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State of Arts: Tribological Properties of Composite materials

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ABSTRACT: This article attempts to describe testing methods used in tribology. It namely demonstrates the contact of solid mechanics and nature of surface interaction. Behaviour of polymers and their composites are recently increased. With the introduction of sustainable development, composite materials now become more noticeable 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. 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. . It reviews several factors which control the wear and frictional characteristics of such materials, that is, additives, fibres, interfacial adhesion, tribology environment, operating parameters, and composite geometry.

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

I.INTRODUCTION

The word "Tribology" is derived from the Greek word *tribos* means "rubbing". Tribology is defined as the science and technology of interacting surfaces in relative motion. The tribology generally deals with the technology of lubrication, control of friction and preventing of wear of surfaces having the relative motion under loading condition. Tribology is the art of preventing operational analysis to problem of economic significance like maintenance, reliability, friction, wear and tear from household application to spacecraft. It illustrates typical example relating wear process due to relative motion, human related tribology and spacecraft related tribology in Fig.1 [1][2]

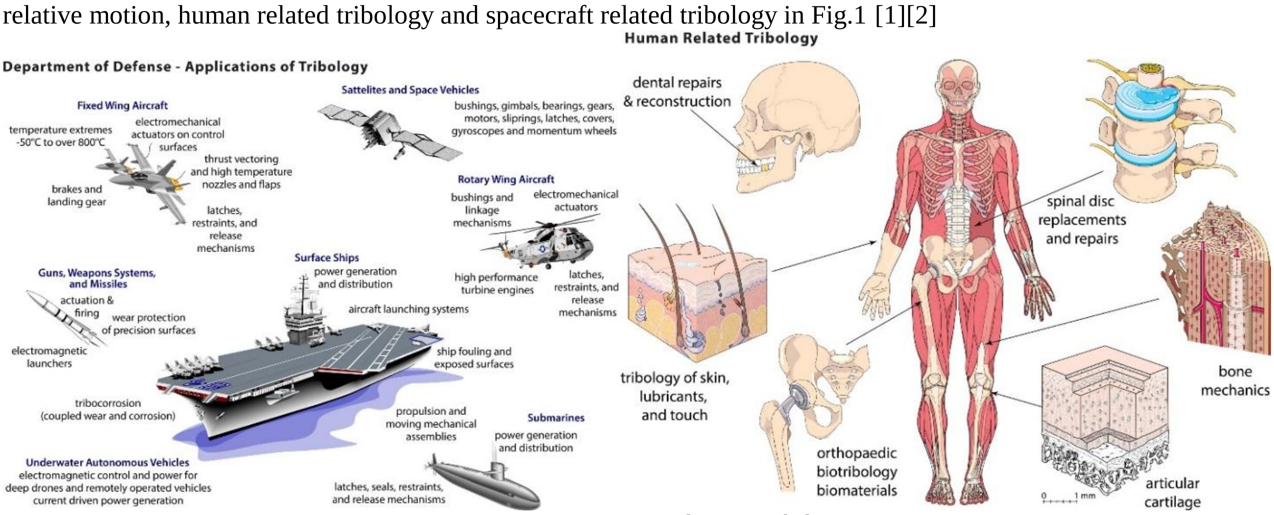

Fig. 1 Marine and Human tribology

(A) ORIGIN OF TRIBOLOGY

Our ancestors were concerned with reducing friction in translationary motion, and in this respect records show the use of wheels from 3500 BC. Drills were made during the Paleolithic period from drilling holes or producing fire and they were fitted with the bearings made from bones. A tomb in Egypt provides evidence of the use of lubricant. A chariot in the tomb still contains some of the original animal fat lubricants in its wheel bearings. A ball thrust bearing dated about 40 AD was found in Lake Nimi near Rome.[3][4]

