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Ceramic Machining: Assessment of Current Practice and Research Needs in the United States

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[1]At Boulder, CO 80303.
[2]Some elements at Boulder, CO 80303.

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Ceramic Machining: Assessment of Current Practice and Research Needs in the United States

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EXECUTIVE SUMMARY

Advanced structural ceramics, such as silicon nitride, are attractive for many advanced applications due to their high strength at elevated temperatures, resistance to chemical degradation, wear resistance, and low density. Despite these advantages, there are considerable impediments to the introduction of advanced ceramics. With current technology, fabrication costs are high, compared to other materials, and component reliability is uncertain. The cost of machining can be as high as 90 percent of the total cost of some high precision components; and damage produced during machining can be detrimental to the performance and can produce premature failure.

A study was conducted to assess the current state-of-the-art in the machining of advanced ceramics and to identify research areas which could lead to significant improvements. In conducting the assessment, an extensive literature search was carried out, visits and discussions were held with industrial companies interested in ceramic machining, a telephone survey was conducted on ceramic machining shops, a research-in-progress database was consulted, individuals were invited to visit NIST and discuss different aspects of ceramic machining, and a workshop was held at NIST in September 1990, to identify specific industrial needs in ceramic machining.

The results of the assessment with regards to the needs in the machining and production of parts made from advanced ceramics is summarized as follows:

Reduction in Cost: The cost associated with machining is a major ontributor to the overall high cost of advanced ceramic components. Although, significant costs are also associated with raw materials, processing, and quality control, the primary impediment to the introduction of most advanced ceramic parts into the market place is the high cost of machining. Therefore, research efforts should be focused on developing methods and procedures for cost-effective machining of ceramic components.

Optimization Data: With the exception of a few publications, there is little machining data available for advanced ceramics. There is a critical need for data to be used for the purpose of cost estimating, component design optimization, and selection of machining parameters. In the absence of such information, the operator takes the most conservative route, i.e., slow removal rates and a concomitant increase in the cost of machining.

Rapid Machining Methods: Advanced ceramic materials are difficult to machine with most conventional methods, with the exception of abrasive machining utilizing diamond. Abrasive machining of advanced ceramics, however, is slow compared to metals. Innovative techniques are needed to increase the rate of material removal. But it is extremely important to recognize that an increase in machining rate may lead to an unacceptable level of surface and subsurface damage in the finished part. Therefore, the development of rapid machining methods must be accompanied by damage assessment and control.

Damage Assessment: Performance and reliability of ceramic components are strongly influenced by damage introduced during machining. Surface finish and machining damage are especially sensitive to small changes in machining conditions. There is a need for reliable and fast in situ and post-machining damage assessment techniques. Development of sensors for real-time

measurement of surface finish and damage assessment has the potential to increase manufacturing productivity significantly.

Automation: Present ceramic machining practice is oriented towards labor-intensive small-scale production and heavy reliance on operator skill. If advanced ceramics are to be extensively used, automated production techniques are needed to make millions of components. This requires additional research to develop new machine tools, special part-handling techniques, and on-line inspection to control machining damage, surface finish and part dimensions.

In order to take advantage of the unique properties of advanced ceramics and facilitate their introduction into the market place, a coordinated research program is needed. The overall objectives of this program should be to develop an advanced technology for machining of advanced ceramics. Based on our discussions with industry and the analysis of published literature, we recommend a broad research program, consisting of the following areas:

- Optimization of the Grinding Process
- Chemically Assisted Machining
- Grinding Wheels for Machining of Ceramics
- Direct Damage Assessment Techniques
- NDE Techniques for Machining Damage Evaluation
- Sensors for Real-Time Surface Finish and Damage Assessment
- Standard Reference Materials
- Post-Machining Treatments for Damage Control
- Innovative High-Strength Machinable Ceramics
- Automated Systems for Large-Volume Production

The ultimate goal of this program is to further the utilization of advanced structural ceramics in industrial applications by increasing the cost-effectiveness of ceramic components. It is recommended that these projects be carried out jointly by government laboratories and industry to facilitate technology transfer, and that all research activities funded by the government be coordinated to minimize the possibility of duplication of effort.

ACKNOWLEDGEMENTS

Many individuals representing different industrial companies and academic institutions were contacted for information during the course of this assessment. We would like to acknowledge their willingness to provide the requested information and thank them for their encouragement. In addition to the individuals who were formally contacted, many others provided information in informal conversations, which increased our awareness of the problems in ceramic machining. Particularly, the cooperation of the United States Advanced Ceramics Association is appreciated.

We are grateful to the NIST Ceramics Division and the Precision Engineering Division Staff, for their support and encouragement. We would like to give a special thanks to S. M. Hsu, S. J. Dapkunas, C. Evans, and J. Carpenter.

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COVER PHOTOGRAPH

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1. INTRODUCTION

Advanced structural ceramics, such as silicon nitride, are attractive for many advanced applications due to their high strength at elevated temperatures, resistance to chemical degradation, wear resistance, and low density. These materials are currently being used, or proposed for, a wide variety of applications; some are listed in Table 1. Electronics, telecommunications, optical systems, sensors, catalysts, bone replacements, heat exchangers, heat engines, and material processing equipments are all either benefiting from, or projected to benefit from, advanced ceramic materials [Katz 1989].

The advanced ceramics industry in the United States consists of approximately 100 different companies with sales equal to about $14 billion per year and growing at a rate of about 8 percent per year [Eckert and Weatherall 1990]. The contribution of advanced ceramics to the ceramic industry is approximately 14.1 percent, based on sales, as shown in Table 2. About 70 percent of advanced ceramics are used for electronic applications, 18 percent for structural applications and 12 percent for coatings. The use of structural ceramics is expected to grow at a rate of 4 percent per year, unless there is significant penetration into the automobile market. Then, it is estimated that the market for structural ceramics would double every 5 to 7 years, and increase to $5 billion by the year 2000 [Office of Technology Assessment 1988]. However, this estimate carries the caveat that the following challenges be addressed:

- The technical feasibility of replacing metal engine parts with ceramics must be demonstrated;
- Ceramic material and component reliability must be improved so that more accurate design predictions can be made;
- Improved nondestructive evaluation techniques must be developed; and
- Fabrication costs must be reduced.

Considerable progress has been made in meeting the first challenge. A variety of engine wear parts (valves, liners, cams, rings, and bearings) have been fabricated from ceramic materials and, successfully implemented in test engines. Advances are also being made in improving the reliability of advanced ceramics. In addition, within the past 20 years a large effort has been devoted to the development and evaluation of nondestructive evaluation (NDE) techniques for ceramics. The basic problem has been that quality control of ceramics requires surface flaw detection in the 10 μm range. This is an order of magnitude below that which is commonly used for metals. Accordingly, a variety of new approaches have been developed. Although none of these are routinely used at present, there appear to be no serious barriers to their use.

Undoubtedly, one of the main barriers to the use of advanced ceramics as mechanical components is the high cost of machining when compared with currently used metal alloys. This conclusion was confirmed at the Ceramic Maching Workshop held at the National Institute of Standards and Technology in September 1990. See Appendix A.

The objective of the workshop was to identify the potential for cooperative research between NIST and the ceramics industry. Representatives from the structural and electronic ceramics industry,

Table 1. CURRENT AND FUTURE MARKETS FOR ADVANCED CERAMICS
[Wortendyke 1989]

• **Aerospace**

- advanced electronics
- bearings
- combustors
- fuel cells
- fuel systems and valves
- high temperature auxiliary power units, low weight components for rotary equipment such as starters
- seals
- structures
- thermal protection systems
- turbine engine components

• **Automotive**

- advanced reciprocating engines
- advanced rotary regenerators
- catalytic converters
- drivetrain components
- electronic substrates
- fixed boundary recuperators
- fuel injector components
- low heat rejection diesels
- turbines
- turbocharger rotors
- valves and valve seats
- waterpump seals

• **Bioceramics**

- artificial teeth, bones and joints
- heart valves

• **Chemical Process Industry**

- catalysts and igniters
- mechanical seals
- nozzles
- radiant tubes and burners
- recuperators
- reformers
- refractories
- valve components

• **Defense**

- armor
- bearings
- engine combustor sections
- gun barrel liners
- improved armor
- optics
- rocket nozzles
- SDI (optical/heat transfer properties)
- submarine shaft seals
- tank power trains

• **Electric Power Generation**

- bearings
- ceramic gas turbines
- cogeneration
- filters (gas clean-up)
- fuel cells (solid oxide)
- high temperature components
- reactor pump seals

• **Electronics**

- advanced multilayer integrated packages
- electro-optic packaging
- multilayer capacitors
- optical wave guides
- pressure and gas sensors
- semiconductor packages
- substrates
- superconductors

• **Environmental**

- advanced components and systems for environmentally harsh processes
- filters and scrubbers
- incinerator liners and after-burners
- radiant burners and boilers
- wastewater treatment

• **Metals Processing**

- boats
- burners
- crucibles and ladles
- cutting tools and dies
- insulation
- molten metal filters
- seeded gel abrasives for metal/ceramic finishing

• **Oil Industry**

- bearings
- blast sleeves
- flow control valves
- pumps
- refinery heaters

as well as users and machine tool manufacturers were invited to this meeting and were given the opportunity to present their views and perspectives on the need for research in ceramic machining. Twenty-one individuals from industry participated. The United States Advanced Ceramic Association (USACA) was also represented. Both NIST personnel and industry attendees presented research results pertinent to ceramic machining. The following list of research needs were identified by the industrial speakers present:

- Reduction in Cost
- Novel Processes for Machining
- Production Volume to Price Interaction

- Mechanisms of Machining of Ceramic Parts
- Effect of Machining Parameters on Performance
- Creative Automation Technology
- Identification and Quantification of Machine Tool Characteristics
- Grinding Wheel Design
- Grinding Fluid Behavior
- Measurement of Surface Roughness and Quality
- Grinding Machine to Surface Interactions
- Accuracy of Machining Cost Projections

Table 2. SALES OF CERAMICS BY INDUSTRY
[Eckert and Weatherall 1990]

Glass	56.5%
Porcelain	14.7%
Advanced Ceramics	14.1%
White Ware	9.3%
Refractories	5.4%

The primary concern of the industrial participant was the high costs associated with machining of advanced ceramics. In this regard, it is important to compare machining costs for metals and advanced ceramics by considering the fabrication of a particular component. To carry out the comparison it must be assumed that both materials require the same machining method, namely grinding. Clearly, if grinding was necessary for the ceramic component, while high-speed turning or a high-rate forming process could be utilized for the metal component, the metal would be favored. Obviously, in a real situation all costs in producing a component would be balanced against performance requirements before making the actual choice of material.

To demonstrate the importance and source of high machining cost of ceramics, a comparison was obtained from Therm Advanced Ceramics, which involved the grinding of the root section of a turbine blade. The results of their comparison providing a breakdown of the various costs are presented in Tables 3* and 4. The advanced ceramic was silicon nitride and the metal a superalloy. The hypothetical job involves the production of 2000 turbine blades per month over a 5-year period. The estimated cost of grinding the silicon nitride blade root is approximately 30 percent higher than grinding the superalloy blade root. The major contribution, amounting to 90 percent of the increase, resides in the increased labor for grinding the ceramic parts and for dressing the grinding wheels. The increased labor for grinding is associated with the slower material removal rates and more stringent surface finish

* Tables and figures citing non-SI units are quotations from non-NIST sources.

Table 3. COST COMPARISON IN MACHINING CERAMIC AND METAL TURBINE BLADE ROOT (Therm Advanced Ceramics)

Production Parameters	Ceramic	Nickel Alloy
Part Tolerances	0.0004"	0.0004"
Surface Finish Required	16 micro inch	32 micro inch
Operations per Part	12	12
Grinding Wheel Geometries/Part	5	5
Grinding Wheels Used	1/1200 Parts (Diamond)	1/200 Parts (Alumina)
Grinding Wheel Dressing	0.6 h/40 Parts	0.0833 h/20 Parts
Part Setup	240 h/Lot	240 h/Lot
Lot Size	2000 Parts	2000 Parts

Notes:

1. The hypothetical job estimated herein is based on:
   a. Final machining of near form cast 3" gas turbine rotor blade root stocks.
   b. Therm Advanced Ceramics experience in machining such ceramic and metal gas turbine components.
2. Cost estimates are for a 5-year run at 2000 blades/month - 120000 parts.
3. Part and production process qualification complete prior to production run.
4. Grinding is the only machining operation used.
5. Machining labor priced at $45/hour; engineering labor at $60/hour.

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requirements to maintain strength of the ceramic parts. The increased labor for wheel dressing is connected with the use of diamond wheels rather than easily dressed aluminum oxide wheels which can be employed for the superalloy parts. The cost of consumables (grinding wheels and fluid) is three times higher for the ceramic blade but amounts to only a fraction of 1 percent of the per blade cost. These results demonstrate the importance of developing rapid machining capabilities for ceramic materials if ceramics are to compete directly with metals.

Therm Advanced Ceramics also prepared a cost estimate for smaller production runs, Figure 1. When the run is limited to only 10 to 100 parts, the cost per part is extremely high for both the ceramic and the metal components. This is a result of the large contribution made by the setup and nonrecurring

Table 4. COST COMPARISON IN MACHINING CERAMIC AND METAL TURBINE BLADE ROOT (Therm Advanced Ceramics)

	Ceramic Part		Nickel Alloy Part	
	Time (h)	Cost	Time (h)	Cost
Part CAD/CAM	100	$6,000	100	$6,000
Fabricate Tool and Fixture	550	$24,750	550	$24,750
Total Setup and Nonrecurring Engineering	650	$30,750	650	$30,750
Pro-rata Setup and Nonrecurring Engineering	0.005	$0.26	0.005	$0.26
Labor: Part Setup	0.120	$5.40	0.120	$5.40
Labor: Wheel Dress	0.075	$3.38	0.208	$0.94
Labor: Grinding	2.405	$108.23	1.859	$83.66
Total Consumables	---	$0.68	---	$0.22
Per Blade	2.605	$117.95	2.005	$90.48

Notes: Consumables include grinding wheels and cutting fluid.

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engineering expenses. However, for simpler designs, and also for metals with a greater machinability than superalloys, parts can be made by turning or milling while an equivalent ceramic part would be ground. Under such circumstances the ceramic part would be much more expensive.

Thus, in the absence of major technical barriers, it is clear that high machining costs impose a significant impediment to the widespread use of advanced structural ceramics in mechanical components. The NIST Workshop, referred to earlier, indicated that a focussed effort would be necessary to reduce machining costs. A similar conclusion has been made in a report issued by the Oak Ridge National Laboratory [Stinton 1988] and a workshop sponsored by the National Science Foundation [Kennedy and Skaar 1989]. Therefore, it was decided to conduct a comprehensive assessment of the present status of ceramic machining and subsequently to define a research program that would result in significant improvements in machining practices and a concomitant reduction in the cost of machining.

In conducting the assessment, a comprehensive literature search was carried out, visits and discussions were held with industrial companies interested in ceramic machining, a telephone survey was conducted of ceramic machining shops, a research-in-progress database was consulted, and individuals

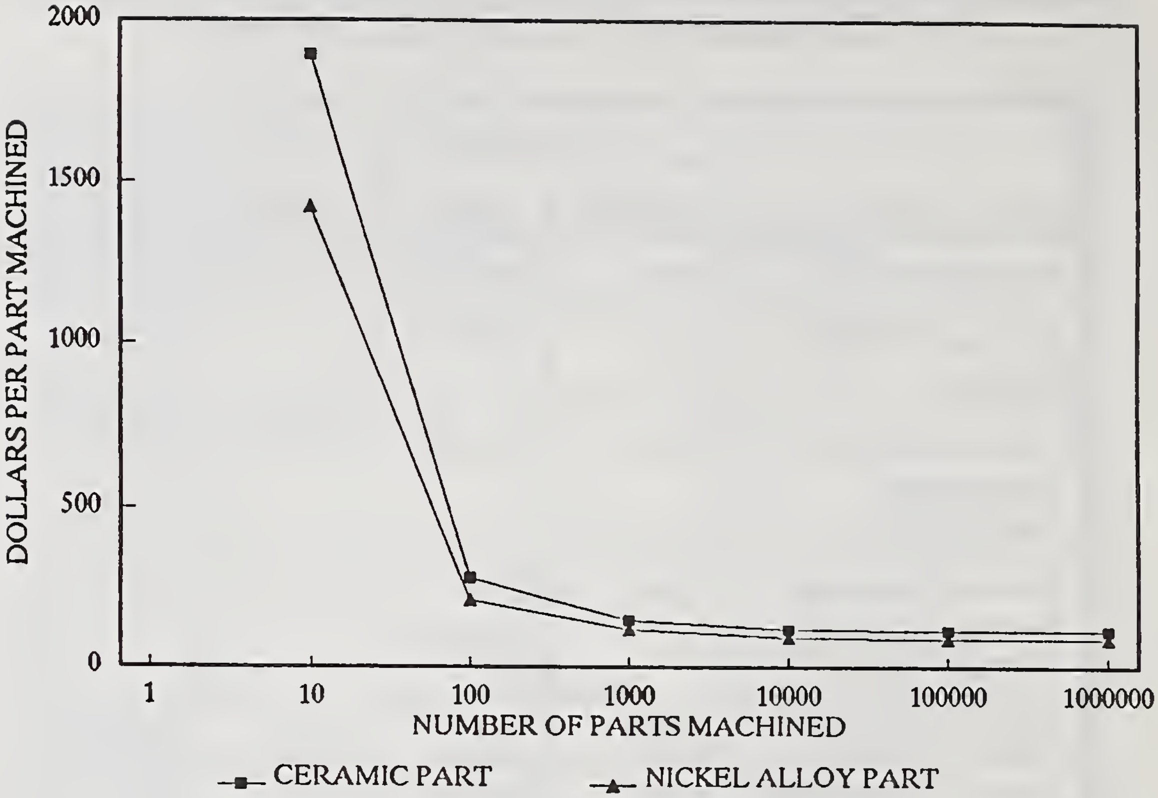

Figure 1. Cost per part as a function of number of parts machined (Therm Advanced Ceramics).

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were invited to visit NIST and discuss different aspects of ceramic machining. The assessment was focused on obtaining answers to several questions: What is the precise nature of the problem? Is the available data and information reliable? Are the present approaches too conservative, or are the economic incentives for improvements insufficient? Is the current technology adequate, or is additional work necessary? Should the current machining methods be optimized, or should new techniques be developed? What types of research projects are needed to address the short-term and long-range machining problems? To what extent are industry and government researchers addressing the problem? The results of the assessment are presented in this report and provide the basis for the recommended program of research.

2. MACHINING METHODS AND PRACTICES

Forming methods that require extensive plasticity such as stamping, forging and drawing, which are of great importance in metal component fabrication, can only be applied to advanced ceramics in the green state. In principle, given an appropriate atmosphere, high pressure, and elevated temperature, plastic working of advanced ceramics could be accomplished. Under ordinary conditions, however, advanced ceramics exhibit limited ductility even at temperatures close to the melting point. Research in progress [Hahn et al. 1991] has shown that certain nanocrystalline ceramics can be worked at temperatures as low as 600°C - 800°C as a result of grain boundary diffusion-controlled creep processes. Strain rates as high as 10^{-4} s^{-1} can be achieved. This is high for creep processes in ceramics, but is still extremely low compared to plastic forming rates of metals. Therefore, machining is the only viable fabrication method applicable to advanced ceramics in the fully sintered state.

A wide variety of methods that are currently being used, or have been proposed for machining of advanced ceramic components, are reviewed in this chapter. These methods, which are classified as abrasive, nonabrasive, and combined processes, are listed in Table 5. They are not unique to advanced ceramics and indeed were developed primarily for application to metals. Some of these methods such as grinding, honing, lapping, polishing, and ultrasonic machining are extensively used for ceramics. Others have been proposed and require additional research and development. Turning and milling methods, although extensively used in metal machining, have only limited application to advanced ceramics in their fully sintered state because of high rates of tool wear and severe workpiece surface damage. However, turning and milling principally with polycrystalline diamond tools are employed quite effectively to machine advanced ceramics in the green state. Unfortunately, this does not eliminate the need for finish machining of densified ceramic parts.

Table 5. MACHINING METHODS FOR ADVANCED CERAMICS

ABRASIVE METHODS	NONABRASIVE METHODS
Grinding	Electrical Discharge Machining
Honing	Laser Beam Cutting
Lapping and Polishing	Electron Beam and Ion Beam Cutting
Ultrasonic Machining	Friction Cutting and Microwave Cutting
Liquid Abrasive Jet Cutting	
Single-Point Turning	

COMBINED METHODS
Electrochemical Grinding
Thermally Assisted Turning
Mechanical-Electrical Discharge
Chemical-Electrical Discharge

2.1 Abrasive Methods

2.1.1 Grinding

Many different modes of grinding can be identified, i.e., reciprocating, internal-cylindrical, external-cylindrical, centerless, creep-feed, etc. However, they all have as a common element the use of a circular wheel or tool that is rotated about its axis of symmetry with some part of the periphery sliding against the workpiece. The entire tool, a layer a few millimeters thick, or only a single layer such as in plated tools, consists of bonded abrasive grains. The tool may range in size from a tiny submillimeter abrasive coated drill to massive grinding wheels more than a meter in diameter. A variety of different abrasives are used. For metals the most common are aluminum oxide and silicon carbide. For application to advanced ceramics only the superabrasives, diamond and cubic boron nitride (CBN) are used, with diamond being the primary choice. Cubic boron nitride, although significantly harder than other advanced ceramics, has been shown to wear much more rapidly than diamond [McEachron and Lorence 1988].

Because of the complexity of grinding, it is common to view the process in terms of several separate but interdependent elements. Metzger [1986] in his book on superabrasive grinding identifies three elements: the workpiece, the machine, and the grinding wheel. Recognizing the importance of the grinding fluid and the dressing tool, Cooley and Wapler [1984] list a total of five elements, shown in Figure 2. In a production setting all of the factors identified in Figure 2 must be considered and optimized interactively to maximize cost-effectiveness. This procedure is quite familiar to the machining industry where it is applied in the grinding of metals, cermets, and a variety of other conventional materials. Significant advances within the various elements will be required, however, before a comparable level of capability is reached with advanced ceramics.

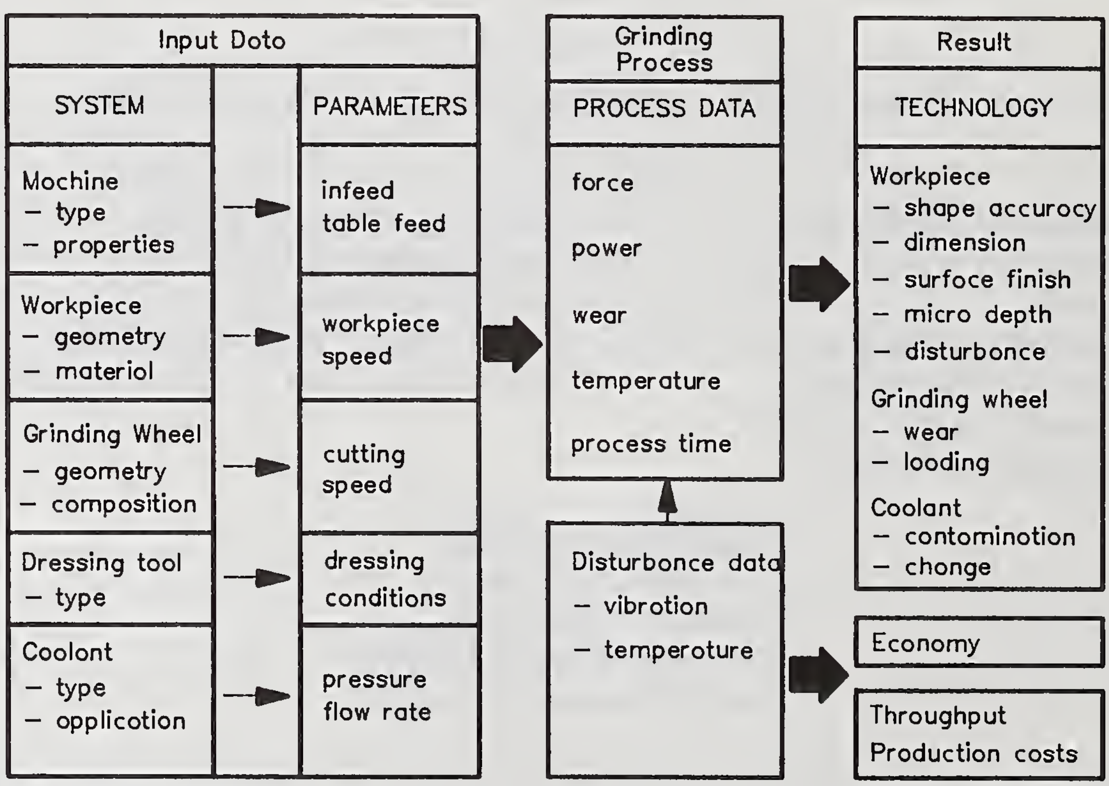

Figure 2. Grinding system relationships [Cooley and Wapler 1984].

One mode of grinding which is particularly promising for application to advanced ceramics is creep-feed grinding. With this method an increased material removal rate may be achieved without sacrificing strength and surface finish [Kong et al. 1991]. In creep-feed grinding, a very large depth of cut is taken at low advance speeds. With brittle materials, down-grinding is employed to maintain much of the material in compression as illustrated in Figure 3. As the workpiece moves into the wheel, the bulk of the material is removed at the front of the wheel. The forces are also highest at that location. Progressing towards the bottom of the wheel, the forces fall off rapidly and the effective grinding depth is reduced. In this way damage is minimized and surface roughness is reduced. This was clearly demonstrated by Konig and Wemhoner [1989] in grinding experiments on siliconized silicon carbide. The effect of depth of cut and feed rate on damage are illustrated in Figure 4. In this example, material removal rate was maintained constant by balancing feed rate and cutting depth. Characteristic strength is significantly higher at large depths of cut and low feed rates.

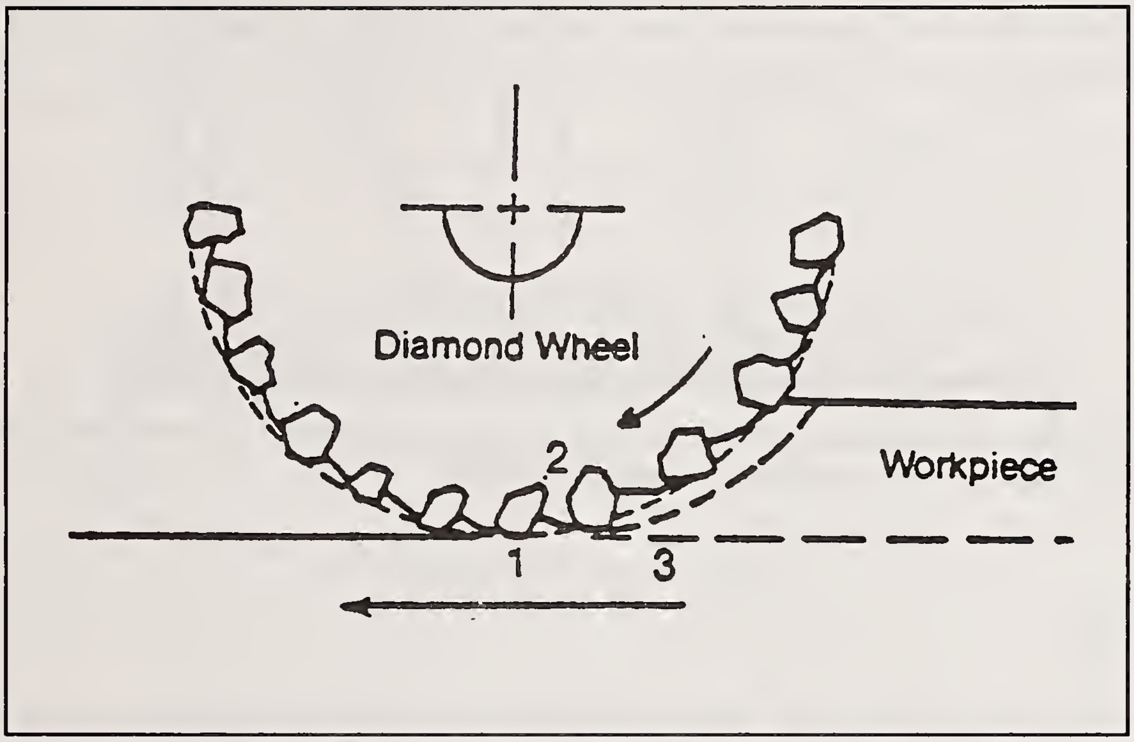

Figure 3. Schematic of creep-feed grinding [Subramanian 1987].

