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Process Parameters of Ultrasonic Machining

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Abstract: Ultrasonic machining is also known as Ultrasonic Vibration machining. It is one of the most widely used machining processes. Few key parameters of USM are abrasive size, the effect of slurry, effect of amplitude, the effect of frequency, effect of tool and work material, and etc. To obtain high results in terms of accuracy and precision, we need to consider the optimal value of these parameters. The optimal parameters vary depending on the situation.

Keywords: Ultrasonic machining, Material Removal Rate (MRR), Abrasive size, Slurry, Amplitude, Frequency, Tool and Work material.

I. INTRODUCTION

Ultrasonic Machining (USM) is also known as Ultrasonic Vibration Machining. It the removal of material by the abrading action of grit-loaded liquid slurry circulating between the workpiece and a tool vibrating perpendicular to the work surface at a frequency above the audible range. It is a type of machining in which the abrasive slurry will be flowing freely between the workpiece and vibrating tool, which produces less amount of heat and there is no contact is present between the workpiece and tool. Hence the grinding pressure is more which helps in machining materials brittle in nature. Example: glass, sapphire, ruby, diamond and ceramics.

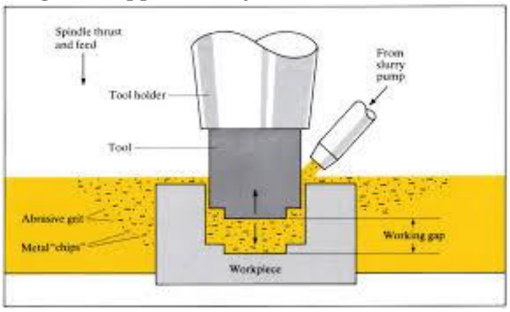

Figure 1: Ultrasonic machining

In the ultrasonic machining process, the tool undergoes vibration in a specific direction, intensity and frequency. The process is performed by its tool decides the construction of the machine. Generally, the frequency of oscillation of the tool is very high in the abrasive slurry. The tool at high-speed oscillation drives the abrasive grain through a small gap, approximately 0.02-0.10 millimetre against the workpiece. In ultrasonic machining, the tool of the desired shape vibrates at ultrasonic frequency (19 to 25 kHz.) with amplitude of 15-50 microns over the workpiece. The shape that needs to be cut on the workpiece is first taken into consideration and depending on that we need to select the workpiece so that it is the mirror image of the shape needed to be cut on the workpiece.

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II. PROCESS PARAMETERS

A. Abrasive size

Ramulu et al.,(2005) examined Material Removal Rate (MRR) and surface integrity in USM of ceramics silicon carbide and titanium diboride. Using silicon carbide and boron carbide grits, the MRR, surface integrity, microhardness and flexural strength was evaluated. The experiment explored that MRR was found to change with respect to the abrasive material, tool material and abrasive size, such as material removal rate increased with the increase in abrasive size. The material removal rate increases with the increase in abrasive size up to a limit after which it decreases. Effect of MRR and Grit diameter for SiC and TiB_2 was represented in Figure 2a and Figure 2b respectively.This was also found in MRR v/s diameter of grit for titanium diboride/silicon carbide workpiece, increase in MRR was not similar to that found in SiC workpiece.

