Advanced ceramics are attractive for many applications due to their superior properties. One of the reasons for hindering the market expansion of advanced ceramics is the high cost of machining with current technology. There is a significant need for the development of machining processes that are capable of achieving high material removal rates while maintaining surface/subsurface damage to the machined parts at an acceptable level. One such process is rotary ultrasonic machining (RUM), which is a hybrid machining process combining the material removal mechanisms of diamond grinding and ultrasonic machining. This paper reviews issues in process development, process modeling, and phenomena involved in this set of machining processes. Directions of future research are presented.

Introduction
Advanced ceramics are attractive for many applications due to their superior properties such as high strength at elevated temperatures, resistance to chemical degradation, wear resistance, and low density. However, there exist considerable impediments to the market expansion of advanced ceramics. One of the primary impediments is the high cost of machining with current technology compared to other materials. Up to 90% of the total cost of some high-precision components can be the cost of machining. Therefore, there is a significant need for the development of new machining processes for advanced ceramics.

At present, the most frequently used method for machining advanced ceramics is diamond grinding. The problem with diamond grinding is that, under normal conditions, the surface and subsurface damage to the machined parts is significant.

Ultrasonic machining (USM) is considered as "probably the most frequently used machining method for advanced ceramics" next to grinding. Figure 1 is a schematic illustration of USM. The tool (shaped conversely to the desired hole or cavity) oscillates at high frequency (typically 20 kHz) and is fed into the workpiece by a constant force. An abrasive slurry comprising water and small abrasive particles is supplied between the tool tip and the workpiece. Material removal occurs when the abrasive particles, suspended in the slurry between the tool and workpiece, impact the workpiece due to the downstroke of the vibrating tool. USM has the following shortcomings: material removal rate (MRR) is very low, it is very difficult if not impossible to drill deep holes, and the accuracy is limited.

Rotary ultrasonic machining (RUM) is a hybrid machining process that combines the material removal mechanisms of diamond grinding and USM, resulting in higher MRR than that obtained by either diamond grinding or USM. Experimental results\(^2\) have shown that the machining rate obtained from RUM is nearly 6–10 times higher than that from a conventional grinding process under similar conditions. In comparison with USM, RUM is about 10 times faster.\(^3\) It is easier to drill deep holes with RUM than with USM. Improved hole accuracy is also reported.\(^4\) Other advantages of this process are superior surface finish and light tool pressure.\(^5\)

In RUM, the slurry is replaced with abrasives bonded to the tool. A rotating core drill with metal bonded diamond abrasives is ultrasonically vibrated while the workpiece is fed toward the core drill at a constant pressure. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill, and keeps it cool. This is illustrated in Figure
2. The term rotary ultrasonic machining also refers to another process, where the rotation of the workpiece is introduced into USM. This will not be covered by this review.

The aim of this paper is to review the state of the art of the RUM process. The following sections will discuss historical background, development of equipment, experimental and theoretical work on RUM, extension of RUM to other processes, and directions for future research.

Figure 1. Schematic Illustration of USM.

Figure 2. Schematic Illustration of RUM.
**Historical Background: From USM to RUM**

**A Brief Review of USM History**

Although the principle of ultrasonic machining was recognized as long ago as 1927, L. Balamuth was the first to give useful description of the technique of ultrasonic machining in British Patent No. 602801 (1945). Since then, ultrasonic machining has attracted great attention and has found its way into industry on a relatively wide scale. By 1953–54, the first ultrasonic machine tools (mostly on the basis of drilling and milling machines) had been built. By the 1960s, ultrasonic machine tools of various types and sizes for a variety of purposes had been seen and some models had begun to come into regular production.

The rapid progress in this field can also be seen from the number of published papers. Up to the early 1960s, some 300–400 papers had been published covering the various aspects of ultrasonic machining. Much of this material was brought together by two monographs: *Ultrasonic Machining of Intractable Materials* by A. I. Markov (1966) and *Ultrasonic Cutting* by L.D. Rozenberg et al. (1964); both were originally published in Russian in 1962 and later translated into English.

