

EFFECT OF HEAT TREATMENT ON THE ABRASION RESISTANCE OF THERMOPLASTIC POLYMERS

Ayman A. A., Zeidan E. B., Hamed A. M., Ali W. Y.

Faculty of Engineering, Taif University, P. N. 888, Al-Taif, K. S. A.

ABSTRACT

In the present work, the effect of heat treatment of the test specimens of the common used polymers such as polyethylene, (PE), polypropylene, (PP) and polystyrene (PS) on their friction coefficient and wear was investigated.

Based on the experimental observations, it was found that as the rate of cooling decreased hardness increased and consequently friction coefficient remarkably decreased. Quenched test specimens in oil, water and salt water possessed relatively lower hardness with relatively higher values of friction coefficient. The variation of friction coefficient increased with increasing the temperature of the heat treatment. Besides, wear of the tested polymers decreased as the cooling rate decreased. The effect of heat treatment on wear significantly increased with increasing temperature of heat treatment. PE showed the highest effect by heat treatment followed by PP and PS. The change in the friction and wear properties of polymers caused by heat treatment can be attributed to the change of their crystallization.

KEYWORDS

Heat treatment, polyethylene, polypropylene and polystyrene, friction, wear.

INTRODUCTION

Polymers heat treatment is considered one of the most effective methods of modification to widen their application. The heat treatment of polymers can improve their mechanical and tribological properties. 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. Gears, bearings and other machine elements are exposed to a load spectrum consisting, amongst others, of a relative movement, causing heat and wear, and a surface pressure in an application dependent environment. This is especially true for systems without external lubrication, where melting, material fatigue and wear are the lifetime-limiting factors.

Material properties such as the mechanical behaviour and melting-temperature significantly affect the performance of the machine elements such as gears and bearings. The mechanical and thermal properties of several semi-crystalline thermoplastics can be enhanced by radiation cross linking by changing the chemical structure of the polymer under the influence of electron beam irradiation. This cross linking mainly occurs in the amorphous regions of semi-crystalline thermoplastics. Due to the use of cooled moulds in the injection moulding process these regions are usually located near the surface, which is especially critical in tribological applications. Combined with the enhanced temperature resistance a significant extension of the operating range of thermoplastic gears is expected [1 – 8]. Machine elements consisting of this radiation cross linked polymer can be operated at higher ambient temperature and resist higher friction loads.

Polymers that can be radiation cross linked are polyethylene (PE), polybutylene terephthalate (PBT) and polyamides (PA), [9]. Polyamides show good abrasion resistance, but their continuous operating temperature limits the application area. For medical applications polyethylene implants (UHMWPE) are frequently irradiated, [10], combining sterilization with an enhancement of wear resistance resulting from cross linking.

The influence of heat treatment of polyamide (PA 6) and polytetrafluoroethylene (PTFE), polymethylmethacrylate, (PMMA), and polyethylene terephthalate (PETP) on their friction and wear was investigated, [11, 12]. The tested polymers were heated up to 50, 80, 100 and 120 °C, while PTFE was heated up to 50, 100, 150 and 200 °C then furnace, air, and water cooled. Scratch test was carried out to investigate wear resistance and friction coefficient of the tested polymers. Test results show that, friction coefficient and wear of the tested polymers were much influenced by heat treatment. As the cooling rate increased, both friction and wear decreased and the water cooled test specimens represented minimum wear and friction. Besides, no significant enhancement in friction and wear was observed for PTFE test specimens, except at 200 °C of treatment temperature, slight reduction in friction and wear was observed.

Polymers heat treatment is considered one of the most effective methods of modification to widen their application. It was concluded that heat treatment of polyamide improved its tribological properties, [13, 14]. This effect is a result of crystal phase increase in the polyamide structure, where the elastic part of polyamide viscoelasticity increased causing significant increase in compressive strength and heat conductivity.

Thermal preconditioning has a very strong effect on the macroscopic behaviour of glassy polymers. Polyvinyl chloride (PVC) test samples were quenched and annealed. The quenched samples exhibited uniform deformation in tension while annealed samples showed necking. The temperature effect on the macroscopic behavior of glassy polymers like polystyrene (PS) and polymethylmethacrylate (PMMA) was investigated at different temperature using compression and tensile tests. It was found that temperature plays an important role on the mechanical properties of polymers. It was shown that yield stress and strain softening decrease as the temperature decreases. In tensile tests, PMMA showed a transition from brittle

at elevated temperature. In contrast polystyrene was found to be brittle in the entire range of temperatures used during investigation. In a recent study of the effect of temperature on the polystyrene toughening, [15], it was found that strain softening decreases as the temperature increases. Furthermore, the transition from brittle to ductile was determined at certain level of strain softening. At a certain level of temperature PS possessed a ductile behavior.

