Abrasion in wear and manufacturing processes

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Abrasion by hard particles is responsible for wear in many practical situations, but can also be employed usefully in the manufacturing processes of grinding and polishing. This lecture presents a brief overview of abrasion, an historical survey of polishing and then discusses abrasion test methods.

Parole chiave: tribologia, grinding, trattamenti superficiali, processi

INTRODUCTION

Abrasion is responsible for wear in many practical applications; indeed it has been suggested that about 50% of all industrial wear problems can be ascribed to abrasion [1]. Abrasion is also widely used in manufacturing, to produce smoothed and shaped surfaces. Abrasive wear is defined by ASTM as 'wear due to hard particles or hard protuberances forced against and moving along a solid surface' [2]. This lecture examines abrasion processes over a wide range of length scales, and discusses some useful applications of abrasion, as well as exploring our understanding of polishing and grinding from an historical perspective. Some recent developments in laboratory-scale abrasive wear testing are also reviewed.

ABRASIVE WEAR

Abrasive wear occurs in the presence of small hard particles and relative sliding motion. The particles may either be fixed to a counterbody as illustrated in Figure 1(a), which leads to 'two-body abrasion' or be free to slide and roll as in 'three-body abrasion' (shown in Figure 1b). For many purposes it is useful to describe the motion of the particles against the wearing surface, giving a classification into either 'grooving (or sliding) abrasion' or 'rolling abrasion' [3]. Grooving abrasion causes pronounced linear scratches on a metallic surface, whereas rolling abrasion results in multiple indentations and produces a surface with no significant directionality. Abrasive wear is also sometimes classified as either 'low stress', where the abrasive particles remain relatively undamaged, or 'high stress', in which the particles experience extensive fracture.

The rate of wear is influenced by the hardness of the particles. If they have a lower hardness than the surface, then wear will be much lower than with harder particles. For a solid particle to indent a surface by scratching, its indentation hardness must be greater than that of the surface by a factor of at least ~1.2. The commonest natural abrasive is crystalline silica (quartz) which has a hardness (Vickers or Knoop) of ca. 8 to 10 GPa (800 to 1000 kgf mm^{-2}). Since even a hard martensitic steel will have a hardness less than 1.2 times this, it is clear that steels and non-ferrous metals will be especially susceptible to abrasive wear by natural quartz. Materials which contain hard phases, such as cermets and hard-facing alloys, often also contain softer phases. Ceramic materials, however, may be sufficiently hard and homogeneous to resist indentation by most common abrasive particles, and these materials can therefore provide useful wear resistance in the form of bulk materials or coatings. Because they are so hard, even harder abrasive particles such as diamond, silicon carbide or alumina must be used to grind or polish them.

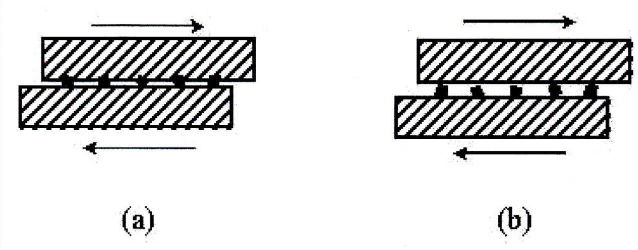

Fig. 1. (a) 'two-body' or grooving abrasion, in which the particles are fixed to one surface; (b) 'three-body' abrasion, in which the particles are free to roll or slide between the surfaces.or damage.

Fig. 1. (a) abrasione 'a due corpi', in cui le particelle sono fissate a una superficie; (b) abrasione 'a tre corpi', in cui le particelle sono libere di rotolare o scivolare fra le superfici.

The fundamental mechanisms responsible for abrasive wear can involve both plastic flow and brittle fracture. Plastic flow can occur alone, but both can sometimes take place together, even in materials like inorganic glasses which are brittle on a large scale. In the simplest models for abrasive wear it is assumed that either plastic flow or brittle fracture provides the dominant wear mechanism.

For 'grooving' abrasion of a ductile material by hard particles an equation identical to the Archard wear equation for (non-abrasive) sliding wear can be derived [4, 5]:

$$Q = KN / H \qquad (1)$$

Here Q is the volume removed from the surface per unit sliding distance, N is the normal load on the contact (assumed to be distributed between the abrasive particles) and H is the indentation hardness of the surface which is being worn. K is dimensionless, and has a value which is typically between 10^{-2} and 10^{-3} for the grooving abrasive wear of metals.

