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Rotary Ultrasonic Machining of Advanced Materials: A Review

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Abstract - **Superior properties of advanced materials (such as carbon fiber-reinforced polymer, optical K9 glass, sapphire and alumina dental ceramics, titanium alloy etc.) supports them to find their applications in the wide range of industries like aircraft, electronic, automobile etc. However, the machining of these materials becomes quite difficult because of their high hardness, high strength-to-weight ratio, brittleness etc. These materials can easily be machined by one of the cost-effective machining process called as rotary ultrasonic machining. In the present research work, the different investigations on advanced materials using rotary ultrasonic machining performed by various researchers are critically reviewed and reported. Rotary ultrasonic machining is a non-conventional hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining. This machining process is consists of a rotary core drill tool with metal-bonded diamond abrasives which vibrates ultrasonically and continuously fed towards the work piece. The basic principles of rotary ultrasonic machining, mechanisms of tool wear and the effect of operating parameters (such as ultrasonic power, rotational speed, feed rate and coolant type) on material removal rate, tool wear rate, cutting force and surface finish of different advanced materials are also reviewed and highlighted, for application in numerous industries.**

***Keywords* -** Rotary ultrasonic machining, diamond grinding, high strength-to-weight ratio, sapphire, material removal rate, surface finish, tool wear.

1. INTRODUCTION

Advanced materials include a variety of materials that possess superior properties which makes them suitable for the wide range of industrial applications. Though formation of complex shapes and profile in these materials is still a challenge because of their properties [1]. Machining of these materials with conventional methods resulted with poor surface finish and high surface cracks as these processes involved high cutting force [2-5]. Advancements in the field of machining processes are attempting to provide some fruitful solutions. Properties and industrial applications of different advanced materials are shown in Table 1.

Table 1: Properties and various applications of different advanced materials in summarized form

Material	Applications	Properties
Dental ceramics (macor)	Aesthetic restorations, molar crowns, veneers, inlays	High strength, superior wear resistance, low tensile strength
Optical K9 glass	Optics, thermodynamics, electronics, fluidics,	High hardness, high strength, low fracture toughness, corrosion resistance
Glass BK7	Optical industries	High hardness, high brittleness
Sapphire	High speed IC chips, thin film substrates, various electronics and mechanical components	Great hardness, good thermal stability, chemical inertness, good light transmission

Rotary ultrasonic machining (RUM) is one of the cost-effective machining processes available for the machining of advanced materials [6-8]. RUM is a non-traditional machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining (USM), resulting in higher material removal rate (MRR) than that obtained by either diamond grinding or USM [8]. Figure 1 (a) illustrates the rotary ultrasonic machining process.

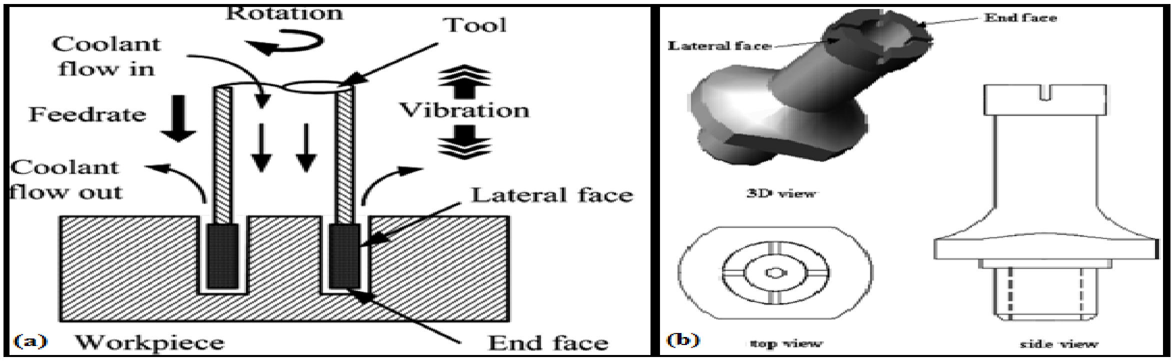

Figure 1: (a) Illustration of RUM process [7], and (b) views of cutting tool [6]

A rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction and fed towards the work surface at a constant feed rate. Coolant is continuously pumped through the hole in the middle of the drill to perform following functions; to flush away the debris, prevent congestion of the drill, and keep the machining zone cool [6, 7]. RUM was invented in 1960 [9, 10], it has been used to machine many different types of brittle materials, such as ceramics, silicon and glass. Efforts have also have been made to develop models to predict the material removal rate in RUM from input parameters [9].

