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Methods of wear testing for advanced surface coatings and bulk materials

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Abstract

This paper examines methods of assessing the wear resistance of coated and uncoated materials. Test equipment for sliding wear, erosion, impact and dynamic wear tests is discussed. Processes for measuring wear rates are highlighted and a simple procedure for conducting wear tests to simulate industrial wear problems is given. The wear test selected and the wear conditions encountered in real applications should conform in order for specialists to make adequate judgement on the life of a particular component in service. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Industrial wear problems; Test equipment; Wear testing

1. Introduction

Wear occurs to the hardest of materials, including diamond, wear studies having focused on surface damage in terms of material-removal mechanisms, including transfer film, plastic deformation, brittle fracture and tribochemistry [1]. With the development of surface engineering design, the need to evaluate the properties of new raw materials and substrate-coating combinations is important. In many research works to date, the authors have investigated the effects of contact abrasion, erosion and impact effects on uncoated components, mainly as separate problems [2]. More recently, experiments and testing on coated materials have occurred and some standardised, and experimental test equipment has been produced to meet specifications on wear resistance. Standard test methods such as pin-on-disc are used extensively to simulate rubbing action in which plastic yielding occurs at the tip of individual asperities. This testing is mainly carried out on a microscopic scale and in thin films technology [3].

Thick coatings such as those produced in thermal spraying and weld facing seldom experience penetration during the carrying out of some of the standard wear tests that are available. It is unclear whether behavioural models developed for thin, hard coatings necessarily apply to thicker coatings [4]. The type of wear occurring under combined impact and sliding wear has hardly been studied according to Swick et al. [5]. Under the actions of continuous and intermittent cutting processes involving impact and abrasive wear, the different parameters are highlighted and compared in Figs. 1 and 2, respectively.

1.1. Wear of engineering materials

There are many types of wear that are of concern to the user of coatings, including sliding wear and friction, low- and high-stress abrasion, dry particle erosion, and slurry erosion [6]. Reducing the coefficient of friction has many advantages in machining processes but it may also require a change in tool design [7]. In practice it is possible for a coating to wear and the substrate to be unaffected. Also, the substrate may deform without any noticeable wear of the coating. It is claimed by Wick [8] and confirmed from practice, that hard coatings applied to cutting tools increase tool life by two to ten times that of uncoated tools. Hard coatings have some disadvantages, which include porosity, insufficient bonding to the substrate and, in some cases, limited thickness [9]. Coatings experience shear, tensile and compressive stresses which may lead to failure by cracking and spalling [10]. In applications of material wear, one or

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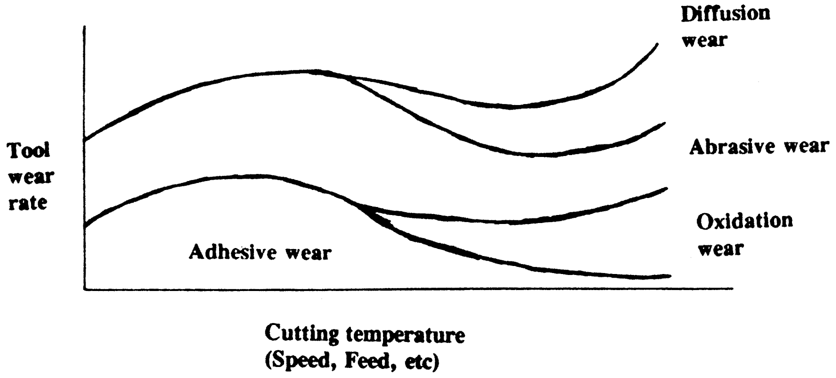

Fig. 1. Wear mechanisms for continuous cutting.

