

TESTING METHODS IN TRIBOLOGY: A REVIEW

Umar Nirmal, Jamil Hashim, Saijod T.W. Lau

Faculty of Engineering and Technology, Multimedia University,
Jalan Ayer Keroh Lama,
75450, Melaka, Malaysia.
Tel: +606 2523007, Fax: +606 2316552
nirmal@mmu.edu.my, nirmal288@yahoo.com

ABSTRACT

This article attempts to describe some of the testing methods commonly used in tribology. It namely illustrates the contact of solid mechanics and nature of surface interaction. With the advent of sustainable development, composite materials now become more prominent in many applications. Many natural fibres in polymeric composites are being introduced in aviation industry, construction, industrial applications, automotive parts, bearing and many others, making tribo-testing more demanding. Relevant to this, the testing methods elaborated here are focused on the different types of wear test rigs used for testing of solid specimens for composite materials. Different mechanisms of wear and sliding friction of materials subjected to different wear test rigs which are built based on ASTM standards simulating the real time conditions are explained. Typical factors contributing to the wear performance of a material such as interfaces temperature (i.e. test specimen / counterface) under dry and wet tribo-testing conditions and roughness property are also detailed.

Keywords: Tribology testing methods, wear test rigs, roughness, composite material, natural fibre.

1. INTRODUCTION

Tribology is defined as the study of friction, wear and lubrication of interacting surfaces in relative motion. The importance of tribology at present time is crucial since most design applications involve 'wear and tear' process when subjected to relative motion. Medalia (1980) reported that about 63% of wear has contributed to the total cost of industries. Interestingly, these contribution factors (friction, heat, wear, etc.) cannot be eliminated completely; however, they can be minimized. According to the famous law regarding conservation of energy, it states that the total amount of energy created can never be destroyed; it can only be transformed from one

state to another, for an example, kinetic energy is transformed into useful work, friction and heat dissipation to the surroundings. To link the above idea in terms of tribology, Figure 1 is presented. It illustrates two typical examples relating wear process due to relative motion; the human skeleton (c.f. Figure 1a) and the inline four stroke engine (c.f. Figure 1b). Thus, depending on the severity of the wear process, these areas (red spots) have a certain period of life span. This naturally occurring process (i.e. the decrease of output power of a car engine versus time) can be improved by means of extending its life span using tribology technology.



a) The human skeleton



b) Four stroke inline engine

Figure 1: Typical spots on the importance of tribology

From the past decade up to present time, many researchers had introduced advance materials as a substitute to the conventionally used materials as these modified materials are excellent in wear and friction, light in weight and improved life span (El-Tayeb, 1997). For an instance, Nautiyal et al. (1983) observed that the factors responsible for wear of a piston ring sliding against cast iron combustion chamber were its surface temperature, peak combustion pressure, total energy of the wearing surfaces and other physical properties of the material under sliding. As such Dahm et al. (2003) proposed to replace the conventional piston rings with ceramic matrix nano composite piston rings as the latter had smooth wear (i.e. micro scale wear) which contributed in low wear rates during the test.

Nevertheless, new applications involving natural fibres in polymeric composites are being introduced in various areas such as housing construction materials (Hariharan et al., 2005), industrial applications (Satyanarayana et al., 1990), automotive parts fabrication (John et al., 2008), bearing applications (El-Sayed et al., 1995), structural and non-structural applications (Sreekala et al., 2002). Hence, scientific principles and calculating methods of creating new materials / composites and estimation of its wear resistance of friction nodes as well as physical simulation of friction and wear processes on a small-sized laboratory test machine need to be carried out experimentally before a proposed material/composite is commercially introduced in the market (Dahm, et al., 2003; Pogosian 1973). Prior to this, a suitable type of wear test rig should be used with appropriate parameters selected which reflect the real time application of the material/composite. Examples of this parameters are testing techniques, type of

counterface used against the test samples, sliding velocities, sliding distances, applied loads, contact conditions and orientations of the test specimen with respect to the sliding direction of the counterface.