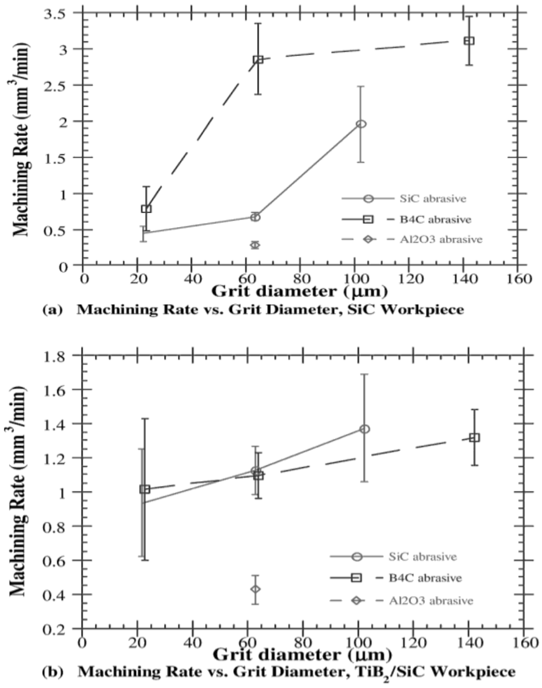

Figure 2. Machining vs Grit size

The overcut difference of the machine slots at entry and exit was found. The taper is usually found to be decreasing with increase in grit size. But it was found that for boron carbide the taper decreased with a decrease in grit size and for silicon carbide it was found to be increasing. The surface roughness was also tested. Usually the surface roughness is finer for small abrasive grits.

For silicon carbide the surface roughness increased with grit size 400. 200 grit size silicon carbide was comparatively fine.

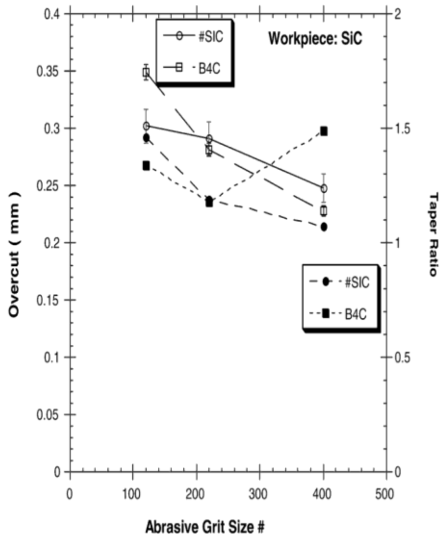

Figure 3. Overcut vs Grit size

Kumar et al. (2010), considered 3 factors in there research; these were tool material, grit size and power rating. The research reveals that High carbon steel showed better performance and effective MRR on the workpiece, the reason is that high carbon steel has more hardness than titanium. The MRR was found to be increasing with increase in coarseness. It decreased further when the grit size increased from 320 to 500 at a small rate. The reason is that as the abrasive particle is coarse more energy is impacting the workpiece removing big chunks of material.

When the size of the workpiece crosses a limit, the size becomes the mean gap between the workpiece and tool and because of less energy impacting the workpiece lesser, MRR is obtained, it is represented in Figure 4.

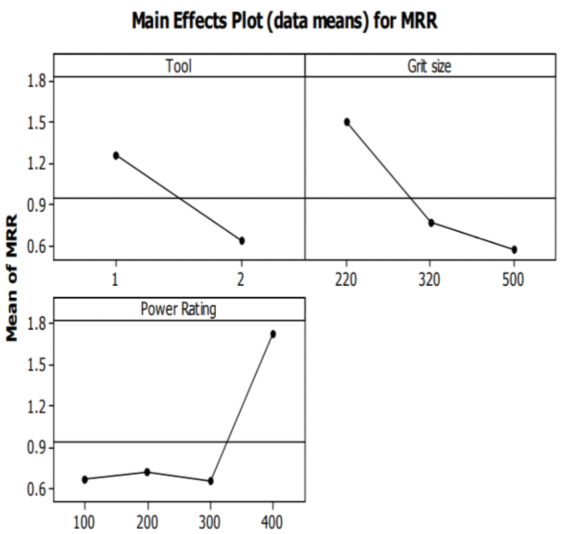

Figure 4. Main effect plot for MRR

The effect of Tool Wear Rate (TWR) for different grit sizes was noted. The tool wear is the weight lost by the tool. The TWR is said to be in the same manner as that of MRR. Coarse abrasive particles impact more on the surface of the tool and thus there is an increased fracture rate. It that TWR was maximum for maximum MRR for a particular grit size-power level combination. This is shown in Figure 5.

