

C 314

Bibliotheek Hoofdkantoor TNO
's-Gravenhage 31 OKT. 1969

Communication No.

000360

Centraal Laboratorium
TNO

G. Salomon and A. W. J. de Gee

Wear Research in Europe

Authorized Reprint from the Copyrighted Evaluation of Wear Testing
Special Technical Publication 446



Published by
American Society for Testing and Materials
1916 Race Street, Philadelphia, Pa. 19103

TNO
9641

Wear Research in Europe

REFERENCE: Salomon, G. and de Gee, A. W. J., "Wear Research in Europe," *Evaluation of Wear Testing, ASTM STP 446*, American Society for Testing and Materials, 1969, pp. 23-41.

ABSTRACT: Until recently, the continental European trend was towards the finding of practical solutions in industry, rather than towards fundamental aspects or problems, typical for aerospace research. The first topic for detailed discussion is "abrasion and erosion." In this respect, the classical work of the Russian and German schools is related to recent developments in Great Britain. Rain erosion and cavitation erosion are mentioned as "modern subjects" which are intensely studied all over Europe.

As a topic for discussion, adhesive wear rates second. Here, the influence of mutual solubility of the sliding components and the interplay with oxide film formation, tool wear, new developments in bronze bearing research, and wear in atomic reactors are discussed.

KEY WORDS: abrasion, bronze bearing, cavitation, erosion, rain impingement, tribochemistry, tribology, wear adhesive, wear cutting, deformation, tool, atomic reactors, flooring materials, evaluation, tests, wear tests

Language, cultural, and political barriers have retarded co-operative research on wear in Europe, at least on a scale comparable to the efforts made in the United States. However, common patterns do exist and show that, until recently, the continental European trend was towards the finding of practical solutions in industry, rather than towards the evaluation of basic principles. Since the late thirties, this situation has been quite different in Great Britain, where several schools contributed to the formulation of first principles which, frequently, formed the nucleus of later developments in the United States and other parts of the world.

Before endeavoring to present the state-of-the-art in Europe, our method of selecting topics should be amplified. Firstly, as the subject

¹ Senior research associate, Central Laboratory TNO, Delft, The Netherlands.

² Head of Tribology Department, Metal Research Institute, TNO, Delft, The Netherlands.

of this review is *wear research*, European contributions to hydrodynamic and elasto-hydrodynamic theory of lubrication will not be discussed. Nor shall we deal with Russian [1]³ and French [2] contributions to the analysis of friction phenomena or with other Russian work on the chemistry [3] and physics [4] of boundary lubrication. Much of this has been reviewed and discussed at the Third Conference on Lubrication and Wear (London, 1967) [5]. Other review articles cover *inter alia* progress in theoretical analysis [6], national [7], and international developments [8].

Secondly, in selecting topics for presentation, recent results published originally in other languages than English are given preference. If these two criteria are applied, the systematic study of abrasion and erosion phenomena becomes the foremost topic. A subject, rating second, is adhesive wear. Here, the following aspects will be discussed: the influence of mutual solubility of the sliding components and the interplay with oxide film formation, tool wear, new developments in bronze bearing research, and, as an example of the use of intricate test methods and the application of basic principles to modern technology, wear in atomic reactors.

Abrasion and Erosion

Far from showing any "gap," European research is rapidly moving towards advanced technologies in this area. The literature on the past and the conventional testing techniques can be readily retrieved from a documentation service arranged by BAM (Bundesanstalt für Materialprüfung) [9]. A recent German conference [10] covers a broad spectrum of conventional industrial wear testing and evaluation of materials.

Definitions and Test Methods

A summary of recent definitions and experimental techniques may serve as a base for detailed analysis. Terms and definitions are being formulated by an International Working Party [11].

Abrasion is wear by displacement of material from surfaces in relative motion, caused by the presence of hard protuberances or by the presence of hard particles, either between the surfaces or embedded in one of them. The second solid may be friable. If hard particles are present between the surfaces, both surfaces may be affected. Abrasive wear may occur in the dry state or in the presence of a liquid.

Erosion is loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles. Erosion in which the relative motion of the solid particles is nearly parallel to the solid

³ The italic numbers in brackets refer to the list of references appended to this paper.

