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Prediction of Tool and Nozzle Flow Behavior in Ultrasonic Machining Process

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***Abstract*—**The use of hard and brittle material has become increasingly more extensive in recent years. Therefore processing of these materials for the parts fabrication has become a challenging problem. However, it is time-consuming to machine the hard brittle materials with the traditional metal-cutting technique that uses abrasive wheels. In addition, the tool would suffer excessive wear as well. However, if ultrasonic energy is applied to the machining process and coupled with the use of hard abrasive grits, hard and brittle materials can be effectively machined. Ultrasonic machining process is mostly used for the brittle materials. The present research work has developed models using finite element approach to predict the mechanical stresses sand strains produced in the tool during ultrasonic machining process. Also the flow behavior of abrasive slurry coming out of the nozzle has been studied for simulation using ANSYS CFX module. The different abrasives of different grit sizes have been used for the experimentation work.

***Keywords*—**Stress, MRR, Flow, Ultrasonic Machining

I. INTRODUCTION

THE application of ultrasonic energy for material removal was first introduced by Wood and Loomis. The high frequency (about 70 kHz) onto a glass rod was applied for removing material out of the glass substrate while grinding grits were supplied during material processing. Ultrasonic machining offers a solution to the expanding need for machining brittle materials such as single crystals, glasses and polycrystalline ceramics, and for increasing complex operations to provide intricate shapes and work piece profiles. This machining process is non-thermal, non-chemical, creates no change in the microstructure, chemical or physical properties of the work piece and offers virtually stress-free machined surfaces. It was found that it was possible to drill holes in the glass substrate, and the first paper on this research topic was published [1]. Titanium and its alloys are finding prime applications in industries due to their unique properties [2]. However, the high cost of machining is one of the limiting factors for their widespread Use. Tremendous efforts are being made to improve the existing machining processes. Ultrasonic machining is an efficient and economical mean for precision machining of glass or ceramic materials [3-4]. The ultrasonic machining of tough materials like titanium and its alloys was done. However, because of its complexity, the mechanism of the material removal process is still not well understood.

Experimental investigations were conducted to understand machining characteristics of titanium and its alloys with high speed steel .It was investigated that as the tool slows down considerably and even stops, as penetration depth increases [5-6]. The slurry may wear the wall of the machined hole as it passes back towards the surface, which limits the accuracy, particularly for small holes. The ultrasonic method is based on abrasion phenomena on. The brittle material is removed by blows from grains of a harder abrasive, which is under the control of a tool that vibrates with comparatively small amplitude [7]. For a long time, rotary ultrasonic machining was viewed merely by merely as an improvement of conventional USM. One of the major differences between USM and RUM is that USM uses a soft tool (such as stainless steel, brass and mild steel) and slurry loaded with hard abrasive particles while in RUM the hard abrasive particles (diamond) are bonded on the tools. Rotary ultrasonic machining is performed by a cutting tool that vibrates at constant high frequency (typically 20 kHz) [8-9]. In USM process, an abrasive slurry or suspension is fed into the space between the work piece and the longitudinally vibrating tool. Under the action of the constant reciprocating force applied to the tool, the abrasive particles in the slurry remove material from the work piece in the form of minute particles. As material is removed, a cavity is formed in the work piece. This high-speed reciprocation of the tool drives the abrasive grains across a small gap against the work piece. The impact of the abrasives is principally responsible for material removal [10-11]. Ultrasonic machining is known for its ability to and rotation speed of spindle limit the cutting speed, resulting machining of brittle and hard materials such as glass, silicon, quartz, crystal nitride, sapphire, ferrite and fiber optics. A tool vibrating at a frequency of 20-30 KHz with amplitude of 0.025 mm generates accurate, mirror image-shaped cavities. In USM process, the material is removed by the impact of abrasive grains to which kinetic energy is the ultrasonic vibration of abrasive systems. The Micro- USM has also been successfully applied to drill micro holes with 5um in diameter. However the tool design and fabrication (sometimes of multiple tools) and the adverse effect of tool wear on the accuracy of machined components continue to pose challenges in achieving the full potential of micro-USM process. These problems become more critical for mesomicroscale components [12-14].The direct mechanical contact between the tool and work piece results in mechanical deformation, heat generation and distortion. The corresponding tool wear results in poor accuracy and height cutting forces. This process is not affected by the electrical or chemical characteristics of the work material. Holes of any shape can be produced and it has no high-speed moving parts. The power

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consumption is about 5.0 watt hour/mm^3. However, in USM, the slurry has to be fed to and removed from the gap between the tool and the work piece. Electric Discharge machining and electrochemical machining was used to generate micro shapes ranging from micro holes to 3D complex shapes [15]. In RUM process, the specific tool wear (the ratio of the volume of material removed to the volume of tool wear) was used to evaluate tool wear [16]. The effects of process parameters (static load, ultrasonic vibration and amplitude, diamond concentration, diamond type, grit size, and bond strength) on specific tool wear were investigated experimentally. However, specific tool wear measurements were made to study the mechanisms of tool wear in RUM [17]. The modes of the material removal mechanism included hamming, abrasion and hobbing as depicted [18-20].