Having such knowledge, a tribo-testing machine which is capable to simulate the wear and frictional test based on the selected parameters is developed. From available published works, there are numerous types of tribo-testing machines. They differ with one another based on the suitability of the test for a specific application. Thus, the aim of this paper is to explain the various types of tribo-testing machines used in performing different types of test which reflects the real time conditions. In conjunction to that, the work further illustrates on common ways in presenting data/results upon completion of a tribological experiment/test.

2. TYPES OF TRIBO-TESTING MACHINES

2.1 Dry sand rubber wheel

(Pogosian 1973; Rajesh et al., 2002; Kim et al., 2002)

Its schematic is shown in Figure 2. It is built based on ASTM G65 standard where its recommended specimen size is 70mm x 20mm x 7mm. The rubber wheel is in contact with the specimen when a load is applied. Sand particles (i.e. fine, grain or coarse) are introduced at a certain flow rate to the rubbing zone during the test. The flow rate can be varied based on the outlet diameter of the sand hopper. Since it involves sand, the test is abrasive. Adhesive testing is possible if sand is not used. Typical application of test involves the wear performance of tire treads, bushes, bearings and rollers.

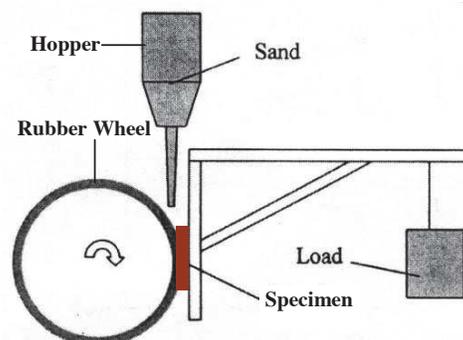


Figure 2: Schematic view of a dry sand rubber wheel wear test rig

2.2 Pin on drum

(Rajesh et al., 2002; Stevenson et al., 1996; Mutton 1978; Mutton, 1980; Blickensderfer et al., 1988)

Figure 3 illustrates the pin on drum wear test rig. It is built based on ASTM A514 standard. The specimen travels linearly with the help of the power screw while the drum rotates at a desired speed with the help of the drive chain. The speed of the specimen and the drum can be controlled by means of a speed controller incorporated at the motor system. Test can be abrasive if drum is coated with abrasive paper of different grades. Without abrasive paper, test is adhesive. Drum can be of different material (i.e. stainless steel, aluminum, cast iron, mild steel, etc) based on the suitability of the test conducted simulating the real time conditions. Application of test involves sliding of goods on rotating rollers or conveyer belts.

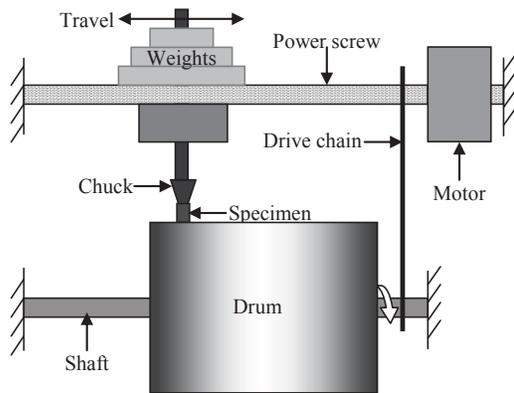


Figure 3: Schematic view of a pin on drum wear test rig

2.3 Linear tribo machine

(Yousif et al., 2010)

The schematic view of the linear tribo machine is presented in Figure 4. Its stainless steel counterface moves linearly with the help of the power screw which is directly coupled to the motor. Test can be abrasive when the stainless steel container is filled with abrasive particles, else the test is purely adhesive. A frictional indicator is connected to a load cell to measure frictional forces and a speed controller is used to vary the counterface sliding speed. Dead weights are applied parallel to the test specimen. The counterface can be of different material for different test conditions. For the adhesive test, water can be incorporated in the sliding container for the purpose of simulating the wear under wet contact conditions. Application of test involving linear tribo machine replicates the characteristics

of linear sliding of window panels, doors, hinges and drawers.

