Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 11, November-2019

Process Characteristics in Ultrasonic Machining

Tejaswi Hegade*, Jnaneshwar R. K.*, Likhith R. Nagarjuna*, Prahalad P. Babu*,
Srikanth A.K.* Dr T.S. Nanjundeswaraswamy**
JSS Academy of Technical Education,
Bangalore

***Abstract*:- Ultrasonic Machining is a mechanical material removal process that makes use of ultrasonic waves and abrasive slurry to remove the material from the workpiece. Ultrasonic Machining is mainly used to machine hard and brittle materials with low ductility. USM is generally used to machine materials with hardness above 40 HRC (Rockwell Hardness Number). Ultrasonic Machining came into prominence due to the development of new materials that were harder than most available materials and these include high strength, stainless and heat resistant steels, and alloys, titanium, ceramics, glasses, etc. Using Traditional machining processes on these materials proved to be ineffective as even harder materials are required to make tools to machine them and chipping or fracturing of these materials occur and results in poor surface finish. Hence, to overcome the ineffectiveness of traditional machining processes nontraditional machining processes were developed and ultrasonic machining is one of them. USM makes use of microcracking mechanics to machine these hard and brittle materials. To optimize this machining process, it is important to understand how different output parameters like material removal rate, surface finish, tool wear, and accuracy are affected by different process parameters like amplitude and frequency of vibrations, grain diameter, static load, etc. Proper optimization is very important as it affects machining time, product cost, and other process characteristics. The following report gives an overview of these parameters and how this affects the different process characteristics of the Ultrasonic machining process.**

Keywords: Material removal rate,surface finish, accuracy, tool wear.

INTRODUCTION

The term ultrasound refers to sound waves that have frequencies greater than the upper audible limit of the human ear i.e. 2 kHz. In today’s modern world ultrasounds are used in a variety of fields. Ultrasounds are widely used in the detection and ranging, microscopy, communication, casting and welding of metals, forming of plastics, nondestructive testing, etc.

As USM doesn't heat the workpiece during machining it does not harm the physical properties of the workpiece by keeping the microstructure intact.

Ultrasonic Machining can also be used to machine complex structures with very high accuracy and precision.

Ultrasonic Machining does not leave behind any significant amount of residual stress in the workpiece during machining.

1. MATERIAL REMOVAL RATE

There are four main parameters on which the material removal rate of an Ultrasonic machine depends on; the workpiece; tool; slurry and machine-related factors. The above factors have been reviewed and presented.

Workpiece Properties

Workpiece material properties like fracture toughness and hardness on material removal rate of ultrasonic machine on brittle and hard materials (Komaraiah & Narasimha Reddy, A study on the influence of workpiece properties in ultrasonic machining, 1993) it was found that MRR use to decrease with an increase in work material hardness and fracture toughness in a controlled condition. (Zeng, Li, Pei, & Treadwell, 2005) it was found that MRR reduces machining composites of higher fracture toughness like whisker-reinforced material the particle yielded higher values of material removal rate based on low fracture toughness. while machining with the ultrasonic machine the material with higher flexural strength demonstrated better surface integrity. (Goetze, 1956) have outlined the ultrasonic abrasion of brittle and hard materials using a stationary ultrasonic machine. It was found that as the hardness of material increases the machining rate decreases . (Kumar, 2013) investigated the performance indices of ultrasonic machining on workpiece material properties. Effects of input parameters namely, grain size, tool geometry, abrasive material type were observed on basis of material removal rate, tool wear rate, penetration rate on six different numbers of workpiece material and three different tools. It was found that while machining with USM the workpiece with higher fracture toughness took a long time for machining while better machining efficiency was obtained when brittle and hard materials were used. Work materials with higher hardness and toughness caused more tool wear whereas the softer and brittle work materials resulted in lesser tool wear. (Khairy, 1998) had presented an assessment of the influence of work material properties on mechanism of material removal in USM. It was observed that when brittle and hard materials like glass when machined by brittle fracture at selective cleavage planes. whereas plastic deformation before failure was observed in tough materials. (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988)concluded that The plasticity of work material is associated with low productivity. The impact hardness has been found to have an adverse effect on machining rate. However, while machining annealed steel, machining rate observation was significantly better than normalized or quenched ones

(Kennedy & Grieve, 1975)concluded that such a behavior contradicted generally accepted criterion. however, this unusual behavior can be explained as, considering the increase in tensile strength of steel upon normalizing or quenching, which is unfavorable from the point of view of Ultrasonic machining.

