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Modern Approaches for the Production of Ceramic Components

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Abstract

New materials are vitally important in industrial development. They are mostly the start of a technology chain leading to the final product via a number of value-added stages. Application experience often produces feedback for improvement and optimization of the production process and the material itself. Machining ceramics makes high demands in terms of component quality and process economics. 'Ceramic-adapted machining' is therefore essential for production of advanced ceramic components. This includes both optimization of existing processes and development and testing of new machining technologies. This article presents material-adapted machining technologies and their potential for advanced ceramic components. © 1996 Elsevier Science Limited.

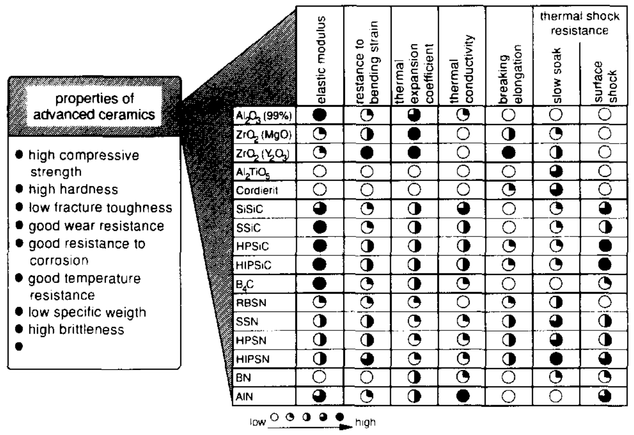
Neue Werkstoffe haben für die industrielle Entwicklung eine herrausragende Bedeutung und stehen meist am Anfang einer Technologiekette, die über verschiedene Wertschöpfungsstufen zum Endprodukt führt. Mit den Erfahrungen aus der Anwendung geht häufig ein Rückkopplungsprozeß einher, der zur Verbesserung und Optimierung des Produktionsprozesses und des Werkstoffes selber führt. Keramische Werkstoffe stellen insbesondere an die Bearbeitung sehr hohe Anforderungen bezüglich erreichbarer Bauteilqualität und Wirtschaftlichkeit. Das Kriterium 'keramikgerechte Bearbeitung' beim Einsatz von Hochleistungskeramik ist deshalb eine wichtige Vorraussetzung für die Herstellung keramischer Komponenten. Neben der Optimierung bestehender Verfahren beinhaltet dies auch die Entwicklung und Erprobung neuer Bearbeitungstechnologien. Im Rahmen dieses Beitrages sollen daher werkstoffgerechte Bearbeitungstechnologien und deren Potentiale für Bauteile aus Hochleistungskeramik vorgestellt werden.

1 Introduction

The current situation in technical competition and further development means that components in equipment and machinery are more and more often required to meet high design specifications. Wear resistance, thermal resistance, reduced weight and resistance to chemicals — these are requirements often laid down in technical specifications for components in aerospace and in machinery and plant manufacture.

In many cases these high requirements cannot be met by conventional materials, so advanced ceramics is often the approach used. Compared with metallic materials, they feature superior compressive strength and hardness, which are only slightly reduced at temperatures up to 1000°C. They have further useful functional properties such as excellent wear resistance and corrosion resistance, and low specific weight; their major disadvantage is low ductility (Fig. 1).[1]

A successful market strategy for advanced ceramic components requires the complete production process to be tailored specifically to ceramics, in order to realize their outstanding engineering properties with sufficient reliability and at acceptable cost. This adaptation to current market needs is the only way to develop further applications. The most important requirement for cost-effective and reliable production of advanced ceramic components is 'ceramic-adapted finish machining'. This involves the optimization of existing processes, and also development and trial of innovative machining techniques. Job-order production is an important approach here. An example is the manufacture of floating seals, which is not only for series production such as water pump seals, but increasingly also for small series production with batch sizes often less than 100 units.



	elastic modulus	restance to bending strain	thermal expansion coefficient	thermal conductivity	breaking elongation	thermal shock resistance: slow soak	thermal shock resistance: surface shock
Al_2O_3 (99%)	●	◔	◕	◔	○	○	○
ZrO_2 (MgO)	◔	◑	●	○	◑	◔	○
ZrO_2 (Y_2O_3)	◔	●	●	○	●	◑	○
Al_2TiO_5	○	○	○	○	○	◕	○
Cordierit	○	○	○	○	◔	◕	○
SiSiC	◕	◔	◑	◕	○	◔	◕
SSiC	●	◔	◑	◑	○	◔	◑
HPSiC	●	◑	◑	◑	◔	◔	●
HIPSiC	●	◑	◑	◑	◔	◔	●
B_4C	●	◔	◑	◔	○	○	◔
RBSN	◔	◔	◔	○	◔	◑	○
SSN	◑	◑	◔	◔	◑	◕	◑
HPSN	◑	◑	◔	◔	◑	◕	◑
HIPSN	◑	◕	◔	◔	◑	●	◕
BN	○	○	◑	◔	○	◔	◔
AlN	◕	◔	◑	●	○	○	◕

Fig. 1. Properties of advanced ceramics.

The purpose of this article is to indicate the machining technologies that can be used for advanced ceramics, and the potential available from tailoring the machining process to the material. The main focus will be on manufacture of structural ceramic components, where component cost and quality are mainly determined by the machining operations.