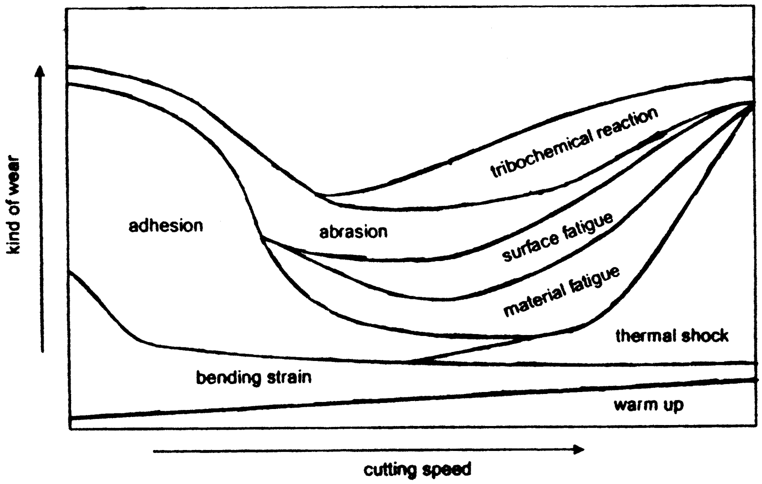

Fig. 2. Wear mechanisms in interrupt cutting processes [40].

more of the following will be operational [11,12]: (i) abrasive wear; (ii) adhesive wear; (iii) erosive wear; (iv) fretting wear; (v) surface fatigue; and (vi) delamination.

1.2. Coating characteristics

In practice, coatings may confer one or more of the following wear resistant properties: (i) corrosion protection; (ii) wear resistance; (iii) hardness; (iv) high melting temperature; (v) low permeability and diffusion for oxygen to prevent internal substrate corrosion; (vi) high density, to avoid gas flux through open pores to the substrate; (vii) stress free or in a state of compressive stress at the working temperature; and (viii) good adhesion.

2. Wear test criteria

In selecting a suitable wear test, the following points should be considered: (i) ensure that the test selected is measuring the desired properties of a material; (ii) whether the material is in bulk form or is a thick or thin coating; (iii) whether the forces and stress limited are suitable for the test; (iv) whether abrasives be present, considering the abrasive size, form and velocity; (v) whether the contact between the components is rolling, sliding, impact or erosion only, or a combination of these, bearing in mind that the surface finish of the test samples should be similar to that of the actual components; (vi) whether temperature and humidity factors are important; (vii) whether the test environment is similar to the actual working environment; (viii) the duration of the test; and (ix) whether the materials used in testing is typical of the actual materials used in the machine parts.

3. Wear test methods

Tests are used for quality control functions such as thickness, porosity, adhesion, strength, hardness, ductility, chemical composition, stress and wear resistance. Non-destructive tests include visual, penetrant dies, magnetic particle and acoustic techniques. Many tests for coated and uncoated cutting tools are conducted on machine tools, including lathes, mills, drills, punches and saws [13,14]. These test methods provide almost

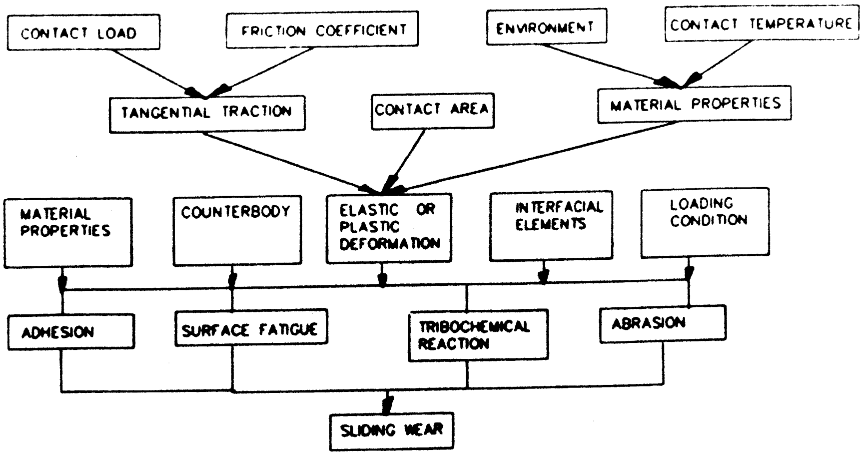

Fig. 3. Factors influencing wear during sliding contact.