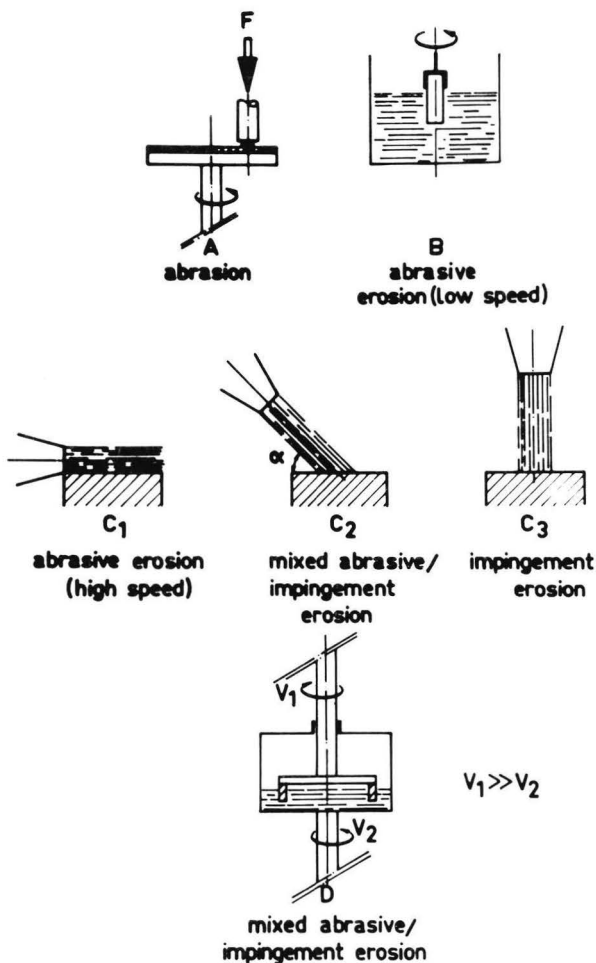


FIG. 1—Basic principles of experimental methods, used in evaluating the resistance against abrasion or erosion or both.

surface is called *abrasive erosion*. Erosion in which the relative motion of the solid particles is nearly normal to the solid surface is called *impingement erosion*.

The clear distinction which is made now between abrasion, abrasive erosion, and impingement erosion is due to a growing insight in the mechanisms of "surface-particle interactions." This has been developed largely, although not exclusively, by European workers in the field. Figure 1 illustrates the basic principles of the experimental methods used in evaluating the resistance against abrasion or erosion or both. In Methods A, B, and C₁, the abrasive particles move approximately parallel to the solid surface of the test specimens.

Method A is the "emery paper method," where the test specimen is pressed against the surface of a rotating disk, covered with a surface layer with abrasive properties (for example, emery paper). In more advanced forms of equipment, the specimen may move gradually inwards or outwards with respect to the center line of the rotating disk (thus, for instance, forming a spiral track) or it may rotate along an axis normal to the surface of the disk or both. Obviously, all sorts of intricate wear tracks can thus be obtained. Considerable use has been made of experience, gained with this type of cheap testing equipment in the evaluation of industrial products ranging from hard-facing metals to flooring materials.

In Method B, the test specimens are attached to a shaft, which rotates in a bed of abrasive particles or in a slurry consisting of abrasive particles and water or other more corrosive liquids. As the vessel, containing the abrasive, rotates at a low speed, a continuous displacement of abrasive particles at the interface is effectuated. This type of test rig is particularly suited for the study of the erosive action of relatively slowly moving particles, typical for the transportation of slurries and for dredging operations.

Method C, where a surface is damaged by solid particles, entrained in a streaming fluid, simulates the erosive action of fast moving particles, important in many engineering applications. Typical examples are the high-speed, pneumatic transportation of solid particles, gas turbines (blade erosion due to particles leaving the combustion chamber), and rocket engines (part of the surface damage to the exhaust nozzle wall is attributed to the action of particles from the combustion chamber). On the credit side of high-speed particle attack are useful applications, for example, shot peening, sandblasting, and erosive drilling of hard materials.

An important parameter in Method C is the angle of contact between the colliding particles and the solid surface. As will be shown, this "impact angle" α exerts an enormous influence on the relative rate of wear of different materials.

Finally, in Method D test plates are attached vertically to the outer end of an arm, moving through a mass of abrasive powder or a slurry. Here, the angle of contact is *not* well defined, and, thus, the method does not yield unambiguous results. Nevertheless, it has been applied with considerable success in the evaluation of materials used in dredging operations.

Experimental Results and Theories

The concept of abrasion resistance, as derived from Test Method A (Fig. 1), is coupled to the names of Khrushchov and Babichev (Moscow) [12], Wellinger and Uetz (Stuttgart) [13] and, more recently, to that of

Richardson (Bedford, England) [14, 15].

The conclusions obtained in the Soviet Union, Germany, and England can be summarized by stating that the resistance against abrasion by very hard abrasives is primarily a function of the "effective hardness," resulting from the microcutting action of the abrasive particles. This "effective hardness" will depend on the rate of strain hardening of the metal and the applied conditions. The relative wear resistance of different metals is determined in part by the ratio between volume elements, which become fully strained and hardened and other volume elements, which are abraded before hardening is completed. Because, generally, surface strain hardening by abrasives is extremely effective, work hardening prior to abrasion (for example, shot peening) or age hardening have little effect on the ultimate abrasion resistance of the metal. For technically pure metals this means that the abrasion resistance is a linear function of the hardness, measured in the fully annealed state [12, 13]. A complicated alloy such as copper beryllium (CuBe_2), when age hardened, shows an increase in hardness by a factor of 3.5, but no corresponding increase in wear resistance [13].

