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FOREIGN REPORT

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"The Wear of Non-Metallic Materials" 3rd Leeds-Lyon Symposium on Tribology

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The 1976 Symposium on "The Wear of Non-Metallic Materials" was the third in a series, alternating between the University of Leeds, U. K., and INSA (Institute Nationale Scientifique Applique), Lyons, France, which promises to be a fruitful and long continuing one. Each institution has a strong substantive research program in tribology.

Each symposium concentrates on a specialized topic in the field of tribology, and provides a lively forum for discussion of the latest research. Proceedings may be purchased by inquiry to either institution. The 1975 Symposium, held in Lyon, was on the topic of Turbulence. It was reviewed in Foreign Report in the January 1976 issue of J.O.L.T.

The 1977 Symposium will be held in Lyon on the topic "Surface Roughness Effects on Lubrication."

The 1976 Symposium was attended by research workers from eleven countries: United Kingdom (84), France (14), Netherlands (7), U. S. A. (5), Ireland (2), Sweden (2), Germany (1), Denmark (1), Canada (1), USSR (1), and Iraq (1). Some 37 papers were presented. The classes of non-metallic materials covered included polymers (e.g. polyethylene), biological materials, rubber, fibrous materials, and carbon-graphites.

The keynote address by Professor David Tabor of Cambridge University [1][1] set the stage for the meeting by reviewing some of the experimental evidence on the behavior of polyethylene and other polymers. He suggested that wear mechanisms can be divided into three main groups. The first is adhesion between the sliding surfaces, and applies to unlubricated surfaces of almost all materials. The second includes non-adhesive processes such as abrasion by hard particles (or asperities), cracking and fatigue of the surface as a result of normal stress and the weakening of subsurface layers in viscoelastic materials as a result of hysteretic losses. The third is interaction between the non-adhesive and the adhesive process to produce a type of wear that appears to have characteristics of its own. This includes the fragmentation of brittle solidsand the fatigue of metals and composite materials by the combined effect of normal and tangential stress.

The paper dealt also with recent work in Tabor's laboratory on the wear of thermoplastics, especially polyethylene (PE) and polytetrafluoroethylene (PTFE). Low density PE has a high friction and transfers a relatively thick lumpy film of polymer on to the countersurface. The friction and wear can, however, be reduced by incorporating into the polymer a lubricant which diffuses to the surface. By contrast high density PE and PTFE are low friction materials which transfer a very thin highly oriented film of polymer on to the countersurface. These properties are probably the result of a smooth molecular profile and low intermolecular forces.

Tabor pointed out that in practical engineering applications both HDPE and PTFE give too high a wear rate. Apparently the thin transferred polymer film is continuously laid down and wiped away. However, if 30 percent Pb_3O_4 and 5% CuO are incorporated into the polymer, the wear rate, after an initial running-in period, falls by a factor of about 100. Detailed experiments with filled HDPE show that this is associated with the formation of a relatively thick polymer film firmly attached to the rubbing surface. Further, once this film has been formed an unfilled polymer gives low wear for a long period. Since the effect is observed when rubbing on steel but not glass it is assumed that the primary effect of the fillers is chemical. The detailed oxidation action of the fillers and the way in which the film is attached and worn away require further study.

The following sections review the papers presented in the several specialized areas covered.

The Wear of Polymers

Four papers were on aspects of the dry wear of polymers. Rhee and Ludema [2] reported on the rubbing of polyoxymethylene (Delrin) and Nylon against stainless steel. A transfer film of polymer soon forms on the steel. By comparing the composition of the gases evolved during rubbing with the results of pyrolysis tests, using a mass spectrometer, they established that in this system the transfer film reaches a temperature 50C above the polymer's melting point. As the severity of rub was increased, this temperature remained constant until the transfer film was lost, and the wear rate then increased more than three orders of magnitude.

Eiss, Warren, and Pruin [3] used a pin on disc apparatus at 0.2 cm/sec and 750 passes to study the effect of PCTFE crystallinity and the mild steel surface characteristic on the polymer transfer film.

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[1] Numbers in brackets designate References at end of Report.