Equation (1) suggests that the volume of material removed by wear should be proportional to the sliding distance, and also to the normal load on the particles; this type of behaviour is often observed. Wear rate also varies inversely with hardness for pure metals, but more complex behaviour is seen for alloys.

Models for abrasive wear by brittle fracture are usually based on the crack patterns associated with a hard, sharp indenter [6]. Lateral cracks which grow towards the surface from beneath the indentation, or from beneath the plastically-formed groove in grooving, are responsible for material

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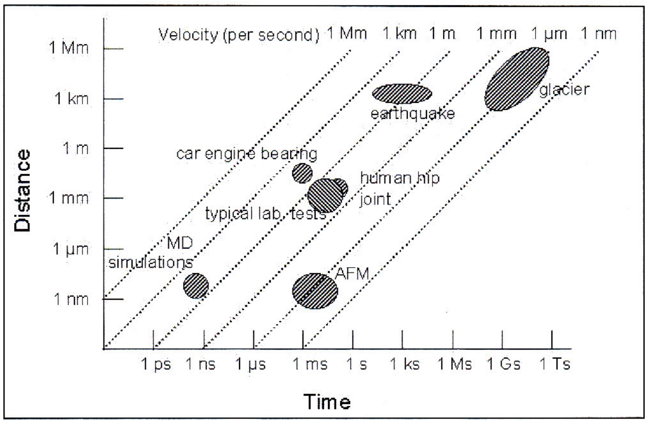

Fig. 2. Chart representing abrasion processes over a wide range of length and time. The distance and time scales are logarithmic; the diagonal lines represent constant sliding velocities.

Fig. 2. Diagramma che rappresenta i processi di abrasione per un range di lunghezza e tempo. Le scale di distanza e tempo sono logaritmiche; le linee diagonali rappresentano velocità di scorrimento costanti.

removal. Both fracture toughness Kc and hardness H play important roles in controlling the occurrence and extent of lateral cracking, and they therefore control the wear rate. Several different models have been proposed, which suggest that the wear rate will be inversely proportional to both H and K_c, raised to powers of about 1/2. They do not take into account the influence of microstructure on wear rate in brittle materials such as bulk polycrystalline ceramics or hard coatings, nor are they applicable to the wear of hard materials by rather softer abrasive particles.
The range of length and time scales involved in mechanical processes can be illustrated on a chart, as in Figure 2. With logarithmic scales on both axes, this allows a very wide range of phenomena to be compared over length scales which extend from interatomic distances (ca. 0.1 nm) to the size of the Earth (ca. 10 Mm), and from the time of one atomic vibration in a solid (ca. 0.1 ps) to a human lifetime (ca. 2.4 Gs). In this diagram, sliding speeds can be plotted as straight lines of slope 1, and areas can be used to show the regimes of lateral distance and time (or sliding speed) over which particular tribological processes occur.
The range of sizes and sliding speeds involved in typical machine components occupies quite a small area in Figure 2: from millimetres to metres, and from millimetres per second to, at most, hundreds of metres per second. Some specific tribological elements are shown in Figure 2: the main bearing of an automobile engine, a synovial joint in the human body (the hip joint), and the range of conditions used in typical laboratory abrasion tests. Neither engine bearings nor human synovial joints should normally experience abrasive wear, but it can be important in both under certain conditions. For example, contamination of oil or grease by hard grit particles can lead to serious abrasion in both plain and rolling element bearings [7,8]. In artificial hip joints, the presence of fine isolated scratches on an otherwise smooth metallic femoral head can cause rapid abrasion of the polymer acetabular cup in which it slides [9].
Abrasion does not only occur on an engineering scale, but also in geological processes. Both earthquakes and glaciers involve sliding over large length scales, but at rather different speeds. The fragments of rock which are produced on the fault plane by an earthquake will undoubtedly lead to large-scale abrasion, but observation and analysis of these phenomena are not straightforward. As a glacier slides it can drag boulders along its path, pressing them against the underlying rock. Typical linear features of plastic grooving are produced and are visible once the glacier has melted away, and there are often also crescent-shaped crack patterns on the rock surface, features associated with fracture [10].
Scanning probe microscopes can be used to study abrasion damage on a much smaller scale, and also to produce it. Scratching by a sharp indenter has been used, for example, to study the behaviour of silicon surfaces on a sub-micrometre scale [11], while recently multiple indenters have been used to 'plough' furrows across solid surfaces and in this way to produce precisely controlled grooves as a novel method of device fabrication [12]. Metallic conductor tracks as fine as 0.15 µm wide have been demonstrated.

