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Rotary Ultrasonic Machining of Hard to Machine Materials- A review

Dinesh Sindhu[1*], Pankaj Chandna[2], Lalit Thakur[3]

Reseach Scholar, Department of Mechanical Engineering, NIT Kurukshetra-136119, India
[*]Corresponding Author E-mail:*dinesh83sindhu@gmail.com*

Professor, Department of Mechanical Engineering, NIT Kurukshetra-136119, India
E-mail: *pchandna08@gmail.com*

Assistant Professor, Department of Mechanical Engineering, NIT Kurukshetra-136119, India
E-mail: *lalitthakur@nitkkr.ac.in*

Abstract: Rotary ultrasonic machining (RUM) is among the best cost- efficient machining practice for the processing of numerous hard to machine materials. RUM is a non-traditional mechanical procedure which integrates the material removal ethics of ultrasonic machining (USM) and conventional diamond grinding. The current article gives a summary of the experimental investigations carried out in the past on RUM of hard to machine materials. The mode of material removal, effect of process parameters on the performance characteristics of RUM has been critically reviewed. Also, some directions for future work are also been discussed.

Keywords: Hard to machine materials, Rotary ultrasonic machining, Mechanism of material removal, surface roughness

I. INTRODUCTION

The quality of manufactured goods is fetching supreme importance in the current age of industrial rejuvenation and development. This gives rise to the development of some new materials, such as advanced ceramics, composites, advanced glasses, diamond, titanium, and carbides etc., which are having superior properties like high hardness and brittleness, high wear resistance, high pressure and temperature during cutting etc. These materials are gaining numerous applications in different modern industries including aerospace, medical, automotive, nuclear, and electronic industries[1–3]. Owing to some of the superior properties, the processing of these materials by conventional machining methods is associated with some common drawbacks like deprived machinability, high cost and low production [4]. Among the available pioneering machining practice available for machining these hard to cut materials, Rotary ultrasonic machining (RUM) is been reported has one of the best cost-effective and precise machining practice used for machining hard to cut materials [5–7].

RUM is a no-traditional mechanical machining practice which integrates the material removal philosophy of static ultrasonic machining (USM) and diamond grinding, consequential to high material removal rate (MRR), and enhanced hole quality contrasted to USM and diamond grinding[7–9]. Figure 1 schematically describes the working principle of RUM[10]. In RUM, a center drill tool on which diamond abrasives are impregnated with metallic bond is vibrated ultrasonically and at the same type fed to the workpiece at a fixed feed rate[11]. A predetermined quantity of coolant is pumped through the center of the drill that cleans the debris, prevents the blocking of the drill, and keeps the machining zone cool [6, 7]. RUM has been used in the past for efficient machining of numerous hard to cut materials namely ceramics, composites, titanium alloy, glasses, sapphire, and carbon fiber reinforced composites (CFRP) etc. [12–17].

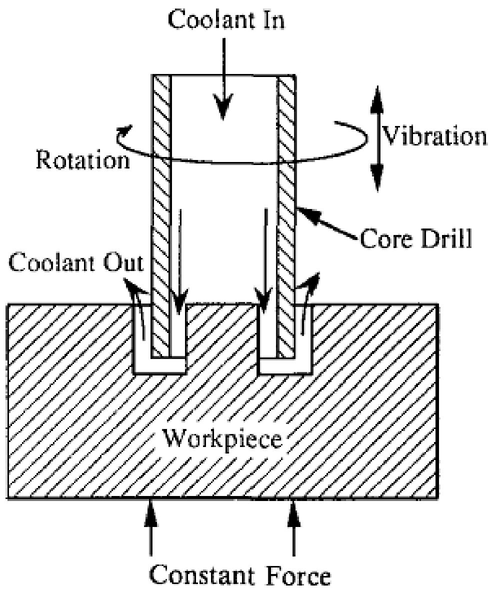


Figure 1 Working principle of RUM[10]

II. MECHANISM OF MATERIAL REMOVAL

As discussed in the previous section, RUM integrates the mechanism of USM and diamond grinding process, the exists three type of material removal mechanism in RUM [18, 19]:

a) Impacting: the abrasive particles on the end face of the tool impacts the surface of the workpiece by hammering action at different location by the revolving motion of tool.

b) Abrasion: the micro grooves are formed on the surface of the workpiece by combined action of tool feed and its revolving motion.

c) Extraction: material is extracted from the surface with application of tool vibration and its revolving motion simultaneously.