Application of creep-feed grinding is not achieved without complications. Since the grinding forces are considerably higher, a more powerful machine with a greater machine rigidity is required to avoid excessive deflections and associated loss of accuracy. The workpiece itself must, of course, be able to support the increased loads, and greater care is required in fixturing. The long wheel contact length and high specific grinding energies also place increased demands on the grinding fluid, and its delivery. To address the delivery problem, special slotted wheels have been designed to increase the access of the grinding fluid and have been shown to be quite effective [Suto et al. 1989]. However, no attempts have been made to develop special fluids for creep-feed grinding of ceramics. It is clear that applying creep-feed grinding technology to advanced ceramics offers a significant opportunity to obtain increased machining rates without sacrificing strength or component integrity.

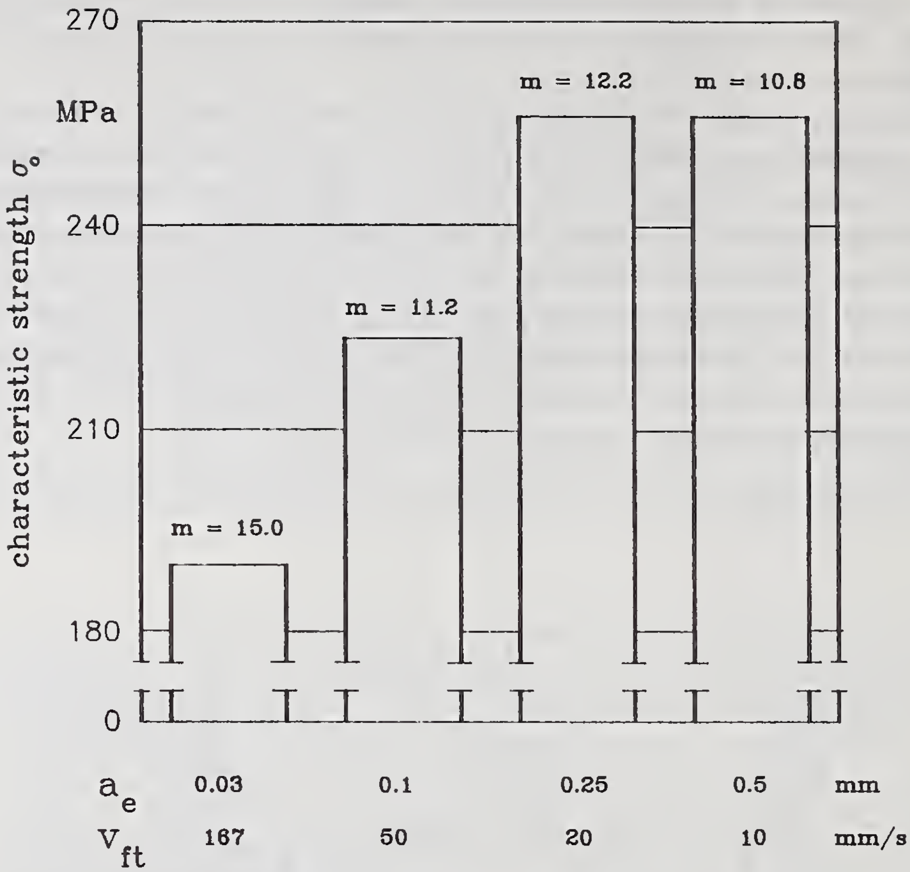

Figure 4. Strength of siliconized silicon carbide at constant removal rate as a function of infeed (a_e) and feed rate (v_{ft}), adapted from Konig and Wemhoner [1989].

2.1.2 Honing

Honing, like grinding, also uses fixed abrasives; and for application to advanced ceramics, diamond is the abrasive of choice. Much of the discussion on grinding also pertains to honing. The main difference between honing and grinding is the much lower surface speeds employed in honing. Honing, in general, is not used to remove large amounts of material. Its primary application is in obtaining a desired surface finish and in correcting errors in dimensional tolerance left by other more rapid machining methods. The most frequent application of honing is in the finishing of internal cylindrical surfaces; the honing of automobile engine cylinder walls being a most notable example. Applications such as the latter may be highly automated with complete control over all aspects of the process, including automatic gaging of the part dimensions. Honing is also applied to external surfaces, for example, in finishing gear teeth, valves, and the outside surfaces of ball and roller bearing races.

A review of honing methods and applications can be found in the Metals Handbook [Davis 1989]. Only brief mention is made of ceramics. As with grinding, the honing of ceramics requires diamond abrasives, and there is a similar concern about workpiece damage.

One advantage honing has over grinding is in the small amount of heat produced, since honing is a low-speed operation compared to grinding. Thus, damage and workpiece distortion associated with heating are minimized. The fact that honing involves little heating also influences the cutting fluid requirements. There is less concern about cooling requirements; but additives are needed to impart lubricity. As in grinding, it does not appear that there have been special efforts to develop honing fluids specifically for application to advanced ceramics.

2.1.3 Lapping and Polishing

Similar to honing, lapping is largely a finishing process employed on parts that have already been machined to near final dimensions. Lapping differs from honing in that it is a loose or free abrasive process. Lapping is conducted by pressing the workpiece against a rigid surface, often cast iron, covered with a slurry of abrasive particles. Some of these particles are embedded into the lapping tool surface and produce a cutting action on the workpiece. Other particles that roll between the two surfaces, are also involved in the removal process. A distinction that is sometimes, but not always, made between lapping and polishing is in the use of a soft and flexible surface for polishing and a harder and rigid surface for lapping. Lapping is employed to obtain precise tolerances, remove damage, and improve surface finish. Polishing is used primarily to remove damage and achieve very smooth surfaces. Figure 5 shows a schematic of these processes.

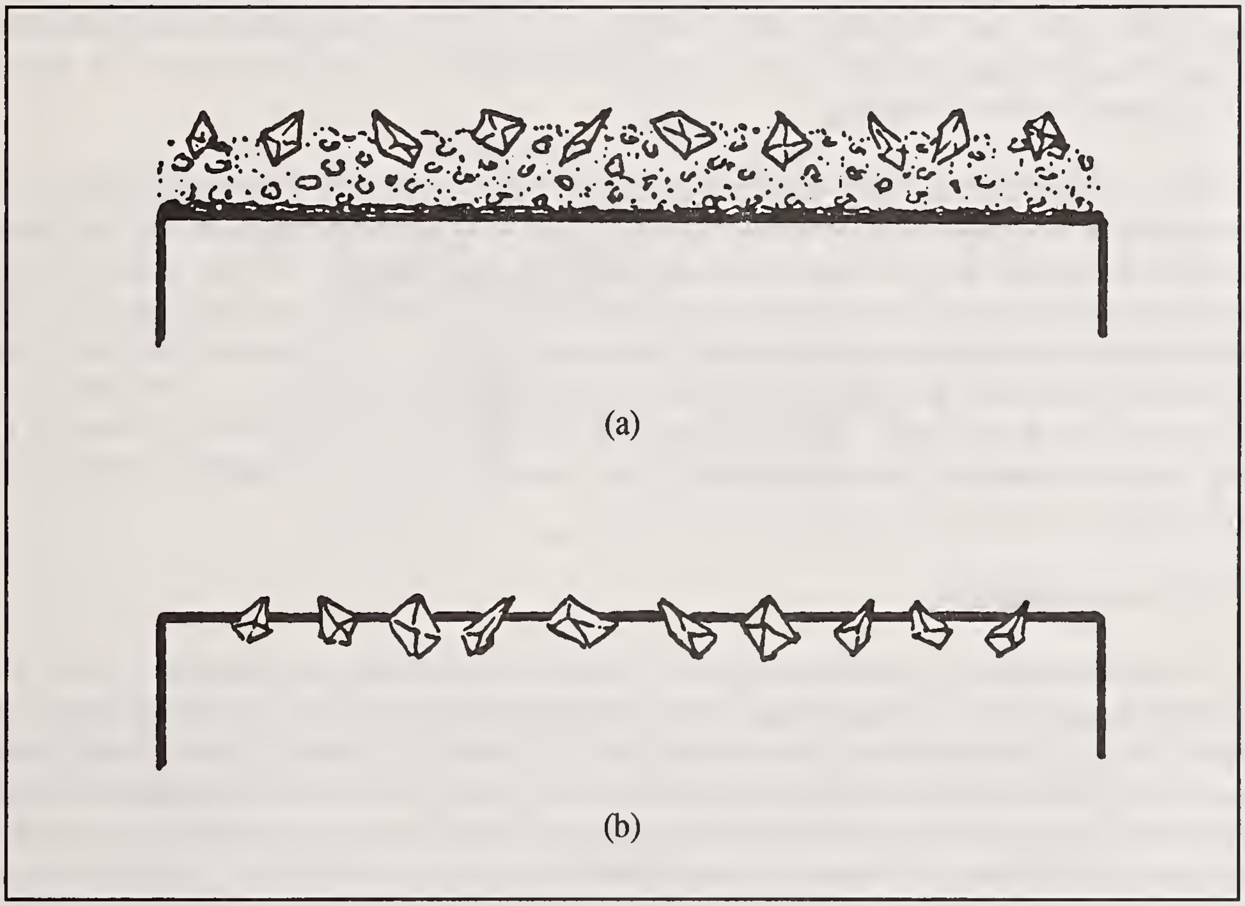

Figure 5. Sketch of abrasive grit held in (a) a soft pad, and (b) a hard pad [Rostoker et al. 1987].

Recent developments in lapping and polishing of advanced ceramics have focussed on improved sizing of abrasive grit, on combined chemical and mechanical processes, and on machine design improvements [Rostoker et al. 1987, Subramanian 1988, and Konig and Popp 1988]. The importance of grit size uniformity is clear. With a narrow size distribution, the chance of scratching the polished surface with an oversized abrasive particle is minimized. Grit size uniformity is also crucial in order to achieve high precision and flatness in lapping and polishing operations.

Machine design changes in recent years have emphasized close tolerance lapping and polishing, and high specimen throughput. Modern high precision lapping machines emphasize a firm substrate for the abrasive so that close tolerances can be maintained, and this also necessitates uniform abrasive size. Automated operation is emphasized, and a reduction in the number of steps is sought in the usual sequence of abrasive changes from coarse to fine size to improve production efficiency [Rostoker et al. 1987]. Stowers et al. [1988] have reviewed some recent developments in polishing, which included float polishing, elastic emission machining and magnetic fluid polishing. Although this review is directed toward finishing processes for large optical components, some of the techniques may be applicable to advanced ceramics.

In float polishing, the workpiece floats on the polishing fluid as a result of hydrodynamic action at high rotational speeds [Namba and Tsuwa 1977, 1978, 1980a 1980b, 1980c, and Bennett et al. 1987]. Elastic emission machining is based on a the same principle as the float polishing [Mori et al. 1983, Mori and Ikawa 1985, Mori and Yamauchi 1987, and Mori et al. 1987]. The primary difference between this method and float polishing is that a rotating polyurethane sphere is used for the lap, as compared to a hard tin disc used in float polishing.

Two variations of magnetic fluid polishing have been developed. Saito and Niikura [1987] have used a magnetic fluid (containing abrasive particles) to form a polishing pad in which the magnetic fluid levitates and forces the abrasive grains against the workpiece surface. In the process developed by Kurobe and Imanaka [1984], the polishing compound is pressed against the workpiece by a thin rubber sheet separating the polishing compound from the magnetic fluid. The magnetic fluid polishing process has been applied to polishing of curved surfaces of lithium niobate [Suzuki et al. 1989] and silicon nitride balls [Umehara and Kato 1990]. Although lapping and polishing are important in ceramic machining processes and the technology is well advanced, there appears to be some potential for improvements by chemical assistance, which is discussed later.

2.1.4 Ultrasonic Machining

Ultrasonic machining encompasses rotary ultrasonic machining and ultrasonic impact machining. In both methods the tool is vibrated along its axis normal to the surface of the workpiece at a frequency of typically 20 kHz. Otherwise the two methods differ substantially. Rotary ultrasonic machining utilizes diamond coated grinding tools, most often core drills, in a drilling or vertical milling configuration. It is distinguished from ordinary milling and drilling operations only in that the rotating tool is vibrated with an amplitude of 0.025 to 0.05 mm while being held against the workpiece. The vibration serves to reduce friction, assist in the access of cutting fluid, and facilitate the removal of swarf. The net result is an increase in machining rate. The tools are generally limited to a diameter no greater than 50 mm. In addition to core and solid drills, rotary ultrasonic machining has also employed small grinding and thread cutting wheels. Clearly much of what was discussed in grinding is also applicable to this method. The influence of grinding parameters, bond and abrasive properties, and cutting fluids should bear a similar importance. Thus, improvements in the grinding process for ceramics should also be applicable to rotary ultrasonic machining.

In ultrasonic impact machining the tool itself does not incorporate abrasive particles and does not contact the workpiece. In this method an abrasive containing slurry is circulated between the vibrating tool and the workpiece, Figure 6. The vibratory motion of the tool is imparted to the fluid and abrasive particles. Impact of the particles with the workpiece results in indentation and fracture with the consequent removal of material. The rate of removal is extremely sensitive to the gap between the workpiece and the vibrating tool. Next to grinding, ultrasonic impact grinding is probably the most frequently used machining method for advanced ceramics. Recent progress using this approach has been reviewed by Rhoades [1985]. More rapid machining may be possible with special fluids and higher vibration frequencies.

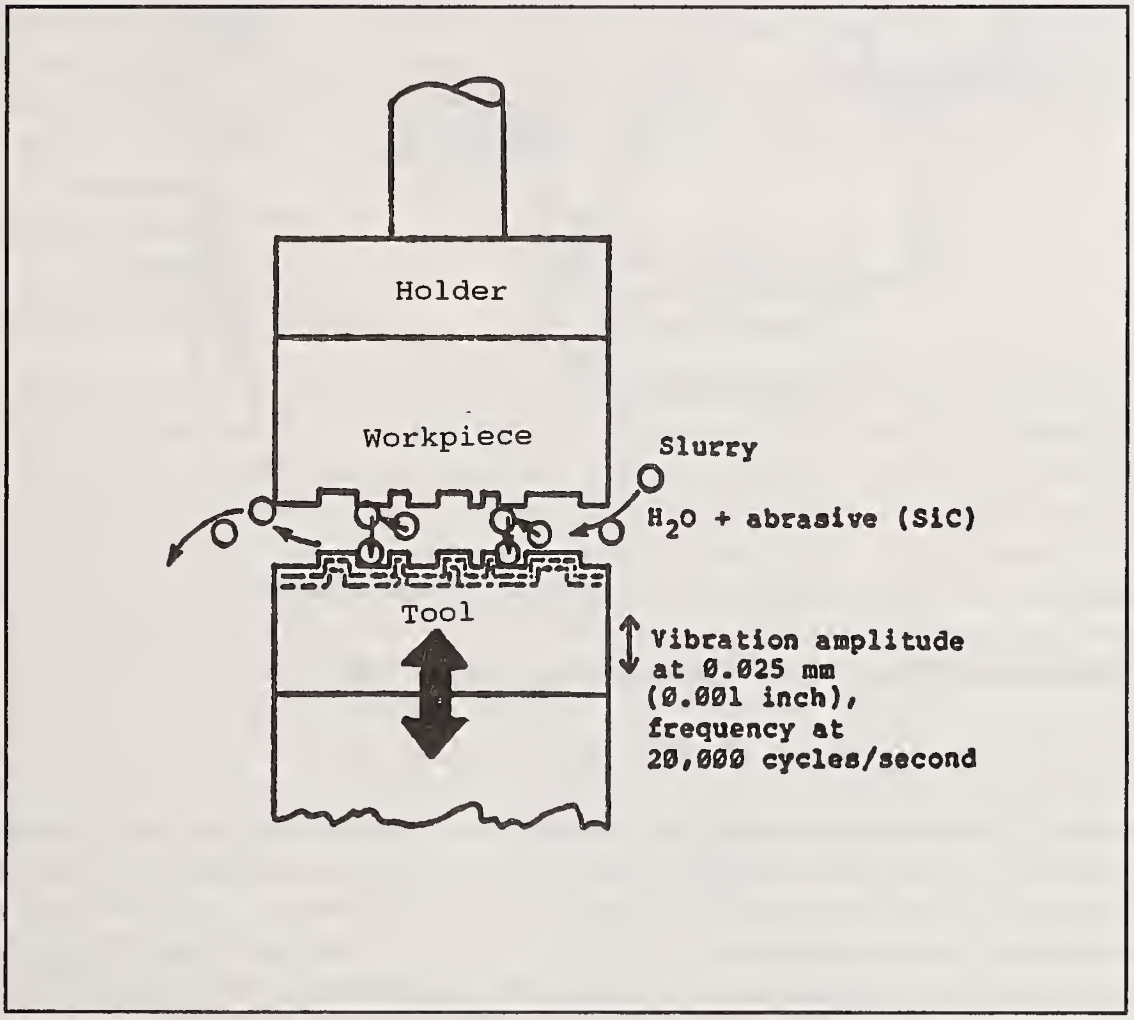

Figure 6. llustration of the ultrasonic impact machining, adapted from Rhoades [1985].

2.1.5 Liquid Abrasive Jet Cutting

Jordan [1986] has reviewed recent developments and applications of liquid jet cutting. Liquid jet systems are usually applied to cutting tasks, as illustrated in the schematic sketch in Figure 7, rather than to shaping or surface finishing. This method has been frequently applied to porous materials where very high cutting rates have been reported [Kim et al. 1987]. However, liquid jet cutting is not effective on hard and dense advanced ceramics, where cutting rates are much lower.

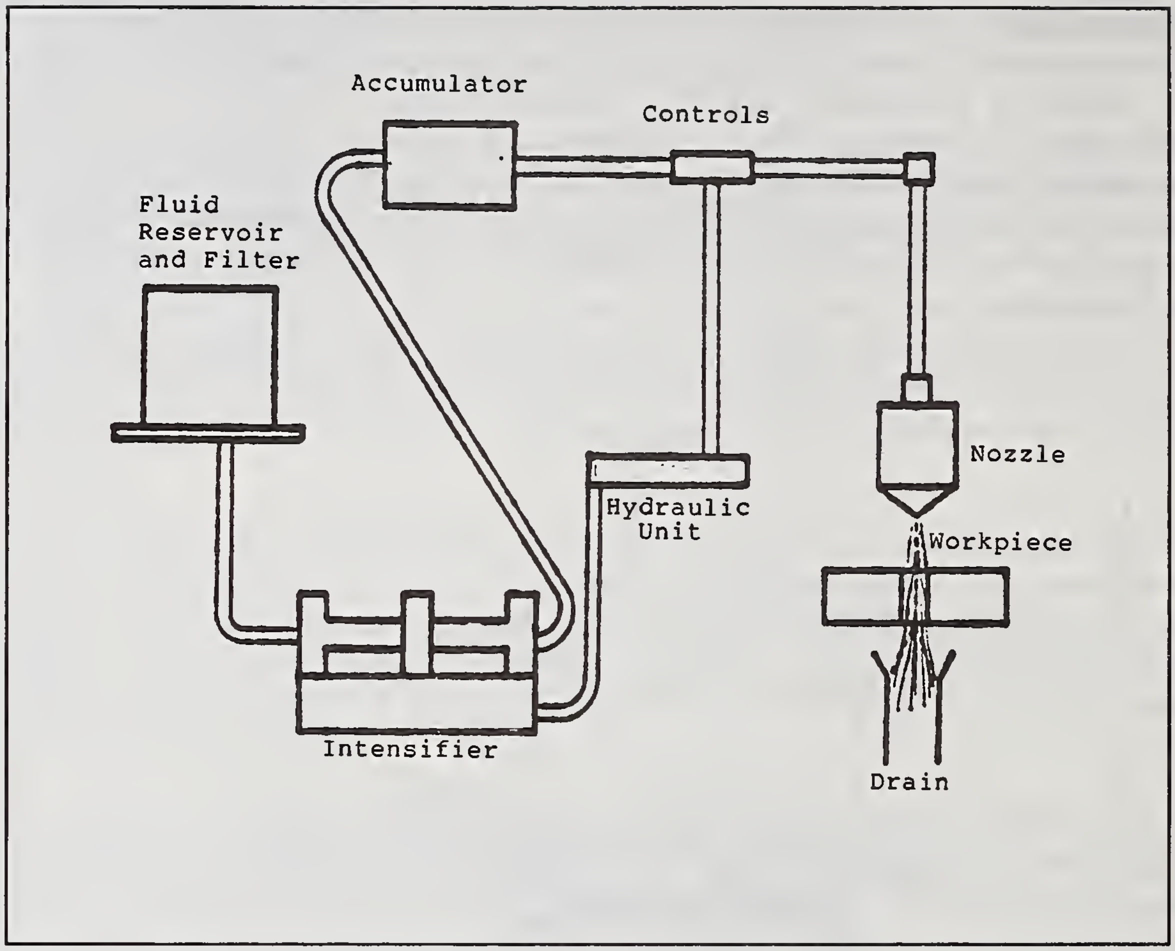

Figure 7. Schematic of liquid jet cutting apparatus, after Firestone [1979].

Addition of abrasive grit to the fluid stream has enabled the application of liquid jet cutting to advanced ceramics. This approach combines slurry erosion removal processes with localized fracture due to liquid cavitation. The incorporation of abrasive particles, however, will introduce an additional element of machining damage appropriate to erosion. The liquid abrasive jet method does not easily lend itself to the fabrication of components requiring a close tolerance and a fine surface finish.

2.1.6 Single-Point Turning

Certain soft ceramics, porous ceramics and ceramics in a sub-sintered or green state may be machined by single-point turning and milling methods. In these operations, wear and fracture of the tool are major concerns. A dull or damaged tool results in degradation of tolerance and inflicts considerably more damage to the workpiece. To minimize tool wear, sintered polycrystalline diamond tools are often employed.

During the last decade, considerable attention has been focused on single-point diamond turning process, which utilizes a polished single crystal diamond tool and requires an especially designed machine tool to allow very close control of the depth of cut and machine tool vibrations [Schinker 1991, Sugita et al. 1983, Veda et al. 1983, Veda et al. 1991, and Nakajima et al. 1989]. Single-point diamond turning was developed as a technique for producing highly smooth and precise surface contours for specialized applications, for example optical components and contact lens molds. Since the process is inherently adaptable to computer control for producing curved surfaces in an automated manufacturing environment, it will likely see expanded use in the future.

The machining geometry is shown schematically in Figure 8. In general, elastic-plastic deformation and microfracture (especially in brittle materials) occur in the workpiece ahead of the tool edge. If the conditions are established properly, most of the microfracture damage that occurs at a depth up to t_{eff} is subsequently removed as part of the chip. Single-point diamond turning has been successfully applied to a limited number of materials in producing very close tolerance surfaces of high smoothness and low levels of damage [Bifano et al. 1988, and Blake and Scattergood 1990]. Other materials that oxidize or dissolve diamond (carbon), such as steels, cannot be cut in this way, unless special precautions are made to reduce the wear of the diamond tool [Evans 1991]. Application of single-point diamond turning to advanced ceramics also requires special precautions to minimize tool wear.

2.2 Nonabrasive Methods

2.2.1 Electrical Discharge Machining

Many applications of electrical discharge machining (EDM) to advanced ceramics have been reported in the past 5 years. EDM requires the workpieces to have an electrical resistivity less than 100Ω-cm. Thus, EDM can not be used for machining of glasses and some ceramics. Koenig and Panten [1988] have used EDM on silicon-infiltrated silicon carbide. Iwanek et al. [1986] have applied this method successfully to siliconized SiC and hot-pressed SiC materials. One means, to extend the application of EDM to other ceramics, has been to modify the composition of the material to reduce resistivity. For example, the addition of TiC or TiN to silicon nitride and to alumina have produced sufficient conductivity for EDM according to Martin et al. [1989]. Petrofes and Gadalla [1988] have also described the application of EDM to composite ceramics, e.g., Si_3N_4-TiN, SiC-TiB_2 and cermet materials. Much effort appears to be underway in Japan exploring EDM for advanced ceramics and composites. It is not clear, however, whether EDM can be regarded as a low damage machining method since it typically leaves a surface layer of melted or heat-affected material containing a high level of residual stress and numerous microcracks.

2.2.2 Laser Beam Cutting

Focused laser beams have been used to cut a large variety of materials, including ceramics. Chryssolouris and Bredt [1978] have reported an innovative approach that uses two laser beams intersecting within the workpiece to cut "blind" kerfs, Figure 9. Certain cutting geometries may lend themselves well to such a technique, particularly when segments of workpiece material need to be removed. Copley [1985] and Wallace and Copley [1989] have described techniques for laser shaping of ceramic surfaces such as silicon nitride.

Soni and Rajan [1985] and Kerth [1991] have described the use of pulsed lasers to drill advanced ceramics with success. Recently, Taya and Ramulu [1988] have reported laser machining of three-dimensional forms on ceramic-matrix composites.

In a study of the effect of machining on mechanical properties, Gardner and Beauchamp [1987] reported no loss of fracture strength from laser machined alumina. Since there is no mechanical contact,

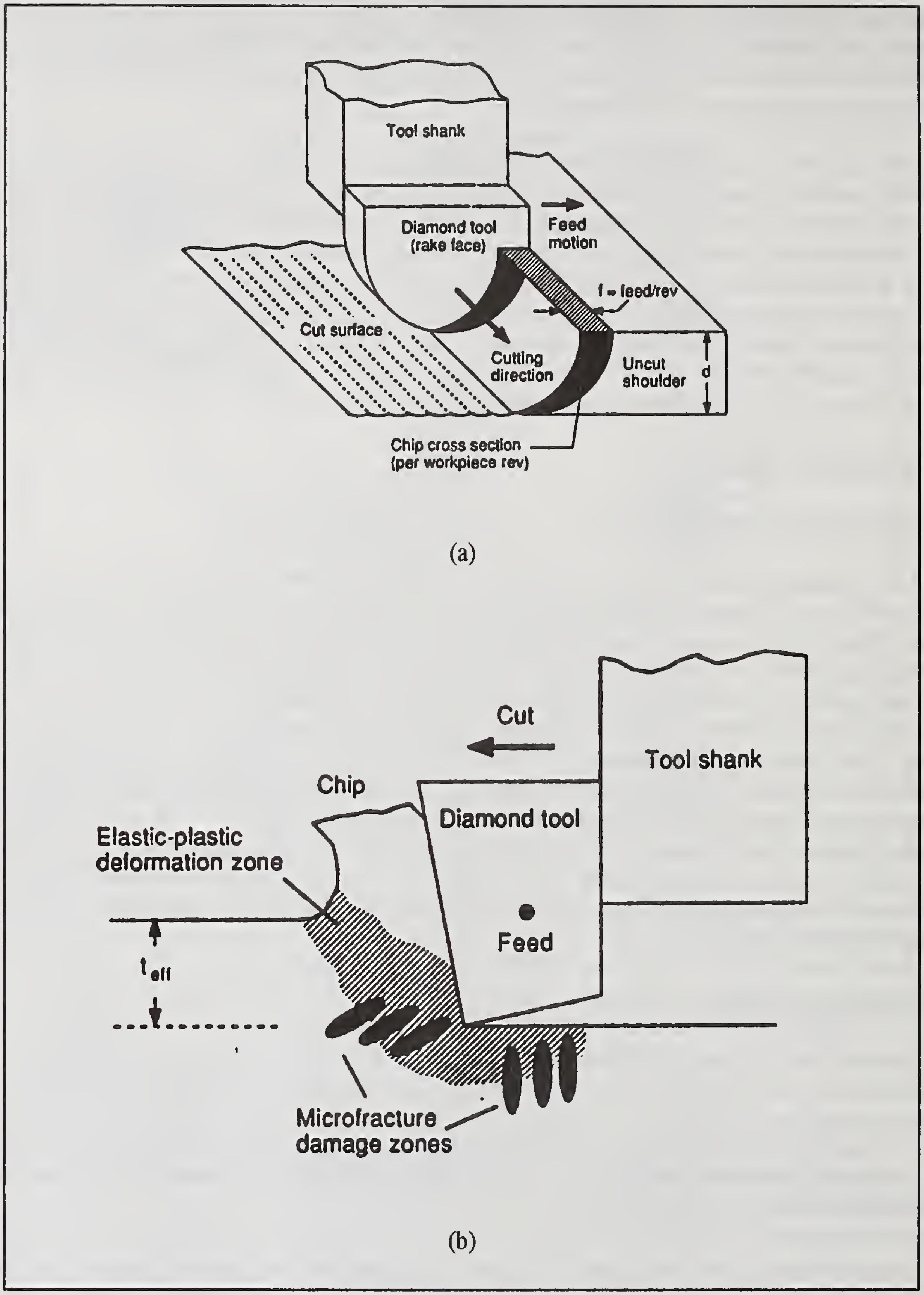

Figure 8. (a) Schematic of cutting geometry in single-point diamond turning, (b) details of damage formed during cutting in schematic cross section [Blake and Scattergood 1990].

