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INFLUENCE OF HEAT TREATMENT ON THE FRICTION AND WEAR OF POLYURETHANE COATINGS

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ABSTRACT
The friction coefficient and wear resistance of polyurethane coatings were investigated in the present work. Scratch test was carried out to determine the friction coefficient and wear scar width of the tested coatings. Heat treatment processes such as annealing, tempering and quenching were carried out to study their effect on the tribological properties of the tested coatings.

It was found that, at temperature of heat treatment of 50 °C, friction coefficient significantly increased with increasing normal load. Annealed polyurethane of single layer coating displayed the lowest wear. When the coating thickness increased up to 0.5 mm (double layer) significant friction decrease was observed. Annealed coatings displayed the lowest friction values, while as received ones showed the highest values. Friction coefficient displayed by triple layers polyurethane coating recorded higher friction for quenched test specimens followed by tempered and annealed ones. For temperature of heat treatment of 75 °C significant increase in friction coefficient was predicted. Polyurethane coating of double layers showed the lowest friction coefficient values compared to single and triple layers. Friction coefficient displayed by the scratch of triple layers polyurethane showed slight friction increase. Quenched coatings represented the highest values, while annealed ones showed the lowest ones.

Wear displayed by the scratch of single layer annealed polyurethane that heat treated at 50 °C showed the lowest wear. Quenched coatings displayed relatively higher wear than tempered and annealed coatings. Wear displayed by double layer polyurethane showed relatively lower values than that observed for 0.2 mm coatings. Quenched coatings displayed the highest wear values followed by the tempered coatings. Wear of triple layer polyurethane showed slight increase compared to double layers coatings. When the temperature of heat treatment increased to 75 °C, slight increase in wear for single layer polyurethane coatings was observed. Annealed coatings showed the lowest wear. Wear displayed by triple layers (0.8 mm) polyurethane represented the lowest values compared to single and double layers coatings. Annealed coatings showed the lowest wear values.

INTRODUCTION
The possibility of coating the steel sheets by polyurethane to resist sand abrasion was discussed, [1, 2]. The tested coatings were aimed to coat the vehicle surfaces as well as lamp covers to defeat sand erosion during dusty storms. Two types of tests were carried

out. The first was air sand erosion, while the second was scratch test to measure the wear resistance of the proposed coating. Based on the experimental results, it was found that for the sand erosion test as the coating thickness increased wear decreased. The results of the scratch test, showed that friction coefficient displayed by 0.26 mm coating significantly increased up to maximum then decreased with increasing load. As received tested coating showed the higher wear, while the annealed coatings displayed lower wear. Friction coefficient decreased down to minimum then increased with increasing coating thickness. The lowest values of friction coefficient were observed for as received coatings. Wear drastically decreased down to minimum then increased with increasing coating thickness. The sand erosion testing of transparent polymeric coatings of steel sheets was investigated.

Frequently aircraft, tank and helicopter gas turbine engines are operated in a desert environment where the gas turbine compressor rotor blades and vanes are exposed to erosive media such as sand and dust. Base metal erosion leads to increased fuel consumption, efficiency loss, and can cause damage to compressor and turbine hardware. Erosion resistant coatings can be used to prolong the life of compressor airfoils in a sand erosion environment, [3]. The key features of two selected coating architectures are outlined. Selected erosion performance data with different erosion media are presented. Excellent mechanical properties of single layer nitride coating such as high hardness and Young's modulus make it a very attractive material for the protection against the different types of wear, [4]. Mechanisms of solid particle erosion of metals and brittle materials, such as Ti-N and other nitride coatings have been discussed. It was demonstrated that the erosion rate of brittle coating compared to ductile coatings is lower at low impact angle but is higher at high impact angle, [5]. Brittle/ductile multilayer systems have also been applied successfully in commercial applications.

The sand erosion rates of novel compositions of hard ceramics such as tungsten carbide, silicon nitride, silicon carbide, and partially stabilized zirconia have been tested in air-sand erosion facilities. A new testing facility that ensured stable and reproducible erosion testing with sand velocities and concentrations up to 250 m/s and 5 wt. % in air, respectively, was built, [6]. Special rig design features allowed accurate sand consumption monitoring during each test. High-speed photography was used to determine the sand velocity distribution at each test setting. High-speed visualization of the sand impact on the material surface demonstrated fragmentation of almost every sand particle in the range of velocities of 60 m/s and higher. The evidence of extensive fragmentation contributed to understanding the origin of the erosion resistance of hard ceramics.

Selection of materials capable of withstanding sand erosion is one of the major problems encountered when designing valves for oil and gas severe service applications, [7 - 9]. The erosion problem is particularly acute for gas choke valves where natural gas, initially compressed to 20 - 50 N/mm^2, may reach sonic velocity within the choke trim. The enormous fluid velocity accelerates entrained sand particles that subsequently impinge onto walls of the valve parts as well as the downstream pipe work.

The angle dependence of the erosion rate was obtained by testing the materials at an impact angle of 30° with the sand velocity of 105 m/s. It is generally believed, [10, 11] that for brittle materials such as hard ceramics a maximum erosion rate occurs at 90°,

whereas for ductile materials this occurs at oblique impact angles. The erosion rate increases with the sand concentration because of the increased opportunity of sand particles impacting the steel surface, [12]. It was proposed, [13], that during each impact, plastic deformation takes place at the vicinity of the impact when the yield strength of steel is locally exceeded. Multiple impacts could generate a plastically deformed layer near the eroded surface with the increased yield strength due to strain hardening, reducing the erosion rate.

