the friction and wear displayed by the tested polymers filled by 5.0 wt. % paraffin oils and reinforced by CNTs, Figs. 8 - 13. Generally, friction coefficient showed lower values than that observed for composites free of oil. Friction coefficient slightly decreased with increasing CNTs content. It seems that the friction decreased because nanotubes could act as a third body in the contact region. Presence of oil in multi-pores inside polymer matrix, where they work as reservoirs of oils and leak up to the sliding surface is responsible for friction decrease. Presence of oil decreases friction coefficient due to the film formed on sliding surface, where the contact will be between partially polymer composites/steel and oil/steel due to the mixed lubrication regime offered by the oil film. HDPE composites displayed minimum friction coefficient, while PS showed the highest values. Besides, oil impregnated in the matrix enhances the release of NCTs from the matrix during sliding, which then prevented direct contact of worn surfaces, worked as rollers and hence decreased friction coefficient.

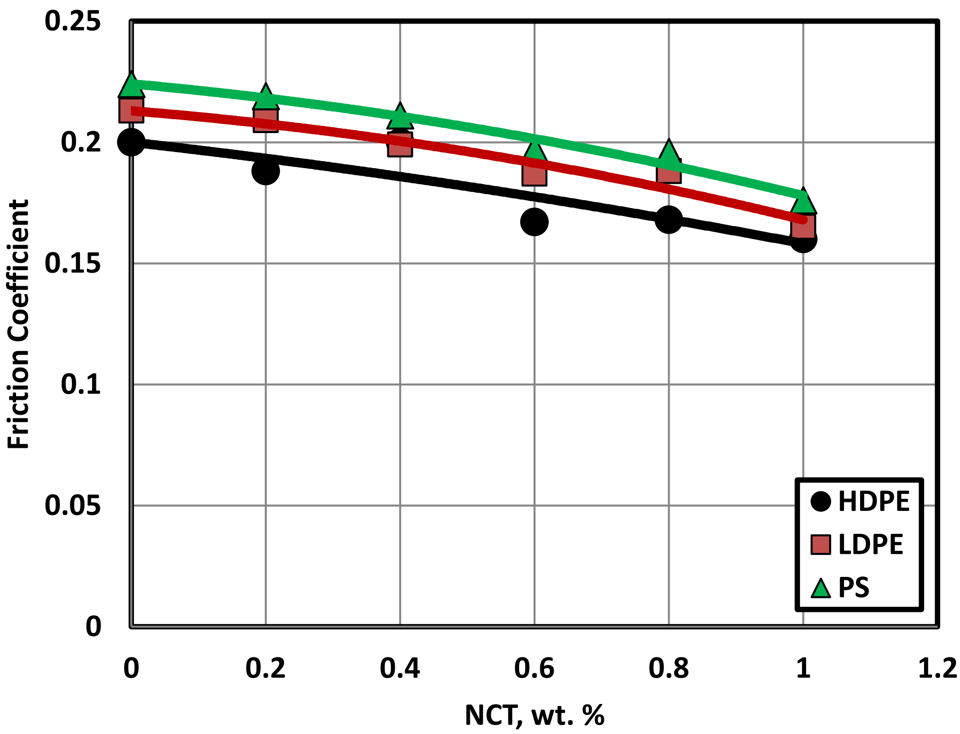

Fig. 8 Friction coefficient displayed by polymers filled by 5.0 wt. % oil and sliding against steel at 1.2 N load.