Figure 2 depicts all the three mechanism involved in RUM[19]

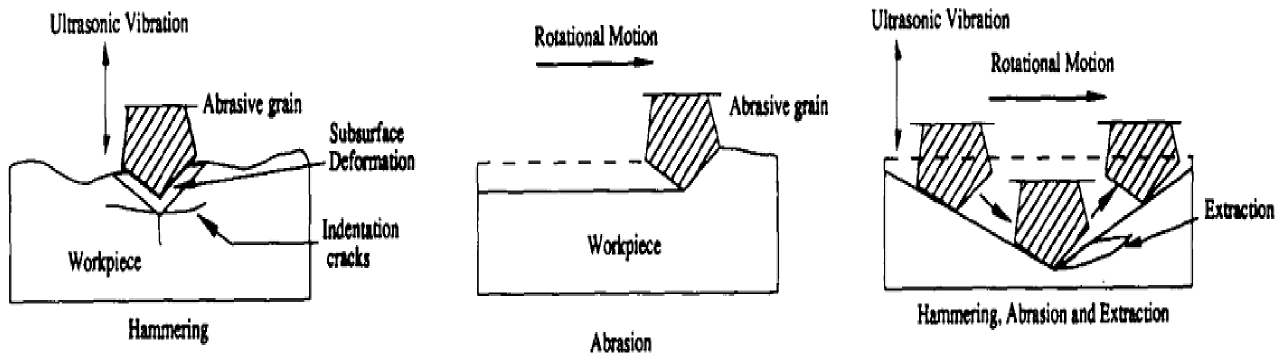


Figure 2 Material removal mechanism of RUM[19]

The main mode of material removal in RUM of brittle materials was found to be brittle fracture[14]. However, some researcher experimentally demonstrated the incidence of plastic flow in the machining of hard and brittle materials besides the brittle fracture[10, 20].

III. EFFECTS OF RUM PARAMETERS ON PERFORMANCE CHARACTERISTICS

This section of papers intended to evaluate the effects of RUM parameters on the performance characteristics for hard to cut materials based on the earlier studies.

a) Effects on material removal rate (MRR)

Different researchers investigated the effects of RUM parameters on the MRR of various hard to cut materials in the past and stated RUM as one of the most appropriate process to manufacture due to its higher MRR. Cong et al. [12] experimentally investigated the effects of different parameters on MRR for RUM of CFRP/Ti stacks and reported an improvement in MRR as compared to customary drilling. During the RUM of CFRP composites MRR was found to be less affected with change in spindle speed while MRR was found to increase linearly with tool feed rate as demonstrated by Figure 3.

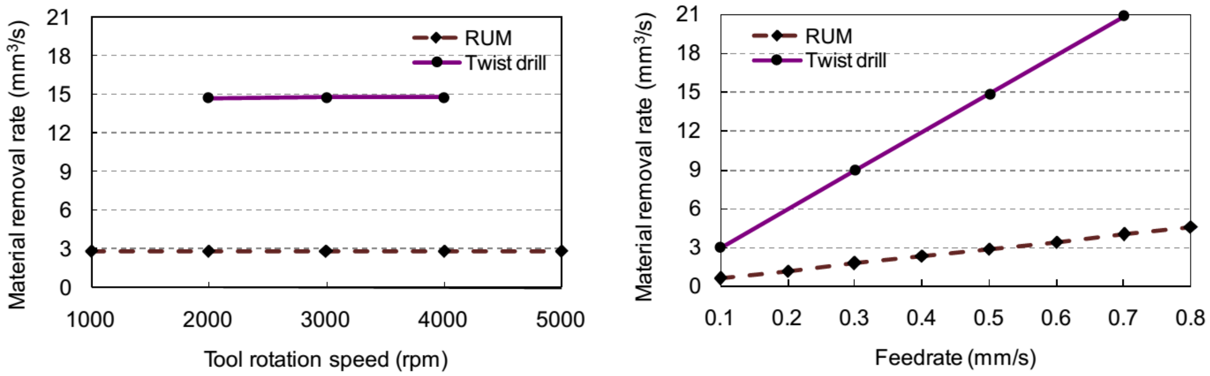


Figure 3 Effects of tool rotational speed and feed rate on MRR in RUM compared with twist drill[9]

Similar kind of results on MRR were also found by Churi et al.[13] during the machining of titanium alloy as given in Figure 4.