Tool Characteristics

(Komaraiah & Narasimha Reddy, A study on the influence of workpiece properties in ultrasonic machining, 1993) observed the influence of tool material properties i.e., the hardness of glass on the material removal rate in ultrasonic machining. The result obtained stated as MRR increased with an increase in the hardness of the tool material. a number of different tool material was arranged in increasing order of superiority like mild steel < titanium < stainless steel < silver steel < niamonic-80 A < thoriated tungsten. significantly different amounts of work-hardening were observed in tool material used by which contribution of variation in their machining performance. (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988)reported that higher material removal rates using a high carbon steel tool can be achieved which was of higher hardness in comparison to other tools that are used for experiment diamond tips tool have good material removal characteristics. (Kennedy & Grieve, 1975) stated that machining rate is directly proportional to the shape factor and tool form. The tool form defines the resistance to slurry circulation: a rectangular cross-section tool yields better machining rate than a square cross-section tool of same area .use of hallow tools reports of higher material removal rate than a solid geometry with same area of cross-section . (Goetze, 1956) investigated a study on effect of tool geometry on the penetration rate obtained in the USM of ketos tool steel. on tools having equal contact areas, for larger perimeters tool reported that it was found that penetration rate had increased. This was explained based on difficulty of adequately distributing the abrasive slurry over the machining zone. Many have reviewed the theory and art of designing the tool, but it is not understood fully still it is ongoing. There are many designs of usm some are cylindrical, stepped, conical and exponential types. Recently, finite element modeling (FEM) has been used for symmetric horn shapes. The analysis can take into consideration the weight of the tool. Designing a horn can be achieved that converts the longitudinal ultrasonic action into a mixed lateral and longitudinal vibration mode. This lateral motion obviously aids contouring work.

Jingsi (2018) developed a simulation model of Ultra Sonic Machining using a mesh-free numerical technique, the smoothed particle hydrodynamics (SPH). The crack formation on the work surface was studied for two abrasive particles and the interaction of these abrasive particles in USM. The simulation was verified experimentally and the SPH model was proven capable of predicting the machining performance.

Jatinder (2013) proposed some models for estimation of machining rate, also the effect of operating parameters on material removal rate, surface finish, and tool wear rate. He reviewed rotary mode USM, hybrid USM and process capabilities of USM. It also pointed out the limitations of USM, gaps observed from the existing literature reviews and the directions for future research.

Kennedy et al. (1975) presented a detailed review of ultrasonic machining using the researches and experimental results available in 1975. First, he explained the process parameters and the basic effects on the material removal rate. Explained the influence of acoustic parameters, static load, abrasive slurry, abrasive wear and tool wear, workpiece material conditions and the geometry of cut on the material removal rate. Demonstrated the relation of material removal rate with surface texture, accuracy, and repeatability. After reviewing all the information, he concluded that while research and development workers agree over many of the parameter effects, there still exists contradictory evidence regarding some others.

Ravinder et al. (2016) presented a contrast to the surface defects in ultrasonic machining and other thermal-based machining processes like electric discharge machining, laser beam machining, etc. he listed all the models of material removal mechanisms introduced since 1956 to 1999. Explained the effects of process parameters on material removal rate. Reviewed the research and experimental data regarding the optimization of process parameters. He concluded that Performance measures in USM process are dependent on the work material properties, tool properties (hardness, impact strength, and finish), abrasive properties and process settings (power input, static load, and amplitude). The material removal in USM has been found to occur by propagation and intersection of median and lateral cracks that are induced due to repeated impacts of abrasive grains.

Dieter (1956) conducted experiments to determine the effect of peak-to-peak amplitude, the frequency of vibration ‘f’ and the abrasive particle diameter d and the ratio of the mass of abrasive to the mass of water used in compounding the slurry. It was seen that within the range under investigation the quotient V/2•fd is a constant for a critical ratio of the mass of abrasive to that of water. It is also shown that events occurring within the volume of a cube having sides equal to are of fundamental importance in the ultrasonic machining process. A phenomenological equation is derived from which the most probable machining rate can be calculated for the range under investigation.

