



Reciprocating Friction and Wear Performance of Epoxy/Al₂O₃ Polymer Nanocomposites

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Abstract- By using an immediate cross-linking procedure, five samples were created. Neat epoxy and epoxy filled with 0.5, 1.0, 1.5 and 2.0 wt% of Al₂O₃ nanorods. At three different reciprocating speeds of 20, 40 and 60 mm/s (corresponding frequencies were 4, 8 and 12 Hz for a wear stroke length of 5 mm) wear tests were performed on all samples using a 'linearly reciprocating ball on flat tribometer' against an ASE 304 stainless steel counter surface at room temperature with a constant load of 15 N. It was found that with an increase in reciprocating speeds, specific wear rate increases because of greater frictional heating and material softening. It was also observed that with an increase in reciprocating speeds, the coefficient of friction reduces, as frictional heating leads to surface softening, reducing adhesion. An increase in the wt% of Al₂O₃ as reinforcement in the epoxy matrix improves wear resistance and reduces the coefficient of friction up to 1.5 wt% reinforcement in the epoxy; a further increase in Al₂O₃ reduces wear resistance and increases the coefficient of friction. minimal important change, lumbar decompression, radiculopathy, patient-centred care

Keywords : Epoxy, Al₂O₃, Nanocomposites, wt%, Friction, Wear, Surface Roughness



I. INTRODUCTION

Polymers are created via the polymerization of many small molecules (monomers) into a covalently bonded chain. Special features of polymers are resistance to environmental corrosion, ability to sustain impact load, low density, high specific strength, quiet operation due to vibration and noise absorption. However, there are some inherent shortcomings, such as lower load-carrying capacity, higher friction and wear rates than those with liquid-lubricated metals, poor thermal conductivity and limited dimensional stability due to thermal expansion. Hence, neat polymers are generally not adequate for the required end use. To overcome the shortcomings of the above-mentioned neat polymer, the reinforcement of nanosize particles is made in the polymer matrix.

In composite materials one of the phases is usually discontinuous, stiffer and stronger which is called reinforcement, whereas the less stiff and weaker phase is continuous and called a matrix. The properties of composite materials depend on the properties of its constituents, geometry, weight fraction, etc. Out of which, an important parameter is the volume (or weight) percentage of reinforcement. The degree of reinforcement depends on several factors, including whether the polymer is crystalline or not and the amount of crystallinity that has developed. Semi-crystalline polymers are more efficiently reinforced than amorphous polymers. Because reinforcement becomes surrounded by a microcrystalline structure, which binds the reinforcement more firmly to the polymer [1]. Reducing the particle size to a nanoscale level is assumed to reach a significant efficiency [2]. Nanosize particles as reinforcing material show their quantum size effect, surface effect and volume effect, which make the nanocomposites have excellent wear resistance and good corrosive resistance, excellent heat resistance, high strength and low creepage [3]. Recently, nanometer sized inorganic compounds such as TiO_2 , ZnO , SiO_2 , Al_2O_3 , Si_3N_4 etc. were tried as the fillers of fabric composites and polymers to improve the tribological properties [4–9]. Epoxy-base matrix composites have tremendous potential to substitute for traditional metallic materials [10]. Epoxy resin (EpR) is one of the most common thermoset polymers. Polymer nanocomposite has the advantages of low cost and simplified manufacturing processes [11]. Wear is the loss of materials on the surfaces of two rubbing bodies. The changes in the surface layer arise from mechanical stresses, temperature and chemical reactions [12]. While a broader definition of wear includes any form of surface damage caused by rubbing processes on one surface against another [13]. The amount of wear in any system will, in general, depend upon a number of factors, such as the applied load, machine characteristics, sliding speed, sliding distance, the environment, and the material properties. The value of any wear test method lies in predicting the relative ranking of material



combinations. It does not attempt to duplicate all the conditions that may be experienced in service (for example, lubrication, load, pressure, contact geometry, removal of wear debris, and presence of corrosive environments); there is no assurance that the test will predict the wear rate of a given material under conditions differing from those in the test [14]. In case of composite in which aluminium 6063 mixed with TiC, B₄C, and carbide particles using stir casting process, shown superior to base Al alloy 6063. The sliding velocities selected were 2, 2.5, and 4 m/s. It was observed that the wear rate marginally increases with the increase of sliding velocity. This may be due to plastic deformation on the surface and the formation of high temperature because of high velocity. At higher velocity, temperature increases due to this thermal softening taking place, and this leads to more wear [15].