2 Machining of Green Ceramics

Analysis of the production process for a ceramic component (Fig. 2) shows that cost and flexibility of manufacture depend not so much on the raw material or the preparation costs, but more on forming operations. This includes not only the original shaping of the component with techniques such as injection moulding, casting or pressing, but also machining in green or white state before sintering, and above all the final machining operation. This machining currently accounts for about 70–80% of component costs.

For small-to-medium production batch sizes, machining in the unsintered 'green' condition permits high flexibility and good economics compared with other forming processes[2] and permits considerable reduction of tool cost. It is possible to use geometrically simple semi-finished products, giving good homogeneity and density distribution in the green part, and thus high component quality after sintering.[3] This also gives high accuracy in the sintered component. This is extremely important, reducing the amount of material to be removed in the sintered state to achieve the desired final geometry. This reduces expense in the very time- and cost-intensive final machining stage (near-net-shape). This approach is being pursued in the ceramics industry, but so far there has been practically no systematic study of process design for machining in the green state. Company internal know-how is based mainly on empirical data, but this makes inadequate use of the available technological reserves.

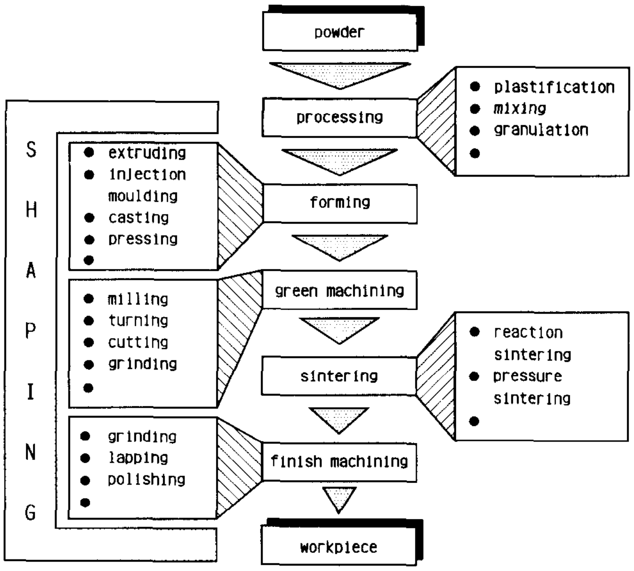


Fig. 2. Production steps of ceramic components.

The technological reserves (Fig. 3.) refer not only to process specification, i.e. the selection of machining parameters and depth of cut; another important point is specification of tool geometry. Selection of cutting material and its exact specification are essential. The example in Fig. 3 shows very clearly how much the cutting material influences machining costs, which are largely determined by tool life and tool costs. Polycrystalline diamond (PCD) tools have proven to be optimal in turning operations, while tungsten carbide seems to be a possibility for drilling operations, due to the low cutting speeds involved.

A major problem in machining green components is the low strength of the material and the resulting problems in clamping and handling the workpieces. The clamping fixtures used are often the same as those used in metal working, but these have considerable disadvantages in transmission of forces and in sensitivity. Improvements can be made by vacuum clamping or by using flexible force-transmission elements.

The situation with available machine tools is similar; here again, machine concepts and components are not adapted to the specific requirements for machining green components. The high abrasiveness of the material requires measures to protect the bearings and slideways of the machine tool. PCD and other advanced cutting materials also need high peripheral speeds and spindle speeds for economic operation. Other improvement capabilities are the extraction of machined material, and in some cases also the precipitation and recycling of this material.

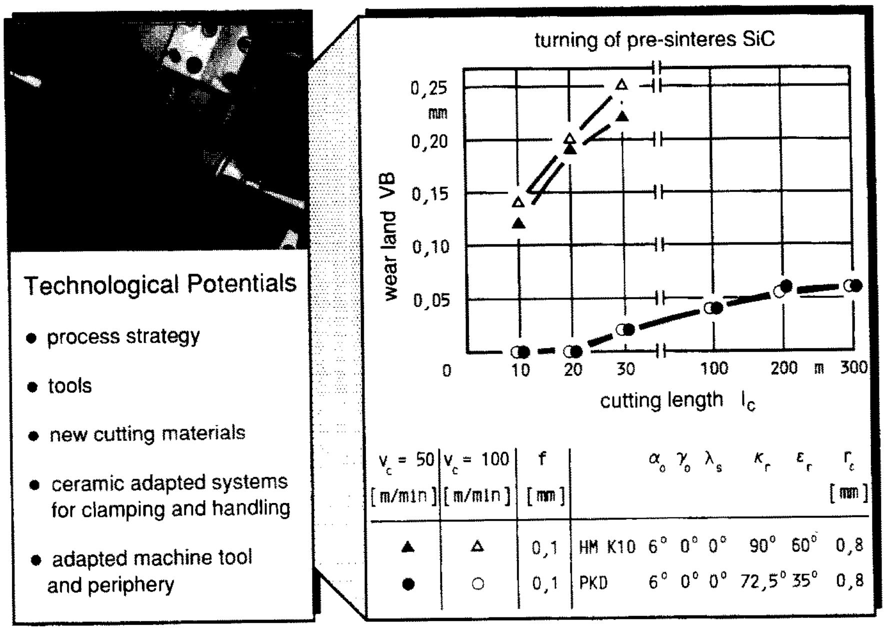


Fig. 3. Improving the economics of machining green ceramics by using technological reserves.