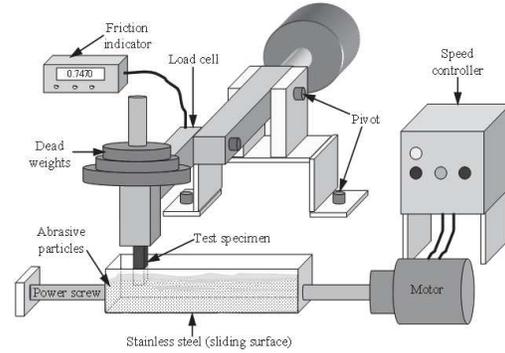


Figure 4: Schematic view of a linear tribo machine

2.4 Block on ring

(Pihl III et al., 2002; Reinicke et al., 1998)

A schematic view of a block on ring tribo test machine is presented in Figure 5. It is built in accordance with ASTM G77, G137-95 standards. The specimen with size of 10mm x 20mm x 50mm is in contact parallel to the side of the counterface. Contact area of the test specimen subjected to the counterface is variable. A load cell is directly incorporated in the load lever of the machine to capture frictional forces during the test. A counter weight balancer is incorporated at the end of machine's load lever to balance the lever arm prior testing. This is done when no load is applied. Depending on the nature of the test, counterface can be of various types (i.e. metal, cast iron, titanium, aluminum, stainless steel, etc). Generally, this test is simulated for applications such as sliding or rolling wear behavior of tire treads, pulleys, camshafts and bearings materials.

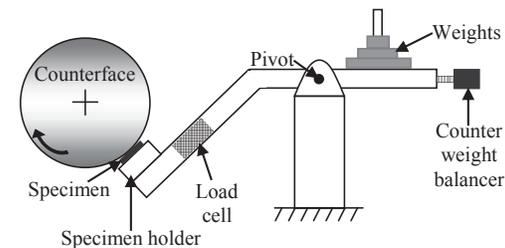


Figure 5: Schematic view of a block on ring tribo test machine

2.5 Pin on disc

(Hummel et al., 2004; Mergler et al., 2004; Bijwe et al., 2002; Bijwe et al., 2001)

Its schematic view is presented in Figure 6. Built based on ASTM G99 standard, its working principle is the same as block on ring. However,

the test specimen with size of 10mm x 10mm 20mm subjected to the counterface exhibits a constant contact area throughout the test. The test specimen is set perpendicular and horizontal to the counterface. Typical application of test includes sliding wear of various materials where constant contact area of interest.

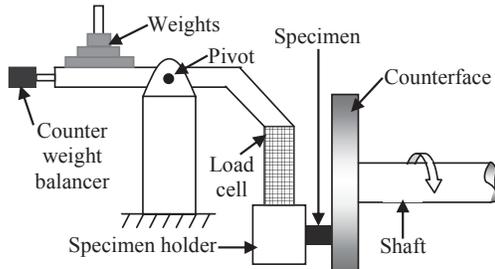


Figure 6: Schematic view of a pin on disc tribo test machine

2.6 Block on disc (Hummel et al., 2004; Mergler et al., 2004; Bijwe et al., 2002; Bijwe et al., 2001)

Figure 7 illustrates a portable block on disc tribo test machine which is built on a small scale. It is designed in accordance with ASTM G99 standard. Specimen with size of 10mm x 10mm x 20mm is subjected vertically to the counterface where the contact area is constant. A portable infrared thermometer can be incorporated to the block on disc machine for the purpose of measuring interfaces temperatures during the test. Test can be adhesive and abrasive subjected to dry sliding mode. A speed controller unit is connected to the motor to vary the counterface speed while a digital frictional indicator is connected directly to the load cell to capture frictional forces during the test.

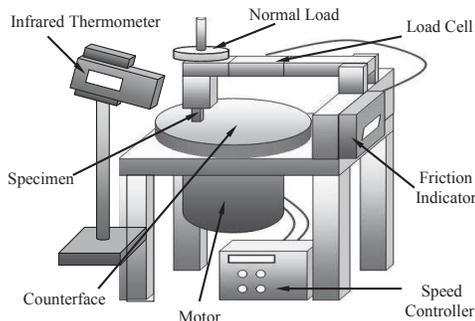


Figure 7: Schematic view of a block on disc tribo test machine

3. PRESENTATION OF DATA / RESULTS

Various methods are adopted to present / display the characteristics behaviour on wear and

frictional performance of a desired material. This section summarizes some common methods on data presentation as it is mostly preferred by worldwide researchers.

