EGTRIB Journal
JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 15, No. 2, April 2018, pp. 12 - 30 ISSN 2090 - 5882
(Received January 19. 2018, Accepted in final form March 25. 2018)

TRIBOLOGICAL PROPERTIES OF HEAT TREATED HIGH DENSITY POLYETHYLENE REINFORCED BY COPPER WIRES

Mayada S. A. and Ali W. Y.

Department of Production Engineering & Mechanical Design, Faculty of Engineering, Minia University, El-Minia – 61111, EGYPT.

ABSTRACT

The friction and wear of high density polyethylene (HDPE) composites reinforced by unidirectional continuous copper wires of 0.4 mm diameter are discussed in the work. Heat treatment processes (annealing, tempering and hardening) were carried out to study their effect on the tribological properties of the tested specimens.

Based on the experimental observations, it was found that friction coefficient displayed by the scratch of HDPE reinforced by copper wires decreased with increasing number of wires up to 8 then it started to increase at 10 wires. It seems that the presence of copper wires decreased the hardness of the polymeric materials so that the material removal by the indenter was easier while at number of wires 10, friction became between the scratching tool and wires themselves due to narrow area between wires that caused the increase of the friction coefficient. The influence of heat treatment of test specimens on their friction and wear was investigated. By annealing at 90 °C and hardening at 120 °C, friction coefficient significantly increased with increasing normal load while it decreased by tempering at 110 °C. Tempered specimens displayed the lowest friction values, while specimens without heat treatment showed the highest values. Friction coefficient displayed by HDPE composites reinforced by unidirectional continuous copper wires recorded lower friction for tempered test specimens followed by hardened and annealed ones.

Wear scar width of the tested composites slightly decreased with increasing number of wires. The wear decrease of the tested composites can be explained on the basis that the presence of wire reinforcement can restrain the deformation of the polymer matrix. Besides, plastic deformation, grooving and smearing of surface can be decreased by the strengthening effect of the reinforcement as well as the retarding action of the copper wire against the motion of the indenter. By annealing at 90 °C and hardening 120 °C the wear scar width increased with increasing normal load while it decreased by tempering at 110 ° C. Annealed specimens displayed relatively higher wear scar width

than hardened and tempered specimens. Tempered specimens showed the lowest wear scar width values.

KEYWORDS

Friction coefficient, wear, scratch, high density polyethylene, copper wires, annealing, hardening, tempering.

INTRODUCTION

Polymers play an important part in materials and mechanical engineering, not just for their ease in manufacturing and low unit cost, but also for their potentially excellent tribological performance in engineered forms, [1]. In the pristine or bulk form, only a few of the polymers would satisfy most of the tribological requirements; however, in the composite and hybrid forms, polymers often have an advantage over other materials such as metals and ceramics. Polymer tribology, as a research field, is now well mature given that roughly 50 plus years have seen publication of numerous research articles and reports dealing with a variety of tribological phenomena on a considerably large number of polymers, in bulk, composite and hybrid forms. Tribological applications of polymers include gears, a range of bearings, bearing cages, artificial human joint bearing surfaces, bearing materials for space applications including coatings, tires, shoe soles, automobile brake pads, nonstick frying pans, floorings and various types of surfaces for optimum tactile properties such as fibers. The list is growing. For example, in the new area of microelectromechanical systems (MEMS), polymers (such as polymethylemethacrylate) (PMMA) and poly(dimethylsiloxane) (PDMS)) are gaining popularity as structural materials over the widely used material, [2]. Often, Si is modified by a suitable polymeric film in order to enhance frictional, antiwear or antistiction properties, [3].

The friction and wear of polyethylene (PE) matrix composites reinforced by unidirectional continuous steel and copper wires of different diameters were discussed, [4, 5]. On the basis of experimental results, it was found that friction coefficient displayed by the scratch of reinforced PE decreased with increasing number of wires. As the load increased friction coefficient increased. It seems that the presence of metallic wires decreased the hardness of the polymeric materials so that the material removal by the indenter was easier. Wire diameter had insignificant effect on friction coefficient. The friction and wear of polypropylene matrix composites reinforced by unidirectional continuous copper wires are discussed, [6]. It was found that friction coefficient displayed by the scratch of PP reinforced by copper wires showed slight decrease with increasing number of wires, where the load had insignificant effect on friction coefficient. The change of wire diameter had slight effect on friction coefficient. The hardness decreased close to the wire due to the change of the cooling rate, where the zone near the copper wire was cooling faster and causing a decrease in polymer hardness.

Wear of the tested composites slightly decreased with increasing number of wires. Increase of wire diameter showed insignificant effect on wear which significantly increased with increasing normal load. The wear decrease of the tested composites can be explained on the basis that the presence of wire reinforcement can restrain the

deformation of the polymer matrix. Besides, plastic deformation, grooving and smearing of surface can be decreased by the strengthening effect of the reinforcement as well as the retarding action of the copper wire against the motion of the indenter.

The effect of different filling materials, namely, silicon oxide, iron, copper, glass fiber and aluminum oxide on friction and wear of polyamide was investigated, [7, 8]. It was found that addition of glass fiber of concentration up to 10 wt. % as well as sand, (10 - 20) pm, and concentration of 5 wt. % reduced friction and improved wear resistance. Polyamide fibers as filling material in polyamide coatings enhanced abrasive wear resistance. The enhancement increased with increasing fiber concentration and decreasing fiber diameter, [9]. Bi-directional cross plied reinforcement displayed considerable wear reduction. Tin coated steel wire as short fibers reinforcing polyamide coatings displayed minimum wear rate. The best performance was observed for the perpendicular short fibers.

Polymer composites are extensively used in many of tribological applications such as automotive and agricultural machinery as well as chemical industries. It was found that polyphenylene sulfide (PPS) composites filled with short carbon fibers and submicro-scale titanium oxide particles were prepared by extrusion and subsequently injection-molding, [10]. Polyamide 4, 6 and its aramid fiber composites were tested as candidate materials for tribological applications, [11]. Over the range of tests, the average coefficient of friction results showed that the Polyamide reinforced by 15 wt. % aramid fibers generally had the lowest values compared to the other types of samples. Friction and dry sliding wear behavior of glass and carbon fabric reinforced vinyl ester composites have been presented, [12]. The results show that the coefficient of friction and wear rate increased with increase in load/sliding velocity and depends on type of fabric reinforcement and temperature at the interphase.

Heat treatment of the polymers is considered one of the most effective methods of modification to widen their applications. Heat treatment of polymers improves their mechanical and tribological properties, [13]. This effect is a result of crystal phase increase in the polymer structure, where the elastic part of polymer viscoelasticity increases causing significant increase in compressive strength and heat conductivity. The physical and mechanical properties of polyamides are affected by the degree of crystallization, which can be controlled by the change of cooling rate during the production process. Presence of small particles such as fine silica dust in polyamide matrix can alter the nucleation and cause significant increase in tensile strength and hardness accompanied by reduction in the ductility and impact strength. It is essential to consider the variation of the morphology of the cast polymer because of the difference in the cooling rate from the surface to the center, where the outer surface will be less crystalline due to the rapid solidification rate and may be less resistant to wear.

In the current study, the friction and wear of HDPE composites reinforced by unidirectional continuous copper wires of 0.4 mm diameter are discussed in this work and the influence of heat treatment (annealing, hardening and tempering) on friction and wear was investigated.

EXPERIMENTAL

Specification of Test Specimens

The test specimens prepared from HDPE were in rectangular shape with 20 × 40 mm^2 and 3.0 mm thickness and reinforced by copper wires of 0.4 mm diameter. The numbers of wires reinforcing the test specimens were 0, 2, 4, 6, 8 and 10. The wires were distributed perpendicular to the direction of motion.

Preparation of Test Specimen

To prepare test specimens, HDPE which reinforcement of copper wires were molded in a die of 60 × 100 × 6 mm^3 at 150 °C temperature by using hydraulic press Fig. 1,2. These composites required approximately 1 hour in room temperature for cooling, after that the specimens were heat treated by annealing, tempering and hardening then experiments were carried out.

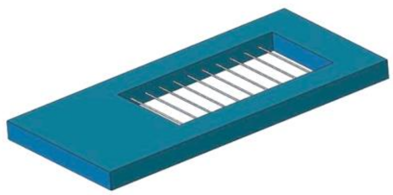

Fig. 1 Molding die of the test specimens.