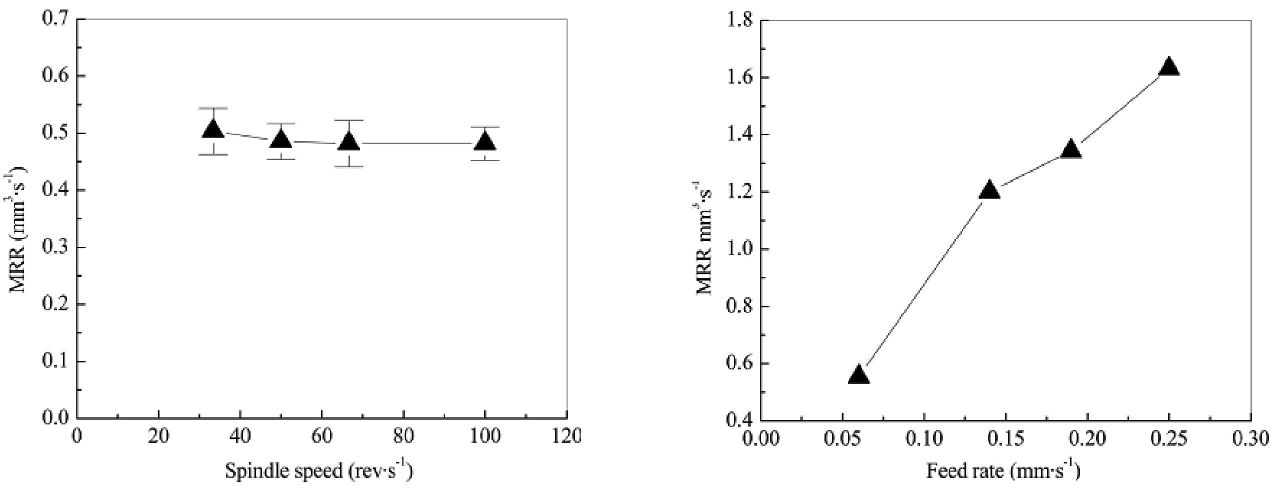


Figure 4 Effects of spindle speed and feed rate in RUM of titanium alloy[13]

Li et al[17] reported an improvement of about 10 % in MRR during the machining of CMC panels with RUM and concluded that spindle speed, feed rate and ultrasonic power have significant effects on MRR.

b) Effects on surface roughness (SR)

SR is an important aspect during the machining of a product. A number of researchers had performed experimental studies on RUM to figure out the SR relation with different input parameters. Churi et al[21] during their investigation on RUM of SiC reported that feed rate has the most significant effect on the SR with a P-value of 0.069 followed by grit size , spindle speed and ultrasonic power as described in Figure 5.