3.1 Wear performance

Wear process of a material can be defined as the tendency of a material to loose weight from the removal and deformation process on the material surface as a result of mechanical action of the opposite surface due to relative motion (Hummel et al., 2004; Harsha et al., 2002). Many researchers prefer to express wear performance of a material in terms of specific wear rate. Specific wear rate can be defined as follows:

$$W_s = \frac{\Delta V}{F_n \cdot D} \quad (1)$$

where;

W_s = Specific wear rate, mm^3/Nm
 ΔV = Volume difference, mm^3
 F_n = Normal applied load, N
 D = Sliding distance, m

Therefore, the wear performance of a material is said to be superior if the specific wear rate is low (i.e. material / specimen exhibits low volume loss). However, there are a lot of other factors contributing to the wear performance of a material subjected to tribological test. Naming a few, the contact condition of the test specimen (i.e. dry / wet), orientation of the test specimen with respect to the sliding direction of the counterface and the types of reinforcements used (i.e. natural fibre / resin) are critical factors / parameters in affecting the wear performance of a material.

3.2 Frictional performance

Friction performance of a material can be defined as the force resisting the relative motion between two sliding interfaces. Generally, higher frictional performance implies the superiority of a material in exhibiting low friction coefficient values during tribological testing. Friction coefficient can be expressed as follow:

$$\mu = \frac{F_r}{F_n} \quad (2)$$

where;

μ = Friction coefficient
 F_r = Friction force, N
 F_n = Normal force, N

Theoretically, the component of F_r is contributed by two main elements such as adhesion force, F_a , and deformation or ploughing force, F_d (El-Sayed et al., 1995). Their corresponding relation to friction force is shown in Eq. (3).

$$F_r \approx F_a + F_d \quad (3)$$

F_a can be determined from the shear strength (τ_s) multiply with area of material contact (A); Eq. (4) (Rabinowicz 1995) while F_d is expressed in Eq. (5) (Rabinowicz 1995; Stolarski 2003; Bhushan 1999).

$$F_a = \tau_s \cdot A \quad (4)$$

$$F_d = \frac{2 \cdot F_n \cdot \tan \theta}{\pi} \quad (5)$$

where;

θ is the attack angle / roughness angle of the asperity

In summary, it can be said that from Eq. (3), (4) and (5), there are multiple factors affecting the frictional coefficient of a material. Factors such as the roughness angle of the asperity with respect to the contacting surface can be minimized when the contacting surfaces are smooth ($\theta \approx 0$). In regard to this, many reported works used various grades of abrasive sand papers to achieve a relatively smooth surface by the contacting bodies. After due research, Figure 8 proposes one possible way in achieving smooth surfaces between the test specimen and counterface before experiment start-up.