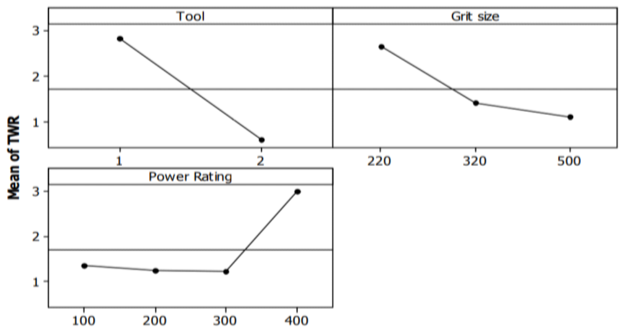

Figure 5. Main effect plot for TWR

Das et al., (2014) conducted experiments on workpieces of highly purified aluminium and bio-ceramic material. It was found out that fine grain abrasive gave low MRR and coarse grain gave high MRR. The coarse grain strikes the workpiece with high kinetic energy as it has high weight and thus MRR is high, it is represented in Figure 6.

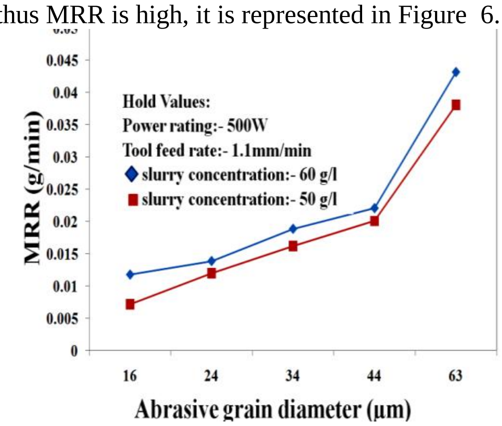

Figure 6: Abrasive Size vs MRR

Overcut criteria were classified into Overcut of Large Diameter (OLD) and Overcut of Smaller Diameter (OSD). OLD and OSD were found to be low for fine grain and were found large for coarser grain. There is less contact surface in case of a fine abrasive particle of small diameter, it is represented in Figure 7 and Figure 8.

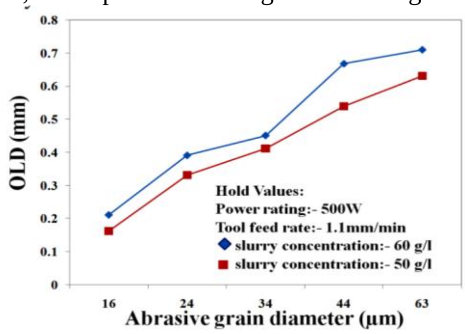

Figure 7: Abrasive Size vs OLD

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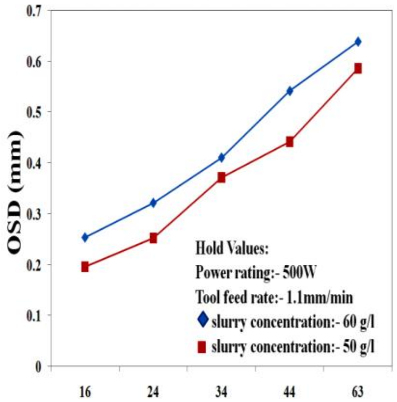

Figure 8: Abrasive Size vs OSD

Pedro et al. gave the following conclusion in their paper. It was noted that the surface roughness is linearly proportional to the grit size. This happens as the number of abrasive particles increased per unit area of the tool. Along with this, the skewness was studied under certain conditions. The skewness is a parameter that defines the variation in the wear mechanism on the USM surface. It was found that this factor increased with the increase in grit size. This explained the transition of the smoothness of the surface to a rough one.

Ravinder et al., (2016) research explored that course the grain the higher the material removal rate. The surface density of the particle leads to the high material removal rate as the coarseness of the particle increases, it is coined as hammering action. Research also reveals that the increase in power and the grit size will improve the machining rate.

Lalchhuanvela et al., (2012) conducted research to know the impact of grit size of the abrasive particles on the MRR in ultrasonic machining process, in general, it is assumed that the MRR increases with increase in grit size. In the experiment, it is identified that the MRR decreased with the initial value to the mean value of grit size. This effect was found even though there was an increase in power and concentration in slurry. Thus, it was concluded that the MRR increases with an increase in grit size only up to a limited value.Sanjay et al., (2015) had found the following result in his experimentation. As we know as there is an increase in grit size the MRR increases. But this was found to having a limit. In actual, the MRR was found to decrease after reaching a certain value of grit size. The material removal rate due to the hammering mechanism will exhibits. The decrease in density of surface leads to increase in effective stress with increase in grit size all leading to the high MRR.

