WEAR PROCESSES IN MANUFACTURING

SHYAM BAHADUR AND JOHN H. MAGEE, EDITORS

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Foreword

This publication, *Wear Processes in Manufacturing,* contains papers presented at the symposium of the same name held in Atlanta, Georgia on May 6, 1998. This symposium was also held in conjunction with the May 7–8 standards development meetings of Committee G-2 on Wear and Erosion, the symposium sponsor. The symposium was chaired by Professor Shyam Bahadur, Iowa State University; John H. Magee, Carpenter Technology, served as co-chairman. They also both served as STP editors of this publication.

Overview

The importance of tribological phenomena in engineering has long been recognized. The evidence for this lies in the extensive studies on tool wear performed over many decades. The same is the case with studies related to the friction and lubrication in deformation processing as evidenced by a number of conferences and related publications. In spite of this, the interaction between the tribologists and manufacturing researchers has not been great. The objective of this symposium was to provide a forum for these researchers for a mutually beneficial interaction.

There are many manufacturing processes in which wear and friction play dominant roles. In the present era of increased productivity, processing at high speeds contributes to the rapid wear of tools. The current emphasis on quality also demands tighter tolerances, which requires, among other things, the use of tools with less wear. In forming processes the wear of tools and dies occurs because of the stresses needed to deform material and the difficulty of lubrication in high contact stress situations. In processes performed at high temperatures, lubrication is a serious problem because of the lack of suitable lubricants and the difficulty of maintaining a lubricant film between the contacting surfaces. The absence of good lubrication results in adverse consequences such as rapid tool wear, surface damage such as galling, and increased power requirement. The recognition of tool wear as the limiting factor for high speed machining and as the factor contributing to the impairment of surface integrity has caused tool companies to invest heavily in the development of wear-resistant tools for machining. There are processes such as grinding which use two-body abrasion mechanism for material removal. Similarly, superfinishing operations use three-body abrasion for achieving the desired surface finish. Finally, minimizing erosive wear damage on critical components is often the key to a successful manufacturing process.

The collection of papers published in this volume may be grouped into the following categories. These categories are: abrasion in ceramic grinding, wear of cutting tools, friction in vibratory conveyers, and erosion in manufacturing. A brief summary of the papers in each category is provided below.

Abrasion in Ceramic Grinding

There were two papers presented in this category. One of the papers presented the two-body belt abrasion test for assessing quantitatively the grindability of new ceramic compositions. The test establishes a belt grindability index as the measure of grinding ease reported using the units of wear factor. A project funded by the US Department of Energy demonstrated that this test provided repeatable results which correlated well with the actual grinding behavior. The test is similar to one of the several abrasion testing geometries mentioned in the ASTM Standard G-132.

Using a similar test setup, another paper investigated the effect of variables such as belt speed, load, cutting fluid, and specimen rotation on the material removal rates in grinding. The cutting fluids investigated were mineral oil, water-glycol mixture, and biodegradable soybean oil. This paper presented the results of surface damage in grinding under different conditions and emphasized the detrimental effect of temperature rise in grinding.

Wear of Cutting Tools

In this category, a maximum number of papers were presented. One of the papers presented the tool life study for face milling inserts under various cutting conditions, with and without coolant. The material used for machining was 4140 steel and the milling inserts were C5 grade. One of the main conclusions of the study was that coolant does not always enhance the tool life. Optical and scanning electron micrographs showing the tool wear were presented and the wear mechanisms were identified.

Another paper presented tool wear results from the machining of austenitic 303 and 304 stainless steels with varying carbon, nitrogen, and copper contents. It was demonstrated that tool life increased by increasing the copper and nickel contents and by decreasing the carbon and nitrogen contents. The results of this study are important from a practical standpoint because machining of austenitic stainless steels poses special problems particularly in regards to early tool failure.