Hu et al. (2002) tried to construct a model for material removal rate **in** rotary ultrasonic machining which is a combination of diamond grinding and ultrasonic machining. The proposed model will predict the MRR for the case of magnesia stabilized zirconia. The results from the model agreed well with the trends observed by the experimental observations made by other researchers. Further, the relationships have been studied by changing one variable at a time. A five-factor two-level design is used to study the relationships between MRR and the controllable machining parameters. This study provided the main effects of these variables, and two-factor interactions and three-factor interactions among these variables. He concluded that for main effects, static force, vibration amplitude and grit size have significant effects on MRR. The static force has the most significant effect on MRR.

Kavad et al. (2017) reviewed the effects of Material Thickness and Ultrasonic Machine Parameters on Material Removal Rate While Ultrasonic Machining of Glass Fiber Reinforced Plastic. He used a full factorial design of the experiment used with three control factors –amplitude, pressure, and thickness of the GFRP sheet. Analysis of variance for MRR is carried out using MINITAB software. 3-Way ANOVA technique is used for determining level of significance for individual parameter effect as well as interaction effect of combination of input parameters. He concluded that thickness and amplitude are the most significantly affecting factor for MRR in ultrasonic drilling of glass fiber reinforcing plastic and pressure is not significant factor. It also shows that as the pressure is increased MRR is increased for the same amplitude.

2. SURFACE FINISH

Surface finish in ultrasonic machining refers to the nature of the machined surface defined by three characteristics: lay, surface roughness, and waviness. Through extensive investigations researchers have found out that abrasive grain size is the main factor that governs the surface finish of the workpiece (Singh & Khamba, 2006; Kumar, 2013; Kennedy & Grieve, 1975; Komaraiah, Manan, Narasimha Reddy, & Victor, 1988; Ramulu, 2005). No evidence has been found out that confirms the dependency of surface finish on static load (Kennedy & Grieve, 1975).

One significant advantage that ultrasonic machining has is that significant heat is not developed in the workpiece and thus preventing the formation of a thermally damaged work surface. (Kumar, 2013).

2.1. Effect of Abrasive Grain Size on the Surface finish

The variation of surface roughness with the mesh number of the grain size used is given in Fig. S1, as recorded by Komaraiah er al. Many investigators have found out that the value surface roughness decreases, i.e. surface finish increases for any workpiece with the increase in mesh number, i.e. a decrease in grain size. (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988; Kennedy & Grieve, 1975; Ramulu, 2005). It is evident from Fig. 1 that the abrasive grain size has a substantial impact on the surface roughness of the machined surface and hence on surface finish. This variation can be credited to the mechanical properties, microcracking and fracture of the workpiece surface during ultrasonic machining.

The increase in roughness value with an increase in grain size can be explained by the depth of indentation the abrasive particles cause on the workpiece surface. The depth of indentation is given by (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988)

$$\delta_w = \frac{(d - x)}{(1 + q)}$$

Where,

δ_w is the depth of indentation.

d is the average abrasive grain size

x is the distance between the workpiece and tool and,

q is the ratio of workpiece hardness and tool hardness.

It is clear from the equation that the depth of indentation increases with an increase in abrasive grain size. Large abrasive grain size results in the formation of micro craters on the workpiece surface. Thus, increasing surface roughness and decreasing surface finish.

The decrease in surface roughness with a decrease in abrasive grain size can be attributed to the fact that finer grains chip off smaller chunks of material from the workpiece surface hence resulting in the smooth surface finish (Ramulu, 2005). But it has to be noted that an increase in abrasive concentration for small abrasive size results in the rough surface finish (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988; Ramulu, 2005; Jain, Sharma, & Kumar, 2011)