A single correlation for sand erosion of a "family" of polyurethanes is presented. By "family" is meant a group of chemically similar compounds, [14]. The natural time of a viscoelastic fluid: its significance and measurement, observations regarding the number of dimensional parameters in viscoelastic constitutive equations has been used together with the Pi theorem to prepare a single dimensionless correlation for a group of materials with similar but different forms of constitutive equations, different forms of stress-deformation behavior. Results of a large number of erosion tests on artificially generated and relatively dense sand–mud mixtures are presented, [15]. Soil sample compositions are varied concerning clay–silt and sand–silt ratio, and clay mineralogy. An experimental approach to accelerated laboratory testing sand erosion in high pressure flow channels of complicated 3D configurations was developed, [16]. The channels were designed for erosion-resistant valves in natural gas and oil severe service applications. A testing facility that operated at 40 bar of nitrogen pressure with silica sand as an erodent was built and calibrated. The flow channels were manufactured from organic glass (PMMA) in separate plates that facilitated weight loss measurements in different parts of the channels as well as erosion visualization. The particular grade of glass was selected after testing erosion in a range of materials in order to find close resemblance to stainless steel in terms of both the erosion rate angle function and the velocity exponent.

The operating environment in Middle East is particularly severe in terms of the high ambient dust concentrations experienced throughout the Eastern and Western Provinces, [17]. During severe dust storm conditions dust concentrations of the order of 100 to 500 times higher may be encountered. It was found that the vast majority of airborne in the Eastern Province are concentrated in the smaller sizes. 95 % of all particles are below 20 μm and 50 % of all particles are below 1.5 μm in size. The dusty storms continue for long times in Gulf area. The erosion of vehicles body has an accelerated rate.

In the present research, it is aimed to investigate the effect of heat treatment on the friction coefficient and wear of polyurethane coating. The thickness of the coating and the effect of heat treatment (annealing, tempering and quenching) are investigated.

EXPERMINTAL

The scratch tester shown in Fig. 1 was used. It consisted of a rigid stylus mount, a diamond 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, 10 and 12 N. Scratch resistance force was measured using a load cell mounted to the loading lever and connected to display digital monitor. The test specimen was held in the specimen holder which mounted in a horizontal base with a manual driving mechanism to move specimen in a straight direction. The scratch force was measured during the test and

used to calculate friction coefficient. The test was conducted under dry sliding condition at room temperature. An optical microscope was used to measure scratch width with an accuracy of ± 1.0 μm. The test specimens were prepared from carbon steel sheets (40 × 40 mm) and coated by single, double and triple polyurethane layers of approximately 0.2, 0.5 and 0.8 mm thicknesses respectively.

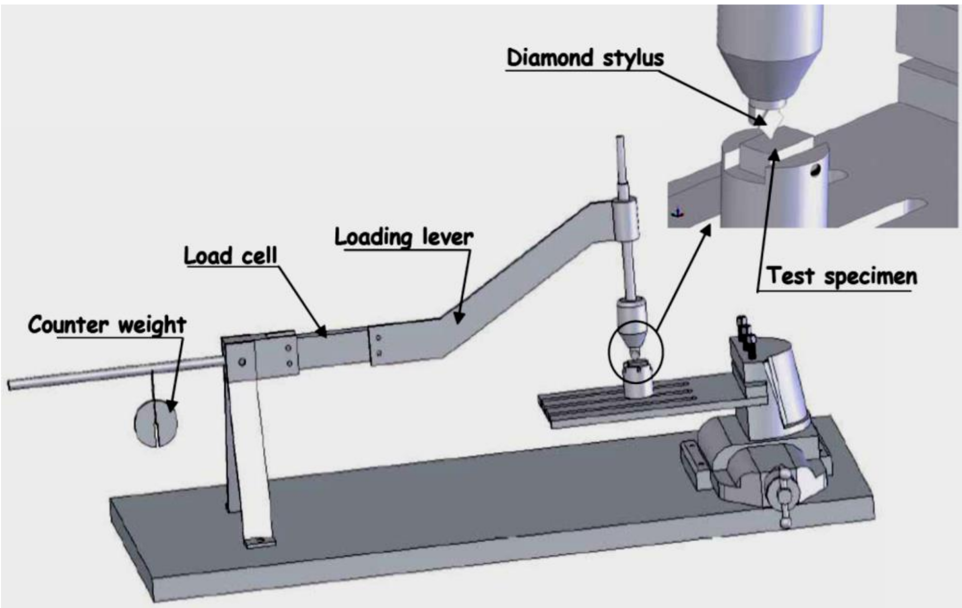

Fig. 1 Arrangement of scratch test rig.

RESULTS AND DISCUSSION

The results of the experimental work carried out in the present work are shown in Figs. 2 – 13. Friction coefficient displayed by the scratch of single layer polyurethane heat treated at 50 °C is shown in Fig. 2, where friction coefficient significantly increased with increasing normal load. As received polyurethane coating displayed the highest wear followed by quenched, tempered and annealed tested coatings. It was found that annealing of polymers increased hardness, [18]. In scratch test as the hardness of the material increased the volume of removed material decreased and consequently the shear area decreased causing a decrease in friction coefficient.