USM is also referred as ultrasonic impact grinding and ultrasonic grinding. Ultrasonic machining of ceramics has the following advantages. Both conductive and non-conductive materials can be machined, and complex three-dimensional contours can be machined as quickly as simple ones. The process does not produce a heat-affected zone or cause any chemical/electrical alterations on workpiece surface. A shallow, compressive residual stress generated on the workpiece surface may increase the high cycle fatigue strength of the machined part.

However, in USM, the slurry has to be fed to and removed from the gap between the tool and the workpiece. Because of this fact, there are some disadvantages of this method: material removal rate slows down considerably and even stops as penetration depth increases; the slurry may wear the wall of the machined hole as it passes back toward the surface, which limits the accuracy, particularly for small holes; and the action of the abrasive slurry also cuts the tool itself, thus causing considerable tool wear, which in turn makes it very difficult to hold close tolerances.

**A Brief Review of RUM History**

In order to overcome the shortcomings of USM, RUM was invented in 1964 by Percy Legge, a technical officer at United Kingdom Atomic Energy Authority (UKAEA). In his first RUM device, slurry was abandoned and the combination of abrasive slurry and metal tool was replaced by a diamond impregnated tool and rotating workpiece. Because the workpieces were held in a rotating four-jaw chuck, this device had the following drawbacks: only circular holes could be machined, and only comparatively small workpieces could be drilled.

Further improvement carried out at UKAEA led to the development of a machine comprising a rotating ultrasonic transducer. The rotating transducer head made it possible to precisely machine stationary workpieces to extremely close tolerances. With differently shaped tools, the range of operations could extend to end milling, tee slotting, dovetail cutting, screw threading, and internal and external grinding.

The work at UKAEA became almost the only source of English literature on RUM in the 1960s. Several years later, Russian literature on RUM appeared with work done at Moscow Aviation Institute. In the 1970s, reports on RUM in the United States began to appear. The work was carried out at Branson Sonic Power Company.

All the above technical articles were devoted to explaining the principle of RUM and describing the equipment and diamond tools. Experimental investigations on the relations between the process input variables (such as vibration amplitude, static force, rotational speed, grit size, etc.) and the output variables (such as MRR, tool wear, surface finish, etc.) were carried out by Russian and Japanese researchers and reported in literature in the 1970s.
For a long time, RUM had been viewed merely as an improvement of USM. Another perspective of RUM is to consider it as a hybrid process that combines two machining processes: diamond grinding and USM.2,28,29

Research work on RUM has been on for about five years at University of Illinois. A five-variable, two-level factorial design was used to run experiments of RUM on magnesia-stabilized zirconia to study the influences of input variables on MRR at the primary level as well as second level interactions.2,28 Two models were developed for RUM of ceramics. One was theoretical in the sense that it explained the material removal process fairly well by applying indentation fracture theory.2,30 The other was mechanistic in the sense that the predicted MRR with this model (by using a mechanistic parameter) agreed well with experimental results.31

Prior to the work at University of Illinois, material removal in RUM of ceramic materials had been exclusively attributed to brittle fracture in the available literature. The results of work at University of Illinois have shown that plastic flow could be another material removal mode in RUM of ceramic materials.32

**Development of RUM Equipment**

RUM equipment includes the machine and the tool. The principal components of a RUM machine are an ultrasonic spindle kit, a feed mechanism, and a coolant system.

A commercial rotary ultrasonic spindle kit is shown in Fig. 3. It comprises an ultrasonic spindle, a power supply, and a motor speed controller. The ultrasonic spindle contains an ultrasonic transducer. The power supply converts 50-Hz electrical supply to high-frequency (20 kHz) AC output. This is fed to the piezoelectric transducer located in the spindle. The transducer converts electrical input into mechanical vibrations. By changing the setting of the output control of the power supply, the amplitude of the ultrasonic vibration can be adjusted. The rotational motion of the tool is supplied by the motor attached atop the spindle and different speeds can be obtained by adjusting the motor speed controller.

Two different feed mechanisms are reported. The head down feed mechanism is shown in Fig. 4,17 and workpiece up-feed mechanism is shown in Fig. 5.2 Both mechanisms use constant pressure control rather than constant feed rate.