Leonardo da Vinci (1452-1519) first investigator a scientific approach to friction. He derived the laws of friction and introduced the concept of coefficient of friction. In 1699 very long time Amontons rediscovered the laws of friction. Again Augustin Coulomb verified these laws and gave the fiction force is independence of velocity of motions. He was clear distinction between static friction and dynamic friction.[3][4]

II. NATURAL FIBER COMPOSITE MATERIALS

In recent years, the concept of 'eco-materials' has gained key importance due to the need to preserve our environment. The meaning of eco-material includes 'safe' material systems for human and other life forms at all times. The interest in natural fiber reinforced composites is growing rapidly both in terms of their industrial applications and fundamental research. Their availability, renewability, low density and price as well as satisfactory mechanical properties make them an attractive ecological alternative to glass, carbon and other man-made fibers used for the manufacturing of composites.[5]

Fiber reinforced polymers (FRPs) offer a combination of strength and modulus that are either comparable to or better than many traditional metallic materials. In addition, fatigue strength as well as fatigue damage tolerance of many composite laminates are excellent. For these reasons, FRPs have emerged as a major class of structural materials and find applications in almost all material domains such as house furnishing, packaging, sports, and leisure and in many other weight-critical components in aerospace, automotive and other industries.[6]

Fibers like cellulose, wool, silk etc. plentifully available in nature are also used in composites. Cellulosic fibers like henequen, sisal, coconut fiber (coir), jute, palm, bamboo, cotton and wood, in their natural conditions. It is well known that natural fibers impart high specific stiffness, strength and biodegradability to polymer matrix composites. Also, cellulosic fibers are readily available from natural sources and most importantly, they have low cost per unit volume.[6]

Polymer composites are often used as engineering as well as structural components functioning in hostile workplaces where they are subjected to different wear situations. Wear is defined as the damage to a solid surface usually involving progressive loss of materials, owing to relative motion between the surface and a contacting substance or substances. The effect of wear on the reliability of industrial components is recognized widely and the cost of wear has also been recognized to be very high. The direct costs of wear failures (i.e. wear part replacements), increased work and time, loss of productivity as well as indirect losses of energy and the increased environmental burden are real problems in everyday work and business. In catastrophic failures, there is also the possibility of human losses. Although wear has been extensively studied scientifically, still wear problems persist in industrial applications. This actually reveals the complexity of the wear phenomenon.[7][8]

There are quite a few terms to describe various wear modes which can be clubbed into four principal categories viz. abrasion, adhesion, erosion and surface fatigue. Generally, abrasive wear occurs when two surfaces in contact move against each other and the harder particle in one cut through the other. This form of wear comes into play when a tangential motion causes the material removal by the simultaneous micro-ploughing and micro-cutting. However, wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or the loss from either surface is termed as adhesive wear. Similarly, surface fatigue is another wear process that takes place when tiny wear particles are dislodged from a surface by fracture on repeated rolling or sliding on the surface. Finally in the erosion wear mode, a progressive loss of material occurs from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles.[8]

Polymers and their composites form a very important class of tribo-engineering materials and are invariably used in mechanical components, where wear performance in non-lubricated condition is a key parameter for the material selection. Nowadays much attention is devoted towards the study of solid particle erosion behavior of polymer composites due to the high potential use of these materials in many mechanical and structural applications. Hence, erosion resistance of polymer composites has become an important material property, particularly in selection of alternative materials and therefore the study of solid particle erosion characteristics of the polymeric composites has become highly relevant. Differences in the erosion behavior of various types of composite materials are caused by the amount, type, orientation and properties of the reinforcement on one hand and by the type and properties of the matrix and its adhesion to the fibers/fillers on the other hand. A full understanding of the effects of all system variables on the wear rate is necessary in order to undertake appropriate steps in the design of machine or structural component and in the choice of materials to reduce/control wear.[1][8]

