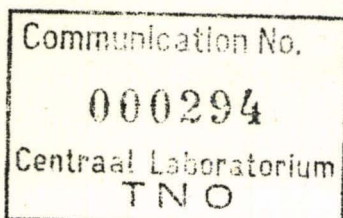


Conf. Lubrication and Wear.
 Inst. of Mech. Eng. (LONDON).
 September (1967).
 Session 4: Lubrication and Materials.

107



Paper 24

PLASTICS AND RUBBERS IN MACHINE DESIGN

By G. Salomon*

The principal materials used are briefly discussed. A general approach becomes possible through a description of their 'mechanical spectrum'. Friction of polymers depends mainly on their viscoelastic response. Wear of plastics is also closely related to their ultimate properties, but that of conventional rubbers is complicated by the superposition of chemical changes. Polymers and compounded materials can corrode and abrade even hard metals. The designer of bearings has still to rely on qualitative information; recent work on materials for gears, however, has yielded useful design data.

INTRODUCTION

'IN THE STRICT SENSE of the term there are very few "novel" bearing materials' (1)†. This statement, taken from the 1957 Conference, must be repeated and even extended to organic materials for gears, seals, belts and wheels. There is, however, a need for better communication on two levels: first, between the suppliers of raw materials and the manufacturers of machine parts; secondly between the latter and the designer. Most raw materials are *not* specifically made for the manufacture of bearings and gears. Some of the major suppliers have recently commenced large-scale research to assist both the designer and the manufacturer of machine parts with more than superficial data sheets.

Raw materials are compounded and cured to proprietary compositions and mostly tested on proprietary machines with fancy names. Only a small number of friction and wear studies on well-defined materials and tested under sound physical conditions have been published. This literature (Appendix 24.1) combined with suppliers' information (Appendix 24.2) forms the basis of this paper.

MATERIALS

Volume cost of most organic engineering materials is lower than that of non-ferrous metals or of stainless steel. Mass production is also frequently cheaper with polymers. Their low thermal conductivity, high coefficient of expansion and their moderate thermal stability are easily

recognized as limitations in design. Sorption of lubricants excludes the use of several of the newer plastics and rubbers.

Plastics

The classical thermosetting bearing materials are phenol-formaldehyde and melamine-formaldehyde, fibre and fabric reinforced, resins. Newer products with polyester resins as a binder are on the market and the potentialities of the higher priced epoxy-resins are being studied in many laboratories. Three types of nylons (the chemical name polyamides is preferred on the Continent) are available: nylon 6.6, nylon 6 and nylon 6.10; they differ in modulus, melting point and processing characteristics. Nylon 6.10 is used only to a limited extent. Competitive materials of the same prototype contain different additives, which influence crystallization, light aging and thermal stability; they can also contain mould release agents and other processing aids.

Polyacetal (or polyoxymethylene, also quoted as acetal resins) has been on the market since 1960. Reference is made to the trade product Delrin (SI) where comparison with competitive products of similar quality is not yet possible. Polyacetal, a crystallizing polymer, is similar to the nylons in low friction and (noise) damping properties, but superior in dimensional stability and chemical resistance. Polyethylene (p.e.) and several other common plastics and the new, high-temperature-resistant polymers will be referred to later; they are all used occasionally but cannot serve as a general purpose raw material.

Although the position of polytetrafluorethylene (p.t.f.e.) has not considerably altered since the 1957 Conference, some new uses will be discussed below. The clear p.t.f.e.

The MS. of this paper was received at the Institution on 6th March 1967.

* Central Laboratory TNO, Delft, The Netherlands.

† References are given in Appendix 24.1.

resin is mechanically weak, expensive and therefore almost useless as an engineering material. Polytetrafluorethylene has the function of a solid lubricant when combined with load-carrying fillers, fibres or with a porous metal.

Fibres and fillers for plastics

Thermohardeners are too brittle as clear resins, and are therefore always combined with paper, cotton or other cheap reinforcing fibres. The use of asbestos fibres for heat-resistant compounds is well-established; a variety of types (2) is on the market. Glass filaments, glass fibres (about 0.5 in long) and the new, short glass fibres (less than 0.05 in long) are extensively applied in reinforced plastic structures (3), including experimental bearings. The increase in modulus when glass fibres are combined with nylons and acetal resins also opens new approaches to stiffer gear materials. Ground glass and glass flakes have recently been added to protective coatings as they improve abrasion and erosion resistance (4). In processing glass-filled polymers orientation of the fibre in the skin (5) can lead to widely differing mechanical properties of skin and core. A composite of high specific modulus is produced by combining carbon fibres or carbon woven structures with resins; they could find application as bearings.

Powdered fillers are added mainly as cheap extenders to plastics; they *weaken* the mechanical properties in tensile loading and increase the apparent compression hardness. Solid lubricants, when added in large quantities, have a weakening effect on ultimate properties. A few per cent of graphite and molybdenum disulphide can have a useful function (see below); however, these additives do *not* primarily influence the coefficient of friction.

Rubbers

General and special purpose rubbers are extensively used in seals, brake linings, bearings, belts and tyres. Most of these materials reach the designer as compounded proprietary products. Specifications are based mainly on conventional *physical* testing and on service trials, but the inferior quality of such machine parts experienced in service is attributable largely to *chemical* factors or to an unsuspected variability of *rheological* properties.