Crystalline polymer exhibited higher wear rates than amorphous polymer, a fact which the authors correlate with the 30% greater energy to rupture of the amorphous polymer. Lowest wear occurred on the smoothest surfaces, and when sliding was in the direction of the grinding furrows.

Furber, Atkinson, and Godet [4] studied the dry wear of Nylon under reciprocating motion. Under constant load, two wear regimes are found at the higher loads as sliding is continued up to 250 km. The higher wear rate, which occurs at the later time, is ascribed to surface fatigue, and cracks perpendicular to the sliding direction are observed. At lower loads, this phenomenon is not seen. Nylon filled with MoS_2 exhibits a lower wear rate and no evidence of fatigue wear is seen.

Play, Floquet, and Godet [5] reported on the friction and wear properties of a composite material consisting of a polyimide matrix containing 25% of teflon as tested in a reciprocating disc and sector distributed-contact machine. Friction coefficient is found to be independent of load, but under severe conditions there is an initial period at $f = 0.1$ and a later period at $f = 0.2$. During the $f = 0.1$ period, the calculated contact temperature is 80C and the teflon content at the surface is nearly the same as in the bulk material; but during the $f = 0.2$ period, the calculated contact temperature is over 180C and the teflon content at the surface is depleted. The dwell time at $f = 0.1$ appears to increase with the rate of wear, suggesting that good performance requires a balance between teflon consumption and matrix wear.

Four papers were on the lubricated wear of polymers. Evans [6] reported on the wear rates of several polymers and polymer composites during sliding in a number of liquids against a stainless steel surface. With hydrodynamic effects minimized, polymers that do not form transfer films during sliding may exhibit reduced wear rates in the presence of a liquid. This was found both with amorphous polymers such as polymethyl methacrylate and polyphenylene oxide, and with crystalline polymers wuch as polyacetal (Delrin). However, wear rates of amorphous polymers are higher than in dry sliding in liquids whose solubility parameters (square root of cohesive energy density) are close to that of the polymer. When the liquids are non-solvents, the high wear rates are due to stress cracking. Plasticization of PPO had no effect on wear rate until high concentrations of about 50% were reached.

Abouelwafa, Dowson, and Atkinson [7] studied the wear properties of low density polyethylene containing small amounts of dimethyl silicone fluid of 30,000 cs. viscosity. Addition of 1 to 10 percent silicone reduced the density (voids were present), yield stress, fracture stress, shear strength and hardness of the polymer. Pin on disc wear tests were conducted at $0.25\ ms^{-1}$ on mild steel using 9.5 mm diameter conical ended pins with 120° cone angle and a 3 mm tip. At constant load, initially rapid wear rates settled to roughly constant values. At 5 and 10 percent silicone, the wear rates were reduced by a factor of ten to $2 \times 10^{-6}\ mm^3/N.m$.

Pascoe and Dzhanakimedor [8] evaluated oil filled polyacetal and Nylon 6 polymers, sliding aluminum or copper against the face of a rotating polymer disc. The slider was in the form of wire fed around a cylinder loaded against the disc. The cylinder could be rotated during a test, bringing fresh slider surface into position. Tracks on the disc became polished, with flakes detaching at the trailing cage indicating cohesive failure possibly aided by oil accumulation.

Dowson, Mustafaev, and Gillies [9] studied the lubricated wear of ultra-high molecular weight polyethylene using a three-pin on disc tester with a load of 100 N/pin and a speed of 0.24 m/s. The conical ended pins of (7) were used. Results were:

Condition	Wear Rate ($10^6 mm^3/Nm$)	Coeff. of Friction
Dry	0.544	0.42
Mineral Oil	0.138	0.09
Mineral Oil + 1% Steric Acid	0.069	0.05