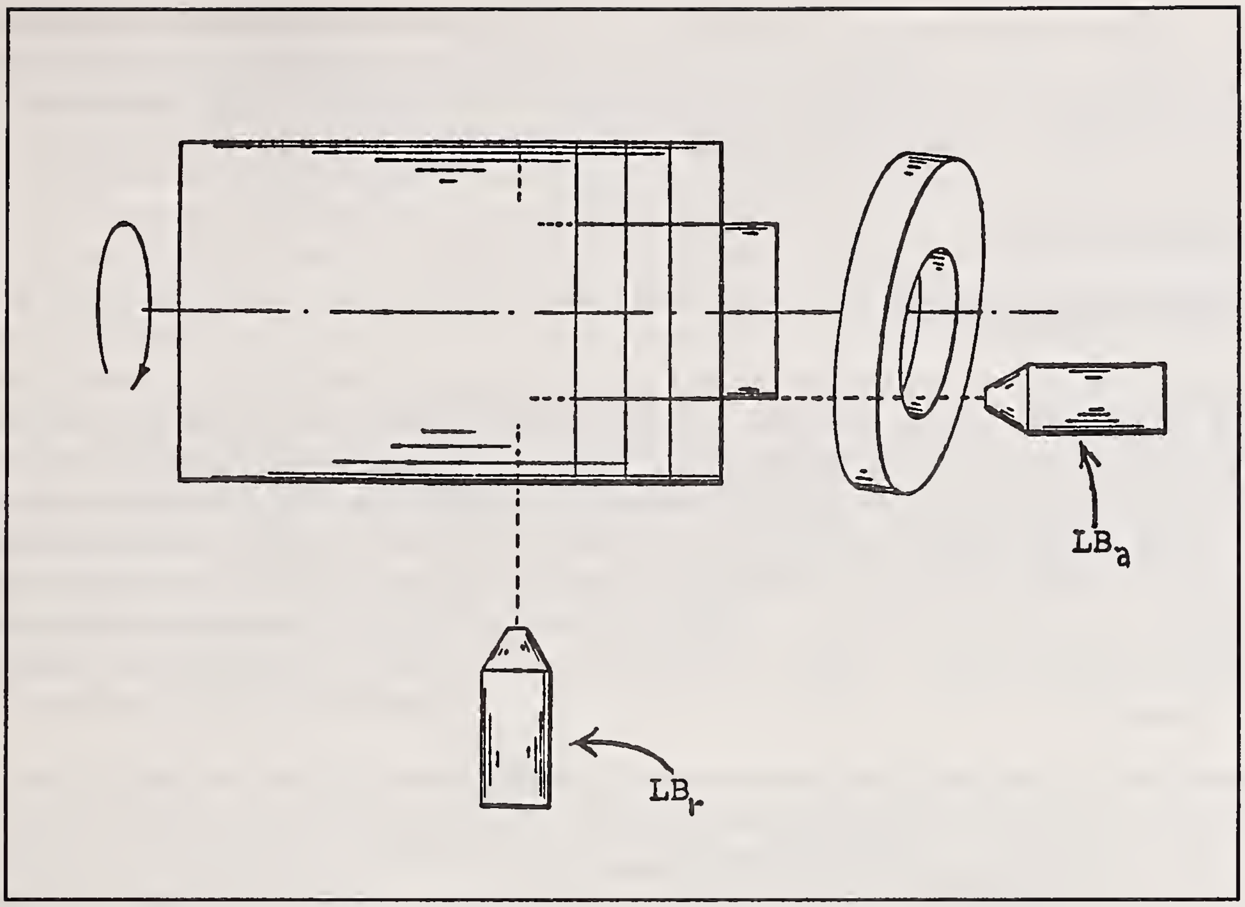

Figure 9. Schematic illustration of a laser turning system [Chryssolouris and Bredt 1987].

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the machining damage may be low, unless the material is particularly sensitive to thermal shock; in which case, the machining damage can be extensive.

2.2.3 Electron Beam and Ion Beam Cutting

Recently reported work has involved cutting of green or low-density ceramic materials. Horio et al. [1987] described efforts to improve the electron beam effectiveness in a pulsed system used to cut alumina sheets. Mochel et al. [1984] described a technique to machine holes and slots in a thin alumina sheet which they believed was suitable for nanolithography applications.

Ion beam applications have been reported by Daudin et al. [1988] in connection with surface smoothing of alumina films by sputtering, and by Miyamoto et al. [1984] on the use of an argon ion beam to machine alumina surfaces with possible application to biological implants. Applications of both ion beams and electron beams in machining are only suitable for cutting and drilling thin sheets of ceramics and, therefore, are not suitable for shaping large ceramic components.

2.2.4 Friction Cutting and Microwave Cutting

Friction cutting of ceramics has been described by Childs and Clemens [1987], where a water cooled rotating mild steel disk was used to cut narrow slots in alumina and silicon nitride. Localized microwave heating has been used by Taniguchi et al. [1972] to pierce sintered alumina. In this process, a wafer of sintered alumina was pierced by local melting and explosive discharge of the molten material from beneath the surface. While these methods are suitable for cutting and slicing operations, they are not generally suitable for achieving a contoured surface with a high tolerance.

2.3 Combined Methods

2.3.1 Electrochemical Grinding

Rhoades [1985] has described the use of electrochemical dissolution in combination with mechanical grinding for machining metals. As diagrammed in Figure 10, an electrolyte (water with dissolved sodium chloride, for example) is sprayed onto the grinding wheel and the surface being machined. A potential is applied between a metal-bond grinding wheel (cathode) and the workpiece (anode). Electrochemical action forms a reacted surface layer on the workpiece, which is removed by the grinding wheel. An advantage of this method lies in the expected low level of residual damage in the workpiece. Some advanced ceramics, notably the carbides, have sufficient electrical conductivity to permit electrochemical attack. There is no indication, however, that this approach has been tried for advanced ceramics.

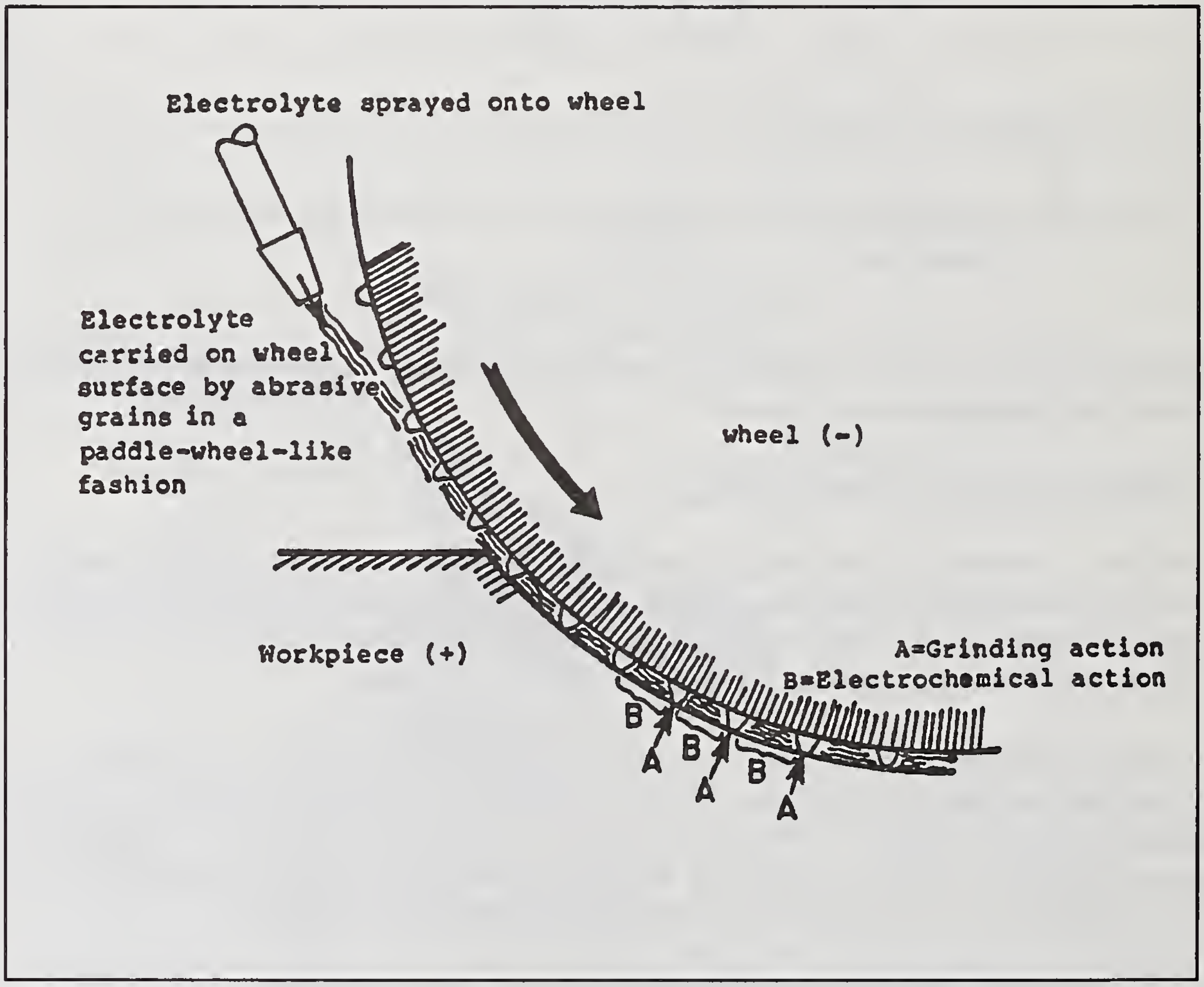

Figure 10. Sketch of the electrochemical grinding process, after Rhoades [1985].

2.3.2 Thermally Assisted Turning

Plasma torch heating of the workpiece during turning has been reported to be effective for some engineering ceramics [Kitagawa and Maekawa 1990]. This method involves heating the workpiece material to temperatures as high as 1000°C in front of a polycrystalline diamond compact (PDC) or CBN cutting tool. Where machinability is improved, it results from a transition to a more plastic type of deformation and removal processes at the elevated temperature. Although tool wear was reduced by a factor of 8 in turning silicon nitride, it was still unacceptably high. Materials sensitive to thermal shock, for example alumina and zirconia, did not show improved machinability by plasma torch heating.

In another study, successful hot-machining of mullite and silicon nitride was reported by Uehara and Takeshita [1986]. Konig et al. [1991] have reported a method for laser-assisted turning of hot-pressed silicon nitride with CBN cutting tools. Rice and Steinkuller [1975] have described the use of a laser heating source in advance of a diamond cutting tool to render the ceramic material more plastic in mechanical response. Nevertheless, thermally assisted turning does not lend itself to large-volume production, because of short tool life and poor surface finish.

2.3.3 Mechanical-Electrical Discharge

The combination of electrical discharge and ultrasonic machining methods has been reported by Uematsu et al. [1988] in experiments to machine titanium diboride with a metal bonded diamond tool. They reported increased material removal rates and a high removal ratio of 110 (workpiece loss/wheel loss) under the conditions chosen. Applicability of this method to other materials of sufficient conductivity for EDM needs to be explored.

2.3.4 Chemical-Electrical Discharge

A combination of wire electrical discharge machining with electrochemical reaction in an electrolyte has been reported by Tsuchiya et al. [1984]. This method was applied to silicon carbide and non-conducting specimens of glass, alumina, and silicon nitride that were immersed in a suitable electrolyte solution to permit conduction. The method permits cutting of surface contours in an effective manner without a direct contact between the tool and the workpiece. Cutting rates for the ceramics reportedly ranged from 0.12 to 0.14 mm/min. Further research is needed to evaluate the feasibility of this process for large-volume production of advanced ceramics.

3. ASSESSMENT OF INDUSTRIAL NEEDS AND CURRENT RESEARCH

Successful implementation of advanced ceramics in industrial applications has a large implication for broad sectors of industry. Companies most directly concerned with machining and utilization of advanced ceramics consist of ceramic materials suppliers, component manufacturers, original equipment manufacturers (OEM's), machine tool manufacturers, abrasives suppliers, grinding wheel manufacturers, and the ceramic machining industry. Each industry segment has a somewhat different interest and motivation for using advanced ceramics. Selected companies in each sector were surveyed to obtain information on their needs and current research and development activities in ceramic machining. A survey of government programs and published literature was also conducted to assess the current status of research being conducted in ceramic machining.

3.1 Current Industrial Practice

In order to determine the present status of machining practice, and to assess the needs of the ceramic machining industry, a telephone survey was conducted and several visits were made to firms in the ceramic machining industry. The questions asked are listed in Table 6.

There are approximately 30 independent shops that specialize in the machining of ceramics. Most of the shops are small with less than 10 employees, but a few have as many as 50 employees. In addition to these employees, several material suppliers and manufacturers of abrasives, grinding wheels, and machine tools have set up machine shops for ceramics, recognizing the need for improved ceramic machining technology. These shops are well equipped and have two functions: advancing the technology and assisting component manufacturers in the development of methods to fabricate specific components. Almost all of the machine shops involved in ceramic machining have acquired the necessary skills for machining of ceramics and difficult-to-machine materials. The expertise, however, is associated with particular machinists who have acquired the skills through experience.

In addition to the general machine shops, there are a number of companies with specialized equipment such as laser cutting, waterjet cutting, electrical discharge machining, and chemical etching, which can be used for ceramics but are primarily used for a variety of other materials.

The results of the telephone survey and visits are summarized as follows:

(1) Most of the surveyed shops that specialized in ceramics worked primarily with alumina, although most of them claimed some experience with other ceramics. Some of the shops also worked with composites, cermets, and difficult-to-machine metals.

(2) Silicon nitride and silicon carbide give the most problems in machining. This, of course, may be due to the fact that these are relatively new materials and experience is still limited.

(3) The shops surveyed used diamond grinding almost exclusively. Several had also set up ultrasonic abrasive machining equipment. Most of the other techniques previously described like laser cutting, single-point diamond turning, waterjet cutting, etc., were not used. They do not plan to use these techniques in the future because of the extra capital

Table 6. QUESTIONNAIRE USED IN OBTAINING INFORMATION FROM CERAMIC MACHINING INDUSTRY

1. Do you machine just ceramics or other materials?

Alumina	____________	Metals	____________
Silicon carbide	____________	Composites	____________
Silicon Nitride	____________	Superalloys	____________

2. What types of machining do you do on ceramics?

Diamond grind	____________	Other:	____________
Ultrasonic	____________		
Thermal	____________		

3. Do you develop your own techniques; if not, where does the technology come from?

   Material supplier
   Wheel supplier
   Technical literature
   Other

4. Do you use special equipment or standards?

5. Do you work from prints supplied by customers?

6. What do you see are major technical problems that need to be resolved?

   Machinability data
   New techniques for more rapid machining
   Improved equipment
   NDE and quality control

7. What do you see are the critical factors in ceramic machining?

Operator skill	____________
Machine quality	____________
Properties of wheel	____________
Fluid	____________

8. What types of ceramic materials give biggest problems?

costs. However, if there was new equipment that substantially reduced costs, they would have to acquire it to maintain their own competitive position.

(4) The shops develop their own techniques for each material with which they have not had previous experience. They claim that help is sometimes available from wheel suppliers, but that help is limited. They rarely go to the material supplier or inspect the technical literature.

(5) Machinability data are rare for ceramics. The shops develop their own. Most shops cited this as the major problem area. There are no established standards and no central sources of information pertaining to the grinding of ceramics. Each task must be handled on a case-by-case basis. Their approach is very conservative; minimal removal rates are used to avoid surface damage and breakage. The conservative approach and the lack of an appropriate source of information greatly increases the cost of machining.

(6) There is a lack of information on damage measurement and control. This contributes to the costly conservative approach used in machining. Also, because of the sensitivity of ceramics to chipping and fracture, there is an abnormal amount of waste. New methods to hold, grip, and transport ceramic parts are needed.

(7) Almost all shops cited operator skill as the critical factor in machining ceramics. Many of their machinists had more than 15 years experience and had developed their own special techniques. Unfortunately, this is costly and incompatible with large-volume production.

3.2 Ceramic Machining Research in Industry

Some research in improved machining procedures is carried out in industry. This research is primarily concerned with the relation between machining parameters and product performance as indicated by strength, surface finish and residual damage. The research results are used to develop procedures for machining of specific components. Within industry it was found that there were several different approaches to the development and application of advanced ceramics. Although, these different approaches cannot be generalized, the following patterns were noticed. The OEM's generally have a wait-and-see attitude. They have few incentives to pioneer in the development and use of ceramic components and prefer to wait until they are economically feasible. They often rely on outside experts to provide ceramic components and are primarily concerned with component evaluation rather than with fabrication techniques. Component manufacturers (bearings, piston rings, valves, etc.), however, do have a strong interest. They evaluate the potential market for ceramic components and move aggressively when opportunities exist. The component manufacturers depend on the ceramic material suppliers to supply either the final component or information on machining techniques. Some of the ceramic material suppliers have set up their own machine shops, and others work with outside machine shops to promote the development of production techniques for specific components.

Discussions on ceramic machining were also held with abrasive suppliers, diamond wheel manufacturers and machine tool builders. All agreed that they were increasingly being asked questions about ceramic machining, and that the current state-of-the-technology did not provide adequate answers. The abrasives manufacturers are quite active in understanding and improving their products. Thus, they participate in ceramic machining research with the aim of demonstrating the capability of their products, and work closely with the grinding wheel manufacturers to develop better grinding wheels. They also work closely with OEM's and component manufacturers in setting up production processes.

The machine tool manufacturers feel that current equipment is adequate for present practice; however, additional research will be needed to develop production machinery to make millions of ceramic parts with adequate control of damage, finish and dimensions. It was agreed that if ceramics are to be used extensively, large-volume production techniques with adequate on-line inspection would be required to reduce dependence on operator skill.

3.3 Industrial Needs

It was the general consensus of the respondents that much could be done to improve the conventional grinding process as applied to advanced ceramics. Industry trends in this direction were identified and include creep-feed grinding, improved grinding wheels, improved knowledge of grinding effects on performance, and more rigid machine tools. However, progress in advancing the ceramic machining technology is very slow. Therefore, research and technology development programs should be accelerated to keep pace with materials development efforts and industrial needs.

From all of the information that has been accumulated, several points emerge:

(1) Conventional grinding techniques will be used for the foreseeable future. Machinability data are needed for ceramics for the optimization of the grinding process. Once removal rate and damage criteria are established on an economic basis, potential advancements can be explored on a rational basis.

(2) Damage introduced by machining is the overriding concern regardless of the machining process used. Rapid machining is possible with current technology, but surfaces are left severely damaged and material properties deteriorate. Methods must be developed to measure surface damage in ceramics, and damage must be correlated with machining parameters and material properties. Pre- and post-machining treatments may be useful to remove residual machining damage. In-process inspection methods are needed for controlling the machining damage.

(3) Certain techniques appear to have potential for increasing the removal rate while minimizing damage. These include creep-feed grinding, and chemically assisted processes. These should be explored in greater detail.

(4) A coordinated program is needed that provides inputs and cooperation from ceramic component manufacturers, abrasive and wheel manufacturers, material suppliers and fabrication specialists. Without a cooperative program, progress will be slow and sporadic.

3.4 Current Government Programs

An informal survey was conducted to determine the extent of ceramic machining research activities in Federal laboratories and government programs. This survey included database searches (Defense Technical Information Work Unit Survey), phone calls to material departments of appropriate government agencies and laboratories (DOD, DOE, NASA, Navy, Army, and Air Force research offices, military laboratories and national laboratories), and a review of recent technical society bulletins which announce research awards. This survey revealed a dearth of research and development in the area of ceramic machining.

The National Science Foundation has supported a limited amount of research on machining of glass and ceramics over recent years. Specific research projects include: temperature measurements in grinding, laser processing of carbides and nitrides, ductile-regime grinding and ultra-precision machining of glass components, and surface finishing of ceramics. These projects, however, are not coordinated to achieve a specific overall program objective; but rather seek basic science information.

The Army Material Laboratory at Watertown Arsenal had a variety of programs which included development of conventional and nonconventional machining methods and tooling for ceramics, electrical discharge machining, waterjet cutting, laser cutting, damage characterization and control, and post-machining treatments. However, this program has now been discontinued.

The basic research offices of the Navy (ONR), Air Force (AFOSR), and Army (ARO) are not currently supporting research in ceramic machining; neither are the Navy and Air Force materials laboratories. The Bureau of Mines, NASA, and most other government organizations do not have any current programs on machining of ceramics.

3.5 Research Activities in Other Countries

Although the main thrust of this survey was to analyze the status of ceramic machining in the United States, it was deemed necessary to inquire into the research activities in other countries. An examination of recent papers published in the English language indicated that researchers in Japan, Germany, and the United Kingdom are very active in research related to machining of advanced ceramics. Publications from Japan are mostly concerned with the development of new and innovative machining techniques, for example, in the areas of polishing and ductile-regime grinding. Those from Germany and the United Kingdom mostly deal with the development of specialized machine tools and creep-feed grinding. Based on this examination, it can be safely stated that the total number of papers related to ceramic machining from Japan, Germany, and the United Kingdom exceeds those published by the researchers in the United States. This, however, does not include papers published in non-English language journals, which were not available for this assessment. A noted example of the activities in Japan and Europe is the availability of two new machine tools from Japan and the United Kingdom for grinding of advanced ceramics. Considering the research papers and the industrial activities related to ceramic machining outside the United States, it can be concluded that a coordinated research and development program would be crucial to sustain the economic position of the United States in the Global market of advanced ceramics.

3.6 Recent Publications

To more completely define the research issues for a coordinated program, an additional literature search was conducted to examine certain areas in greater detail. Three areas were selected:

- Optimization of the Grinding Process,
- Chemically Assisted Machining, and
- Machining Damage and Detection.

This literature search included a variety of databases (Ceramic Abstracts, Patents, Compendex, Engineering Index, and the National Technical Information Service) and covered a period of 20 years. The search key words are listed in Table 7. A total of 741 usable abstracts were retrieved as applicable to the three subjects listed above. The distribution of abstracts among different machining methods is given in Table 8. Results of the literature search showed that abrasive machining accounted for 43 percent of the publications. Most of the publications concerned with nonabrasive methods applied to cutting as contrasted to machining for contour generation. This was particularly true for directed energy beams. The survey also showed that chemical effects during machining have been investigated, but not in an extensive or thorough manner. The results of the literature search are described in the following three sections.

Table 7. LITERATURE SEARCH KEY WORDS

Process	Material
Machining	Ceramic
Finishing	Aluminum Oxide
Grinding	Silicon Nitride
Polishing	Silicon Carbide
Cutting	Zirconium Oxide
Honing	Boron Carbide
Lapping	Silicon Dioxide
	Alumina

Table 8. DISTRIBUTION OF ABSTRACTS RETRIEVED ON MACHINING METHODS

Abrasive Methods (318)	Nonabrasive Methods (105)
Grinding (190)	Electrical Discharge Machining (28)
Honing (9)	Chemical and Electrochemical Machining (12)
Lapping and Polishing (34)	Laser Beam Cutting (55)
Ultrasonic Machining (30)	Electron Beam and Ion Beam Cutting (8)
Liquid Abrasive Jet Cutting (16)	Friction Cutting and Microwave Cutting (2)
Turning and Cutting (39)	
Combined Methods (25)	NDE and QC (156)
Chemical Polishing (15)	Materials and Misc. (137)
Electrochemical Grinding (5)	
Thermally Assisted Turning (3)	
Mechanical-Electrical Discharge (1)	
Chemical-Electrical Discharge (1)	

4. OPTIMIZATION OF THE GRINDING PROCESS

The dominant position of grinding in machining of ceramics can be attributed to a combination of several important characteristics. These include: great flexibility in generating different workpiece geometries, relatively low-tool forces and tool wear, and low workpiece damage. These same characteristics are also the basis for the important position that grinding holds in the machining of metals. The other abrasive methods may exhibit some of these capabilities, but not all. Honing, lapping, polishing, and ultrasonic methods produce very low damage and smooth surfaces. Intricate geometries can be generated with ultrasonic machining. Honing and lapping are outstanding in their ability to produce close tolerances. However, for all these methods under most conditions, removal rates are relatively low compared to grinding. Only limited precision and control of geometry is possible with liquid abrasive jet machining except in cutting thin sheets where excellent results can be obtained. Otherwise, liquid abrasive jet machining is restricted mainly to cutoff operations. Thus, of these methods grinding is the most broadly applicable to machining of ceramics, while the others are employed for specific tasks to which they are uniquely suited.

The purpose of this section is to review the fundamental mechanisms of material removal processes during grinding and analyze the effects of important parameters that must be optimized in a production process. The parameters that control the removal rate and damage formation are specifically highlighted. Some recent advances in grinding are discussed and recommendations are made on important directions for research in grinding of advanced ceramics.

4.1 Fundamentals of Abrasive Removal

The abrasive methods, including grinding, all employ hard particles to remove material from the workpiece. Forces applied to the abrasive particle (largely inertial in the case of ultrasonic impact and liquid abrasive jet machining) cause it to penetrate and remove material from the surface by some combination of chip formation, fatigue and fracture processes. The details of the process are determined by the nature of the abrasive particle (shape, strength, size, etc.), the properties of the workpiece, the interaction forces between the particle and workpiece, the time dependence of these forces, and the nature of the surrounding environment. The physics and chemistry involved are complex and only understood on the basis of greatly simplified models.

The simplest model of material removal by abrasion considers the penetration of the tip of a single hard particle into the surface of the workpiece (Figure 11). As penetration occurs in a brittle material, elastic displacement is followed by plastic flow and fracture. Fracture is considered to occur only after a threshold load is applied to the particle. According to Evans and Marshall [1981] the threshold load, P^*, is given as:

$$P^* = \zeta \ (K_c^4/H^3) \ f(E/H) \qquad (1)$$

where K_c is the fracture toughness; H, the hardness; and E, the elastic modulus of the workpiece material. The function f(E/H) and the dimensionless constant ζ depend on the type of crack, shown in Figure 11. For most brittle materials the threshold loads are quite small. Machining at loads, or correspondingly at particle penetration depths, less than the threshold is generally referred to as ductile-regime grinding [Bifano et al. 1991]. The critical depth of cut for silicon nitride and silicon carbide is approximately 100 nm [Bifano and Fawcett 1991, and Mizutani et al. 1990]. The technology of ductile-regime grinding is

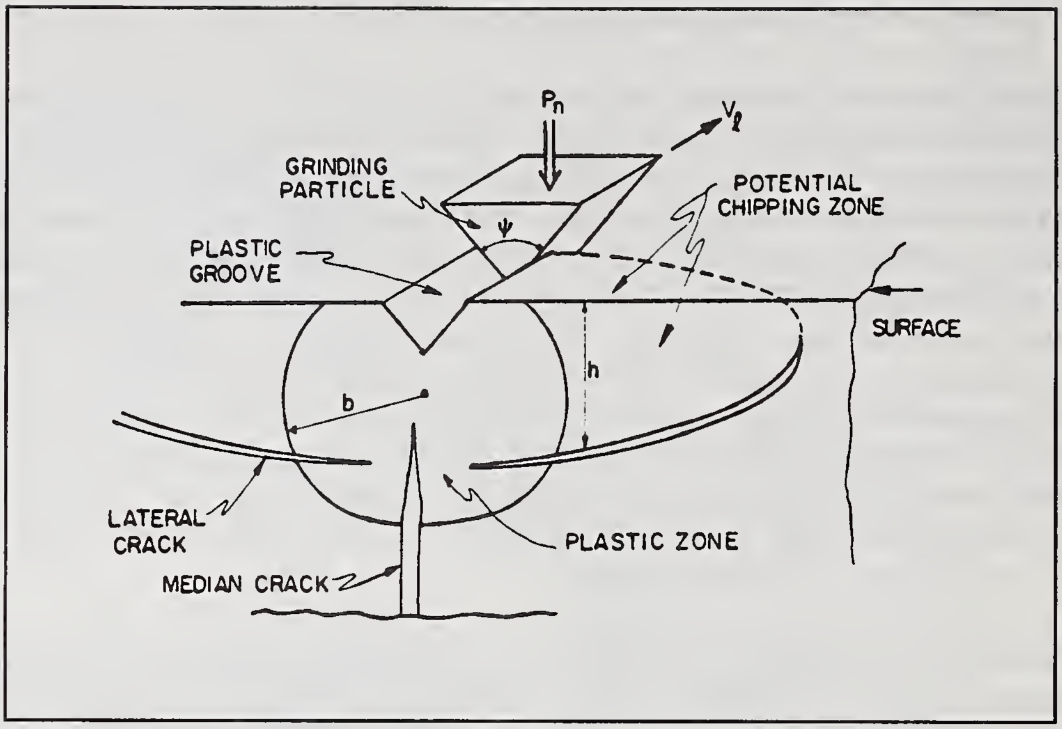

Figure 11. Lateral fracture mechanism [Evans and Marshall 1981].

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still under development and is highly specialized in nature. To control the particle penetration depth, the machines employed must be of the highest precision and rigidity. Also, a close temperature control is required.