![Figure 3. Commercial rotary ultrasonic spindle kit.](image)

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Figure 4. Head down feed system.\textsuperscript{17}

Figure 6 shows the tools for various operations.\textsuperscript{17} Two types of diamond tools can be used for rotary ultrasonic machining: diamond impregnated tools and electroplated tools. Electroplated tools are relatively cheaper but diamond impregnated tools are more durable.\textsuperscript{17,25}

**Experimental Work on RUM**

The effects of the process parameters (applied static pressure, rotational speed, ultrasonic vibration amplitude, ultrasonic vibration frequency, diamond type, abrasive size, diamond concentration, bond type, etc.) on the process performances (material removal rate, tool wear, surface roughness, etc.) have been investigated experimentally.\textsuperscript{2,24–28,33} The major conclusions are summarized in this section.

**Effects of Individual Process Parameters**

**Effects of Static Pressure** The static pressure has a great effect on MRR. As the static pressure increases, MRR increases to a maximum value and then decreases (see Fig. 7(a)). As the static pressure increases, the torque increases (see Fig. 7(b)). As the static pressure increases, tool wear increases (see Figure 7(c)).
Surface roughness increases as the static pressure increases (see Fig. 7(d)). Markov and Ustinov\textsuperscript{25} reported that as the static pressure increases, surface roughness decreases to a minimum value and then increases.

**Effects of Vibration Amplitude** The effects of vibration amplitude are shown in Fig. 8. As the vibration amplitude increases up to some value, MRR increases. A further increase of vibration amplitude above this value results in a reduction in MRR. The reduction in MRR was attributed to "an excessive increase in alternate loading on the diamond grits and a weakening of the bond."\textsuperscript{25}

**Effects of Vibration Frequency** The vibration frequency used in the reported experiments ranges from 17.5 to 44 kHz. Experiments on the effect of vibration frequency appeared only in one paper.\textsuperscript{24} The trends of the experimental results are shown in Fig. 9, within the frequency range of 24.5–43.5 kHz.

**Effects of Rotational Speed** The influence of rotational speed on MRR is shown in Fig. 10. The influences on other outputs (such as tool wear and surface roughness) have not been reported.

**Effects of Diamond Concentration** MRR increases as the diamond concentration increases up to an optimum value. A further increase in diamond concentration results in lower MRR (see Fig. 11(a)). The effects of diamond concentration on tool wear and surface roughness are also shown in Figs. 11(b) and (c). According to Markov and Ustinov,\textsuperscript{25} it is due to "the considerable reduction in the mechanical strength of the diamond-impregnated layer" that a further increase in diamond concentration results in lower MRR and greatly increased tool wear.

**Effects of Grit Size** Figure 12 shows the effects of diamond grit size on MRR, tool wear, and surface roughness. For surface roughness, Petrukha et al.\textsuperscript{24} reported that $R_a$ increases to a maximum value and then decreases as the grit size increases.

**Effects of Diamond Type** Natural diamond and high-strength synthetic diamond give better performances than weaker synthetic diamond. With natural diamond the MRR is lower but the tool wear is less and $R_a$ is smaller than with the strong (high-strength) synthetic diamond.

**Effects of Bond Type** As the bond strength is increased, MRR is reduced and tool wear is particularly reduced, see Figure 13. Also, stronger diamond requires stronger binders.
Figure 6. Various tools for different operations:17 (a) trepanning and boring, (b) T-slotting, (c) countersinking and V-slotting, (d) dovetailing (male and female), (e) single thread forming, (f) multiple thread forming, (g) facing, (h) spherical end boring and slotting.

Effects of Coolant  Coolant is essential in RUM. Without it, the debris will stick on the tool and work surface, causing the feed speed to slow down. Moreover, the tool may be “burnt or completely ruined by high temperatures in the cutting zone.”25

In most reported experiments, water was used as coolant. Kubota et al.27 stated that there is no difference between water and machine oil in point of MRR.

Systematic work has not been reported on the effects of different types of coolant in RUM.

Interactions Between Different Parameters
Strong interactions between different parameters have been observed by several researchers. Figures 14–16 show some results from a factorial design experiment.2,28

The interaction between the rotational speed and the static pressure was also reported by Kubota et al.27 They observed that each rotational speed has its own optimum pressure that yields maximum MRR and that higher rotational speed results in smaller optimum pressure. This observation is illustrated in Fig. 17.
Effects on Strength Degradation

Attempt has been made to determine the effects of RUM on strength degradation. The diametrical compression test was performed on the machined cores (with 0.5-in. diameter and 0.25-in. length) of magnesia-stabilized zirconia. The results of a factorial design experiment show that the strength is significantly influenced by grit size, static pressure, and vibration amplitude at interaction levels only.