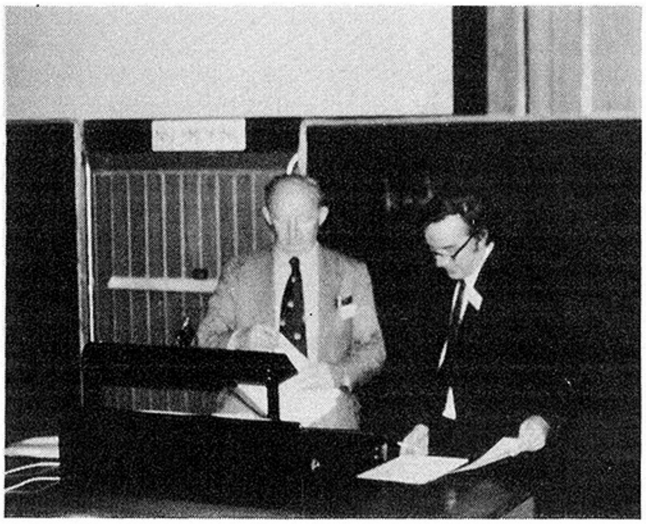

Fig. 1 The Conference organizers, Professor D. Dowson of the University of Leeds, and Professor M. Godet of INSA, Lyon

Fig. 2 Modern exterior of Mechanical Engineering Building at Leeds

The authors suggest that the contact zone is in a mixed lubrication regime, but ascribe the reduced specific wear rate to either hydrodynamic action, boundary lubrication or reduced interface temperature.

Five papers discussed the mechanical and thermal aspects of polymer wear. Godet and Play [10] discussed the need for bridging the gap between the results of standard test data (e.g. pin on disc wear rates) and the basic information needed to design bearings and bushes for practical dry bearings. They emphasized the importance of numerical methods for determining the stress distribution in complex geometries, of specimen-mounting resiliance on friction measurement, and the role of transfer films on friction and wear processes. Challen and Dowson [11] described an analytical procedure for estimating the interface temperature in a sliding contact, since the onset of a high wear regime as speeds and/or loads are increased is probably due to declining mechanical properties of a polymer as temperature is increased. In addition to coefficient of friction, load, velocity and bulk temperature, the temperature rise is a function of film heat transfer coefficients and geometry of the stationary and moving bodies.

Rhee and Ludema [12] described a technique for estimating the maximum temperature in a sliding contact. Noting that polymers decompose to release monomers or multiples of monomers, they monitor the gaseous species emitted by polymer sliding surfaces and relate these to the known decomposition behavior of the polymer. Experimentally, they found emission over a wide range of loads and sliding velocities and concluded that peak or maximum local temperatures are at or slightly above the decomposition temperature over a wide range of estimated average surface temperatures.

Anderson and Robbins [13] compared the wear rates of polyethylene and polyacetal at equivalent temperatures generated either by low bulk temperature and high sliding velocity or by high bulk temperature and low sliding velocity and found then to be roughly the same. Dowson, et al. [14] studied the wear rate of ultra-high molecular weight polyethylene against stainless steel of varying roughness. A minimum wear rate was found at a surface roughness of 15 μ in. from tests covering a range from 0.24 to 68 μ in. Some members of the audience cited practical experience confirming the notion of an optimum roughness for minimum wear, and discussion centered on the possibility that a stable transfer film could not be established on very smooth metal surfaces.

Wear of Biological and Implant Materials

Four papers were presented in this area which is coming to represent a most important application of materials such as ultra-high molecular weight polyethylene. Swanson [15] described the fibrous nature of cartilage and the role of hyaluronic acid and synovial fluid. It thus appears that in some hips (and possibly in other joints) the first stage of osteoarthrosis can be caused by fatigue failure of the cartilage, which in turn is caused by unusually high stresses. These could result from either anatomical features or unusually high loads; and there is the possibility of changes within the cartilage reducing its resistance to fatigue, so that a given stress may cause fatigue failure in one individual but not in another.