Pure gum rubbers are rarely used in engineering. Rubbers are combined with 'reinforcing' black or white fillers to composites (6). Such filler particles are in the microinch range (200–700 Å) and when properly cured they adhere to the rubber matrix, even under the most severe conditions of friction and wear.

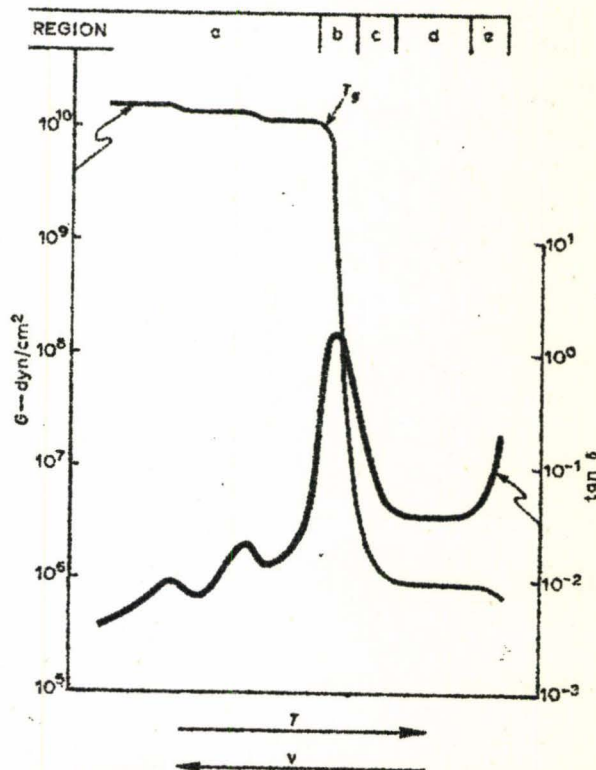
Many rubbers crystallize on stretching with a corresponding reversible change of dynamical properties. Polyurethanes, chemically related to the polyamides or nylon, are a class of crystallizing elastomers. Until recently the high-priced pure gum rubbers, prepared by casting, were chiefly used; millable rubbers which can be compounded with fillers are now on the market (see below). Polyurethane polymers are also used as highly flexible, positive seals in refrigerating machines.

Thin film lubricants

The efficient use of minute quantities of lubricants was clearly recognized at the 1957 Conference (7). The significance of the 'dwell time' stated there is not always fully appreciated. A thin film (20–200 Å, 0.1–1 μin) of a low shear strength solid is mostly sufficient to prevent stick-slip between polymer and a smooth (metal) surface. Many ingredients added to rubbers and plastics produce this effect. Typical mould release agents, such as silicones or polyfluorocarbons (8), can be intentionally added to the friction couple: frequently a trace of grease, a drop of oil or of water are sufficient. Lubricants in combination with organic materials function primarily as parting agents or as coolants, their load-carrying capacity being of minor importance only.

RHEOLOGICAL PROPERTIES

The mechanical behaviour of polymers depends in a characteristic manner on temperature and frequency. These rheological properties should be grasped properly in order to make full use of polymers in mechanical engineering. At small strains, in the linear elastic region, the shear modulus G and the damping losses $\tan \delta$ can be related to polymer structure. The generalized relaxation spectrum is shown in Fig. 24.1. Schematically, a distinction between five different regions can be made. In the hard, glassy region a, G is high and similar to that of other rigid solids. Damping is low but mostly still higher than



T_g = glass-rubber transition temperature.

Fig. 24.1. Generalized relaxation spectrum

that of hard metals. The narrow region b, on the temperature scale, shows a sudden steep drop in G by a factor of about 10^3 . At the same time damping increases exponentially and near the temperature T_g , the so-called glass transition temperature, molecular units become flexible. Whether a polymer is called a plastic or a rubber is determined by the position of T_g on the temperature scale. After a further small increase in temperature, region c, the polymer becomes tough, rubbery and, on still further heating, thermoplastic. It is here that the rubbery properties of the polymer are fully developed. At a still higher temperature, region d, the polymer shows viscous flow, and energy dissipation is small again, although still higher than in the glassy phase. Finally, in the last phase, region e, the intermolecular forces become weak enough to allow rapid flow; stresses are then relaxed so fast that the polymer does not exhibit any elastic recovery. However, this limiting temperature is frequently so high that decomposition commences at prolonged heating. By vulcanizing a rubber or, what is essentially the same, cross-linking a resin, this flow phase can be almost suppressed, and the elastic properties of the polymer are retained until decomposition occurs.

Extensive measurements have yielded fairly complete 'mechanical spectra' of the polymers discussed in this survey; they are interpreted in terms of molecular building stones, network structures and crystallinity (9). The large contribution made by the crystalline phase (nylons, polyacetals, polyurethanes) to modulus and damping is quite comparable to the more familiar role of crystal phases in alloys.

Any measured friction coefficient (f) depends on the ratio of two different rate processes:

$$\frac{\text{The rate of making an adhesional contact}}{\text{The rate of breaking an adhesional contact}}$$

The *making* process can range from very long periods in static friction to brief contacts. The *breaking* corresponds either with the rate of elastic recovery or with that of shearing a thin, fully strained layer. This rate is of the order of 10^{-3} to 10^{-5} sec, even if the macroscopic displacement is very slow. As a consequence the viscoelastic and ultimate properties of the polymer described by the low temperature or high frequency part of the mechanical spectrum, the left-hand part of Fig. 24.1, will always influence the friction process significantly.