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Previously, tribological performance of synthetic fibres such as glass, carbon and Kevlar reinforced polymeric composites has been extensively studied. Nowadays, natural fibres are becoming an alternative reinforcement for polymers due to their excellent advantages, i.e. renewable, environmental friendly, low cost, flexibility of usage, lightweight, natural recyclable and biodegradable. There are numerous applications such as housing construction materials, furniture and automotive parts. From mechanical point of view, it has been proven that natural fibres enhanced the mechanical properties of neat polymers. In general, the tribo-performance of polymeric composites is influenced by many factors such as test technique and operating parameters. On the other hand, reinforcing the polymers with fibres could significantly improve the tribo-performance of neat polymers or worsen them. In the natural fibre/polymer composites, the interfacial adhesion of the fibres to the matrix plays an important role in control the mechanical properties of some polymeric composites. [6][9]

III. TRIBO-TESTING MACHINES

(A) Dry sand rubber wheel

During this test an abrasive material (purified silica sand) is introduced between the specimen and a rotating rubber wheel in order to subject the specimen to constant wear as the abrasive is pulled between the rubber surface and the surface of the specimen. This is what is known as a low stress abrasion test, meaning the abrasive sand is not fractured during the test.
It is shown in Fig 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 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.[10][11]

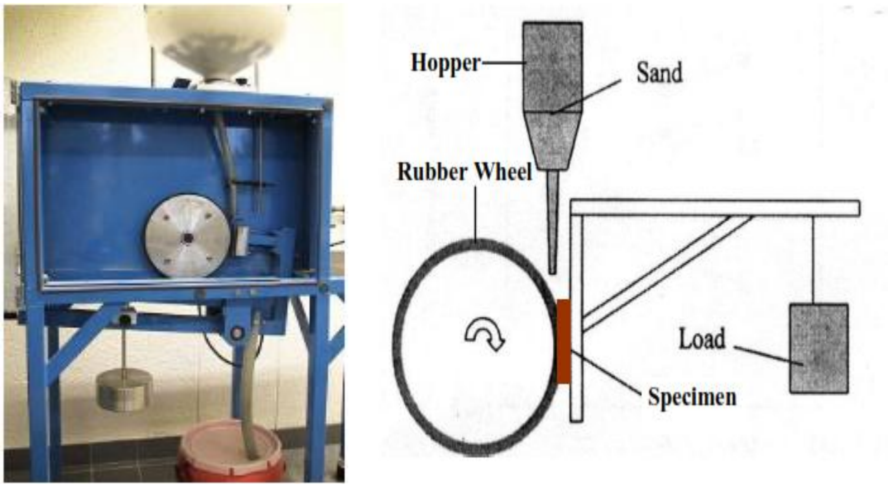

Fig 2. Dry sand rubber wheel

(B) Pin-on-Disk Abrasion Testing

The pin-on-disk wear machine is a common wear test rig because it is so versatile. As the name indicates, a pin slides on a horizontally-oriented rotating disk. The test specimens can be identical or different metals or non-metals, the surfaces can be dry or lubricated or the disk can be coated with a wide variety of abrasives. Sliding speed is controlled by rotational speed and sliding path diameter. Contact pressures are controlled by applied load and pin diameter.
The Pin-on-Disk Tribometer, shown in Fig 3, consists of a flat, pin or sphere which is attached to a stiff elastic arm that is weighted down onto a test sample with a precisely known weight. The sample is rotated at a selected speed. The elastic arm ensures a nearly fixed contact point and a stable position in the friction track formed by the pin on the sample. The kinetic friction coefficient is determined during the test by measuring the deflection of the elastic arm, or by direct measurement of the change in torque by a sensor located at the pivot point of the arm. Wear rates for the pin and the disk are calculated from the volume or weight of material removed during the test. With this machine, one can control test parameters such as speed, contact pressure, and time. With the right environmental chamber, one can also

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control and measure the effect of humidity, temperature, and atmospheric composition. The pin-on-disk measurement is usually done per ASTM G99-05 Standard Test Method for Wear Testing with a pin-on-disk apparatus.[10][11][3]