Johnson, Dowson, and Wright [16] exposed cylindrical specimens of articular cartilage to repeated impact loading with the specimen protected by a constant pH (7.4) solution. Peak stress was 5.6 MN/m^2 with a rise time of 50 ms and a decay time of 100 ms. Three of ten specimens developed splits or cracks at the surface which were found to run deeply at an oblique angle to the surface. There was also evidence of disruption of the surface fibers. Wright [17] discussed the problems involved in using neutron radiation exposure as a technique for studying the wear resistance of hard dentile tissue under abrasive action by a dentifrice. Electron microscope studies of abraded dental tissue showed clear evidence of a limited amount of fracture along the edges of abrasive tracks and it was clear that radiation enhances the contribution that this feature makes to the wear rate. Similar fracture occurred with fully brittle materials but the magnitude of the fracture material was usually much higher and led to a wear rate which was often tenfold higher than that which occurs with a metal of similar hardness. The data obtained from these studies suggested that the wear of high filled polymer materials, although remaining inversely proportional to indentation hardness, is nevertheless also controlled by a factor which includes a term that reflects the sensitivity of the structure to fracture. Similar behavior may be expected from other highly filled polymers which show limited ductility and which are typical of dental restorative materials.

Atkinson, et al. [18] studied in detail the wear areas on ultra-high molecular weight polyethylene cups from artificial hip joints used by patients for up to 12 years. High and low wear areas were observed. Optically the high wear areas appeared smooth and polished, and small fatigue cracks, 1 μm long, were observed.

The Wear of Rubber

Ludema [19] pointed out that a complete physical model of the rubber wear process should account for four key observations:

- On a glass surface and in high humidity, a rubber of high strength will slide indefinitely at low speed, without wear. On the other hand, high wear, perhaps massive shearing, will occur if a weak rubber is used, or if the experiment is done at higher speeds or in a vacuum where adsorbed water film is reduced in thickness.
- On a surface with gentle undulations, and where the coefficient of friction is low, the failure of rubber does not initiate at the surface. Rather if sliding proceeds for a long time and at high speed there is chemical degradation of the rubber at some depth below the surface.
- On a surface with gentle undulations (low harshness) and where the friction is high there is tensile failure of the rubber behind the asperity, and there is wear with continued sliding.
- On a lubricated surface consisting of very sharp protuberances the rubber becomes severely cut and scratched, with some wear. Without lubrication there is severe wear.

Moore [20] pointed out that wear or abrasion is a consequence of local energy dissipation (friction × velocity), so that wear can be defined as the extent of surface deterioration following exposure to friction. More specifically, the friction of elastomers is a thermally-activated, molecuar-kinetic, stick-slip process. The recent discovery of Schallamach waves occurring within the contact area between soft rubber sliders and smooth surfaces is shown to be another manifestation of the molecular stick-slip process. In this case, the rupture of molecular bonds (which gives rise to microscopic wear effects) is caused by inward buckling of the rubber surface, and it is conjectured that the overall direction of rupture is at a greater angle to the sliding interface than had previously been appreciated. A highly-simplified model of the frictional process shows that surface buckling is directly attributable to incompressibility effects.

Hurricks [21] discussed the problem of selecting rubber for paper transport elements of office machinery. The somewhat contradictory properties of high friction and low wear rate are desired. Tests were run at 120 mm/sec, a normal load of 0.6 Kg, and a total feed of up to 20,000 sheets. Wear could be expressed as

$$V = AL^n$$

where V = wear volume, L = length of paper, and A and n are constants. A is a function of load, speed, paper roughness, etc., and in-

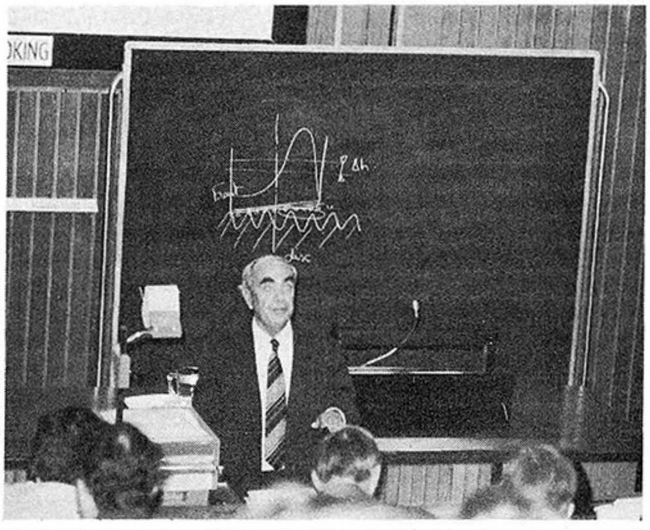

Fig. 3 Dr. J. Dowling of University of Leeds discussing the surface wear of artificial hip joints [18]