Kainth et al. (1979) research revealed that MRR dropped after a certain value of grit size along with other parameters. There is a deviation from theoretical studies to the actual result data. Studies showed that there is a fracture in the abrasive particles if its size reduced, abrasive particles strength and number. In this experimentation the abrasive size was assumed to be spherical. Understudy it was found that the abrasive particles were having irregular shape.

Ektermanis et al,.(1965) experiment found that there is an increase in MRR for coarser grains. The reason was that the momentum and kinetic energy of the particles were high as they were larger particles. As the feed rate increased or as the tool advanced the workpiece for depth, the MRR decreased. It was seen that the fracture of the abrasive particle leads to lower MRR.

Deng et al.,(2002) explained that the fracture toughness is an important factor in MRR and surface roughness under low amplitude. Khamba et al. (2008) explained that the abrasive is one of the factors that affect the tool wear rate. The research identified that the tool wear rate increased with the increase in the coarseness of the abrasive particle, the reason for the increase in tool wear rate is because of the increase in the impact force on the tool as there is increase in the coarseness of the grain. Also, this coarser grain leads to decrease in surface roughness of the workpiece. Vinod et al. (2011) explained that the tool material and the abrasive particle both play a significant role in MRR.Kumar et al. (2010) conducted experiments using boron carbide as abrasive. In case of Boron carbide more MRR was found as compared with Al or SiC used as abrasive. The experiment was conducted on the coarseness of grains was done and was found that the course the grain the higher the MRR. The two main mechanism of MRR i.e. hammering and impact of the particle was reported in this experiment.

B. Effect of amplitude on MRR

In the research of Sumit et al., (2009) it is explored that the amplitude produced by the vibrating tool is generally not sufficient for cutting purposes. Hence there is a tool that is linked to the transducer through a concentrator that is usually a convergent wave sufficient to obtain the necessary amplitude at end of the tool. The concentrator is in the form of a variable cross-sectional bar and is designed to transmit vibration to the tool from the transducer with increased amplitude. We take values of either the frequency or amplitude depending on the practical considerations. Increase in amplitude of vibration increases MRR. To maximize the amplitude of vibration concentrator should operate at resonance frequency. Under certain circumstances this limits also the maximum size of abrasive to be used. The magnetostrictive material restricts the strength of the transducer amplitude, while the amplitude of vibration varies from 0.01 mm to 0.06 mm. We have a graph which shows the relation between Amplitude and MRR: As shown in Figure - 9 and 10.

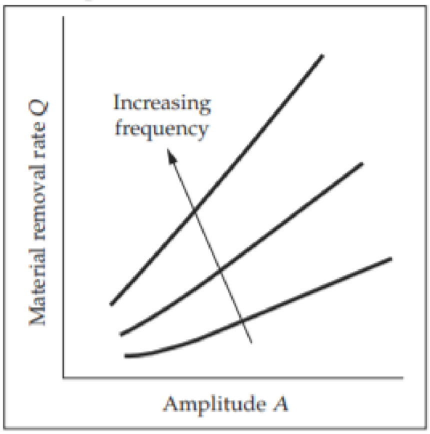

Figure 9: Amplitude vs MRR.

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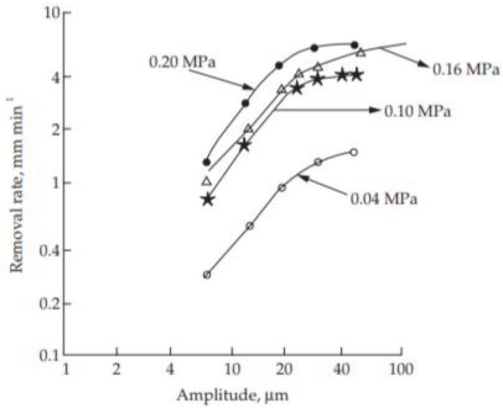

Figure 10: Amplitude of tool oscillates with MRR.