Fig. 2, (A) Pressing the test specimens.

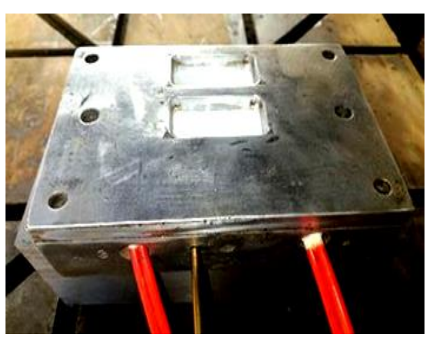

Fig. 2, (B) Heating of the test specimens.

Heat Treatment Process

Influence of heat treatment of HDPE on their friction and wear was investigated by applying the three processes of heat treatment, Fig. 3;

1. Annealing: - specimens were heated in furnace up to 90 °C / 4h then furnace cooled.

2. Hardening: - specimens were heated in furnace up to 120 °C / 4h then quenched (rapidly cooling in water).

3. Tempering: - Specimens were heated in furnace up to 110 °C / 4h then air cooled.

Fig. 3 Heat treatment of the test specimens.

TEST METHOD

Friction Test

Scratch tester shown in Fig. 4 was used in the experiments. It consists of a rigid stylus mount, a steel stylus of apex angle 90° and hemispherical tip. The stylus was mounted to the loading lever through three jaw chuck. A counter weight was used to balance the loading lever before loading. Vertical load was applied by weights of 2, 4, 6, 8 and 10 N. Scratch resistance force was measured using load cell mounted to the loading lever and connected to display digital monitor. The test specimen was held in the specimen holder mounted in a horizontal base with a manual driving mechanism to move specimen in a straight direction. The test specimens were scratched by an indenter. The test was conducted under dry conditions at room temperature. The test specimen under scratch action is shown in Fig. 5. The scratch force was measured during the test, then friction coefficient was calculated by using the relationship:

$\mu = F / N$

Where μ is the friction coefficient, F friction force and N normal load.

An optical microscope was used to measure scratch width with an accuracy of ± 1.0 µm. The evidence of the scratch test on the surface of the test specimen is shown in Fig. 6.

Hardness Test

Shore D Durometer instrument was used. Hardness was measured in a various distances from copper wire.

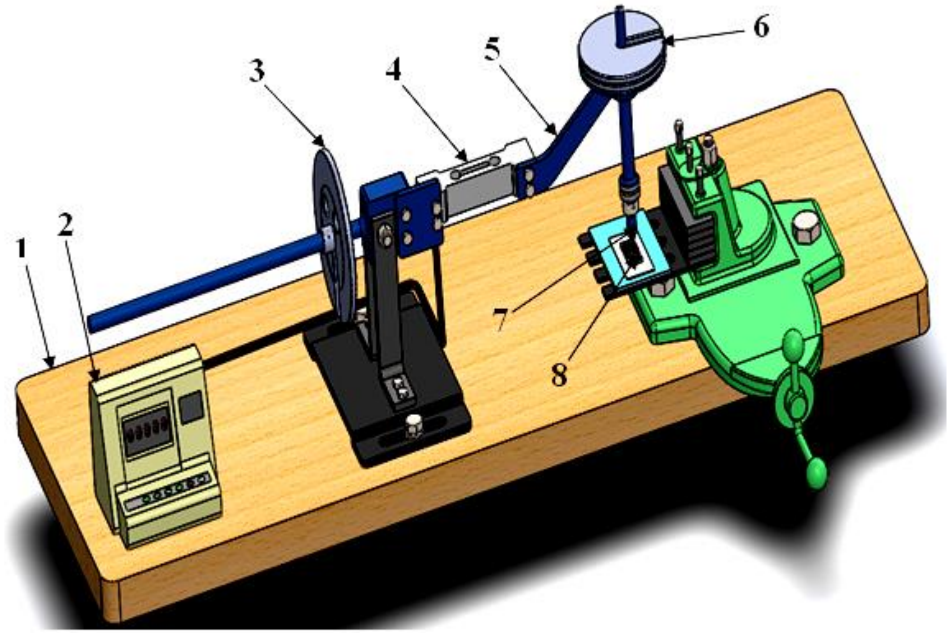

Fig. 4 Arrangement of scratch test rig; 1. Base, 2. Friction Force Screen, 3. Counter Weight, 4. Load Cell, 5. Loading Lever, 6. Normal Loads, 7. Scratching tool, 8. Test Specimen.

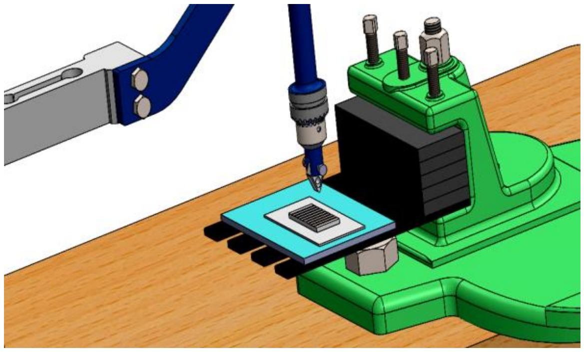

Fig. 5 Details of scratch.

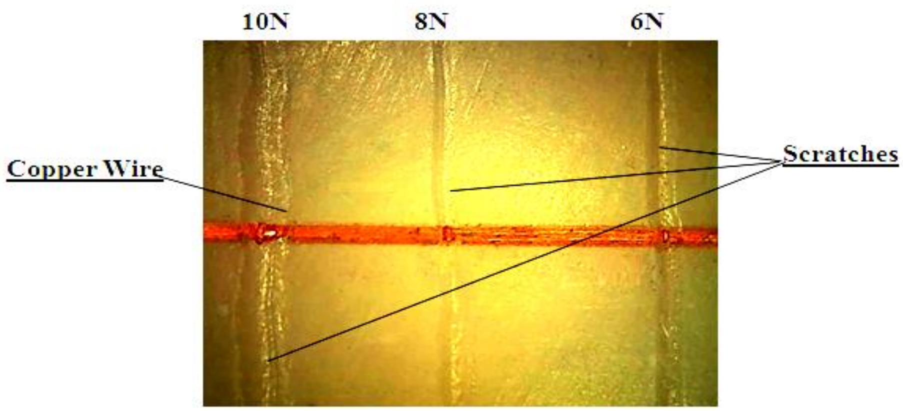

Fig. 6 scratch tests on the surface of the test specimen.

RESULTS AND DISCUSSION

Friction

The results of the experimental work carried out in the present work are shown in Figs. 7 – 22. As the load increased, friction coefficient increased due to the increased material removed during scratch. This behavior can be explained on the basis that as the load increased, the scratching tool embedded deeply in the HDPE matrix abrading relatively higher HDPE volume. Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires, Figs. 7, 8 showed significant decrease with increasing number of wires up to 8 wires then it started to increase at 10 wires. This behavior may be attributed to the fact that, the copper wires as good heat conductor transferred heat during molding out of the polymeric materials. This process increased the rate of cooling causing softening of HDPE matrix. As the cooling rate increased hardness of the tested polymers decreased and consequently friction coefficient remarkably decreased as the material removal by the indenter was easier. As result of that, the increased number of copper wires decreased the friction coefficient while at 10 wires, the friction becomes between the scratching tool and wires themselves due to narrow area between wires caused increase of friction coefficient. At 10 N loads, friction coefficient decreased from 0.130 for unreinforced HDPE to 0.081 for HDPE reinforced by 8 wires then increased to 0.114 for HDPE reinforced by 10 wires. The specimens without heat treatment displayed the highest friction coefficient.