There are three papers in this section that deal with the effect of coatings and/or other treatments on cutting tools. One of these investigated the wear behavior of cemented carbide and TiC-coated cemented carbide tools in turning operations under different cutting conditions. The data from these tests together with the data from literature is used in constructing the wear maps. The latter are drawn with cutting speed and feed rate as the machining parameters. This kind of information is useful in selecting the cutting conditions for extended tool life. Another paper investigated the machining of a high strength steel alloy with grooved inserts, coated with plasma and chemical vapor deposition (PVD and CVD) processes, for different combinations of cutting speeds and feeds. Apart from the generation of machining data, the focus in this study was on the wear mechanisms, failure modes and tool lives of the inserts. The authors found that surface finish improved with a mixed carbide grade of insert (WC + TaC), and multilayered CVD coating produced a better surface finish. The third paper dealt with the investigation of coatings, substrates and substrate treatments that would increase the life of cemented carbide slitter knives used to slit magnetic media from wide rolls into narrow product form. The treatments tried in this work were ion implantation, implantation of boron, titanium nitride PVD and CVD coatings, and diamond-like carbon (DLC) coating. It was concluded that the coatings failed because of inadequate adhesion between the coating and the substrate. The plasma enhanced CVD titanium nitride coating gave good results but it was not considered economical.

A paper in this section deals with the tribology of wood machining such as tool wear, tool-wood frictional interactions, and wood surface characterization. The studies included the identification of friction and wear mechanisms and modeling, wear performance of surface-engineered tool materials, friction-induced vibration and cutting efficiency, and the influence of wear and friction on the finished surface. Various wood species were investigated from soft pine to hard maple and the results revealed significant variations in the coefficient of friction, an important parameter when modeling chip formation.

Friction in Vibratory Conveyor

In this paper, the problem of feeding connectors using vibratory conveyors to machines that assemble input/outpot (I/O) pins to the metallized ceramic substrate, as used in the computer industry, was studied. The motion of a single I/O pin on an in-phase, linearly oscillating conveyor using the classical model of friction was modeled and the results were compared with those from the experimental observations. The implications of these theoretical and experimental results are discussed in terms of the practical application of in-phase vibratory conveyors in manufacturing.

Erosion in Manufacturing

One of the papers studied the wear of pipe materials as used in a pilot plant which transports DRI (Direct-Reduced-Iron) pellets at high temperatures in the manufacture of steel. Included in this study were also the new candidate materials for pipes. The materials tested were 304 stainless steel, high chromium white castings, hard coatings based on high chromium-high carbon alloys, cobalt alloys and aluminum oxide. The samples from both the pilot plant and laboratory showed that erosion was the dominant mechanism of wear. The next paper introduced an electrochemical technique to assess erosion in aqueous and other systems that involve an electrolyte as the erosion fluid. The potential and the usefulness of this technique to measure slurry erosion, fretting corrosion and cavitation were also discussed.

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Abrasion in Ceramic Grinding

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USE OF A TWO-BODY BELT ABRASION TEST TO MEASURE THE GRINDABILITY OF ADVANCED CERAMIC MATERIALS

REFERENCE: Blau, P.J. and Zanoria, E.S., **"Use of a Two-Body Abrasion Test to Measure the Grindability of Advanced Ceramic Materials,"** *Wear Processes in Manufacturing, ASTM STP 1362,* S. Bahadur, J. Magee Eds., American Society for Testing and Materials, 1999.

ABSTRACT: The same properties that make engineering materials attractive for use on severe thermal and mechanical environments (e.g., high hardness, high temperature strength, high fracture toughness) generally tend to make those materials difficult to grind and finish. In the mid-1990's, a belt abrasion test was developed under subcontract to Oak Ridge National Laboratory to help to assess the grindability of structural ceramic materials. The procedure involves applying a 10 N normal force to the end face of a 3 x 4 mm cross-section test bar for 30 seconds which is rubbed against a wet, 220 grit diamond belt moving at 10 m/s. By measuring the change in the bar length after at least six 30-second tests, a belt grindability index is computed and expressed using the same units as a traditional wear factor (i.e., mm^3/N-m). The test has shown an excellent capability to discriminate not only between ceramics of different basic compositions, e.g. Al_2O_3, SiC, and Si_3N_4, but also between different lots of the same basic ceramic. Test-to-test variability decreases if the belt is worn in on the material of interest. The surface roughness of the abraded ends of the test specimens does not correlate directly with the belt grindability index, but instead reflects another attribute of grindability; namely, the ability of a material to abrade smoothly without leaving excessive rough and pitted areas.