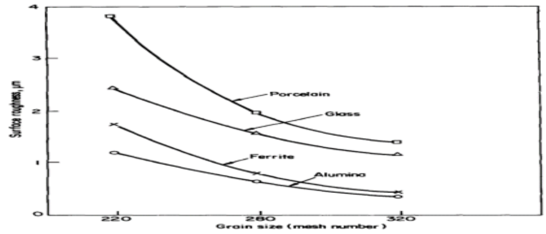
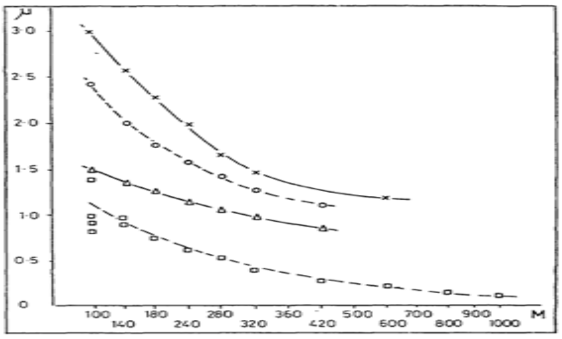


Figure1 variation of surface roughness with abrasive grain size



Cae

Figure2-surface finish s a function of garin size of Boron Caribde when machining various materials

Various experiments have found out that under the same machining conditions the material removal rate in conventional ultrasonic machining is greater than the material removal rate in rotary ultrasonic machining. Thus the surface roughness of the machined surface in the case of conventional ultrasonic machining is greater than the surface roughness in the case of rotary ultrasonic machining (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988). Thus, it can be concluded that rotary ultrasonic machining has a far greater surface finish when compared to conventional ultrasonic machining. A comparison of surface roughness in conventional and rotary ultrasonic machining for various materials is shown in Figure 3

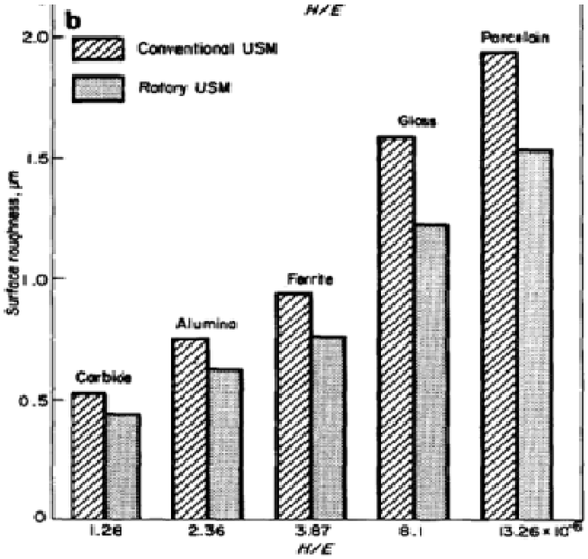


Figure 3: comparision of surface roughness in conventional and rotary usm for various materials

It has also been found out that rotary ultrasonic machining has less surface roughness when compared to conventional ultrasonic machining for the same value of material removal rate. The improvement in the quality of machining in rotary ultrasonic machining can be attributed to the creation of additional stresses in rotary ultrasonic machining (Komaraiah, Manan, Narasimha Reddy, & Victor, 1988; Singh & Singhal, 2016; Ramulu, 2005).It has been found out that maximum peak to valley roughness is approximately twice the size of the average peak to valley roughness. This fact proves the non-uniformity of the machined surface in ultrasonic machining (Ramulu, 2005).

2.2. Effect of Workpiece Material Properties on Surface Finish

Various investigations have concluded that materials with high material removal rates have high values of surface roughness (Kennedy & Grieve, 1975; Komaraiah, Manan, Narasimha Reddy, & Victor, 1988; Singh & Khamba, 2006). The following equation gives the relationship between the volume of material removed, fracture toughness, hardness, and static load applied:

$$\forall \propto \frac{P^{\frac{5}{4}}}{K_c^{\frac{3}{4}} H^{\frac{1}{2}}}$$

Where,

$\forall$ is the volume of material removed during each indentation of a brittle material.

P is the static load applied.

K_c is the fracture toughness of the workpiece material.

H is the hardness of the workpiece material.

It is clear from the equation that that for a material with low value of denominator has a higher volume of material removed. Hence, different materials have different material removal rates (Kumar, 2013). The value of surface roughness in variation with the material removal rate is shown in Figure4

From the equation, we can also conclude that for materials having high hardness, the surface obtained after machining will have very low surface roughness because low material removal rate is observed in hard materials. Hence ultrasonic machining produces smooth surfaces in harder materials. It can also be noted that materials which have higher fracture toughness will have low material removal rate and hence have low surface roughness value and smooth surface finish. Hence ultrasonic machining produces smooth surface finish in materials having high fracture toughness and hardness.