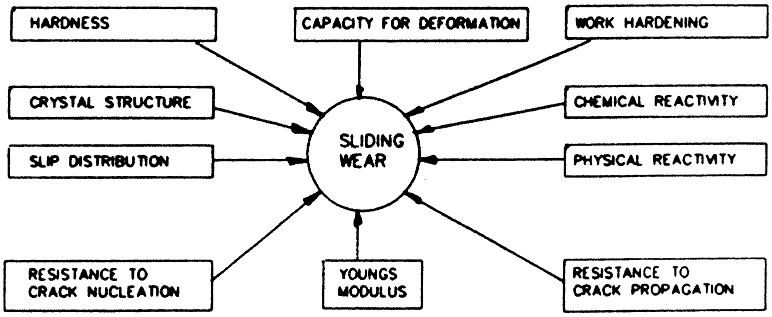

Fig. 4. Metallurgical properties, influencing sliding wear.

identical conditions to those experienced in manufacturing. Machining tests subject cutting tools to many wear parameters, including impact and shock, abrasion, adhesion and hot corrosion. The limitations of these tests depend on the machine power available and the quality of the machine tool. Other coated components that are not used as cutting tools are assessed by laboratory wear tests and compared to field studies. Such equipment includes nano- and micro-hardness testers, fatigue testers, acoustic, and scratch-type test equipment, etc.

3.1. Abrasive and adhesive test equipment

Hardness is often used as an initial guide to the suitability of coating materials for applications requiring a high degree of wear resistance. The effect of the hardness of a wearing material however is complicated, as different wear mechanisms can prevail in service. Scratch hardness is the oldest form of hardness measurement. Mohs in 1822 categorised materials using this process, giving diamond a maximum scratch hardness of ten. Most scratch type tests developed from this simple technique. Abrasive tests are described by Kato et al. [15] and others [16,17]. Adhesion is characterised by both scratch- and indentation-tests as reported in the literature [18,19]. In indentation adhesion tests, a mechanically stable crack is introduced into the interface of the coating and substrate. The resistance to propagation of the crack along the interface is used as a measure of adhesion. In scratch-adhesion tests, a stylus is drawn over the surface under a continually increasing normal load until the coating fails. Factors influencing the wear mechanisms during sliding contact are shown in Fig. 3 and the metallurgical properties influencing sliding wear are shown in Fig. 4.

3.2. Pin-on-disc

Research conducted by Glaeser and Ruff reported that pin-on-disc were the most widely used wear test processes, followed by pin-on-flat [20]. Other applications of pin-on-disc include material wear and friction properties at elevated temperatures and in controlled atmospheres [6]. Almond et al. [21] used a pin-on-disc apparatus for testing ceramics and cemented carbides on alumina discs using the pin as the test material. In a two-body abrasion test, a coated pin is pressed against a rotating abrasive paper making a spiral path to avoid overlapping [22,23]. This test process is very common for thin coatings. Using a diamond tip as the abrading tool, Kato et al. [15] used a pin-on-disc test to operate within the chamber of a Scanning Electron Microscope (SEM) to examine abrasion effects. Scratch testing in