On the other hand, hardening by heat treatment (for example, martensitic hardening of steel), which strongly influences the rate of strain hardening, improves abrasion resistance.

These concepts are applicable only if the hardness of the abrasive particles exceeds the maximum attainable "effective hardness" appreciably. If this is not the case, plastic deformation of the wearing surface does not occur. Wellinger and Uetz [13] have shown that then the rate of oxidation and removal of the oxide film primarily determine wear resistance. Obviously, temperature and environment will contribute to this type of abrasive wear.

Abrasive wear of hard and brittle nonmetallic materials depends on ultimate strength rather than on plasticity and strain hardening. Abrasion resistance, therefore, is related almost linearly to the scratch hardness of brittle solids. Brittle materials cannot absorb much mechanical energy and are less abrasion resistant than metals of corresponding indentation hardness. Soft polymers have much damping capacity, but they are readily strained to the limit; they can compete with metals in impingement erosion resistance rather than in abrasion resistance. The foregoing broad picture is schematically shown in Fig. 2. In the English Speaking World [16-21] much progress has been made recently in the analysis of factors determining the cutting action of the abrasive in Method A (Fig. 1). On the other hand, the kinematics of Methods B and C_1 are too complex for more than a superficial, qualitative analysis.

Impingement erosion (Method C_3 , Fig. 1) and mixed abrasion and impingement erosion (Method C_2 and D, Fig. 1) were also studied extensively by Wellinger and Uetz. Their empirical results on the per-

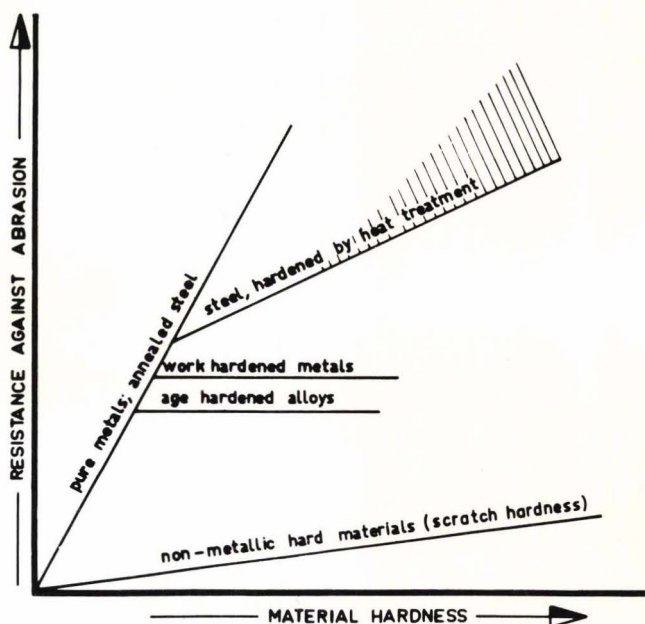


FIG. 2—Resistance against abrasion as a function of material hardness for different materials (after Wellinger and Uetz [15]).

formance of plates of a variety of materials exposed to dry or wet blasting are summarized in Ref 13. Again, the volume of removed material (per weight unit of the abrasive) depends on elastic modulus, yield point, and rate of strain hardening, but now the angle of impact (α) becomes of primary importance.

Starting from earlier work by Finnie (formerly of Shell, Emeryville) [22] and Bitter (Shell, Amsterdam) [23], Neilson and Gilchrist (Edinburgh) [24] succeeded in deriving an analytical method, which relates erosion resistance of materials to the angle of impact.

In their analysis Neilson and Gilchrist distinguish between a *cutting wear* factor and a *deformation wear* factor. The first is associated with the micromachining action of abrasive particles which attack a solid surface under a small angle (abrasive erosion), while the deformation term takes care of the effects, associated with impact under approximately 90 deg (impingement erosion). Further, they assume that the following factors should be accounted for in any relationships describing erosion damage:

1. Normal component of kinetic energy of the impacting particles is absorbed in the specimen surface and accounts for deformation wear, which is associated with the repeated blows suffered by the specimen.

These blows eventually cause cracking and spalling of surface material. Essentially, deformation wear can be considered to be a fatigue phenomenon.

2. For certain hard materials, subjected principally to deformation wear, there is a limiting component of velocity normal to the surface below which no erosion takes place. This limiting value is dependent on particle shape.

3. Kinetic energy component parallel to the surface is associated with cutting wear.

4. For cutting wear and large angles of attack, the particles come to rest in the surface, and the total parallel component of kinetic energy contributes to cutting wear. For small angles of attack, however, the particles may sweep into the surface and finally leave again with a residual amount of parallel kinetic energy.