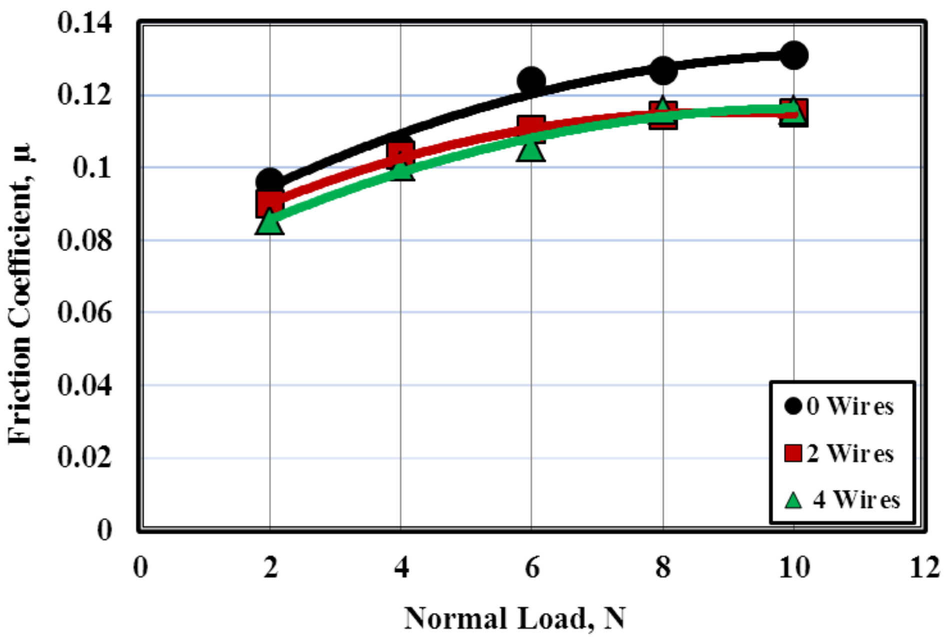

Fig. 7 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires.

The influence of heat treatment of the copper wires reinforcing HDPE composites on friction coefficient is illustrated in Figs. 9–14. Friction coefficient displayed by the scratch of HDPE reinforced by copper wires annealed at 90 °C and hardened at 120 °C Figs. 9-12, showed significantly increased with increasing normal load. Friction coefficient decreased with increasing number of wires up to 8 wires then it started to

increase at 10 wires. Friction coefficient displayed by the scratch of hardened HDPE composites at 120 °C recorded lower friction followed by those annealed at 90 °C. Unheated specimens showed the highest friction coefficient. The change in the friction caused by heat treatment can be attributed to the change of polymers crystallization. Heat treatment improves the mechanical and tribological properties of polymers. This effect is a result of crystal phase increase in the polymer structure, where the elastic part of polymer viscoelasticity increases causing significant increase in compressive strength and heat conductivity.

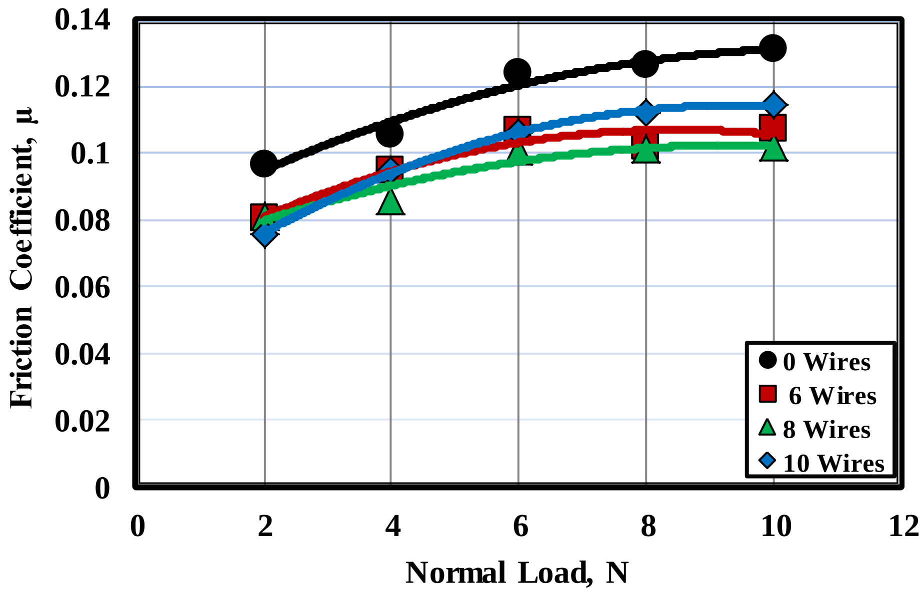

Fig. 8 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires.

Friction coefficient displayed by the scratch of HDPE tempered at 110 °C, Figs. 13 - 14, showed that as the load increased, friction coefficient decreased. This might be because of increasing the ductility by tempering. Friction coefficient displayed by tempered recorded the lowest value followed by hardened and annealed.

Wear

The wear displayed by the scratch of the tested composites is shown in Figs. 15 - 16. It was observed that wear scar width decreased with increasing number of copper. This behaviour may be attributed to the strengthening effect of copper wires as well as the effect of cooling rate. Reinforcing HDPE composite by copper wires was achieved to develop the mechanical properties and increase the wear resistance. The influence of heat treatment of the copper wires reinforcing HDPE composites on wear is illustrated in Figs. 17 – 22. Wear scar width significantly increased with increasing normal load by annealing and hardening while it decreased by tempering. HDPE composites free of copper wires showed relatively higher wear than that reinforced by copper wires. Wear followed same trend of friction coefficient, where tempered specimens showed the lowest wear. Annealed specimens displayed relatively higher wear than hardened and tempered tested composites. The specimens without heat treatment displayed the highest wear scar width while tempered recorded the lowest wear scar width.

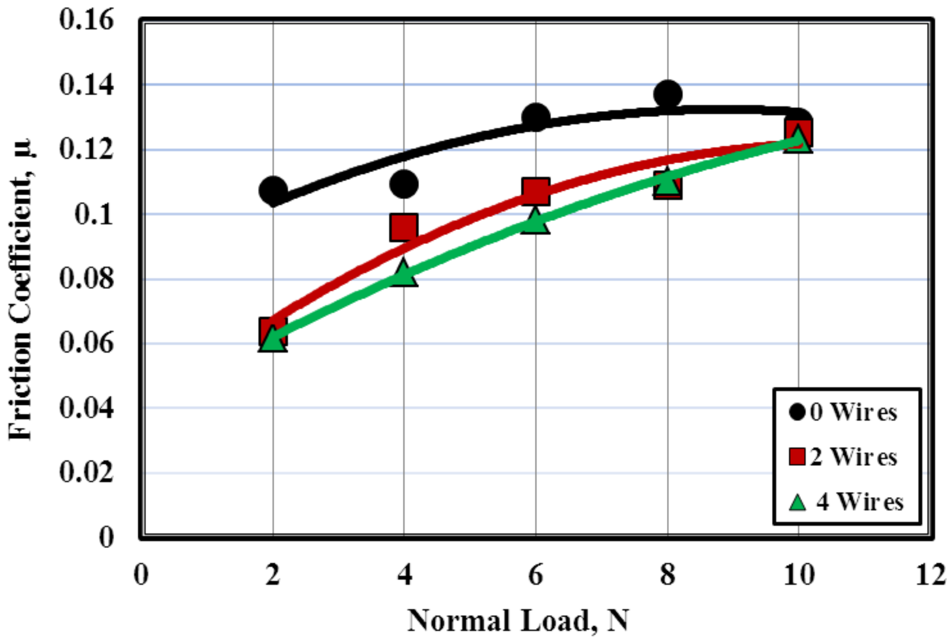

Fig. 9 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and annealed at 90 °C.