FRICITION, LUBRICATION AND WEAR

When seen in context (10) the contribution made by rheological properties to the build-up of friction losses is fairly well understood (11). Low heat conductivity and the ensuing changes of material properties are next to be considered in design. When low friction is desirable, formation of low shear strength interlayers by compounding or boundary lubrication should be attempted. Finally the (mostly) adverse effect of a rough surface must be taken into account. In the analysis of wear a knowledge of the ultimate properties of polymers, their resistance to

oxidation and their reactivity with metals becomes essential. Emphasis on the combined effect of these factors is changed with the applied conditions from plastics to rubbers.

Plastics

The upper limit of friction at low rates of sliding was studied in a modified four-ball machine (12). The three types of nylon rubbed against the same materials or against steel all reached $f = 0.6$ after some time, and stick-slip was observed. The friction force was reduced by an order of magnitude on addition of a non-polar oil, but stick-slip vanished only on addition of a polar oil. For polyethylene (p.e.) rubbed against steel the friction remains low under any condition, while p.e. rubbed against the same material reaches $f = 0.4$ under heavy loads. Polyethylene systems are readily lubricated even by non-wetting liquids. Finally, p.t.f.e. between hard mating surfaces shows a very low friction at the highest loads for *slow* speeds; addition of lubricants has no beneficial effect.

Most suppliers of nylon point out that 'static' values of $f = 0.6$ can be reached and that $f = 0.4$ is sometimes observed under prolonged heavy loading. These limiting upper values of course depend entirely on the heat losses of the friction couple. In 'cool' running testing rigs $f = 0.2$ is a reasonable average value. Another important parameter is the equilibrium water content (2.0–2.5 per cent) of the nylon, which contributes to toughness (abrasion resistance!). Fluctuations in moisture of the atmosphere influence modulus and dimensional stability. The acetal resins, more particularly Delrin, are in this respect superior—they absorb very little water. They are also less prone to stick-slip friction and $f = 0.6$ is rarely observed.

The resistance to abrasion of unfilled plastics increases with hardness and toughness. Unorientated nylon is very extensible and therefore tough—comparable to soft metals. Drawn nylon bristles are, however, brittle in one direction and they are readily abraded (14). Many plastics can accommodate wear debris and abrasive particles by embedding them in the surface. As with other materials, the rate of abrasion by hard grains depends on the particle size of the abrasive (15).

While the adhesive wear of metals is influenced by the mutual solubility and the presence of oxides in the mating surfaces, the wear of thermoplastic materials is determined mainly by the flow properties of the polymer. Mostly mechanical wear is the combined result of abrasive and adhesive processes. In practice impact damage of the surface can be an additional factor. The relative wear rate of polymers measured in a variety of tests is:

Nylons: Delrin: thermohardened resins: thermoplastics
= 1:2.5:5–10:10–20

The small difference between nylons and Delrin is well-established. Wear resistance of the other materials depends of course on filler and fibre content; the highest wear rates being comparable to those of the softer metals.

Application of plastics is based on design for no-wear rather than for 'mild' wear. Recent studies (16) (17) were undertaken to assist the designer who has to deal with metallic or organic surface coatings. It is indeed possible to predict the conditions for 'zero-wear' of the order of the surface finish from a knowledge of slider geometry and the physical properties of materials. In the event of mild wear, the wear rate can be estimated from additional data on the applied conditions (18).

Plastic pipelines used for the transport of granular material are susceptible to erosive wear. Modulus, rebound elasticity and tear strength all contribute to the wear resistance, which in turn depends critically on the angle of incidence between the solid surface and the stream of impacting abrasive particles (19).

Erosion due to rain, encountered by aircraft, and damage caused by shock waves, produced in the collapse of cavitation bubbles, occur at still higher rates of impact. Again the ultimate properties of organic materials are of primary importance (20).

The friction of a polymer film is conveniently studied on a Capston friction machine for belts. Static friction depends essentially on the viscoelastic properties of the material and surface roughness. When a large number of asperities were produced on the polymer surface, static friction decreased considerably. The frictional behaviour could in fact be expressed by a single material constant, the deformation index. Another method to reduce film friction is coating with low shear-strength solids. Here frictional properties are predictable from the critical surface energy of the solids (21). More sophisticated equipment was developed to measure dynamic film friction as a function of percentage slip. Results were at least qualitatively expressed in terms of the viscoelastic properties of these cellulose acetate films. Although of great practical importance, the origin of triboelectrical charges on such films is not yet properly understood. Therefore the same type of equipment was used to measure the build-up of electrostatic charges (22) (23). Other types of polymer films increase in density during aging, with a corresponding decrease in friction force, presumably because the film is gradually stiffened by crystallization (24). A closely related field is the frictional behaviour of felts and textiles. Suffice it to state that changes in friction are also explained in terms of contacting surface asperities and of viscoelastic properties of the fibre (25) (26).