In the case of a sliding stainless steel pin on different types of material such as cloth-reinforced ebonite (gear fiber), glass fiber-reinforced plastic (glass fiber), nylon, and polytetrafluoroethylene (PTFE), the normal load range was 10 to 20 N, and the sliding velocity range was 1 to 3 m/s. In each trial, the duration of rubbing was 30 minutes. It was observed that wear rates of tested materials increased with increasing sliding velocity, and the rates of increment are different for different types of materials. Variation of wear rate (from 1.33 to 3.80, 0.27 to 1.5, 0.1 to 1.5 and 0.13 to 0.27 mg/min) with the variation of sliding velocity from 1 to 3 m/s for gear fiber, glass fiber, nylon, and PTFE, respectively. The wear rate increased due to reduced shear strength at higher sliding velocity [16]. In the case of epoxy resin 398 as a matrix having filler as glass fiber and graphite powder in different wt%. A pin-on-disc setup was used to investigate the dry sliding wear characteristics of the composites as per ASTM G99-95 standards against a hardened En-32 alloy steel disc with a hardness value of 62 HRC, a thickness of 8 mm, and a surface roughness of 10 μ m Ra. A variation of specific wear rate with applied load of 30 N and sliding distance of 2000 m under varied sliding velocities was made. It was noticed that the specific wear rate of tested composites increases with increasing sliding velocity [17]. In the case of epoxy filled with 60% woven glass fibers, the effect of normal loads and sliding velocities on the friction and wear behavior sliding against a steel disc in dry condition is investigated experimentally using a pin-on-disc type wear and friction monitor. Tests are conducted at normal loads of 5, 10, 20, 30, 40, and 50 N and the sliding velocities of 0.5, 1, 2, and 3 m/s. Friction and wear are influenced by the duration of sliding, normal load, and sliding velocity. It was investigated that the friction coefficient increases with the increase of sliding velocity for all levels of normal load; this may be due to more adhesion of the sliding disc with the composite. The wear loss increases with the increase of normal load and sliding velocity. The highest friction coefficient has been recorded at 3 m/s velocity, whereas the lowest friction



coefficient was recorded at 0.5 m/s velocity. The highest wear loss is recorded at 3 m/s velocity, whereas minimum wear loss is recorded at 0.5 m/s velocity [18].

It was observed that the sliding velocity has a more significant effect on the sliding wear as compared to the applied load and variations of wear rate with operating time [19]. Applied load and sliding speed play significant roles in the wear behavior of polymers and composites. They also showed that applied load has more effect on the wear than the speed for composites [20-21].

II. MATERIAL AND EXPERIMENTAL METHODS

1. Material

Low molecular weight epoxy with bisphenol A (LY 556) as matrix material and hardener (HY 951) were used in this work. Huntsman Advanced Material, India, provided both of the materials. At room temperature (25 °C), the densities of the epoxy and curing agent hardener utilized are 1.17 g/cc and 0.98 g/cc, respectively. In this study, cylinder-shaped alumina (Al_2O_3) nanorods were used as reinforcement. These Al_2O_3 nanorods were 5–10 nm in diameter, up to 50 nm in length, 40 m²/gm of specific surface area, and 4.0 gm/cc in density. These Al_2O_3 nanorods were provided by Sigma Aldrich Pvt. Ltd. and used in the present work to strengthen the epoxy in its natural state without any surface modification.

2. Synthesis of epoxy/ Al_2O_3 polymer nanocomposite

Al_2O_3 nanorod-reinforced epoxy nanocomposites were created using an immediate cross-linking technique. This study employed epoxy, a liquid polymer. Alumina particles of the requisite weight percentages (0.5, 1.0, 1.5 and 2 wt%) were heated at 150 °C for 4 hours to remove moisture before being used to prepare the samples. After that, dried alumina nanorods were manually mixed for 10 minutes with acetone and the necessary amount of epoxy resin.

This mixture was then subjected to an hour-long sonication. Following that, acetone was eliminated from the mixture using a hot plate procedure. The mixture was placed in a vacuum for 30 minutes in order to release the trapped gases created by the sonication process. Then hardener was gradually included in the mixture, such that the hardener-to epoxy ratio was 1:10. To release any gases that may have been trapped, this mixture was once again maintained in a vacuum for five minutes. Finally, the



mixture was put into a vertical acrylic mold and allowed to cure for 24 hours at room temperature. These samples were then taken out of the molds and post-cured in a hot air oven at 100°C for four hours.