RUM has been employed for the machining of CFRP composites [1, 7, 11-14], titanium alloy [6], optical K9 glass [15-17], BK7 glass [18-20], ceramic matrix composites [21], sapphire [17] and alumina [21, 22] etc. Table 2 shows the summary of different advanced materials with RUM.

This article presents a critical review of previous researches performed by various investigators on rotary ultrasonic machining of different advanced materials such as CFRP composites, alumina, sapphire, titanium, optical glass etc. in a view to explore the effects of several process input variables (ultrasonic vibration, feed rate, tool rotation speed, power supply) on output responses.

2. VARIOUS PROCESS RESPONCES IN ROTARY ULTRASONIC MACHINING

The appropriate selection of process variables plays a vital role in any machining process as it well affects the process outcomes. In this section of research paper, previous investigations done by different researchers in order to study the effects of several input variables (such as spindle speed, feed rate, ultrasonic power, etc.) on different process outcomes (MRR, cutting force, surface roughness etc.) have been reviewed and explored.

2.1 Material Removal Rate

As the tool rotational speed increases, the indentation volume changes proportionally and the MRR increases [8]. As reported in past researches, variation in the range of process parameters also affects the MRR in RUM. For ceramic matrix composites [21], MRR increases with an increase in tool spindle rotation speed (17 rps to 50 rps), however for titanium alloy [6] there was not such increase in MRR reported as spindle speed ranges from 33.4 rps to 100 rps. Li et al., [21] performed investigation for ceramic matrix composites and reported that MRR increases with an increase in feed rate (0.09 to 0.15 mm/sec). These results are consistent with the investigation performed for titanium alloy [6], CFRP composites [12] as shown in Figure 2. RUM of carbon fiber-reinforced epoxy plate [7] reported that material removal rate increases with feed rate.

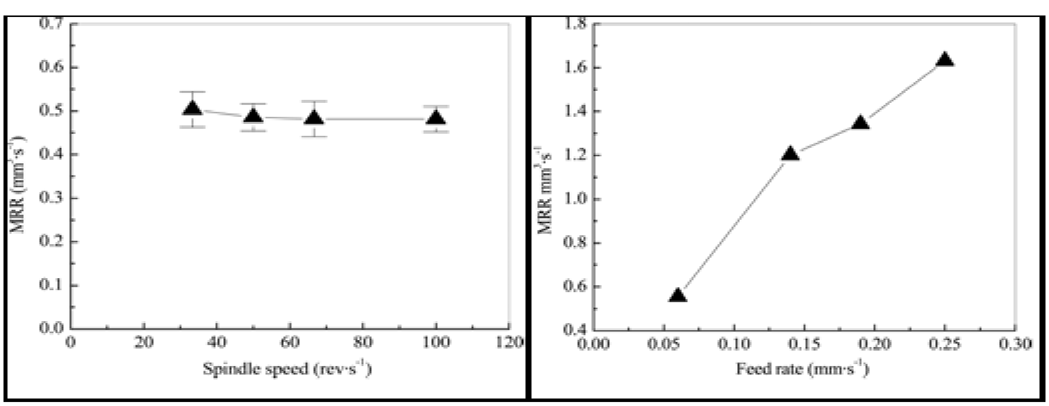

Figure 2: Effects of spindle speed and feed rate on MRR [3]

For titanium alloy [6], the MRR at different levels of ultrasonic power was found almost constant however for ceramic matrix composites [21], MRR increases as ultrasonic power increased from 35% to 50% as shown in Figure 3. This difference could be owing to the fact the variation associated with their composites drilling tests was relatively large [6].