It is observed from the main effects plots (Figure .9 and 10) as said by Bhosle et al (2014) that with the increase in amplitude from 0.7 to 1(%), as the vibration intensity increases there is energy increase in the tooltip. Thus the surface roughness increases due to the increase in the impact of the abrasive particle on the surface. Also, the tool deterioration is found to increase due to the increase of the slurry flow consisting harder abrasive particles, which are collided on the tip of the tool. This can also be the result of the cavitational effect. Regarding MRR, it reduces due to the continuous impacts between the grains of the abrasive and the work material might lead to a huge amount of plastic deformation leading to the formation of work-hardened layer and thus the MRR decreases.

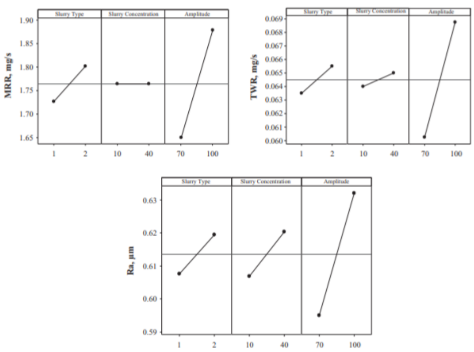

Figure 11: Amplitude of tool vs MRR, TWR, Surface roughness

According to Kavad et al., (2017) research, the increase in MRR with an increase in amplitude may be attributed to the higher momentum imparted to the abrasive particles before striking the workpiece at higher amplitudes. The larger momentum increases the energy with which the abrasive particles collide with the work surface and hence the size of the micro-crack or micro-crater created by each impact. This, in turn, increases the MRR.

Table 12 shows the results obtained by Sumit et al., (2009) in a USM process which was done by varying the amplitude of vibration. The research revealed that increasing the amplitude of tool vibration, will increase the material removal amount.

Table 12: Amplitude of tool with other different parameters.

The initial mass of workpiece in gram	The final mass of workpiece in grams	Amplitude %	Mass of material removed(in grams)
40.035	40.022	70	00.013
40.076	40.035	80	00.041
40.022	39.785	90	00.037
39.785	39.770	100	00.015

Kavad et al., (2017) research revealed that the increase in MRR with an increase in amplitude may be attributed to the higher momentum imparted to the abrasive particles before striking the workpiece at higher amplitudes. The larger momentum increases the energy with which the abrasive particles collide with the work surface and hence the size of the micro-crack or micro-crater created by each impact. This, in turn, increases the MRR. From these results it can conclude that to achieve effective machining of work material is achieved by increasing the amplitude to an optimum value. On the other hand, is also reported that Bhosle et al., (2014) that increase in amplitude also increases the surface roughness of a work material by 1.0 to 3.8 micrometres. And it can be noted that amplitude has 48% effect on the machining process or MRR.

C. Effect of Frequency on MRR

MRR is found to be dependent on the frequency. The resonant frequency is to be maintained to get high amplitude at the tooltip which maximizes the acoustic system utilization. The MRR is proportional to the frequency. While in actual practice there is slight variation. Frequency varies from the lower limit to the upper limit i.e., 15,000 Hz to 25,000 Hz as referred by Sumit et al., (2009). Figure 13 represents the relation between frequency and penetration similarly figure 14 represents the frequency and MRR.

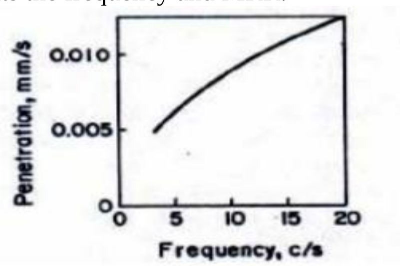

Figure 13: Variation of the frequency with penetration

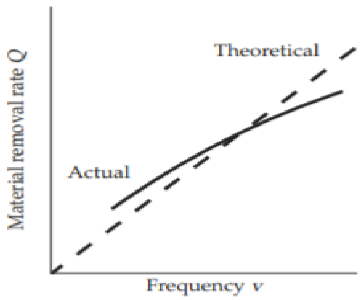

Figure 14: Variation of the frequency with MRR.

Grieve (1975) research reveals that MRR is directly proportional to the velocity of the abrasive particles, it is represented in figure 15.