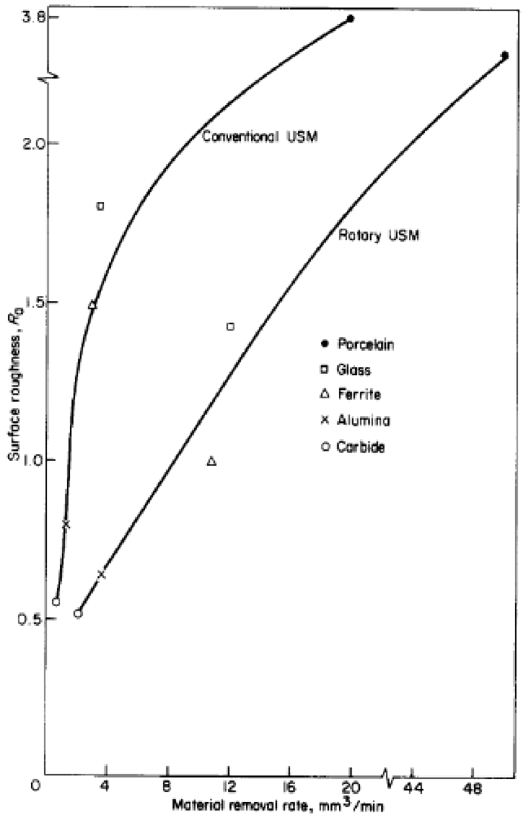


Figure 4 The value of surface roughness in variation with the material removal rate

2.3. Effect of Tool Materials on the Surface Finish

It has been observed that the finish of the tool also has a significant impact on the surface finish obtained on the workpiece as any irregularities on the tool surface are reproduced on the workpiece (Kennedy & Grieve, 1975). It is desirable that the tool has better surface finish than the one required on the workpiece.

It has also been observed that the hardness of the tool materials also impacts the surface roughness. Tool materials with high hardness produce work surfaces with less surface roughness and vice versa. The value of surface roughness as a function of Brinell hardness number of the tool material is shown in Figure5

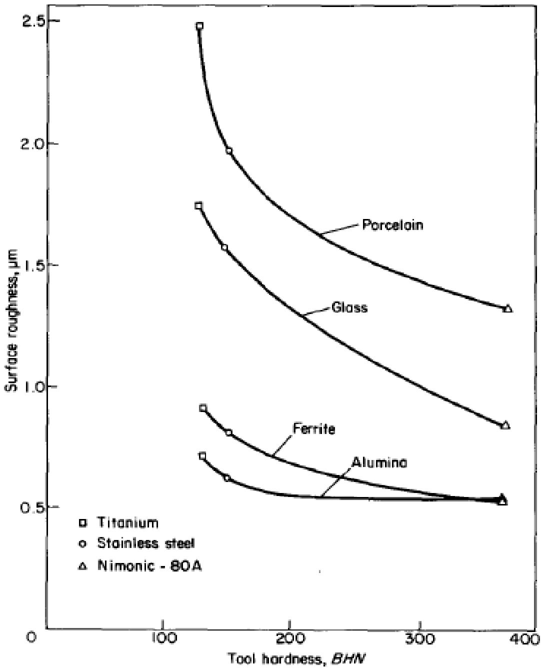


Figure 5 The value of surface roughness in variation with the tool hardness

2.4. Effect of Amplitude and Frequency of Vibrations on Surface Finish

It has been established that the material removal rate in ultrasonic machining increases with an increase in amplitude of the tool vibrations (Kennedy & Grieve, 1975; Kumar, 2013; Ramulu, 2005). Thus, we can conclude that an increase in amplitude of tool vibrations and increase in the value of surface roughness can be observed. Thus, for smoother finish the amplitude of tool vibrations must be low.

2.5. Effect of Slurry Concentration on Surface Finish

Many researches have reported that the material removal rate increases with slurry concentration. Thus, surface roughness increases with increase in slurry concentration. Thereby, producing a rough surface. This increase in surface roughness can be credited to the clogging of abrasive particles (Ramulu, 2005).