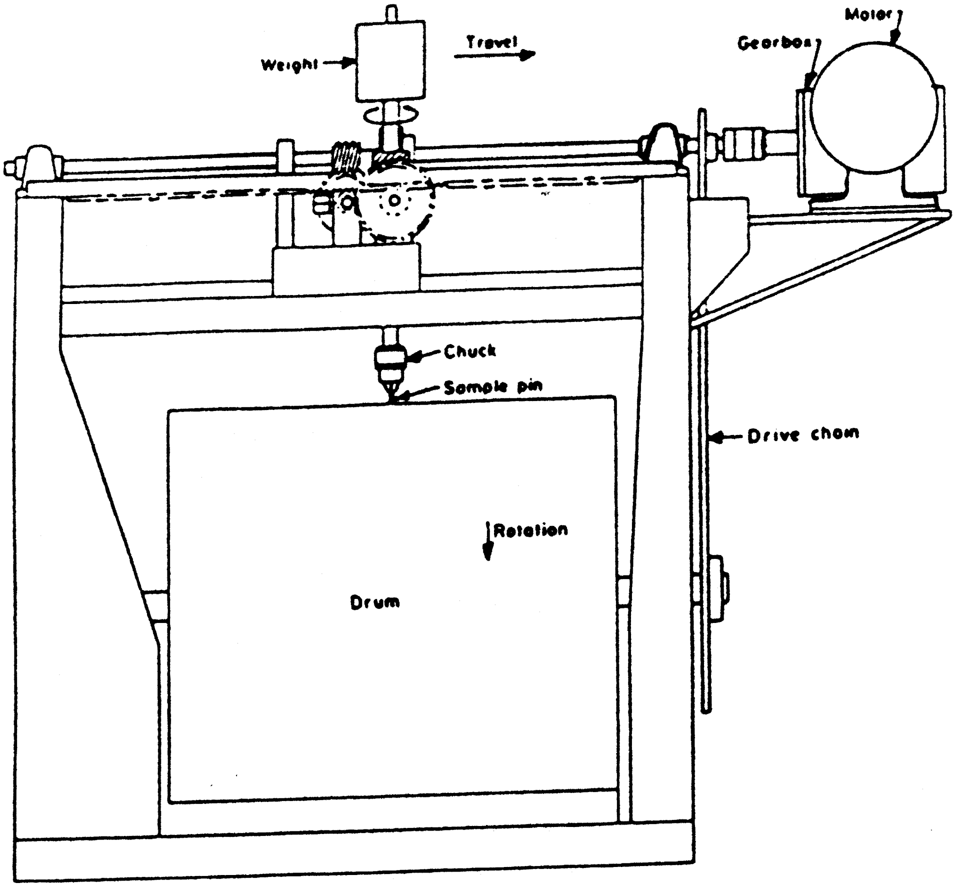

Fig. 5. Schematic diagram of pin-on-drum apparatus.

conjunction with SEM provides a useful method of analysing single-point wear mechanisms of coated systems through an assessment of the deformation and fracture produced.

3.3. Pin-on-drum abrasive wear test

In this test, one end of a cylindrical pin specimen is moved over abrasive paper with sufficient load to abrade material from the specimen and crush the fixed abrasive grains. This test simulates the wear that occurs during crushing and grinding of ore in which the abrasive (the ore) is crushed. The pin also rotates while traversing, as indicated in Fig. 5. This ensures that the pin always contacts fresh abrasive. This is a high-stress abrasion test, as the load is sufficient to fracture the abrasive particles.

3.4. Repeated impact wear test

Equipment described by Blickensderfer and Tylczak [24] involved balls made from alloys being dropped 3.4 m onto a column of balls, with each successive ball receiving an impact on each side. The first ball receives maximum impact whilst the last one receives the least. This rig, as shown in Fig. 6, tests materials for spalling due to impact and shock only. It does not take account the orientation of the samples, which latter can be up to 50 mm diameter. The samples are also subjected to rebound, which gives a double-impact effect. An impact testing machine for determining the dynamic cushioning properties of plastic foams is reported by Shestopal and Chilcott [25] and shown in Fig. 7. This process is pure impact and has many limitations, as described in the reference. Brenner et al. [26] used a test rig to combine impact and its effect on adhesion at elevated temperatures for iron spheres impacting on an iron plate. The impact forces are transmitted to piezoelectric load cells, which produces a pulse on a screen that equivalent to the applied load.

3.5. Adhesion tests using acoustic amission monitoring

Experiments conducted by Diniz et al. [27] used acoustic emission to monitor the changing of workpiece surface roughness caused by an increase in tool wear during finish turning. Adhesion tests conducted by Kubo and Hashimoto [28] made use of a modified scratch test with a steadyily-increasing load. This test is designed to evaluate thin film properties such as adhesion [29,30], and the critical load at which the film becomes detached is detected by acoustic emission. A diamond indenter tip is normally employed in this test, along with a camera and SEM to observe how the films are scratched. Fig. 8 presents a schematic representation of a scratch coating adhesion test using acoustic emission.

3.6. Rubbing tests

An ASTM standard [31] uses a crossed-cylinder apparatus for testing similar and dissimilar metals, and alloys and coated systems under unlubricated conditions. A rotating cylinder (100 rpm) is forced at right angles against a stationary cylinder. The volume of material loss is determined by means of an appropriate equation.

3.7. Block-on-ring test

This test, ASTM G77-83 [32], makes use of a rotating metal ring acting against a fixed block. It makes a line contact when the test begins, as shown in Fig. 9. This test allows variations in materials, speeds, loads, lubricants, coatings and different operating atmospheres. Wear is calculated using the volume loss of the block and the weight loss of the ring.