It was observed that the microhardness of polymeric surfaces decreased as cooling rate increased, [16, 17]. This behavior was found when the microhardness of polyamide coatings was measured to investigate the effect of the metallic reinforcement on the cooling rate during preparation. Addition of solid lubricants, metallic and nonmetallic powders to polymeric materials such as graphite, molybdenum disulphide, bronze, tin and lead powders was tested to reduce friction and wear. It was observed that favourable wear resistance was exhibited as a result of providing friction reducing materials and affecting the cooling rate of the polymers.

The aim of the present work is to investigate the effect of heat treatment on the friction and wear of polyethylene (PE), polypropylene (PP) and polystyrene (PS).

EXPERIMENTAL

Three types of the most common used polymeric materials are tested, polyethylene (PE), polypropylene (PP) and polystyrene (PS). The tested materials were in form of flat sheets ($50 \times 50 \times 4$ mm). Test specimens were heated up to 60, 80, 100 and 120 °C for 10 hours then furnace, air, oil, water and salt water cooled, Figs. 1 – 3.

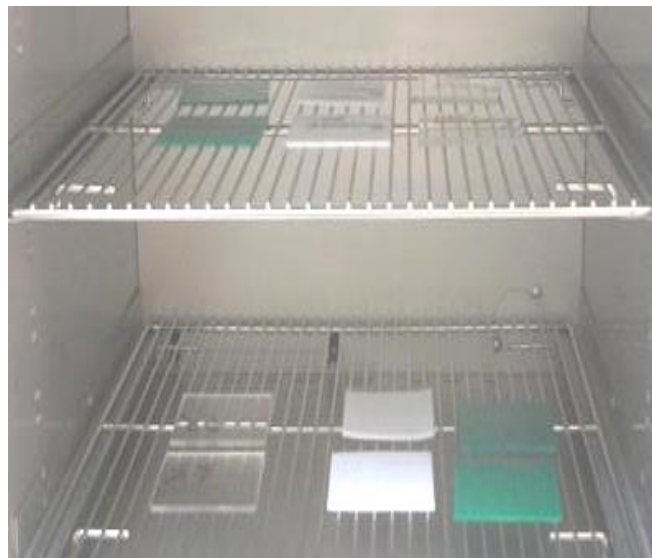


Fig. 1 Heating of the test specimens.

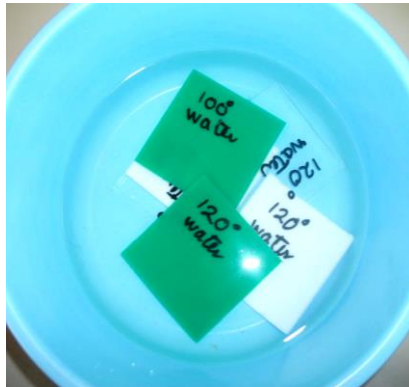


Fig. 2 Cooling in water.

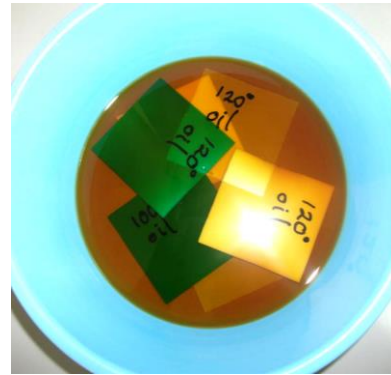


Fig. 3 Cooling in oil.

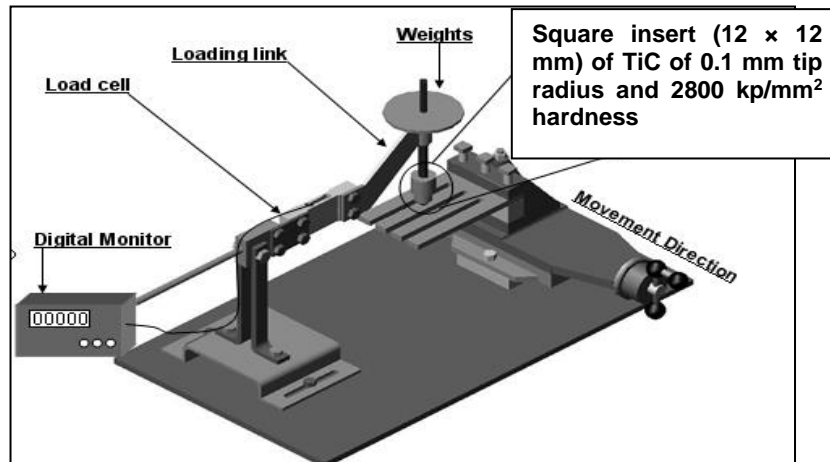


Fig. 3 Details of the test rig.