Lateral, median and radial cracks are generated during the abrasive interaction, but removal of material is considered to result principally from the extension of lateral cracks along the path of the abrasive particle. Based on a model for lateral crack extension, Evans and Marshall [1981] have developed the following relation for the volume of material removed by an abrasive particle, in a grooving process:

$$V = \alpha_3 \frac{P_n}{K_c^{1/2} H^{5/8}} (E/H)^{4/5} \ell_i \qquad (2)$$

where P_n is the peak normal load; ℓ_i the length of the groove; and α_3 a material independent constant. This equation has been shown to be in reasonable agreement with experiments for a relatively wide range of different materials, demonstrating the general applicability of the concepts involved.

The Evans and Marshall model can be applied to honing and polishing, where material removal is primarily the result of translating particles with respect to the surface to produce grooves. In lapping, the motion of the particles is considered to be predominantly rolling rather than sliding [Indge 1990]. Rolling of the irregular particles is accompanied by repeated indentation of the surface. Fracture, particularly at adjacent indentations is the mode of material removal. Similarly, indentation by the impact of energetic particles is the primary mode of removal in ultrasonic machining and liquid abrasive jet machining. Removal rate is a function of particle velocity, shape, mass, and attack angle, with the highest removal rate being at normal incidence for brittle materials.

Although lateral cracks are the most important with respect to material removal, median and radial cracks, which are normal to the surface, are the most critical in terms of strength limiting damage. The dependence on load, hardness, and toughness which applies to the extension of lateral cracks is similar for radial and median cracks [Evans and Marshall 1981]. Thus, rapid material removal achieved by large lateral crack extension will also result in larger and more damaging median and radial cracks.

The low thermal conductivity of some ceramics can also contribute to an increased susceptibility to damage. Thermal stresses associated with high local temperatures may lead to larger cracks. A dull and rounded grit which slides and deforms the surface without removing appreciable material is a major source of frictional heating and increased temperatures. Excessive temperatures are not only damaging to the workpiece but also to the abrasive particle, and hasten the degradation of the grinding fluid.

With complete control over abrasive particle size, shape, and contact dynamics, the workpiece removal rate and damage would also, in principle, be under complete control. This is an ideal situation that is not likely to be achieved in practice given the random shape and orientation of the abrasive grit, uncertainties concerning the motion and forces applied to the grit, and variations in the workpiece properties. Nevertheless, it is important to bear these principles in mind when considering abrasive machining processes and the possibilities of their improvement. It might also be noted that these principles lead to the set of rules of which most experienced practitioners are aware: maximum removal rate with minimum associated damage is achieved by employing grit that is sharp, of the narrowest possible size distribution, and in the highest concentration consistent with the removal of swarf.

4.2 Elements of the Grinding System

Having given a brief discussion of the physical basis of the removal process, the following discussion will provide a short overview regarding the practical aspects of grinding. Greater detail is available in several text books [Metzger 1986 and Malkin 1989] and handbook articles [Davis 1989, Drozda and Wick 1983, and King 1985]. As mentioned previously, it is convenient to consider the grinding process in terms of the five elements of the system: machine tool, grinding wheel, truing and dressing, grinding fluid, and workpiece. The first four of the elements will be discussed in this section. References to the workpiece, specifically advanced ceramics components, is made throughout this report.

4.2.1 Machine Tool

Machines used to grind ceramics are generally the same as those employed for metals. For application to ceramics one of the most important machine characteristics is that of rigidity. Because of the greater hardness of ceramics, the normal force in grinding is usually higher than that for metals. Thus, to minimize deflections, high rigidity of the spindle, table and feed mechanisms is required. Freedom from vibration and precise control over all machine motions is also necessary in order to avoid excursions in machining forces which are likely to increase the level of workpiece damage. Precise control is also required by the fact that the final depth of cut may need to be very small to minimize damage and produce a smooth surface. In general, a machine tool with computer numerical control (CNC) is preferred. The more advanced machine shops specializing in the machining of ceramics are generally aware of these machine requirements, but other shops often are not.

4.2.2 Grinding Wheel

The grinding wheel is in many respects the most important element in the grinding of advanced ceramics. The wheel consists of the grit, bonding medium, and perhaps a hub or other means of supporting the grit/bond composite structure. The grit must be sufficiently hard and strong to penetrate the workpiece and withstand the interaction forces during chip removal and must also have a high resistance to the thermal and chemical degradative processes encountered during grinding. The function of the bond is to hold the grit in a more-or-less rigid manner with the grit extending out from the bond sufficiently to engage the workpiece. The concentration of grit should be a maximum, consistent with the removal of swarf and other wheel characteristics. Some important bond properties are strength, hardness, elastic modulus, resistance to thermal and chemical degradation, thermal conductivity, wear resistance and dressability. Porosity and sometimes solid lubricants are incorporated in the bond structure to achieve desired performance.

As noted earlier, diamond is the principal abrasive employed in the grinding of advanced ceramics. Diamond is anisotropic in strength, showing cleavage on {111} planes and reduced wear resistance on certain other planes and directions [Field 1979]. A major source of weakness or friability is the presence of flaws and grain boundaries. Abrasive grit may be either natural or synthetic [Metzger 1986]. Grit prepared from natural diamond is crushed and sieved. Each particle is typically a single crystal, irregular in shape and quite tough. Synthetic diamonds are prepared by a quasi-static, high-temperature, high-pressure process, or explosively. High-temperature, high-pressure synthesized diamonds may be either monocrystalline or polycrystalline. Explosively formed diamond is polycrystalline with an extremely small microcrystalline grain size. Polycrystalline grit shows considerably greater friability than monocrystalline grit. Friability is an extremely important property in abrasive grit [Metzger 1986] since it is through this mechanism that the self-sharpening characteristics are obtained. Abrasive grit is available both uncoated and coated with metal, usually nickel or copper. Metal coating improves retention in the bond, may hold friable grit together, and acts as a heat sink preventing thermal damage to the bond.

In general, there are four different bonding systems used for superabrasive grinding wheels. These are: vitreous, resin bond, metal bond, and plated. Each bond system has its own characteristics which influences performance and application [Subramanian 1988]. Vitreous wheels are prepared by mixing abrasive particles with clay, feldspar, frit and usually other additions, and firing at elevated temperatures. Vitreous bond diamond wheels are a more recent development [Cooley and Wapler 1984] and have demonstrated the ability to remove material at very high rates [Hoshimoto et al. 1984]. The excellent truing properties and ease of dressing are also distinct advantages of the vitreous bond. Resin bond wheels typically employ a thermosetting phenolic resin. Resin bonds hold the abrasive in a relatively resilient matrix and can result in less workpiece damage. For this reason resin bond wheels are the most widely used in grinding advanced ceramics. Metal bond wheels are formulated by sintering the abrasive with powdered metals, principally bronze alloys. Metal bond wheels are often used in cut-off applications. Because of their high strength, metal bond wheels can be quite thin; this minimizes kerf losses. Plated wheels are prepared by suspending abrasive particles in an electroplating or electroless-plating solution and depositing a layer on the wheel blank. Plated wheels of small dimensions are often used to drill holes or machine intricate shapes.

Not only are there wide differences in properties associated with different bond classes but also significant differences exist within each class. Each wheel manufacturer has its own proprietary formulations and may offer many different variants of each bond. Combining the different bonding media with the several different types of diamond grit available, there are many dozens of different wheels from which to choose. Wheel manufactures may even provide custom formulations to meet a given customer's requirements. A standard ANSI code is used to identify abrasive type, size, hardness grade, concentration, bond type and other characteristics. However, there is no standard regarding performance or application; and these features depend greatly on each manufacturers formulation.

In developing a wheel for application to advanced ceramics [Kuroshima et al. 1985 and Sugishita et al. 1991] it is necessary to optimize the bond and grit components with respect to the properties of the workpiece, required finish, tolerance, machine tool, grinding fluid, and the type of grinding operation, e.g., internal, external, etc. An overriding consideration is, of course, the overall strength and safety of the wheel. All of the foregoing factors result in a very large matrix of properties to consider. In practice, once wheel safety is established, emphasis is usually given to providing required finish, dimensional tolerances, and avoiding obvious forms of workpiece damage such as chipping and visible fracture. This is largely accomplished by selecting an appropriate bond type, grit size, and adjusting feed rates. Because of the relatively high rates of wheel wear experienced when grinding advanced ceramics and the high cost of diamond wheels, minimizing wheel wear becomes an extremely important issue.

Wheel wear occurs by several mechanisms: attritive wear of the diamond grit, grit fracture, grit pullout, and fracture or wear of the bond phase itself. Here, attritive wear of the grit refers to mechanical, thermal, chemical, or a combination of wear processes that result in relatively smooth rounding of the grit rather than larger scale fracture which leaves sharp points and edges. With advanced ceramics, attritive wear of diamond is relatively rapid, which dulls the grit and results in workpiece damage and poor grinding performance. It is for this reason that it is advantageous to employ friable polycrystalline diamond instead of tough monocrystalline grit. For softer ceramics, for example glass, for which attritive wear is small, the tougher monocrystalline grit are preferred.

Although the self-sharpening qualities of friable grit are an important advantage, the concentration of exposed grit is continuously diminished, effectively reducing the available abrasive points. Here, compensating wear of the bond would expose fresh grit and maintain the concentration. This can be achieved to some extent with resin and vitreous bonds and is an important factor in bond formulation and choice.

4.2.3 Truing and Dressing

Wheel truing and dressing are very important elements in the grinding operation. The term truing refers to the process which is used to obtain and maintain a desired wheel profile geometry and concentricity. Dressing is the process by which fresh and sharp abrasive grit are exposed. It is accomplished mainly by removing a small amount of bond, although dulled grit may also be removed. The dressing of a used wheel may only involve the removal of adhered workpiece or decomposed grinding fluid materials. The distinction between the terms "truing" and "dressing" is not always clear and correctly made. In some cases the term dressing refers to both processes. Also, some truing methods provide a dressed surface without additional treatment. The very properties that enable the grinding of advanced ceramics are also those that tend to make diamond grinding wheels difficult to true and dress. While truing and dressing of conventional aluminum oxide and silicon carbide grinding wheels is often done with a single or multiple point diamond tool, this is not possible with diamond wheels.

Truing of diamond wheels can be accomplished by a number of methods [Green 1985, and Metzger 1986]. One of the most widely used methods is brake truing. The brake truing device consists of a vitreous aluminum oxide or silicon carbide wheel which is mounted on a spindle containing a braking mechanism. With the truing wheel held against the rotating diamond wheel, braking results in sliding as well as rolling, so that a grinding action takes place between the two wheels. Wear of the truing wheel is, of course, rapid. Better results are said to be obtained by employing a motorized truing wheel which is driven faster than the diamond wheel [Metzger 1986].

Crush truing can be employed with vitreous and recently developed crushable metal bond wheels [Green 1985, and Metzger 1985]. In this method a freely turning wheel of mild steel is held against the rotating diamond wheel with sufficient force to crush the surface of the diamond wheel. This method has been widely used to true and dress vitreous aluminum oxide and silicon carbide wheels.

Dressing is accomplished by holding a soft aluminum oxide stick against the wheel, thereby wearing away the bond. Resin bond wheels may also be dressed by grinding a mild steel block which produces long chips that cut away the bond [Metzger 1986]. Dressing by means of an abrasive fluid jet has been demonstrated by Salje [1985]. Electrical discharge machining (EDM) [Kaiser 1977, and Shore et al. 1991] and electrochemical machining (ECM) [Murata et al. 1985, Ohmori et al. 1991 and Suzuki et al. 1991] have been employed in dressing metal bond wheels. The latter methods can be used for continuous dressing during grinding. With this approach wheel dressing can be adjusted according to grit wear and the maximum efficiency in grinding rate maintained. A schematic of the in-process wheel dressing used by Murata et al. [1985] is shown in Figure 12.

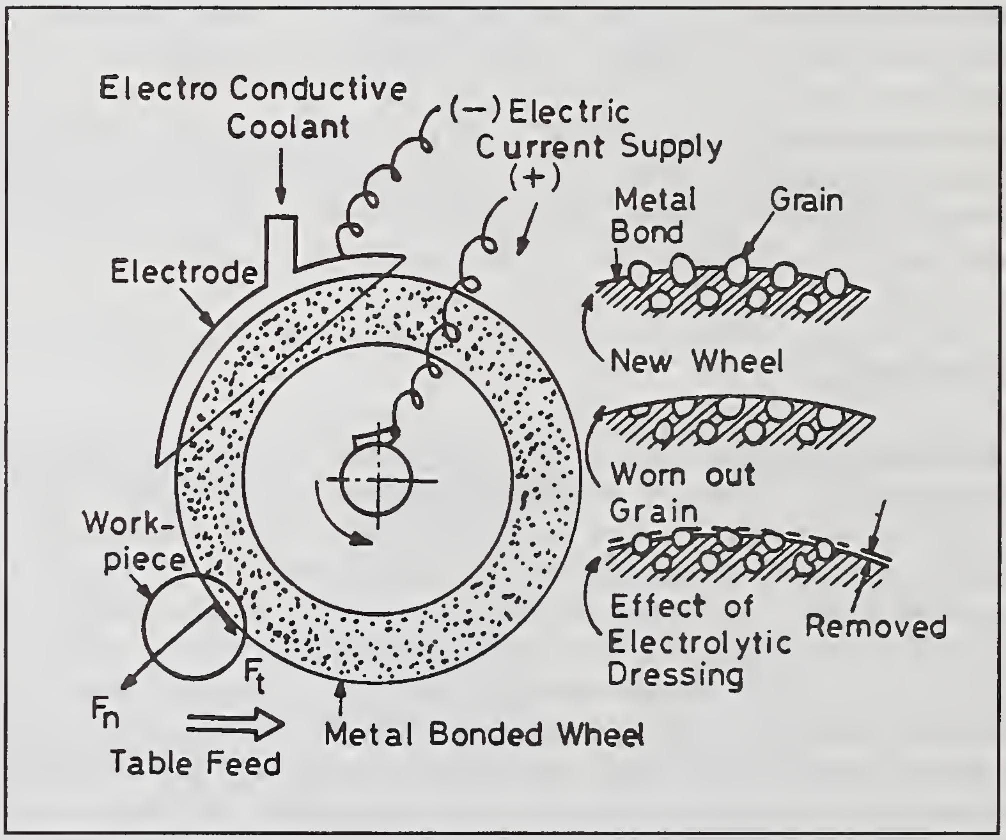


Figure 12. Schematic of in-process wheel dressing by electrochemical machining [Murata et al. 1985].

The selection of an appropriate grinding wheel for metals applications is fairly well established by each manufacturer, although there may be many trade-offs to consider. For example, rapid removal rate is usually accompanied by higher wheel wear which in turn affects achievable precision of form and surface finish. For application to advanced ceramics, recommendations regarding wheel type and appropriate grinding parameters can be obtained from wheel manufacturers. Many of the shops queried in this study stated that such recommendations have not been satisfactory. It was thought that this was due to the sensitivity to different machine characteristics, workpiece properties, and operator practices. It was suggested that a more successful approach to wheel selection was through the provision of a trial wheel to the customer for evaluation. The customer would then report back to the wheel manufacturer problems such as insufficient wheel wear life (G-ratio), incorrect surface roughness, a tendency towards burning, or excessive workpiece chipping. The wheel manufacturer could then provide a different wheel or make certain adjustments in the formulation, all based on knowledge about the relationship between grinding characteristics and wheel properties gained from previous experience.

Many opportunities exist for enhanced performance in the grinding of advanced ceramics by improving wheel properties. These include optimizing grit properties such as friability and shape, matching grit and bond wear characteristics for application to specific advanced ceramic materials, and developing improved truing and dressing methods. This could also include the optimization of bond materials for continuous dressing methods. For example, the development of conductive resin bonds would permit continuous EDM or ECM truing and dressing.

4.2.4 Grinding Fluid

The main functions of the grinding fluid are to control the temperature of the wheel and workpiece, and carry the swarf away from the contact. In addition, the fluid may also lubricate the wheel/workpiece contact, thereby reducing the friction force and also frictional heating. The lubrication function is especially important where there is a tendency for the workpiece material to adhere to and "load" the wheel. While serving these important functions, the grinding fluid must possess a number of other characteristics. It must be stable and durable and not be hazardous to operating personnel and the environment, and should not contribute to, or better, should protect the equipment from corrosion.

Using the most effective grinding fluid can allow higher wheel and table speeds, greater depths of cut, increased wheel life, better surface finish, reduced subsurface damage, and improved dimensional control. Clearly, the grinding fluid is an important element in the grinding process.

Grinding fluids used for metals can be classified into three types: mineral oils, soluble oils, and chemical fluids. These will be described shortly. But, first, we must recognize that grinding fluids contain various additives to improve their performance. Additives are used to reduce friction and wear at the cutting interface, to retard chemical degradation of the fluid, and to protect the workpiece from severe reactions with the fluid. Other types of additives are used as emulsifiers, foam inhibitors, and bacteriocides.

Straight mineral oils and mineral oils plus polar and extreme pressure (EP) additives are usually used in low speed grinding and metal cutting. Because of the higher heat capacity of water compared to mineral oils, it is assumed that waterbase fluids perform better in controlling the grinding temperature. Recent research, however, has shown that mineral oils are superior to waterbase fluids in performance, even at higher speeds [Osman and Malkin 1973, and Howes 1990]. To explain these results, we must consider that approximately 50 percent of the heat is generated from sliding at the abrasive/workpiece and abrasive/chip interfaces. The rest comes from deformation in the shear zone. Therefore, waterbase fluids may be efficient in controlling the overall workpiece temperature by removing the heat from the cutting zone. However, mineral oils and the additives will reduce friction and thus the heat generated at the sliding interfaces [Mittal et al. 1984, Mould et al. 1972a and 1972b, and Wakashiro et al. 1990]. This action will have a direct effect in reducing the machining damage in the cutting zone. Furthermore, the lubricating additives decrease the rate of wear of the abrasive grains [Duwell et al. 1988], and reduce the adhesion tendency between the chips and the wheel.

Although mineral oils are superior to waterbase fluids, they are not generally used in the United States because of fire and health related safety hazards, which would require special containment and improved ventilation. The oil mist generated during high speed grinding can make the area around the machine slippery and, therefore, hazardous. Also, inhalation of the hydrocarbon vapors could be harmful. Disposal of the used mineral oils is costly. The alternative is to use soluble oils, which are emulsions of oil in water, where the fraction of water is generally much greater than that of oil. These fluids contain additives as emulsifying agents, as well as polar and extreme pressure additives for friction reduction. Soluble oils have the advantage of high heat capacity of water, as well as the lubricating capability of the mineral oils and lubricous additives. One disadvantage of the soluble oils is their white milky color, which obscures vision of the cutting zone.

Chemical fluids are mixtures of water and water soluble additives, such as polyglycols, amines, alcohols, and phenols. These fluids are transparent but they do not, in general, have the lubricating capability that either mineral oils or soluble oils have.

The high stresses and temperatures generated at the grit/workpiece contact provide favorable conditions for chemical reactions which can exert a significant influence on the grinding process. The reactions may involve the workpiece, the grinding wheel (both grit and binder), the grinding fluid and the air atmosphere. Any pair or combination of several of these entities may participate in the reaction. As an example, it is well known that diamond is not a satisfactory abrasive for grinding iron and ferrous alloys unsaturated in carbon. The affinity of these materials for carbon is such that carbon atoms from the diamond diffuse into workpiece resulting in a high wear rate of diamond. Cubic boron nitride (CBN), however, is much more stable with respect to reaction with ferrous alloys and is an effective abrasive for these materials. On the other hand, CBN presents an interesting example of the effect of the environment, in this case the grinding fluid, on wear. CBN performs poorly in the presence of many waterbase fluids, exhibiting wear rates many times greater than with mineral oil grinding fluids [Metzger 1986].

There are numerous examples [Malkin 1989] of the improvements that can be gained by selecting a fluid that through chemical means increases the capability to grind a material at higher rates. Sulfur and chlorine additives are used in grinding fluids for metals. Other additives are used to grind glasses. Similar examples are not available in the case of advanced ceramics, although in discussions with ceramic machine shops, it was stated that some fluids were notably better than others.

4.3 Suggested Technical Approaches

Considering the widespread use of grinding and the fact that significant opportunities exist to improve the grinding technology for application to advanced ceramics, a focused research and development effort could result in substantial economic benefits. Particularly, research efforts should concentrate on obtaining machining data for grinding optimization, development of grinding fluids and diamond wheels specifically designed for advanced ceramics, development of high-strength machinable ceramics, and design changes to the machine tool. Some of these research areas are described in more detail in Section 7. Certain fundamental mechanistic issues also need to be investigated; for example, the mechanism of material removal involving multigrits as opposed to the present model that involves only a single grit, the effect of other crack systems in addition to the lateral cracks, and the effect of environment on crack extension. Research on machine tools should focus on design changes that would allow further utilization of potentially important processes of creep-feed grinding [Konig et al. 1991] and ductile-regime grinding [Mizutani et al. 1990]. Some new concepts of machine tool design [Salmon 1990] also need to be considered. Other issues related to chemical effects during grinding and detection of machining damage are described in more detail in the following sections.

5. CHEMICALLY ASSISTED MACHINING

In the literature search only a few publications were found that considered chemical effects on the abrasive machining of ceramics. Most of these publications were concerned with the drilling of rocks and polishing of glass. The results reported in the publications were analyzed with respect to applicability to ceramic machining, and are reported in this section. Based on the analysis of the published literature, it is suggested that abrasive machining processes including grinding, liquid abrasive jet cutting, ultrasonic machining, and single-point turning, may benefit from chemical assistance, introduced by the grinding or cutting fluid.

In general, the fluid appears to play a stronger role in the process than just temperature and friction control and swarf removal. The chemicals can affect the workpiece, the abrasives and their wear rates, the transfer of material, the action of the swarf, the properties of the wheel, and other factors. The effects may be either beneficial or harmful and each case must be independently investigated. Although chemical techniques may have a series of beneficial effects, they can not be so aggressive as to endanger the working environment, or add great complexity to ceramic machining processes.

5.1 Chemical Effects in Machining

Corrosion rates of advanced ceramics in liquids are reasonably rapid only for certain specific combinations of materials and environments [Anonymous 1990]. Examples are phosphoric acid acting on alumina, sulfuric acid and nitric acid on tungsten carbide, and sodium hydroxide and potassium hydroxide on Si/SiC composites. In all these cases, temperatures near 1000°C are needed to achieve sufficiently fast reaction rates. Chemical milling techniques have been developed for difficult to machine metals, e.g., titanium. It is possible that such an approach would succeed for ceramics with particular machining requirements.

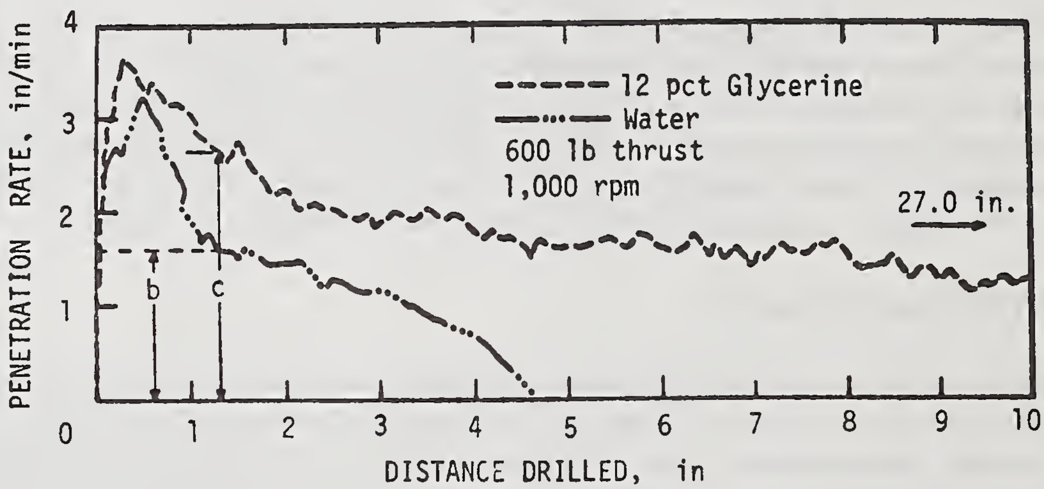
Molten salts are known to be corrosive to ceramics [Jacobson 1986]. In studies of sintered SiC it was found that thin films of Na_2CO_3 (in CO_2 atmospheres), Na_2SO_4 (in O_2 atmospheres), and Na_2SO_4 (in SO_3 atmospheres) all reacted significantly at temperatures of 1000°C. The mechanisms generally involved silicate formation and dissolution in the molten salt. In studies of alumina, aqueous solutions of sodium borate were found to be corrosive at 900°C [Scott et al. 1986]. Whether such reactions can be utilized in other ways at lower temperatures appropriate to chemically assisted machining is not clear; further study is needed.

Yeomans and Page [1989] have reported on liquid metal attack of zirconia-toughened alumina, sialon, and silicon nitride ceramics. In the latter material, grain boundary phases were particularly susceptible. Liquid metals studied included iron-based and nickel-based alloys at temperatures in excess of 1000°C.

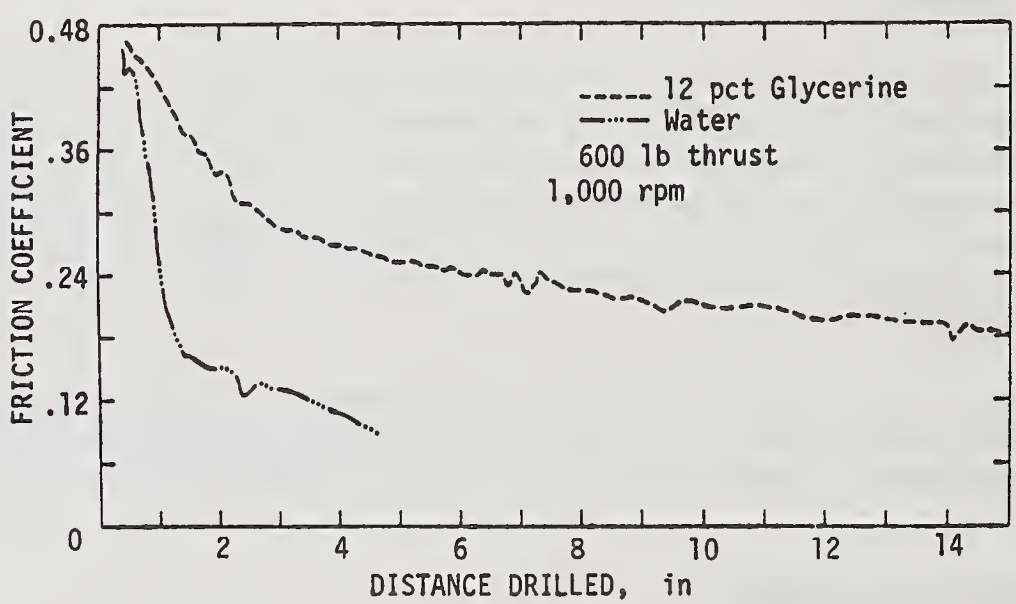
5.2 Chemical Effects in Drilling

Extensive studies of chemical effects on diamond drilling of stone have been reported [Cooper 1979, and Mills and Westwood 1980a]. It was found that the effect of liquids on drilling hard stone was that of a reduction of diamond wear rather than a direct effect on the stone itself. In one study it was found (Figure 13) that addition of 12 percent glycerine to water reduced the rate at which the drill penetration rate decreased with drilling distance, and at the same time maintained a higher torque (i.e., friction coefficient) during drilling [Cooper 1979].

The effect of normal alcohols on diamond drilling of granite also has been studied by Cooper and Berlie [1976]. They reported a significant improvement in drill penetration characteristics upon alternating the substitution of a series of alcohols for water as the drilling fluid. Figure 14 shows the observed reduction in loss of penetration rate for the drill. The results were interpreted to reflect a reduction in wear of the diamonds in the drill bit.



(a)



(b)

Figure 13. Effect of environment on (a) drilling penetration rate in quartz, and (b) friction coefficient derived from torque on the drill [Cooper 1979].