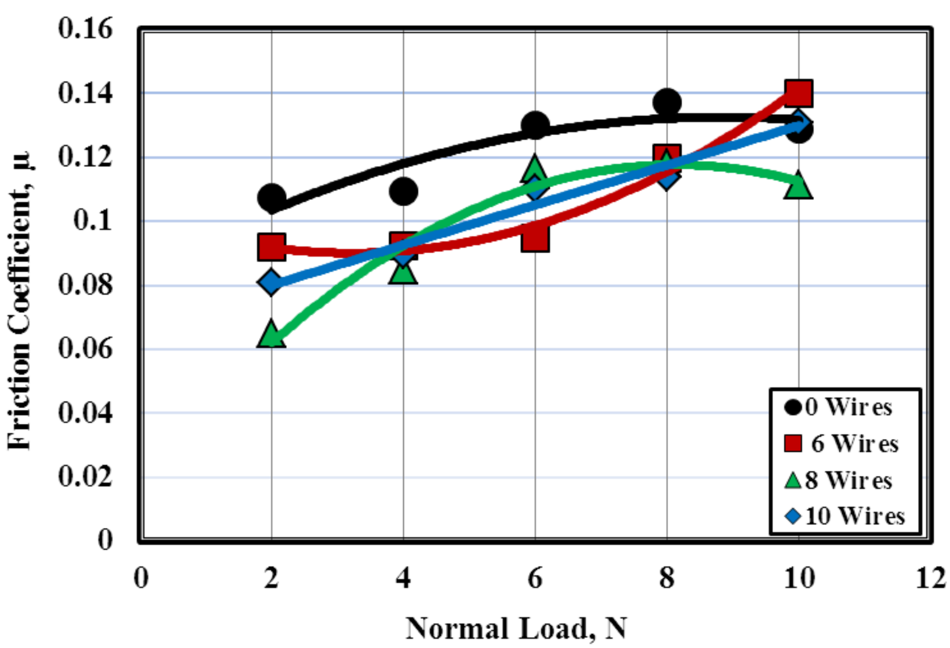

Fig. 10 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and annealed at 90 °C.

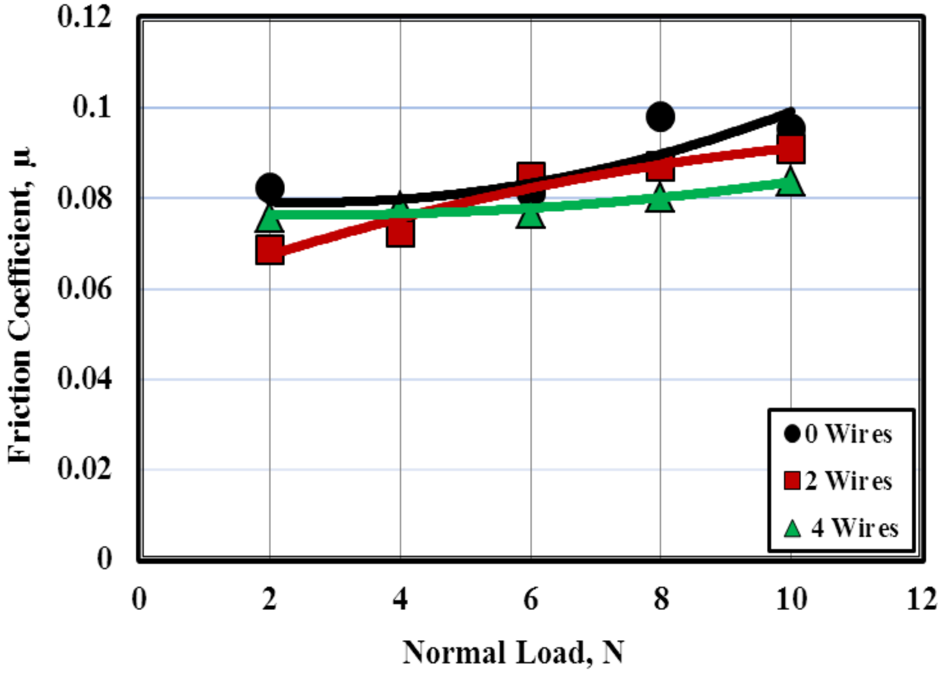

Fig. 11 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and hardened at 120 °C.

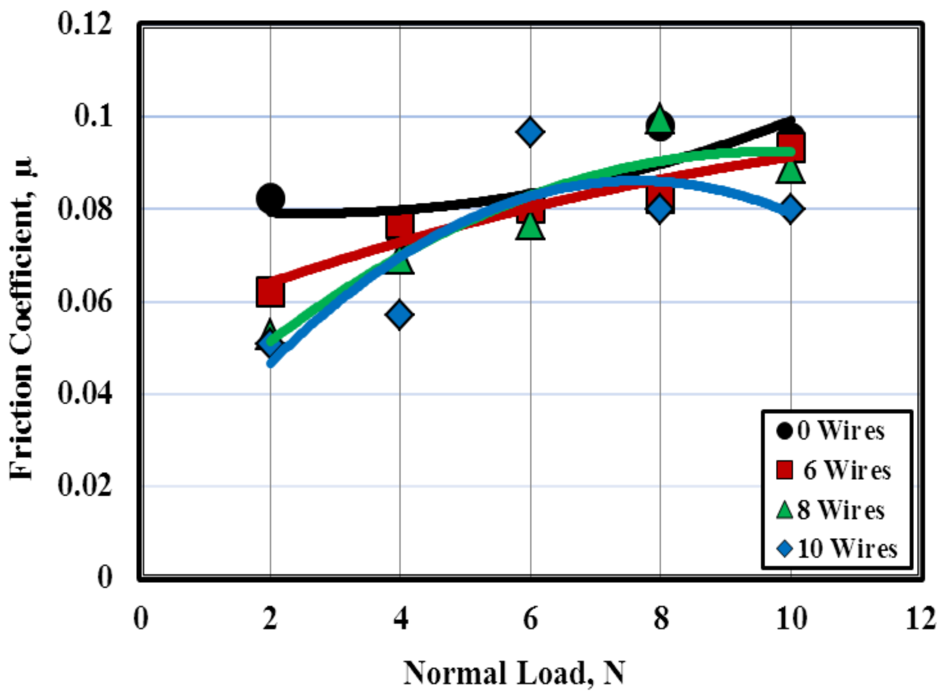

Fig. 12 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and hardened at 120 °C.

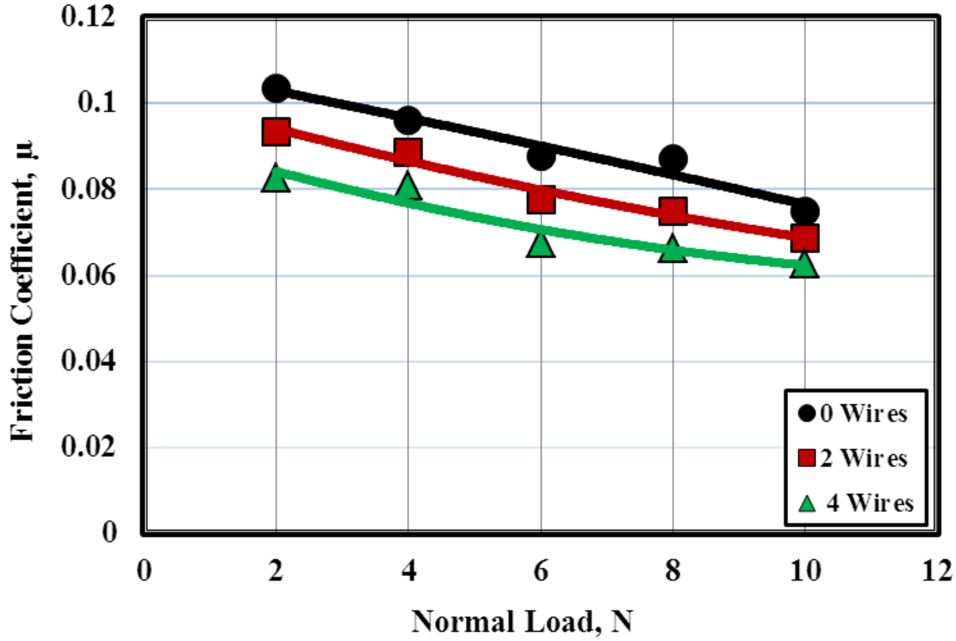

Fig. 13 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and tempered at 110 °C.