The test rig, used in the experiments was top scratching tester equipped with an indenter to produce a scratch on a flat surface with a single pass. The details of the test rig is shown in Fig. 1. The indenter, used in experiments, was a square insert (12×12 mm) of TiC of tip radius of 0.1 mm and hardness of 2800 kp/mm^2 . The scratch force was measured by the deflection of load cell. The ratio of the scratch force to the normal force was considered as friction coefficient. Wear was considered as the wear scar width of the scratch. The width was measured by optical microscope with an accuracy of $\pm 1.0 \mu\text{m}$. The tested surface was ground by an emery paper (500 grade) before testing. The load was applied by weights. The test speed was nearly controlled by turning the power screw feeding the insert into the scratch direction that was adjusted to be 2 mm/s. The applied load values were 10 and 20 N.

RESULTS AND DISCUSSION

Friction coefficient displayed by the scratch of PE at 10 and 20 N loads is illustrated in Figs. 4, 5. Generally. The effect of heat treatment on the friction coefficient is clearly shown. The lowest cooling rate in the present work was caused by furnace followed by air, oil and water cooling, while the highest rate was displayed by salt water cooling. Two trends are shown in Fig. 4. The first one resulted from furnace and air cooling, where friction coefficient remarkably decreased with increasing temperature of heat treatment. This behaviour confirms that the test specimens possessed relatively higher hardness than the other ones. The reduction in friction is due to the increase of the hardness of the polymer causing significant increase in polymer shear strength so that the indenter could not embed deeply in the tested materials. It can be concluded that as the rate of cooling decreased hardness of the tested polymers increased. The second trend was displayed by oil, water and salt water cooling, where friction coefficient significantly increased with increasing temperature of the heat treatment. This behaviour confirms that quenched test specimens in oil, water and salt water possessed relatively lower hardness. The increase in friction is attributed to the increase of plastic deformation of the polymer causing significant decrease in shear strength. This observations indicated that as the rate of cooling increased hardness increased. The same trend was observed for load values of 20 N, Fig. 5. The values of friction coefficient increased for PE cooled by air, oil, water, while PE cooled by furnace showed decreasing trend of friction coefficient with increasing the temperature of heat treatment. It can be concluded that friction coefficient strongly depends on the cooling rate after heating as well as the temperature of the heat treatment.

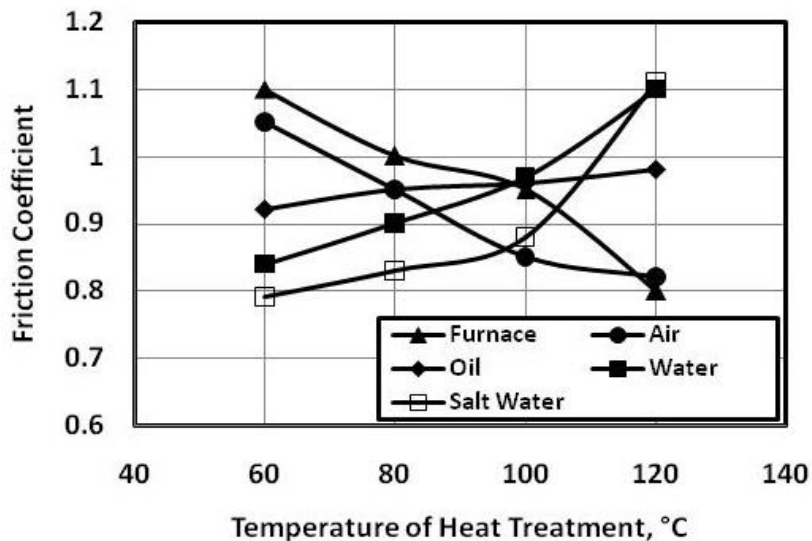


Fig. 4 Friction coefficient of PE at 10 N load.

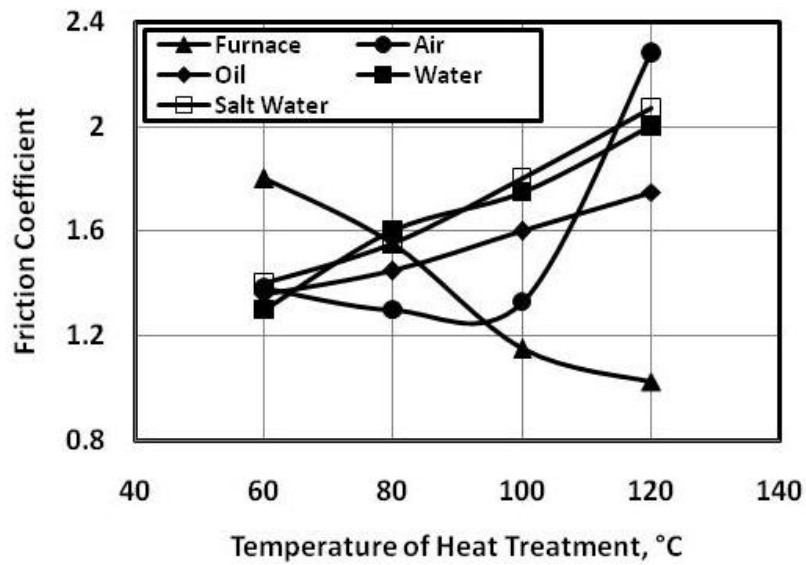


Fig. 5 Friction coefficient of PE at 20 N load.