3. Density measurement

Weighting equipment ('mettler toledo' ME155DU/A, capacity 152 g - 4 mg, least count 0.1 mg) was used to determine each sample's density. Each sample's density was determined using the Archimedes method.

$$\rho = \frac{M \cdot \rho_a}{M - M_a} \quad \dots \dots \text{Eq. 1}$$

Where ρ is density of sample (in g/cc), M is mass of samples in air (in g), M_a is mass of samples dipped in acetone (in g) and ρ_a is density of acetone (in g/cc).

4. Friction and wear measurement

The tribological properties of epoxy and epoxy containing Al_2O_3 nanorods were experimentally evaluated in accordance with ASTM standard G133-05 (2016). Dry sliding wear tests were performed using a 'linearly reciprocating ball on a flat tribometer' (specifications: Company Rtec instruments, maximum load up to 5000 N, temperature range 120–1200 °C, stroke 1–30 mm, and frequency up to 70 Hz). A counter surface of ASE 304 stainless steel balls with a 70 HRC room temperature hardness was used. All the samples were shaped like plates with dimensions of 20×10×10 mm.

Prior to the wear testing, the samples were polished with sandpaper of varying grades, up to 2000 grade. At room temperature, a normal load of 15 N was used throughout the test, and the reciprocating speeds were set at 20, 40 and 60 mm/sec corresponding frequencies were 4,8 and 12 Hz for a wear stroke length of 5 mm. During the test, a total of 60 meters of sliding distance were covered. Three different wear tests were performed on each sample, with the average result being utilized.

Frictional force is displayed internally on the 'linearly reciprocating ball on flat tribometer' control panel when the test is being done. The usual applied load was divided by the frictional force to determine the coefficient of friction. The specimen's weight was measured before and after the test with an accuracy of 0.1 mg using an electronic balance. The difference between a specimen's mass before and after wear is referred to as mass loss. The volume loss is then determined by multiplying the mass loss by the density of the corresponding samples.



III. RESULTS AND DISCUSSION

1. Wear test

Table 1 illustrates the impact of wt% of reinforcement on the specific wear rate at room temperature (25 °C) for different reciprocating speeds of 20, 40 and 60 mm/sec.

Table 1: Specific wear rate for various samples ($\times 10^{-6}$ mm³/N.m)

	Reciprocating Speeds		
	20mm/s	40 mm/s	60 mm/s
Sample	Specific wear rate ($\times 10^{-6}$ mm ³ /Nm)		
Pure Epoxy	4.8503	6.1518	7.5021
Epoxy + 0.5% Al ₂ O ₃	4.1538	4.925	5.8526
Epoxy + 1.0% Al ₂ O ₃	3.4038	4.1538	4.9355
Epoxy + 1.5% Al ₂ O ₃	2.8532	3.5238	4.3507
Epoxy + 2.0% Al ₂ O ₃	3.1528	3.852	4.6503