GRINDING AND POLISHING IN MANUFACTURING

Grinding and polishing, which both involve controlled abrasion, have been used and developed over many hundreds of years to produce smooth surfaces, either plane or with specific and well-controlled shapes. In order to optimise these processes, a good understanding is needed of the mechanisms involved. Sir Isaac Newton studied the polishing process for glass in connection with the manufacture of lenses and mirrors. He wrote that 'the smaller the particles are, the smaller will be the scratches by which they continually fret and wear away the glass till it be polished; but, be they never so small, they can wear away the glass no otherwise than by grating and scratching it, and breaking the protuberances; and therefore polish it no otherwise than by bringing it to a very fine grain, so that the scratches and frettings of the surface become too small to be visible.' [13] Two hundred years later, Lord Rayleigh concluded that the process of grinding, in which local fracture of the glass could be detected readily with an optical microscope, was distinctly different from polishing. Rayleigh suggested that 'in the process of grinding glass surfaces, the particles of emery, even the finest, appear to act by pitting the glasses, i.e. by breaking

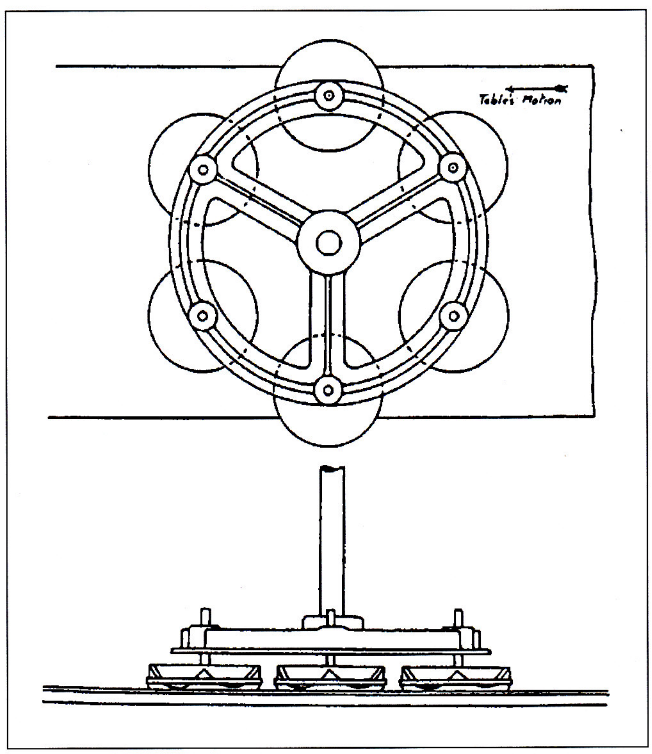

Fig. 3. Plan and side views of a polishing machine, with six independently rotating heads, used to flatten and polish a sheet of glass (from ref. 19).

Fig. 3. Viste in piano e laterale di una macchina lucidatrice/levigatrice con sei teste rotanti indipendenti, utilizzate per livellare e lucidare una lastra di vetro (darif. 19).

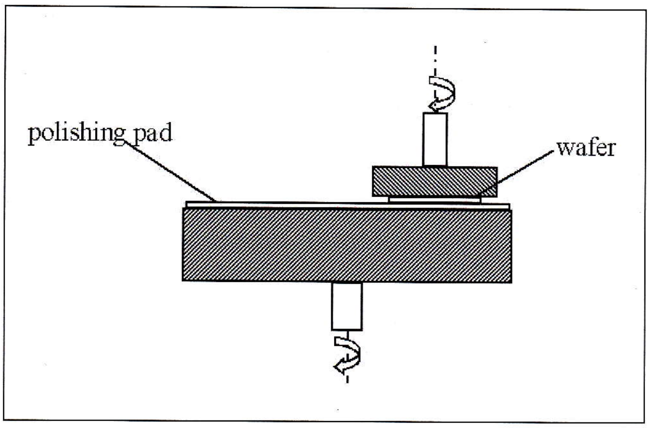

Fig. 4. Schematic diagram showing the process of chemical-mechanical planarization (CMP), as applied to semiconductor wafers.