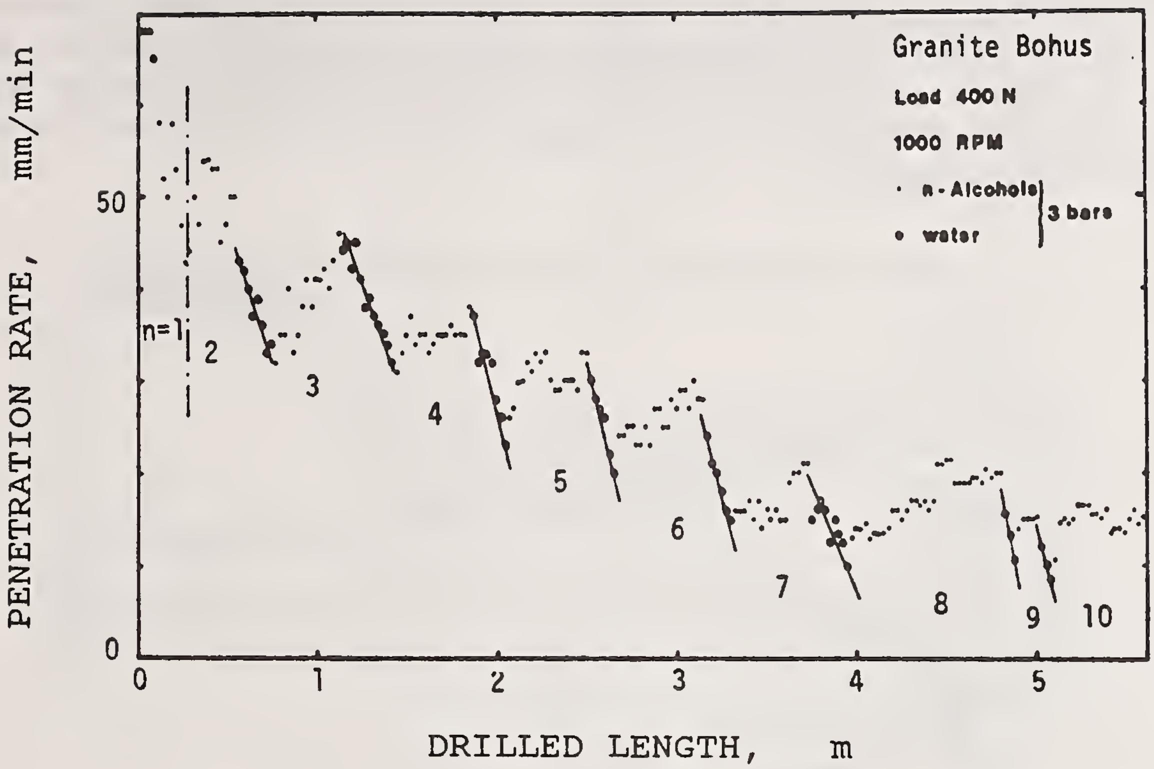


Figure 14. Effect of environment on drilling rate in granite, alternating water and a series of alcohols [Cooper and Berlie 1976].

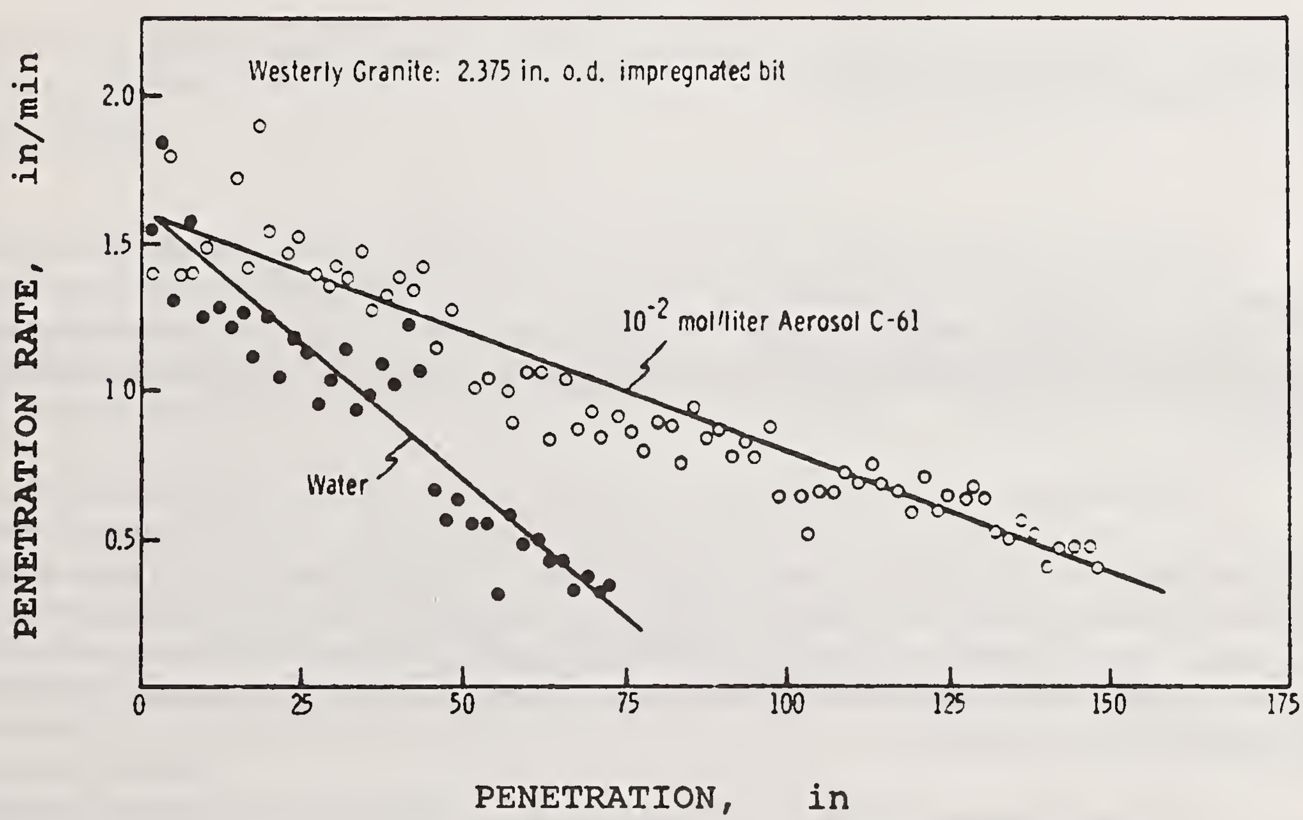


Figure 15. Effect of environment on drilling rate in granite [Mills and Westwood 1980a].

Mills and Westwood [1980a] have reported a study of the effect of one chemical additive on diamond drilling in granite. The effect of using a commercial cationic surfactant in aqueous solution is shown in Figure 15. It is seen that the additive did improve the penetration rate of the diamond drill compared to that observed with water as a drilling fluid. In an earlier study of another additive [Mills and Westwood 1977], the authors also reported a significantly improved diamond drill penetration rate in granite as shown in Figure 16.

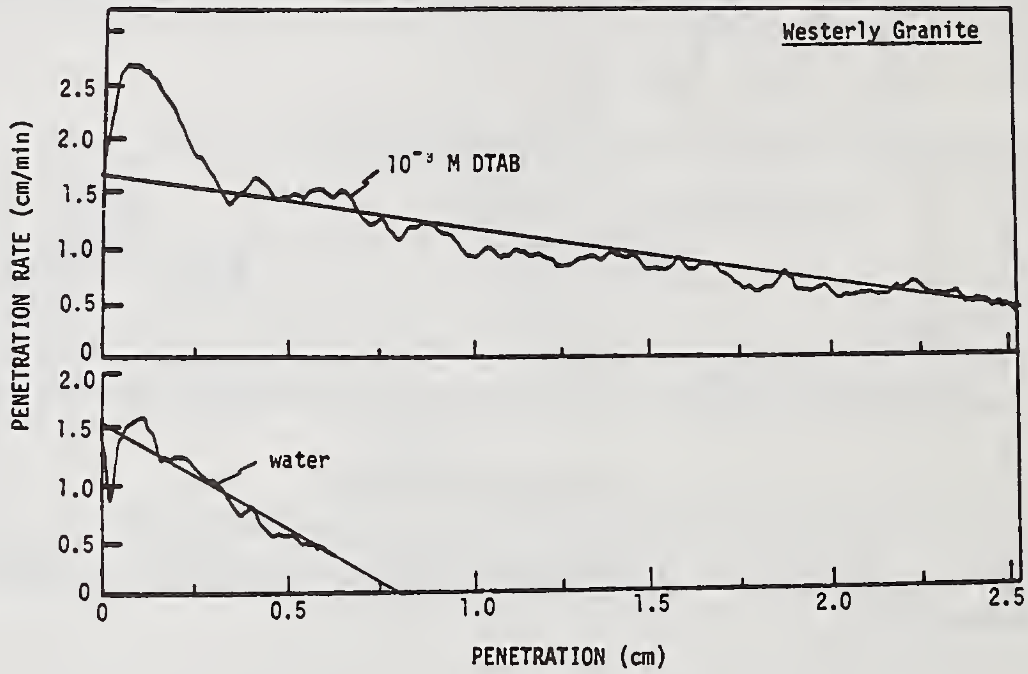


Figure 16. Effect of environment (dodecyl trimethyl ammonium bromide, DTAB) on drilling rate in granite [Mills and Westwood 1977].

Mills and Westwood [1980b] have also reported chemo-mechanical effects on diamond drills applied to other types of hard rock. Figure 17 shows such a comparison using a 0.25 percent solution of a cationic surfactant (FBH) in water. While the initial drilling rates were similar, the surfactant extended the life of the bit by a factor of 2 to 3 compared to water, in which the diamond wore more rapidly.

Similar effects to these for drilling of rock have been reported for drilling an alumina ceramic. Swain et al. [1975] found a good correlation between maximum drilling rate with diamond core drills and the isoelectric point (no net surface charge) of the surfaces and various alcohols and aqueous fluids. As shown in Figure 18, in all three cases the drilling rate maximum corresponded to the isoelectric point. They also measured surface hardness by microindentation and found that it was maximum at the isoelectric points. The authors suggested that cutting occurred by a brittle process that was most efficient at maximum surface hardness.

Mills and Westwood [1980a] and Westwood et al. [1981] have reviewed and discussed the apparent diversity of findings in the literature on the influence of chemistry on mechanical behavior and on drilling behavior. They point out the complexity of the processes involved. While one mechanism,

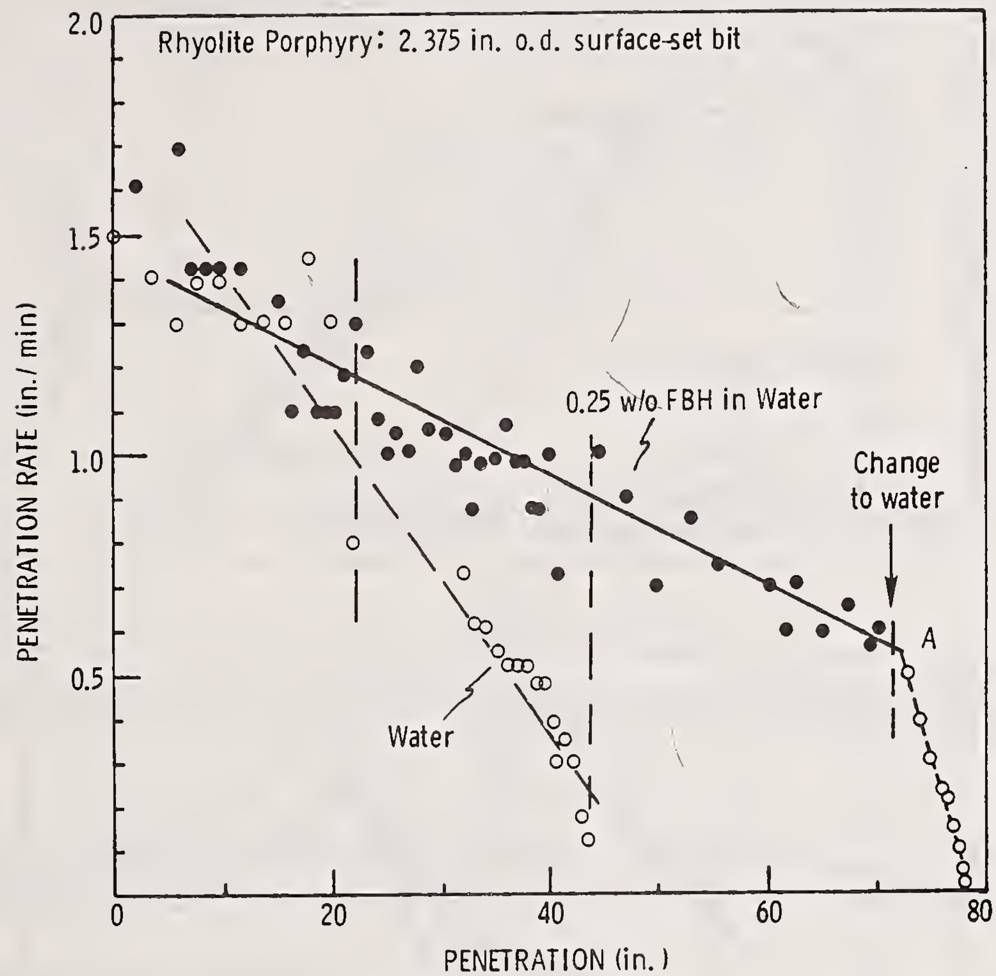


Figure 17. Penetration rate for rock drilling using water and water plus 0.25% FBH [Mills and Westwood 1980b].

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absorption-induced changes in surface energy, may occur in special cases, it cannot be the general mechanism because of kinetic requirements. They also state that another mechanism, the effect of adsorbed surface species on dislocation mobility in a solid being mechanically stressed, cannot be generally invoked; and they reference experimental evidence for support. They concluded that for the case of diamond drilling in hard rock, it appears that the controlling mechanism is wear of the diamond grit.

In drilling soft ceramics, however, environmental effects on the flow-fracture behavior of the solid can be controlling. Figure 19 shows some results of Westwood et al. [1981] on drilling calcite, a relatively soft mineral. The initial portion of the drilling curve shows a small decease in the drill penetration rate due to drill wear occurring in the butyl alcohol environment. Upon adding 10% water to the alcohol, drill penetration rate increased abruptly, indicating an effect of the environment on the calcite surface behavior.

While Westwood and co-workers state that substantial improvements in drilling, up to a factor of five or more, can be expected, they emphasize that this is only true if the proper conditions are

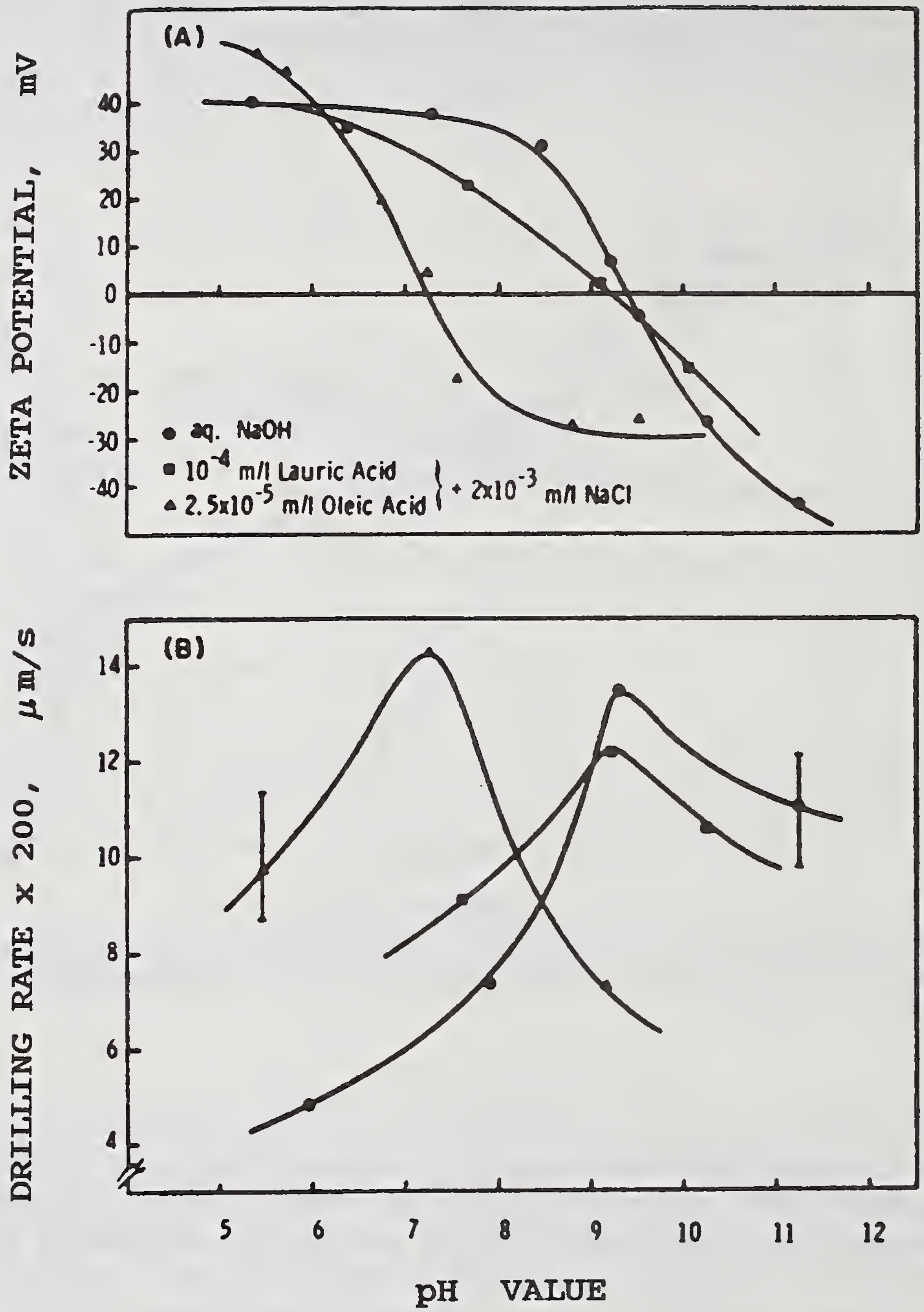

Figure 18. Effect of pH on (a) zeta potential, and (b) drill rate in alumina for three solutions [Swain et al. 1975].

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present. Those conditions involve drill speed, drill bit geometry, additive concentration, and material type and hardness, among other factors, since the chemo-mechanical effects are strongly influenced by adsorption kinetics. They state that under unsuitable conditions, there may be no observable effects.

In another view of the subject, Cuthrell [1979] has discussed the effects of chemical environments on ceramics, glass, and minerals during cutting. He states that hydrogen effects are crucial, and that

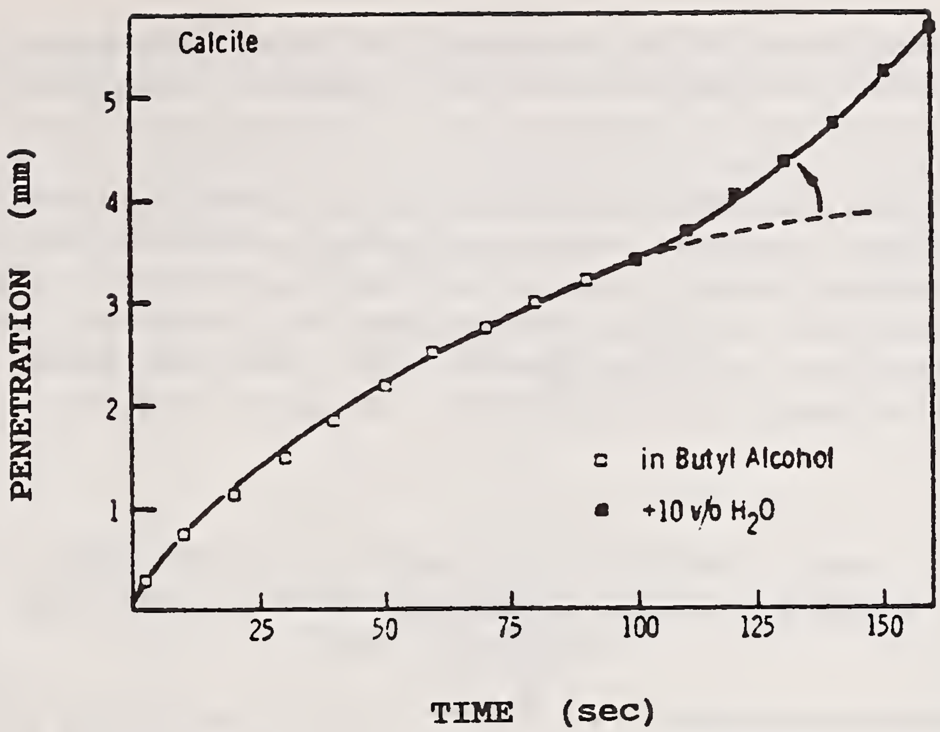

Figure 19. Drilling penetration rate for calcite using two solutions [Westwood et al. 1981].

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hydrogen availability is dependent on the type of binding in the liquid. It is not yet clear how applicable this explanation may be.

5.3 Chemical Effects in Polishing

Abrasive polishing of surfaces utilizes fine grit abrasive particles and low contact pressures in order to control cutting depths to small amounts for the desired high surface smoothness. As a result, low material removal rates are obtained. These conditions are such that chemical effects from the polishing environment can be significant.

Vora et al. [1982] have studied the process of obtaining highly smooth surfaces of silicon nitride using two oxides of iron. Polishing was done using dry powders at moderately high pressures to create high contact temperatures, inducing reactions at the contact spots. Surface roughness (peak-to-valley) less than 20 nm was obtained. The polished surface contained silicon oxynitride and traces of iron. While polishing rates were small, up to 1.6 μm/h, surface scratching was avoided because of the relative softness of the oxide particles compared to the silicon nitride.

Rostoker [1990] has reported the development of a proprietary chemical additive that leads to increased polishing rates on fused silica using small (3 μm) alumina grit, while retaining the usual good surface finish. The importance of using small size grit is related to residual workpiece damage, and to surface finish.

Yasunaga et al. [1979] reported on the differences measured in polishing silicon surfaces with various soft abrasives in both dry and wet (water) environments. As shown in Table 9, the relative difference in polishing rate for the two environments can range from 20% to a factor of 8 times depending on the system. In all cases the material removal rate is low, but the surface finish quality was stated to be high.

Sugita [1986] has reported a vibratory method of polishing MgO crystals in water that leads to very good surface finishes presumably through chemo-mechanical effects on the surface. Sugita et al. [1979] previously described the results of a study of polishing of sapphire (0001) crystal surfaces in water without abrasive particles by the use of a rotating alumina disk. The friction of the contact caused removal of a hydrated layer on the sapphire surface without appreciable damage to the underlying sapphire. This method produced fine surface finishes in the order of 20 nm rms.

Table 9. MEASURED POLISHING RATES FOR (111) SURFACE OF SILICON UNDER DIFFERENT CONDITIONS [Yasunaga et al. 1979]

Powder	Grain Size (μm)	Polisher	Environment	Polishing Rate (μm/h)
$BaCO_3$	3 - 10	Cloth	Dry	1.16
		Cloth	Wet	0.17
	2 - 4	Bakelite	Dry	2.60
		Bakelite	Wet	0.30
Fe_3O_4	10 - 20	Cloth	Dry	0.68
		Cloth	Wet	0.28
$CaCO_3$	4 - 7	Cloth	Dry	0.59
	2 - 3	Cloth	Dry	0.97
SiO_2	2 - 3	Bakelite	Wet	1.30
	0.5	Cloth	Dry	1.00
		Cloth	Wet	0.85
	0.01 - 0.02	Cloth	Dry	1.91
		Cloth	Wet	1.05
CeO_2	2 - 3	Bakelite	Wet	0.91
Diamond	1	Cloth	Dry	2.2 - 4.2

Glass surfaces are well known to be sensitive to the polishing environment, and the results of Cook [1990] shown in Table 10 illustrate this. The polishing rate shown varies by over a factor of 50 times depending on the cation species in the polishing compound. Ce^{4+} cations produce the highest rates in the conditions used. Cook discusses the role of chemistry in mechanical polishing of glass, and notes that the highest polishing rates found in two separate studies corresponded to the isoelectric pH point of the surface; Figure 20 shows one set of results.

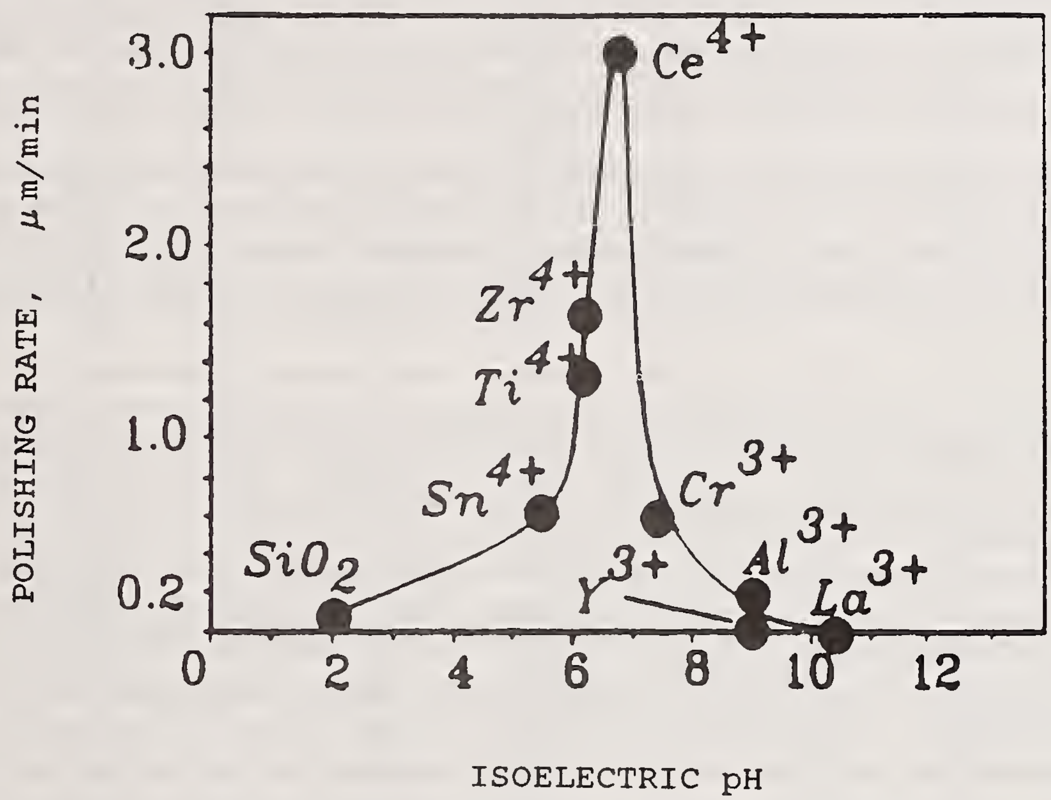

Figure 20. Polishing rates for glass using different cationic species, showing the isoelectric points in each case [Cook 1990].

The results obtained by Bifano et al. [1992] and Gollini and Jacobs [1991] clearly show the strong influence of the chemical environment on polishing of glass. For example, Gollini and Jacobs have shown that the process of material removal in polishing of glass can be changed from a brittle process to a ductile process by changing the chemistry of the carrier fluid. In this study, alcohols of various chain lengths and other fluids such as ethylene glycol, glycerol, and aniline were used.

Duwell et al. [1985] have drawn attention to the importance of chemical effects in abrasive polishing of titanium. By adding phosphate compounds to the water solution used to flood the surface, they found improved performance with both alumina and silicon carbide abrasives. They proposed that cationic adsorption on the SiC grit surfaces probably explained the better performance of that abrasive in their tests.

Table 10. POLISHING RATE DATA FOR GLASS BY SELECTED POLISHING COMPOUNDS [Cook 1990]

Cations and Compounds	Coordination No.	R-O Bond Strength (kcal/mol)	Polishing Rate* (μm/cycle)	Polishing Rate** (μm/cycle)
Ce^{3+}	6	61.4	4.9	2.98
Cr^{3+}	6	41.8	3.5	0.59
Th^{4+}	6	70.1	6	-
Fe^{3+}	6	29.5	3.1	-
Ga^{3+}	6	39.8	-	-
Zr^{4+}	8	62.4	2.8	1.62
Ti^{4+}	6	71.3	3.0	1.31
Sn^{4+}	6	41.8	2.8	0.61
Ni^{2+}	6	17.8	1.8	-
Zn^{2+}	4	31.5	0.9	-
Hf^{4+}	6	63.1	6	-
In^{3+}	8	33.6	-	-
Mn^{4+}	6	37.3	1.5	-
Fe^{2+}	6	19.3	6	-
Al^{3+}	6	63.2	1.8	0.19
Y^{3+}	6	72.5	-	-
Al^{3+}	6	63.2	6	-
Sc^{3+}	6	72.5	6	-
Ce^{3+}	6	68.3	4	-
La^{3+}	6	66.7	-	0.075
SiO_2	4	102.5	0.01	-

Note: Consult reference for additional explanation
* Data from Kaller, see [Cook 1990]
** Data from Silvernail, see [Cook 1990]

5.4 Chemically Assisted Grinding

In concept it is possible to have significant chemical interactions between the local environment in a grinding system and any or all of three elements: the workpiece, the grinding wheel matrix, and the diamond abrasive. As an example, Bifano et al. [1988] have reported a dramatic increase in the brittleness of the grinding process (i.e., a decrease in the allowable depth of cut for ductile grinding) for both fused silica and quartz but much less an effect for silicon, upon substituting alcohol for water as the grinding fluid. Beneficial effects on diamond wear during rock drilling were noted earlier. Other studies have shown the advantage of chemical attack on the wheel bond matrix as an effective means of continuous dressing of the wheel for optimum relief of the diamond grains [Murata et al. 1985].