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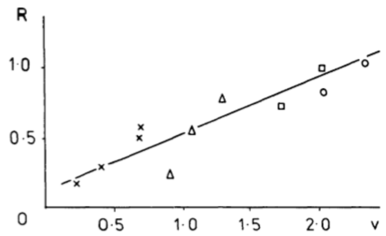

Figure 15: Abrasive particle velocity vs Machining rate.

The above graph also shows that the frequency utilized during machining process should be the acoustic system's resonant frequency, to obtain the maximum amplitude at the tip of the tool and hence attain the maximum utilization of the acoustic system.

D. Effect of Slurry (Abrasive-Water mixture)

Generally, slurry means a mixture of some materials in their powdered form is mixed with water or any other solvent which helps to form a type of paste for machining purposes in case of ultrasonic machining. In Ultrasonic machining we generally use Boron Carbide, Aluminium Oxide, and Silicon Carbide. Sumit et al., (2009) experiment explored that Boron Carbide is the fastest, have greater cutting capability and can be used comparatively for a long time for cutting than other materials. Aluminium Oxide is not used generally in machining process because it wears out very quickly when compared to the other two materials.

Silicon Carbide is used in USM because it is abundantly available in nature and would provide a better MRR and is available at the lowest cost than others. The improved flow of slurry results in an enhanced machining rate. Slurry concentration generally will be around 30 - 60 %. Sumit et al., (2009) research identified that if the volume of abrasives mixed with water and a change in the concentration, change of slurry causes the dust settling on the machining table and hence slows down the machining process. The actual concentration of slurry must be checked at the regular intervals of time.

Sumit et al., (2009) study explored that the temperature of the abrasive slurry should be maintained between 5-6° by the use of a refrigerating cooling system, so the heat obtained at work zone may be absorbed by this mixture and can be let out for disposal or for reuse.

"Machining rate reaches an optimum value with 30% slurry concentration approximately". The MRR value decreases with increase in slurry concentration due to increases in the viscosity of the slurry due to this there will be difficulties in the flow of slurry to work-tool interface and the flow characteristic of slurry will not be up to the required characteristic for the smooth flow of the process. Abrasive slurry system: mixing of fluid medium and abrasive particles takes place prior to pressurization in a separate chamber to create the slurry. Higher wear rates throughout the equipment experienced using this system, but less expensive. It is represented in figure 16.

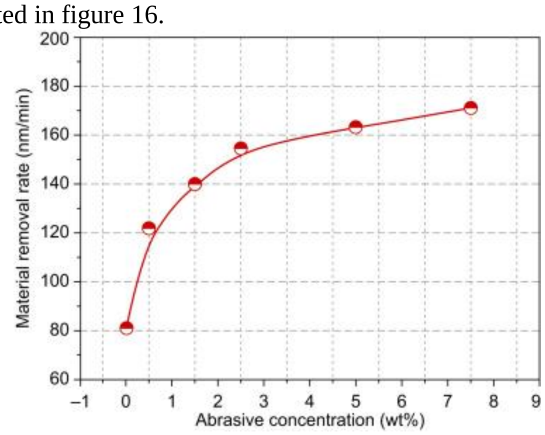

Figure 16. MRR vs Abrasive concentration.

Table 17 shows some of the materials details which are used in USM machining process..

Table 17: Abrasive materials and its properties used as a slurry in USM.

Material	Crystalline Structure	Density (g/cm^3)	Young's Modulus (GPa)	Static Hardness (GPa)	Fracture Toughness K_{ic}(MPa-m$^{1/2}$)	Cutting Rate (μm/s)	R_a (μm)	R_z (μm)
Alumina	FCC/Polycrystalline	4.0	210-380	14-20	3-5	3.8	1.5	10.9
Zirconia	Tetragonal/ Polycrystalline	5.8	140-210	10-12	8-10	2.3	1.7	10.7
Quartz	Trigonal/Single crystal	2.65	78.3	16.0-15.0	0.54-0.52	8.4	1.5	9.6
Soda-lime glass	Amorphous	2.5	69	6.3-5.3	0.53-0.43	26.5	2.5	14.0
Ferrite	Polycrystalline	-	180	6.8	1	28.2	1.9	11.6
LiF	FCC/Single crystal	2.43	54.6	0.95-0.89	1.5	26.5	0.8	4.6

The machining rate and MRR depends on slurry concentration, so by considering many properties as mentioned in table 17 an optimized slurry concentration needs to be select according to the properties of the workpiece materials.