KEYWORDS: abrasion, abrasive wear, abrasive belts, ceramics, grinding, wear of ceramics

Structural materials, such as superalloys, intermetallic alloys and engineering ceramics, have been developed to achieve high hardness, high temperature strength, and high fracture toughness. However, these strong materials also tend to be difficult to grind and finish. In the 1990's, the U.S. Department of Energy supported a series of projects to help reduce the cost of machining advanced ceramics. One of these projects resulted in the development of a two-body belt abrasion test for quickly and quantitatively assessing the grindability of new ceramic compositions. Several publications describe this test method and the rationale behind its development [1-4]. This test was developed with a focus on simplicity, repeatability, ease of operator training, acquisition of rapid results, reduction of subjectivity, and the correlation of results with grinding behavior. It is similar to one

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of the several abrasion testing geometries mentioned in ASTM Standard Test Method for Pin Abrasion Testing (G-132-95) except that the path of the specimen repeats over the same portion of the belt instead of being constantly exposed to new abrasive. The belt abrasion test and its ability to distinguish between ceramic materials will be described in this paper.

Grindability means different things to different people. To some, it implies the relative ease by which stock can be removed from the surface of a particular workpiece material. To others, it refers to the ability of a material to be ground at high rates of material removal without adversely affecting the surface quality or ultimate function of the part. In the present work we will use the former definition. More formally stated:

> **grindability**, n. - the relative ease by which material can be mechanically removed from the surface of a body by a relatively-moving, abrasive counterface applied to it under controlled conditions.

Grindability can be qualitatively assessed (e.g., "material A grinds more easily than material B"), or quantitatively assessed using a numerical value of some kind. Quantitative assessments require measurement of material removal under well-specified abrasive machining conditions.

There are many kinds of grinding (surface grinding, cylindrical grinding, belt grinding, creep-feed grinding, etc.), so it is entirely possible that any particular measure of a material's grindability may not correlate in the same way to all the different grinding processes. Thus, once a measure of grindability has been established, the user of the test must establish its correlation with the specific grinding process or processes of interest. Obviously, the closer the grindability test conditions approach of the grinding process of interest, the greater the likelihood that the grindability test results will be directly applicable. In the present case, we worked to develop a repeatable and quantitative grindability test which could be quickly, easily, and cost-effectively applied to small specimens of material with unknown grinding characteristics so as to provide initial guidance for selecting grinding parameters for that material. Structural ceramic materials are particularly difficult and costly to grind, and therefore were used as the focus of this work.

Test Method

Early in the development of the grindability concept, it was decided to use a belt abrasion test since it offered a cost-effective means to remove material compared with using a grinding wheel-based method. Grinding wheel-based methods have uncertainties arising from wheel-to-wheel variations as well as in the repeatability of dressing and truing operations. Grinding wheels can also develop lobes with prolonged use, and this introduces additional variations. Belts can be manufactured with extremely uniform dispersions of grits, and their low cost, relative to grinding wheels, means that a new belt can be used for each test series. This was particularly important in the case of ceramic grinding where diamond is usually the preferred abrasive.

The test method used a 220 grit diamond abrasive belt. This particular type of abrasive belt was seamless, which eliminated specimen bouncing over the typical end-to-end belt joint. The test specimen's cross-sectional dimensions were those of the "Type B specimen" in the ASTM Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature (C-1161). This allowed the same lot of ceramic specimens to be tested for both flexure strength and grindability. Even broken flexure specimens provided sufficient material for the grindability testing since only the end face, not the center section, can be used.