Rubbers

Early Russian work (27) (28) was mainly concerned with the change of 'rubber' friction over a wide range of temperatures; it therefore included the behaviour of technical rubbers in the glass-like state. In recent years reasonable agreement between different viscoelastic friction models has been reached (11) (29); cf. Fig. 24.1. Tyre friction can now be discussed in terms of rubber hysteresis, slip angle and surface roughness of dry and wet roads. The adhesion friction of a conventional, high resilience rubber tread at a certain slip angle can be expected to be the

highest on a flat (glass) plate, and to decrease with increasing surface roughness of the 'road'; this was confirmed experimentally. Next it was shown that a high hysteresis tread compound could almost compensate the adverse effect of surface roughness (30). As high hysteresis means higher operating temperatures and higher fuel consumption a compromise has to be found by the tyre compounder.

Good tyre to ground adhesion, even under severe wet weather conditions, is all-important for a landing aircraft. Research on tyre hydroplaning, performed since 1960 at N.A.S.A.-Langley Research Center, has led to the separation of two types of traction loss. In *dynamic* hydroplaning the runway must be flooded beyond a critical fluid depth, while in *viscous* hydroplaning a thin fluid film is present on the runway (31). An inclined slider bearing was used as a model to estimate the influence of surface roughness on the squeeze film in viscous hydroplaning (32). Next steel spheres were combined to a macroscopic model of surface asperities; the draping of a rubber pad around these spheres, on impact loading, was measured (33). A similar model, but now made of rubber spheres pressing against a steel plate, served in a recent study of the mechanical interaction between a rotary rubber seal and a steel shaft (34). Friction in different types of machinery can thus be derived from the measurable, viscoelastic properties of rubbers.

About 60 per cent of all rubber is consumed annually in the form of tyres. A good deal of this rubber is worn away, but the loss is not always 'undesirable' as wear in starting and braking a vehicle contributes to stable driving conditions. The following classification of wear processes emerges from an extensive literature (35).

Mechanical abrasion and cutting wear of rubbers is attributed to local stress concentration and the resulting large strains. Rubbers with reasonable ultimate properties at very high rates of deformation (10^4 per cent/s) and elevated temperatures (100°C) are likely to have superior abrasion resistance (36). The wear resistance of flooring materials is also related to the ultimate properties at very high rates of deformation (37). The shear rate of the thin deformed layer at the interface can be very high, even at moderate speeds of sliding (11), and this, in turn, can lead to localized rupture of the strained polymer.

Wear attributable to *dynamic fatigue* occurs on truck tyres even under moderate loads and speeds. The detachment of rubber particles, of random microscopical size, gives a smooth abraded surface. Mechanical fatigue is due to the gradual growth of microscopic cracks; it takes place only above a certain limiting strain (e.g. 80 per cent), which depends on the rheological properties of the rubber. Oxidative fatigue is induced by ozone and/or oxygen, even at quite small nominal strains; it is limited by the chemical nature of the rubber. Synthetic rubbers of the e.p.t.-type (ethylene-propylene ter-polymers) are susceptible only to mechanical fatigue. E.p.t.-rubbers are, however, not yet ready for general purpose application in tyres.

Under severe conditions, such as during locked wheel sliding, *thermal degradation* of the rubber takes place. Tread reversion, i.e. degradation of the vulcanized rubber to the tacky state of the green stock, can be the result of overheating or of the combined effect of heating and oxidation. The degraded surface layer is readily rubbed off. Curiously enough, an extreme form of this thermal wear is observed with hydroplaning aircraft tyres, when a rubbery layer is formed on the (wet) landing strip and leads to serious loss in traction. The well-known phenomenon (38) is probably caused by the generation of superheated steam in the skidding tyre footprint (37). This in fact is an ideal condition to produce 'reversion' of vulcanized rubber.

Rubber tyres and belts have mostly a backing of fibre cord. The fatigue properties of the fibre are even more important than the wear resistance of the rubber. The origin of cord failure has been analysed (39).

Polyurethanes constitute an entirely different class of elastomers. The toughness of these materials is reflected in their high tear strength and in tensile strength values superior to those of natural rubber. Their best performance is shown at high hardness levels, suitable for such applications as small heel top-pieces and solid tyres on factory trucks. A similar balance of properties can be approached, but probably not quite equalled, with compositions based on the millable polyurethane rubbers. Tests performed at RAPRA indicate that the abrasion resistance measured in the laboratory reaches values two to ten times superior to that found for a corresponding general purpose rubber tyre tread. Indeed, performance in service is superior to rubbers, but somewhat limited by high speeds and heavy loads. These compounds have a high hysteresis, leading to high heat generation under rapid deformation and a fairly rapid loss in strength with temperature. Therefore their superiority in abrasion resistance diminishes with severity of conditions (40). As stated above, these limitations probably depend on the crystallinity and the melting range of polyurethanes.

CORROSIVE AND ABRASIVE PROPERTIES OF TECHNICAL POLYMERS

The proper functioning of p.t.f.e. in bearing applications is presumably due to the transfer of a thin polymer layer on to the mating metal surface. The phenomenon may be more general with thermoplastic materials, but proper experimental evidence is lacking. Under heavy friction duty polymers degrade locally; they become tacky and stick to the metal surface; such transferred layers can be self-lubricating (41). A temporary compensation of any seizure tendency is a desirable property of (overloaded) plastic bearing couples, but it has catastrophic consequences with brake linings (where oxidation is promoted by metallic fillers). The oxidation products of many polymers are quite reactive with steel (and other metals) and can therefore cause specific types of corrosion (42).