3 Finish Machining

3.1 Process design

There are only a limited number of processes available for machining advanced ceramics, unlike metallic materials. Processes with a geometrically defined cutting edge (such as turning, drilling and milling) cannot be used because of low tool life. Processes with a geometrically undefined cutting edge therefore have to be used, to distribute the removal work, and thus also tool wear, to as many cutting edges as possible.

The various production processes may be divided into conventional processes and innovative processes (Fig. 4). At present, the main processes used in industry are grinding, lapping and polishing. There is a wide variety of grinding processes (OD grinding, ID grinding, surface grinding, cut-off grinding), making it possible to produce a wide range of component geometries. Lapping can be used only to produce flat or curved geometries, owing to the machining principle involved. The innovative processes currently include special-purpose applications such as ultrasonic machining of very fine bores in industrial applications. Other applications are still at the pre-industrial stage.

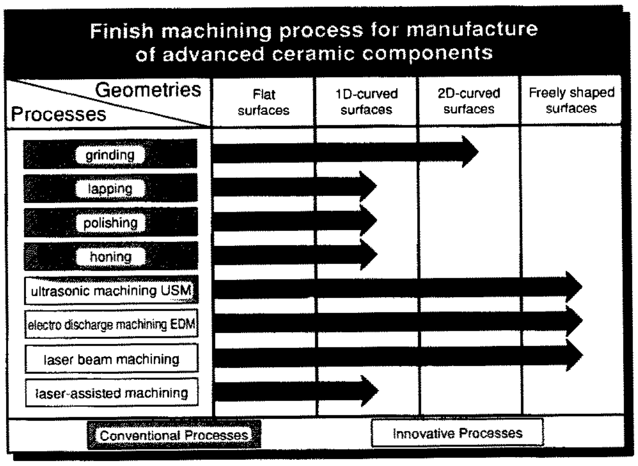


Fig. 4. List of innovative and conventional processes for finish machining of advanced ceramics.

3.2 Grinding

Ceramic materials are so hard that grinding can be done only with diamond tools. Economic production is dependent on specification and conditioning of the grinding wheel for the process and the material. Correct specification of the machining process requires knowledge of the material-specific fracture and removal mechanisms. Material behaviour on penetration by a hard body, as in the grinding process, can be studied by indentation and scratching tests. Vickers diamond indentation tests can be used to simulate the vertical penetration of a cutting edge into the workpiece material. Alongside this static method, it is also possible to simulate the dynamic processes that occur in grinding, by means of single-grit tests. Just one diamond grit is attached to the periphery of a grinding wheel, and engages the workpiece under the same conditions as in the grinding process (Fig. 5).

The low deformation capability of the ceramic material has a considerable effect on the cutting edge load and chip thickness in the chip-forming process. For example, with silicon-infiltrated silicon carbide, it is possible under low cutting edge load to observe ductile material behaviour in this inherently brittle material. Plastic deformation occurs without crack formation at the corners of