If it is assumed that for cutting wear ϕ units of kinetic energy must be absorbed by the surface to release one unit mass of eroded material and that the corresponding parameter for deformation wear is ϵ , the above factors immediately lead to the following relationships:

$$W = \frac{\frac{1}{2} M (V^2 \cos^2 \alpha - V_p^2)}{\phi} + \frac{\frac{1}{2} M (V \sin \alpha - V_{el})^2}{\epsilon} \alpha < \alpha_0 \quad (1)$$

(A) (B)

and

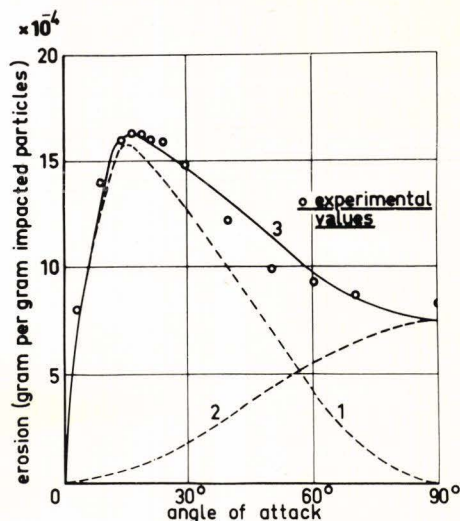
$$W = \frac{\frac{1}{2} M V^2 \cos^2 \alpha}{\phi} + \frac{\frac{1}{2} M (V \sin \alpha - V_{el})^2}{\epsilon} \alpha > \alpha_0 \quad (2)$$

(A') (B)

where W is the erosion produced by M units of mass of the particles at an angle of attack α and a particle velocity, V . V_{el} is the velocity component normal to the surface below which no erosion takes place in certain hard materials, and V_p is the residual parallel component of particle velocity at small angles of attack. Part B accounts for deformation wear and Parts A and A' account for cutting wear at small angles of attack and large angles of attack respectively. α_0 is the angle of attack at which V_p is zero, so that at this angle Eqs 1 and 2 predict the same erosion.

These formulas effectively account for the erosion versus angle of attack curves found by Wellinger and Uetz. In fact, they do facilitate much of the correlation of experimental results. The erosion versus angle of attack characteristics predicted by them for a particular material depend on the relative magnitude of the cutting and deformation wear constants ϕ and ϵ . For instance, cutting wear predominates when the equations are used to describe erosion of a soft metal, for example, aluminium.

The theoretical case of an ideal ductile material which does not suffer



- (1) Ideal ductile material (theoretical case).
 (2) Extremely brittle material (for example, glass).
 (3) Aluminum eroded by 210- μ m aluminum oxide particles at 424 ft/s.

FIG. 3—Erosion versus angle of attack curves for different cases (after Neilson and Gilchrist [24]).

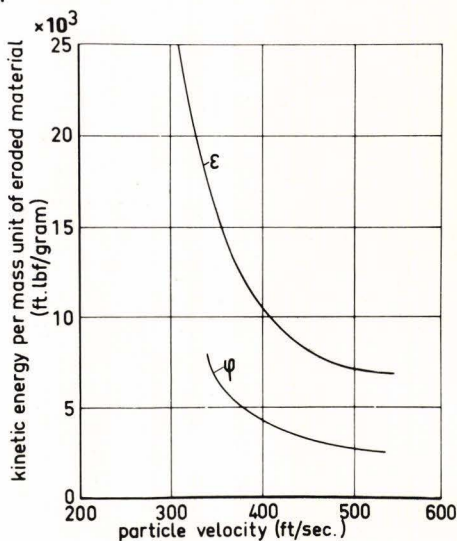


FIG. 4—Erosion parameters ϕ and ϵ as a function of particle velocity for aluminum plates eroded by 210- μ m angular particles of aluminum oxide (after Neilson and Gilchrist [24]).

fatigue effects is represented by Curve 1 in Fig. 3. Here, ϵ approaches infinite and Term B in Eqs 1 and 2 is zero. The opposite case, for example, that of an extremely brittle material (for example, glass), is represented by Curve 2 in Fig. 4. Now, cutting wear is negligible and

Terms A and A' in Eqs 1 and 2 can be neglected. Some practical case, in which neither cutting wear nor deformation of wear can be neglected, is represented by Curve 3 in Fig. 4. The experimental values shown were found for aluminium eroded by 210- μm aluminium oxide particles at 424 ft/s. The introduction of the parameters ϕ and ϵ has facilitated the correlation of empirical data, but theoretical interpretation has to wait for further fracture mechanics. The values of both ϕ and ϵ depend on velocity and geometry of the erosive particles. Neilson and Gilchrist determined the variation of ϵ and ϕ with particle velocity for aluminium plates eroded by 210- μm angular particles of aluminium oxide. The results are shown in Fig. 4. The pronounced influence of velocity may be an effect of the rate of strain hardening of the material on impact. This conclusion is supported by the observed strong dependence of the ratio ϕ/ϵ on particle shape.