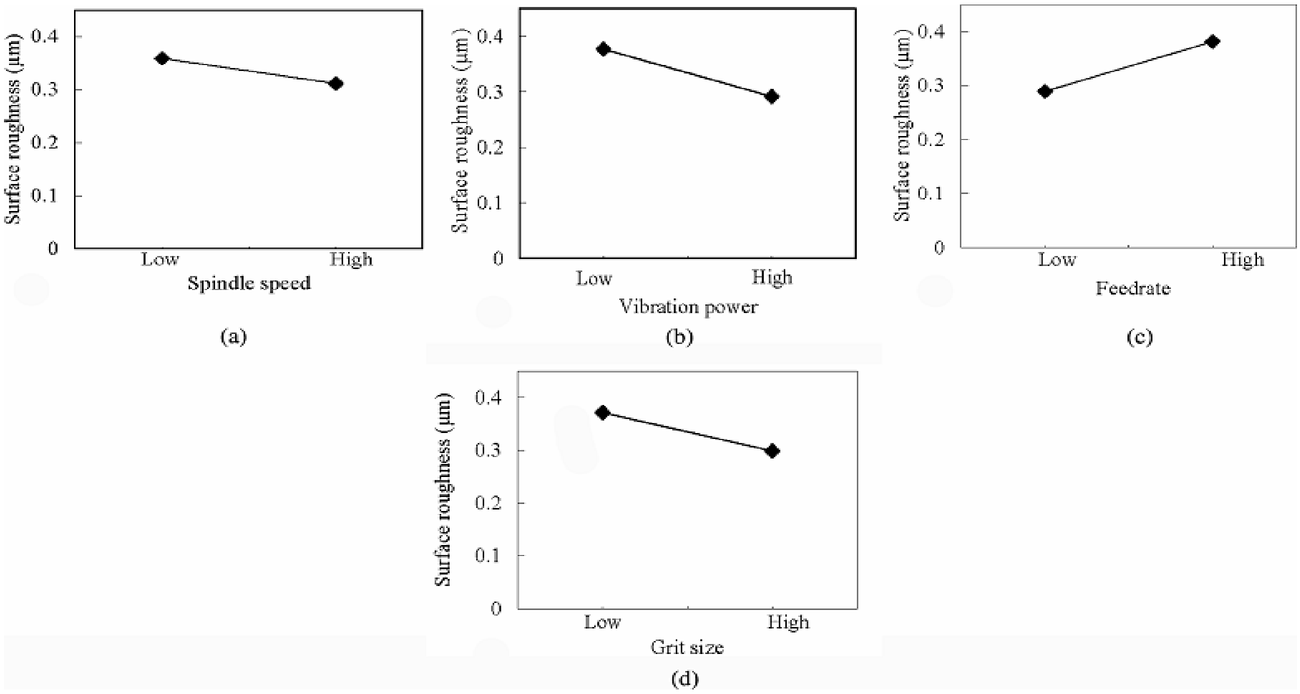


Figure 5 Effects of different RUM parameters on SR[21]

In an another study carried out by Zhang et al[22] on RUM of Optical K9 glass, increased SR was associated with increase in ultrasonic power and tool feed rate while SR decreases by the increment in spindle speed.SR was also reported to be increased with increase ultrasonic power during the RUM of CFRP and decreases as the speed of tool rotation increases for both cutting fluid and cold air as coolant as shown by Figure 6[23]. Kuruc et al[24] experimentally validated the RUM of poly-crystalline boron nitride by achieving a SR as low as 0.24 µm.

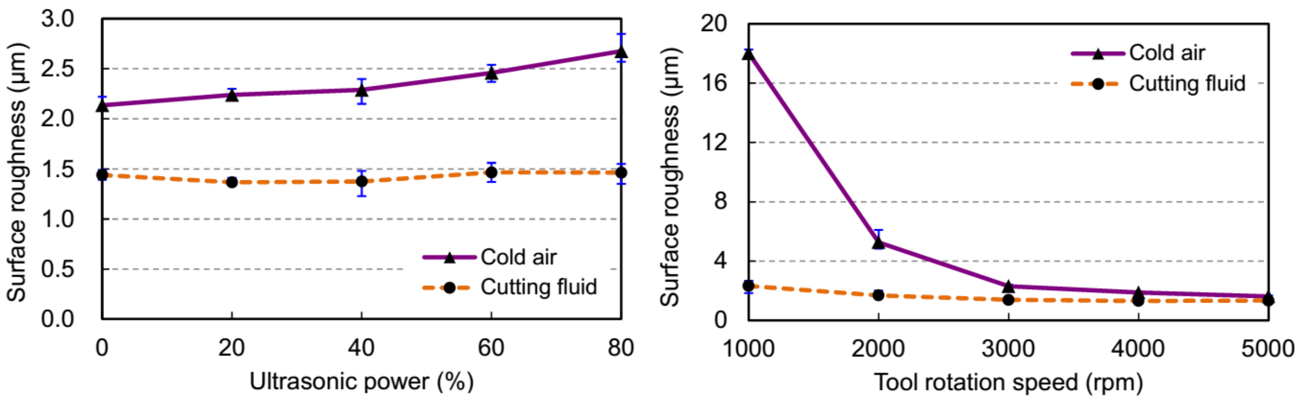
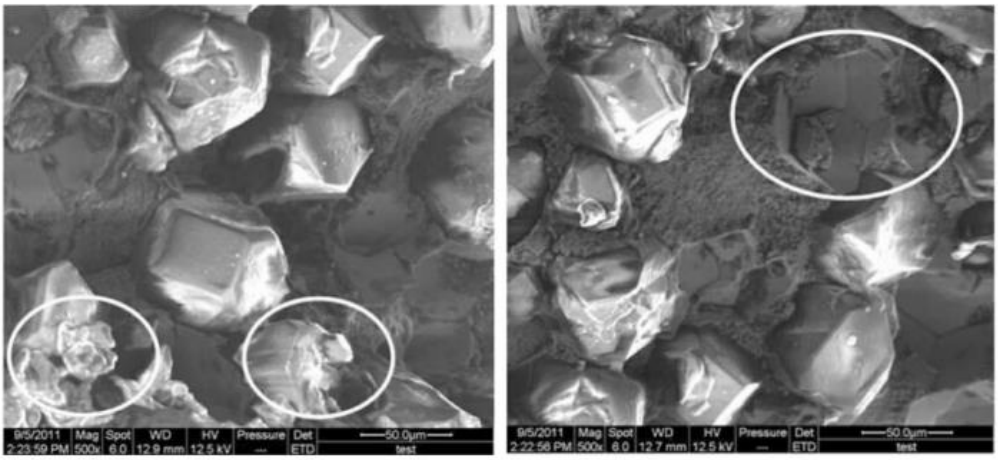