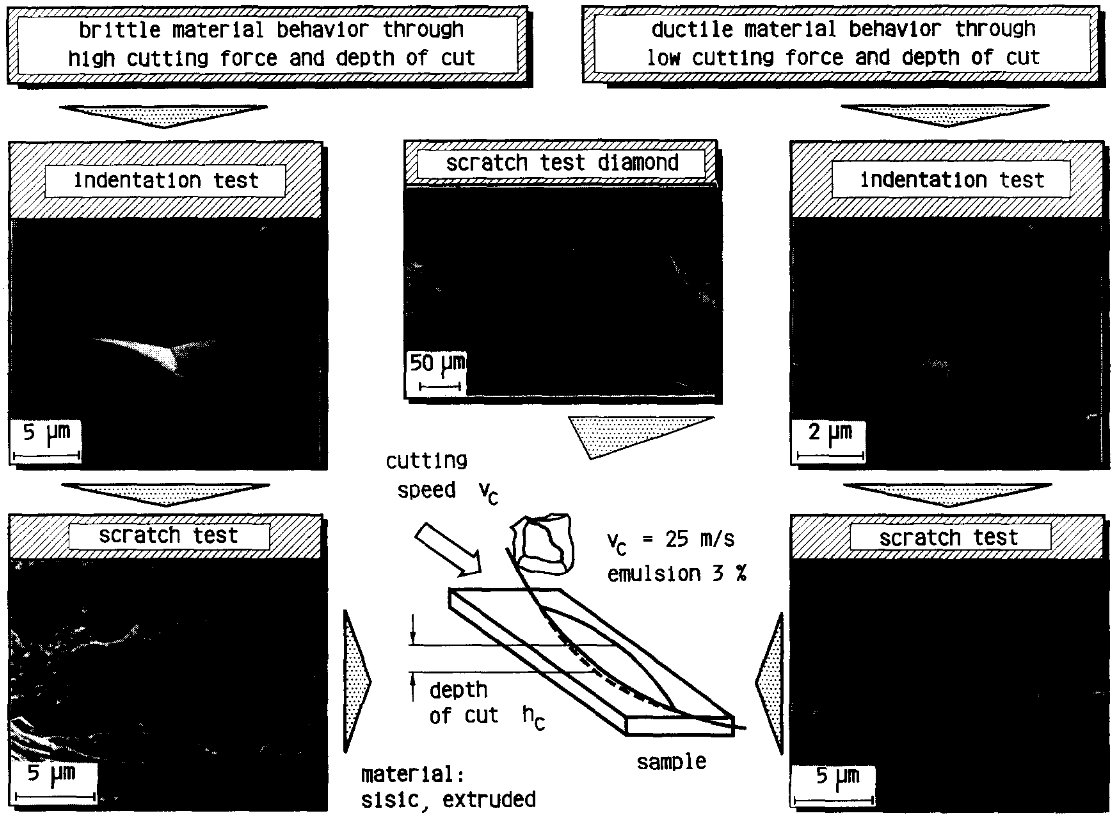


Fig. 5. Cutting edge load and depth of cut determine the material removal mechanism of ceramics.[7]

the diamond grit impression; this is apparent as bulges at the edges of the indentation. Material behaviour changes under higher grit load. As the diamond grit penetrates more deeply into the material, critical tensile stresses are exceeded at the corners, and cracks develop from there into the surrounding material.

This means that in single-grit scoring tests, high chip thickness produces mainly brittle material removal. With the material SiSiC, a change in scoring depth from 1·2 mm to 0·6 mm causes a considerable change towards ductile material behaviour. As the single grit runs through the material, there are deformations to the side, generating a clearly evident scoring track.

Alongside cutting edge load and chip thickness, cutting edge shape is another factor that influences chip-forming behaviour. A sharp cutting edge tends to produce point-load as it penetrates the workpiece material; the stress state below the cutting edge is subject to pressure only in a small area, and exclusively tensile stresses are created in a radial direction, tending to promote crack formation.[4,5] A large radius on the cutting edge tends to generate mainly compressive stress in the workpiece; this stress state seems to favour the activation of sliding systems even in low-ductility ceramic materials, and thus largely suppresses crack formation by viscous flow behaviour.[6]

In summary, the basic studies and model analyses on the chip-forming mechanism of advanced ceramics produce clear results. Transition to ductile material behaviour is possible even with brittle materials. Low cutting edge loads and chip thicknesses, and the use of a rounded cutting edge shape favour ductile material behaviour. All the evidence suggests that this is the key to reducing surface damage from crack formation and crack propagation.

However, production engineers still have to work out how to use this knowledge. Apart from appropriate tool selection and conditioning, they can exert considerable influence on the variables cutting edge load, chip thickness and cutting edge shape (depending on the grinding process) with variation of the process parameters in feed, depth of cut and peripheral speed. The example of OD grinding demonstrates the benefits in systematic implementation of the knowledge from basic studies of the chip-forming mechanism.

At conventional wheel peripheral speeds of v_c = 25 m/s, a certain material removal rate is achieved at low cutting speed. There are only a small number of wheel/workpiece engagements. The chip thickness on the individual cutting edges is therefore relatively large. However, the same material removal rate is also possible at high wheel peripheral speed. This means more cutting edges are

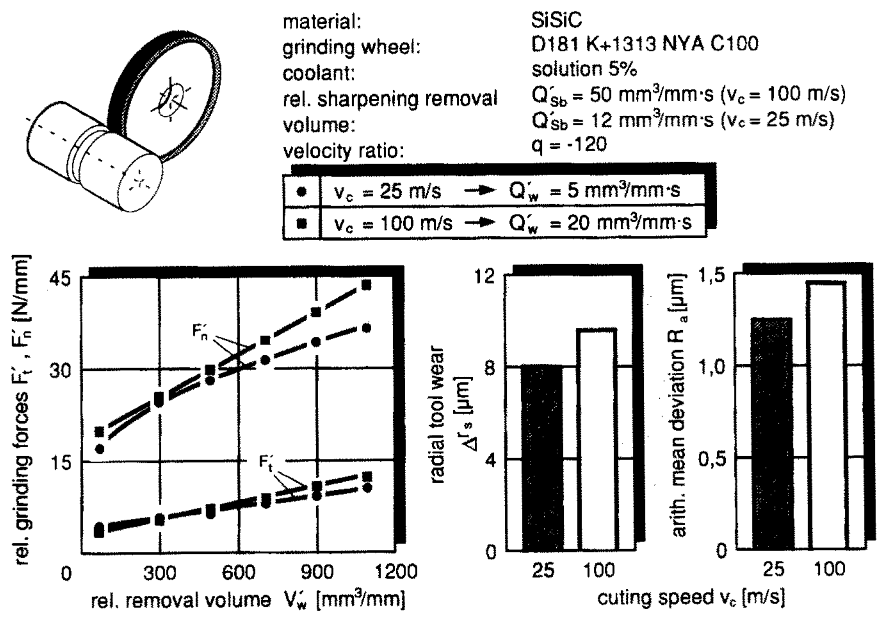


Fig. 6. High speed grinding leads to process optimization in combination with high material removal rates.[8]