Fig. 4. Diagramma schematico che rappresenta il processo di planarizzazione chimico-meccanica (CMP), applicata a wafer semiconduttori.

out small fragments...(whereas)...during polishing...it seems probable that no pits are formed by the breaking out of fragments, but that the material is worn away (at first, of course, on the eminences) almost molecularly.' [14]

It is now known that Rayleigh was more correct than Newton: for scratches in glass which are narrower than about 1 μm, brittle fracture does not occur as there is not enough energy available to grow the cracks, and a groove is formed by plastic deformation [15]. However, it is also clear that the polishing of glass involves some tribochemical processes as well, and is not purely mechanical.

A great deal of attention has also been paid to the polishing of metals, with contributions by many distinguished researchers. Rabinowicz [16] and Samuels [17] have both presented good historical reviews, and have critically discussed the evidence for various mechanisms. It is now well-established that the polishing of metals is caused by plastic deformation on a very small scale, and often also involves some additional tribochemical activity. In spite of this, Beilby's proposal [18] that the polishing of metals was associated with the formation of an amorphous surface layer continued to receive support for much of the 20th century.

An early and influential researcher into the grinding and polishing of glass was F W Preston, who was proposed an empirical model for these important manufacturing processes, which he used to optimise the production of flat glass sheets. Before the float glass process was introduced in the 1950s, flat glass was produced by abrasive processing. Rotating grinding and polishing heads were pressed against the glass, as shown in Figure 3. In this machine, six independently rotating heads carried abrasive-charged felt pads. Preston wrote in 1927: 'Consider a piece of glass and a polishing felt pressed together with a pressure of p and moving with a velocity relative to one another of v. Then there is good experimental evidence to believe that the amount of glass polished off in time t is proportional to pvt.' [19]. This relationship is now often referred to in the polishing community as the 'Preston equation', but is exactly the same as equation (1), the Rabinowicz equation for abrasive wear, which was proposed several decades later. Most later models for the lapping and grinding of glass have used the Preston equation as their basis [20]. Abrasive stock removal, surface profiling and finishing are core manufacturing processes for certain glass artefacts, and play a major role, for example, in the production of glass cathode ray tube screens. It has been estimated that more than 30% of the production costs of these items is accounted for by the grinding and polishing processes [21].

Another application of grinding and polishing in which it is essential to predict material removal rate accurately is in the production of mirrors for astronomical telescopes. This was a major reason for Newton's interest in the processes at the end of the seventeenth century. The four 8.2 m diameter mirrors for the VLT (very large telescope) project at the European Southern Observatory at Paranal in Chile provide a modern example. This terrestrial instrument is expected to provide resolution which is even better than the Hubble space telescope. The mirrors are 175 mm thick discs of low-expansion glass-ceramic which are ground and polished under computer control to achieve the required local material removal rate and final dimensions [22]. The final mirror completed in December 1999 has been claimed to be the 'best astronomical mirror in the world', with a precision of form of 8.5 nm over its surface [23].

Chemical mechanical polishing or planarization (CMP) is another precision polishing process for which a detailed model is required. CMP is rapidly becoming a key step in the manufacture of semiconductor devices. It involves a combination of abrasive polishing with chemical etching. Figure 4 shows the mechanical action, which is broadly similar to the early method shown in Figure 3 for polishing flat glass sheets. Current semiconductor devices (2001) have a typical linear dimension (e.g. conductor width) of 0.15 μm: this is predicted to fall to 0.13 μm in 2002, 0.10 μm in 2005 and as low as 70 nm in 2008. The wafer surface must be extremely flat so that such fine features can be reproduced by UV photolithography with very small depth of focus. CMP plays a central role in achieving this flatness, as well as in new processes for producing multilayer circuits, such as the 'damascene' technique.

Much attention has been given to modelling CMP recently, in order to predict and control the material removal rate. Even now, the simple Preston equation is usually used as an empirical starting point [24].

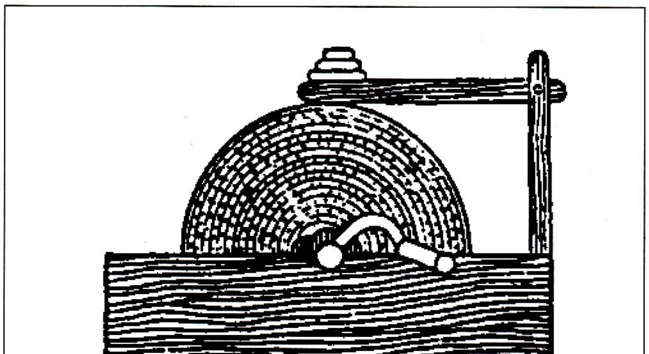

Fig. 5. Grindstone proposed by Lomonsov for use as a laboratory abrasion test in St Petersburg, Russia, in 1752 (from ref. 25).