The surface of seals and 'O'-rings can become mechanically weakened, when in contact with hydraulic or

other functional fluids, even if the rubber compound is nominally non-swelling in the liquid. As a consequence, 'particulates' in the micron size range are rubbed off and contaminate the fluid. This type of 'corrosive' wear should be taken into account in the design of (missile) hydraulic guidance systems (43).

Hard polymers are quite abrasive as clear resins and scratch even tool steel; this is experienced in the wear of metallic moulds (44). Soft fillers used in the plastic industry can contain hard, abrasive particles. Glass fibres, used for reinforcement, are very abrasive when broken. Certain types of graphite are well-known to be abrasive. Surprisingly enough the lubricant type of graphite, MoS₂, and other solid lubricants scratch and abrade bronze and steel (45). Systematic work on the abrasiveness of plastics is in progress (46).

DESIGN

Detailed engineering data are available from the manufacturers of raw materials (Appendix 24.2). A supplier of machine parts reports on the design and use of thermoplastics in the machinery of locks, canals, tunnels, shipyards and other advanced marine applications in the Low Countries (S2). A house journal follows the progress made in the use of p.t.f.e. (S3). The technical literature is based mostly on such data, and cannot be properly separated from these primary sources of information (47).

Design with p.t.f.e.

While rolling friction losses are clearly linked to the mechanical spectrum of the polymer (11), sliding friction properties appear to depend also on microstructure and crystallinity (48). P.t.f.e. is readily transferred to a mating surface; when rubbed *slowly*, orientation takes place and influences the *f*-value (49). The (high) rate of wear depends *inter alia* on the type and shape of filler particles (51) (52).

Filled p.t.f.e. bearings are most suitable to accommodate slow movements and heavy loads of bridges and tunnels. The rheological properties of such bearing discs have recently been described in a form useful to the designer (53) (54). Data for the design of various p.t.f.e. bearings are available (55) (56). P.t.f.e. is outstanding under extreme conditions, e.g. corrosive seawater (57) and space engineering. Glass-fibre-reinforced p.t.f.e. has found application at low temperatures in refrigerating machines. Recently attempts have been made to apply p.t.f.e. piston rings in high temperature compressors, but flash temperatures surpass the thermal stability of the polymer (58).

Design of plastics bearings (S1-S7)

Recent review articles cover plain plastics bearings (59), nylons (60) (61) and plastics in general (62) (63). The principal thermoplastic resins used are nylons and polyacetals. One review mentions the limited application of chlorinated polyethers, polycarbonate and of a high density polyethylene (63).

Reinforced thermosetting materials are capable of operating under heavy loads in dirty and corrosive conditions and of adjustment to additional heavy shock loading. Their application in (steel) mills offers substantial economic advantages in power consumption and bearing life (62). Whether more recent compositions will ultimately reach the quality of hard wood (*lignum vitae*), used in certain marine journal bearings, remains to be seen.

Thermoplastics are thermal insulators, a shortcoming compensated by suitable design of the bearing (62). The conventional PV value should be replaced by a limiting load for each speed range. Above a certain speed level, which depends on the heat flux of the friction couple, even a very light load will disturb the thermal equilibrium. Creep in compression, which increases exponentially with temperature, limits the dimensional stability of such bearings. Corrosion resistance is of course excellent. Boundary lubricants function primarily as parting agents. Full lubrication with oil or water provides good cooling, but now a small degree of swelling (over periods of months) can force the designer to use a generous clearance. Graphite added to nylon can presumably serve as an anti-oxidant for oxygen dissolved in water (60). There is no evidence that MoS_2 added in small quantities functions as a lubricant (64); it might, however, influence the crystallization (of nylon), but so do other powdered solids. Plastics do not inhibit corrosion of the mating metal surface. Any roughening and pitting of the metal will therefore increase the rate of cutting or abrasive wear of the bearing. In this situation the solid lubricant, even when present in the plastic in only small quantities, can transfer to the metal surface, and reduction of wear (64) rather than of friction becomes important.

As a high filler concentration reduces the ultimate properties of resins, early attempts to develop solid lubricant-plastics composition achieved only limited success. However, a thermo-hardened MoS_2 -filled proprietary product, capable of carrying high compressive loads, is now available. The combination of low to moderate friction ($f = 0.07$ at $20-50^\circ C$ and 0.20 at $130^\circ C$) with resistance to seawater and oil has led to special applications, for example in hydraulic load transfer equipment and in frames for deck-hatches of ships (S8).

With the advent of polyimides and related high-temperature-resistant thermoplastics, new bearings have been investigated. Graphite (65) or copper (66) filled resins can be run against metal at moderate loads and high speeds over long periods at or even above $200^\circ C$, at least in the absence of oxygen. The low f -value ($0.05-0.1$) seems to be the result of transfer of the polymer to the metal surface and subsequent interpolymer friction (66).

The course of thermal degradation reactions can limit or enhance the usefulness of bearing materials. In contrast to thermoplastics, conventional phenolic resins carbonize and therefore retain a large part of their compressive strength. Some of the new high melting polymers appear to have similar properties. The development of 'fail-safe' high temperature bearings thus becomes feasible.