dependent of n. Constant n is a property of the rubber. SBR rubber exhibited $n < 1$, i.e. a decreasing wear rate. Polyurethanes had $n = 1$, showing wear rate independent of past history. Silicones and neoprenes had $n > 1$, i.e. wear rate increasing with use. Souther and Thomas [22] reported on the wear of tires. They pointed out that the surfaces of worn tires exhibit a series of roughly parallel ridges which are perpendicular to the direction of sliding. Since laboratory abrasion machines have not heretofor given results which correlate with tire wear, the authors developed a line contact device. As the blade passes over the surface of the rubber it pulls the ridges which form the abrasion pattern and they propose that this leads to the growth of cracks in the rubber. Each ridge has a crack on the side which sees a tensile stress when the blade passes over, and as a result of each pass the crack grows in the rubber. This theory relates the abrasion loss to the crack growth properties of the rubber. These have been extensively studied independently and this behavior has been well established using an artifically introduced cut into the edge of a thin strip of rubber and measuring the growth of this cut under repeated stressing. The abrasion results were compared directly with the independently measured crack growth properties of the rubber and excellent agreement was obtained. Using the simple theory there is one arbitrary constant which is chosen to give the best fit for a number of rubbers. A more refined theory has been developed with no arbitrary constants and work is now in progress to test this theory.

Dry Wear

Hepworth and Sikorski [23] presented some modern work in the field of textiles (Leeds is an historical textile center). Most intriguing was their micro apparatus for measuring both frictional and normal forces for wool or mohair fibers drawn over steel blades of 2 μm radius. The process, including the force measurement, was observed with a scanning electron microscope coupled with a video-tape recorder. The audience was shown "movies" of this miniature friction experiment. The authors went on to describe the use of reflectance criteria as an arbitrary method of measuring worsted fabric wear, or the development of "shine." The increased reflectance was found to be due to the progressive removal of cuticular cells until large areas are worn which increase the reflectance value.

Dowson and Economou [24] reviewed the history of lignum vitae from medicine to bearings for ships. While wear tests showed the wood to have properties comparable to some modern synthetics, the authors concluded that lignum vitae would not be much further used for bearings unless the raw materials for the synthetics became much less available.

The Wear of Graphite

Three papers were presented in this area. Lancaster [25] discussed the performance of carbon sliding against carbon, such as occurs in carbon brakes for high performance aircraft. Above a critical combination of load, speed, and ambient temperature, graphitic carbons begin to "dust" with high friction and wear, while non-graphitic carbons show gradual increases in friction and wear. Lancaster experimented with additives impregnated into the carbons, using a pin on ring apparatus. The transition to dusting appears to occur when the temperature of individual asperity contacts reaches a critical value at which insufficient vapor (usually water) is available to form an adsorbed film. The influence of additives is thought to be due to the action of one or more of the three key processes:

- Reduction of friction coefficient,
- Smoother topography from consolidation of wear debris, and
- Additional vapor from decomposition or degradation of the additives.

Six additives, in order of increasing effectiveness, were water, tetrachloromethane, methanol, acetone, benzene, and hexane. Phosphorus oxychloride was particularly effective.

Booser and Wilcock [26] reported results on a series of pin on cylinder tests made over a wide range of speeds and loads. Of particular interest was the behavior under non-ideal conditions where traces of lubricant were deliberately added to the ring surface. The effect was deleterious with carbon graphites, a gum being formed with wear particles which accelerate the wear process.