A possible approach for introducing chemical assistance in grinding is through chemical additives in the grinding fluid. We found no published research directed toward the development of specific grinding fluids for advanced ceramic materials. Grinding fluids currently used for ceramics were apparently designed for grinding of metals and, therefore, have not been optimized for best performance with ceramics.

By utilizing chemically reactive compounds in the grinding fluid, it may be possible to control the cutting process at the abrasive/workpiece interface. Ceramic materials, despite the commonly held view, are not chemically inert, particularly when subjected to mechanical stress. The term "tribochemistry" is used to describe chemical reactions in the presence of mechanical forces or deformation [Heinicke 1984a]. This phenomenon has been used for many years in the processing of ceramic powders [Jimbo 1984, Heinecke 1984b]. For example, the reactivity of silicon nitride with water vapor increases severalfold with mechanical action and yields silicon oxide and ammonia [Volante et al. 1989]. Similar reactions have been observed in tribological studies where silicon nitride slides against silicon nitride [Fischer and Tomizawa 1985, and Tomizawa and Fischer 1987]. Tribochemical reactions between water and alumina, and also water and silicon carbide, have been reported [Gates and Hsu 1991, Dong et al. 1991, and Hegemann et al. 1988].

Recent studies have shown that friction and wear of ceramics are altered by chemical compounds that are normally used in lubricants [Jahanmir and Fischer 1988, Studt 1987, and Gates and Hsu 1991]. It is also important to note that the friction coefficient of ceramics, unlike metals, is considerably reduced by pure hydrocarbon oils that do not contain surfactants [Jahanmir and Fischer 1988, and Deckman et al. 1991]. In a recent study [Gates and Hsu 1991], several chemical compounds were evaluated for their potential use as lubricant additives. Table 11 lists these additives and summarizes the results of friction tests. The results clearly show that most compounds are chemically active toward silicon nitride. Polar additives (e.g., oleic acid), oxygenated compounds (e.g., glycol), and phosphates (e.g., zinc dialkyl dithiophosphate), decrease both the friction coefficient and the wear rate of silicon nitride. Others, such as chlorinated and sulphurized compounds, act as pro-wear agents. These compounds are commonly used as lubricant additives and as additives in some grinding fluids used with metals [O'Brien 1984].

Generally speaking, the polar and the oxygenated compounds adsorb on the contacting surfaces either by physical or chemical adsorption process [Jahanmir and Beltzer 1986a and 1986b]. But phosphates and sulphurized compounds chemically react with the sliding surfaces in the contacting zone, to produce thin films (less than 0.1 μm) on the surface [Jahanmir 1987]. Both the adsorbed films and the reacted films can reduce adhesion and friction at the cutting interface, and thereby control the cutting process [Zhang et al. 1991].

Table 11. FRICTION AND WEAR DATA ON SELECTED MODEL COMPOUNDS
[Gates and Hsu 1991]

Chemical Compound[1]	Dia Increase* Above Hz, mm		Friction Coeff.[2]	Friction Type	Wear Scar Appearance	Film in Scar?
NONE	0.267		0.113	I	smooth	no
Metal Salicylate (overbased)	0.032	antiwear	0.103	IV	smooth	yes
Oleic Acid	0.034	antiwear	0.076	II	smooth	yes—plastic
Glycol A (polypropylene-diol) [1000 MW]	0.042	antiwear	0.077	II	smooth	yes—plastic
Glycol B (polypropylene-triol) [600 MW]	0.072	antiwear	0.078	II	smooth	yes—plastic
Glycol C (polyethylene-diol) [400 MW]	0.077	antiwear	0.063	II	smooth	yes—plastic
Glycol A (polypropylene-diol) [400 MW]	0.279		0.130	III	smooth	no
2, 6-ditertiarybutly-para-cresol	0.281		0.123	I	smooth	no
Ethyl Stearate	0.316	prowear	0.120	I	smooth	no
High Erucic Acid Rapeseed Oil	0.331	prowear	0.120	III	smooth	no
Polyol Ester	0.369	prowear	0.134	I	smooth	no
Fatty and Synthetic Esters	0.396	prowear	0.111	III	smooth	no
Alkyl ZnDP A	0.024	antiwear	0.088	II	smooth	yes—fluid
Alkyl ZnDP B	0.027	antiwear	0.081	II	smooth	yes—fluid
Alkyl/Aryl Phosphonate	0.027	antiwear	0.085	II	smooth	yes—plastic
Aryl Phosphate A	0.036	antiwear	0.081	II	smooth	yes—plastic
Aryl Phosphate B	0.053	antiwear	0.090	II	smooth	yes—plastic
SbDP	0.055	antiwear	0.077	II	blotchy	yes—plastic
Alkyl Phosphate	0.055	antiwear	0.080	II	smooth	yes—plastic
Aryl Phosphite	0.064	antiwear	0.074	II	smooth	yes—plastic
Alkyl Phosphite	0.074	antiwear	0.086	II	smooth	yes—plastic
Acid Phosphate	0.099	antiwear	0.076	II	roughened	yes—plastic
Chlorinated Paraffin	0.377	prowear	0.118	I	smooth	no
Chloro-sulfurized Lard Oil	0.382	prowear	0.147	III	sl. grooved	no
Chlorinated Fatty Acid (FA)	0.426	prowear	0.113	III	sl. grooved	no
Chlorinated FA Ester	0.431	prowear	0.127	III	smooth	no
High MW Substituted Imidazoline	0.156	antiwear	0.077	II	smooth	no[3]
Succinamide	0.187	antiwear	0.131	III	smooth	no
Dinonyldiphenylamine	0.278		0.121	I	smooth	no
Metal Sulfonate A (overbased)	0.011	antiwear	0.108	IV	smooth	yes
Metal Phenate (overbased)	0.042	antiwear	0.096	II	smooth	yes
Metal Sulfonate B (low base)	0.043	antiwear	0.089	II	smooth	yes
OxyMoDP (sulfurized)	0.108	antiwear	0.060	II	smooth	yes—plastic
Antimony dialkyldithiocarbamate	0.260		0.114	I	smooth	no
Sulfurized Hydrocarbon	0.271		0.114	I	smooth	no
Methylene bis(dibutyldithiocarbamate)	0.277		0.125	I	smooth	no
Organo Molybdenum Dithiocarbamate	0.308	prowear	0.072	II	blotchy	yes—plastic
Sulfur-Molybdenmum Compound	0.338	prowear	0.072	II	blotchy	yes—plastic
Sulfurized Fatty Oil	0.378	prowear	0.137	III	smooth	no

[1] 1 wt % in purified paraffin oil
[2] Measured at the end of the test
[3] Significant amounts of film outside the wear scar

* Relative wear scar diameter

Studies on friction of diamond and diamond film [Jahanmir et al. 1989, Buckley 1981, and Gardos and Soriano 1990] have shown that diamond, similar to ceramics, responds positively to hydrocarbon lubricants and polar additives. Therefore, it may be possible to add chemical compounds, that either adsorb or react with the ceramic surface in the cutting zone, to the grinding fluid. Furthermore, the same additives may adsorb on the diamond abrasive particles to reduce friction and wear of the diamond, and also reduce the tendency for the adhesion of the swarf to the grinding wheel.

5.5. Chemically Assisted Liquid Abrasive Jet Cutting

Chemical assistance could conveniently be provided through modification of the fluid in liquid abrasive jet cutting to increase the cutting rates. Water soluble chemical species can be added to enhance the cutting rate through effects that reduce wear of the abrasive particle cutting edges. Other additives could assist in providing viscosity control of the fluid and to improve suspension characteristics of the abrasive particles. Duran [1984] has reported on the use of a dilute solution of alkylaryl polyether alcohol in octyl alcohol for use with boron carbide or silicon carbide abrasive slurry in cutting boron carbide. The additive served to assist in maintaining the abrasive grit suspension by acting as a wetting agent without altering the fluid viscosity or the flow characteristics associated with the jet.

5.6 Chemically Assisted Ultrasonic Machining

As shown in Figure 6, the contact zone in this process involves the tool, the workpiece surface, the free abrasive grit, and a carrier fluid. The ultrasonic abrasive machining method would appear to lend itself directly to chemical reactions between the fluid and either the workpiece or tool surfaces, either to enhance machinability or to extend tool life. If attempts are made to retain the abrasives in the cutting region by design, perhaps to increase efficiency, then wear and fracture of the grit to smaller grit sizes may be a concern. In this case, chemical and environmental effects could be useful to control the processes of grit wear and fracture; and thereby, enhance the machining process. Changes in fluid properties such as viscosity, and the ability to suspend solids, are also advantageous.

5.7 Chemically Assisted Single-Point Diamond Turning

Wear of diamond single crystals is generally controlled by cracking and chipping and is influenced by the chemical environments and thermal conditions during single-point diamond turning [Field 1979, and Wilks and Wilks 1979]. It was pointed out earlier that application of single-point diamond turning to advanced ceramics requires special attention to the wear of the diamond tool. By controlling the chemical and thermal environments during cutting, through properly designed cutting fluids, it may be possible to reduce the tool wear and optimize the removal process. The following examples are cited in support of this argument.

Biffano et al. [1988] and Blackely and Scattergood [1992] have investigated single-point diamond turning of germanium using water as a cutting fluid. Figure 21 shows results from several experiments relating cutting feed rate and chip thickness. In this case, it was possible to use larger depths of cut and feed rates under dry conditions than with water as an environment. Gielisee et al. [1974] have reported that alcohols affect the rates of single-point diamond turning of three types of alumina. The force levels required and the amount of material removed increased as the alcohol chain length was increased. Single-point diamond scratching experiments have also been used to study effects of liquid environment [Van Groenou et al. 1979] on different materials including alumina, magnesia, and glass. It was found that there was little effect on the forces and the energy for grooving by the diamond point. However, there

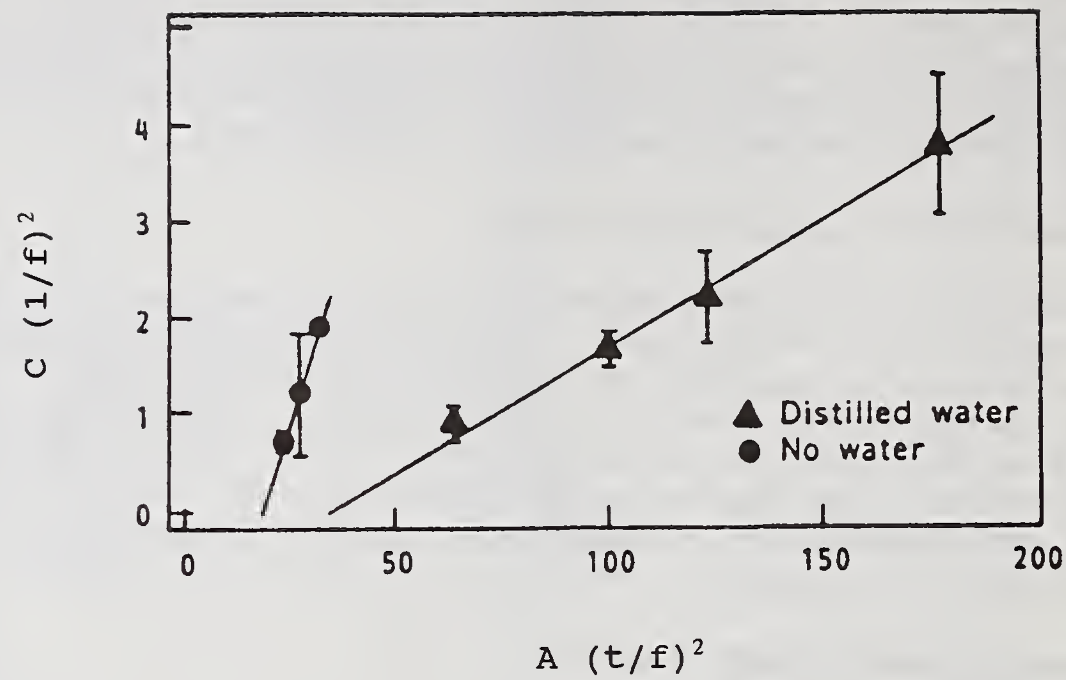

Figure 21. Difference in single-point diamond turning of germanium under two conditions, where t = chip thickness, f = feed rate, and A and C are constants [Blackely and Scattergood 1992].

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was an effect on the damage created in the workpiece during scratching in the different liquids: n-alcohols, dimethyl formamide, dimethyl sulfoxide, and dodecyl trimethyl ammonium bromide.

5.8 Suggested Technical Approaches

The foregoing discussion and the review of the published literature confirms that enhancement of chemical reactions at the interface between the tool and the ceramic workpiece is a feasible method for controlling the material removal process. It is, therefore, suggested that research projects be focused on elucidating the fundamental chemical reactions that may occur during abrasive processes such as grinding, polishing, ultrasonic machining, liquid abrasive jet cutting and single-point turning. The goal of these investigations should be to develop recommendations for the selection of chemical compounds to be added to the grinding and cutting fluids to increase the removal rate and decrease the residual machining damage. It should be recognized, however, that the timescale of reactions is extremely important. The chemical reactions should occur at timescales comparable to the removal rate to be effective, but not so fast that aggressive attack of the machine tool components or the degradation of the surface of the workpiece would occur.

6. MACHINING DAMAGE AND DETECTION

In this section the mechanisms of damage formation during grinding and other abrasive processes are reviewed, and possible approaches that increase the efficiency of material removal and decrease the extent of residual machining damage are discussed. Due considerations are given to nondestructive methods for detecting machining damage and to relationships between damage and resulting material properties.

6.1 Mechanisms of Damage Formation in Grinding

It is important to recall the processes of abrasive removal of materials as schematically shown in Figure 22. The abrasive particle is forced to penetrate the workpiece as the workpiece and the particle are moved relative to each other and parallel to the surface. Depending on the contact conditions and the mechanical properties of the workpiece, chips are generated by plastic flow and/or brittle fracture.

In materials capable of plastic deformation, for example metals, chips are formed by shear in a ductile mode, Figure 22a. In materials that have a limited ductility, for example ceramics, chips are generally formed by a brittle fracture process, as depicted in Figure 22b. Whether the chips are formed by brittle fracture or by plastic deformation, depends on the penetration depth as well as the material's susceptibility to plastic flow [Evans and Marshall 1981, Toh and McPherson 1986, Shaw et al. 1990 and 1991, Subramanian 1987, and Bifano et al. 1988].

Two models have been proposed to describe the chip formation process shown in Figure 22b. The Evans and Marshall [1991] model, shown in Figure 11, is based on the formation and propagation median cracks (vertical to the surface) formed at the boundary between the elastic and plastic zone and the lateral cracks (parallel to the surface) formed as result of residual stresses during unloading. Crushing is also an important mechanism of material removal in brittle ceramics [Larchuk et al. 1985]. Crushing can be described as an unstable fracture process, which involves propagation of cracks at origins distributed throughout the stressed region. The basic distinction between the crushing model and the Evans and Marshall model is that in the former a large number fragments are separated from the surface.

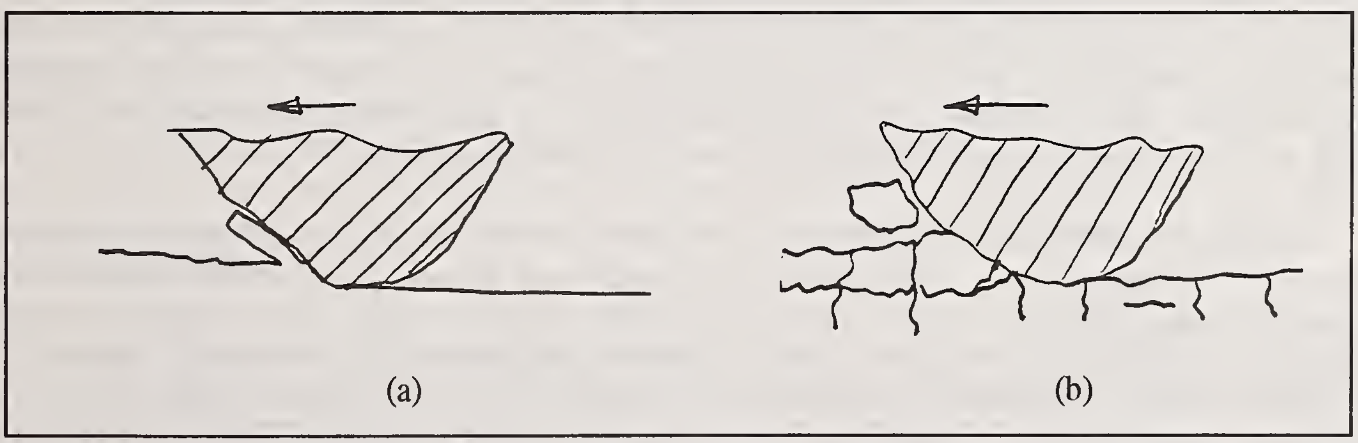

Figure 22. Schematic representation of material removal mechanisms: (a) ductile chip formation, and (b) brittle fracture.

A major consequence of material removal by abrasive action is the generation of damage associated with plastic deformation, fracture, and heat generation. The type and the extent of machining damage strongly depends on the type of removal process, machining parameters, as well as the properties of the workpiece material. Before we describe and classify different types of machining damage, it is instructive to review the types of failure causing defects in ceramics.

Ceramic materials, in general, are susceptible to brittle fracture and, therefore, are sensitive to the presence of flaws or any inhomogeneities which can act as sources for crack initiation or provide easy paths for crack propagation. Processing defects such as pores, foreign particles, large grains, or combinations of these are major sources of failure in ceramics [Rice 1979, Rice and Mecholsky 1979, and Rice et al. 1979]. Service and environmentally induced defects (for example, corrosion pits) are also important causes of failure. A third source of defects that can severely affect the strength of ceramics is damage produced by handling (for example, scratches). The processing related defects can be minimized by controlling the process parameters during powder processing, densification, and sintering. The service and environmentally induced defects can be minimized through proper design and selection of materials for each specific application. As most of the aforementioned defects are carefully eliminated, the machining damage becomes an important strength limiting factor.

The nature of machining damage and its effect on the strength of ceramics has been extensively studied in the past [Rice 1979, Rice and Mecholsky 1979, Koepka and Stokes 1979, Cranmer et al. 1977, and others]. Plastic deformation plays an important role in the removal process, even for brittle materials. Surfaces finished by abrasive processes always contain residual plastic deformation, the extent of which depends on the material and the parameters of the machining operation [Kirchner 1984, Primak 1981, and Hooper and Morgan 1989]. In certain ceramics, for example tetragonal zirconia, plastic deformation results in the development of texture and phase transformation [Whalen et al. 1989, Mehta et al. 1990, and Krishnamurthy et al. 1991]. Another direct consequence of plastic flow is the development of residual stresses, which can be compressive or tensile on the surface [Kirchner and Isaacson 1982 and 1986].

Microcracks generated during machining have a detrimental effect on the strength of ceramic components. The damaging effect of microcracks is depicted schematically in Figure 23, which shows the cross section of a machined surface perpendicular to the grinding direction [Marshall et al. 1983]. Each abrasive particle produces a small semicircular microcrack in proportion to the penetration depth of the abrasive particle. Although an individual microcrack may be too small to be critical, a group of microcracks may act as a larger crack and initiate failure. In the presence of a tensile stress on the surface, or more importantly at the crack front, the crack can propagate rapidly.

Irrespective of the type of chip formed, most of the mechanical energy associated with the process of removal is expended as heat. Sliding at the chip/particle and the workpiece/particle interface results in frictional heating [Malkin and Ritter 1989, Wetton 1969, and Cook 1990]. Heat is also generated by the shear deformation in the shear zone. Some calculations suggest that approximately 50 percent of the total heat generated in grinding of metals is associated with the shear zone [Malkin 1989]. The temperature during grinding of metals can reach as high as 1200°C to 1400°C [Ueda et al. 1985, and Ramanath and Shaw 1988]. The contact temperature in grinding of ceramics with low thermal conductivity can be higher than that for metals, since heat is not efficiently conducted away from the contact zone [Malkin 1989].

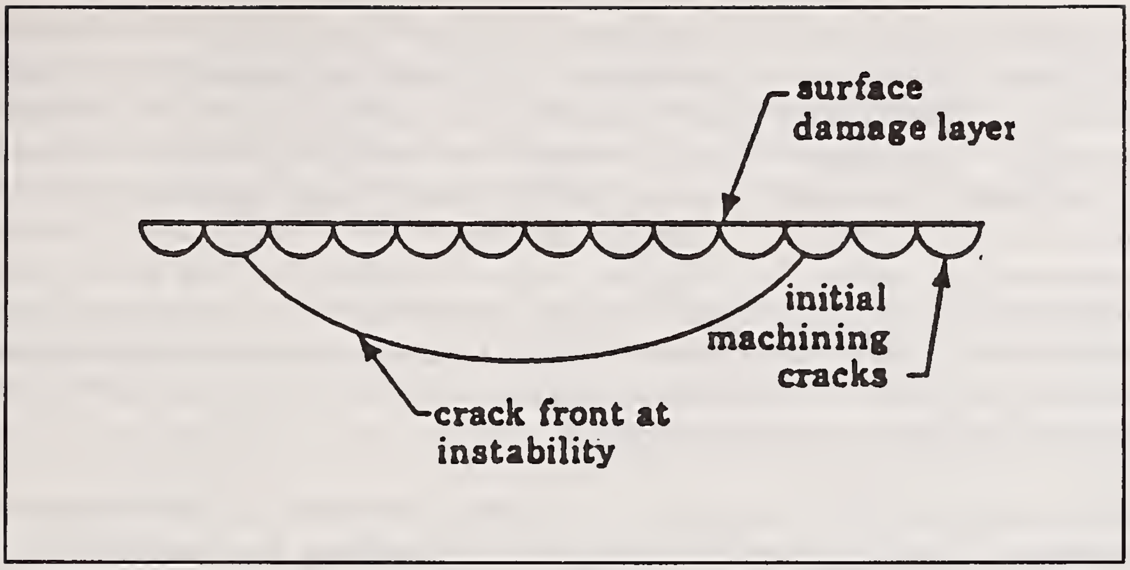

Figure 23. Schematic representation of crack configuration generated by abrasive machining [Marshall et al. 1983].

A direct consequence of the high contact temperatures is chemical reaction between the workpiece and the environment or the abrasive particle. In addition to chemical reactions, diffusion and segregation of various components have been observed [Komanduri and Shaw 1976]. The high rates of heating and subsequent cooling also can give rise to thermal stresses and cracking. It should be noted that the heating/cooling effect can modify the residual stresses in the workpiece. Although, the effect of interface temperature and chemical reactions can play a major role in the grinding operation, this phenomenon has received only limited attention in grinding of metals [Rowe et al. 1991, and Lavine 1991]; and it has not been investigated for grinding of ceramics.

6.2 Grinding Rate and Damage

Grinding rate is usually expressed as volume removed per unit time. In practice, the achievable rate of grinding can be limited by a number of factors: the power capacity of the machine, strength and durability of the wheel, excessive wheel wear, insufficient rigidity to maintain precise dimensions, or the ability of the workpiece to support the applied forces. Most often, however, it is the need to obtain a specified surface finish and surface integrity of the part that limits the grinding rate. Here, surface integrity refers to any form of grinding induced performance limiting damage sustained by the workpiece. As discussed previously, the damage may take the form of cracks, residual stresses, and transformed or chemically reacted layers.

In the routine machining of advanced structural ceramics, at least as it is practiced by the average machine shop, the approach is to employ removal rates that are well below those which are thought to cause damage. As a typical example in ordinary reciprocating surface grinding, down feed is limited to no more than 25 μm, utilizing a table speed of 0.25 m/s and a wheel surface speed of 20 m/s, resulting in a removal rate of approximately 0.6 mm^2/s per mm of wheel width. This approach is clearly arbitrary and sacrifices the possibility of grinding at higher rates with a concomitant increase in productivity, while still maintaining an acceptable level of damage.

In principle, if a large depth of material must be removed by grinding, surface finish and damage may not be as serious a limitation as it might appear. Rapid grinding to remove the bulk of the material might be followed by a final finishing stage to remove earlier damage, leaving only damage associated with the final stage. This approach is, of course, commonly employed in machining metals. Unfortunately, for advanced ceramics, there is no convenient and directly applicable means to determine how much material should be removed to eliminate the damage from course grinding. The problem is, of course, exacerbated by the fact that only one large subsurface crack may be the limiting flaw. "Large," in the case of low fracture toughness advanced ceramics, may mean only a few micrometers in length, which is small in terms of detection when many square centimeters of component surface area must be examined. Detection of such flaws exceeds the capability of all but the most tedious and expensive NDE methods that are currently available.

This leaves proof testing or the preparation of separate test specimens for destructive evaluation of grinding damage. The latter method, although less satisfactory than evaluation of the actual component, has been used in several investigations to study the effect of machining variables [Allor and Baker 1983, Thomas et al. 1987a and 1987b, and Matsuo et al. 1987]. Recently, this approach has achieved a high level of significance with the issuance of ASTM C1161-91 Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature. In this method the flexural strength (also referred to as the modulus of rupture, or MOR) of test bars of prescribed dimensions is determined by three-point or four-point bending tests. The flexural strength and its variability are determined by

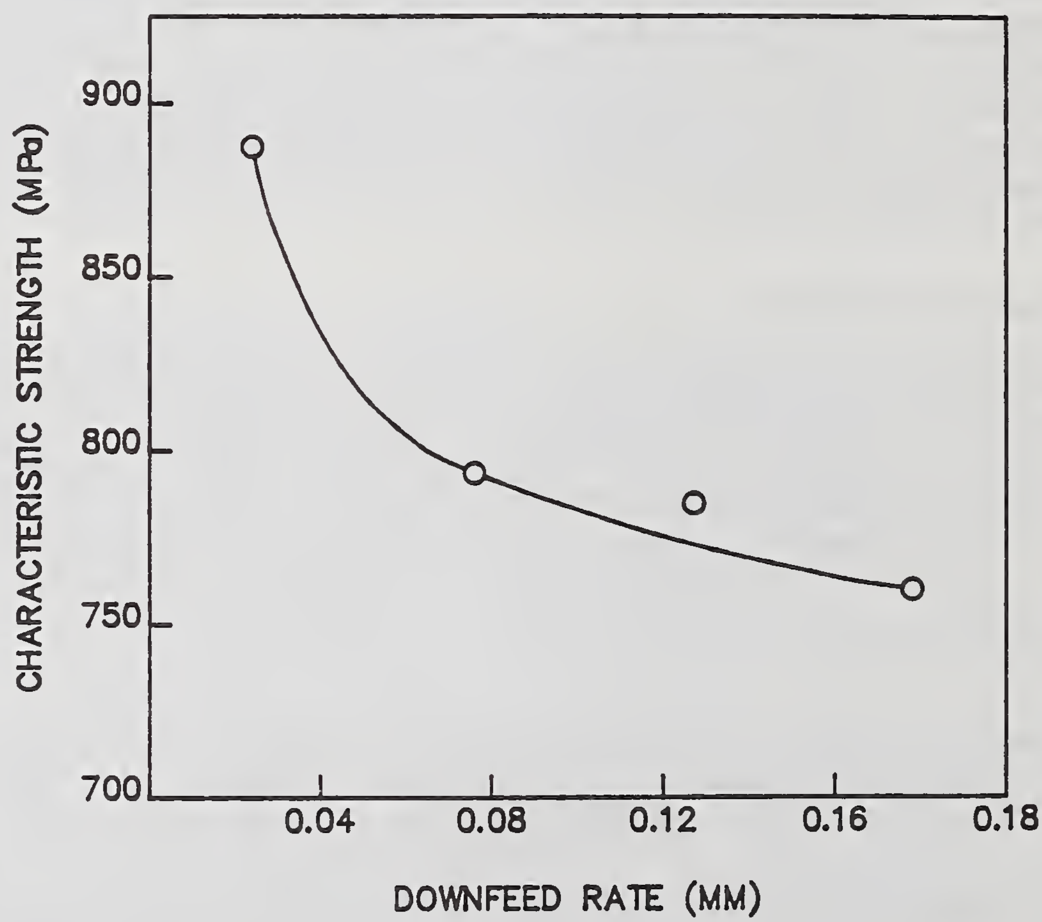

Figure 24. Effect of down feed rate on characteristic strength of machined silicon nitride [Thomas et al. 1987a].

the inherent properties of the particular lot of material and by any damage which may have been introduced during machining, finishing, and other treatments. By following a carefully prescribed preparation procedure set out in the ASTM Standard, the inherent strength of the material can be determined with good statistical significance without the influence of damage due to other sources. Thus, the test can then be used to investigate the influence on strength of different grinding and surface preparation procedures.