Markov and Ustinov stated that "the penetration of microcracks below the surface in ordinary and ultrasonic diamond drilling is twice as deep as the $R_a$ value," but no experimental data was provided.
Theoretical Work on USM and RUM

Material Removal Mechanisms

For a long time, material removal in USM and RUM of ceramic materials has been exclusively attributed to brittle fracture in the available literature. Shaw,\textsuperscript{12} stated that "conventional grinding chips are produced by plastic flow as in all machining operations, whereas the new process involves material removal by brittle fracture." The new process here refers to USM.

Oh \textit{et al.}\textsuperscript{34} concluded that "in mechanical shaping processes for brittle solids, material is removed by the propagation and intersection of cracks." USM is one of such processes.

Miller reported in 1957 that the metallographic inspection of ceramic workpiece surfaces machined by USM showed "no evidence of plastic deformation when the material was chipped out."

Markov\textsuperscript{8} classified materials into three categories with regard to the suitability of USM for machining them. Ceramic materials are in the first group, which "undergo practically no plastic deformation on ultrasonic machining." The material is removed by the propagation of minute cracks. This opinion has been cited by other investigators such as Komaraiah and Reddy.\textsuperscript{35}

Markov \textit{et al.}\textsuperscript{26} believed that "with abrasive machining methods, breakdown of brittle bodies occurs as a result of micro- and macrocracking and the spread of cracks to some
Intersecting one another, these cracks set up a weak layer which is easily fractured as a result of the repeated action of the abrasive.” Markov and Ustinov\textsuperscript{25} stated that, in RUM, “the role of ultrasonic vibrations consists in an intensive process of brittle fracture of the material being machined, as a result of a network of micro-cracks and tear-outs forming on its surface.”

At the beginning of their paper, Petrukha \textit{et al.}\textsuperscript{24} cited that “the application of small-amplitude ultrasonic vibrations to the diamond indenter develops a system of microcracks, and greatly hastens fragmentation of the brittle material.” They seem to believe that material removal in RUM is due to a system of microcracks.

**Figure 9. Effects of vibration frequency.**

**Figure 10. Effects of rotational speed.**
Figure 11. Effects of diamond concentration.

Kubota et al. reported that, in RUM, material is removed by "conchoidal shell-like fractures."

Recently, it has been shown that plastic flow can be another material removal mode in rotary ultrasonic machining of ceramic materials. There exist two material removal modes in rotary ultrasonic machining of ceramic materials: brittle fracture and plastic flow. The ratio of these two modes is dependent on the process control variables, such as vibration amplitude, tool rotational speed, applied pressure, diamond grit size, etc.

**Process Modeling**

The similarity between RUM and USM from a phenomenological point of view warrants a review of pertinent USM models first.

Shaw assumed that MRR in USM is proportional to the volume of material dislodged per impact, the number of particles making impact per cycle, \( n \), and the frequency of tool vibration, \( f \). Assuming that the grains are identical spheres of diameter \( d \), MRR in USM was expressed as:

\[
MRR \propto (d\delta)^{\frac{1}{2}}nf
\]

where \( \delta \) is the depth of indentation. The expression for \( \delta \) was given by:

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Figure 12. Effects of grit size.

Figure 13. Effects of bond strength.
Figure 14. Second order Interactions on MMR.\textsuperscript{28}

\[ \delta = \left( \frac{8F_A d}{\pi KH C (1 + q)} \right)^{1/2} \]

where \( F_A \) is the static force, \( A \) is the vibration amplitude, \( K \) is a constant of proportionality, \( H \) is the hardness of the workpiece, \( C \) is the concentration of the slurry, and \( q \) is the ratio of the hardness of the workpiece to that of the tool.

Shaw’s analysis has two shortcomings. It does not agree quantitatively with experimental results and the proportionality constant \( K \) has to be evaluated experimentally.

Kainth et al.’s analysis of material removal in USM\textsuperscript{36} is capable of calculating MRR quantitatively. However, the predicted MRR is an order higher than the experimental values.