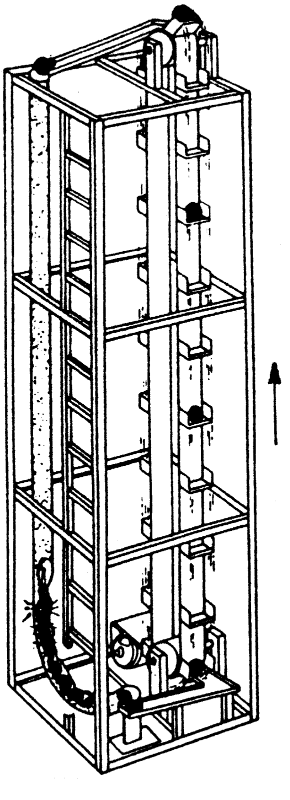

Fig. 6. Schematic diagram of impact test apparatus.

3.8. Taber test

The Taber Abraser, ASTM 1044, is used to measure the low-stress abrasive wear resistance of materials and coatings. Low-stress abrasive wear occurs when hard particles are forced against and move along a flat, solid surface where the particle loading is insufficient to cause fracture of the hard particles. Two- and three-body abrasive wear can be assessed with this method. The Taber apparatus is shown in Fig. 10. The specimen, which is coated or uncoated, is rotated, causing the abrasive wheels to drag and abrade the surface. Wear is normally determined by weight loss.

3.9. Dry sand rubber wheel test

This test, ASTM 65-81 is used to rank the abrasion or scratch resistance of materials to silica sand. It is a low-stress abrasion test and is used for dry wear conditions. In operation, sand particles are trapped between the specimen and a rubber wheel and dragged along as the wheel rotates. The specimen is held against the wheel with a contact force. Cerri et al. [33], using similar equipment, examined the abrasion resistance of carbide powders with several materials and coatings used for applications in abrasive environments. Swanson [34] used a dry-sand rubber wheel test to compare laboratory and field tests under sandy-soil working conditions, and concluded that there was a close correlation between the two.

3.10. Alumina slurry test

An alumina slurry test, standard ASTM 611, is used to simulate high abrasive conditions in a liquid medium [35]. The test rig is shown in Fig. 11. It uses a steel wheel which rotates against a flat coated specimen in a slurry containing sharp alumina particles, subjecting the samples to combined impact erosion. Impact by particles causing erosive wear are described in Fig. 12. The effects of erosion have become a problem associated with airfoils and shrouds in various fans, in compressors and turbines, on helicopter blades, in centrifugal pumps, on valve components and in pipe joints and bends [6]. The extent of erosion depends on the composition, size, and shape of the eroding particles, their velocity and angle of impact, and the composition and microstructure of the surface being eroded.

4. Measuring wear of specimens

One of the simplest ways of measuring wear is based on weight loss during and after a test. This is simple and direct provided that the materials considered are similar and care is taken in the measurements. The

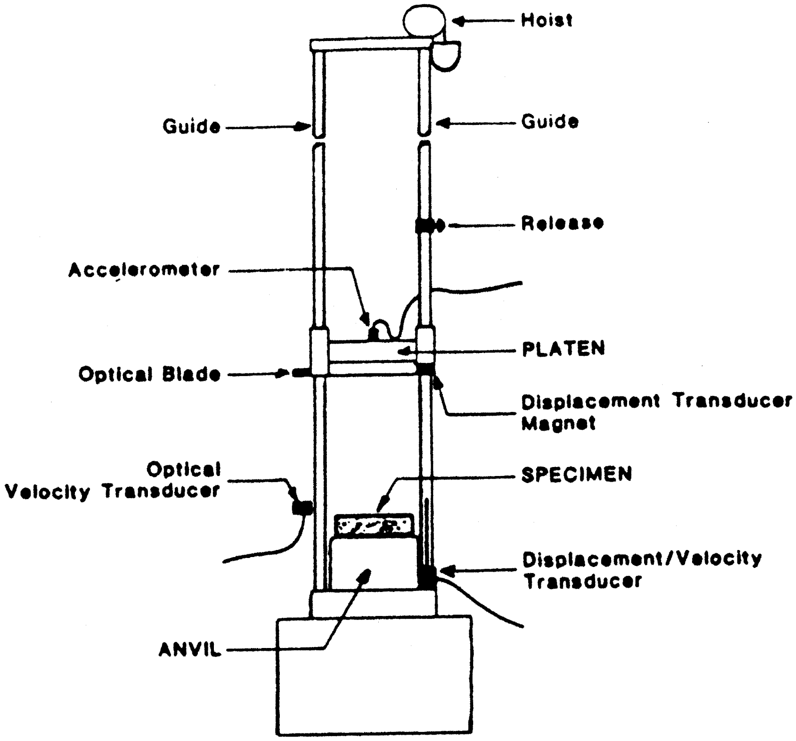

Fig. 7. Impact test for plastic foams.

mass loss can be converted to volume loss and the wear rate calculated with respect to time. For coating applications, if the coating is penetrated, the weight loss is a combination of both substrate and coating(s). In some cases, wear may occur but no mass loss may be experienced, as in the case of plastic flow or deformation.