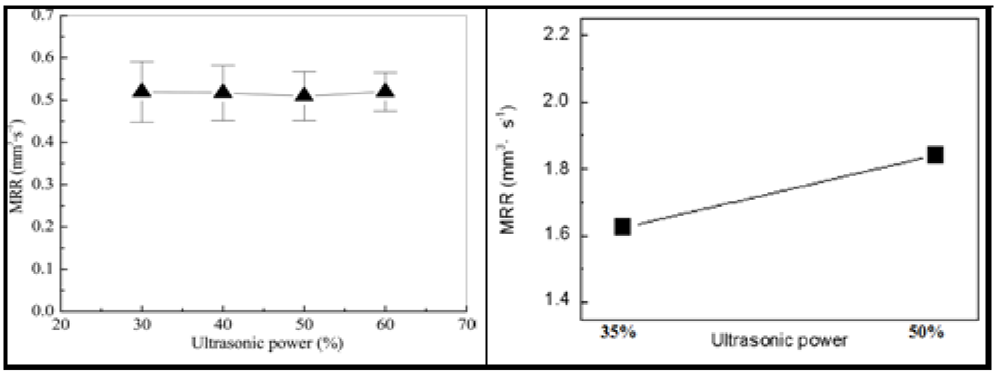

Figure 3: Variation of MRR for different values of ultrasonic power [3, 18]

2.2 Surface Roughness

Surface roughness (SR) of drilled hole and machined rod also get affected by input variables in RUM. Several investigations in RUM have been performed to understand the SR under the influence of different process parameters. Churi et al., [2] reported that for dental ceramics, SR was found reduced when spindle rotation ranges from 2000 rpm to 3000 rpm and then keeps increasing for the spindle rotation of 3000 rpm to 5000 rpm. Similar results were also observed for CFRP composites [7, 11] as spindle rotation speed increased from 1000 rpm to 5000 rpm as illustrated in Figure 4. Optical glass K9 material exposed with rougher surface perpendicular to the feed direction as spindle rotation increased, whereas rougher surface parallel to the feed direction was not sensitive as speed rotation increased [10, 15]. RUM of titanium alloy [6] concluded that SR measured on the machined hole significantly influenced by spindle speed, and it decreases as spindle speed increases from 33.4 rps to 100 rps.

For dental ceramics [2], SR was found increased when feed rate increases from 0.06 to 0.14 mm/sec, and then keeps decreasing as the feed rate further increased from 0.14 to 0.25 mm/sec. Similar trend was also reported for the RUM of titanium alloy [6]. Optical glass K9 material reported with higher surface roughness in the feed direction with higher feed speeds [10, 15]. RUM of carbon fiber-reinforced epoxy plate [7, 11] reported that SR increases as feed rate increases from 0.1 mm/sec to 0.8 mm/sec.

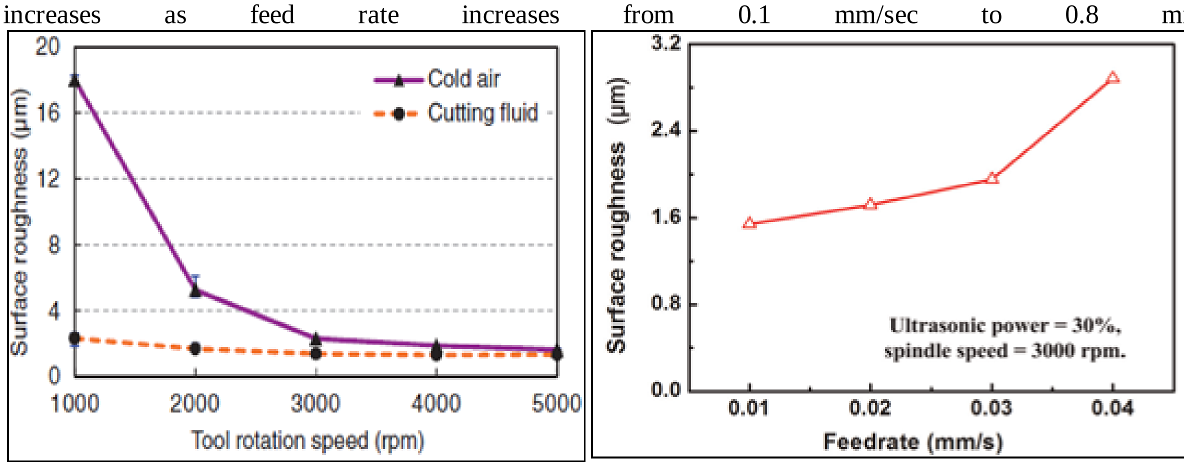

Figure 4: Effects of tool rotation speed and feed rate on SR [2, 8]