Rain Erosion and Cavitation Erosion

The particle velocity in the foregoing experiments did not exceed 0.5 Mach. At higher velocities the hardness and shape of the solid abrasive becomes of minor importance as even liquid droplets cause severe erosion of surfaces. A recent discussion organized for the Royal Society by Bowden [25] brought some 150 physicists together, who discussed fundamental and practical aspects of three related technical problems: rain erosion at about 1.5 to 3 Mach, erosion of turbine blades by wet steam, and cavitation erosion. Obviously, it would make little sense to attempt to separate the large-scale research efforts performed all over Europe, including the Soviet Union, from the contributions made by workers in the United States. The close relationships between cavitation erosion and rain erosion are now worked out, mainly, on a practical testing level by British, French, German, and other European groups, who meet at the so-called Meersburg Conferences [26].

Tests performed at the centers for rain erosion research vary from single impact studies, in which a projectile is fired from a compressed gas gun at a droplet or sphere, which is suspended on an artificial web to the application of complete wind tunnels, specially equipped with rain erosion testing equipment. From a testing point of view the rotating arm test rig [26] takes up an intermediate position.

While the analysis and evaluation of physical parameters is thus rapidly advancing, *tribochemical* aspects of erosion are so far only studied in a few European laboratories, mainly by Thiessen and his associates in East Berlin [27]. Work in progress at Metal Research Institute TNO, Delft, aims at separating and excluding corrosion, from cavitation erosion. To this purpose water free from oxygen, twice distilled under nitrogen pressure, is used in cavitation testing. The

onset of damage is followed on highly polished, stainless, and hard-steel surfaces. An incubation period is found to exist, during which subsurface fatigue damage developed. A relationship between cavitation erosion and deformation wear, due to solid abrasives, seems to exist.

Abrasion of Flooring Materials

Our own group, the Industrial Organization TNO of The Netherlands, deals continuously with abrasion and erosion problems, ranging from the evaluation of abrasives to the testing of metals, leather soles, textiles, carpets, and flooring materials; most of these results are reported only to manufacturers or consumers. The problem of evaluating flooring materials may serve as a well documented example. An analysis of available testing equipment was made some time ago by Harper in England [28]. An International Working Party confirmed that not one of these machines is suitable for accelerated service trials on a broad scale [29]. More recently Harper and his associates [30] established a correlation between the results of service trials and the stress-strain properties of flooring materials at high rates of deformation. Considering the comparatively small, but economically important, differences in the wear resistance of different materials, improved test methods, suitable to estimate the early phases of wear in service trials, are needed. A recent technique, capable of measuring small differences in the thickness of samples is γ -X-fluorescence analysis. Kemper of Central Laboratory TNO adapted this method *inter alia* to the wear testing of organic flooring materials [31]. Whether European industry or Consumer Organization consider testing of flooring materials of sufficient economic importance to adopt such modern research tools remains to be seen.

Adhesive Wear

The British work on the adhesion theory of friction [32] formed the base for recent studies on the tribology of materials in an ultrahigh vacuum. Coupled to space research virtually all the exploratory work on the behavior of ultraclean (metal) surfaces in friction couples stems from the United States [33]. However, much can be learned already by substituting argon as an atmosphere or by applying a conventional, moderate vacuum to the system, or even by combining modern analytical tools, such as microprobe and the various types of electron microscopy are, with conventional friction and wear testing. The concept of adhesive wear is at present studied in respect to several classical and new technologies.

Solubility Concept

When a steel journal is pressed against a bearing material, cold welding will be facilitated by the mutual solubility of the metals. This

correlation between "antifriction" properties of bearing metals and their insolubility in iron was postulated by Ernst and Merchant [34] and experimentally verified by Roach and his associates at General Motors more than ten years ago [35]. A clear picture can be obtained by performing experiments in an argon atmosphere. Work at Metal Research Institute, TNO, Delft [36-38], was aimed at separating the effects of solubility and surface oxidation.

Nascent surfaces, completely freed from oxide films, will stick together as soon as the pressure at the points of transient contact causes local plastic deformation, irrespective of the solubility of the friction partners. On the other hand, the formation of a monolayer of iron oxide (FeO) (as in argon with 20-ppm oxygen) is enough to prevent cold welding and metal transfer in nonsoluble systems (for example silver-iron), which is not the case if the friction partners are soluble (for example, gold-iron). On the upper side of oxygen concentrations, the applicability of the "solubility concept" is limited by the formation of brittle ferric oxide (Fe_2O_3), which has no lubricating properties [39]. Once the interplay of mutual solubility and the formation of soft or brittle oxidation products is fully understood, a more systematic exploration of friction couples can be undertaken.