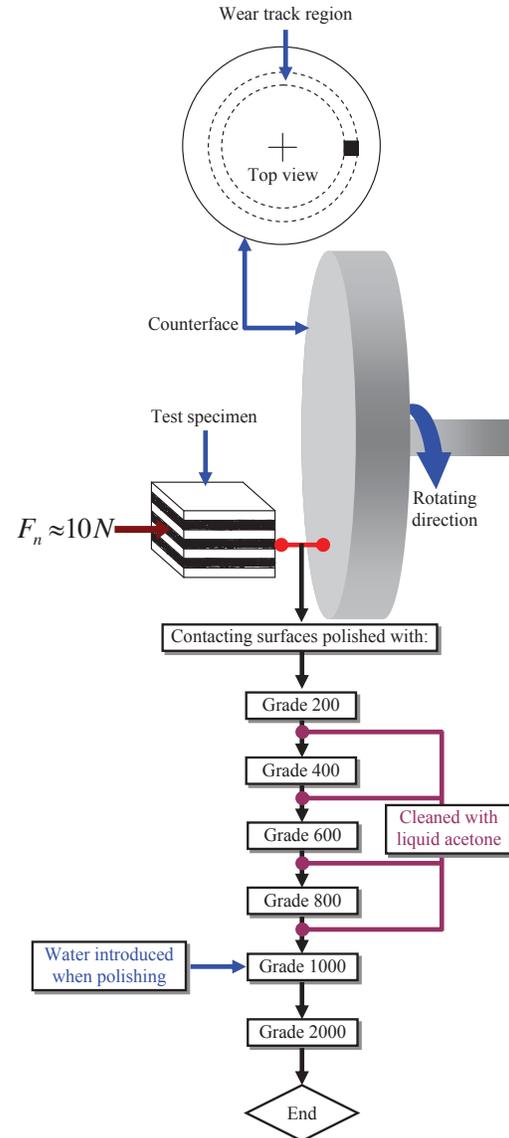


Figure 8: Proposed flow chart in achieving smooth interacting surface before experimental start-up

3.3 Temperature performance

It is important to relate/include temperature characteristics of a material when conducting tribology tests. This is because under dry adhesive wear, surface temperature of the interacting surfaces increases over time. Hence, effects of thermo-mechanical loading will be more significant on the softer phase (Bhushan 2001). This affects the wear and frictional performance of a material over long duration of experimental testing. Following to this, few techniques have been adopted in measuring temperatures during tribological test.

One of the most convenient ways is by using an infrared thermometer (Bhushan 2001). From Figure 9, an infrared thermometer is placed at a fix horizontal distance 'x' away from the test specimen. Accordingly, interfaces temperatures can be measured during the test. However, it is to be highlighted here that the accuracy of temperature measurement varies with the distance 'x'. For example, a temperature measurement at $x = 1$ m will differ with $x = 2$ m for the same test conditions. In other words, temperature measurements will be more accurate when the infrared thermometer is placed closer to the test specimen. However, the main limitation here is due to the design of the machine itself which limits the placement of the infrared thermometer close to the test specimen.

To minimize the measurement error of interfaces temperature, El-Tayeb et al., (2005) incorporated a thermocouple in an un-through hole of 2 mm in diameter which was pre-drilled on the test specimens (i.e. hole located approximately 0.75 mm above the test specimen contacting surface with counterface) during composite fabrication. Following to this, an external heat source was supplied to the counterface by means of a Bunsen burner. Concurrently, two temperature readings were recorded, i.e. from infrared thermometer and thermocouple device (c.f. Figure 10a). Based on the results obtained, a calibration graph was generated where the calibrated linear equation (c.f. Figure 10b) was used to determine the real interface temperatures. This method was reported to be more accurate (i.e. up to 90% accuracy in temperature recordings) (Yousif, et al., 2010; El-Tayeb et al., 2005; Nirmal, 2008) as compared to other measurement techniques (Chang 1983; Hanmin et al.,1987; Malay et al., 1982; Zaidi et al.,1999).

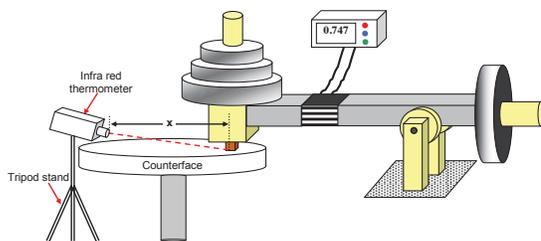
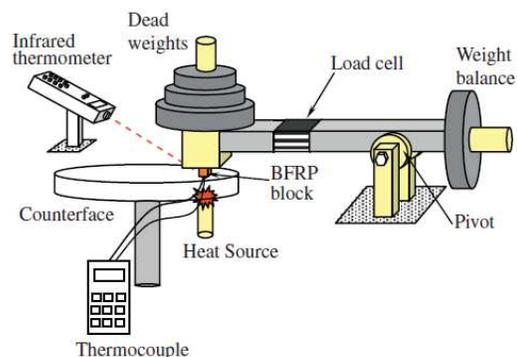
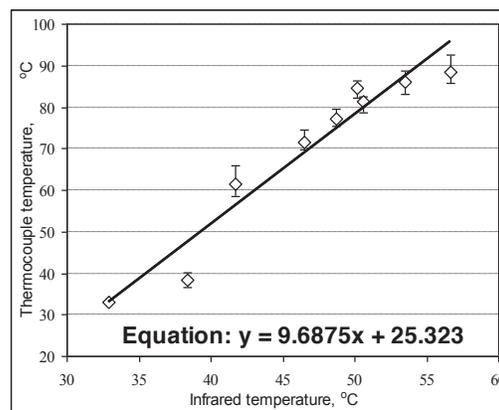