The basic test geometry is shown in Fig. 1, and an exterior view of the testing machine is shown in Fig. 2. The 3.0 x 4.0 mm face of the test specimen was loaded against the belt (4.0 mm face parallel to the belt motion) under an 11.0 N normal force, calibrated using a compression load cell under the specimen tip with the belt motor turned

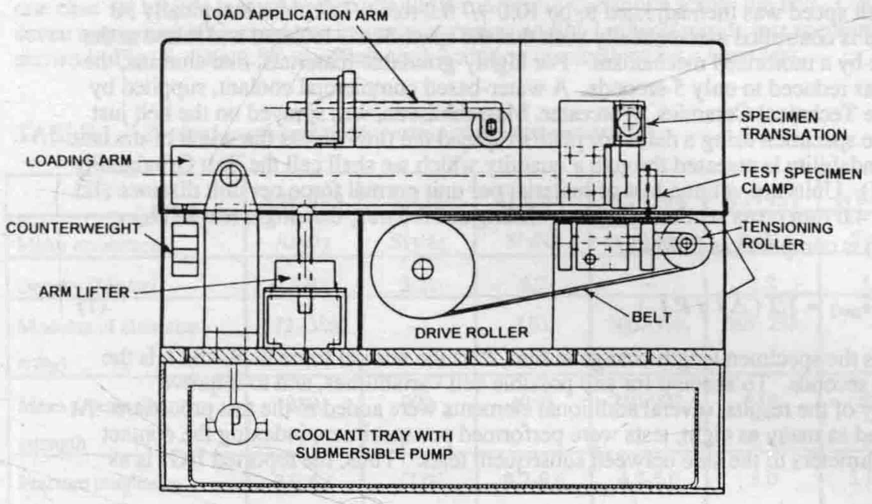

FIG. 1 — *Diagram of the two-body abrasive wear testing machine used to assess the grindability of rectangular ceramic test bars.*

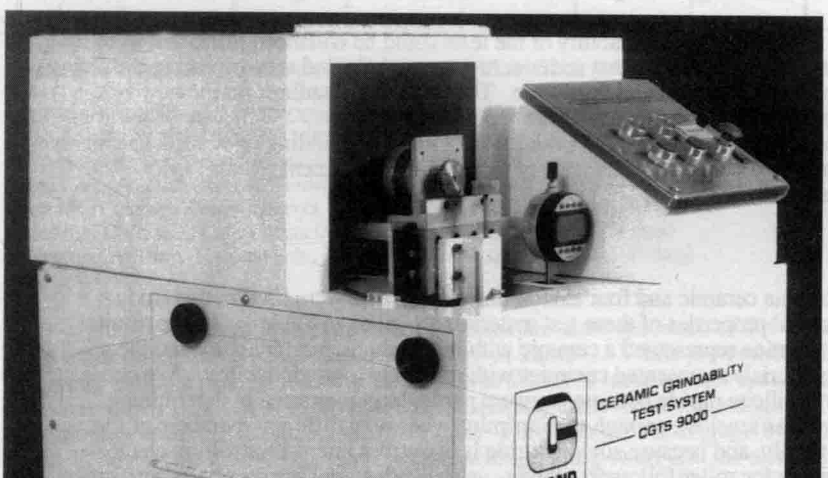

FIG. 2 — *Grindability testing machine used in this investigation. Cycle controls are located on the panel at the upper right. The specimen is mounted in the holder near the center of the photograph and to the left of the dial of the electronic displacement gauge. A motor above the specimen holder moves the specimen to a new position after each test .*

off. The belt speed was then adjusted to be 10.0 +/- 0.2 m/s. Test time is typically 30 seconds and is controlled automatically such that the specimen is lowered and raised at the proper time by a motorized mechanism. For highly-grindable materials, like alumina, the test time was reduced to only 5 seconds. A water-based commercial coolant, supplied by Chand Kare Technical Ceramics, Worcester, Massachusetts, was sprayed on the belt just ahead of the specimen using a deflector plate to spread the flow across the width of the belt.