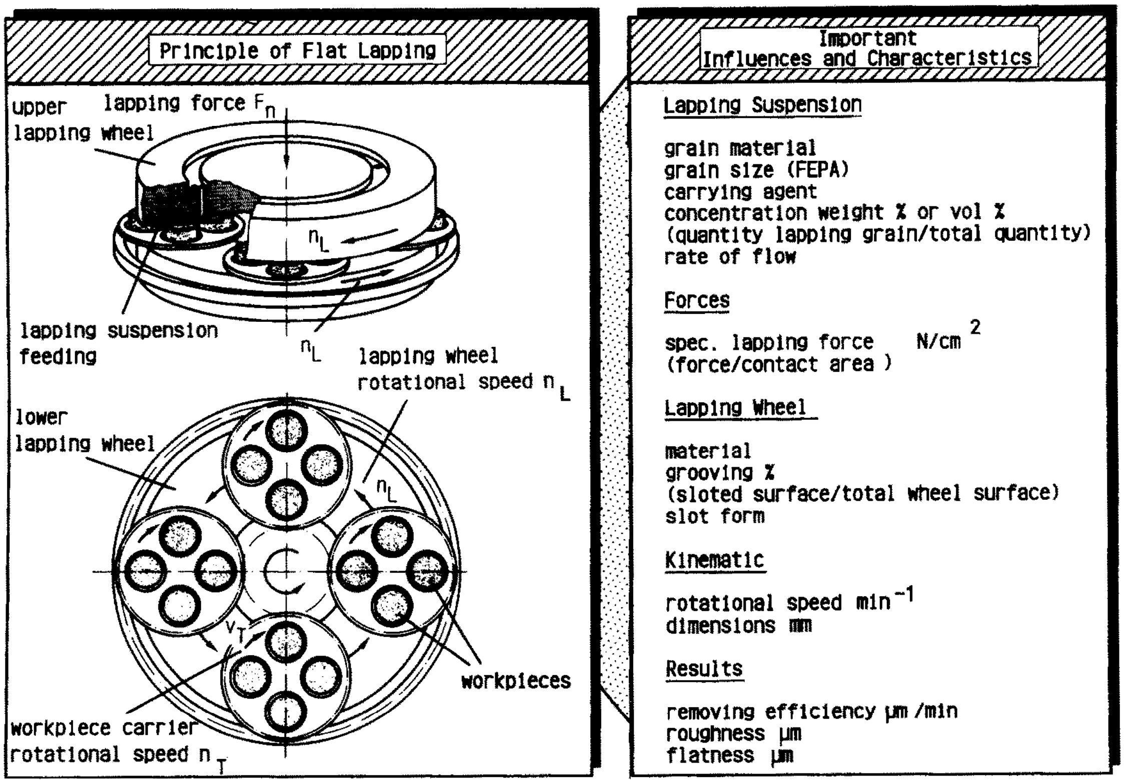


Fig. 7. Principle of lapping plane surfaces.[9]

engaged, i.e. the individual grit has to remove less material per workpiece engagement, thus reducing the chip thickness for the individual grit. This gives a considerably more ductile process, which is less damaging for the component.[7,8]

While increasing cutting speed, it is also possible to increase the material removal rate at theoretically constant chip thickness, as compared with a grinding process at conventional peripheral speed. A comparison of the two processes is shown in Fig. 6. The increase in cutting speed and material removal rate multiplies the material removal by four. The benefits of this machining strategy are accompanied by a slight rise in cutting forces and hence increased wear, and a slight deterioration in surface quality.

3.3 Lapping

There are many applications for ceramic components, e.g. seals and bearings, where flat or plane-parallel functional surfaces are needed, combined

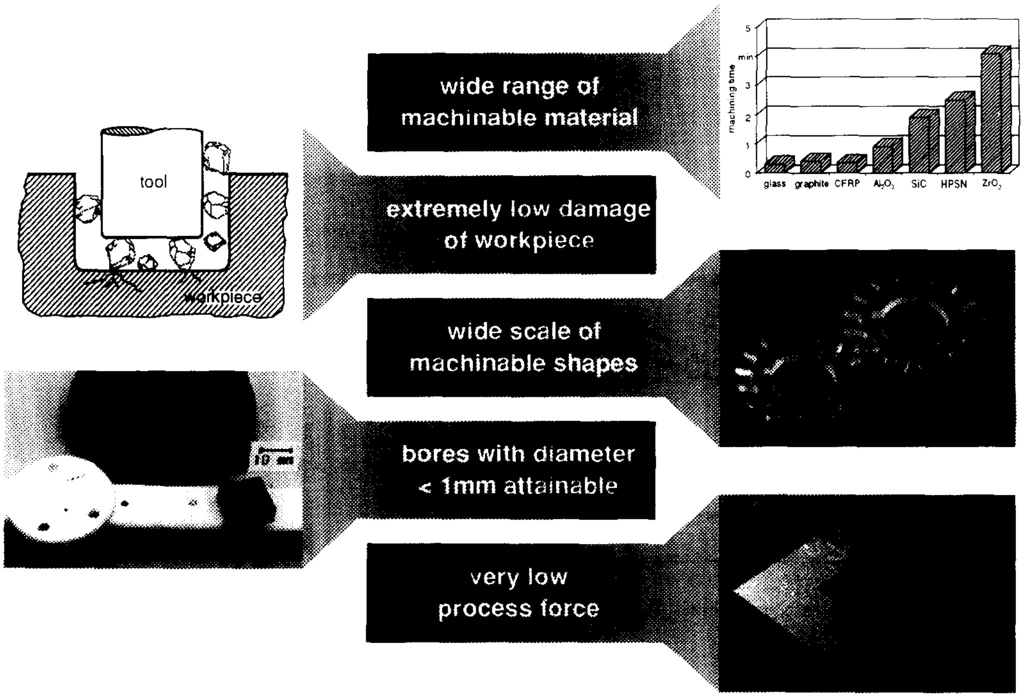


Fig. 8. Overview of the advantages of ultrasonic machining.