The wear volume can be calculated from equations based on the wear scar shape. If the scar shape is regular and symmetrical, accuracy with this approach is possible. The volume of material removed can be measured at intervals using equipment for measuring the depth and width of the wear scar or impact zone. If the wear scar or crater can be drawn accurately on 3-dimensional or solid modelling software, the volume wear can be calculated directly from the software. The dimensions of the abrading tool can also be checked to assist in the volumetric loss. For multi-layered coated systems, the wear volume can be an indication of the total wear loss of the system.

The depth of the wear scar is considered a reliable method for assessing material loss. A surface profilometer can measure and record these values with ease. A more exact method using a profilometer and computer-control equipment was developed by George and Radcliffe [36]. This process produces an isometric plot of the wear scar, the wear scar volumes being calculated by the computer automatically.

A wear coefficient is often used to categorise resistance to contact wear. The method most commonly used is to calculate a wear coefficient K, where:

$$K = \frac{\text{Vol}}{\text{Load}*\text{Sliding distance}} \frac{(\text{mm}^3)}{(N-m)}$$

This coefficient is based on the assumption that the volume wear varies directly with the contact load and the sliding distance. This wear coefficient was suggested by Holmberg and Matthews as a standard for wear testing [37], and coefficient is used for comparing test samples to standards.

5. Experimental analysis

As most engineering components experience complicated wear conditions in practice, a means of testing combined-wear effects seems a logical and necessary process at this time. A test rig was designed and developed by the author to examine coated samples under dynamic wear tests of combined impact abrasion. The impact actions combines shock loading, fatigue, gouging and spalling, whilst the sliding action combines abrasion, adhesion, and fretting wear. Unlike most test equipment described in the literature, this rig uses a reciprocating stylus, the velocity of which is changing continually over the test surface. This type of wear is considered more severe than that of one-directional processes. The results of these tests are provided and discussed elsewhere [38]. Details of the test rig are given in the literature [39].

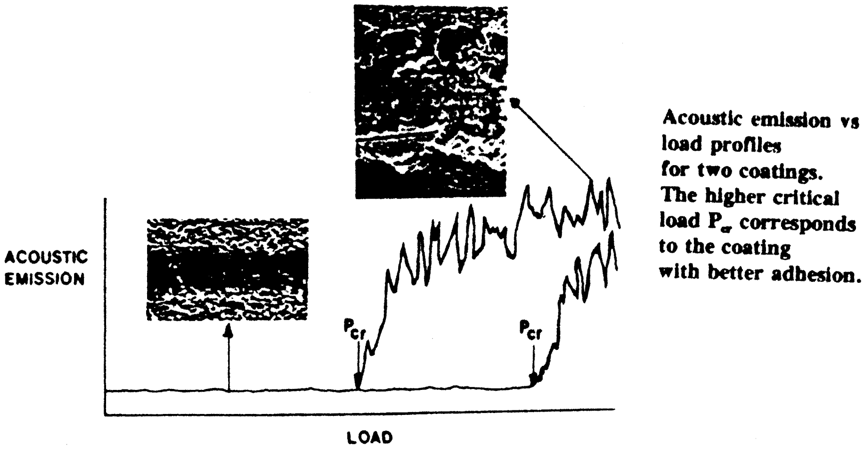

Fig. 8. Schematic diagram of the scratch coating adhesion test using acoustic emission.

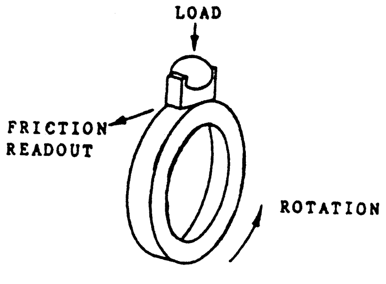

Fig. 9. Block-on-rig test.