Figure 6 The effects of ultrasonic power and tool rotational speed on SR in RUM of CFRP[23]

c) Effects on Tool wear

The effects of different RUM input parameters on tool wear were studied by many investigators in the past. Cong et al[12] drilled about 250 quality holes in CFRP/Ti stacks compared with 4-20 holes using another drilling processes by virtue of low cutting force and torque formed in RUM. Further, the interior and exterior cooling of drill also help in heat dissipation results in enhanced tool life. Gong et al [14] claimed lesser tool wear compared with grinding during the rotary ultrasonic side milling of hard and fragile materials. Zhou et al[25] observed two types of tool wear patterns during rotary ultrasonic face grinding (RUFG) of SiCp/Al composites which includes grain breakage and grain fall-off as shown in Figure 7.The main reason behind these wear patterns were supposed to be the interaction of diamond grains with that of silicon carbon particles in the work material during the machining. The contact time between the workpiece and the tool is reduced because of intermittent RUM process, further, due the presence of cooling liquid the grinding temperature also falls low which consequently improved the tool life.



(a) Breakage (b) Fall-off

Figure 7 Wear patterns of tool during RUFG of Si/Cp/Al[25]

Zheng et al[26] experimentally investigated the tool wear during the RUM of advanced ceramics. The experimental results revealed that attritious wear and the bond fracture were the main type of tool wear whereas grain fracture was not observed during the RUM of Si/C. Also, tool wear occurs in two stages, attritious wear dominates during the first stage and bond fracture in the later stage. In addition, tool wear on the end face is much cruel contrasted with the lateral wear. The Surface topography of the tool end face and lateral face before and after machining drilling is shown in Figure 8.

d) Effects on edge chipping

During the drilling of holes in hard and brittle materials, edge chipping is an important characteristic which need to be reduced as it is directly related to hole quality. Jiao et al[27] experimentally studied the effects of input parameters on edge chipping size during RUM of alumina ceramic and concluded that chipping thickness increases with increase in feed rate while decreases with increase in spindle speed as shown in Figure 9[27].

Wang et al[28] developed a novel experiment process to estimate the machined-induced crack size in brittle materials. According to this novel approach edge chipping size depends undrilled thickness with a directly-proportional relationship as shown in Figure 10.

In a feasible study carried out by Wang et al[29], edge chipping was reduced by a considerable amount of about 60 % by using a step drill in RUM of sapphire and that too without any bad effects on tool life. The reduction rate of edge chipping in RUM sapphire by using different structures of tool is demonstrated in Figure 11 and 12.