with high surface quality. The finishing process mainly used for these components is plane parallel lapping (Fig. 7). One of the main advantages of lapping is that the grits which are held in a suspension only have to be slightly harder than the material to be machined, as new grits are continually supplied, and after leaving the contact zone they are not used again. This means that in most applications it is possible to use boron carbide rather than diamond as required for grinding processes, and this is considerably cheaper.

This process can also be used to machine a number of workpieces simultaneously and from both sides. The loose guidance of the workpieces in workpiece mounts between the top lapping wheel and the bottom lapping wheel is a major advantage, especially in the initial machining of components with sintering deformation, as it is not necessary to clamp the workpieces.

In keeping with the normal force acting between the lapping wheels and the workpiece, the lapping grits are pressed only a little way into the workpiece and lapping wheel surface. The relative movement of the components with respect to the lapping wheel causes the grits to roll over between the two surfaces, so that the penetration of the grit tips induces micro-cracks in the workpiece surface. Interlinking of these cracks causes microscopic workpiece particles to break out, and these contribute to material removal. Apart from this removal mechanism, individual lapping grits may also be fixed temporarily in the lapping wheel surface, thus causing chip-forming material removal on the workpiece surface.[9]

At first sight, the attainable material removal rate in lapping appears to be small. But remembering that a number of components can be handled simultaneously, removal rates are sufficient to make the process cost-effective in many applications, particularly in view of its reliability and the low machine hourly rate. The use of high forces, with coarse grit, can give high material removal rates linked with good surface qualities.

3.4 Ultrasonic machining

Machining ceramics quickly to complex contours causes considerable problems for the conventional production processes mentioned so far, due to the hardness and brittleness of ceramic materials. Ultrasonic vibration lapping is an interesting alternative for cases like this, and in many cases it is the only way to machine high-strength brittle materials. The key benefits of the process are the free selection of geometrical shape within a wide range of capabilities, and the possibility of minimizing forces. This aspect in particular enables the user to generate recesses in a diameter range of less than 1 mm, and to machine thin substrates with a thickness of less than 200 μm (Fig. 8).

Material removal is effected by the supply of lapping compound suspension, comprising water and the abrasive grits suspended in it. To start with, the lapping grits lie loosely between the workpiece and the shaping tool. The high-frequency longitudinal vibration of the lapping tool causes the lapping grits to impact the surface of the workpiece. The physical process mainly comprises hammering the boron carbide grits into

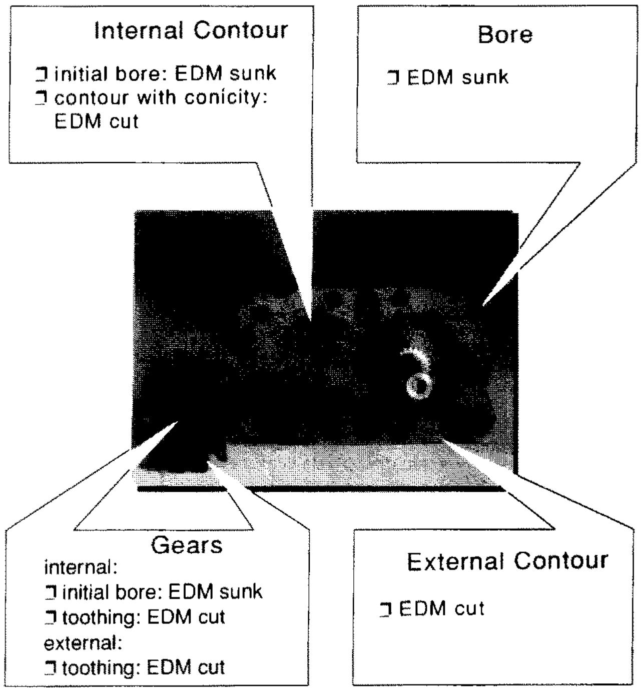


Fig. 9. Gear pump from advanced ceramics made by EDM.

the workpiece surface. This induces cracks in the workpiece in the microscopic size range, and their accumulation over time and space causes material removal. Ultrasonic machining also gives further application capabilities. For example, the working gap can be varied within certain limits, for controlled modification of the surface topography of the workpiece.[10,11]

3.5 Electric discharge machining

Electric Discharge Machining (EDM) is another alternative to conventional techniques. This process exploits the physical phenomenon of material removal due to successive electric discharges between two electrically conducting materials. In order to achieve material removal, this process has to take place in an electrically non-conducting fluid ('dielectric'). In general, the geometry of the component to be manufactured is determined by the shape of the tool. But there are some variants of this process where the contour of the workpiece is determined by tool kinematics. A NC program is used to guide a relatively simple tool in such a way that it can also generate complex geometric shapes.