Friction coefficient of PP at 10 N load is shown in Fig. 6. Furnace cooling test specimens showed slight decrease, while air and oil cooled test specimens showed slight increase in friction coefficient with increasing the temperature of heat treatment. Remarkable friction increase was observed for water and salt water cooled test specimens. Increasing the load to 20 N gave the same trend with relatively higher friction values, Fig. 7. Generally, friction increase was relatively lower than that displayed by PE.

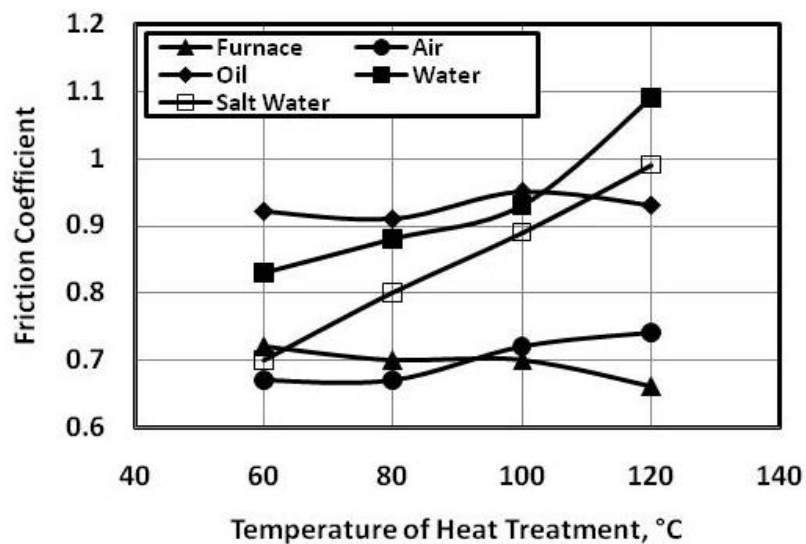


Fig. 6 Friction coefficient of PP at 10 N load.

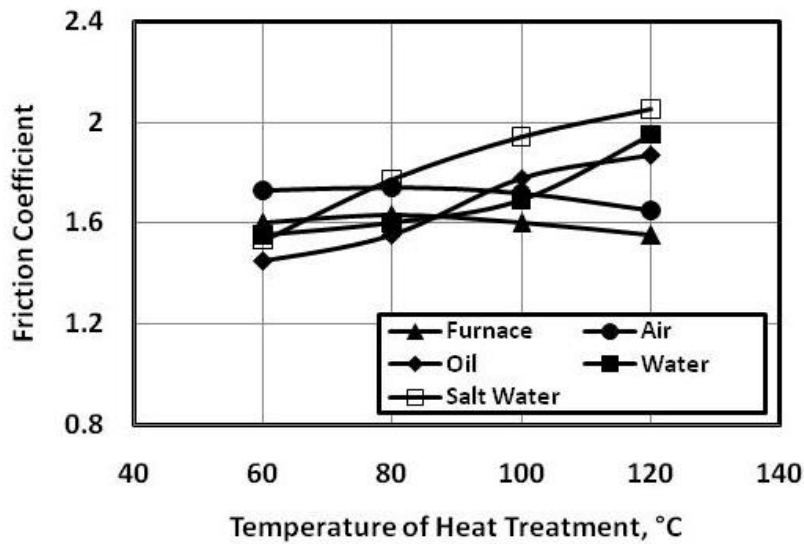


Fig. 7 Friction coefficient of PP at 20 N load.

The effect of the temperature of heat treatment on the friction coefficient of PS at 10, 20 N is shown in Figs. 8, 9 respectively. Furnace and oil cooled test specimens showed no change in friction coefficient, while air cooled test specimens displayed drastic decrease with increasing the temperature of heat treatment, Fig. 8. It seems that cooling in air increased the crystallization of the treated PS. Significant friction increase was observed for water and salt water quenched test specimens indicating that the increase of the cooling rate was responsible for the increase of the plasticity of PS, Fig. 9. As the load increased to 20 N, the friction values were relatively lower than that displayed by PE and PP.