Figure 9: Incorporation of an infrared thermometer to measure interfaces temperatures



a) Temperature calibration process
 (Yousif et al., 2010)



b) Corresponding calibration graph
 (Nirmal, 2008)

Figure 10: Temperature calibration process with corresponding calibration graph

3.4 Roughness profile

The degree of abrasiveness to process equipment of a material subjected to tribology testing is an extensive area of study. For an instance, a tested material resulting in low abrasiveness to process equipment may contribute to an extended life span of the machine noting the fact that the material tested to be 'equipment friendly'. In conjunction to this, it is of great interest to measure surface roughness of the test specimen and the counterface before and after performing a tribological test. Surface roughness can be defined as the variations in the height of the surface relative to a reference plane. It is measured either along a single line profile or along a set of parallel line profiles. Profilometers are commonly used to measure and record surface roughness property of a material.

From available published works (Nirmal et al., 2010; Chin et al., 2009; Yousif et al., 2008), many authors prefer to express surface roughness measurement using Eq. (6).

$$R_a = \frac{a+b+c+d+\dots\dots}{n} \quad (6)$$

where;

R_a = Roughness average, μm

$a + b + c + d + \dots =$ Sum of infinitesimal areas
 above and below the datum
 line, m^2

$n =$ Length of the datum line, m

To further understand Eq. (6), a graphical illustration is presented in Figure 11. From the figure, line 'AB' is placed such a way that the sum of the areas above the line is equal to the sum of the areas below the line. Therefore, a Profilometer working principle is to measure the penetration depth formed by the asperities and local valley thereby producing the roughness average (R_a) value. However, there are also different ways of expressing the roughness property of a material. They are summarized in Table 1.

Table 1: Methods in expressing roughness property of a material

Symbol	Brief description
R_q	Root mean square average
R_{sk}	Skewness average
R_{ku}	Kurtosis average
R_t	P-V distance average (P-V: highest asperity to the lowest valley found anywhere along the profile length)
R_p	Maximum P-M distance average (P-M: height of the highest asperity and the mean line within one sampling length)
R_v	Maximum valley depth average
R_z	Average peak to valley height
R_{pm}	Average peak to mean height
R_{mr}	Material ratio average
R_k	Core roughness depth average
R_{pk}	Reduced peak height average
R_{vk}	Reduced valley depth average

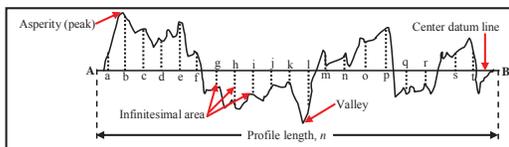


Figure 11: Graphical illustration in determining roughness average, R_a

4. CONCLUSION

The various types of tribo-testing machines, their accessories and applications have been discussed. They differ with one another on the basis of the suitability of the test for specific application. The sole purpose of the various types of tribo-testing machines is to establish the wear performance of materials in real time conditions. There are several factors contributing to tribology testing such as friction coefficient and wear performance of materials, surface roughness of a material/counterface and the degree of abrasiveness of a material. Understanding tribological factors such as roughness angle of the asperity with respect to the contacting surface and their effect on wetness and heat are valuable in assessing the quality of contact; i.e. test specimen against the counterface. Materials with low specific wear rate are considered to be superior (i.e. high wear resistance), while low abrasiveness to process equipment implies a longer extended life span of a particular material.