Tool Wear

The quality of hard machining tools is of much concern to European manufacturers. A co-operative effort, sponsored by OECD⁴, is made to modernize evaluation and machining operations in Europe [40]. Most of this work on tool wear, including metallurgical developments, is of an empirical nature. Dahlwhil in Saarland (West Germany) has made a systematic study of the factors affecting the quality of ceramic tools [41]. He has shown recently that the following relationship exists: on static, compressive loading, adhesion between ceramics, and certain metals increases exponentially above a limiting temperature. This chemical bonding is thought to depend on the mobility of oxygen atoms in the ceramic surface and the affinity of the hard metal for oxygen [42], in fact, a modification of the solubility concept.

Bronze Bearings

Lunn (Copenhagen, Denmark) has recently pointed out [43] that bronze-based bearing metals have been in use for ages, while their optimum composition and structure are not at all known. The argument has been taken up by Matveevsky and his associates in Moscow [44], by de Gee and his colleagues at Delft [45], and by Caubet at St. Etienne (France) [46].

Matveevsky studied the influence of the addition of small quantities

⁴ Organization for Economic Co-operation and Development.

of various alloying elements to copper on the adsorption of lubricating oils. It was shown that addition of as little as 2 percent tin increases the desorption temperature of a "D-1 grade" oil, containing about 0.2 percent fatty acids, from 200 to 250 C. Aluminum and silicon are also very effective in improving the adsorption characteristics of the surface.

The Delft group confirmed the known facts about thin lead film formation by extrusion of lead from the matrix of leaded bronzes and the beneficial function of such films under dry running conditions. When extended to lubricated systems, however, an unexpected difference between chill-cast and sand-cast alloys was found. Sand casting, which produces a coarse lead distribution, results in a much higher load carrying capacity than chill casting. The latter produces finely divided lead. Referring to Matveevsky's work, an explanation could be given in terms of changing oil adsorption characteristics of the bearing surface. Caubet's recent contribution is concerned mainly with the tin concentration of the alloy and with a comparison between aluminium based and copper based alloys. Thus, a continuous line from the mythical, metallurgical data of antiquity [43] to the application of microprobe analysis does exist in Europe.

Wear in Atomic Reactors

A variety of "hostile environments" is found in atomic reactors. The bearing problems have been solved to some extent for the first generation of gas or water cooled reactors. In the design of the second and third (fast breeder) generation, numerous bearing problems are encountered and studied in the Common Market Countries, Scandinavia and Great Britain. Evaluation of conventional materials and the development of new, high-temperature resistant compounds (CaF_2 -graphite) is intensely pursued in France [47]. The Metal Research Institute TNO, Delft, has specialized in the study of fretting due to vibrational contacts [48]. This phenomenon was first encountered in the design of the European ORGEL reactor. Turbulence in the high-boiling organic coolant (terphenyls) produces vibrational contact between different elements of the reactor core. Vibration analysis showed that hammering motions were superimposed on torsional vibrations in the plane of contact between two specimens. Remote controlled test rigs were designed and operated successfully. The wear problem was finally eliminated by a logical extension of the solubility concept. A similar experimental approach is followed in the analysis of still more complex wear problems, envisaged in the design of sodium cooled fast breeder reactors [49].

Tribology in Europe

The British proposal [50] to unite the widely differing activities in

tribo-physics, tribo-chemistry, and tribo-engineering by one general term "tribology" is gradually finding acceptance on the continent of Europe [51]. In the future, wear research will progress within the framework of this new and more flexible concept [52]. A first attempt to co-ordinate the different research efforts of Western European countries (together with the United States, Canada, and Japan) was made when a study group on "Wear of Engineering Materials" was formed, by the Organization for Economic Co-operation and Development. These activities have been continued since five years. Several European countries, which would otherwise have remained completely isolated, were brought together. Nevertheless, it is felt, by OECD as well as among the participants of the group, that, in addition to stronger national co-operative units, international co-operation should be established on a world-wide scale. Within such a framework, European laboratories could co-ordinate their efforts in the area of tribology more effectively than was done in the past.