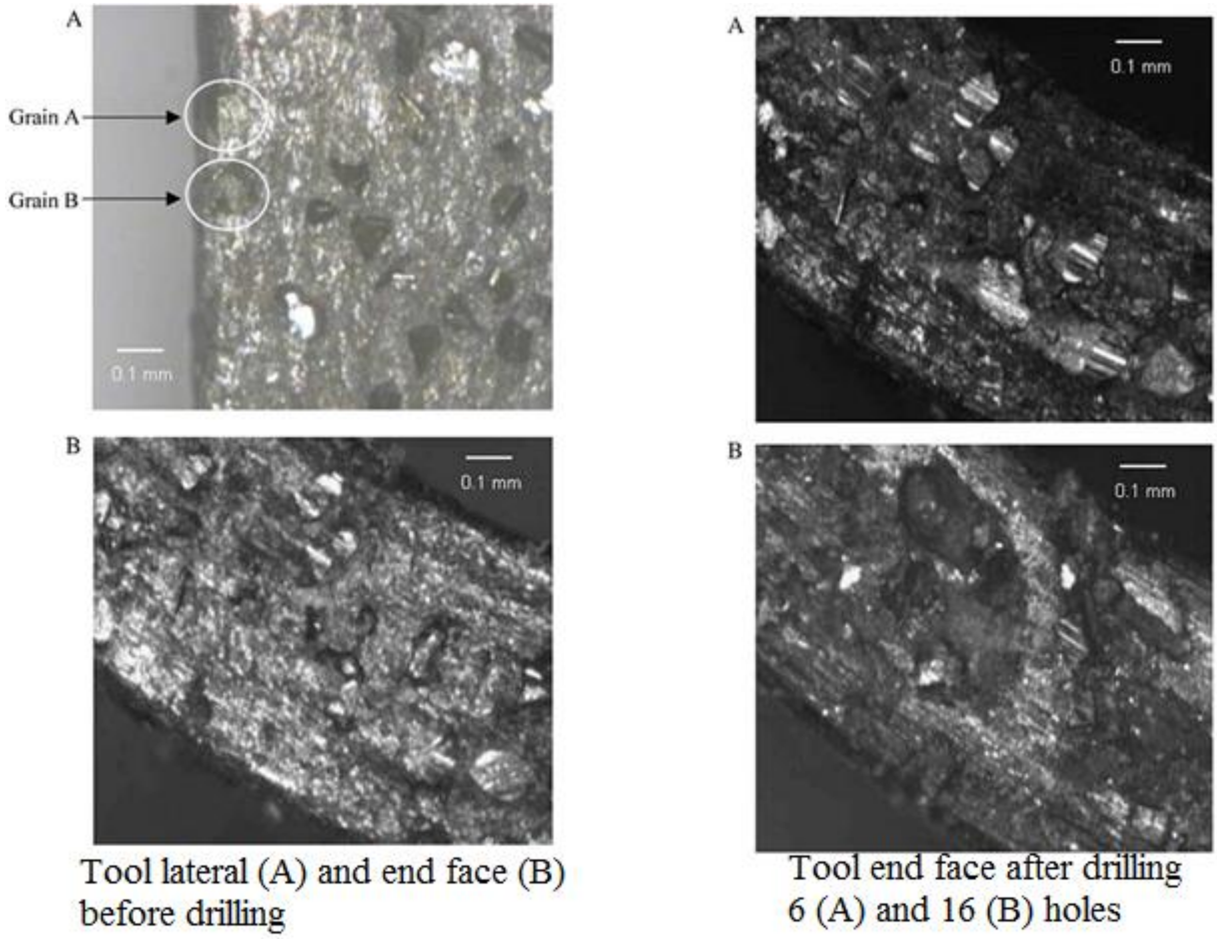


Figure 8 Tool topography after and before drilling[26]

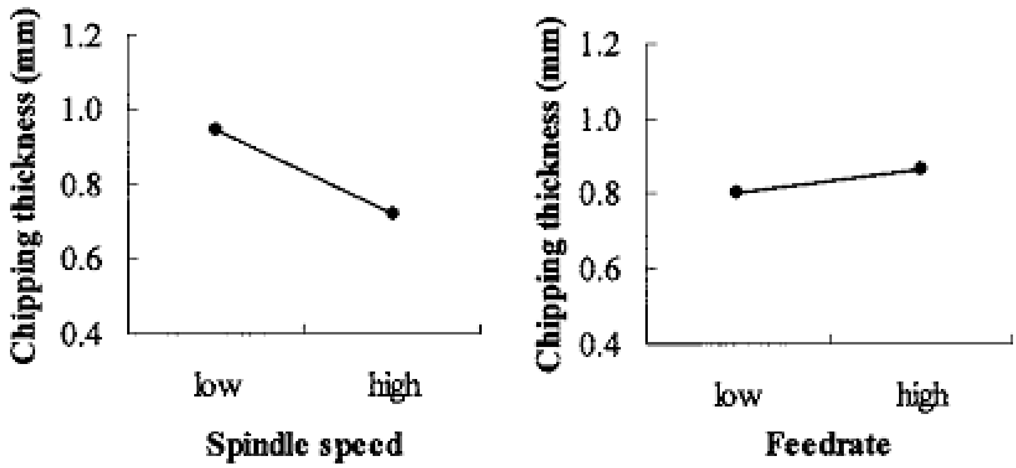


Figure 9 Effects of RUM feed rate and spindle speed on chipping thickness during RUM of alumina ceramics[27]