Increasing the coating thickness to 0.5 mm (double layer) caused significant friction decrease, Fig. 3. Annealed coatings displayed the lowest values, while as received ones showed the highest values at 12 N load. The highest friction values were 0.95 and 0.8 mm for 0.2 and 0.5 mm coating thickness respectively.

Friction coefficient displayed by the scratch of triple layers polyurethane coating that heat treated at 50 °C recorded higher friction for quenched test specimens followed by tempered and annealed ones, Fig. 4. As received coatings showed the lowest friction coefficient. It seems that the coating increase was responsible for that behaviour, where the stylus penetration inside polyurethane coating was much influenced by the heat treatment of the coating. It is known that quenching of polymers decreased the hardness, while annealing increased the hardness.

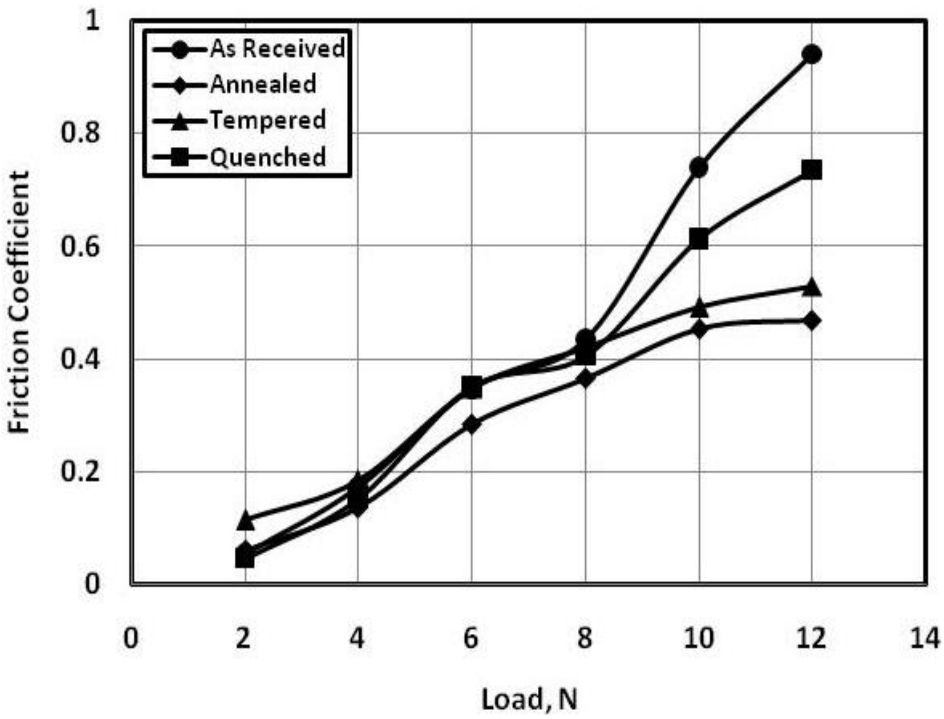

Fig. 2 Friction coefficient displayed by the scratch of single layer polyurethane that heat treated at 50 °C.

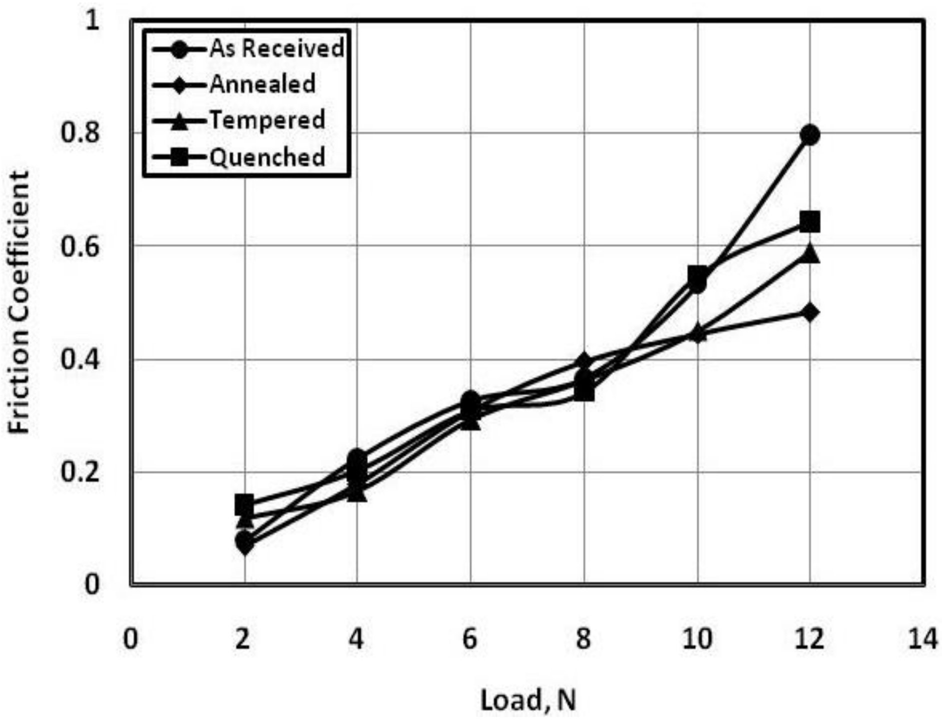

Fig. 3 Friction coefficient displayed by the scratch of double layer polyurethane that heat treated at 50 °C.