References

- [1] Kragelskii, I. V., *Friction and Wear*, Butterworths, London, 1965.
- [2] Barquins, M., Kennel, M., and Courtel, R., "The Behaviour of Copper Single Crystals Under the Influence of a Hemispherical Slider" (in French), *Wear*, Vol. 11, 1968, p. 87.
- [3] Vinogradov, G. V., Pavlovskaya, N. T., and Podolsky, Y. Y., "Investigation of the Lubrication Process Under Heavy Friction Conditions," *Wear*, Vol. 6, 1963, p. 202.
- [4] Vinogradov, G. V., Korepova, I. V., and Podolsky Y. Y., "Steel to Steel Friction Over a Very Wide Range of Sliding Speeds," *Wear*, Vol. 10, 1967, p. 338.
- [5] "Fundamentals and Application to Design," *Conference on Lubrication and Wear*, London, Sept. 1967, *Proceedings*, Institution of Mechanical Engineers, Vol. 182, Part 3A, 1967-1968.
- [6] Bowden, F. P. and Tabor, D., "Friction, Lubrication and Wear: A Survey of Work During the Last Decade," *British Journal of Applied Physics*, Vol. 17, 1966, p. 1521.
- [7] Salomon, G., "A Review of Recent Research on Friction, Lubrication and Wear in the Netherlands," *Proceedings*, Institution of Mechanical Engineers, London, Vol. 180, 1965-1966, Part K.
- [8] de Gee, A. W. J., "Review of the Activities of the OECD Group of Experts on Wear of Engineering Materials," *Proceedings*, Institution of Mechanical Engineers, London, Vol. 180, 1965-1966, Part K.
- [9] Kirschke, K. and Rösener, W., "Documentation on Wear, Friction and Lubrication" (in German and English) 1967 (4 parts), *Bundesanstalt für Materialprüfung (BAM)*, Dahlem.
- [10] "Colloquium on Wear, Stuttgart, Oct. 1966," *Materialprüfung*, Vol. 9, No. 5, 1967; in German with abstracts in French and English; see also for abstracts *Wear*, Vol. 11, 1968, pp. 313-315.
- [11] OECD Paris, Research Group on Wear of Engineering Materials, *Terms and Definitions*, 1st revised issue (working document) 1968; final issue to be published 1969.
- [12] Khrushchov, M. M., "Resistance of Metals to Wear by Abrasion, as Related to Hardness," *Proceedings of the Conference on Lubrication and Wear*, London, Oct. 1957, p. 654, 816, and 874; see also: Khrushchov, M. M. and Babichev, M. A., "Experimental Fundamentals of Abrasive Wear Theory," *Russian English Journal*, (English translation), Vol. 44, 1964, p. 43.
- [13] Wellinger, K., Uetz, H., and Gürleyik, M., "Sliding Wear Studies on Metals and Non-metallic Hard Materials Interacting With Granular Solids" (in German with abstract and captions in English), *Wear*, Vol. 11, 1968, p. 173.
- [14] Richardson, R. G. D., "The Wear of Metals by Hard Abrasives," *Wear*, Vol. 10, 1967, pp. 291-353.
- [15] Richardson, R. C. D., "The Wear of Metals by Relatively Soft Abrasives," *Wear*, Vol. 11, 1968, p. 245.
- [16] Mulhearn, T. O. and Samuels, L. E., "The Abrasion of Metals: A Model of the Process," *Wear*, Vol. 5, 1962, p. 478.
- [17] Goddard, J. and Wilmon, H., "A Theory of Friction and Wear During the Abrasion of Metals," *Wear*, Vol. 5, 1962, p. 114.
- [18] Rabinowicz, E. *Friction and Wear of Materials*, Wiley, New York, 1965.
- [19] Rabinowicz, E. and Mutis, A., "Effect of Abrasive Particle Size on Wear," *Wear*, Vol. 8, 1965, p. 381.
- [20] Larsen-Badse, J., "Influence of Grit Size on the Groove Formation During Sliding Abrasion," *Wear*, Vol. 11, 1968, p. 213.
- [21] Larsen-Badse, J., "Influence of Grit Diameter and Specimen Size on Wear During Sliding Abrasion," *Wear*, Vol. 12, 1968, p. 35.
- [22] Finnie, I., "Erosion of Surfaces by Solid Particles," *Wear*, Vol. 3, 1960, p. 87.