2.6. Effect of Liquid Carrier on Surface Finish

It has been found out that the usage of a liquid carrier with low viscosity in place of water results in a smooth work surface (Kennedy & Grieve, 1975).

It has also been established that the pressure at which the slurry is supplied to the workpiece surface has a remarkable effect on the material removal rate. A high rise in material removal rate can be obtained by increasing the pressure at which the slurry is supplied to the workpiece (Pandey & Shah, 1980).Thus we can say that an increase in pressure at which the slurry is supplied results in an increase in the surface roughness of the worked surface.

3. ACCURACY

Accuracy refers to the degree of closeness of measured dimension to the actual dimension. It is also referred to as the degree of conformity.USM is a nonthermal type process, so machined surface does not contain any undesired effects like recast layer, heat affected zone, etc.

Accuracy of holes produced by Ultrasonic drilling must consider both dimensional accuracies (oversize) and form accuracy (out-of-roundness and conicity). An increase in the diameter/length ratio increases lateral vibrations which causes greater oversize. Kennedy and Grieve have reported that the factors affecting accuracy of USD are: the precision of the machine tool (i.e. the accuracy of the feed motion), the accuracy of the fixtures used, the quality of the assembly element, abrasive grit size, tool wear, transverse vibration effects, and depth of cut.

Shaw and others have shown that surface roughness improves with an increased static load which reduces the abrasive size and suppresses lateral vibrations of the tool, so minimizing the oversize/conicity [out-of-roundness (OOR)] of the holes produced. Adithan and Venkatesh found that the oversize with rectangular holes was greater than that obtained with circular tools.

Effect of Static Load on Accuracy

Experiments were conducted at different static loads, and the out-of-roundness obtained is shown in Fig A1. As the static load is increased there is a reduction in the out-of-roundness of the drilled holes. At higher static loads the lateral vibrations of the tool are suppressed 6 and hence the out of roundness of the drilled hole is reduced. There can also be a reduction in the size of the abrasive particles on account of the crushing action. There will be a natural improvement in the geometry of the hole drilled with the decrease in the grain size. It is recommended for the finishing cuts that the static load be increased.

OOR is a type of form inaccuracy of the circular holes. OOR of the tool occurs due to tool wear (lateral or side wear) as a result of the scouring of the surface of the tool by slurry particles flowing in the machining gap during a drilling operation. It can be decreased by an increase in alumina content of work material. It increases linearly with an increase in grit size. So smaller the grit size OOR can be reduced.

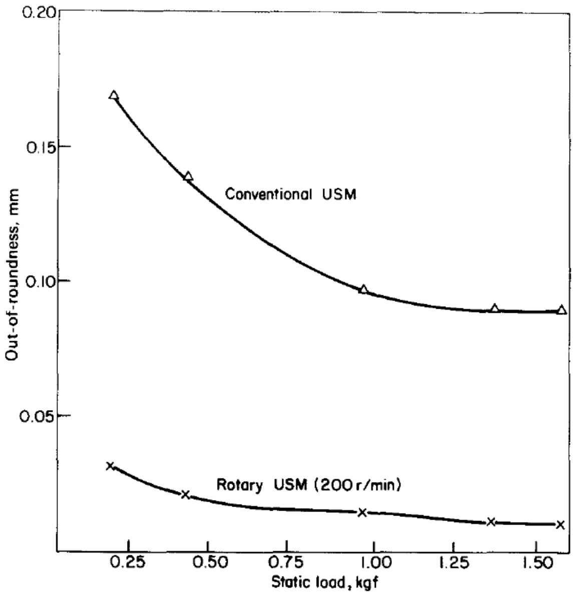


Figure 6 comparision of OOR in conventional machining and rotary usm with respect to static load

Holes produced in ultrasonic machining consist of both types of inaccuracies—dimensional accuracy (hole oversize [HOS]) and form accuracy (OOR and conicity). The accuracy of the drilled hole is affected by different factors such as precision of machine tool, the accuracy of fixture used, abrasive grit size, quality of assembly parts, tool wear, effect of vibration in transverse direction, and aspect ratio. HOS is termed as the difference among the hole diameter at the entrance and actual tool diameter before drilling. In USM, HOS occurs due to inundation of abrasive during operation. Theoretically, it is computed as two times the mean diameter of grit used during machining. The grit size of abrasive material has been identified as the main factor that controls the accuracy of hole in ultrasonic machining.