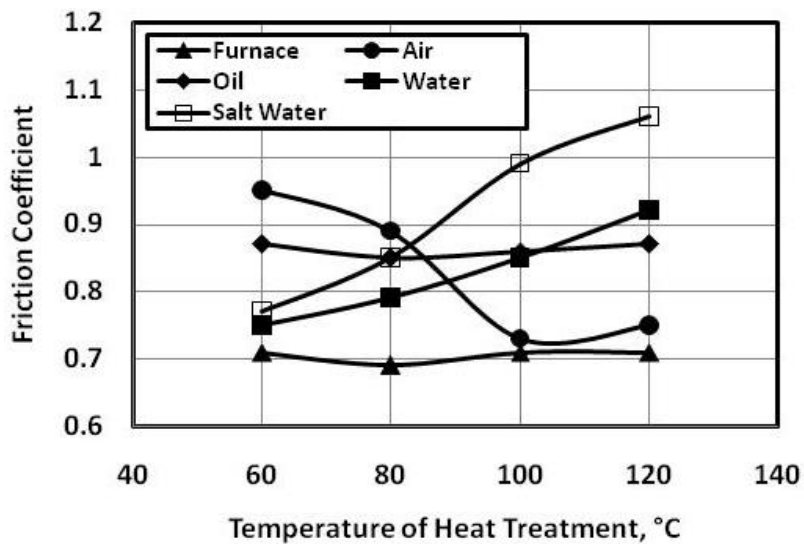


Fig. 8 Friction coefficient of PS at 10 N load.

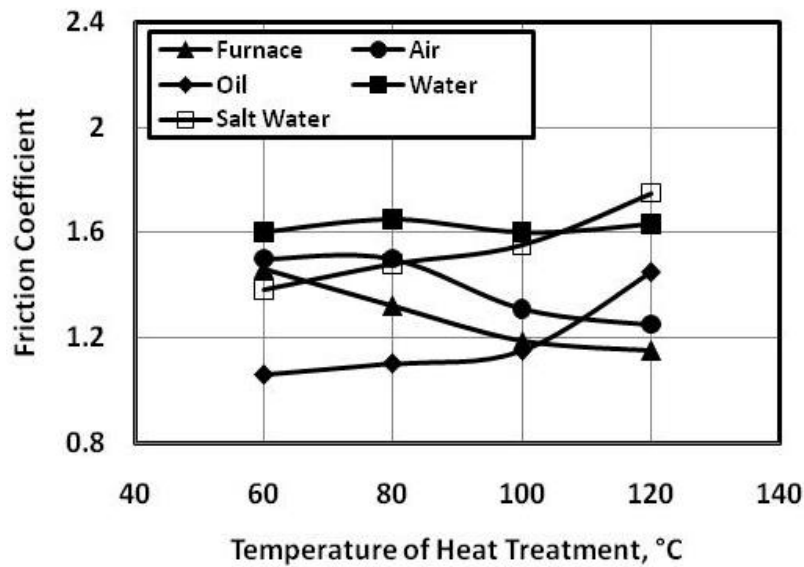


Fig. 9 Friction coefficient of PS at 20 N load.

The results of the wear of the test specimens are shown in Figs. 10 – 15. Wear of PE decreased for furnace cooled test specimens, while increased for the others with increasing temperature of heat treatment, Fig. 10. It is clearly observed that as cooling rate increased wear increased. This behaviour can be explained on the basis that crystallization of the polymers decreased and consequently plasticity increased as the cooling rate increased. The same trend was noticed for results of experiments carried out at 20 N load accompanied by relatively higher values of friction coefficient.

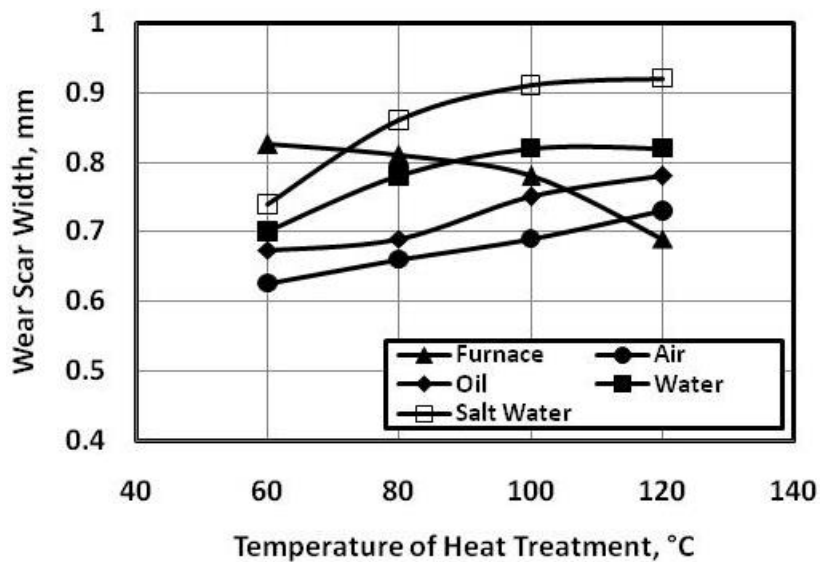


Fig. 10 Wear of PE at 10 N.