- [23] Bitter, J. G., "A Study of Erosion Phenomena," *Wear*, Vol. 6, No. 6, 1963, p. 169.
- [24] Neilson, J. H. and Gilchrist, A., "Erosion by a Stream of Solid Particles," *Wear*, Vol. 11, 1968, p. 111.
- [25] 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," *Philosophical Transactions*, Royal Society, London, Series A, Vol. 260, 1966, pp. 73-315.
- [26] *Proceedings of the First and Second Rain Erosion Conferences*, Meersburg, West Germany, 5-7 May 1965 and 16-17 Aug. 1967; edited by Fyall, A. A. and King, R. B., Royal Aircraft Establishment, Farnborough, England.
- [27] Thiessen, P. A., Meyer, K., and Heinicke, G., "Fundamentals of Tribo-Chemistry" (in German), *Abhandlungen der Deutsche Akademie der Wissenschaften zu Berlin*, No. 1; 1966, Akademie Verlag, Berlin, 1967.
- [28] Harper, F. C., "The Abrasion Resistance of Flooring Materials, A Review of Methods of Testing," *Wear*, Vol. 4, 1961, p. 461.
- [29] International Study Committee for Wear Tests of Flooring Materials, "Performance of Abrasion Machines for Flooring Materials," *Wear*, Vol. 4, 1961, p. 461.
- [30] Warlow, W. J., Harper, F. G., and Pye, P. W., "The Resistance to Wear of Flooring Materials," *Wear*, Vol. 10, 1967, p. 89.
- [31] Kemper, A., "Wear Measurements by Means of γ -X-Fluorescence," *Wear*, Vol. 12, 1968, p. 55.
- [32] Bowden, F. P. and Tabor, D., *The Friction and Lubrication of Solids*, Oxford University Press, London, Part I, 1950; Part II, 1964.
- [33] *Adhesion or Cold Welding of Materials in Space Environment*, ASTM STP 431, American Society for Testing and Materials, 1968.
- [34] Ernst, H. and Merchant, M. E., "Chip Formation, Friction and High-Quality Machined Surfaces," *Transactions*, American Society of Mechanical Engineers, Vol. 29, 1941, p. 299.
- [35] Roach, A. E., Goodzeit, C. L., and Hunnicutt, R. P., "Scoring Characteristics of Thirty-eight Different Elemental Metals in High-Speed Sliding Contact with Steel," *Transactions*, American Society of Mechanical Engineers, Vol. 78, 1956, p. 1659.
- [36] de Gee, A. W. J., "The Friction of Gold-Silver Alloys Against Steel," *Wear*, Vol. 8, 1965, p. 121.
- [37] Begelinger, A. and de Gee, A. W. J., "Sliding Characteristics of Silver Against Iron as Influenced by Oxygen Concentration," *Transactions*, American Society of Lubrication Engineers, Vol. 10, 1967, p. 124.
- [38] de Gee, A. W. J., Begelinger, A., and Vaessen, G. H. G., "The Applicability of the Solubility Concept," contribution to discussion of Session 4, *Proceedings*, Institution of Mechanical Engineers, *Conference on Lubrication and Wear*, London, Oct. 1967.
- [39] Bisson, E. E., Johnson, R. L., and Swikert, M. A., "Friction, Wear and Surface Damage of Metals as Affected by Solid Surface Films," *Proceedings*, Institution of Mechanical Engineers, *Conference on Lubrication and Wear*, London, Oct. 1957, p. 384.
- [40] *Proceedings of Seminar on Metal Cutting*, Sept. 1966, Paris, Organization for Economic Co-operation and Development, Paris, Aug. 1967.
- [41] Dawihl, W. and Frisch, B., "The Wear Properties of Tungstencarbide and Alumina Sintered Materials," *Wear*, Vol. 12, 1968, p. 17.
- [42] Dawihl, W. and Klingler, E., "The Influence of Seizures Between Metals and Sintered Alumina on Their Wear Resistance" (in German) *Wear*, Vol. 11, 1968, p. 467.
- [43] Lunn, B., "The Wear Resistance of Tin Bronzes and Related Alloys," *Wear*, Vol. 8, 1965, p. 401.

- [44] Matveevsky, R. M. and Lozovskaya, O. V., "The Influence of Alloying on the Antifriction Properties of Binary Alloys Under Boundary Lubrication Conditions," *Wear*, Vol. 11, 1968, p. 69.
- [45] de Gee, A. W. J., Vaessen, G. H. G., and Begelinger, A., "The Influence of Composition and Structure on the Sliding Wear of Copper-Tin-Lead Alloys," *Transactions, American Society of Lubrication Engineers*, Vol. 12, 1969.
- [46] Caubet, J. J., "Application of Scientific Methods to Industrial Research Problems," (lecture in French), Paris, March 1968, to be published in French, *Journées d'Etudes du GAMI*, Paris, 1969.
- [47] Blampin, B., "Lubrication by CaF_2 in Hot Air and Carbondioxide" (in French), *Wear*, Vol. 11, 1968, p. 431.
- [48] Commissaris, C. P. L. and de Gee, A. W. J., "Control of Fretting Wear of Sintered Aluminium Powder," Paper 22, Fifth Lubrication and Wear Convention, Plymouth, 1967, Institution of Mechanical Engineers, London.
- [49] de Gee, A. W. J. et al, "Equipment for the Study of Wear Under Conditions of Oscillatory Relative Motion in Liquid Sodium," *Proceedings of the Conference on "Alkali Metal Coolants"*, International Atomic Energy Agency, Vienna, 1967, p. 415.
- [50] Lubrication (Tribology), "A Report on the Present Position and Industry's Needs," London, Her Majesty's Stationery Office, 1966.
- [51] Committee on Tribology, Report 1966-67, London, Her Majesty's Stationery Office, 1968.
- [52] Salomon, G., "Research in the Field of Tribology" (lecture in French), Paris, March 1968, to be published in French; *Journées d'Etudes du GAMI*, Paris, 1969.