Design of plastics gears (S1, S2, S4, S5)

Four different types of gear failure have to be taken into account: tooth fracture, pitting, scuffing and mechanical wear. Superimposed are the wear of mating metal gears and the effects of moisture and of lubricants. The three principal materials are laminated thermo-hardened resins, the nylons and polyacetal. Polyethylene and perhaps other cheap thermoplastics are occasionally used in very light load applications, such as water meters, but the tooth surface of p.e. becomes gradually oxidized and this may cause stick-slip. Glass-reinforced nylon and polyacetal gears are being studied extensively; no published data is as yet available.

German work on laminated resin gears dates back more than thirty years. A recent contribution describes the limiting tooth load for conditions of no-wear. At higher loads these laminates are superior to nylon gears in precision mechanics. Wear of mating brass gears is attributed to faulty design (overloading) (67). Calculations of nylon gears (loading, deformation, temperature, and tooth wear) are reported by one of the German manufacturers of polyamides (68). Similar instructions on the use of Delrin are available from the American supplier (S1). A third German group has carried out an extensive comparison of nylon and Delrin gears (69). Temperature, moisture and lubrication were among the parameters studied. When mated with a steel gear Delrin was found superior in regard to dimensional stability and fatigue life. Wear was very sensitive to surface roughness (of the steel), but mostly equal to or even less than that of nylons. Wear of different types of nylons showed the expected correlation with mechanical properties. The wear rate can go through a maximum, when measured against increasing temperatures.

Scuffing between the flanks of engaging teeth due to overheating and localized melting of the nylon has been observed and also calculated. Measures by which the permissible scuffing load may be increased are given in a recent study (70).

FUTURE DEVELOPMENTS

Emphasis will be laid on improved means of precision mass production. The role of fibre reinforcement, and the type of fibres combined with injection moulding, will require further elucidation.

Indications are that *in situ* polymerization, performed in inexpensive moulds, is sometimes economically attractive; it can be achieved already with nylon 6. By proper control of the process, a higher molecular weight, with a corresponding increase in modulus and decrease in friction, can be reached. Once the new high-temperature-resistant polymers become common engineering materials, production of the shaped part in one step is necessary, because the softening range of the polymer exceeds the working temperature of conventional processing equipment.

Laminated bearings and gears are among the oldest 'composites' of modern time. The future will bring further

improvements by an intentional subdivision of the functional properties of metals, fibres, fillers and plastics, when combined with composites with optimum design properties.