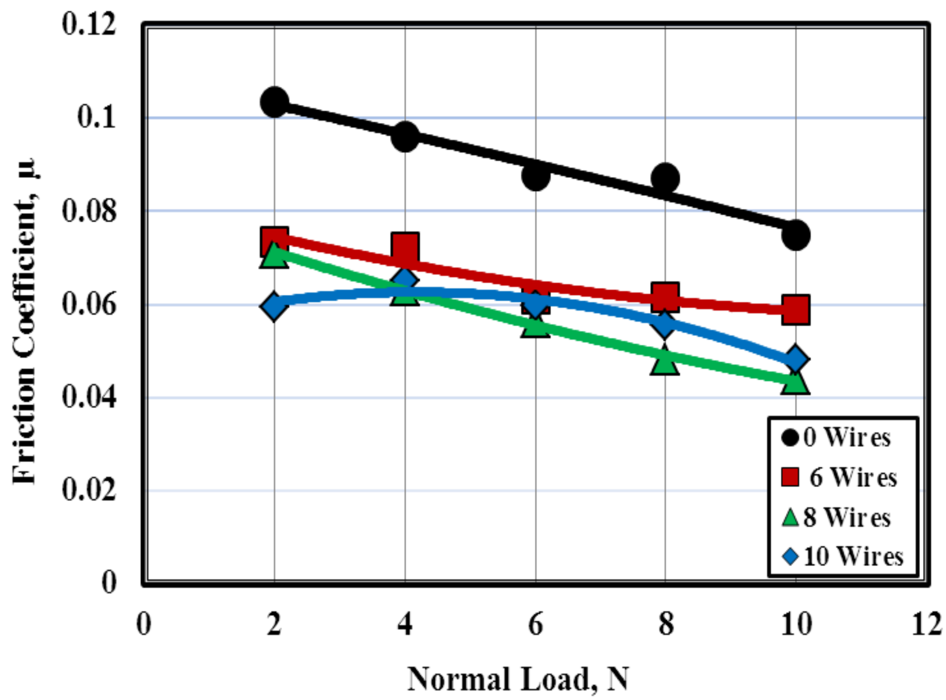

Fig. 14 Friction coefficient displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires treated by tempering at 110 °C.

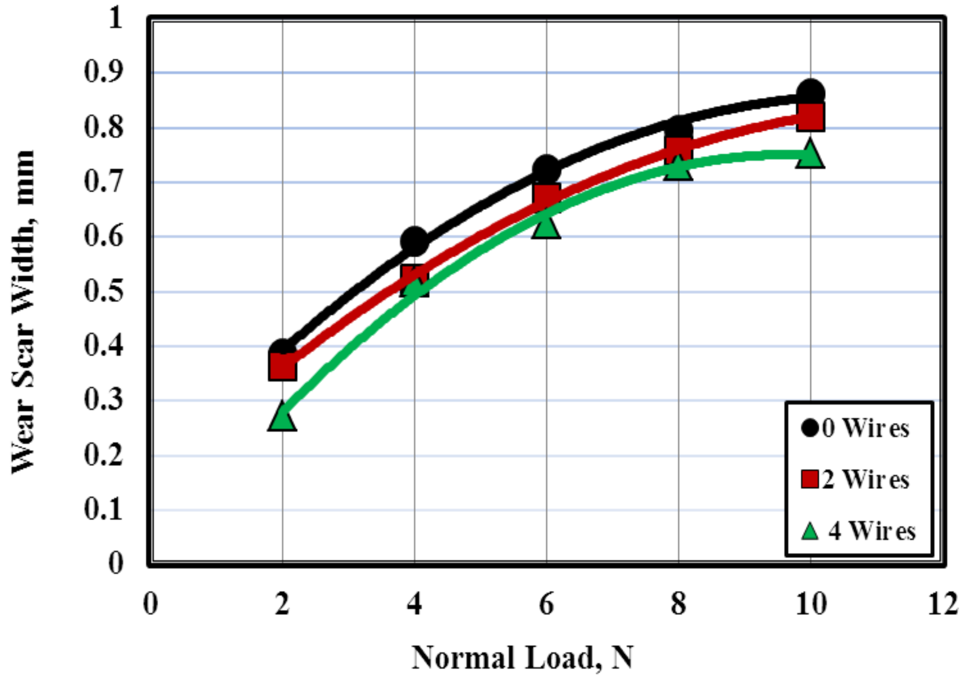

Fig. 15 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires.

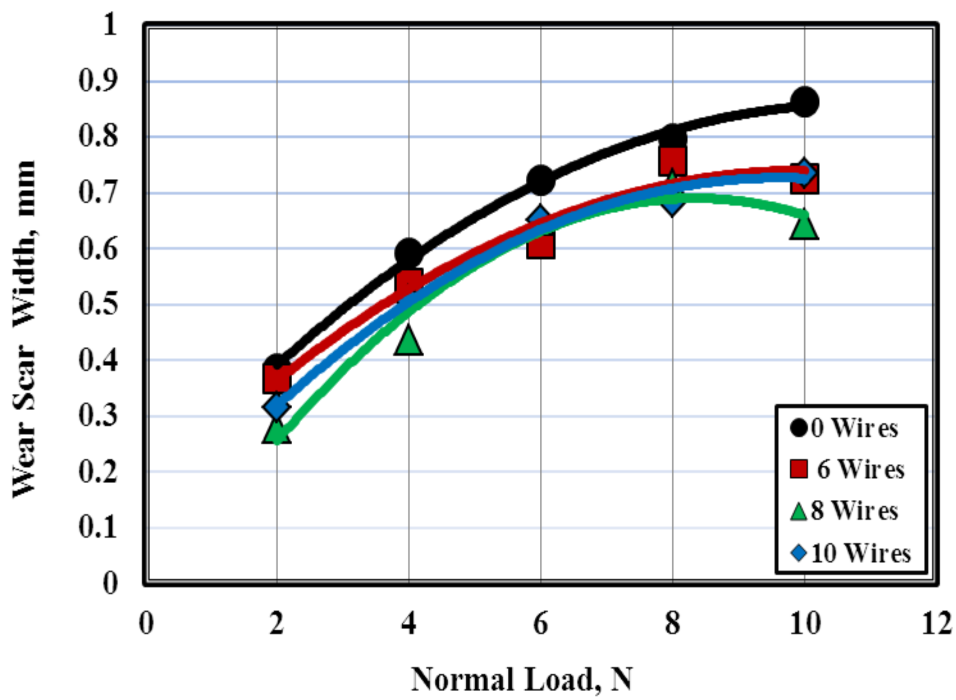

Fig. 16 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires.

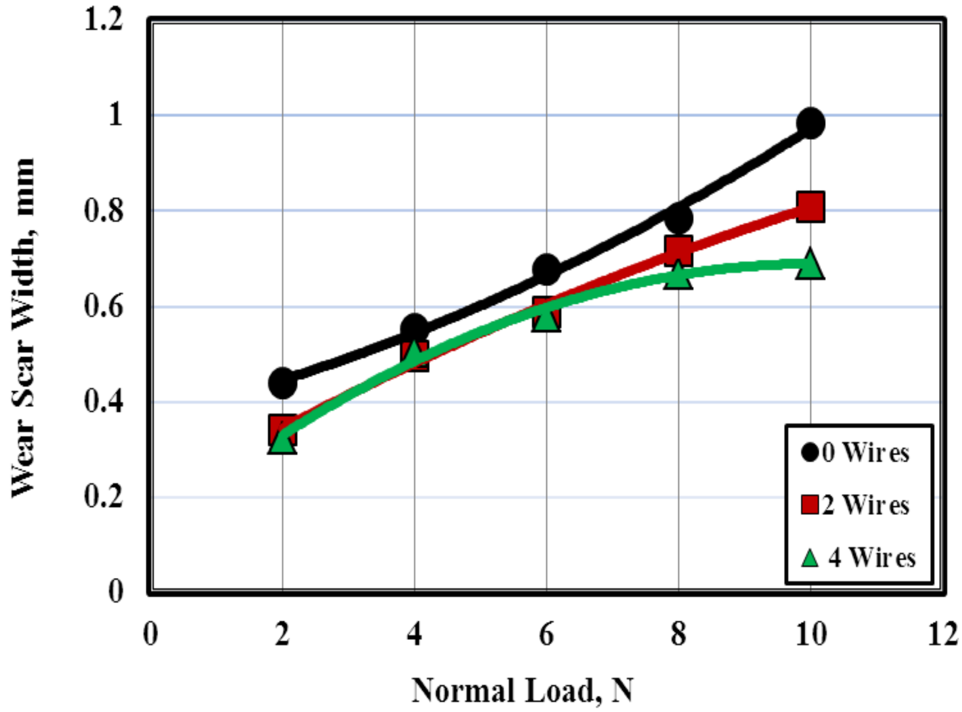

Fig. 17 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and annealed at 90 °C.