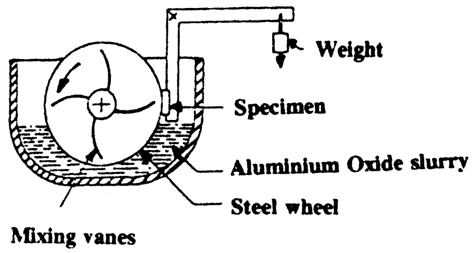

Fig. 11. Alumina-slurry abrasion test apparatus.

6. Conclusions

If wear tests are carried out with a high degree of simulation of the service situation, then the results can be used with considerable confidence in selecting the best wear-resistant coating system. Every wear test, whether for bulk material or coatings, can be complicated by equipment problems, test procedures, sample preparation, inconsistency in abrasive materials and the wrong interpretation, of the test information. Thin coatings require greater care in wear tests in order to avoid penetration, which requires lighter loads and shorter test durations. Surface roughness also influences the tribological performance of a mechanical system. It has also bee shown for thin, hard coatings that the

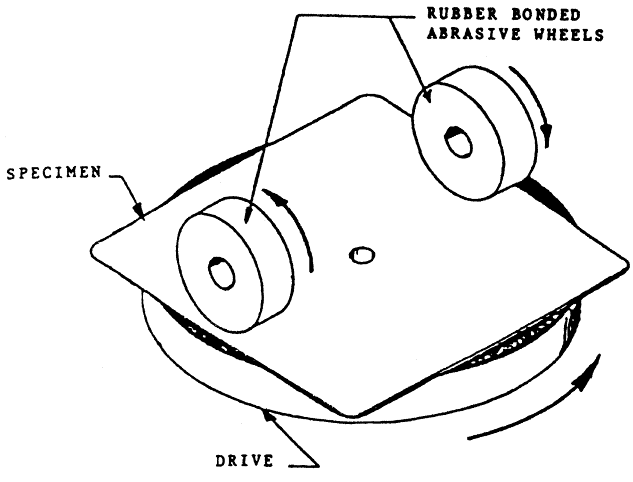

Fig. 10. Schematic diagram of the Taber abrasion apparatus.

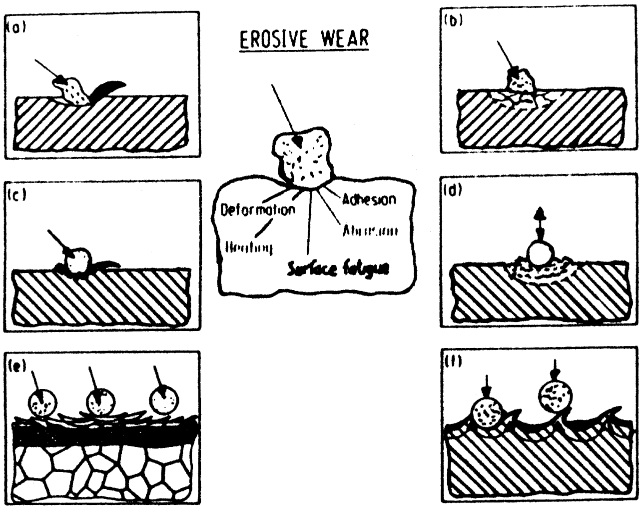

Fig. 12. Erosive wear due to particle impact: (a) microcutting and microploughing; (b) surface cracking; (c) extrusion of material at the exit end of the impact craters; (d) surface and subsurface fatigue cracks due to repeated impacts; (e) formation of thin platelets due to extrusion and forging by repeated impact; (f) formation of platelets by a backward extrusion process.

rougher the surface finish, the lower the coating adhesion, as measured by scratch-testing methods. If significant plastic flow or deformation of materials occur in wear testing, using weight loss may give different results to using wear volume loss. The contours of abrasion or wear scars may make mathematical methods of calculating the wear scar inaccurate. In this event, adhesive tapes used for surface profile or roughness assessment may be used. It is also important to use a simple shape for the abrading tool, such as a hemispherical shape, for the test process. The benefits of applying surface coatings to reduce wear can be measured in many practical ways such as machine efficiency, reduced power requirements and longer running life.

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