Grindability is assessed through a quantity which we shall call the Belt Grindability Index (BGI). Units are volume loss of material per unit normal force per unit distance slid. For a 3.0 x 4.0 mm cross section specimen sliding at 10.0 m/s, the single test $\mathbf{BGI}_{n=1}$ (mm^3/N-m) is computed as follows:

$$\mathbf{BGI}_{n=1} = 1.2\ (\Delta l\ /\ P\ t\ ) \qquad (1)$$

where D l is the specimen length change in mm, P is the normal force in N, and t is the test time in seconds. To account for any possible belt variabilities, and to improve repeatability of the results, several additional elements were added to the test procedure. At least six, and as many as eight, tests were performed per specimen, indexing the contact several millimeters to the side between subsequent tests. Thus, the reported **BGI** is as follows:

$$\mathbf{BGI} = 1.2\ (\Delta L\ /\ N\ P\ t\ ) \qquad (2)$$

where ΔL is the total length change after N tests, each one having a duration of t seconds.

It was found that the repeatability of the tests could be enhanced if the belt were first worn-in by running one complete test series across a new belt, and then repeating the series on the same locations a second and third time. The first set of readings on the new belt were therefore discarded, and the latter were reported here.

Surface roughness data used to evaluate the effects of grinding on the test specimen surface were obtained using a mechanical stylus profiling instrument (Rank Taylor Hobson, Talysurf 10, Leicester, UK) with a 2.5 µm tip radius.

Materials

One alumina ceramic and four silicon nitride ceramics were used in this study. Typical mechanical properties of these test materials are given in Table 1. As the results will show, the alumina represented a ceramic with relatively high grindability and the silicon nitride materials represented ceramics with relatively low grindability. We chose several grades of silicon nitride because we were particularly interested in determining whether the test was sensitive enough to discriminate between different members of the same ceramic family, and because silicon nitride is of current interest for rolling element bearings as well as for roller followers, valves, valve guides, fuel injector parts, and other components in heavy-duty diesel engines.

Results and Discussion

Considerations Related to the Test Method Itself— The ability of an abrasive wear test to discriminate between the wear performance of different materials is reflected by the repeatability of results obtained on the same specimen material. In order to account for possible variations in the characteristics of a given abrasive belt from one location to another, normal procedures call for using the total change in specimen length divided by the total sliding distance after at least six or more, side-by-side 30-second runs. However, in one case we looked instead at the individual run-to-run variations across the belt. Data for seven sequential 30-second test increments (using an SN-1 silicon nitride test specimen) are shown in Fig. 3. The 4.8% coefficient of variation is excellent for a wear test.

TABLE 1 —*Typical mechanical properties of the test materials**

	AD-995	**SN-1**	**GS-44**	**NT-154**	**NT-451**	**NT-551**
Major constituents	Al_2O_3	Si_3N_4	Si_3N_4	Si-Al-O-N	Si_3N_4	Si_3N_4
Density (Mg/m^3)	3.9	3.21	3.2	–	3.2	3.25
Modulus of elasticity (GPa)	372.-386.	—	310.	300.-310.	285.-295.	—
Mean 4-point flexure strength	380.	900.	1050.	750-907.	888.	994.
Fracture toughness (MPa√m)	3.0-4.5	7.0	8.2-8.6	4.7-5.0	5.0	5.5-6.0
Vickers indentation hardness at 98 N load (GPa)	14.7-15.0	14.0	14.6-15.8	—	19.8	—

* Sources of data:
Database on Properties of Ceramics, ORNL Report ORNL/M-3155, Oak Ridge National Laboratory (some NT-451 data)
Life Prediction Methodology for Ceramic Components of Advanced Heat Engines (Vol. 1), ORNL Report ORNL/Sub/89-SC674/1/V1 (NT-154 data)
A. Wereszczak, Oak Ridge National Lab., personal communication (NT-551 data)
Coors Ceramics Data Sheet on Ceramic Properties, Golden CO (AD 995 data).
Japan Fine Ceramics Center, Nagoya, SN-1 properties brochure (SN-1 data)
Allied Signal Ceramic Components Division, Torrance CA (some GS-44 data)
K. Breder, Oak Ridge National Lab., personal communication (some GS-44 data)