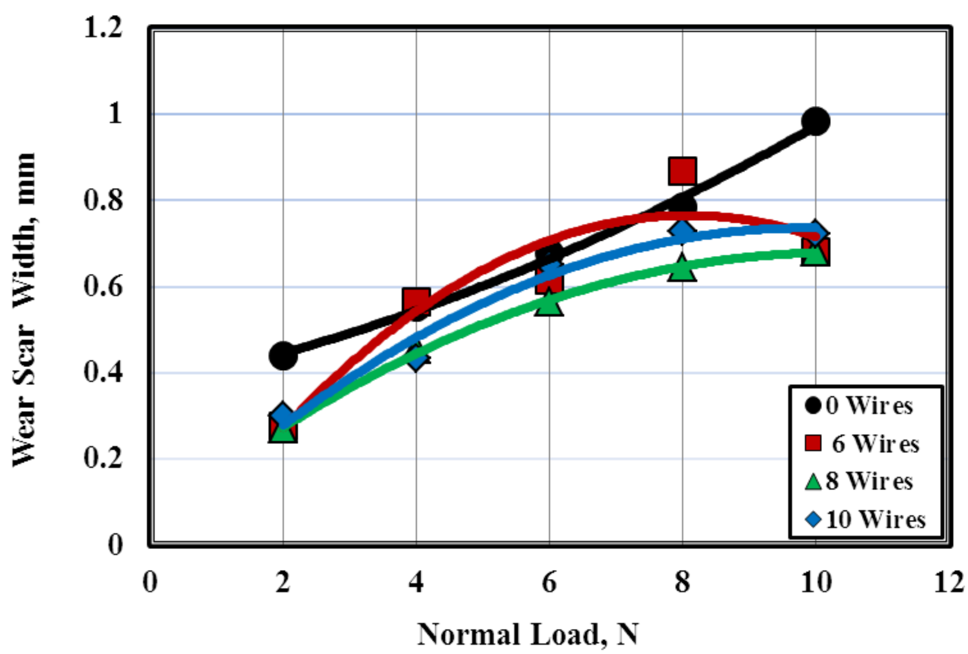

Fig. 18 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and annealed at 90 °C.

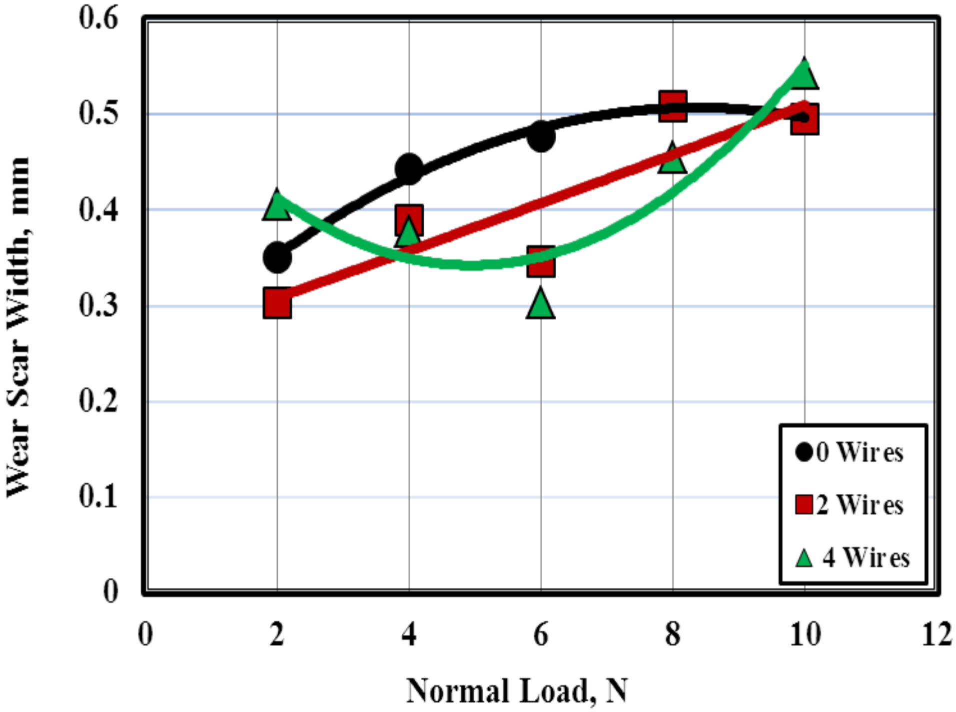

Fig. 19 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires hardnend at 120 °C.

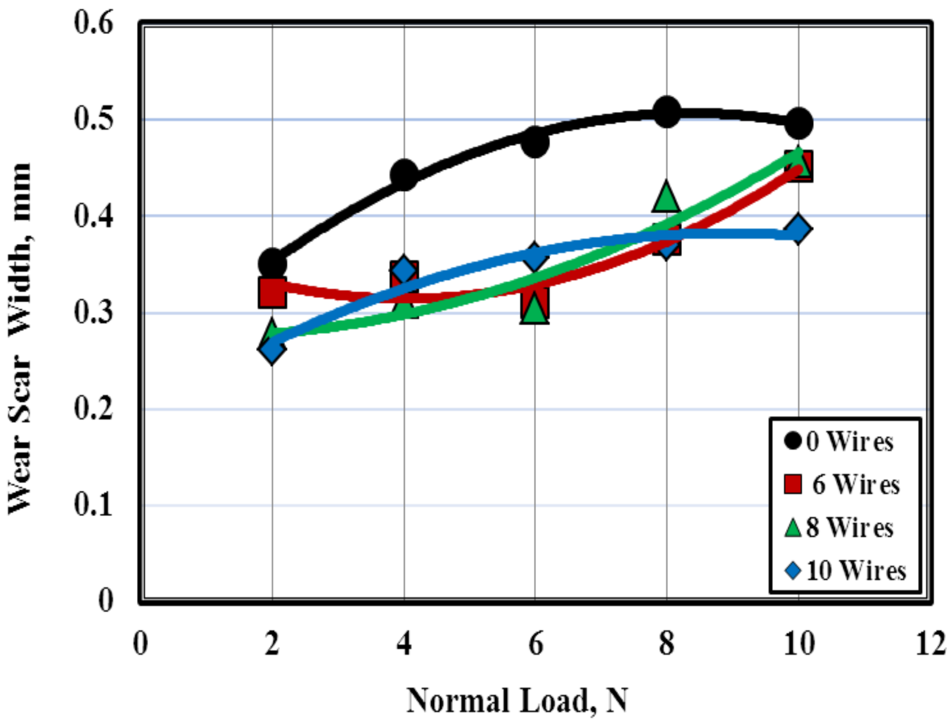

Fig. 20 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires and hardened at 120 °C.

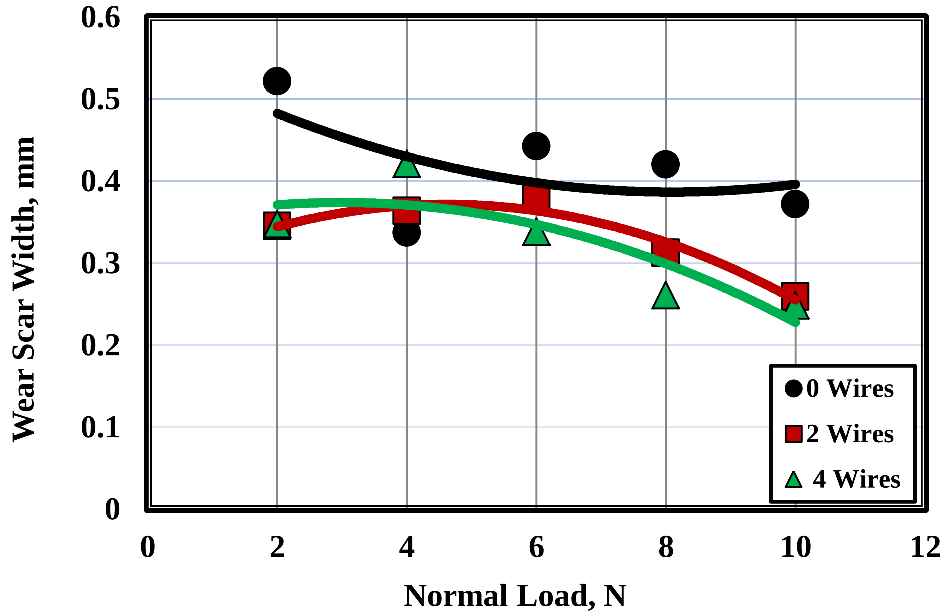

Fig. 21 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires treated by tempering at 110 °C.