Fog. 5. Mola proposta per l'impiego in prove di abrasione da Lomonsov a St Petersburg, Russia, nel 1752 (da rif. 25).

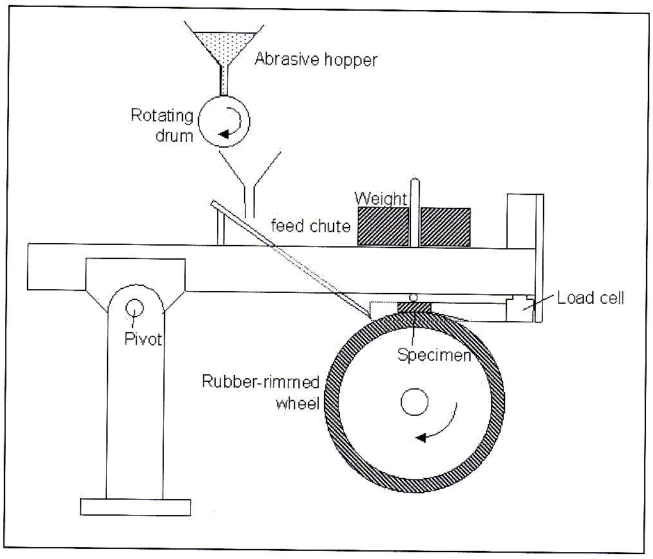

Fig. 6. Apparatus for the dry sand rubber wheel abrasion test (after reference 27).

Fig. 6. Apparato per la prova di usura a secco con mola di gomma e sabbia (da rif. 27).

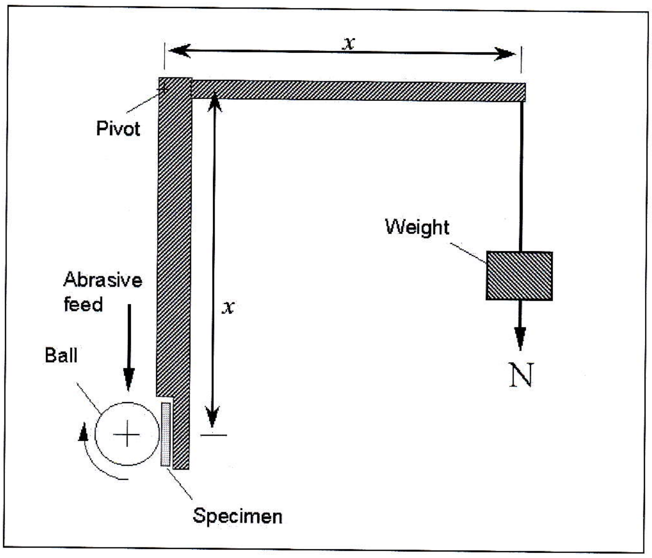

Fig. 7. Apparatus for the micro-scale abrasion test: a steel ball rotates against the surface of the specimen, and abrasive particles are supplied to the contact zone as a suspension in a liquid.

Fig. 7. Apparato per la prova di abrasione su micro-scala: una sfera di acciaio ruota contro la superficie del campione e particelle abrasive vengono immesse nella zona di contatto sotto forma di sospensione in un liquido.

ABRASION TEST METHODS

There are several possible reasons for the experimental study of abrasive wear: to investigate fundamental wear mechanisms; to measure and compare wear rates of different materials under identical conditions; to simulate and optimise related manufacturing processes (such as free-abrasive grinding, lapping and polishing); and as quality assurance tests for coatings and other treated surfaces. Grindstones, as used to produce sharpen knives and other tools, were used for early abrasion testing. Figure 5 shows a grindstone which was described by the Russian chemist and poet Lomonosov in 1752 [25]. He listed it among eight instruments required for a university course in experimental chemistry, stating that students should 'investigate substances, especially metals, by long continued abrasion'.