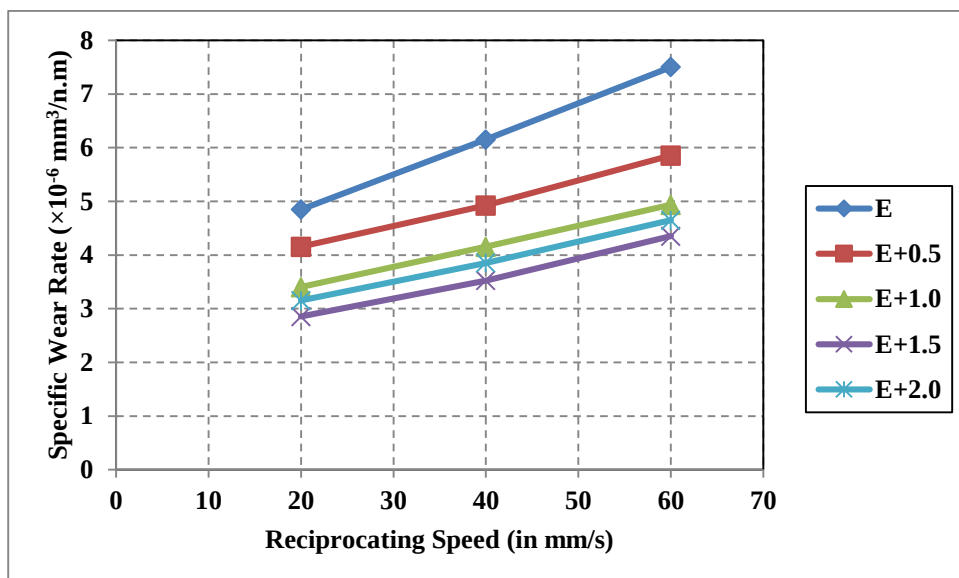


Figure . 1 Variation in specific wear rate for various samples

From figure 1 it can be observed **that** the variation of specific wear rate with reciprocating speed for epoxy and epoxy filled with Al_2O_3 nanorod clearly shows that sliding velocity plays a dominant role in the wear behaviour of the samples. The neat epoxy exhibits the highest wear rate at all speeds, increasing rapidly from about $4.7 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ at 20 mm/s to nearly $7.5 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ at 60 mm/s. This sharp increase is because of lower hardness and resistance to plastic deformation attributed to thermal softening of the polymer matrix, and the formation of adhesive junctions at higher speeds. In contrast, the nanocomposite specimens reinforced with 0.5, 1.0, 1.5, and 2.0 wt% Al_2O_3 nanorod demonstrate considerably lower wear rates across the entire speed range. The presence of rigid and thermally stable Al_2O_3 nanorods enhances the load-bearing capacity, reduces micro-cutting, and limits thermal degradation, resulting in a more gradual increase in wear with speed compared to the neat epoxy.

Among the composites, the 1.5 wt% sample displays the lowest wear rate at all speeds, confirming that higher filler loading forms a more robust reinforcement network and effectively strengthens the matrix against abrasion and fatigue wear mechanisms. While reinforcement of **2.0 wt% Al_2O_3** shows a slight increase in wear due to potential particle agglomeration, which weakens the composite. Thus we can



say that the addition of **Al₂O₃ nanorods helps reduce wear**, but at excessive filler loading (2.0 wt%), agglomeration may counteract benefits. An increase in **reciprocating speeds increases specific wear rate** because of greater frictional heating and material softening.

When compared with previously published research, the present results follow the same behavioral pattern reported for aluminium-based stir-cast composites reinforced with TiC and B₄C, where wear increased with sliding velocity due to thermal softening. A similar agreement is observed with studies on stainless steel pin sliding over polymers such as gear fiber, glass fiber, nylon, and PTFE, which showed increased wear at higher velocities because of reduced shear strength under elevated temperatures. Moreover, earlier investigations on glass-fiber- and graphite-filled epoxy systems also reported that specific wear rate rises with speed due to friction-induced heat generation, consistent with the performance of the neat epoxy in the present study. Likewise, the increasing wear and friction coefficient observed in woven glass-epoxy composites at higher sliding speeds is reflected here, particularly in the steep slope of the neat epoxy curve. Overall, the results strongly support the literature, while clearly demonstrating that the addition of alumina nanorods significantly improves the tribological performance of epoxy by mitigating velocity-induced adhesive wear and thermal softening.

2. Friction test

Table 2 illustrates the impact of wt% of reinforcement on the coefficient of friction at room temperature (25 °C) for different reciprocating speeds of 20, 40 and 60 mm/sec.

Table : 2 Coefficient of friction for various samples

	Reciprocating Speeds		
	20 mm/s	40 mm/s	60 mm/s
Sample	Average coefficient of friction		
Pure Epoxy	0.6055	0.5506	0.5121
Epoxy + 0.5% Al ₂ O ₃	0.5512	0.5018	0.4536
Epoxy + 1.0% Al ₂ O ₃	0.5201	0.4483	0.4154
Epoxy + 1.5% Al ₂ O ₃	0.4312	0.4016	0.3516
Epoxy + 2.0% Al ₂ O ₃	0.4712	0.4303	0.4016