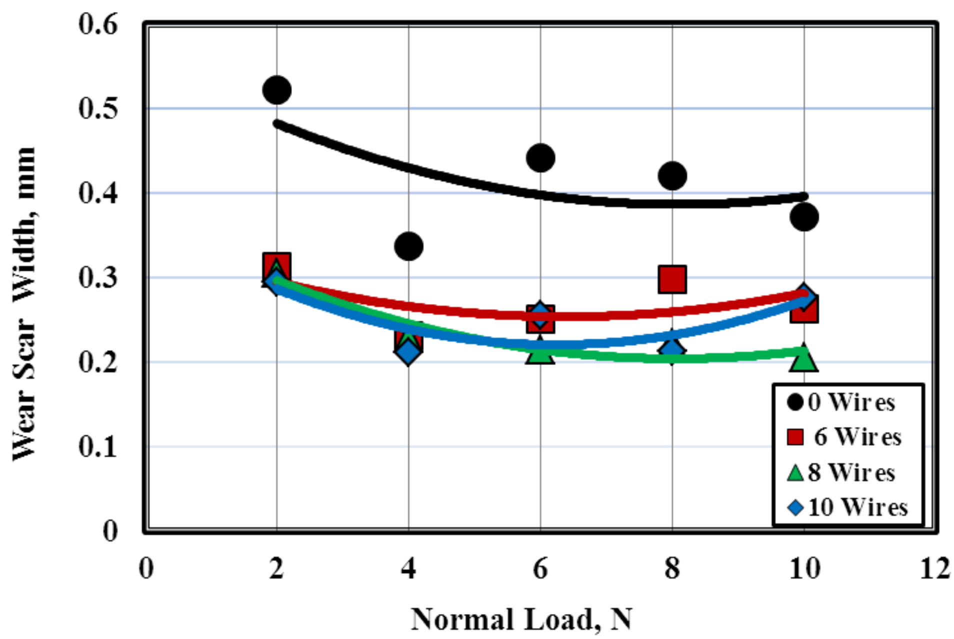

Fig. 22 Wear displayed by the scratch of HDPE reinforced by 0.4 mm diameter copper wires treated by tempering at 110 °C.

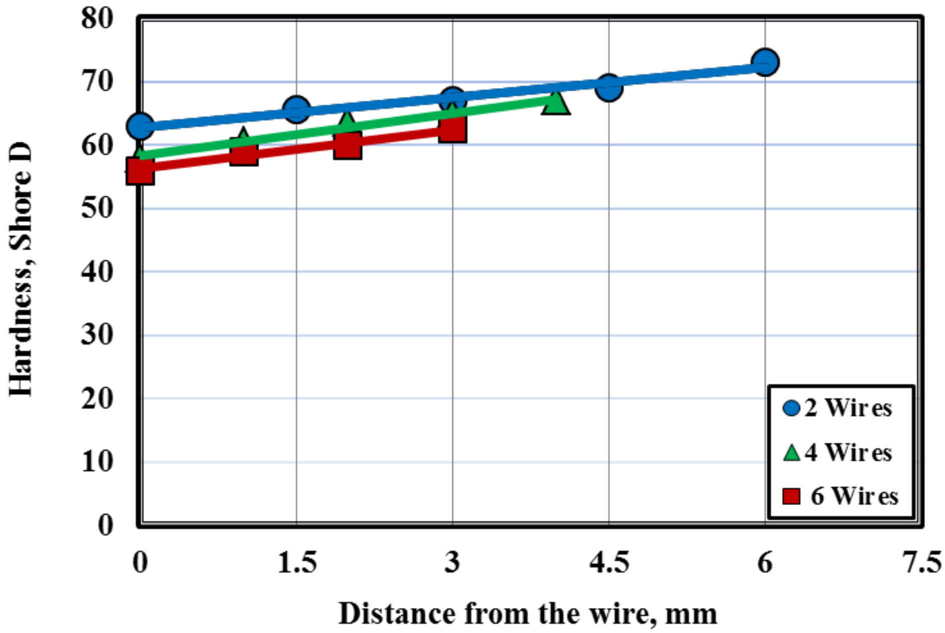

Fig. 23 Hardness distribution on the surface of HDPE composites reinforced by 0.4 mm diameter copper wires.

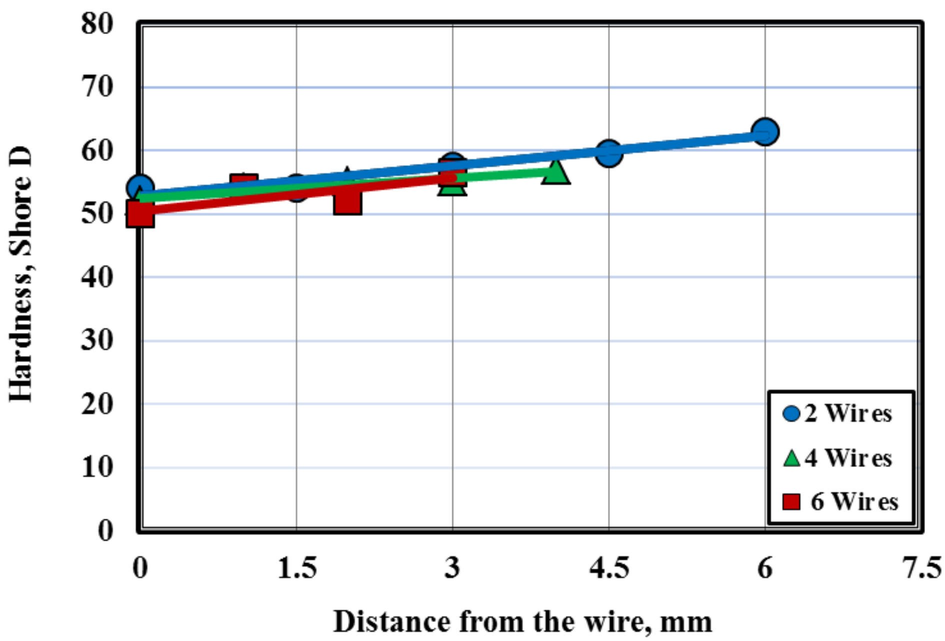

Fig. 24 Hardness distribution on the surface of annealed HDPE composites reinforced by 0.4 mm diameter copper

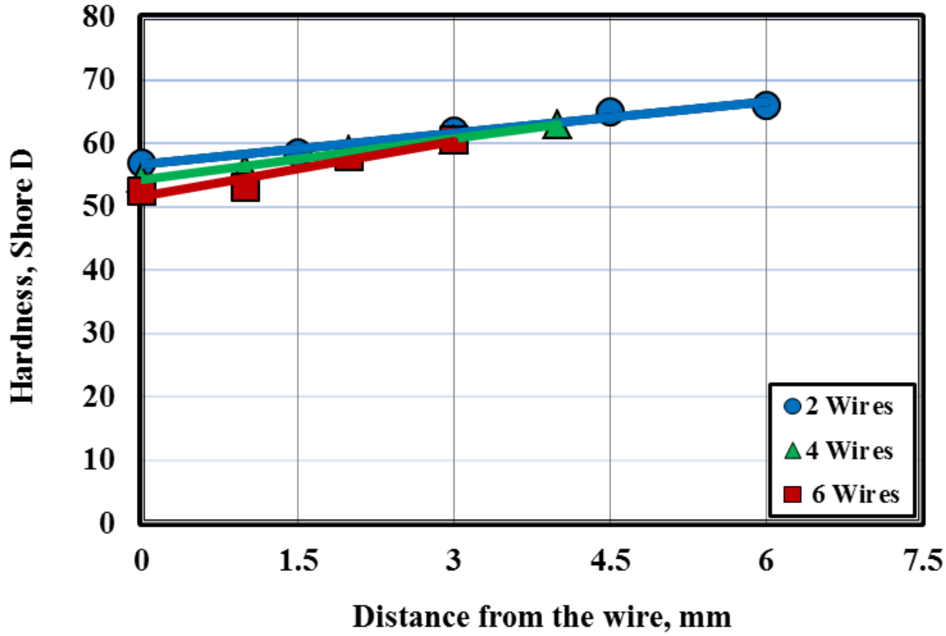

Fig. 25 Hardness distribution on the surface of hardened HDPE composites reinforced by 0.4 mm diameter copper wires.