Several examples can be cited in which the flexural strength testing has been used to determine the effects of grinding variables on damage. Thomas et al. [1987a and 1987b] investigated a number of parameters in grinding hot-pressed silicon nitride and sintered silicon carbide. In Figure 24 the effect on strength of down feed (depth of cut) is shown for silicon nitride. A significant decrease in strength is observed for increasing down feeds, confirming the practice of using small cutting depths. Figures 25 and 26 show the influence of table speed (feed rate) and grit size, respectively, on strength of silicon nitride. At higher table speeds, a statistically significant improvement in strength is obtained. In the case of grit size, as shown in Figure 26, a maximum in strength was obtained with 320 grit. In both cases, the results are counter intuitive in that grinding at greater removal rates (increased table speeds) might have been expected to result in increased damage and lower strength; and similarly, the trend towards increased strength with reduced grit size on going from 150 to 320 grit would have been expected to continue for 600 grit. The latter effect occurred despite the fact that a smoother surface was obtained with 600 grit, implying that the depth of damage might be smaller.

In other experiments Thomas et al. [1987b] investigated the effect of wheel surface speed and grinding direction relative to the axis of the test bars. These results are shown in Figures 27 and 28, respectively. It is seen that increasing the wheel surface speed resulted in higher flexure strength. The

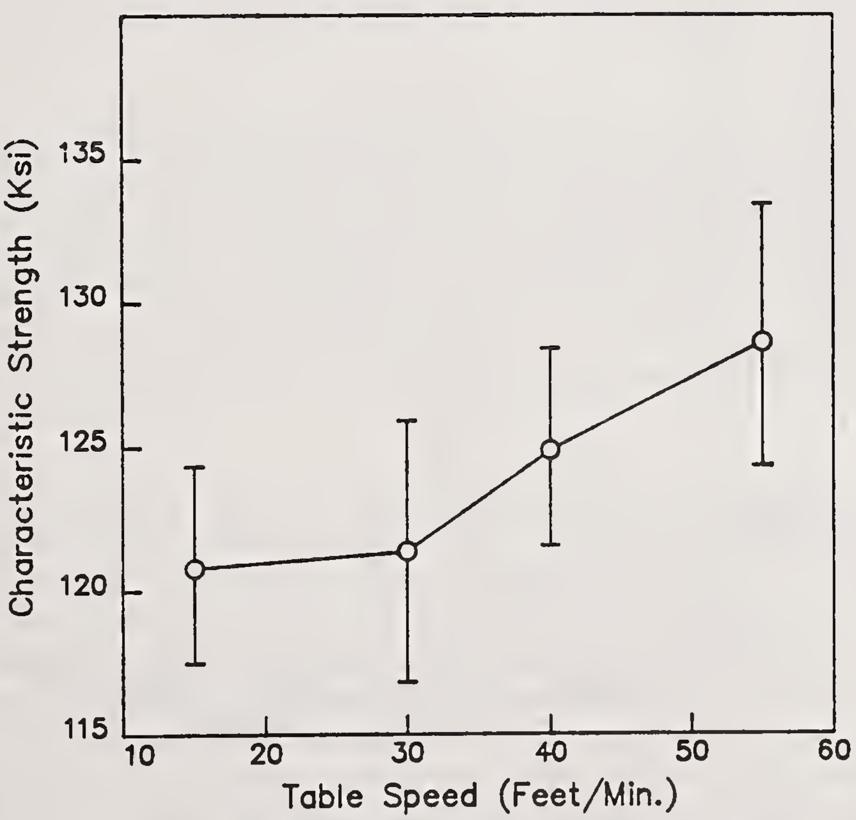

Figure 25. Variation in characteristic strength of silicon nitride with table speed [Thomas et al. 1987b]

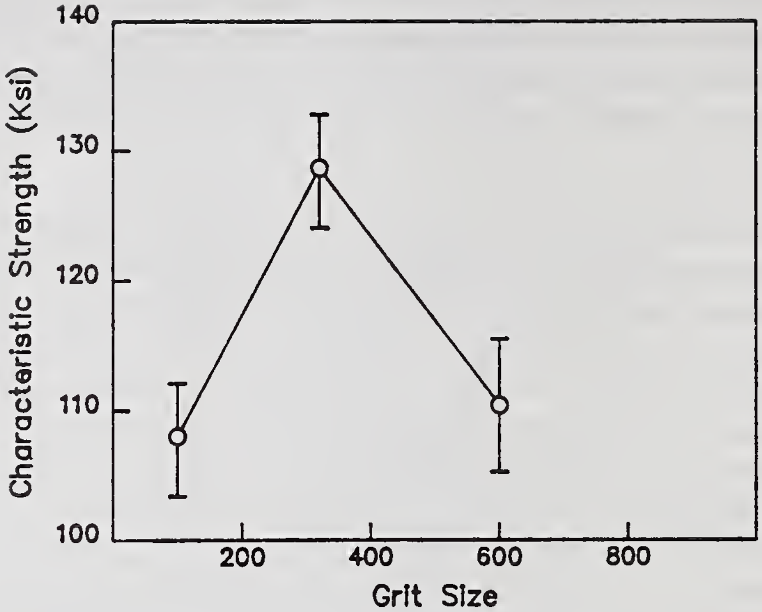

Figure 26. Variation in characteristic strength of silicon nitride with grit size [Thomas et al. 1987b].

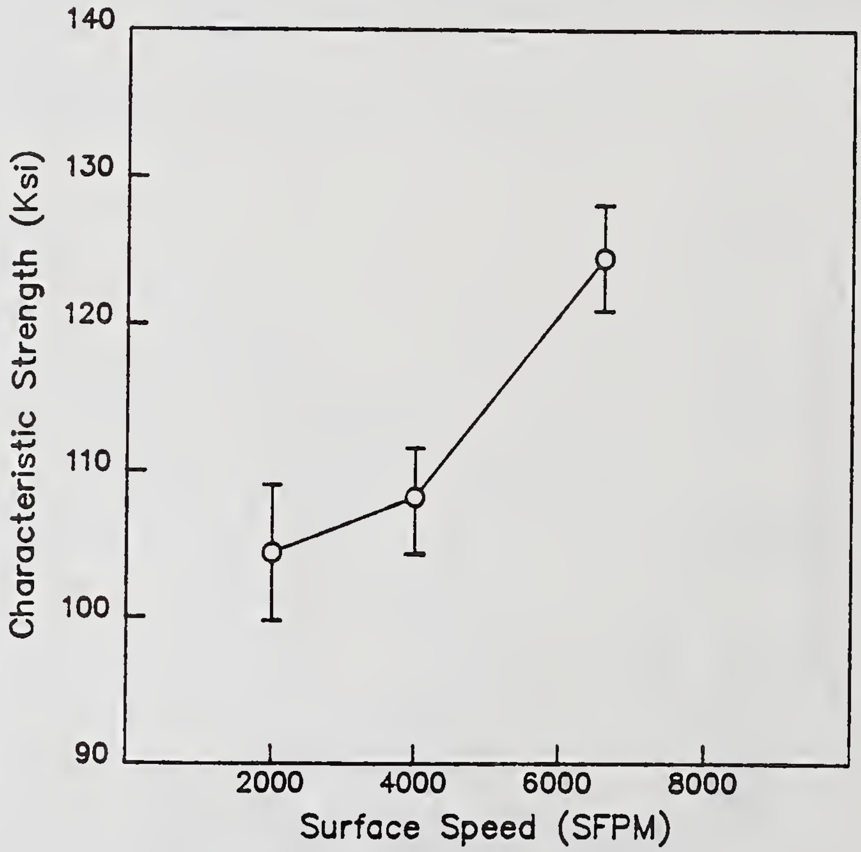

Figure 27. Variation in characteristic strength of silicon nitride with wheel surface speed [Thomas et al. 1987b].

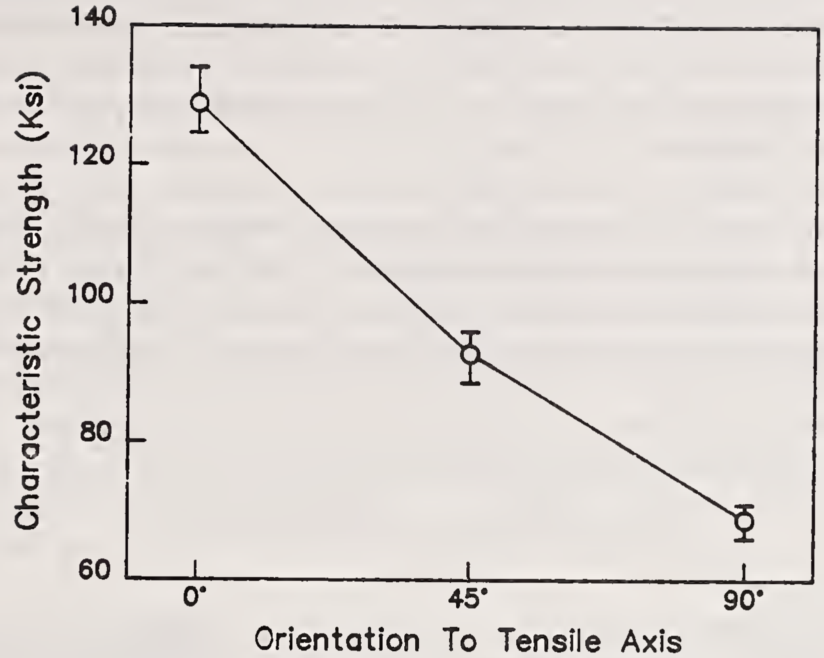

Figure 28. Variation in characteristic strength of silicon nitride with angle between grinding direction and tensile axis [Thomas et al. 1987b].

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surface roughness was also less with increased wheel surface speed suggesting that material removal was accomplished with a smaller grit penetration depth, which may explain the reduction in damage and increase in strength.

The angle between the grinding direction and the tensile axis of the flexure specimens is shown in Figure 28 to have a strong influence on strength. The measured strength was highest when grinding was carried out parallel to the tensile axis and lowest when grinding was in the perpendicular direction. Examination of the fracture surfaces indicated that the exposed flaws were larger in the bars ground in the perpendicular direction. This is apparently associated with the fact that the median cracks, which lie parallel to the grinding grooves, are larger than the radial cracks, which are perpendicular to the grooves. An additional source of decreased strength is that the grinding grooves may act as notches when they are perpendicular to the tensile axis.

The effect of grinding variables on the strength of hot-pressed silicon nitride was also studied by Allor and Baker [1983]. They obtained the same grit size effect observed by Thomas et al. that is, the strength was higher at 320 grit than at either larger or smaller grit sizes. In addition, little effect was observed when two different grinding wheel grit concentrations were employed. In a comparison of resin bond versus plated wheels, they observed a slightly larger strength loss with plated wheels. A similar result was obtained with resin bond versus metal bond wheels, although they had found a significant loss of strength in earlier experiments with the same metal bond wheels. They attributed these disparate results to differences in the skill of the two operators who had ground the specimens. In contrast to the observations of Thomas et al., Allor and Baker found that down feed rate could be increased from 0.0254 to 0.254 mm/pass with little change in strength, although increasing the down feed rate further to 0.762 mm/pass did result in a small decrease in strength.

As a final example the results of Daniels et al. [1989] in grinding sintered silicon carbide are of interest. Daniels et al. carried out experiments with three different types of diamond grit. One grit type did appear to perform better than the others, but in no case was there a consistent loss in strength associated with increasing the down feed from 0.025 to 0.203 mm. The results obtained with one type of grit are shown in Figure 29. In this case there was in fact an improvement in strength compared with a carefully prepared control specimen.

The above examples show that changing the grinding conditions does not always have the same effect. In some cases this may be attributed to the skill of the operator or details of the grinding procedures. Often, however, it appears that the results are specific to the material being investigated. Differences in material microstructure, inherent flaw populations, and toughness could account for the apparent inconsistencies.

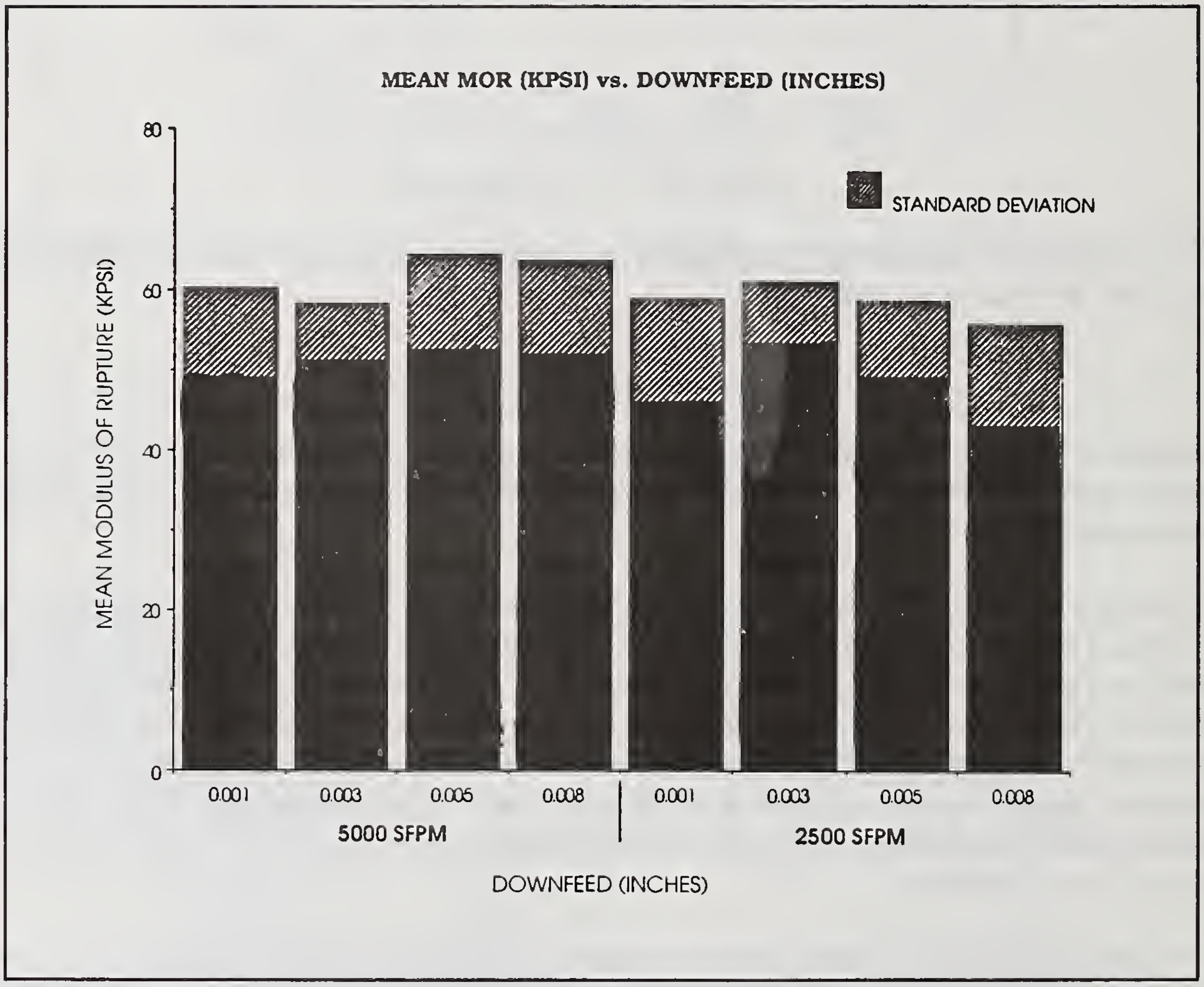

Figure 29. Effect of down feed on mean modulus of rupture (MOR) at two different wheel speeds: 2500 and 5000 surface feet per minute (SFPM) [Daniels et al. 1989].

6.3 Methods of Damage Characterization

Different NDE methods have been developed and are being evaluated for flaw detection in advanced ceramics. However, most of these methods are only suitable for the detection of large flaws.

To detect machining damage, the NDE method must be sufficiently sensitive to resolve small flaws, mostly microcracks, very close to the surface. Also, the entire machined surface is subject to machining damage, which requires a method capable of examining what is often a relatively large area.

Friedman et al. [1986] evaluated several NDE methods to determine which were most suitable for detection of machining damage in silicon carbide. The methods evaluated included optical microscopy, fluorescent dye penetrant inspection, high-frequency surface wave acoustic microscopy, thermal wave imaging, krypton exposure technique, bubble test, and microfocus x-ray. These methods were used to analyze a ground surface and a knoop indentation, simulating a larger surface flaw. Only optical microscopy, surface acoustic wave, and thermal wave techniques detected the Knoop indent. Also, surface acoustic wave and thermal wave techniques seemed promising for the detection of the grinding damage, although the results were not conclusive. A similar conclusion was reached in an international round robin evaluation of machining damage reported by Tonshoff et al. [1989]. They also concluded that conventional inspection and measurement methods lack in resolution, and indicated that several damage evaluation techniques should be used for the analysis of different types of damage introduced by machining.

Visual inspection utilizing liquid penetrants such as fluorescent liquids and white and red dyes, is simple and inexpensive. Although, this method can not detect subsurface cracks and small surface flaws, it can be used for larger surface cracks. In fact, this is the method of choice in most machine shops.

The principle governing the operation of the surface acoustic wave method is illustrated in Figure 30, and a schematic of a complete detection system is shown in Figure 31 [Fahr et al. 1984]. The feasibility of using this method has been evaluated for machining damage, a simulated damage introduced by a

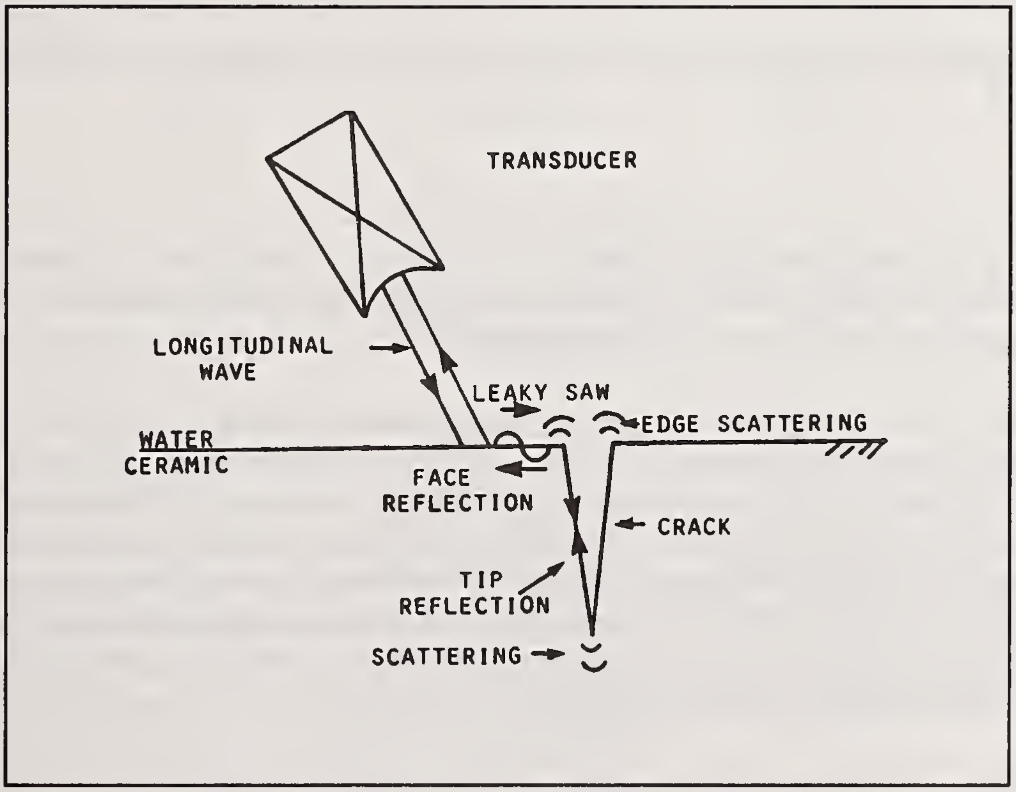

Figure 30. Generation of leaky surface acoustic waves (SAW) and their interaction with a surface crack [Fahr et al. 1984].

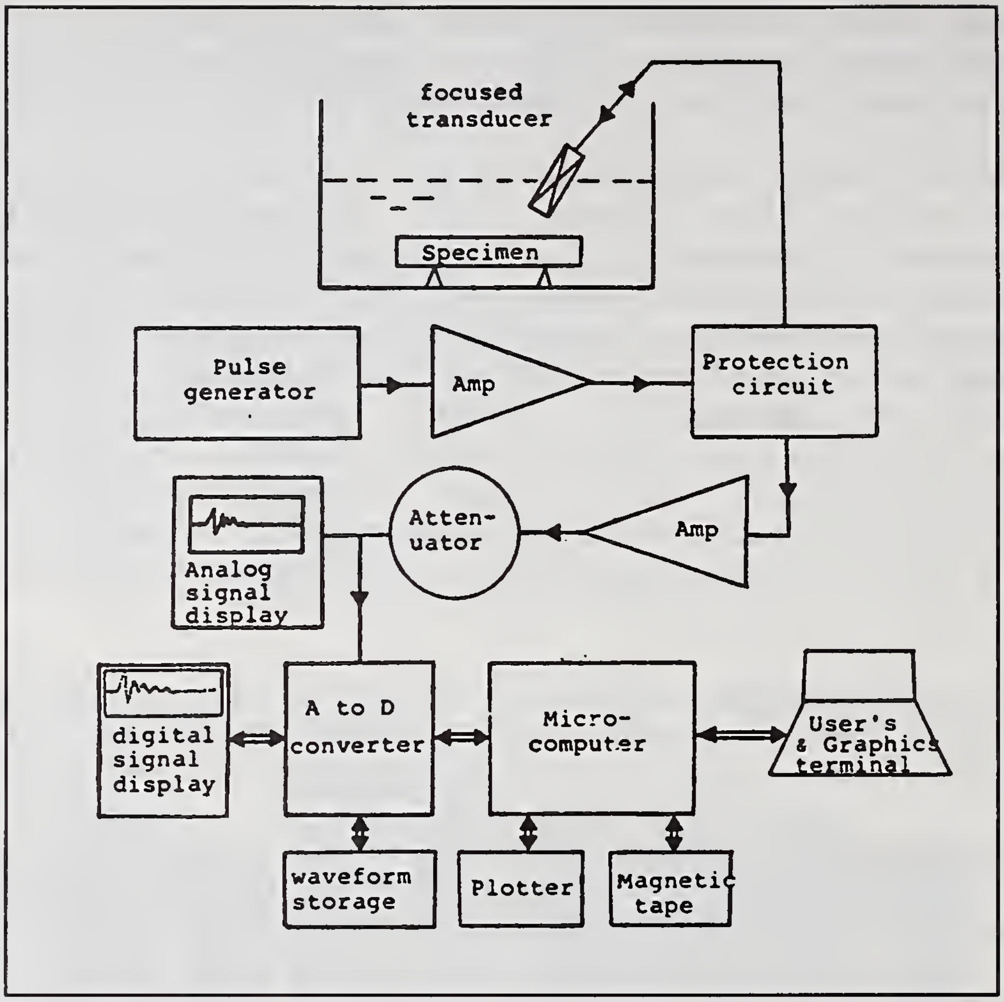

Figure 31. A schematic of a surface acoustic wave detection system and the computer analysis facilities [Fahr et al. 1984].

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scratch [Clarke et al. 1986, and Khuri-Yakub et al. 1984] and propagation of cracks from scratches [Marshall et al. 1983]. Variants of the acoustic wave microscopy technique which are promising for the assessment of machining damage are shown in Figure 32.

Photothermal microscopy and particularly thermal wave imaging are also promising techniques for the assessment of machining damage. The basic principle of operation of the latter method is shown schematically in Figure 33. This method essentially measures the thermal diffusivity of the surface and a thin subsurface layer. Therefore, machining damage that has an effect on thermal diffusivity can be detected. An example of results obtained on silicon nitride abraded with different sizes of diamond grit are shown in Figure 34 [White 1992]. The data clearly show that there is a correlation between thermal diffusivity and the grit size used to abrade the surface. The observed effect can be attributed to the larger amount of damage produced by the larger particles.

In addition to detection of microcracks, it is important to assess the nature and magnitude of residual stresses introduced by machining. Perhaps the most suitable technique is x-ray diffraction, which has been evaluated by several investigators [Johnson-Walls et al. 1984 and 1986, Pfeiffer 1990, Pfeiffer et al. 1988, and Eigenmann et al. 1989]. Generally, residual stress is compressive on and near to the surface. For example, Johnson-Walls et al. [1989] measured a compressive residual stress of 350 MPa in a silicon nitride surface. The measured thickness of the layer with compressive residual stress was 10 μm. It has been reported that the magnitude of the compressive residual stress increases by increasing the depth of cut in diamond grinding [Praddel et al. 1989]; this is perhaps due to a larger amount of plastic deformation for large depths of cut. Although, a compressive surface stress would be expected to increase the strength of a material, experimental results show the opposite. This can be explained by considering the fact that compressive surface residual stresses are always compensated by residual tensile stresses below the surface. If subsurface cracks are located in the tensile region, then the surface compressive stress is ineffective in increasing the strength; and, in fact, the tensile residual stresses cause a reduction in strength.

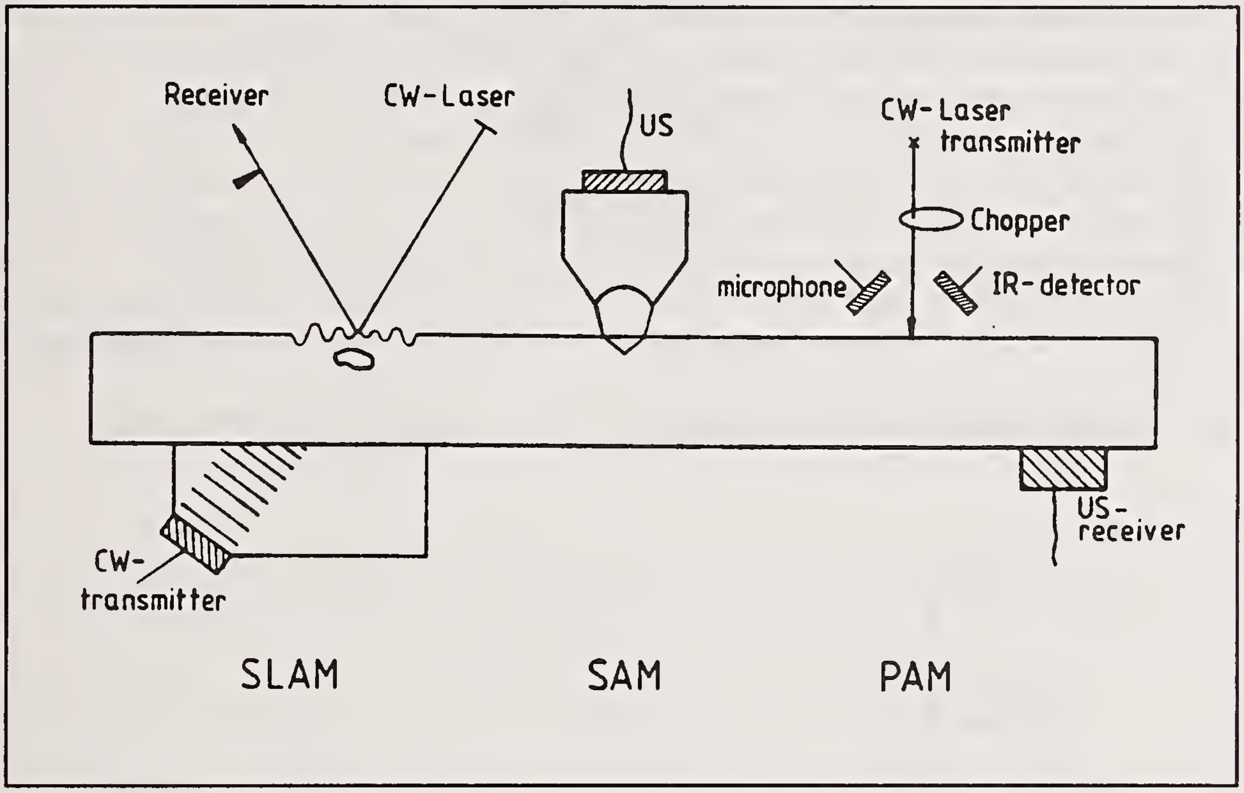

Figure 32. Principles of scanning laser acoustic microscope (SLAM), scanning acoustic microscope (SAM) and photo-acoustic microscope (PAM) [Goebbles 1987].

In a recent review of nondestructive measurement techniques, Brinksmeier [1989] concluded that x-ray diffraction, ultrasonic methods, photothermal microscopy, Raman spectroscopy, and instrumented nano-indentation are promising techniques for the evaluation of machining damage. Raman spectroscopy, which utilizes penetration of light in superficial surface layers, is an important tool for studying the structure, chemical composition and stresses in crystalline and amorphous materials. The instrumented nano-indentation, however, is a quasi-nondestructive technique for evaluating mechanical properties such as hardness and elastic modulus of superficial surface layers.