APPENDIX 24.1

REFERENCES

- (1) LOVE, P. P. 'A review of the papers on bearing materials, solid lubricants, surface treatments, and glands and seals', *Proc. Intern. Conference on Lubrication and Wear* 1957, 361 (Instn Mech. Engrs, London).
- (2) CRYOR, R. E. 'Asbestos reinforced plastics resist heat and chemicals', *Mater. Des. Engng* 1966 **62** (April), 92.
- (3) MURPHY, T. P. 'Reinforced and filled thermoplastics', *Ind. Engng Chem.* 1966 **58** (No. 5), 41.
- (4) SEYMOUR, R. B. Section on 'Protective coatings' in annual review 'Plastics', *Ind. Engng Chem.* 1966 **58** (No. 8), 66.
- (5) KARPOV, V. and KAUFMAN, M. 'Injection moulding of glass reinforced nylon 66', *Br. Plast.* 1965 **8**, 498.
- (6) HOLLIDAY, L. (ed.) *Composite materials* 1966 (Elsevier Publishing Co., Amsterdam).
- (7) BOOSER, E. R., SCOTT, E. H., JR. and WILCOCK, D. F. 'Compatibility testing of bearing materials', *Proc. Intern. Conference on Lubrication and Wear* 1957, 366 (Instn Mech. Engrs, London).
- (8) BOWERS, R. C., JARVIS, N. L. and ZISMAN, W. A. 'Reduction of polymer friction by minor concentrations of partially fluorinated compounds', *Ind. Engng Chem., Product Res. Develop.* 1965 **4** (No. 2), 86.
- (9) HEIJBOER, J. 'Modulus and damping of polymers as related to structure' (in Dutch), *Plastica* 1966 **18**, 489.
- (10) BOWDEN, F. P. and TABOR, D. 'Friction, lubrication and wear: a survey of work during the last decade', *Brit. J. appl. Phys.* 1966 **17**, 1521.
- (11) LUDMA, K. C. and TABOR, D. 'The friction and viscoelastic properties of polymeric solids', *Wear* 1966 **9**, 329.
- (12) MATVEVSKY, R. M. 'The effect of load on the critical temperature of oil in the lubrication of different materials', *Wear* 1961 **4**, 292.
- (13) MATVEVSKY, R. M. 'The effect of the polarity of oil on the friction of some plastics', *Wear* 1961 **4**, 300.
- (14) SELWOOD, A. 'The abrasion of materials by carborundum paper', *Wear* 1961 **4**, 311.
- (15) RABINOWICZ, E. and MUTIS, A. 'Effect of abrasive particle size on wear', *Wear* 1965 **8**, 381.
- (16) CLINTON, W. C., KU, T. C. and SCHUMACHER, R. A. 'Extension of the engineering model for wear to plastics, sintered metals, and platings', *Wear* 1964 **7**, 354.
- (17) CLINTON, W. C., SIRICO, J. L. and PIMBLEY, W. T. 'Wear of thin ferric oxide coatings bonded to mylar tape', *Wear* 1965 **8**, 337.
- (18) BAYER, R. G. 'Prediction of wear in a sliding system', *Wear* 1967: to be published.
- (19) BRAUER, H. and KRIEGLER, E. 'Investigations into the wear of synthetic plastics and metals' (in German), *Chem. Ing. Tech.* 1963 **35**, 697.
- (20) BOWDEN, F. P. (organizer) 'A discussion on deformation of solids by the impact of liquids, and its relation to rain damage in aircraft and missiles, to blade erosion in steam turbines, and to cavitation erosion', *Phil. Trans. Roy. Soc.* 1966 **A260**, 73.
- (21) OWENS, D. K. 'Friction of polymer films: I—Lubrication', *J. appl. Polym. Sci.* 1964 **8**, 1465; 'Friction of polymer films: II—Effect of deformation properties', *ibid.* 1477.
- (22) CUNNINGHAM, R. G. 'Dynamic friction measurements on belts of viscoelastic materials', *J. appl. Phys.* 1966 **37**, 1730.
- (23) CUNNINGHAM, R. G. and COBURN, T. J. 'Charge growth equation for belts of insulating materials passing over grounded rollers', *J. appl. Phys.* 1966 **37**, 2931.
- (24) SCHAEEL, G. W. 'Observations on the coefficient of friction of polypropylene film', *J. appl. Polym. Sci.* 1966 **10**, 653.
- (25) HUFFINGTON, J. D. and STOUT, H. P. 'The friction of fibre assemblies', *Wear* 1960 **3**, 26.
- (26) BROWN, D. K. 'The frictional properties of wool felts', *Wear* 1963 **8**, 22.
- (27) BARTENEV, G. M. and LAVRENTJEV, V. V. 'The law of vulcanized rubber friction', *Wear* 1961 **4**, 154.
- (28) KRAGELSKY, I. V. *Friction and wear*, translated from the Russian by RONSON, L. in collaboration with LANCASTER, J. K. 1965 (Butterworths, London).
- (29) SAVKOOR, A. R. 'On the friction of rubber', *Wear* 1965 **8**, 222.
- (30) SAVKOOR, A. R. 'Some aspects of friction and wear of tyres arising from deformation, slip and stresses at the ground contact', *Wear* 1966 **9**, 66.
- (31) HORNE, W. B., YAGER, T. J. and TAYLOR, G. R. 'Recent research on ways to improve tyre traction on water, slush or ice', *De Ingenieur* 1966 **78** (No. 39), L 39.
- (32) MOORE, D. F. 'A review of squeeze films', *Wear* 1965 **8**, 245.
- (33) MOORE, D. F. and LARSON, D. B. 'A method of determining the damping and elastic properties of rubber used in tyres', *Wear* 1967 **10**, 160.
- (34) JAGGER, E. T. and WALKER, P. S. 'Further studies of the lubrication of synthetic rubber rotary shaft seals', *Lubrication and Wear Group, Preprint P9/67* (Instn Mech. Engrs, London).
- (35) *Rubber chemistry technology*, all relevant literature is reprinted and/or reviewed in the journal.
- (36) ECKER, R. 'Wear of elastomers as a function of tensile strength at high velocities of deformation' (in German), *Materialprüfung* 1966 **8**, 368.
- (37) WARLOW, W. J., HARPER, F. C. and PYE, P. W. 'Resistance to wear of flooring materials', *Wear* 1967 **10**, 89.
- (38) HARDMAN, A. and GOUGH, V. E. 'Unpublished memorandum (1943) of the Dunlop Rubber Co. Ltd', quoted from reference (31).
- (39) MEARDON, J. I. and MOAKES, R. C. 'The wear of coated nylon fabric tarpaulins on lorries and barges', *Wear* 1963 **6**, 366.
- (40) PYNE, J. R. (Private communication: RAPRA work in progress) 1966 (Nov.).
- (41) VINOGRADOV, G. V. and BEZBORODKO, M. D. 'Friction, wear and lubrication of plastics', *Wear* 1962 **5**, 467.
- (42) VINOGRADOV, G. V., MUSTAFAEV, V. A. and PODOLSKY, YU. YA. 'A study of heavy metal-to-plastic friction duties and of the wear of hardened steel in the presence of polymers', *Wear* 1965 **8**, 358.
- (43) KLEMGARD, E. N. and COTY, U. A. 'Wear debris in aerospace hydraulic fluid systems (Buna-N rubber particulates)', *Wear* 1965 **8**, 199.
- (44) LUNDBORG, A. 'Abrasive effect of thermosetting moulding compounds', *Wear* 1958–59 **2**, 141.
- (45) GRATTAN, P. A. and LANCASTER, J. K. 'Abrasion by lamellar solid lubricants', *Wear* 1967 **10**: in the press.
- (46) *Annual Report* 1965, 27 (National Engineering Laboratory, East Kilbride, Glasgow).
- (47) CALDER, N. 'What they read and why', *Probl. Prog. Ind.* 1959 (No. 4) (D.S.I.R., Her Majesty's Stationery Office, London).
- (48) SPERSCHNEIDER, C. J. and LI, C. H. 'A correlation of mechanical properties and microstructure of polytetrafluoroethylene at various temperatures', *J. appl. Phys.* 1963 **34**, 3004.
- (49) TABOR, D. and WYNNE WILLIAMS, D. E. 'The effect of orientation on the friction of polytetrafluoroethylene', *Wear* 1961 **4**, 391.