REFERENCES

- Bhushan, B 1999, *Principles and applications of tribology*, Wiley, New York.
- Bhushan, B 2001, *Modern Tribology Handbook*, CRC Press.
- Bijwe, J, Indumathi, J & Ghosh, AK 2002, 'On the abrasive wear behaviour of fabric-reinforced polyetherimide composites', *Wear*, vol. 253, no. 7-8, pp. 768-77.
- Bijwe, J, Indumathi, J, John Rajesh, J & Fahim, M 2001, 'Friction and wear behavior of polyetherimide composites in various wear modes', *Wear*, vol. 249, no. 8, pp. 715-26.
- Blickensderfer, R & Laird III, G 1988, 'A pinion-drum abrasive wear test and comparison to other pin tests', *J. Test. Eval.*, vol. 16, pp. 516-26.
- Chang, HW 1983, 'Wear characteristics of composites: Effect of fiber orientation', *International Journal of Wear*, no. 85, pp. 81-91.
- Chin, CW & Yousif, BF 2009, 'Potential of kenaf fibers as reinforcement for tribological applications', *Wear*, vol. 267, no. 1550-1557.
- Dahm, KL, Panagopoulos, K & Dearnley, PA 2003, 'The wear response of ceramic matrix nano-composite coatings in simulated piston-ring/cylinder wall test environments', in MPGDaAAL D. Dowson (ed.), *Tribology and Interface Engineering Series*, Elsevier, vol. Volume 41, pp. 511-5.