Other NDE techniques that could be used for machining damage assessment include optical and holographic interferometry [Roszhart 1973, and Goebbles 1987]. These techniques, however, primarily measure the surface profile, and surface roughness.

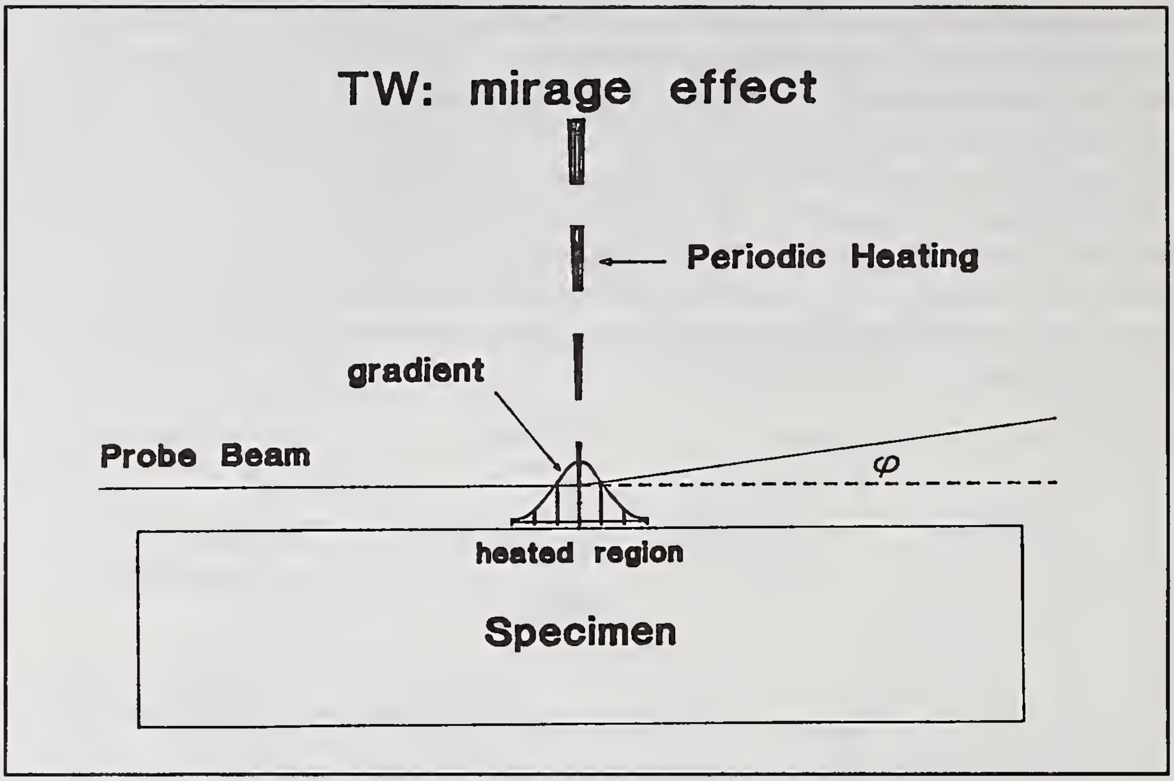

Figure 33. Schematic representation of thermal wave (TW) mirage effect [White 1992].

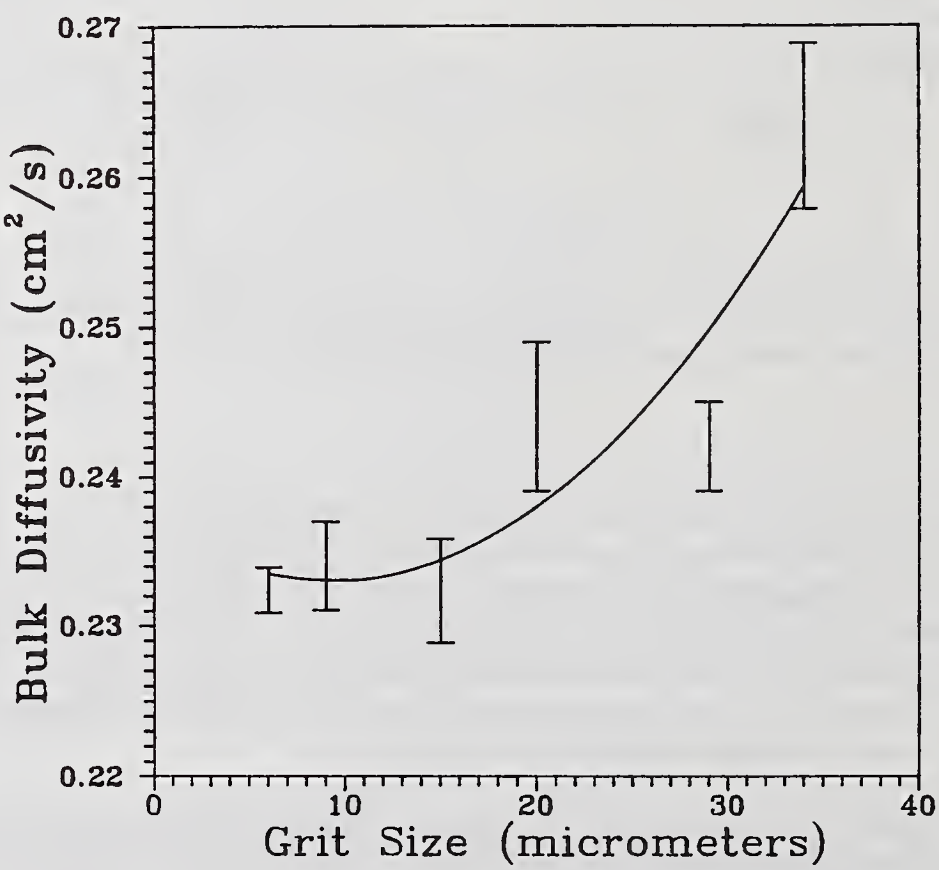

Figure 34. Effect of grit size on thermal diffusivity [White 1992].

6.4 Suggested Technical Approaches

It is recommended that the types of machining damage in different materials under various machining techniques be identified and classified, and that the effect of machining parameters on the extent of machining damage be evaluated. Furthermore, the most detrimental types of damage for different applications must be identified, and the most reliable NDE techniques for detecting such damage should be identified.

In order to increase the material removal rate and at the same time reduce the extent of machining damage, one must recognize the complexity of the grinding operation and analyze the different parts of the process. At the microscale, the interaction between the abrasive particles and the workpiece controls the rate of removal and the type of damage produced. The important parameters controlling the processes at the interface include contact temperature, interfacial forces, and the environment surrounding the cutting zone. The interfacial actions, however, are influenced by the grinding parameters, and by the machine tool characteristics. Therefore, a possible approach for increasing the machining rate in a total grinding system, is optimization of the process through automation and control. This objective requires research and development efforts for sensors to assess the machining damage and surface quality during the operation. For certain applications sensitive to small amounts of machining damage, one may consider post-machining treatments to remove the machining damage and proof testing to increase performance reliability.

7. RECOMMENDED RESEARCH FOR CERAMIC MACHINING

In order to take advantage of the unique properties of advanced ceramics and facilitate their introduction into the market place, a coordinated program is needed. The overall objectives of this program should be to develop an advanced technology for ceramic machining which will remove the barriers that machining presents to the widespread introduction of advanced structural ceramics. The recommended research program outlined in this section is based on our discussions with industry and the analysis of published literature. It is recommended that these projects be carried out jointly with industry to facilitate technology transfer, and that the ceramic machining research funded by the government be coordinated to minimize the possibility of duplication of effort.

7.1 Summary of Needs

The results of the assessment with regards to the needs in the machining and production of parts made from advanced ceramics are summarized as follows:

Reduction in Cost: Machining is a major contributor to the overall high cost of ceramic components. Although, significant costs are also associated with raw materials, processing, and quality control, the primary impediment to the introduction of many ceramic parts into the market place is the high cost of machining. Therefore, research efforts should be focused on developing methods which reduce machining related costs as a means of promoting the manufacture of cost-effective ceramic components.

Optimization Data: With the exception of a few publications, there is little machining data available for advanced ceramics. There is a critical need for data to be used for the purpose of cost estimating, component design optimization, and selection of machining parameters. In the absence of such information, the operator takes the most conservative route, i.e., slow removal rates, which translates to a high cost of machining.

Rapid Machining Methods: Advanced ceramic materials are difficult to machine with most conventional methods, with the exception of abrasive machining utilizing diamond. Abrasive machining of advanced ceramics, however, is slow compared to metals. Innovative techniques are needed to increase the rate of material removal. But it is extremely important to recognize that an increase in machining rate may lead to an unacceptable level of surface and subsurface damage in the finished part. Therefore, the development of rapid machining methods must be accompanied by damage assessment and control.

Damage Assessment: Performance and reliability of ceramic materials are strongly influenced by damage introduced during machining. Surface finish and machining damage are especially sensitive to small changes in machining conditions. There is a need for reliable and fast, in situ and post-machining damage assessment techniques. Development of sensors for real-time measurement of surface finish and damage assessment has the potential to increase manufacturing productivity significantly.

Automation: Present ceramic machining practice is oriented towards labor-intensive small-scale production and heavy reliance on operator skill. If advanced ceramics are to be extensively used, automated production techniques are needed to make millions of components. This requires additional research to develop new machine tools, special part-handling techniques, and on-line inspection to control machining damage, surface finish and part dimensions.

7.2 Recommended Research Projects

7.2.1 Optimization of the Grinding Process

Our discussion with industry indicated that one of their most pressing needs was for information on how to optimize the grinding process to achieve maximum removal rate, minimum residual damage, and lowest cost. As already stated, grinding involves a large number of interdependent parameters, such as, feed, depth of cut, wheel speed, table speed, machine tool characteristics, grinding fluid chemistry, and wheel type. The machining rate and the amount of residual machining damage are very sensitive to the selection of these parameters for each specific material. The main focus of this program activity should be to develop and disseminate such data.

A group of industrial and government participants, having a sound background of experience in grinding advanced ceramics, should be assembled for this project. Different types of ceramics, including silicon nitride, silicon carbide, and composites should be used. All samples should be completely characterized before machining as to structure, residual stress, porosity, impurities, etc. These test samples should be machined to various degrees of severity by the industrial partners. The purpose here is not only to evaluate the effect of different variables on the quality of finished surface but also to determine the variability of current practice. Surface finish and grinding damage should be assessed using the most appropriate techniques. The true test of various machining techniques is to determine how that process affects the performance of the material. For ceramics, strength, wear, fatigue, and microhardness are particularly important for most applications. The test samples which have been fully characterized and machined to different degrees of severity should be measured for these properties. With these measurements, a correlation can be established between machining severity and the selected properties. The machining data and the information regarding strength and performance may be assembled and widely distributed in computerized database format.

7.2.2 Chemically Assisted Machining

As already discussed in the previous chapters, many machining methods have been suggested and are being evaluated. However, progress has been slow due to various technical problems. We must recognize that the simplicity of the machining method and the effectiveness of technology transfer are the primary factors which influence the implementation of research results. One approach which satisfies these requirements is to find innovative means for improving present machining methods. One area which has not received sufficient attention concerns the application of chemical assistance or enhancement. Three methods merit attention with respect to the application of chemical assistance: grinding, ultrasonic machining, and liquid abrasive jet cutting. Since the mechanics of material removal are similar in each of these techniques, the chemical assisted technology could first be developed for grinding and later applied to the other processes.

In grinding, it is possible to have significant chemical interactions between the local environment in a grinding system and any or all of three elements: the workpiece, the grinding wheel matrix, and the diamond abrasive. The simplest, and perhaps most economical method for the delivery of chemical compounds to the cutting zone is through the grinding fluid. Therefore, studies should investigate the effect on the grinding process of chemical compounds added to the grinding fluid and should identify the significant chemo-mechanical interactions that will increase the rate of material removal while minimizing the grinding damage. The outcome of this project, transferred to industry, would be a set of recommendations for grinding fluid additives.

7.2.3 Grinding Wheels for Machining of Ceramics

Research in this area should be focused on the development of grinding wheels and dressing techniques for application to advanced ceramics. In reviewing the critical role that the grinding wheel plays in the grinding process, it was pointed out that wear of the diamond grit was of overriding importance. Grit wear translates directly into higher grinding energies, increased workpiece damage, greater machine tool deflection, higher temperatures and associated degradation of the grinding fluid, and a reduction in the maximum achievable material removal rate. Wear of the grit is determined by the properties of the diamond used, the workpiece properties, grinding fluid chemistry, and the grinding parameters. Systematic investigation of the relationships among these variables should be carried out.

Quantitative information on the extent to which grit wear influences workpiece damage is also of critical importance. Such information could be used to determine the wheel dressing interval, or dressing rate if continuous dressing was employed. An associated effort would be the development of sensors and instrumentation to monitor wheel wear.

Although there appear to be significant opportunities to improve wheel wear life through grinding fluid chemistry and other means, it is unlikely that the problem of grit wear can be eliminated. An important requirement is that wheel wear be just sufficient to eliminate dull grit and expose fresh, sharp grit. Given the often conflicting requirements on bond properties, usually it is not possible to incorporate the necessary degree of controlled bond wear to accommodate grit wear. One solution to this problem is through in-process programmed wheel dressing; that is, wheel dressing would be accomplished during grinding at a rate or in intervals required to maintain sharp grit and/or a suitable level of grinding efficiency. Implementation would require the development of dressable-bond materials, cutting fluids, sensors to detect wheel wear, and adaptive control to accommodate dimensional changes associated with dressing.

7.2.4 Direct Damage Assessment Techniques

A review of the current state of the technology shows that there are no standard methods — non-destructive or destructive — for the direct determination of machining damage. Because of the importance of damage control in the machining of advanced ceramics, such investigations should receive a high priority. A direct method for damage evaluation is suggested in this section; other NDE techniques are discussed in the following section.

The most widely used indirect method for the evaluation of machining damage is the four-point bend test. This test is used to measure the flexural strength of ceramics and can be used to determine the effect of machining damage on strength. However, the bend test typically requires a minimum of 30 specimens, all machined under the same conditions to a close tolerance. Therefore, the bend test can be quite expensive for the determination of the machining damage. While the bend test may be suitable for determining flexural strength, it is not well suited for the evaluations of surface damage that might affect other types of performance, for example sliding wear or contact fatigue. A possible technique to employ is relatively new, and has been used to determine the mechanical properties (modulus of elasticity, hardness, and fracture toughness) of thin surface layers. The depth of indentation can be controlled to within a few tens of nanometers. This technique can be also used to measure the depth of the damage layer. It should be emphasized that the apparatus is already available at several laboratories, but much research is needed to interpret the resulting data on machined surfaces. This project has the potential for establishing a standard test procedure, based on nano-indentation for machining damage evaluation.

7.2.5 NDE Techniques for Damage Evaluation

In the past twenty years substantial effort has been devoted to the development and evaluation of NDE techniques for advanced ceramics. The basic requirement in the quality control of advanced ceramics is surface flaw detection in the 10 μm range or less. This is an order of magnitude below that commonly necessary for metals. Accordingly, a variety of new approaches have been developed for ceramics with various degrees of success. Application of these techniques to the evaluation of machining damage has been limited. For machining damage, it will be desirable to have techniques which give a general measure of damage as well as identifying the largest flaw. Our review of the technical literature, has indicated that the most appropriate NDE techniques are thermal wave measurement, surface acoustic wave, ultrasonics, and x-ray techniques.

The capability of these techniques to assess machining damage should be evaluated by analyzing test samples which have been machined with different severities from polishing to rough grinding. The results should be used to establish the degree to which each technique measures the change of severity. It is also important to use performance tests and known destructive techniques to evaluate the effectiveness of the NDE techniques. In this investigation, the types of damage detrimental to performance should identified. The results of this research can be used to refine the selected NDE techniques and to develop standard procedures for the utilization of these methods for surface damage assessment.

7.2.6 Sensors for Real-Time Surface Finish and Damage Assessment

The ability to control the grinding process in real time and obtain the desired surface finish could lead to a significant increase in productivity. Two approaches should be considered. The first is to develop sensors to directly measure surface finish and damage. At this time optical and ultrasonic methods appear to be the most promising. Projects should be undertaken to develop these methods and use them to control grinding parameters. The second approach involves indirect measurements to control the grinding parameters. These include grinding forces, power consumption, and acoustic emission. The relationship between these quantities and surface finish, and damage, together with the effect of grinding parameters, would have to be established through research.

7.2.7 Standard Reference Materials

It is often necessary to compare the quality of a finished part with a reference standard in order to evaluate the success of the machining technique with respect to the residual damage and surface roughness. It is recommended that fully characterized standard ceramic specimens be developed with a minimum amount of existing damage for evaluation of the quality of machining techniques. The samples must be provided from a single lot of material, in a geometry suitable for the preparation of four-point bend specimens and, if necessary, for other tests. Characterization of the material should include fracture toughness, surface roughness, surface residual stress, and other properties. Industrial laboratories could toughness, surface roughness, surface residual stress, and other properties. Industrial laboratories could purchase these standard reference materials (SRM) and machine them according to their practice. The quality of the finished surface could then be compared with similar data for the SRM to determine whether machining had severely degraded the integrity of the finished surface.

7.2.8 Post-Machining Treatments for Damage Control

Removal of material by any mechanical method will result in a certain amount of damage in the form of lattice defects, microcracks, and residual stress. A possible approach to damage control other than optimization of the machining processes is to develop effective post-machining treatments that mitigate the damage. The following methods should be considered: high temperature oxidation, high temperature annealing, chemical etching to remove damage, ion exchange, tempering, and coatings. Each of these areas must be explored in detail to determine the effectiveness and the economics of the process.

7.2.9 Innovative High-Strength Machinable Ceramics

Past research has established that additions and impurities incorporated within materials can have significant effects on mechanical properties and machinability. An approach that has been successfully followed in metals and glass, that of intentional additions to enable satisfactory machining, may have some promise in the case of structural ceramics. An example of this approach is the development of electrically conductive ceramic composites from which parts can be fabricated by electrical discharge machining. These composites are generally made by adding electrically conducting particles to a non-conductive ceramic such as alumina. The additions that have been successfully implemented include TiC, TiB_2, ZrB_2, and TiN. To overcome the decrease in strength that may result from the addition of the electrically conductive particles, often SiC whiskers are incorporated into the composite [Schuldies and Branch 1991]. Addition of second phase particles to a ceramic composite does not always decrease the strength and fracture toughness. It has been shown by Benison et al. [1991] that addition of aluminum-titanate to alumina increases the material's resistance to fracture as a result of crack bridging, crack deflection, and compressive residual stresses set up during processing. These results suggest that if a sufficient understanding is developed on the interactions between second phase particles and the ceramic matrix, it would be possible to design machinable ceramics for structural applications. This project requires detailed investigation of processing of ceramic composites to optimize the processing parameters for best machinability and strength. In addition to electrical discharge machining, it may be possible to develop ceramic composites with greater machinability by the abrasive processes such as grinding.

7.2.10 Automated Systems for Large-Volume Production

Significant advances have been made in automation and the development of intelligent systems for the production grinding of metal components. Similar systems for the grinding of ceramic components involve additional requirements and challenges. The first requirement for such a system is reliable, fast-acting sensing devices for surface finish assessment and damage detection. The information from the sensors could be fed into a computer for comparison with a set of preprogrammed information. This could be in the form of a knowledge-based system or an analytical model, which would then be used to search for, or calculate, the best parameters for an optimized machining condition. This information would then be transmitted to the control circuitry of the machine tool. Implementation would require the development of machinability databases, knowledge-based systems, and analytical models for grinding optimization, in addition to sensor development. Other important factors that must be considered in an automation system are machine tool dynamics, wheel truing and dressing, and parts handling adapted for ceramic materials. To assess the feasibility of intelligent systems for the production of ceramic parts, a model system should be designed for the production of a specific component, for example a silicon nitride roller-cam follower.

7.3 Program Coordination

The program objectives described are far beyond the capabilities of a single organization. It is estimated that such a program would require several million dollars over a 5-year period. Thus, a coordinated program is necessary which utilizes the skills, experience, and resources from several organizations.

Several government agencies have recently initiated research programs related to ceramic machining. The Department of Energy, Office of Transportation Materials, has started a program on cost-effective ceramics, which includes ceramic machining as one of the program elements. The Defense Advanced Research Projects Agency, Ceramic Materials Program, is now funding several projects to accelerate the introduction of advanced ceramics into military and civilian applications. Some of these projects are concerned with machining and fabrication techniques for ceramic components. The Air Force Manufacturing Technology Program is formulating a 5-year program primarily focused on machine tools and their improvements. One aspect of this program deals with machining of advanced materials. It is important to recognize the need for coordination among these agencies to eliminate the potential for duplication of effort and to advance the technology of ceramic machining through joint efforts.

7.4 Technology Transfer

The information generated in the course of research to resolve the identified needs must be transferred to those who can implement the technology. It should be emphasized that publication of research results in archival journals and reports is slow, and often does not reach the intended audience. Therefore, other direct forms of communication are needed for rapid technology transfer. In this respect, it is important not only to conduct the proposed research in close collaboration with industry, but also to organize frequent lectures and symposia to disseminate the research information generated in this program.

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Appendix A

NIST CERAMIC MACHINING WORKSHOP

1. Summary

A workshop meeting was held on September 19, 1990, at NIST to identify those topics in the field of ceramic machining and finishing which industry felt were critical to the advancement of this field. Twenty-one participants from industry attended. Presentations by industry described both the nature of research that was felt to be important in this area as well as the impact of machining on the cost of ceramic components. A tentative plan of research was developed and industrial participants were requested to respond to the Ceramics Division with comments. It was agreed that industry and government should jointly sponsor a program to address the short-term and long-range needs of the industry to overcome technology barriers.

2. Background

The workshop was organized following discussions with personnel from the ceramic companies and the United States Advanced Ceramic Association. These discussions indicated that commercialization of advanced ceramics for transportation systems was adversely impacted by the cost of machining. The objective of the meeting was to identify critical research priorities in this field and opportunities for cooperative research between the NIST and the ceramic industry.

Representatives from the structural and electronic ceramics industry as well as users and machine tool manufacturers were invited to this meeting and provided the opportunity to present their views and perspectives. Twenty-one individuals from industry participated and are listed in Appendix B. In addition to industrial participants, the U.S. Department of Energy and the United Stated Advanced Ceramic Association were also represented. The meeting was also attended by NIST personnel from three divisions, many of whom presented research results pertinent to ceramic machining.

3. Proceedings

Industrial representatives from Allied Signal/Garrett, W. R. Grace, Co., Carborundum Company, the Norton Company and the Advanced Manufacturing Science and Technology Co., all reported that reduction of machining costs is an important factor in the widespread utilization of advanced structural ceramics. Specifically, it was felt that although desired tolerances and finishes were achievable by machining, the opportunity was present to (1) radically reduce the cost of machining and (2) to significantly improve the quality of surface finish, hence, reliability.

Several industrial participants identified machining and finishing as a primary cause of the high cost of ceramic products. Costs ranged from 10 percent to 15 percent of the total cost of a product where a single operation was required for over 100,000 parts to as high as 80 percent where multiple operations were required for fewer than 25 parts. Other companies reported that for specific components the cost of machining to the preformed stage could account for anywhere from 52 percent to 72 percent, whereas final machining could run as high as 80 percent to 90 percent of the final product cost. A summary of the estimates given by industrial participants is provided in Table A-1.

TABLE A-1. COST OF CERAMIC MACHINING/FINISHING

Machining cost as % of sales

Electronics	17%
Mechanical Seals	17%
Armour	18%
Bearings	55% to preform 80-90% to finish
Prototype Components	62%

Machining cost as a function of number of parts

Less than 25,000	20-80% of direct material cost *
25-100,000	40% of direct materials cost*
More than 100,000	10-15% of direct material cost**

* Multiple Operations
** Single Operation

Machining cost by type of operation

Centerless grinding	3-10%
Rotary Table	15-50%
Free Abrasive	15-30%

The following list of research needs were identified by the various industrial speakers present:

• Reduction in cost of materials, processing and machining required to make ceramic components economically competitive with metal components was agreed to be critical to the future of ceramics technology.

• Novel processes of machining which would allow rapid material removal as well as minimal surface damage to increase part reliability was identified as a desirable goal. Chemically assisted machining for mass production was identified as a high payoff research topic.

• Production volume to price interaction for a given ceramic material requires improved definition particularly in the context of a lower cost approach to manufacturing.

• Mechanisms of machining of ceramic parts require better understanding both on fundamental and applied levels. This knowledge could be readily utilized by designers of machine tools and grinding wheels as well as ceramic component finishers.

• Effect of machining parameters on performance is not well understood. Experiments were cited which showed that machining rates could be significantly increased without a penalty on stress rupture properties. However, the limits of increase possible are unknown and specific relationships between performance and machining rate are unclear.

• Creative automation technology was cited as important and potentially of great use in the field of machining, particularly as it relates to controlling surface properties and to reducing costs.

• Identification and quantification of machine tool characteristics which control the quality of the finished product were cited. Also cited was the necessity for working directly with manufacturers to develop improved grinding machines. Available machines designed for metal working have an insufficient inherent stiffness to allow significant ceramic material removal without adverse deflection of the machine tool elements or the material itself.

• Understanding the nature of grinding wheels and grinding wheel design were identified as areas which could provide significant improvements in the machining process. Well-understood and defined wheel specifications were felt to be limited.

• Research on the nature of grinding fluid behavior and properties was identified as a potentially significant research area. Currently, specific grinding fluids for ceramic machining are not available and it is not clear whether fluids available for metal machining are entirely appropriate for ceramic applications.

• Masurement of surface roughness, flatness, and other dimensional features was felt to require significant attention particularly with regard to the cross referencing of standards between the United States and Europe.

• Grinding machine to surface interactions with regard to the nature of the finish, residual stress and surface and subsurface damage were identified as important. Most of the attendees felt that the ability to measure damage was important to determining the proper machining parameters necessary to manufacture reliable parts.

· Accuracy of machining cost projections requires improvement. Two companies specifically cited this as an area in which they were only moderately able to make accurate estimates to allow bidding on contracts. From this discussion came the suggestion that a machinability center which could determine basic data for industry, which relates machining parameters, machine tool behavior, and surface finish to cost would be a valuable investment.

Another institutional issue which was raised was the need for an interdisciplinary approach to the grinding of ceramic materials. This would necessarily involve the participation of tool makers, wheel makers, instrumentation experts and ceramic manufacturers. In spite of the fact that the ceramic manufacturers procure tools and other equipment from suppliers, they felt the size of their market was insufficient to encourage the tool manufacturers to develop tools specifically for ceramic machining.

4. Research-in-progress

Several NIST staff members described research underway which addressed the needs of the ceramic machining and finishing community. Said Jahanmir, of the Ceramics Division, highlighted research on the effect of surface stress on crack formation and subsequent removal of materials during grinding. He also presented data which identified the variation in material removal rates which can be attributed to chemical activity of lubricating or cutting fluids. Differences of about an order of magnitude were shown for a variety of frictional loading levels.

Also noted was the development of techniques of measuring surface and subsurface structures. A presentation by Grady White, of the Ceramics Division, highlighted recent research in the use of thermal wave analysis to determine the variation of surface finish and subsurface machining damage. The work was felt to have a significant application in determining the predicted performance and reliability of finished components.

A report by Gerry Blessing, Automated Production and Technology Division, highlighted research on the use of ultrasonic interrogation to determine surface finish. It is interesting to note that this research addressed the use of cutting fluids as an ultrasonic transmission medium from the transducer and sensor head to the workpiece itself. Significant correlations between the results obtained by ultrasonic interrogation and subsequent profilometry were shown. It was felt that this technique would have a significant impact for on-line machine tool control.

A fourth talk by NIST staff was presented by Chris Evans who briefly described diamond single-point turning and ductile-regime grinding research conducted in the Precision Engineering Division. This research identified the role of diamond machining of high surface finish ceramic mirror materials.

Following the presentations and a tour of the Automated Manufacturing Research Facility, potential future interactions in the machining area were discussed. A hypothetical project in this area which could be cooperatively addressed by both government and industrial researchers was presented by NIST. This plan addressed rapid machining techniques as well as sensor development. Intellectual property rights, in terms of cooperative R&D agreements were detailed by S. M. Hsu, Ceramics Division. The participants were requested to review the proposed work and to discuss it with their management prior to the USACA meeting of October 2, 1990.

Appendix B

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A study was conducted to assess the current state-of-the-art in the machining of advanced ceramics and to identify research areas which could lead to significant improvements. In conducting the assessment, an extensive literature search was carried out, visits and discussions were held with industrial companies interested in ceramic machining, a telephone survey was conducted on ceramic machining shops, a research-in-progress database was consulted, individuals were invited to visit NIST and discuss different aspects of ceramic machining, and a workshop was held at NIST in September 1990, to identify specific industrial needs in ceramic machining.

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