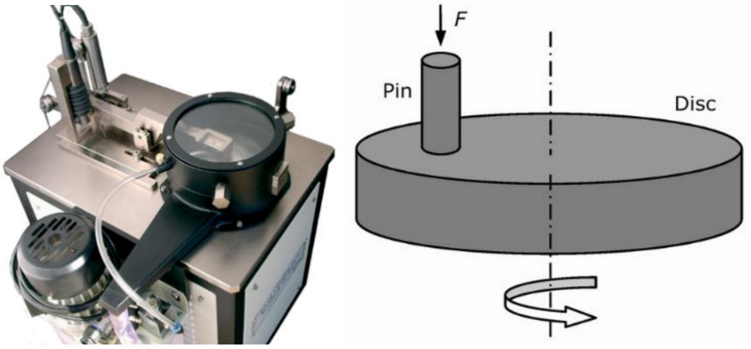

Fig 3 Pin on disk apparatus

(C) Linear Reciprocating Abrasion Testing

The pin-on-disk tribometer can be modified by replacing the rotating disk motor with a one directional reciprocating table as shown in Fig 4. This arrangement reproduces the reciprocating motion typical in many real-world mechanisms. The configuration of the mating surface to the test tablet on the reciprocating table can be point, line, or surface contact. The sample is moved at a controlled speed. The elastic arm ensures a nearly fixed contact point and a stable position in the friction track formed on the sample. The static friction coefficient is determined during the test by measuring the deflection of the elastic arm during each change in direction. Wear rates are calculated from the volume or weight of material removed during the test. The reciprocating abrasion measurement is usually done per ASTM G133-05e1 Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear.[10][3][11]

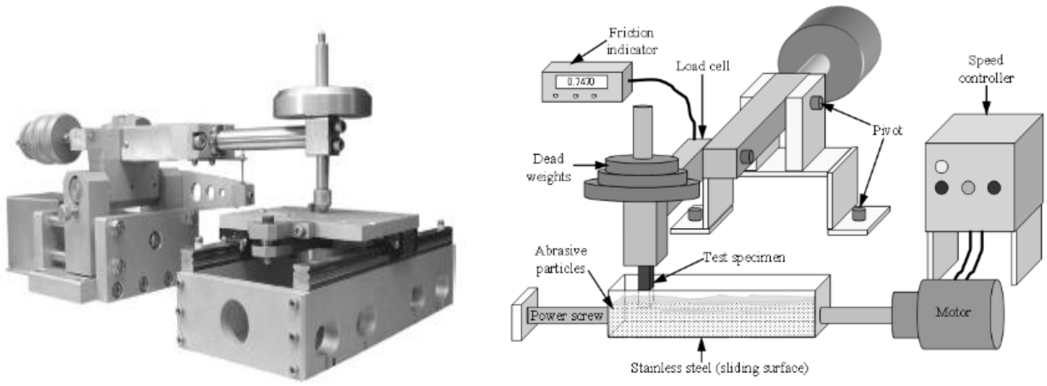

Fig. 4 Linear Reciprocating Abrasion Testing

(D) Falling Abrasive/Erosion Test

Erosive wear refers to surface damage caused by the impingement of materials, solids, liquids or gases, often carrying abrasives, onto a component surface. This erosion tester uses compressed gas to transport many different types of abrasives. The abrasives are precisely metered by a powder feeder and particle velocity is measured with the spinning twin-disk method. The attack angle can be anything between 0^0 and 90^o. Wear rates are usually reported in mass loss per mass flow rate of the abrasive.

A simple, inexpensive reproducible abrasion/ erosion test is the falling abrasive test described in ASTM D968-93(2001) Standard Test Methods for Abrasion Resistance of Organic Coatings by Falling Abrasive. Known weights or volume of sand, gravel, aluminium oxide, or silicon carbide are poured on a plate from a given height through a funnel and tube as shown in Fig 5. The plate is positioned at a 45° angle. The abrasive is collected for reuse. When desired, after many tests, the fines can be removed by sieving. The change in weight per unit weight of abrasive is used to report abrasion/erosion rates.