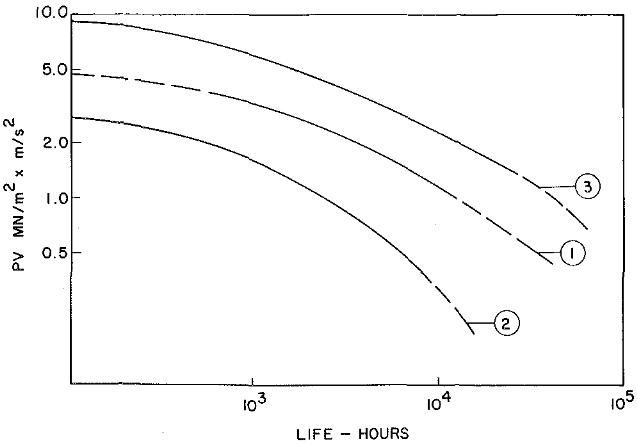

Fig. 4 PV—life relationships for material types 1, 2, and 3 (reference [33])

Gordelier and Skinner [27] discussed experiments on rubbing graphite against rough (abrasive) surfaces, such as may occur in certain gas seals. A small interface gas flow was found to prevent the formation of a transfer layer of graphite, and to maintain the high initial wear rate.

Fracture and Filled Materials

Allen, Brookes, and Shaw [28] discussed the deformation which precedes the formation of the first crack leading to fragmentation and wear of solids deformed by frictional forces. Dislocation etching techniques were used to identify the micro-deformation in ionic crystals deformed by softer sliders. When a hard hemisphere is loaded on a solid surface with tangential stresses added, the internal tangential stress in the sample is augmented on the trailing side, and cracks are seen to initiate there. Play and Godet [29] used chalk to visualize the wear process, using a chalk pin on a flat transparent glass disc. The process of transfer film formation and elimination was directly observed.

Briscoe and Steward [30] offered a progress report, presented by Professor Tabor, on the effect of humidity on the formation and buildup of the transfer film that is essential to a low wear rate with PTFE.

Applications

Connell, et al. [31] described a failure of large hydraulically operated ball valves in large tankers to open after a voyage. The valves used filled PTFE seal rings. The problem was solved by valve redesign rather than a change in material properties.

Crease [32] proposed a new method for presenting wear data on bearing materials. The equilibrium wear rate was found to depend principally on bearing pressure and effective surface temperature. Three plots where recommended and illustrated:

(1) Maximum allowable bearing pressure versus surface temperature for useable wear behavior,
(2) Specific wear rate versus pressure at modest surface temperatures, and,
(3) Specific wear rate of high temperature materials versus bearing temperature.

Below rubbing speeds of 1 m/s, the mean surface temperature is used, $T_{ms} = T_a + C\mu PV$ where C is a constant for a given bearing assembly defined by its overall thermal resistance.

Campbell [33] described the performance and application of metal backed bearings having a polymer lining no more than 0.4 mm thick. The PV limits for the following three types are shown in Fig. 4:

Type 1—Highly cross linked epoxy resin direct bonded to aluminum, with surface perforations to act as oil reservoirs, Type 2—Porous bronze impregnated with a thermoplastic and sintered to a steel backing. Surface indentations form oil reservoirs.

Type 3—A lightly cross-linked resin bonded either to steel or aluminum, with surface indentations.

Soctt, et al. [34] described experiments with dry running rolling bearings employing cages fabricated from fiber-reinforced composites. Both carbon and glass fibers were used. PTFE, polyimide and epoxy resins containing MoS_2 reduced or eliminated wear of the rolling elements. PTFE performed better than the others, apparently because of stronger fiber-matrix bonds, and the ability of PTFE to smear on the rubbing surfaces. When failures of the cage occurred, they appeared to initiate at voids formed during bearing operation at points of fiber depletion.

Lloyd, Dain, and Ettles [35] presented data on scale model (1/5) tests on laminated phenolic bushes used in wheels supporting heavy dock gates. When the bushes rotated with the wheels failures occurred due to axial extrusion of the phenolic and resultant failures of the abutement plate fastenings. When the design was changed so that a shaft rotated in stationary bushes, the extrusion behavior did not occur. The authors recommend reducing the allowable PV in rotating bushes to 50% of the normal maximum.

Wilson [36] reviewed the types of application in which thermoplastics, thermosetting resins, PTFE, elastomers and ceramics are used. In general, they are used when one or more of three conditions exist, namely: (1) no conventional lubricant is present, (2) hydrodynamic lubrication is difficult, e.g. high loads at low speeds, or intermittent motion, and (3) the environment is contaminated.