- El-Sayed, A, El-Sherbiny, MG, Abo-El-Ezz, AS & Aggag, GA 1995, 'Friction and wear properties of polymeric composite materials for bearing applications', *Wear*, vol. 184 no. 1, pp. 45-53.
- El-Tayeb, N 1997, *Science of Tribology, Friction, Wear, and Lubrication*, 2nd Edition edn, Egypt Publishing Company.
- El-Tayeb, NSM, Yousif, BF & Brevern, PV 2005, 'On The Effect Of Counterface Materials On Interface Temperature And Friction Coefficient Of GFRE Composite Under Dry Sliding Contact', *American Journal of Applied Sciences*, vol. 2, no. 11, pp. 1533-40.
- Hanmin, Z, Guoren, H & Guicheng 1987, 'Friction and wear of poly (phenylene sulphide) and its carbon fiber composites: I. Unlubricated', *International Journal of Wear*, no. 116, pp. 59-68.
- Hariharan, ABA & Khalil, HPSA 2005, 'Lignocellulose-based Hybrid Bilayer Laminate Composite: Part I - Studies on Tensile and Impact Behavior of Oil Palm Fiber-Glass Fiber-reinforced Epoxy Resin', *Journal of Composite Materials*, vol. 39, no. 8, pp. 663-84.
- Harsha, AP & Tewari, US 2002, 'Tribological performance of polyaryletherketone composites', *Polymer Testing*, vol. 21, no. 6, pp. 697-709.
- Hummel, SR & Partlow, B 2004, 'Comparison of threshold galling results from two testing methods', *Tribology International*, vol. 37, no. 4, pp. 291-5.
- John, MJ & Thomas, S 2008, 'Biofibres and biocomposites', *Carbohydrate Polymers*, vol. 71, no. 3, pp. 343-64.
- Kim, YS, Yang, J, Wang, S, Banthia, AK & McGrath, JE 2002, 'Surface and wear behavior of bis-(4-hydroxyphenyl) cyclohexane (bis-Z) polycarbonate/polycarbonate-polydimethylsiloxane block copolymer alloys', *Polymer*, vol. 43, no. 25, pp. 7207-17.
- Malay, K & Bahadur, K 1982, 'An investigation of the temperature rise in polymermetal sliding', *International Journal of Wear*, no. 82, pp. 81-92.
- Medalia, AI 1980, 'On structure property relations of rubber', paper presented to Proc. Int. Conf., Kharagpuur.
- Mergler, YJ, Schaake, RP & Huis, VAJ 2004, 'Material transfer of POM in sliding contact', *Wear*, vol. 256, no. 3-4, pp. 294-301.
- Mutton, PJ 1978, *High stress abrasion testing of wear resistant steels and cast irons*, Broken Hill Proprietary, Melbourne, Clayton, Victoria, Australia.
- Mutton, PJ 1980, *High stress abrasion testing of wear resistant materials*, 1, Broken Hill Proprietary, Melbourne Res. Lab, Clayton, Victoria, Australia.
- Nautiyal, PC, Singhal, S & Sharma, JP 1983, 'Friction and wear processes in piston rings', *Tribology International*, vol. 16, no. 1, pp. 43-9.
- Nirmal, SG 2008, 'An Investigation of Wear and Frictional Performance of Betelnut Fiber Reinforced Polyester Composite Under Dry Contact Condition', Multimedia University.
- Nirmal, U, Yousif, BF, Rilling, D & Brevern, PV 2010, 'Effect of betelnut fibres treatment and contact conditions on adhesive wear and frictional performance of polyester composites', *Wear*, vol. 268, no. 11-12, pp. 1354-70.
- Pihtilä, H & Tosun, N 2002, 'Effect of load and speed on the wear behaviour of woven glass fabrics and aramid fibre-reinforced composites', *Wear*, vol. 252, no. 11-12, pp. 979-84.
- Pogosian, AK 1973, 'Forecasting the viability of friction pairs in accelerated tests', *Wear*, vol. 26, no. 2, pp. 175-86.
- Pogosian, AK 1977, *Friction and Wear of Filled Polymer Materials*, Moscow.
- Rabinowicz, E 1995, *Friction and Wear of Materials*, John Wiley and Sons, New York.
- Rajesh, JJ, Bijwe, J & Tewari, US 2002, 'Abrasive wear performance of various polyamides', *Wear*, vol. 252, no. 9-10, pp. 769-76.
- Reinicke, R, Hauptert, F & Friedrich, K 1998, 'On the tribological behaviour of selected, injection moulded thermoplastic composites', *Composites Part A: Applied Science and Manufacturing*, vol. 29, no. 7, pp. 763-71.
- Satyanarayana, KG, Sukumaran, K, Mukherjee, PS, Pavithran, C & Pillai, SGK 1990, 'Natural fibre-polymer composites', *Cement and Concrete Composites*, vol. 12, no. 2, pp. 117-36.
- Sreekala, MS, George, J, Kumaran, MG & Thomas, S 2002, 'The mechanical performance of hybrid phenol-formaldehyde-based composites reinforced with glass and oil palm fibres', *Composites Science and Technology*, vol. 62, no. 3, pp. 339-53.

- Stevenson, ANJ & Hutchings, IM 1996, 'Development of the dry sand/rubber wheel abrasion test', *Wear*, vol. 195, no. 1-2, pp. 232-40.
- Stolarski, TA 2003, 'Modern Tribology Handbook: Vol. 1-Principles of Tribology, Vol. 2- Materials, Coating, and Industrial Applications, Editor-in-Chief: Bharat Bhushan, CRC Press 2001', *Tribology International*, vol. 36, no. 7, pp. 559-60.
- Yousif, BF & El-Tayeb, NSM 2008, 'Adhesive wear performance of T-OPRP and UT-OPRP composites', *Tribology Letters*, vol. 32, pp. 199-208.
- Yousif, BF, Lau, STW & McWilliam, S 2010, 'Polyester composite based on betelnut fibre for tribological applications', *Tribology International*, vol. 43, no. 1-2, pp. 503-11.
- Yousif, BF, Nirmal, U & Wong, KJ 2010, 'Three-body abrasion on wear and frictional performance of treated betelnut fibre reinforced epoxy (T-BFRE) composite', *Materials & Design*, vol. 31, no. 9, pp. 4514-21.
- Zaidi, H & Senouci, A 1999, 'Thermal tribological behavior of composite carbon metal/steel brake', *International Journal of Wear Applied Surface Science*, vol. 144-145, pp. 265-71.