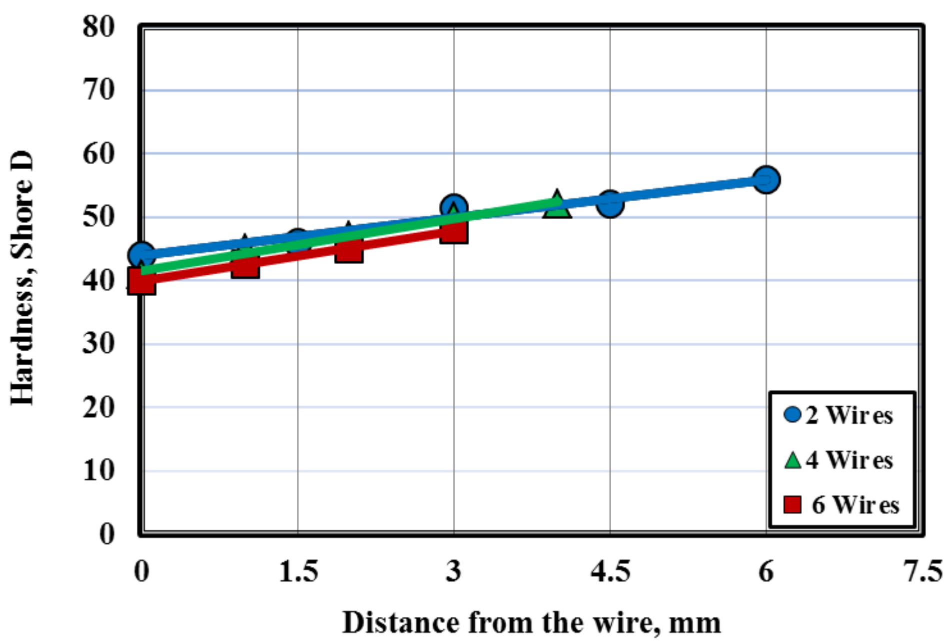

Fig. 26 Hardness distribution on the surface of tempered HDPE composites reinforced by 0.4 mm diameter copper wires.

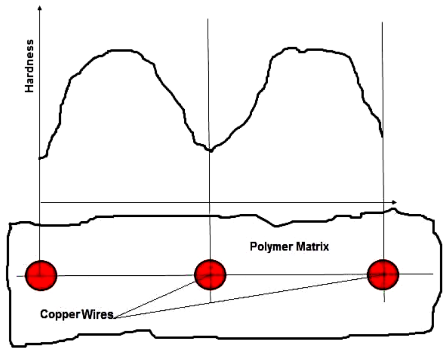

Fig. 27 Hardness change due to the caused by copper wires. [4].

HARDNESS

The hardness of HDPE has been measured to investigate the effect of the copper reinforcement on the cooling rate during preparation, Fig. 23. It has been observed that the hardness decreases close to the wire. The variation of the hardness may be because of changing of the cooling rate where the polymer near the copper wire cooled faster causing a decrease in polymer hardness. The decrease in hardness increased the embedment of scratching tool in HDPE matrix causing a significant wear decrease. Figure 27, showed the variation of hardness due to the presence of copper wires. The highest value of hardness is the nominal hardness before reinforcing the PE matrix by the copper wires, while the hardness decreased near the copper wire. As the hardness decreased the plastic deformation accompanied to scratch increased, while the removed material decreased. When the volume of deformed material is close to that of removed material, the condition of zero wear is approached. Figs. 24-26, showed the influence of heat treatment on hardness. The hardness of HDPE composites decreased with heat treatment. The tempered specimens showed the lowest hardness due to increased ductility by tempering.

CONCLUSIONS

From this study the followings can be concluded:

1. Friction coefficient displayed by the scratch of HDPE reinforced by copper wires decreased with increasing number of copper wires up to 8 then started to increase at 10 wires. As the load increased friction coefficient increased.

2. By annealing and hardening, friction coefficient significantly increased with increasing normal load while it decreased by tempering.

3. Tempered specimens displayed the lowest friction values, while as received ones showed the highest values.

4. Friction coefficient recor(Fig. 22 Hardness change due to the caused by copper wires. hardened and annealed.

5. Wear scar width of the tested composites slightly decreased with increasing number of wires.

6. Tempered specimens showed the lowest wear scar width while as received specimens showed the highest values.

7. Wear scar width significantly increased with increasing normal load by annealing and hardening while it decreased by tempering.

8. Wear recorded lower wear scar width for tempered test specimens followed by hardened and annealed ones.

REFERENCES

1. **Briscoe B.J., Sinha S.K., ''Tribology of polymeric solids and their composites'', in: G. Stachowiak (Ed.), Wear – Materials, Mechanism and Practice, John Wiley & Sons, Chichester, England, pp. 223 - 267, (2005).**

2. **Tambe N. S., Bhushan B., ''Micro/nanotribological characterization of PDMS and PMMA used for BioMEMS/NEMS applications, Ultramicroscopy'', Vol. 105 pp. 238 – 247, (2005).**

3. **Satyanarayana N., Sinha S. K., Ong B. H., ''Tribology of a novel UHMWPE/PFPE dual-film coated onto Si surface'', Sensors and Actuators A: Physical 128 pp. 198 – 108, (2006).**

4. **Eman S. M., Khashaba M. I., Ali W. Y., "Friction Coefficient and Wear Displayed by the Scratch of Polyethylene Reinforced by Copper wires", EGTRIB Journal, Vol. 12, No. 4, October 2015, pp. 15 – 27, (2015).**

5. **Eman S. M., Khashaba M. I., Ali W. Y., "Friction Coefficient and Wear Displayed by the Scratch of Polyethylene Reinforced by Steel Wires", International Journal of Materials Chemistry and Physics, Vol. 1, No. 3, December (2015).**

6. **Eman S. M., Khashaba M. I., Ali W. Y., "Friction Coefficient and Wear Displayed by the Scratch of Polypropylene Reinforced by Copper Wires", EGTRIB Journal, Vol. 13, No. 2, April 2016, pp. 38 - 49, (2016).**

7. **Khattab A., ''Adhesive Wear of Polymeric Coatings'', Proceedings of the Fourth Conf. of the Egyptian Society of Tribology, EGTRIB, 95 Cairo, Egypt, pp. 457 - 464, (1995).**

8. **Ali W., Khattab A., Salem T., ''Wear of Tillage Tools Coated by Reinforced Polyamide Coatings'', Proc. of the Int. Conf. of Advances in Materials and Processing Technologies, AMPT 95, Aug. 1995, pp. 596 - 605, (1995).**

9. **Foley A., Chisholm C., Mclees V., ''Wear of Ceramic-Protected Agricultural Subsoilers'', Tribology Int., April 1988, Vol. 21, No. 2, pp. 97 – 103, (1988).**

10. **Gordon D. H., Kukureka S. N.,'' The wear and friction of polyamide 46 and polyamide 46/aramid-fibre composites in sliding–rolling contact'', Wear, Vol. 267, pp. 669 - 710, (2009).**

11. **Suresha B., Kumar K. S., Seetharamu S., Kumaran P. S., '' Friction and dry sliding wear behavior of carbon and glass fabric reinforced vinyl ester composites'', Tribology International, Vol. 43, pp. 602, (2010).**

12. **Hu G., Zhang S., Yang M., Wang Z., ''Low percolation thresholds of electrical conductivity and rheology in polyethylene terephthalate through the networks of multi-walled carbon nanotubes'', Polymer; Vol. 47, pp. 480 - 488, (2006).**

13. **Ayman A. A., Mahmoud M. M., Omer A. A., ''Enhancement in Mechanical Properties of Polystyrene Filled with Carbon Nano Particulates (CNPS)'', World Journal of Nano Science and Engineering (WJNSE) , Vol. 2 No. 2, pp. 103 - 109, (2012).**