Based on indentation fracture, Prabhakar et al.\textsuperscript{30} developed a theoretical model for calculating MRR in RUM. This is the first attempt to characterize the RUM process. It is very helpful in understanding the underlying material removal mechanisms at play in RUM. However, with this model, we are unable to predict MRR before experiments since its calculation requires the power rating, which has to be observed during the experiments.
A mechanistic model has been developed to predict MRR in RUM of ceramic materials by the same authors. The model is mechanistic in the sense that a model parameter can be observed experimentally from a few experiments for a particular material and then used in prediction of MRR over a wide range of process parameters. This is demonstrated for magnesia-stabilized zirconia, where very good predictions are obtained using an estimate of this single parameter. On the basis of this model, relations between the material removal rate and the controllable machining parameters are deduced. These relationships agree well with the trends observed experimentally by other investigators. It is worth noting that this model can also predict the second order interactions between the process parameters. Figure 18 shows the predicted relation between MRR and the rotating speed. The positive effect of static pressure (or static force) on the effectiveness of increased rotating speed in improving MRR is clearly evident. This is in agreement with the experimental results reviewed earlier in this paper.

**Extension of RUM**

The limitation of RUM is that only circular holes can be machined due to the rotary motion of the tool. Attempts have been made to extend RUM to machining flat surfaces or milling slots. Markov et al. reported the results of their research in machining of deep holes and slots by using a rotating metal-bond diamond tool with ultrasonic vibration. The detailed description of the milling process (machining of slots) was not given. From the drawing of the diamond tool for ultrasonic machining of slots, it can be seen that the direction of oscillation is perpendicular to the feed direction. Tyrrell also reported that slotting could be achieved with diamond wheels when the wall of the diamond wheels would be the cutting surface. This method was described as "surface grinding" by Suzuki et al. Scheme I in Fig. 19 illustrates this approach. In this scheme, it was not the abrasives on the tool bottom but the abrasives on the cylindrical face of the tool that undertook the machining. For the abrasives on the cylindrical face of the tool, the cutting mechanism was abrasion. Two other primary mechanisms in rotary ultrasonic machining, namely, hammering and extraction, were lost.

Tyrrell mentioned that surface grinding could be accomplished with diamond wheels when the tool bottom would be the cutting surface (Scheme II in Fig. 19). The drawback of
Machining Pressure (MPa)

Vibration Amplitude (µm)

Figure 15. Second order interactions on surface roughness.²

this method was that only those surfaces that were smaller than the bottom surface of the tool could be machined.

Kumabe et al.³⁸ reported a new method for precision machining of ceramics. In their method, both the ceramic workpiece and the tool (diamond file) were ultrasonically vibrated. In addition, the tool was vibrated at a low frequency (50 Hz). One shortcoming of this method was that, as Kumabe et al. admitted, "A machine tool takes too much money and time to produce." Even their experimental device was not easy to build. It included two
ultrasonic generators and one oscillator. Furthermore, it could machine only small components because it was difficult to ultrasonically vibrate large ceramic parts.

Another approach to extend RUM to face milling was proposed by Pei et al.\textsuperscript{39} (see Scheme III in Fig. 19). In this approach, the cutting surface is neither the cylindrical surface nor the bottom surface, but a conic surface. The advantages of this approach are that none of the three primary mechanisms of rotary ultrasonic machining is lost, flat surfaces on large workpieces can be machined, and the approach is easy to implement on commercially available machine tools by incorporating some modifications.
Conclusions and Some Directions for Future Research

From this review, the following conclusions can be obtained:

1. Manufacturing of RUM equipment is a mature technique.
2. Experimental work on RUM has been conducted in the UK, USSR, United States, and Japan since the 1960s. Theoretical work on RUM started in the 1990s.
3. Inconsistencies exist about the effects of process parameters because individual parameters may have opposite effects within different ranges, and interactions between different parameters are very strong.

Directions for future work include determining the effects of machining parameters on subsurface damage, evaluating the correlation between strength degradation and machining parameters, developing the dressing techniques for tools, determining the effects of different types of coolant, and carrying out further study of ductile material removal mode in RUM.
Figure 19. Illustration of the three schemes.39

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