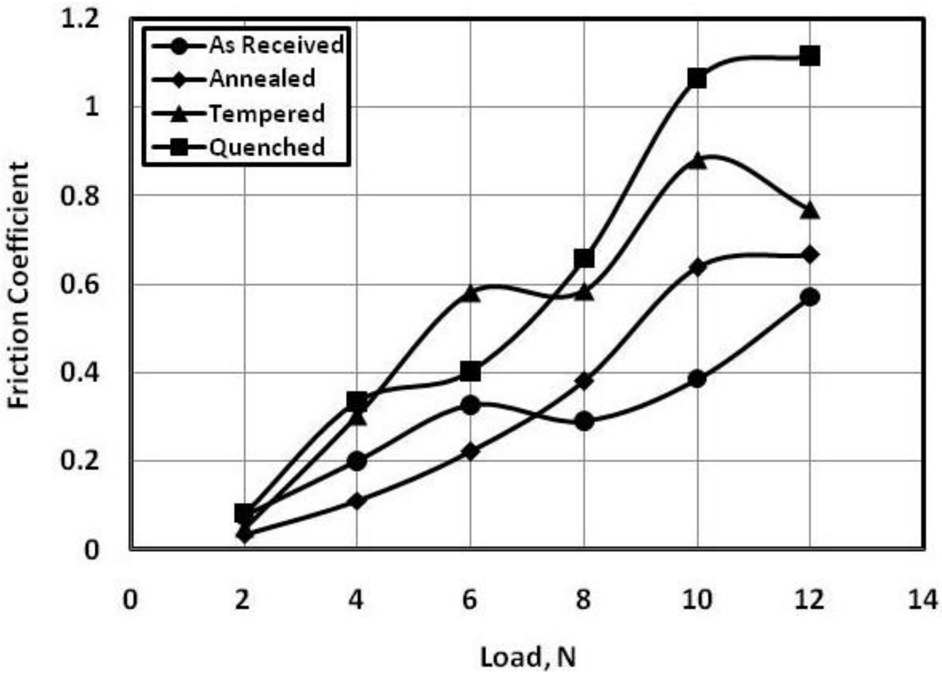

Fig. 4 Friction coefficient displayed by the scratch of triple layers polyurethane that heat treated at 50 °C.

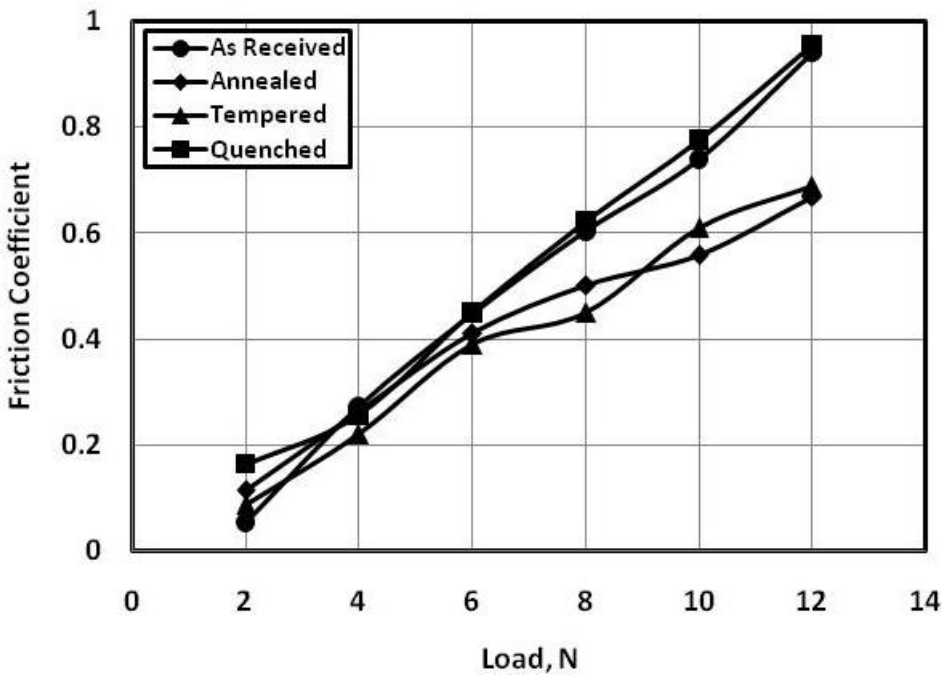

Fig. 5 Friction coefficient displayed by the scratch of single layer polyurethane that heat treated at 75 °C.

Increasing the temperature of heat treatment to 75 °C caused significant increase in friction coefficient due to the increase of the plasticity of polyurethane coatings, Fig. 5. The friction increase might be from the increased depth of penetration of the stylus inside the coating matrix, where the sheared area increased.