Rapid increase in SR was observed during RUM of dental ceramics [5] as ultrasonic power increased from 20% to 40%, and then further increase in ultrasonic power causes reduction in SR. However these results are not consistent with the observation made for titanium alloy [6] because as ultrasonic power increases from 30% to 60%, SR of hole surface decreases. RUM of CFRP composites [11] reveals that SR increased as ultrasonic power increases using cold air as coolant. Rotary mode ultrasonic drilling of glass/epoxy laminates [30] revealed that with an increase in power rating (from 150 to 350 W) surface roughness also increased. Results from RUM of optical K9 glass [10] revealed that surface roughness on the machined hole surface increased with an increase in ultrasonic power. RUM of carbon fiber-reinforced epoxy plate [7] reported that surface roughness decreases as ultrasonic power increases from 0% to 40% and then starts increasing for ultrasonic power of 40% to 60% and then again decreases. In addition, the variation of SR near the exit side was higher than near the entrance side.

2.3 Cutting Force

Investigation of cutting force in RUM is very crucial as it leads to surface and subsurface damages of drilled hole. Zhang et al., [17] performed RUM of sapphire when ultrasonic power and feed rate kept at 20% and 0.04 mm/sec respectively. Results from the study revealed that cutting force decreases as spindle rotation increased from 2000 rpm to 6000 rpm. RUFM of K9 glass [25] resulted in reduction of cutting force as spindle rotation increased from 1000 to 6000 rpm. Similar results were also observed for dental ceramics [2], CFRP composites [11], 92% alumina (Al_2O_3) material [21], optical K9 glass [10], titanium alloy [6] reported significant reduction in cutting force spindle speed increased from 33.4 rps to 100 rps. For different type of work materials, the effects of spindle speed on cutting force also vary [6].

Increased value of cutting force has been revealed during the RUM of sapphire when ultrasonic power and spindle speed were kept at 20% and 5000rpm, and feed rate varied from 0.01 to 0.05 mm/sec [17]. Similar trends were also reported K9 glass [25], dental ceramics [2], ceramic matrix composites [21].

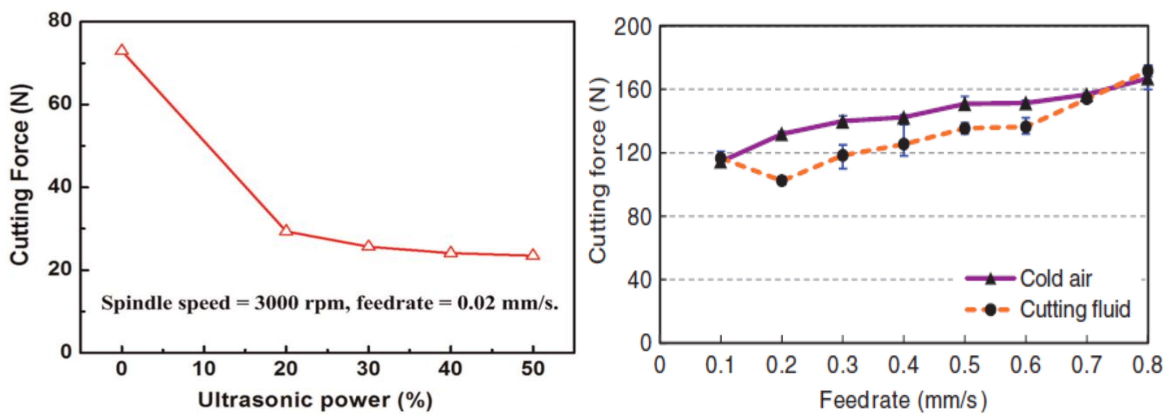

Figure 5: Effects of feed rate and ultrasonic power on cutting force [7, 8]