Ceramic materials basically have to meet just one condition in order to permit the use of EDM — they must have a minimum electrical conductivity (between 10^{-1} and 10^{-2} S/cm). Ceramic materials are generally considered to be electrical insulators, but this is not always the case, and each ceramic material has to be considered individually. The advanced ceramics titanium boride, boron carbide and silicon infiltrated silicon carbide have good electrical conductivity and can therefore be machined by EDM. Other ceramic materials can be given sufficient electrical conductivity by doping.

There are basically four material removal mechanisms in EDM. These are thermoshock, melting and ejection, flaking out of re-solidified material, and grit breakout due to removal of the bonding phase.

The EDM production technique makes it possible to machine ceramic materials with complex three-dimensional contours from simple sintered blanks; the process is fast and can achieve accuracies in the micron range. An example is the ceramic gear pump shown in Fig. 9 for delivering liquid media. The chemicals industry often requires chemically aggressive and/or high-temperature media to be pumped through pipes. The gear pump is completely EDM manufactured from advanced ceramic material, except for the shafts, which are made of stainless steel.[12]

3.6 Laser-assisted machining

Knowledge of the right removal mechanism for the material not only helps to optimize existing production techniques, but also provides the basis for developing new ones, so as to give more flexibility in future machining of advanced ceramics. Laser-assisted hot machining processes are an example of new capabilities arising in hard machining. Machinability can be improved by heating to high temperatures, giving a partial plastification of the material. Thus hot-pressed silicon nitride ceramics are excellent for laser-assisted turning, thanks to thermal properties such as low expansion coefficient and excellent temperature cycling stability.

The implementation of this concept is shown in Fig. 10. The laser beam is coupled in at the machining point by means of a beam guidance and shaping system that is integrated into the machine. The focal point of the laser is about 4 or 5 mm in front of the tool cutting edge, so the material is partly heated up in the vicinity of the shear plane. The machine is a conventional CNC lathe, combined with a CO_2 or Nd-YAG laser source. CBN tools are preferable to diamond tools in this application because of the high temperatures occurring at the cutting point.

The largely crystalline structure of silicon nitride has amorphous areas at its grit borders, so it is possible to achieve a partial plastification of the material by heating it above 1000°C. Heating makes it possible to achieve defined chip removal. The laser beam is an ideal means to heat up the workpiece, due to its high energy density, the good control capability of its energy input and its

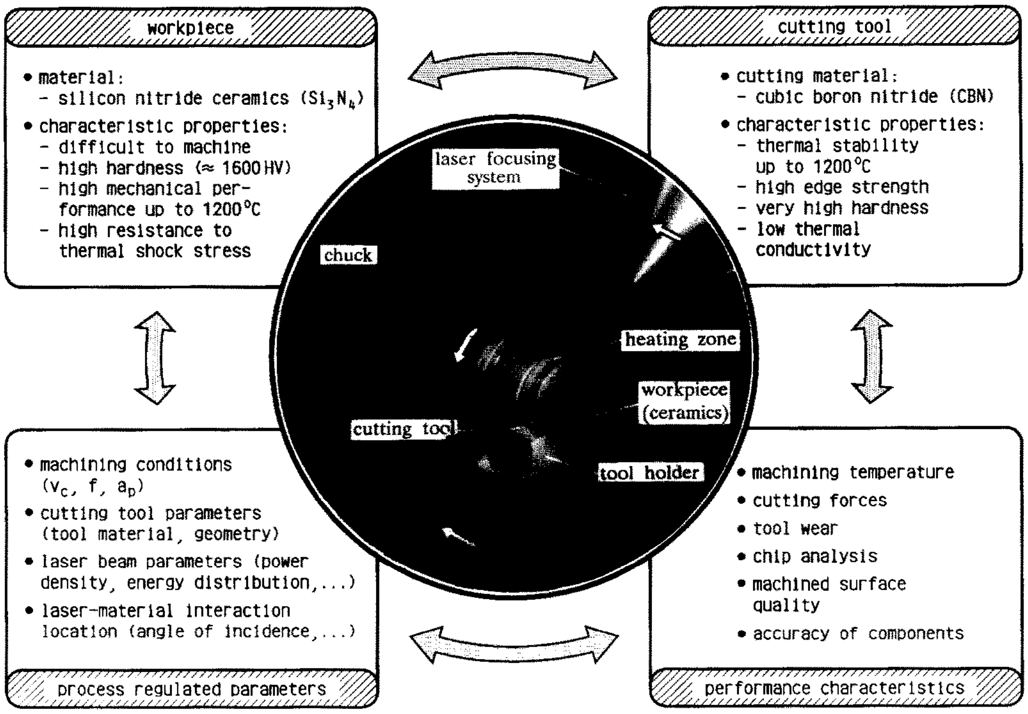
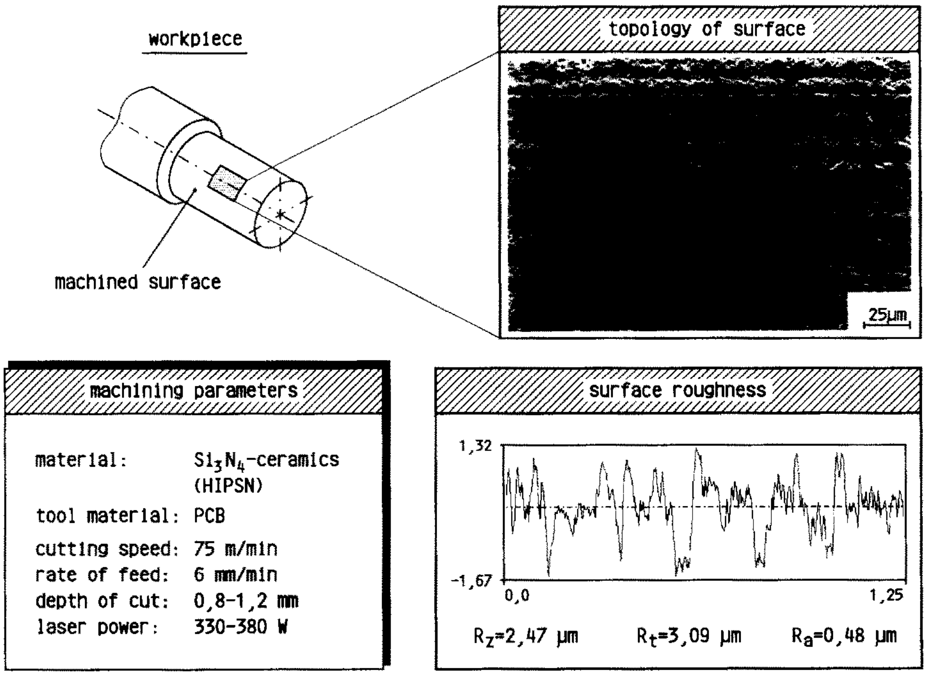