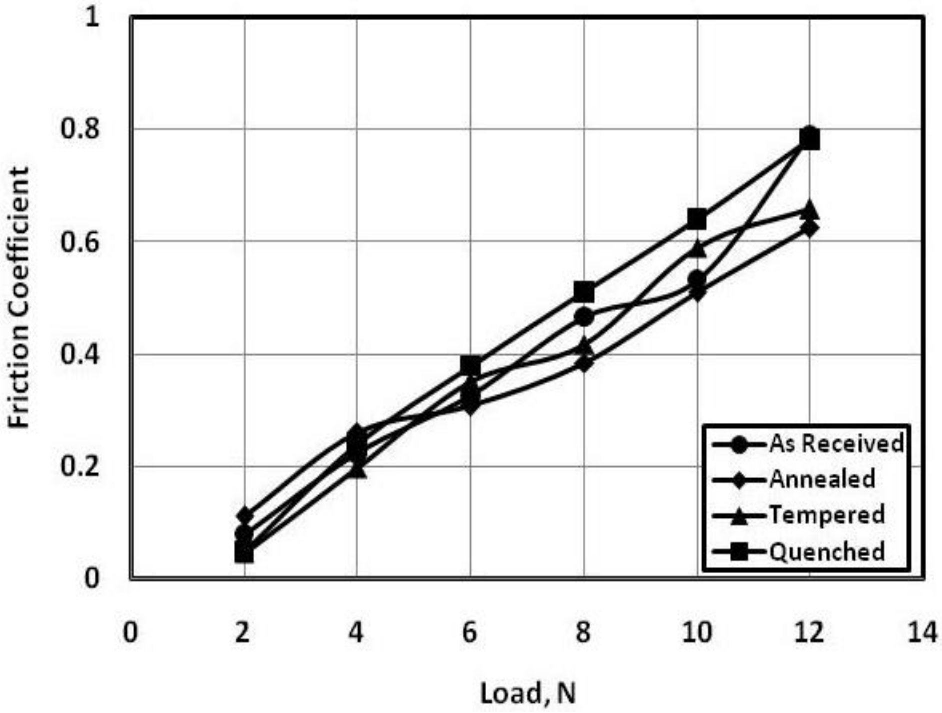

Fig. 6 Friction coefficient displayed by the scratch of double layers polyurethane that heat treated at 75 °C.

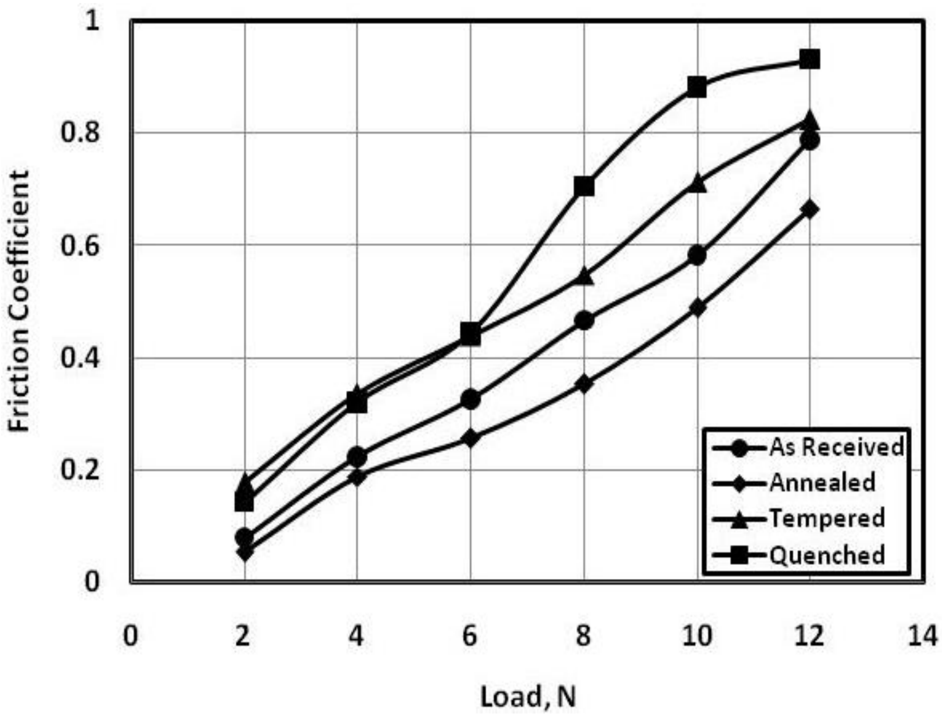

Fig. 7 Friction coefficient displayed by the scratch of triple layers polyurethane that heat treated at 75 °C.

Polyurethane coating of double layers and heat treated at 75 °C showed the lowest friction coefficient values compared to single and triple layers, Figs. 6. The highest friction values did not exceed 0.8 for as received and quenched coatings. This observation could confirm the suitable coating thickness of polyurethane.

Friction coefficient displayed by the scratch of triple layers polyurethane heat treated at 75 °C, Fig. 7, showed slight friction increase. Quenched coatings represented the highest values, while annealed ones showed the lowest values. The friction increase might be from the increase of the depth of penetration of stylus tip inside the coating thickness so that the sheared area increased.

Wear displayed by the scratch of single layer polyurethane that heat treated at 50 °C is illustrated in Fig. 8. The same trend of friction coefficient was observed for wear, where annealed coatings showed the lowest wear. Quenched coatings displayed relatively higher wear than tempered and annealed coatings. Wear displayed by the scratch of double layer polyurethane heat treated at 50 °C, Fig. 9, showed relatively lower values than that observed for 0.2 mm coatings. Quenched coatings displayed the highest wear values followed by the tempered coatings. It seems that as the coating thickness increased the effect of heat treatment increased. Wear displayed by the scratch of triple layer polyurethane heat treated at 50 °C is shown in Fig. 10, where slight increase compared to double layers coatings was observed. Based on this observation it can be suggested to use the double layers polyurethane of 0.5 mm thickness in engineering applications.