For CFRP composites [11, 26], cutting force increase as feed rate increased (0.1mm/sec to 0.8mm/sec). When 92% alumina (Al_2O_3) material rotary ultrasonically machined [22], it resulted in to increased cutting force as feed rate increased from 0.09 mm/sec to 0.155 mm/sec. These observations are consistent with the investigations done for titanium alloy [6]. Results from RUM of optical K9 glass [10] revealed that cutting force increases as feed rate increases from 0.01 mm/sec to 0.04 mm/sec as shown in Figure 5. RUM of sapphire [17] with spindle speed and feed rate of 5000 rpm and 0.04 mm/sec respectively resulted in to reduce cutting force as ultrasonic power increased from 0 to 50%. Same trend was observed for dental ceramics [2], titanium alloy [6], CFRP composites [11]. Results from RUM of optical K9 glass [10] revealed that cutting force decreases as ultrasonic power increased from 0% to 50%.

3. POWER CONSUMPTION IN ENTIRE RUM SYSTEM

Entire rotary ultrasonic machining system consists of different components and each consumes power for performing their intended function satisfactorily. Very few studies have been reported in the literature which explores the power consumption in RUM system. Cong et al., [27] performed RUM of CFRP composites and it was found that as tool rotation speed increases (from 1000 to 5000 rpm) the percentage power consumption of, ultrasonic power supply slightly decreases from 11% to 8%, spindle motor impressively increased from 1% to 15%, coolant pump decreases from 76% to 67%, and air compressor slightly decreased from 12% to 10%. Results from RUM of optical K9 glass [10] revealed that ultrasonic power consumption decreases linearly as spindle speed increased from 2000 rpm to 5000 rpm. Results from RUM of optical K9 glass [10] revealed that ultrasonic power consumption decreased as feed rate increased from 0.01 mm/sec to 0.04 mm/sec as shown in Figure 5.

For CFRP composite material, an increase of ultrasonic power from 0 % to 80 % resulted into slightly increase in power consumption by ultrasonic power supply (0% to 16%), power consumption of spindle motor decreases significantly (from 20% to 3%), whereas power consumption of coolant pump, air compressor and entire RUM system almost kept constant [27]. Results from RUM of optical K9 glass [10] revealed that there was significant increase in ultrasonic power consumption as ultrasonic power increased from 0% to 50%.

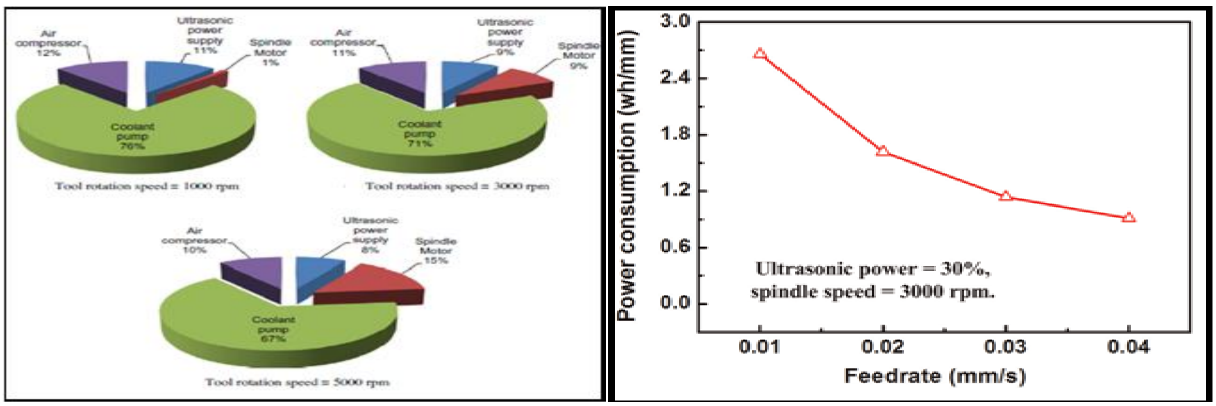

Figure 6: Effects of tool rotation speed and feed rate on power consumption [10, 27]

Table 3: A review of advanced materials machined with rotary ultrasonic machining