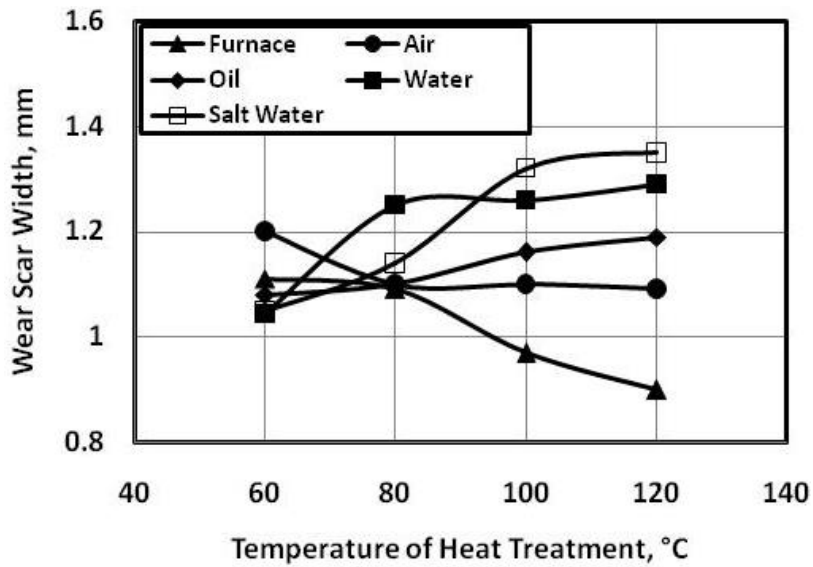


Fig. 11 Wear of PE at 20 N.

Wear of PP recorded relatively higher values than that indicated for PE, Figs. 12, 13. Wear of furnace, air and oil cooled test specimens slightly decreased, while water and salt water cooled specimens increased with increasing the temperature of the heat treatment at 10 N, Fig. 12. The range of the change of wear scar width was between 0.8 and 1.0. This range indicated that the effect of the temperature was not high like PE. The same trend of wear was observed for 20 N load, Fig. 13, where variation of wear was more higher than that observed at 10 N.

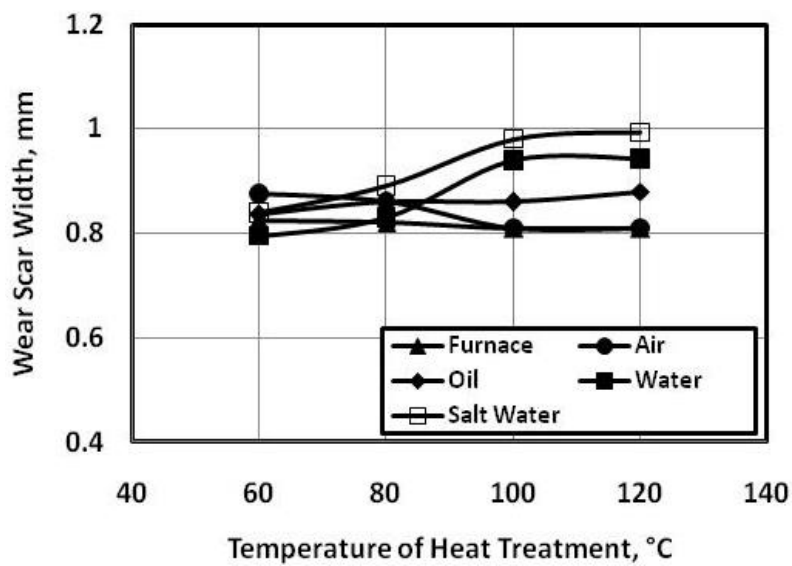


Fig. 12 Wear of PP at 10 N.

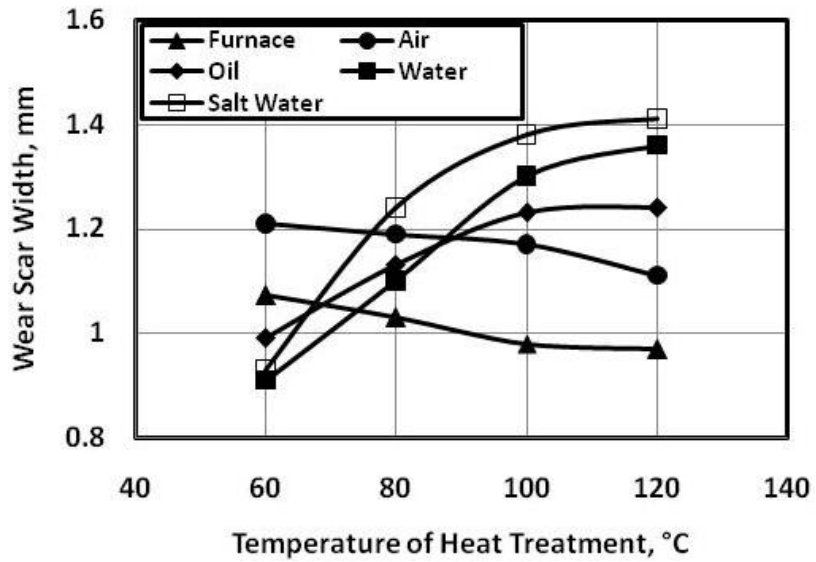


Fig. 13 Wear of PP at 20 N.