- (50) MAKINSON, K. R. and TABOR, D. 'The friction and transfer of polytetrafluoroethylene', *Proc. Roy. Soc.* 1964 **281A**, 49.
- (51) SPEERSCHNEIDER, C. J. and LI, C. H. 'The role of filler geometrical shape in wear and friction of filled p.t.f.e.', *Wear* 1962 **5**, 392.
- (52) LONTZ, J. F. and KUMNICK, M. C. 'Wear studies on mouldings of polytetrafluoroethylene resin. Considerations of crystallinity and graphite content', *Trans. Am. Soc. Lubric. Engrs* 1963 **6**, 276.
- (53) UETZ, H. and BRECKEL, H. 'Friction and wear experiments with p.t.f.e.' (in German), *Wear* 1967 **10**, in the press.
- (54) UETZ, H. and HAKENJOS, V. 'Sliding friction experiments with p.t.f.e.' (in German), *Wear* 1967 **10**, in the press.
- (55) CRESS, H. A. and GOLDGRABEN, J. R. 'Design data on TFE-fabric bearings', *Mach. Des.* 1964 **36**, 151.
- (56) STIJN, R. P. 'Temperature, and environment on the sliding behaviour of polytetrafluoroethylene', *Trans. Am. Soc. Lubric. Engrs* 1966 **9**, 149.
- (57) CRAIG, W. D. JR. 'Operation of p.t.f.e. bearings in seawater', *Lubric. Engng* 1964 **20**, 456.
- (58) HART, R. R. 'Performance of p.t.f.e. based piston rings in an unlubricated reciprocating compressor', Lubrication and Wear Group 1966, Preprint P1/67 (Instn Mech. Engrs, London).
- (59) FORRESTER, P. G. 'Materials for plain bearings' in *Modern materials* (GONSER, B. W. and HAUSNER, H. H. (eds)) 1964 **4** (Academic Press, New York and London).
- (60) STEINBUCH, R. T. 'Nylon 6 as a bearing material', *Wear* 1962 **5**, 458.
- (61) HACHMANN, H. and STRICKLE, E. 'Polyamides as sliding bearing materials' (in German), *Konstruktion* 1964 **16** (No. 4), 121.
- (62) PINCHBECK, P. H. 'A review of plastic bearings', *Wear* 1962 **5**, 85.
- (63) FABIAN, R. J. 'Plastics bearing materials', *Mater. Des. Engng* 1964 **59** (March), 90.
- (64) POWERS, T. E. 'Molybdenum disulphide in nylon for wear resistance', *Mod. Plast.* 1960 **37**, 148.
- (65) TODD, N. W. and WOLFF, F. A. 'Polyimide plastics withstand high temperatures', *Mater. Des. Engng* 1964 **59** (Aug.), 86.
- (66) BUCKLEY, D. H. 'Friction and wear characteristics of polyimide and filled-polyimide compositions in vacuum', *N.A.S.A. tech. Note D-3261*, 1966 (Feb.).
- (67) SACHSE, H. 'Wear problems of plastic gears' (in German), 1961 *VDI-Ber.* (No. 47), 175.
- (68) HACHMANN, H. and STRICKLE, E. 'Polyamides as materials for gears' (in German), *Konstruktion* 1966 **18** (No. 3), 81.
- (69) CORNELIUS, E. A. and REMSHARDT, F. 'Studies on oil-lubricated gears of thermoplastic materials' (in German), *Konstruktion* 1965 **17** (No. 11), 437.
- (70) INGEN HOUZ, A. J. 'Scuffing as a factor in the design of nylon gears', *Wear* 1967 **10**, 118.

APPENDIX 24.2

SUPPLIERS' INFORMATION

The following technical guides have been used as sources of information in writing this paper. Communication of additional data on proprietary products by several suppliers is gratefully acknowledged.

- (S1) Delrin, Du Pont de Nemours International, S.A., Geneva:
 - a. Delrin acetal resins, 1962.
 - b. Gears of Delrin acetal resins and Zytel nylon resins, 1962.
- (S2) ERTA, N.V. Robert Tavernier, Tiel, Belgium:
 - Technical guide 1965 (in Dutch, translation available).
- (S3) The Journal of Teflon, Du Pont, Geneva, 1966 **7** (Nos 1-6) and earlier volumes.
- (S4) Zytel, Du Pont, Geneva:
 - Nylon resins, design and engineering data, 1962.
- (S5) B.A.S.F., Ludwigshafen am Rhein:
 - Kunststoffe, Werkstoffblätter, 1966 (data on friction and wear properties, integrated already in this survey, will be published).
- (S6) AKU, Plasttrading Ltd, Zeist, Holland:
 - Glassfibre reinforced Akulon K2-62V (in Dutch), 1966 (June).
- (S7) Polypenco Inc., Reading, Pennsylvania, U.S.A.:
 - Nylatron GS, Nylon, Technical Information Sheets, 1962.
- (S8) Molykote Mitteilungen (Munich) 1966 **11** (No. 40), 9; Molygium 20.