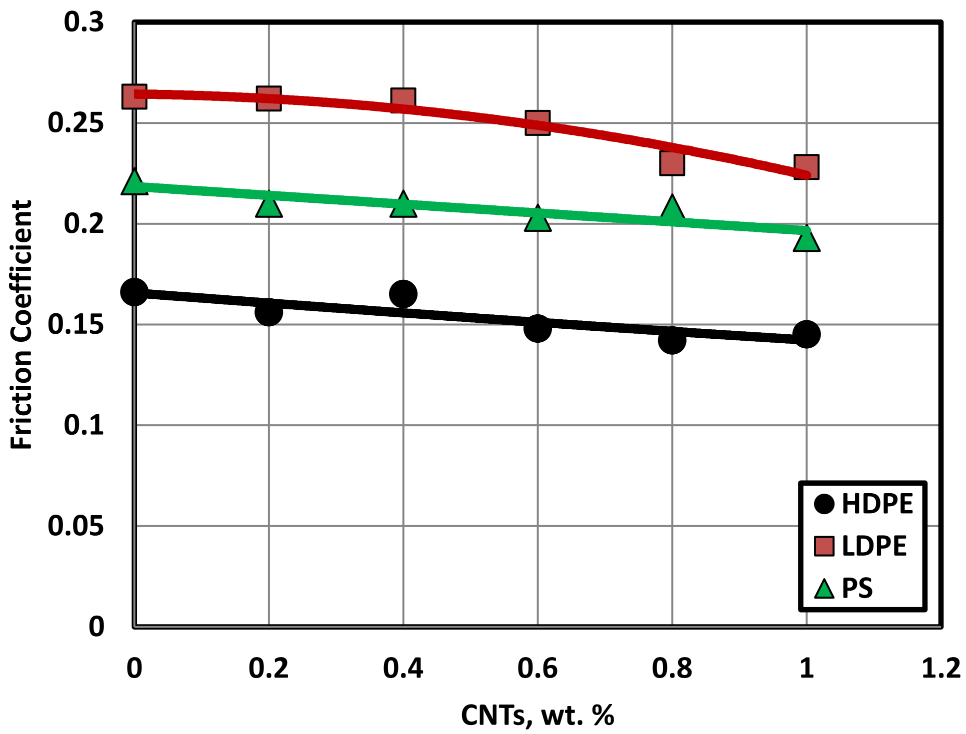

Fig. 9 Friction coefficient displayed by polymers filled by 5.0 wt. % oil and sliding against steel at 1.8 N load.

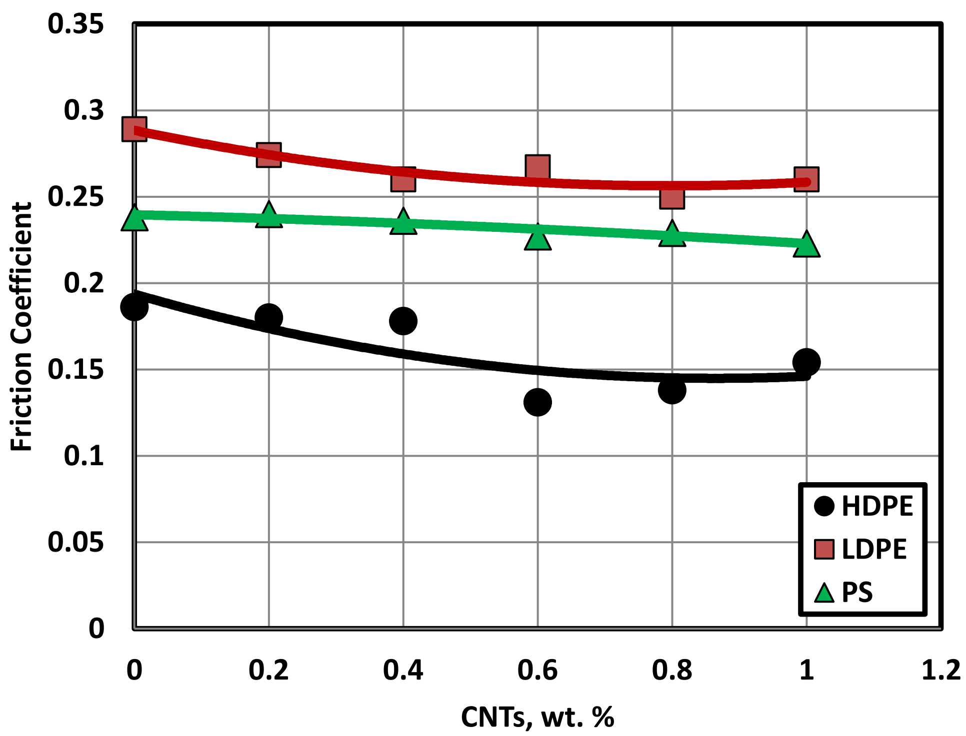

Fig. 10 Friction coefficient displayed by polymers filled by 5.0 wt. % oil and sliding against steel at 2.4 N load.