Wear of PS at 10, 20 N load is illustrated in Figs. 14, 15. Generally PS gave relatively lower wear than PE and PP, Fig. 14. Besides the effect of the temperature on the friction coefficient was relatively lower than that observed for PE and PP.

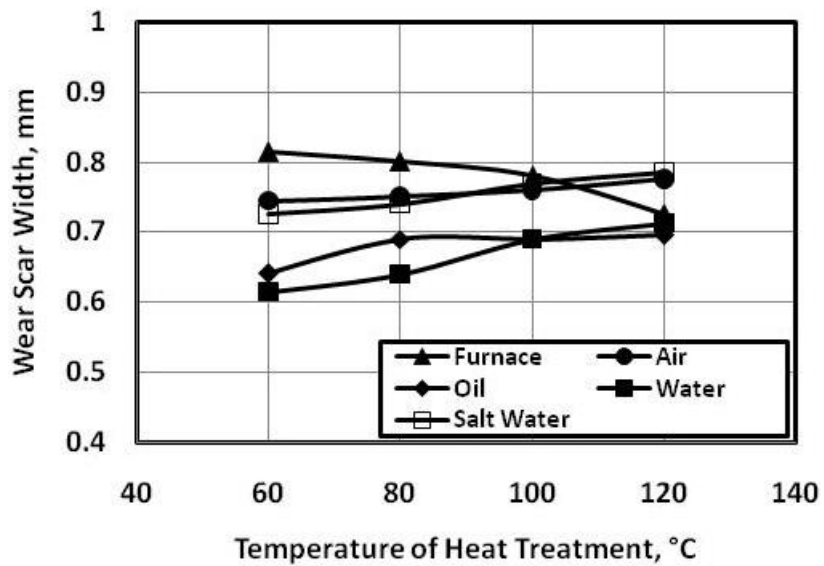


Fig. 14 Wear of PS at 10 N.

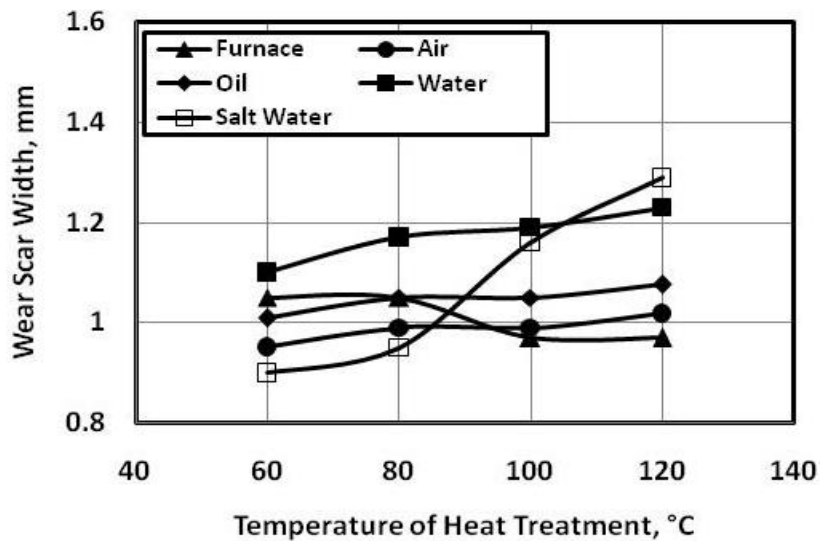


Fig. 15 Wear of PS at 20 N.

The change in the friction and wear properties of polymers caused by heat treatment can be attributed to the change of their crystallization. Most polymers can only stretch out for a short distance before they fold back on themselves. In fact, very few polymers can stretch out perfectly straight, and those are ultra-high molecular weight polyethylene, and aramids like Kevlar and Nomex. A single polymer chain may be partly in a crystalline lamella, and partly in the amorphous state. Some chains even start in one lamella, cross the amorphous region, and then join another lamella.

No polymer is completely crystalline. Crystallization makes a material strong, but it also makes it brittle. A completely crystalline polymer would be too brittle to be used as plastic. The amorphous regions give the polymer toughness, that is, the ability to bend without breaking. In semi-crystalline polymers the mode of crystallization influences the morphology and hence mechanical properties. Slow crystallization near the melting point results in larger, more perfect crystals; faster crystallization produces smaller spheres with many more tie molecules. The presence of that morphology requires a more complex model and the mechanical properties of most semi-crystalline materials are influenced by both crystalline and amorphous regions: degree of crystallization is important. Crystalline regions are stiffer than amorphous regions. Taking polyethylene as a representative semi-crystalline polymer, values can be obtained for the Young's moduli of the various phases which contribute to the overall modulus.