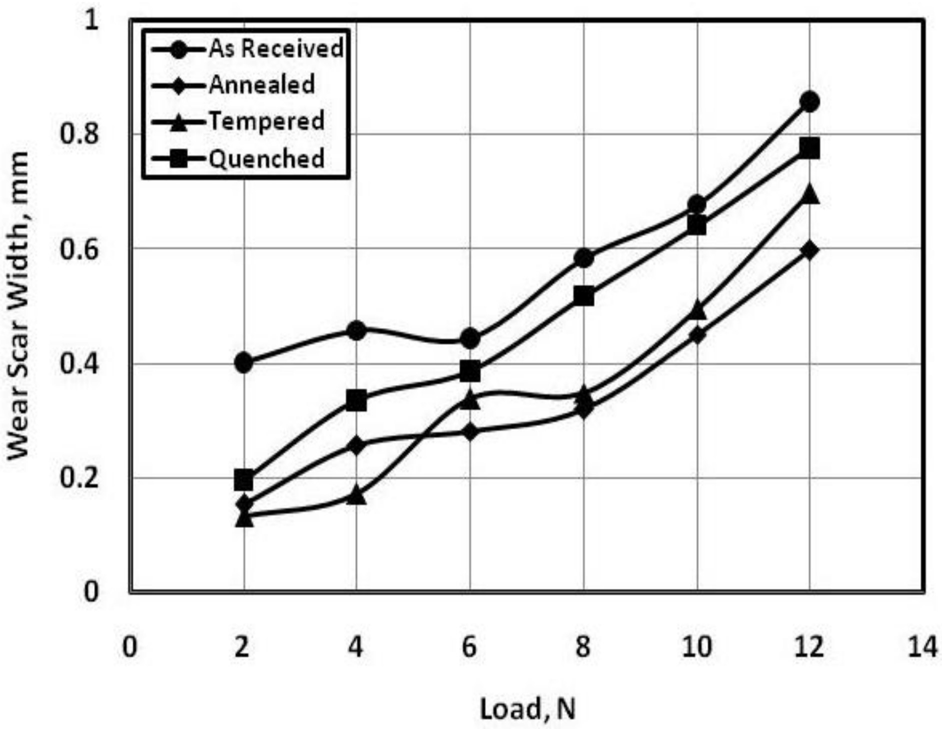

Fig. 8 Wear displayed by the scratch of single layer polyurethane layer That heat treated at 50 °C.

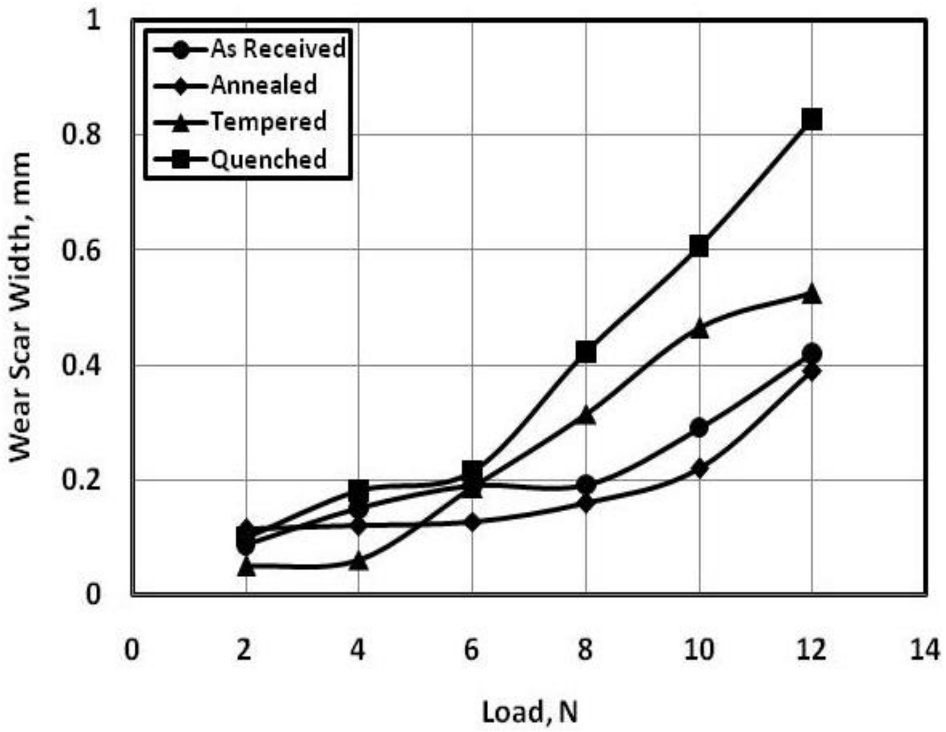

Fig. 9 Wear displayed by the scratch of double layer polyurethane heat treated at 50 °C.