Sr. No.	Investigators	Work Material	Input Parameters	Characteristics Investigated	Findings/Results
1.	Cong et al., [27]	CFRP composites	Ultrasonic power, tool rotational speed, feedrate, CFRP type	Power consumption	Coolant Pump consumed higher than 65% of the entire RUM system power consumption.
2.	Cong et al., [31]	CFRP composites	Tool rotation speed, feed rate, ultrasonic power	Cutting temperature	Cutting temp. was highest at 60% ultrasonic power and 3000 rpm.
3.	Zhang et al., [17]	Sapphire	Spindle speed, feed rate, ultrasonic power	Cutting force, Edge chipping size	Cutting force is 170.64 N at 0% ultrasonic power, 5000rpm and 0.04 mm/sec. ECS is highest at 2000 rpm.
4.	Zhang et al., [25]	K9 glass	Spindle speed, feed rate, cutting depth	Cutting force	Cutting force: 3.8 N at 1000 rpm. At feed rate of 100 mm/min cutting force was 3 N.
5.	Jiao et al., [22]	92% alumina (Al_2O_3)	Spindle speed, ultrasonic power, feed rate, grit size	Cutting force, Chipping thickness	Cutting force: 1057 N at 1000 rpm, 0.155 mm/sec, 30% ultrasonic power.
6.	Churi et al., [2]	Dental ceramics (macor)	Spindle speed, feed rate, ultrasonic power	Cutting force, SR, Chipping size,	Cutting force : higher at 2000 rpm and 20% ultrasonic power. SR: Higher at 5000 rpm and 0.138 mm/sec feed rate.
7.	Wu et al., [23]	Alumina	Spindle speed, feed rate, ultrasonic vibration power, grit size	SR, cutting force	SR (hole): 2.55 µm at 0.4 mm/sec feed rate and 2000 rpm.
8.	Liu et al., [1]	CFRP	Spindle Speed, feed	TWR, MRR, Torque	Lower torque and cutting force

		composites	rate, frequency		observed as compared to conventional drilling.
9.	Zhao et al., [16]	K9 glass	Feed rate, spindle speed, resonant frequency	Cutting force	Max. cutting force: 133.051 N at feed rate 5mm/min. and 5000rpm
10.	Liu et al., [32]	Alumina oxide ceramic	Feed rate, ultrasonic power, spindle speed	Tool wear, exit cracks	Tool wear: 42.169 µm at 13 mm/sec feed rate, 75% ultrasonic power.
11.	Cong et al.,[28]	CFRP/Ti stacks	Tool rotation, ultrasonic power, feed rate	Cutting force, SR, torque	Cutting force ranges from 140 to 477N. Torque ranges from 0.3 to 1.37 N-m.
12.	Cong et al., [13]	CFRP/Ti stacks	Tool rotational speed, ultrasonic power, feed rate	Torque, tool wear, cycle time, cutting force	Cutting force and torque are highest at 2000 rpm, Tool wear high at 0% ultrasonic power

4. CUTTING TEMPERATURE IN RUM

Cong et al., [31] investigated the cutting temperature in RUM of CFRP composites resulted that an increase in maximum cutting temperature was reported as tool rotation speed rises from 1000 rpm to 3000 rpm, while the further increment in rotation speed (3000 to 4000 rpm) led to decrease the maximum cutting temperature as shown in Figure 7.

Decrement in maximum cutting temperature has been found as feed rate incremented (0.1 to 0.5 mm/sec.) because lower feed rate resulted in to longer grinding time which generates more heat causes higher temperature [28].