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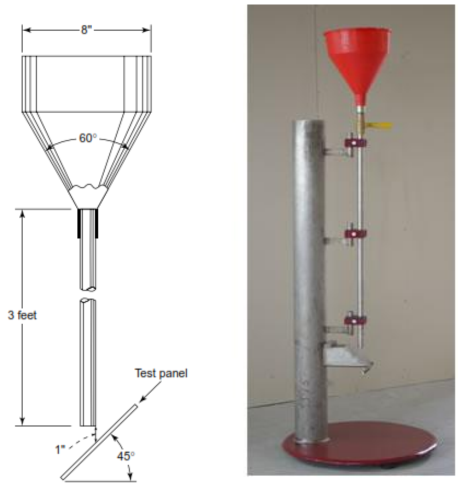

Fig 5 Falling Abrasive/Erosion Test

(E) Slurry Erosion Tests

The wet or slurry erosion test machine consists of a slurry pump, flow sensor, test chamber with specimen holder, associated piping and a logic controller that regulates the compressed air supply to the pump. The standard slurry is composed of a 1:10 ratio of AFS 50-70 silica sand and filtered water. The slurry is re-circulated through a piping loop via a mixing tank/reservoir and emitted in a high-speed jet at an average velocity of 16 m/s. Wear metric is mass loss per mass flow rate during testing. A simpler test is described in ASTM G75-07 Standard Test Method for Determination of Slurry abrasivity and Slurry Abrasion Response of Materials. The relative effect of slurry abrasivity is determined by measuring the mass loss of a test plate after it has been driven in a reciprocating motion in a trough containing the slurry. The test consists of measuring the mass loss of a part per unit time.

IV. TRIBO-CHARACTERIZATION OF POLYMER COMPOSITES

(A) Wear mechanism

Wear of polymers occurs due to plastic deformation, brittle fracture and fatigue. Hence, they are reinforced with fibers and the resultant composite supports the dynamic stresses induced by an applied load and the tangential frictional stresses that ultimately prevent wear. Wear of polymer composites is not an inherent material property, but depends on the wear mechanism (abrasion, adhesion, fatigue and chemical degradation) external conditions (temperature, contact pressure, velocity and environment), relative movements (sliding, multiple/single pass, reciprocating and impacting), contacting materials (roughness and hardness of the metallic counterparts, bonded or loose sharp particles and third-body interface) and composite materials (polymer matrix, type and structure of reinforcement, filler/matrix interface and internal lubricants). Tribo-properties are also very sensitive to the environmental conditions (such as atmosphere, humidity and temperature) in addition to the experimental parameters. [12]

- **Effect ofoperatingparameters**

i. *Load:*In the case of polymericmaterials,an increase in the applied load increases the wear and reduces the friction coefficient. An increasing load leads to elastic and plastic deformation at the contacting asperities which then increases the real area of contact. This increase in the real area of contact due to asperity collapse influences the friction coefficient.

ii. *Slidingspeed*:An increase in velocity decreases the friction coefficient and increases the wear rate.However,the setrends depend on the type of material.

iii. *Temperature*:The friction coefficient tends to drop with increasing temperature.Thermal softening of polymers decreases surface hardness and increases the real areas of contact. This can lead to rapid increases in both the friction coefficient and wear.

iv. *Counterfaceroughness*: There exists an optimum surface roughness of the counter face at which the friction and/or wear rate is minimal. However, the results are contradictory because while for some

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composites the minima of friction coefficient and specific wear rate match the minimum of average surface roughness Ra, for other composites no such matching is found.