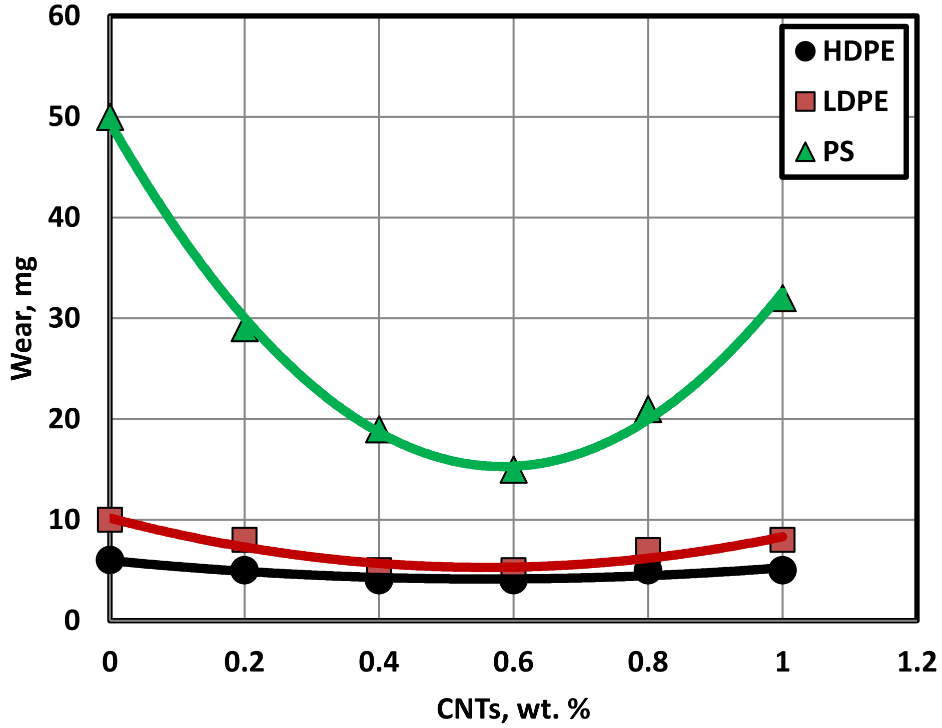

Fig. 11 Wear of polymers filled by 5.0 wt. % oil and sliding against steel at 1.2 N load.

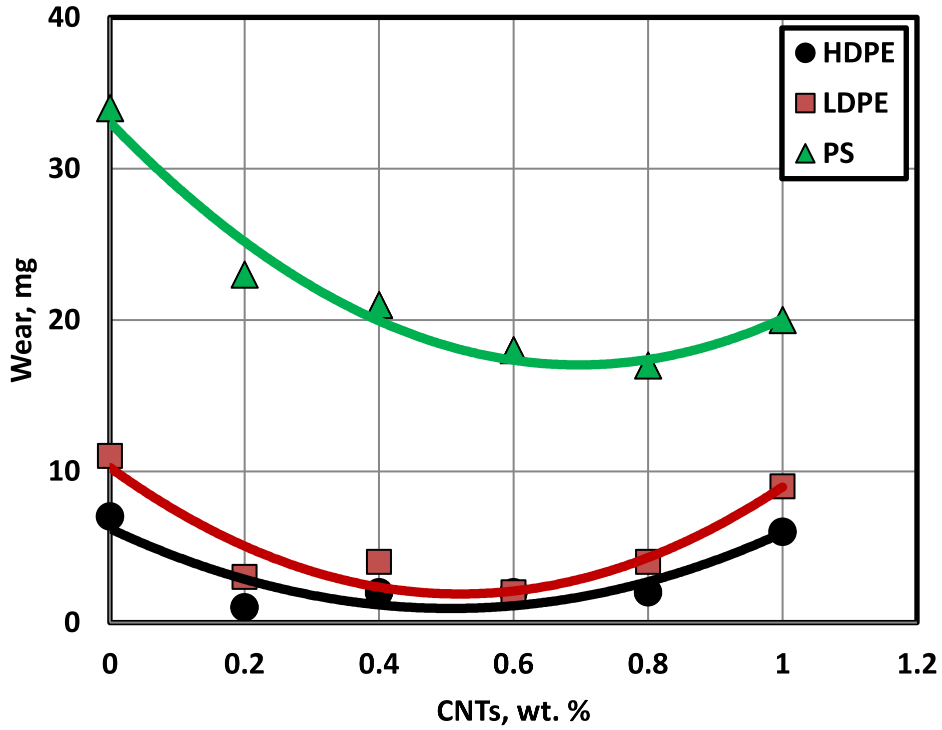

Fig. 12 Wear of polymers filled by 5.0 wt. % oil and sliding against steel at 1.8 N load.