Ramulu* reported that overcut increases with the diameter of the abrasive particle, and it can be expressed as a function of grit size. Angular deviation and dimensional deviation (both flat and corner) are decreased with increasing grit numbers. Better accuracy is obtained at lower slurry concentration (30–40%) and at normal flow rate.

Komaraiah* reported that the mechanical behavior of the workpiece influences the accuracy of the drilled holes. The materials which have higher hardness to modulus of elasticity ratio tend to have more out of roundness, as shown in Fig A2. Once again, the rotary mode of USM exhibits better performance than conventional USM. In any workpiece material the out-of-roundness is less for the rotary mode.

Various investigators as cited in reference have suggested various rules for side clearance being related to the geometry, size, and distribution of abrasive grains. The amount of oversize of the holes is greater at entry than at exit resulting in unavoidable conicity due to tool wear. The oversize at the bottom of the hole is of the same order as the smallest abrasive size. Conicity can be reduced by using tool materials of tungsten carbide and stainless steel, an internal slurry delivery system, tools with negative tapering walls or fine abrasives. Dimensional accuracy of the order of ±5 lm can be obtained. Conicity is reduced at higher static loads and for prolonged operating times since tool wear is less with finer abrasives. Using combined tools with negative taper improves accuracy.

The injection of slurry to the machining zone decreases conicity and increase precision. Re-passing with the use of fine abrasives can eliminate conicity. OOR is mainly due to lateral vibrations and inaccuracy in the feed motion at entry, but at the exit, it is due to microchipping of the work material. It decreases with increase in static pressure and machining time.

0.125

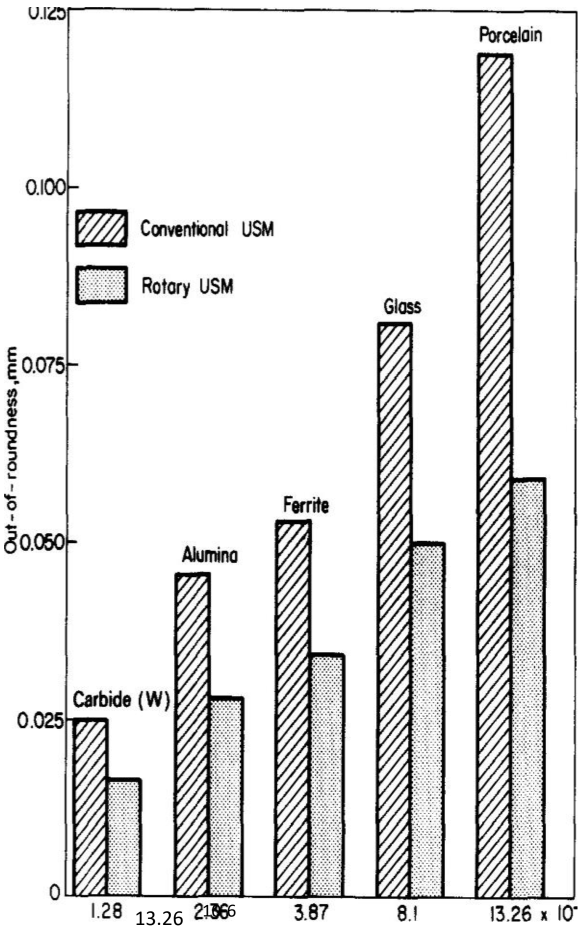


Figure 7 6 comparision of OOR in conventional machining and rotary usm with respect to static pressure

4. TOOL WEAR

Tool wear is a very important factor in ultrasonic machining. It has a large impact on the material removal process and hence influences the machining performance.

It was found out that tool materials having high flexibility slowed the wear of the abrasives and thus improved machining efficiency (Wang, Shimada, Mizutani, & Kuriyagawa, 2018).

It has been reported that in ultrasonic drilling tool wear increases linearly with the number of holes which indicates that longitudinal tool wear increases with an increase in machining time under the same conditions.