We also conducted an experiment in which the same specimen of SN-1 was used three times on the same belt. Results are shown in Table 2. While pre-conditioning the belt using multiple runs on the same position was shown to increase the repeatability of the measurement, it is not clear that one could consistently achieve the same degree of belt pre-conditioning with different specimen materials. Furthermore, the average BGI rises by about 15% with the first re-use. Belt loading with grinding swarf and the effects of the test material's hardness on the blunting of fresh cutting points would add other factors to what the test is actually measuring. In other words, a hard material of low abrasive wear rate would affect the belt pre-conditioning differently than a soft material. Therefore, adoption of pre-conditioning procedures might improve repeatability for a given material but it might also alter the relative grindability number from one material to another by including factors other than grindability alone. These issues remain for further study and test method refinement.

Test method ASTM G-132-95 recommends that the test specimen be moved continually across fresh, unused abrasive material during the tests. In contrast to this, the present method does not traverse the specimen until the test increment is completed (typically, 30 s; equivalent to 394 passes). Since actual production operations like surface

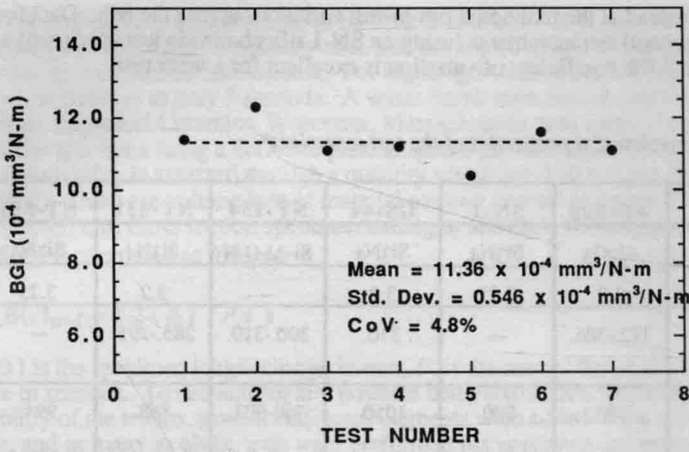

FIG. 3 — *BGI values calculated for seven sequential runs conducted several millimeters apart on the same belt. There appears to be no systematic variation in BGI with lateral position across the belt.*

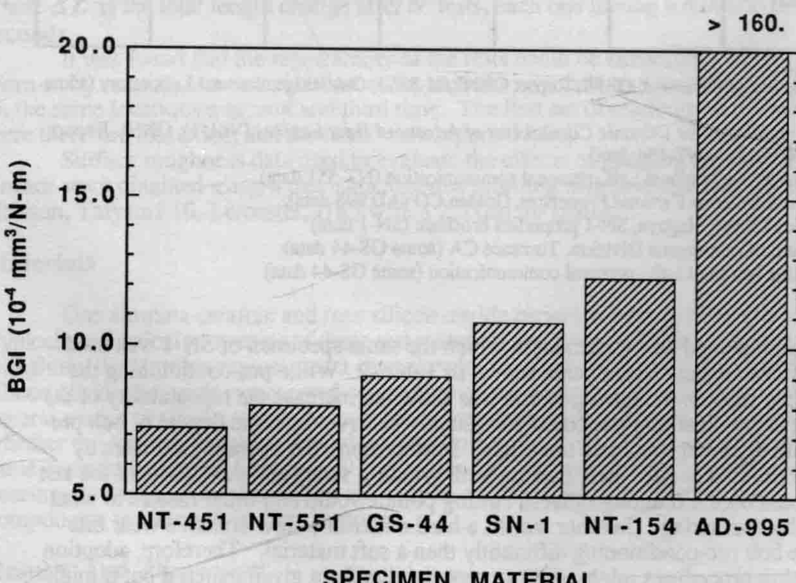

FIG. 4 — *BGI values for five silicon nitride materials and alumina.*