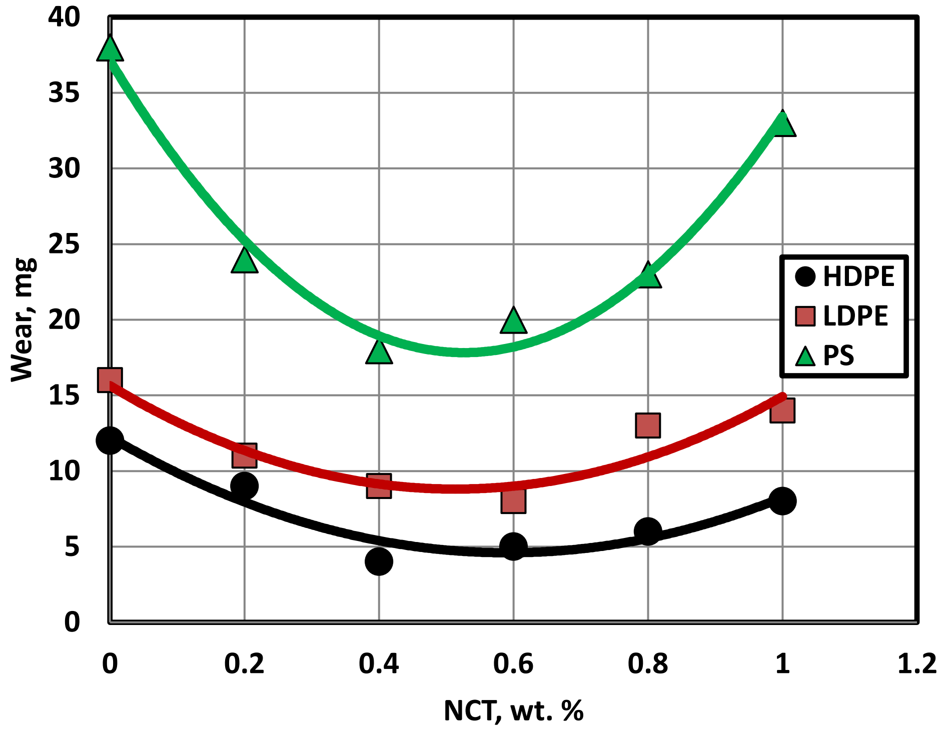

Fig. 13 Wear of polymers filled by 5.0 wt. % oil and sliding against steel at 2.4 N load.

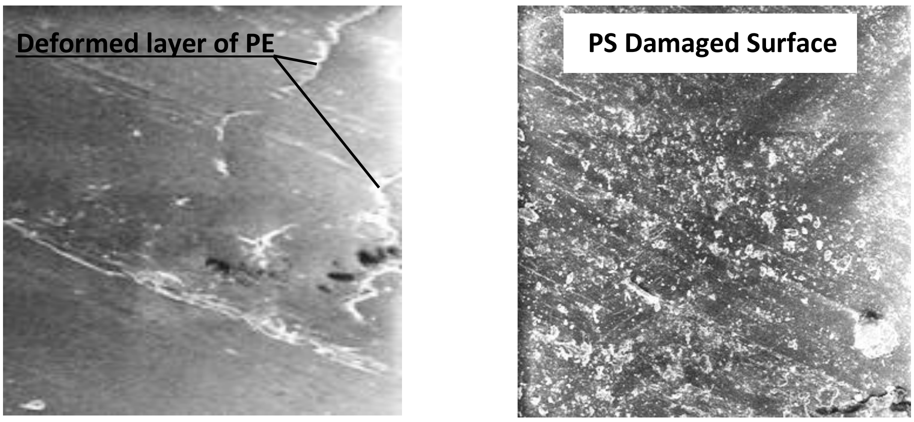

Fig. 14 Evidence of wear on PE and PS surfaces.

Wear of polymers filled by 5.0 wt. % oil is shown in Figs. 11 – 13. The same trend of the composites free of oil is noticed for the oil filled ones. Values of wear were lower in the presence of oil in the matrix of the polymer. A possible reason is that the CNTs can efficiently delay the onset of matrix cracking and increase the fracture toughness due to their high aspect ratio and strong interfacial bonding. It was proved that the hardness of the composites increased by increasing the CNTs content. This may be regarded to its relatively high mechanical properties and aspect ratio. The hardness of composites was increased due to the overlap and stacking of CNTs, which reduce the movement of polymer molecules, lead to increase the resistance of material to scratch, cut, and plastic deformation. Hardness of materials depended on the type of forces that bond between atoms and the strong linkages at the interface between phases. CNTs increase

the coherence of the mixture, which increases the hardness of composites as shown. It is thus cleared that the incorporation of CNTs as reinforcing agent helps to increase the load-carrying capacity and mechanical properties of polymer composites. The evidence of wear on the surfaces of PE and PS is shown in Fig. 14, where PE suffered from severe plastic deformation. PS showed very tiny wear particles distributed on the worn surface accompanied by severe damage.

COONCLUSIONS

1. Friction coefficient slightly increased with increasing NCTs content. Friction coefficient of PS composites gave the highest values followed by LDPE and HDPE.

2. Wear drastically decreases down to minimum then significantly increased with increasing CNTs content. Minimum wear values were observed at 0.6 wt. % CNTs.

3. Friction displayed by the tested polymers filled 5.0 wt. % paraffin oils and reinforced by CNTs showed lower values than that observed for composites free of oil. Friction coefficient slightly decreased with increasing CNTs content. HDPE composites displayed minimum friction coefficient, while PS showed the highest values.

4. Values of wear were lower in the presence of oil in the matrix of the polymer. Incorporation of CNTs as a reinforcing agent helps to increase the load-carrying capacity and mechanical properties of polymer composites.

5. It is recommended to use HDPE filled by 5.0 wt. % paraffin oils and reinforced by CNTs as self lubricated bearings at dry sliding applications.

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