CONCLUSIONS

1. As the rate of cooling decreased hardness of the tested polymers increased and consequently friction coefficient remarkably decreased.
2. Quenching test specimens in oil, water and salt water possessed relatively lower hardness with relatively higher values of friction coefficient.

3. The variation of friction coefficient increased with increasing the temperature of heat treatment.
4. Wear of the tested polymers decreased as the cooling rate decreased. The effect of heat treatment on wear increased with increasing temperature of heat treatment
5. PE showed the highest effect by heat treatment on friction coefficient and wear followed by PP and PS.
6. The change in the friction and wear properties of polymers caused by heat treatment can be attributed to the change of their crystallization.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the University of Al-Taif for its fully funding this research project (project number 658/1431).

REFERENCES

1. Feulner R., Brocka Z., Seefried A., Kobes M. O., Hülder G., Osswald T. A., "The effects of e-beam irradiation induced cross linking on the friction and wear of polyamide 66 in sliding contact", *Wear* 268, pp. 905 – 910, (2010).
2. Künkel R., Brocka Z., Ehrenstein G.W., "Strahlenvernetzung für tribologische Anwendungen", *KGK Kautschuk Gummi Kunststoffe* 58, pp. 168 - 172, (2005).
3. Brocka Z., Schmachtenberg E., Ehrenstein G.W., "Radiation cross-linking of engineering thermoplastics for tribological applications", in: *SPE Proceedings ANTEC*, Cincinnati, USA, pp. 1690 - 1694, (2007).
4. Z. Brocka, G.W. Ehrenstein, "Radiation-induced crosslinking: crosslinked PA6 for circuit carriers", *Kunststoffe International* 94, pp. 88 - 94, (2004).
5. Brocka Z., Ehrenstein G.W., "Cross-Linking of thermoplastics to improve the thermo-mechanical properties", in: *21st Annual Meeting of the Polymer Processing Society (PPS-21)*, Leipzig, Germany, (2005).
6. Wiedmer S., Gellner D., Friedrich K., "Effect of electron-beam radiation on thermoplastic composites", *Plastics, Rubber and Composites* 34, pp. 76 - 84, (2005).
7. Rouif S., "Radiation cross-linked plastics: a versatile material solution for packaging, automotive, Electrotechnic and Electronics", *Radiation Physics and Chemistry* 71, pp. 525 – 528, (2004).
8. Z. Brocka, *E-Beam-Radiation Crosslinked Polyamides for Tribological Applications*, *Materialy Polimerowe – Pomerania-Plast*, Kolberg, Poland, , pp. 55 - 56, (2007).
9. Chapiro A., "Polymer irradiation: past–present–future", *Radiation Physics and Chemistry* 63, p. 207, (2002).
10. Schwartz C. J., Bahadur S., Mallapragada S.K., "Effect of crosslinking and Pt–Zr quasicrystal fillers on the mechanical properties and wear resistance of UHMWPE for use in artificial joints", *Wear* 263, pp. 1072 - 1080, (2007).
11. Mohamed, A. H., Youssef, M. M. and Ali, W. Y., "Influence of Heat Treatment on Abrasive Wear of Polyamide and Polytetrafluoroethylene", *Bulletin of the Faculty of Engineering, El-Minia University*, Vol. 20, No. 1., July 2001, pp. 114 – 123, (2001).

12. Mansour, H., Mahmoud, M. M. and Ali, W. Y., "Influence of the Heat Treatment on the Wear Resistance of Polymeric Materials" Journal of the Egyptian Society of Tribology, Vol. 2, No. 1, April, pp. 33 – 42, (2004).
13. Kosicki, J. Ets ., "The Effect of Polyamide 6 Thermal Modification on Interactions Between Lubricants and Bearing Surfaces", EUROTRIB'81 Congress Papers, Vol. IV, Warsaw, (1981).
14. Kosicki, J. E., "behaviour of Heat Treated Polyamide Used for Big Sliding Bearings", Proceedings Of The V Int. Congress on Tribology, EUROTRIB' 89, Vol. 2, June 13 - 16, 1989, Espo, Finland, pp. 404 - 408, (1989).
15. Ayoub N. M., M. Sc. Thesis, "Toughening of Polystyrene by Network Modification", Eindhoven University of Technology, Faculty of Mechanical Engineering, (2000).
16. Ali W. Y., Khattab A. A. and Salem T. M., "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).
17. Ali W. Y., "The Friction and Wear of Oil Impregnated Polyamide Coatings Filled by Metal Powders", First International Conference On Mechanical Engineering Advanced Technology For Industrial Production, ASSIUT, EGYPT, MEATIP 1, Dec. 27 - 29, (1994).