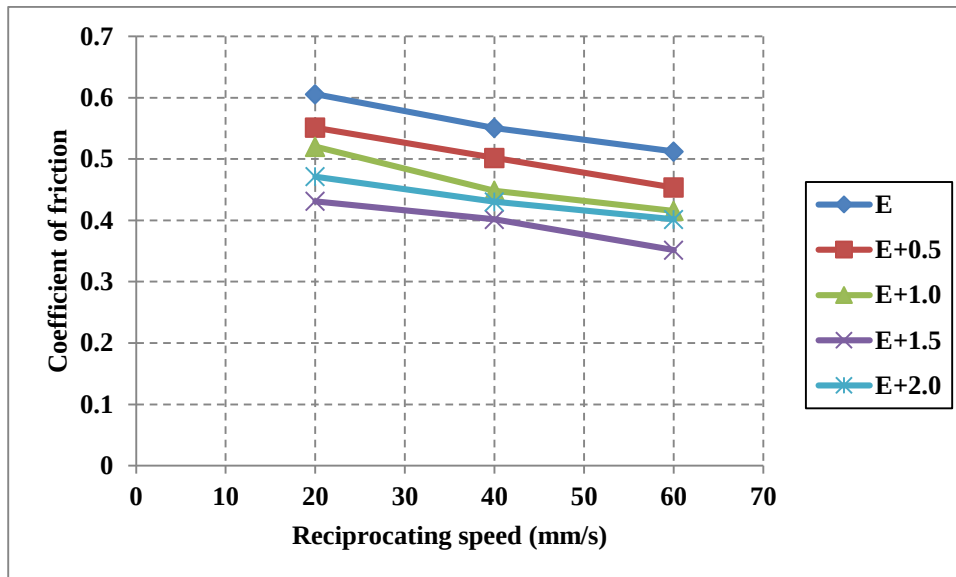


Figure . 2 Variation in coefficient of friction with reciprocating speed

From Figure 2, it can be seen that coefficient of friction decreases progressively with increasing reciprocating speed for all tested samples, with neat epoxy exhibiting the highest friction values across the entire speed range. At low speed (20 mm/s), friction is relatively high due to pronounced asperity interaction and adhesion between the epoxy surface and the steel counterface. As the speed increases to 40 and 60 mm/s, thermal softening of the epoxy matrix and the formation of a thin transfer film reduce interfacial shear strength, resulting in a noticeable drop in friction. Reinforcement with Al_2O_3 nanorods significantly lowers the coefficient of friction compared to pure epoxy, and this effect becomes stronger with increasing filler concentration. The composites containing 1.5 and 2 wt% nanorods show the lowest friction values at all speeds, indicating enhanced load-bearing capability, increased surface hardness, and reduced adhesion-dominated interaction. **At 2.0 wt% Al_2O_3 , the coefficient of friction slightly increases**, likely due to **particle agglomeration** leading to rougher sliding conditions. The gentler decline in friction for the reinforced composites with rising speed shows that the Al_2O_3 nanorods help stabilize the tribological interface by minimizing thermal softening and promoting a more uniform transfer film. These observations are consistent with earlier literature, where polymer- and epoxy-based composites similarly exhibited reduced friction at higher sliding velocities and improved tribological performance with the inclusion of hard reinforcements such as glass fibers, graphite, TiC, and carbide



particles. Overall, the obtained results confirm that sliding speed and nanoparticle reinforcement play critical roles in controlling frictional behavior, with higher speeds and higher Al_2O_3 content contributing to smoother, more stable sliding.

IV. CONCLUSIONS

- **Pure epoxy** has the highest specific wear rate due to its lower hardness and resistance to plastic deformation.
- Wear resistance increases with an increase in **wt% of Al_2O_3** nanorods up upto 1.5 wt%, and **1.5 wt% Al_2O_3** provides the best wear resistance due to optimal particle dispersion and load-bearing capacity.
- Reinforcement of **2.0 wt% Al_2O_3** shows a slight increase in wear due to potential **particle agglomeration**.
- An increase in **reciprocating speeds increases specific wear rate** because of greater frictional heating and material softening.
- **Pure epoxy has the highest COF** due to its softer nature and higher adhesion to the counter surface.
- **Adding Al_2O_3 nanorods from 0.5 to 1.5 wt% in an epoxy matrix reduces the coefficient of friction, and 1.5 wt% Al_2O_3 provides the lowest coefficient of friction.**
- **At 2.0 wt% Al_2O_3 , the coefficient of friction slightly increases**, likely due to **particle agglomeration** leading to rougher sliding conditions.
- **With an increase in reciprocating speeds, the coefficient of friction reduces**, as frictional heating leads to surface softening, reducing adhesion.