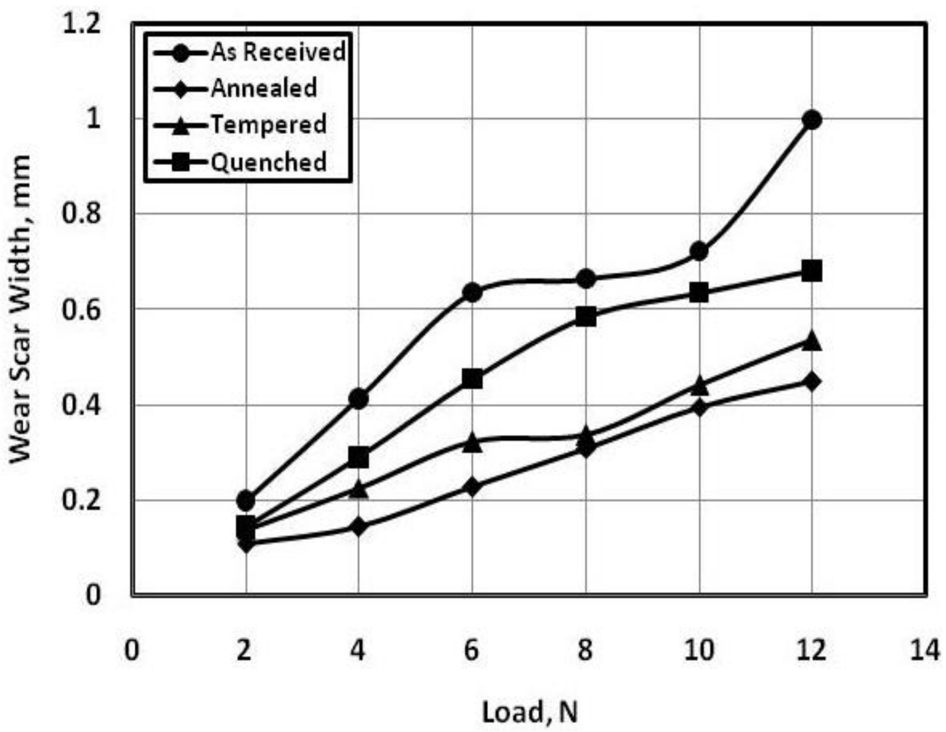

Fig. 10 Wear displayed by the scratch of triple layer polyurethane that heat treated at 50 °C.

Increasing the temperature of heat treatment caused slight increase in wear for single layer polyurethane coatings, Fig. 11. Quenched coatings displayed the highest wear

followed by as received and tempered ones, while annealed coatings showed the lowest wear.

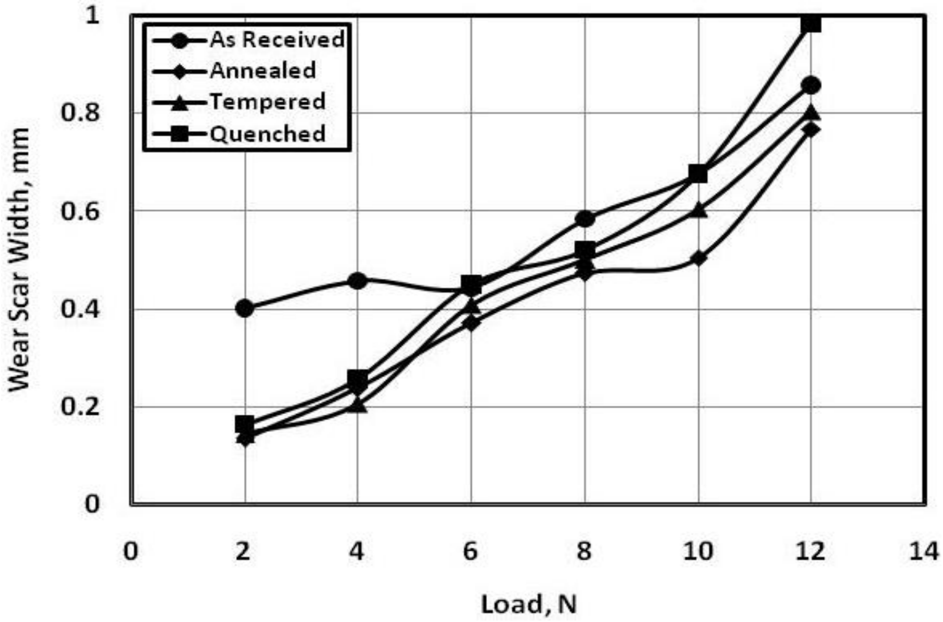

Fig. 11 Wear displayed by the scratch of single layer polyurethane that heat treated at 75 °C.