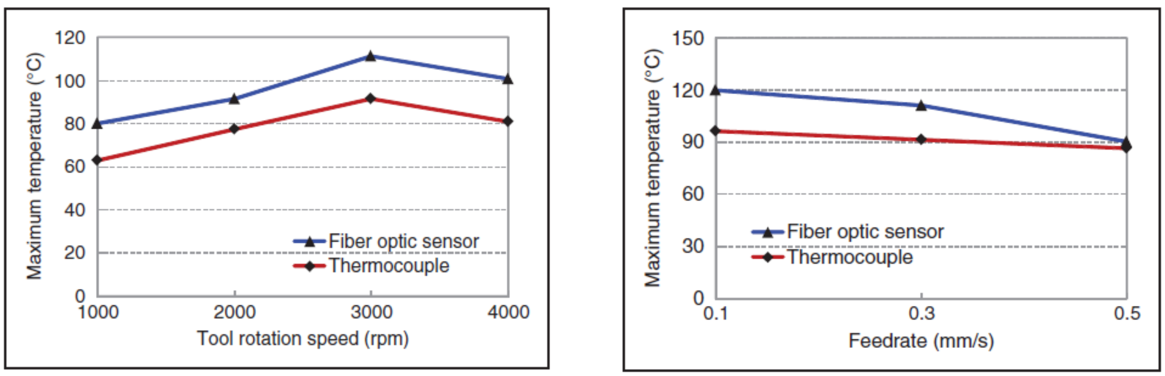

Figure 7: Effects of tool rotation speed and feed rate on maximum cutting temperature [31]

Ultrasonic power also affects the cutting temperature in RUM. For CFRP composites [31], the dramatic increase in maximum cutting temperature was observed when ultrasonic power varied from 20% to 60%. This increase in cutting temperature has been occurred due to increase in vibration amplitude as ultrasonic power increases which further resulted in to higher penetration depth of diamond grains, and increased interaction force between the abrasive grains and work piece material.

5. GAPS OBSERVED FROM LITERATURE REVIEW AND DIRECTIONS FOR FUTURE ADVANCEMENT

Based on the various investigations done by different researchers, there is tremendous scope for further research in many crucial aspects of RUM process. Some of the research gaps and potential future developments are summarized as follows:

1. There is a critical need for developing the models of process performances such as cutting force, tool wear rate, surface roughness, material removal rate etc. Very few studies available in the literature which includes the prediction model for process characteristics.
2. Some input parameters such as diamond abrasives concentration, grain size etc. must be involved in research work in a view to investigate their effects on the process performance measures.

3. Application of simulation tools and fuzzy logic modeling might be applied for checking the validity of proposed models. So that this would be used by machine operators and process planners as reference which ultimately save the time.
4. Multi-response optimization can be performed by using traditional grey relational analysis, principal component analysis, desirability function etc. as well as non-traditional methods such as particle swarm optimization (PSO), teaching learning based optimization (TLBO), harmony search (HS) etc. The optimized results from these both methods can also be compared with each other.

6. CONCLUSIONS

In this present research work, past investigations done by various researchers have been critically reviewed in a view to explore the effects of several input variables (such as spindle speed, ultrasonic power, feed rate etc.) on performance measures (such as material removal rate, surface roughness, cutting force, cutting temperature, power consumption etc.) in rotary ultrasonic machining (RUM) of advanced materials and mechanisms involved in tool wear are also highlighted. In addition, following conclusions could be drawn regarding various aspects of RUM:

- Machining of dental ceramics with RUM resulted with minimum surface micro cracks as this process produces low force. Fewer subsurface cracks are found with RUM as compared to diamond grinding.
- Type of coolant used in RUM also affects the tool wear, cutting force and torque generated. Machining of CFRP composites with RUM reveals that cold air as coolant gives higher surface roughness, cutting force and torque under most conditions. Larger feasible regions are found at higher cold air pressure, and dry machining is not feasible at high ultrasonic power with low feed rate.
- More portion of the power consumption is carried by coolant pump as compared to other components of entire RUM system such as air compressor, spindle motor etc.
- Maximum cutting forces of RUM are smaller than that of conventional diamond drilling, side grinding and face grinding operation.
- Surface morphologies are performed to investigate different material removal mechanisms in RUM of optical K9 glass. Pulverization is reported as another mechanism of material removal besides brittle fracture and plastic deformation. In surrounding fracture areas, pulverized areas were found major as compared to fractured areas.
- It is also observed that the effects of spindle speed on cutting force vary for different type of work materials. Cutting force decreases with increased ultrasonic power and spindle speed, and increases with higher feed rate.
- Surface roughness of the drilled hole tends to increase with high feed rate and ultrasonic power, and decreases at higher tool rotation speed. In addition, RUM of carbon fiber-reinforced epoxy plate reported with higher variation in surface roughness near the exit side than near the entrance side.

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