REFERENCES

1. Tewari U., Bijwe J., "Recent development in tribology of fiber reinforced composites with thermoplastic and thermosetting matrices", *Advances in Composite Tribology*; (1993) p 159-207
2. Friedrich K., Zhang Z., Schlarb A., "Effects of various fillers on the sliding wear of polymer composites", *Composites Science and Technology* 65; (2005) p 2329-2343



3. Wang H., Yan L., Dujuan L., Wang C., Zhu Y., "Investigation of the tribological properties: Core-shell structured magnetic NiO nanoparticles reinforced epoxy nanocomposites", *Tribology International* 83; (2015) p 139-145
4. Vlasveld DPN, Parlevliet PP, Bersee HEN, Picken SJ. "Fibre-matrix adhesion in glass-fibre reinforced polyamide-6 silicate nanocomposites", *Compos Part A*; (2005) p 1-11
5. Wang QH, Xue QJ, Liu WM, Chen JM., "The friction and wear characteristics of nanometer SiC and polytetrafluoroethylene filled polyetheretherketone", *Wear*; (2000) p 140-146
6. Shi G., Zhang MQ., Rong MZ., Wetzel B., Friedrich K., "Sliding wear behavior of epoxy containing nano-Al₂O₃ particles with different treatments", *Wear*; (2004) p 1072-1081
7. Shi G., Zhang MQ., Rong MZ., Wetzel B., Friedrich K., "Friction and wear of low nanometer Si₃N₄ filled epoxy composites", *Wear*; (2003) p 784-796
8. Li F., Hu KA., Li JL., Zhao BY., "The friction and wear characteristics of nanometer ZnO filled polytetrafluoroethylene", *Wear*; (2002) p 877-882
9. Iizuka T., Kita H., Hirai T., Osumi K., "Tribological behavior of W₂C nanoparticle reinforced Si₃N₄ matrix composite", *Wear*; (2004) p 953-961
10. Nayak R., Dasha A., Ray B., "Effect of epoxy modifiers (Al₂O₃/SiO₂/TiO₂) on mechanical performance of epoxy/glass fiber hybrid composites" *Procedia Materials Science*, Vol. 6; (2014) p 1359-1364
11. Lin L., Eun D., "Tribological properties of polymer/silica composite coatings for microsystems applications" *Tribology International* 44; (2011) p 1926-1931
12. Bely VA, Sviridenok AI, Petrokovets MI, Savkin VG, "Friction and wear in polymer based materials" Oxford: Pergamon Press; (1982) p 416
13. Nordin N., Yussof F., Kasolang S., Salleh Z., Ahmad M., "Wear rate of natural fiber : long kenaf Composite" *Procedia Engineering* 68; (2013) p 145-151
14. ASTM G 99 – 95A (Reapproved 2000); Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus
15. G. Ramanan, J. Edwin Raja Dhas, R.R. Neela Rajan et al., "Fabrication and wear characterization of stir cast AA7075-TiCp reinforced composite", *Materials Today: Proceedings*
16. M.A. Khairula , M.A. Alima and Z. Abdinb, "An experimental investigation of wear behavior of gear fiber, glass fiber, nylon and polytetrafluoroethylene" *Engineering e-Transaction (ISSN 1823-6379)* Vol. 3, No.2, December 2008, pp 38-42
17. A.R. Annappa & S. Basavarajappa (2014) Studies on dry sliding wear behaviour of functionally graded graphite particle-filled glass-epoxy composites, *Composite Interfaces*, 21:5, 395-414, DOI: 10.1080/15685543.2014.870866



18. P. Sarkar , N. Modak, Pr. Sahoo, "Effect of Normal Load and Velocity on Continuous Sliding Friction and Wear Behavior of Woven Glass Fiber Reinforced Epoxy Composite", Materials Today : Proceedings 4 (2017), p 3082-3092
19. Y. Q. Wang, J. Li, Sliding Wear Behavior and Mechanism of Ultra-high Molecular Weight Polyethylene, J. Mater. Sci. and Eng. 266 (1999) 155-160.
20. H. Pihtili, N. Tosun, Investigation of the Wear Behavior of a Glass Fiber-Reinforced Composite and Plain Polyester Resin, Comp. Sci. and Tech. 62 (2002) 367-370.
21. H. Pihtili, N. Tosun, Effect of Load and Speed on the Wear Behavior of Woven Glass Fabrics and Aramid Fiber-Reinforced Composites, Wear, 252 (2002) 979-984.