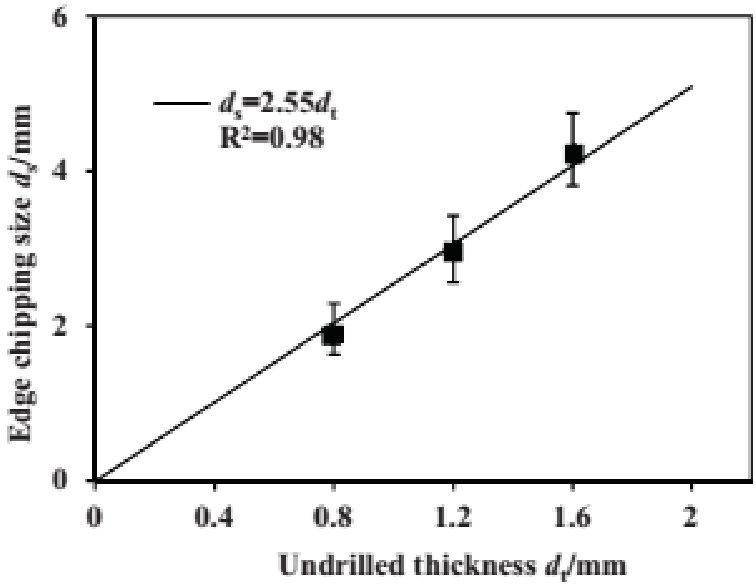


Figure 10 Relation between edge chipping undrilled thickness[28]

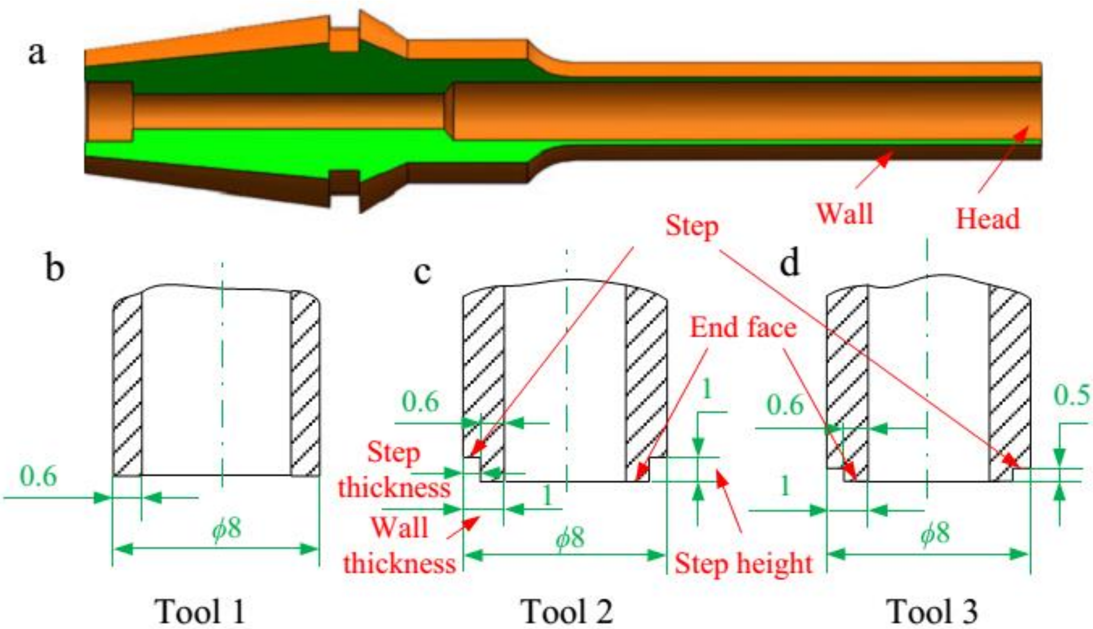


Figure 11 Geometry of tool used in RUM of sapphire glass for edge chipping reduction[29]