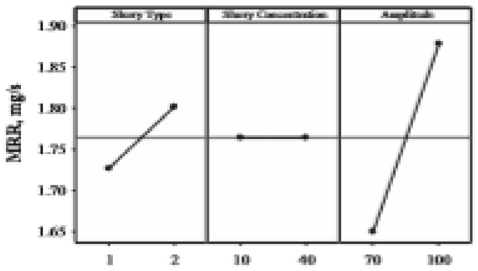

Figure 18: Slurry concentration on MRR.

In general, MRR becomes constant for a particular value range of slurry concentration and this is based on the experimental values. At the other end few researchers like Grieve (1975) opinioned that MRR depends on the grid size concentration and hardness of abrasive particle. Cutting rate is proportional to the concentration up to certain limit.

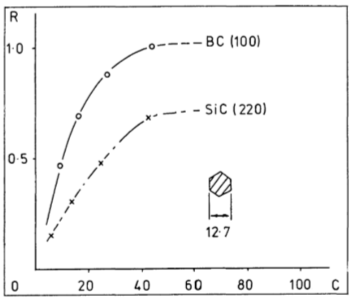

Figure 19: Slurry concentration vs Machining rate

Figure 19 represented the relationship between MRR and slurry concentration when soda lime is used as working fluid and this graph is based on experimental results.

E. Effect of Tool and Work Materials

Since the tool has to withstand the vibrations, it should not wear out quickly. The harder is the tool material, the faster the wear rate of the tool will be. As the tool wears out quickly and machining with this tool makes the surface machined to be rough and also will lead to an unfavourable metal removal rate. As shown in Figure 19 we can understand how important is tool hardness and which can be considered as a parameter. Generally, tough malleable materials such as alloy steel and stainless steel would give satisfactory machining results. Because using aluminium has a very short life.

The mass of the tool has importance in USM because having high mass absorbs the ultrasonic energy that is used for machining and hence there is a reduction in efficiency of machining. Equally the length of the tool used in USM has importance in machining process because greater the length of the tool the greater is tool overstressing. The length of the tool is usually lesser than 25 millimetre.

The slenderness ratio of the tool must lesser than 20 in USM machining. The under-sizing of the tool is directly proportional to the grain size of the abrasive. It is sufficient if:

Tool size= (Hole size) – 2(Abrasive size)

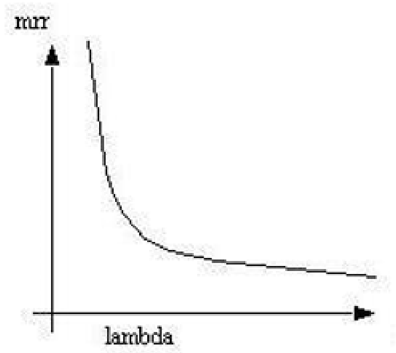

Figure 20: MRR and Lambda (ratio of workpiece /tool hardness)

From the figure 20, it can be concluded that when tool hardness increases which in turn decreases the lambda value and hence MRR increases. The different tool materials were arranged in the increasing order of superiority as mild steel < titanium < stainless steel< silver steel < niamonic-80A <throated tungsten Jatinder Kumar et al.,(2013). It is found that material removal rate is larger, diametric tool wears resistance, and lower surface roughness is obtained when a harder tool material is used. It is also stated that both the hardness and the impact strength of the tool material would influence the longitudinal tool wear, which in turn decreases the MRR and surface roughness increases.

III. CONCLUSION

Ultrasonic Machining is a non-thermal process, used to machine both conductive and non-conductive materials, it is most suited for the materials have hardness more than 40 HRC. Horn is designed by considering the following properties such as high mechanical strength, good acoustic properties, corrosive resistant, high-quality soldering and brazing characteristics. For efficient material removal rate design of horn and tool playes a import role by enhancing resonant in USM.While designing tool wear resistance, elastic properties, fatigue strength, toughness and hardnes of the materials need to consider. Optimum size of the abrasive with higher slurry concentration leads more Materal Removal Rate.

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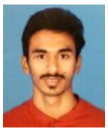

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