- **Effect of fiber reinforcement**

Fiber reinforcement in polymer matrices is an effective method of developing, tribologically significant composites. Various types of fiber reinforcement, such as discontinuous or short fiber reinforcement, continuous or long (unidirectional) fiber reinforcement and woven fabric or bidirectional reinforcement, are available, and these offer a great deal of scope to tailor a range of properties. For polymers that possess high specific wear rates in the unreinforced condition,almost any type of reinforcing fiber results in significant reductions in wear and improvement in mechanical properties. Commonly used synthetic fibers such as glass,carbon,graphite and aramidareall available as short,long or fabric for reinforcement in thermosets as well as thermoplastics. Among all these fibers, continuous carbon fibers reinforced in a thermoset resin exhibit excel enttribological properties such as low wear rate in sliding wear mode in severe operating conditions.

- **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.
The surface roughness is evaluated by the height, R_t and mean roughness index R_a of the micro-irregularities. It is the arithmetic mean of the absolute values of the heights h_i between the actual and mean profiles. Profilometer working principle is to measure the penetration depth formed by the asperities and local valley thereby producing the roughness average (Ra) value.

- **Significance of composites in tribology**

The availability of arrange of fibrousreinforcement,fillers,matrices and processing techniques offers ample scope for tailoring properties in composites as required for a specific application. For instance, if high strength properties are required, such as for structural applications as in aircraft structures, radomes, etc., then composites can be fabricated having high tensile strength and modulus, high impact strength in order to maintain structural integrity and high abrasion– erosion resistance. For anti-friction materials that are used in bearings, apart from structural and dimensional integrity, the material should possess low friction coefficient and low wear. For friction materials that are used in clutches, brakes, etc., strength properties are secondary and tribological properties such as high friction coefficient and low wear are of primary concern.
Among the four groups of tribo-materials PMC shave shown immense potential, mainly because of theirself-lubrication properties, light weight and resistance to wear, corrosion and organic solvents. In PMCs, the polymeric matrices are generally used as binders and their role is to transfer the stress to the filler/fibrousreinforcement.Engineeringpolymerssuchasthermosets (epoxy, polyester, phenolics, vinylesters, etc.) as well as thermoplastics (polyetheretherketone,polyimides,polypropylene,polyethersulphone,etc.)andelastomers (rubber, etc.) are used as matrices to fabricate PMCs. High performance, high temperature thermoplastics are used as matrices for making componentswhichareexpectedtofunctionundersevereoperatingconditions such as high load, high speed, high temperature and extreme environmental conditions. Similarly, there is a range of fibrous reinforcement comprising both synthetic (glass, carbon, aramid, graphite, etc.) as well as natural (jute, cotton, sisal, sunhemp, bamboo, etc.) fibers available which can be used individuallyorincombination.Theyareusedinlow,mediumandhighstressstructuralapplicationssuchas boat building, chemical plants and the automotive and aerospace industries due to their ease of fabrication into complex shapes, high strength to weight ratio, excellent corrosion resistance, good weathering properties, and good thermal and electrical insulation.Inlow stress applications such as panels, cladding, doors, shower cabinets, small boats, etc. glass fiber reinforced PMC sact as space filling panels,supporting their own weight but not subjected to any significant external loads.
PMCs are promisingastribo-materials because of their inherent properties such as self-lubrication, lowcost, lightweight,quiet operation,better friction properties, ease of fabrication and resistance to wear, corrosion and organic solvents. They are used as seals, bearings, gears (low friction, low wear), conveyer belts(lowwear),turbine or

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pumpblades(lowwear),brakes,tyres(lowwear and moderate friction), dental applications (low wear) and hip replacements in which the substitute material should have low wear and low friction coefficient.

V.CONCLUSION

Various test methods were adapted for mechanical characterization of natural fibre reinforced polymer composites. The various tribo-testing machines with 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 purpose of the various types of tribo-testing machines is to establish the wear performance of materials in real time conditions. The tribo testing are several factors involved to testing such as friction coefficient and wear performance of materials, surface roughness of a material/counter face and the degree of abrasiveness of a material. Factors are effects on roughness angel of the asperity with respect to the contacting surface and their effect on wetness and heat generated between test specimens against the counter face. 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

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