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2 "Transfer Films and Severe Wear of Polymers," S. H. Rhee and K. C. Ludema, University of Michigan.

3 "On the Influence of the Degree of Crystallinity of PCTFE On Its Transfer To Steel Surfaces," N. S. Eiss, J. J. Warren, *Virginia Polytechnic* Institute and State University; and T. F. J. Quinn, University of Aston.

4 "Wear Mechanisms for Nylon 66," K. Furber, J. R. Atkinson, and D. Dowson, University of Leeds, England.

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8 "The Wear Characteristics of Oil Filled Plastics," M. W. Pascoe, Brunel University; A. K. Dzhanakmedov, Baku, U.S.S.R.

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10 "Mechanical Aspects of Dry Friction and Wear t Testing," M. Godet, D. Play, Institute National des Sciences, Appliquees, de Lyon.

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12 "The Surface Temperatures of Rubbing Polymers by Mass Spectrometry," S. H. Rhee and K. C. Ludema, The University of Michigan.

13 "The Influence of Temperature Generation on the Wear of Some Polymers," J. C. Anderson and E. J. Robbins, National Centre of Tribology, Risley.

14 "The Influence of Counterface Roughness on the Wear Rate of Polyethylene," D. Dowson, The University of Leeds; J. M. Challen, University of South Wales; K. Holmes, British Leyland; and J. R. Atkinson, University of Leeds.

15 "*Mechanical Breakdown of Articular Cartilage in Osteoarthrosis*," S. A. V. Swanson, Biomechanics Unit, Imperial College.

16 "The Fracture of Articular Cartilage Under Impact Loading," G. R. Johnson, Derbyshire Royal Infirmary; D. Dowson and V. Wright, University of Leeds.

17 "Wear of Hard Dental Tissues and Restorative Materials," K. H. R. Wright, National Engineering Laboratory, East Kilbride.

18 "The Wear of Total Replacement Hip Joints in the Human Body—A Topographical Survey of The Surfaces of Worn Acetabular Cups," J. R. Atkinson, University of Leeds; J. Charnley, Centre for Hip Surgery, Wrightington Hospital, Wigan; J. H. Dowling and D. Dowson, University of Leeds.

19 "The Wear of Rubber," Prof. K. C. Ludema, University of Michigan.

20 "Some Observations in the Interelationship of Friction and Wear in Elastomers," D. F. Moore, University College, Dublin.

21 "The Friction and Wear of Elastomers Sliding Against Paper," P. L. Hurricks, Xerox Corporation (U. K.) Ltd.

22 "Some Recent Studies in Rubber Abrasion," E. Southern and A. G. Thomas, Malaysian Rubber Producers Research Association.

23 "Friction and Wear of Fibrous Fabrics," A. Hepworth and J. Sikorski, Textile Physics Laboratory, Department of Textile Industries, The University of Leeds.

24 "The Wear of Lignum Vitae," D. Dowson and P. N. Economou, The University of Leeds.

25 "Additive Effects on The Friction and Wear of Graphite Carbons," J. K. Lancaster, Royal Aircraft Establishment, Farnborough.

26 "Assessment of Carbon Graphite Wear Properties," E. R. Booser, General Electric Company, Schenectady, New York, USA; D. F. Wilcock, Mechanical Technology Inc., USA.

27 "Graphite Wear Against Rough Surfaces—The Effects of Sliding Distance and Interface Gas Flow," S. C. Gordelier and J. Skinner, Central Electricity Generating Board, Berkeley.

28 "Pre-Fracture Deformation of Solids Subjected to Frictional Forces," G. J. C. Allen, C. A. Brookes, M. P. Shaw, The University of Exeter.

29 "Visualization of Chalk Wear," D. Play, M. Godet, Institut National des Sciences, Appliquees, Lyon.

30 "The Wear of Carbon Filled P.T.F.E. in Controlled Environments," B. J. Briscoe and M. D. Steward, University of Cambridge.

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33 "The Lubricated Wear of Plastic Lined Bearings," G. R. Campbell, The Glacier Metal Company Limited.

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