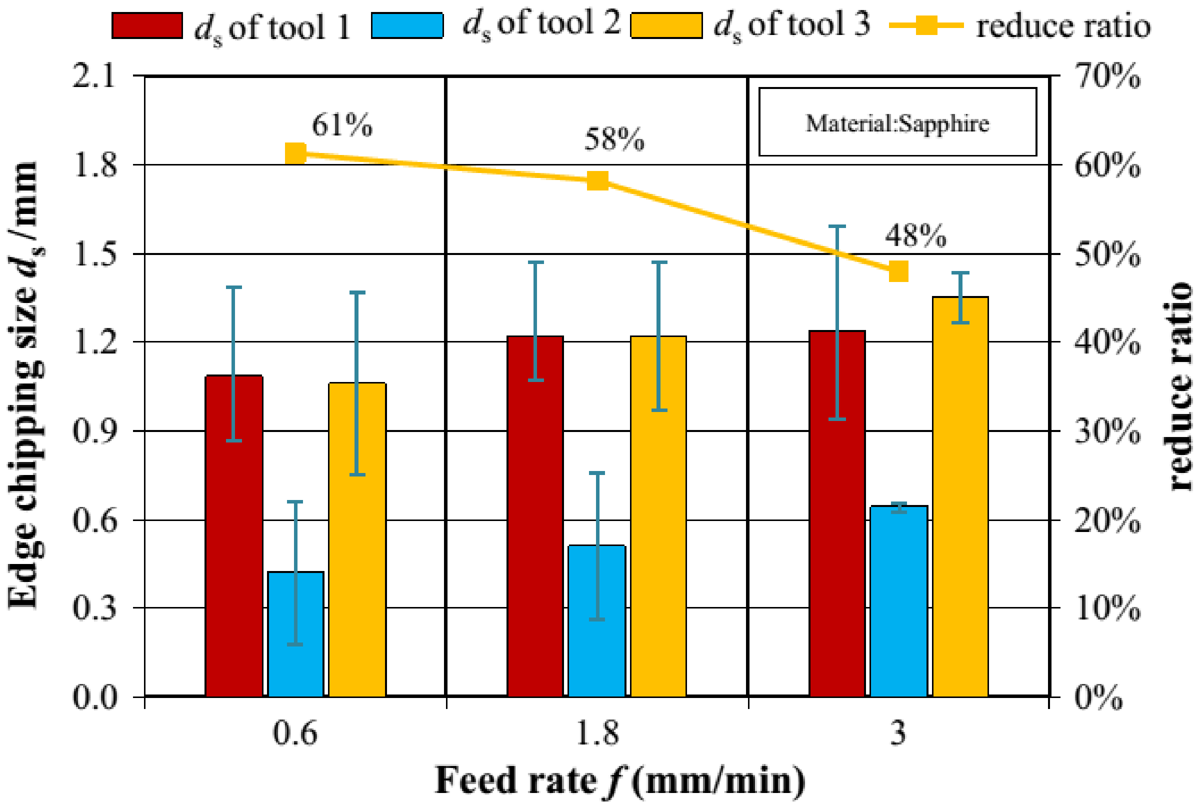


Figure 12 Edge chipping size during RUM of sapphire along with reduction ratio using different shapes of tool[29]

IV. CONCLUSIONS

This paper extensively reviewed the basic principle of RUM, mechanism of material removal, effects of several input parameters on the performance characteristics of RUM. Following conclusions are drawn by reviewing the past work done on the RUM of hard to cut materials:

1. As contrasted with USM, RUM delivers better results in case of MRR, SR, and hole accuracy.
2. The main mode of material removal in RUM of brittle materials is brittle fracture; however, ductile mode can be achieved by proper setting of input parameters.
3. The most significant factor that influences the performance of RUM output characteristic is the feed rate. Ultrasonic power and spindle speed also affects the response significantly.
4. The tool wear in RUM occurs at end face and lateral face of the tool. The attritious wear and bond fractures are the two-main type of wear along with grain pull-off in some cases.

V. FUTURE SCOPES

Based on the past research work completed in the field of RUM, a few future scopes are summarized as below:

1. Most of the researchers in the past investigated the effects of RUM parameters on output response by considering one factor at a time, so it is very important to study the effects of different parameters on the output attributes of RUM simultaneously.
2. The use of multi-objective optimization approaches such as response surface methodology (RSM), genetic algorithm (GA), and particle swarm optimization (PSO) can lead to evaluate

the effects of input parameters on machining performance for further understanding of the mechanism of RUM.

3. The soft computing techniques like artificial neural network (ANN), fuzzy logic and simulation tool for modeling of RUM performance characteristics can be used for further validation of developed models.

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical statement: The authors declare that they have followed ethical responsibilities.

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This volume is dedicated to Late Sh. Ram Singh Phanden, father of Dr. Rakesh Kumar Phanden.