Fig. 10. Technology investigations for laser-assisted machining -- laser-assisted turning of structural ceramics.



machining parameters

material:	Si_3N_4-ceramics (HIPSN)
tool material:	PCB
cutting speed:	75 m/min
rate of feed:	6 mm/min
depth of cut:	0,8-1,2 mm
laser power:	330-380 W

Fig. 11. Surface quality of laser-assisted turning.[13]

narrow heat influence zone compared with other energy sources.

In order to ensure sufficient energy input in the material, it is essential to attune the parameters laser output, focusing and cutting speed to the feed rate in such a way that the surface before the cutting point is heated to a sufficient temperature (>1100°C) down to the depth of cut per revolution. The laser's rapid action produces a very steep temperature gradient, creating surface temperatures above the disintegration temperature of about 1900°C. This permits direct material removal by the thermal effect of the laser, and chip removal. The detritus particles are vacuum extracted directly at the cutting point.

Apart from the laser material removal, there is also real plastic chip formation on the ceramic material. As with metal working, a chip is formed in the shearing zone. In the temperature range between 1100°C and 1200°C, there is almost exclusively flank wear and cutting edge rounding. If the machining temperature is carefully chosen, there is no breakout on the cutting edge, even in interrupted cutting. Only inadequate tool heating or chatter vibrations lead to premature tool failure due to cutting edge breakout.[13]

A fundamental question in laser-assisted turning, with the application of thermal energy, is how far the component surface is damaged. No thermal stress damage has been found in surface roughness measurements, SEM photos or strength analyses. The surface of a part machined by laser-assisted turning is shown in Fig. 11. This technique permits achievement of surface qualities equivalent to medium grinding quality.[14] These results prove that hot machining technology can be used with success in the hard machining of ceramic components. The resulting perspectives are reason enough to continue improving such innovative processes, to prepare them for industrial application.

4 Outlook

Following this summary of developments in machining advanced ceramics, the following aspects are important for implementation of production systems tailored to ceramic machining.

It is important to reduce production cost and improve flexibility, especially in view of the many applications of ceramic components which can only be implemented in small lot sizes, and because these are applications where the economics of ceramics have to be compared very carefully with those of competing materials.

This may be illustrated by comparison with the way the metal working industry has developed. There, production depth of individual manufacturing plants has been reduced by increasing the flexibility and transparency of operating structures. This was only possible thanks to the production of standardized semi-finished products. This situation does not yet exist in today's ceramics industry; many manufacturers do all production steps in-house, from powder manufacture right up to finished components. But this structure could be changed by using semi-finished products, provided they are available in large quantities and at low prices, and they are capable of reliable quality control. Such semi-finished products might be made in the green, white or sintered state of the ceramic material.

Further processing of these semi-finished products could be handled by specialist companies that work with the requisite flexibility. They could use production processes involving high capital investment or requiring extensive technical know-how, but this makes economic sense only if the production facilities are well utilized. So specialization makes sense, as demonstrated over a long period in other sectors of industry. Technologies that are still innovative in ceramics machining could well be used on a sub-contract basis, as the necessary plant and machinery would be utilized better, handling orders from other clients, too.

It is essential to specify final machining techniques that are appropriate to the material, in order to achieve successful implementation of structural ceramic materials, from product ideas to components. Production processes must be designed in such a way as to reduce damage, so as to realize the material-specific strength and reliability parameters in ceramic components.

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