During the early years of the twentieth century, various different abrasive wear tests were developed. One of the few to be standardised was the dry sand rubber wheel test [26]. In this method a stream of dry silica abrasive particles flows between a flat specimen and a rotating rubber-rimmed wheel. The specimen is pressed against the wheel at a fixed load by a dead weight. This test can be modified to provide better control of the experimental conditions, by feeding the abrasive on to the top of the wheel and by incorporating a load cell to measure the tangential force, as shown in Figure 6. With this apparatus the influence of the test conditions on the abrasion process has been investigated in some detail [27].

Recently there has been considerable interest in the 'micro-scale abrasion' or 'ball-cratering' test. Its history has been reviewed by Rutherford and Hutchings [28]. In this method a sphere (often a hard steel ball with a diameter of about 25 mm) or a spherically-crowned disc rotates under a constant load against the surface of the specimen. The abrasive particles are supplied directly to the contact region, suspended in a liquid. Unlike the rubber wheel test, the method results in a wear scar with a shape which conforms accurately to that of the ball and therefore has a well-defined, spherical geometry. This allows the amount of wear to be determined accurately from simple optical measurement of the wear scar, which is relatively large, typically 1 to 3 mm in diameter. The worn region is much shallower than in conventional abrasive wear tests, typically 3 to 30 µm deep. If the specimen is coated, the method can also provide wear measurements for both coating and substrate material. For the test to yield useful results, the conditions must be closely controlled; the data provided from the test must also be analysed in appropriate ways. Significant advances in both these aspects have been made recently [29, 30]. Apparatus in which the ball is driven by a motor and the sample is loaded against it by a dead weight is commercially available and is shown in Figure 7.

By varying the load and the concentration of abrasive particles in the suspension, the particle motion can be changed from two-body, sliding abrasion to three-body rolling abrasion [31]. Under the conditions used for abrasion testing the hydrodynamic film produced by the motion of the sphere in the liquid is much thinner than the size of the abrasive particles and the load is supported almost completely by the particles.

For some applications the micro-scale abrasion test has significant advantages over more conventional methods of abrasion testing. It involves a very shallow depth of penetration, and also tests a small area of the sample. It can therefore be applied to specimens, and for purposes, where conventional tests could not be used, and is attractive as an effectively non-destructive quality assurance method for coatings. The method offers potential for development into a standard tribological test. A modified version, in which the ball is replaced by a cylindrical disc, has also been proposed which can be used to compare the abrasivity of different particles [32].

CONCLUSIONS

Abrasion is responsible for many practical instances of wear. It is also usefully employed in the manufacturing processes of grinding, lapping and polishing. A firm understanding of the underlying tribological principles is required to control abrasive wear, and also to realise the potential of these manufacturing processes. There are still many challenges in these areas. The Preston/Rabinowicz equation, which provides a starting point for modelling abrasion processes, remains a very simple and largely empirically-based relationship. It is still not possible to provide a better model based on a description of the deformation and removal of material by the action of individual particles, and more accurate models usually just involve more complex empirical functions. There are particular problems in the effective description of particle properties, especially shape, and also in characterising the material at the surface during steady-state abrasion. Both tribochemical processes and chemical influences on the fine-scale fracture of brittle materials are undoubtedly important in chemical-mechanical polishing and in the grinding of glasses; these too cannot readily be modelled from a fundamental basis. A role is likely to remain for many years for the careful experimental investigation of abrasion processes, and the further development of well-controlled experimental methods will play a vital part in this.

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A B S T R A C T

ABRASIONE NEI PROCESSI DI USURA E PRODUZIONE

L'abrasione è la principale responsabile dell'usura in molte applicazioni pratiche; si è stimato che le possono essere attribuiti almeno il 50% di tutti i problemi di usura a livello industriale.
L'abrasione è anche ampiamente sfruttata nella realizzazione di oggetti per ottenere superfici lisce o sagomate.
L'usura abrasiva viene definita da ASTM come usura provocata da particelle o protuberanze dure spinte contro e striscianti sulla superficie di un solido ("wear due to hard particles or hard protuberances forced against and moving along a solid surface"). Questa memoria esamina i processi di abrasione su un ampio range dimensionale e discute alcune utili applicazioni dell'abrasione, soffermandosi sull'esplorazione e comprensione delle tecniche di lucidatura e smerigliatura secondo una prospettiva storica. E' inoltre presentata una rassegna dei più recenti sviluppi delle tecniche di laboratorio utilizzate per prove sperimentali sull'abrasione.