It was reported that tool wear is maximum at a particular static load and with an increase in the depth of hole drilled an increase in tool wear can be observed with a subsequent decrease material removal rate (Adithan, Tool, & Brazing, 1981).

It has been found out by many researchers that tool wear is directly proportional to the time machining time and tool wear is also proportional to the wear of the tool that has already taken place (Soundararajan & Radhakrishnant, 1986; Komaraiah & Narasimha Reddy, A study on the influence of workpiece properties in ultrasonic machining, 1993; Adithan, Tool, & Brazing, 1981)

Tool wear has also been found to increase with an increase in the hardness of abrasive grains and an increase in tool wear can be observed with an increase in hardness and toughness of the workpiece material.

It is a well-established principle that tool materials higher value of hardness, fracture toughness, and abrasion resistance results in low tool wear rate (Adithan, Tool, & Brazing, 1981; Jain, Sharma, & Kumar, 2011; Kennedy & Grieve, 1975; Soundararajan & Radhakrishnant, 1986).

REFERENCES

[1] Adithan, M. (1981). Tool wear characteristics in ultrasonic drilling. Tribology International, 14(6), 351-356.

[2] Goetze, D. (1956). Effect of vibration amplitude, frequency, and composition of the abrasive slurry on the rate of ultrasonic machining in ketos tool steel. The Journal of the Acoustical Society of America, 28(6), 1033-1037.

[3] Hu, P., Zhang, J. M., Pei, Z. J., & Treadwell, C. (2002). Modeling of material removal rate in rotary ultrasonic machining: designed experiments. Journal of materials processing technology, 129(1-3), 339-344.

[4] Jain, V., Sharma, A. K., & Kumar, P. (2011). Recent developments and research issues in microultrasonic machining. ISRN Mechanical Engineering, 2011.

[5] Kennedy, D. C., & Grieve, R. J. (1975). Ultrasonic machining-a review. Production Engineer, 54(9), 481-486.

[6] Komaraiah, M., & Reddy, P. N. (1993). A study on the influence of workpiece properties in ultrasonic machining. International Journal of Machine Tools and Manufacture, 33(3), 495-505.

[7] Lalchhuanvela, H., Doloi, B., & Bhattacharyya, B. (2013). Analysis on profile accuracy for ultrasonic machining of alumina ceramics. The International Journal of Advanced Manufacturing Technology, 67(5-8), 1683-1691.

[8] Kumar, J. (2013). Ultrasonic machining—a comprehensive review. Machining Science and Technology, 17(3), 325-379.

[9] Miller, G. E. (1957). Special theory of ultrasonic machining. Journal of Applied physics, 28(2), 149-156.

[10] Pandey, P. C., & Shan, H. S. (1980). Modern machining processes. Tata McGraw-Hill Education.

[11] Ramulu, M. (2005). Ultrasonic machining effects on the surface finish and strength of silicon carbide ceramics. International Journal of Manufacturing Technology Management, 7(2), 3.

[12] Singh, K. J., Ahuja, I. S., & Kapoor, J. (2018). Ultrasonic, chemical-assisted ultrasonic and rotary ultrasonic machining of glass: a review paper. World Journal of Engineering, 15(6), 751-770.

[13] Singh, R., & Khamba, J. S. (2006). Ultrasonic machining of titanium and its alloys: A review. Journal of Materials Processing Technology, 173(2), 125-135.

[14] Soundararajan, V., & Radhakrishnan, V. (1986). An experimental investigation on the basic mechanisms involved in ultrasonic machining. International Journal of Machine Tool Design and Research, 26(3), 307-321.

[15] Wang, J., Shimada, K., Mizutani, M., & Kuriyagawa, T. (2018). Tool wear mechanism and its relation to material removal in ultrasonic machining. Wear, 394, 96-108.

[16] Zeng, W. M., Li, Z. C., Pei, Z. J., & Treadwell, C. (2005). Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics. International Journal of Machine Tools and Manufacture, 45(12-13), 1468-1473.

[17] Singh, R. P., & Singhal, S. (2016). Rotary ultrasonic machining: a review. Materials and Manufacturing Processes, 31(14), 1795-1824.