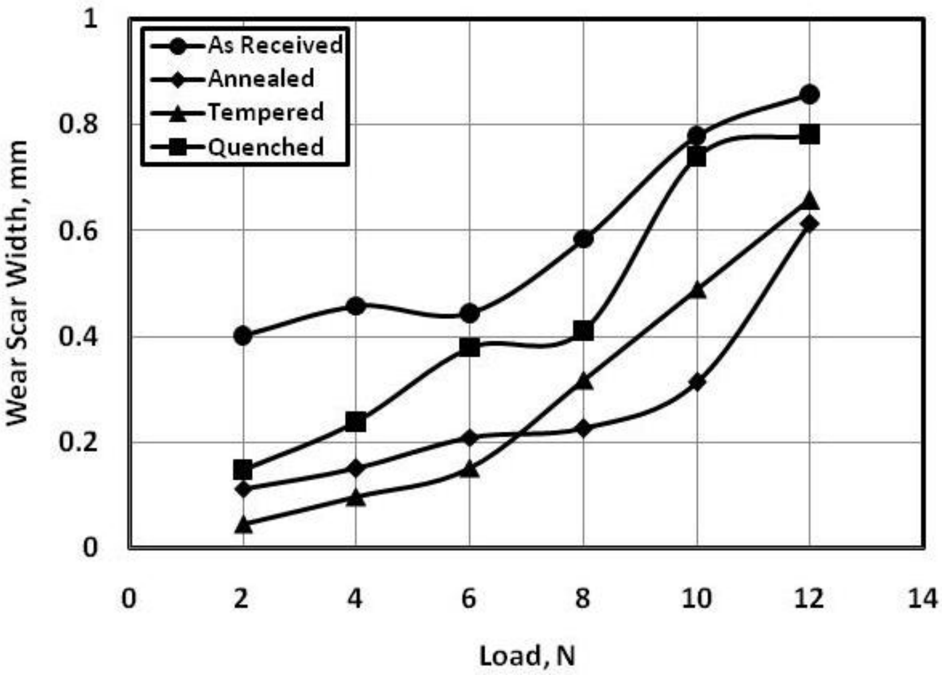

Fig. 12 Wear displayed by the scratch of double layers polyurethane that heat treated at 75 °C.

Significant wear decrease was observed for double layers polyurethane that heat treated at 75 °C, Fig. 12. The wear values were 0.8, 0.61, 0.65 and 0.78 mm for as received, annealed, tempered and quenched polyurethane coatings respectively.

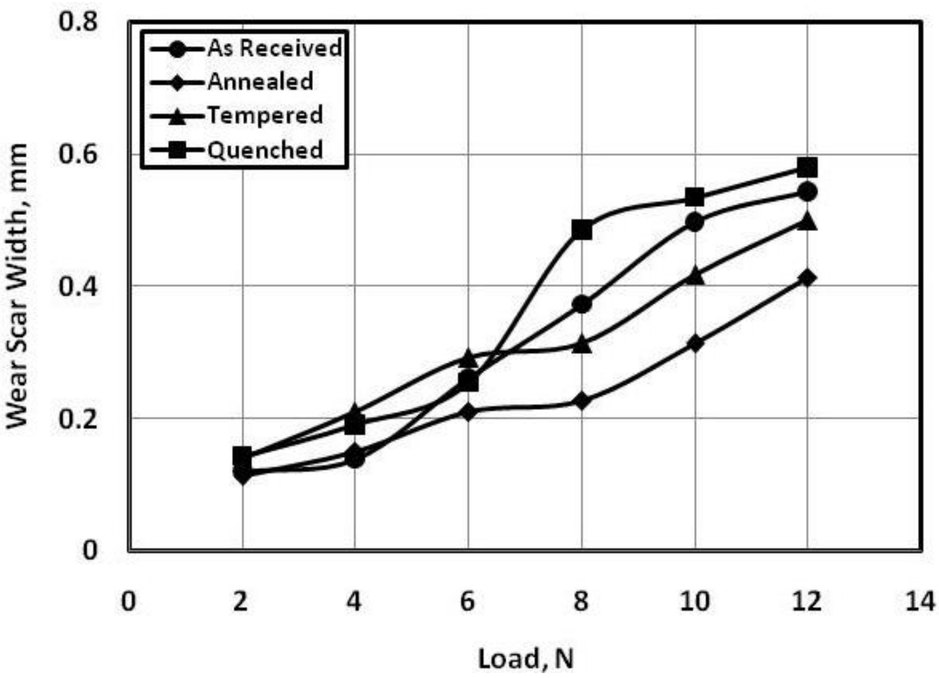

Fig. 13 Wear displayed by the scratch of triple layers polyurethane that heat treated at 75 °C.

Wear displayed by the scratch of triple layers (0.8 mm) polyurethane heat treated at 75 °C, Fig. 13, represented the lowest values compared to single and double layers coatings. Quenched coatings showed the highest values followed by as received, tempered and annealed ones. It seems that as the coating thickness increased the response of the polymer to heat treatment enhanced. Besides, the performance of 75 °C temperature was more effective that 50 °C temperature.

CONCLUSIONS

1. Friction coefficient significantly increased with increasing normal load. Annealed polyurethane single layer coating that heat treated at 50 °C displayed the lowest wear. Increasing the coating thickness to 0.5 mm (double layer) caused significant friction decrease. Annealed coatings displayed the lowest friction values, while as received ones showed the highest values. Friction coefficient displayed by triple layers polyurethane coating recorded higher friction for quenched test specimens followed by tempered and annealed ones.

2. Increasing the temperature of heat treatment to 75 °C caused significant increase in friction coefficient. Polyurethane coating of double layers showed the lowest friction coefficient values compared to single and triple layers. Friction coefficient displayed by the scratch of triple layers polyurethane showed slight friction increase. Quenched coatings represented the highest values, while annealed ones showed the lowest values.

3. Wear displayed by the scratch of single layer annealed polyurethane that heat treated at 50 °C showed the lowest wear. Quenched coatings displayed relatively higher wear than tempered and annealed coatings. Wear displayed by double layer polyurethane showed relatively lower values than that observed for 0.2 mm coatings. Quenched coatings displayed the highest wear values followed by the tempered coatings. Wear of triple layer polyurethane showed slight increase compared to double layers coatings.

4. Increasing the temperature of heat treatment up to 75 °C caused slight increase in wear for single layer polyurethane coatings. Annealed coatings showed the lowest wear.

Wear displayed by triple layers (0.8 mm) polyurethane represented the lowest values compared to single and double layers coatings. Annealed coatings showed the lowest wear values.

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