II. EXPERIMENTATION DETAILS

The experiments were performed on a Sonic-Mill, 500W (Albuquerque, NM) as shown in fig.1.

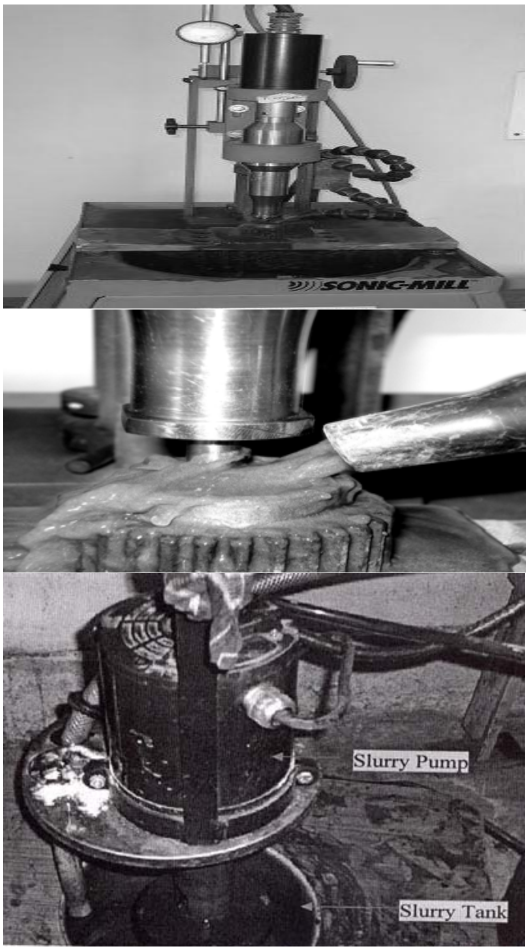


Fig. 1 Experimental set up

The machining of work material was performed using different input parameters. The frequency was varied from 18 to 22 kHz. The three different values of power rating taken were (25, 50, 75) percent. The three different abrasive slurries (Al_2O_3, SiC, and B_4C), each of three grit sizes (220, 320, 500) were adopted with percentage concentrations by volume with water (20, 25,30). Table I and II represents the maximum and minimum strains induced. There was no withdrawal of the tool during the tests.

TABLE I
MAXIMUM VALUES OF STRAIN

Directions	X	Y	Z
NODE	509	503	347
Value	0.543 E-11	0.508 E-11	0.956 E-03
Directions	XY	YZ	XZ
NODE	536	334	333
Value	0.213 E-10	0.433 E-02	0.476 E-02

TABLE II
MINIMUM VALUES OF STRAIN

Directions	X	Y	Z
NODE	333	334	531
Value	0.191 E-10	0.203 E-10	0.585E-02
Directions	XY	YZ	XZ
NODE	338	536	340
Value	0.211 E-10	0.432 E-02	-0.448E-02

Abrasive slurry feed circulation and frequency amplitude was maintained constant. The frequency measurement was performed with the help of a frequency meter. The trials were carried out under maximum material removal rate (MRR) conditions with a tool rotation of 350 rpm. All the experiments were repeated four times; hence four trials were conducted at each experimental run. The output variables were recorded for each trial and then the results for each experimental run were averaged out to obtain the mean value of response variable (TWR) for that particular experiment. The analysis of results has been performed using the MINITAB 14.0 software. As the tool vibrates with sonic velocity as given by equation 1, the he cutting action imposed by the above mentioned machining processes on brittle materials, for example, will yield components with a very poor surface finish and in many cases, results in the chipping and/or fracture of the materials being machined.

$$\text{Sonic velocity} = \frac{E}{\mu}\left[m(m-1)/\left(m^2-m-2\right)\right]^{1/2}$$

Where E = Young’s modulus,

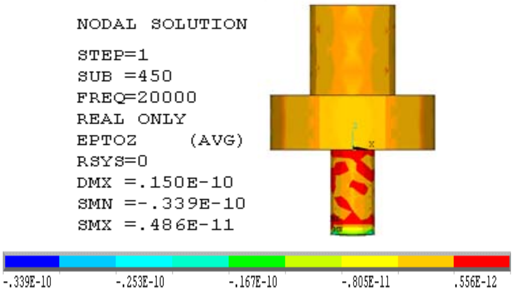
$\frac{1}{m}$ = Poisson’s ratio,

ρ = Density of the material.

III.RESULTS AND DISCUSSION

A. Simulation of stresses on the tool

The software Ansys 11.0 has been used for simulation of stresses on the tool. The finite element method is used to generate the mashes and find the stresses on the tool. The figs 2 and 3 presents the srain produced in the tool and Von mises stress produced. The tool is discredited into twenty nodes and triangular shape elements. The total nodes generated during meshing in the tool are one thousand and twenty two. For the boundary condition, the displacement at gripping surface of tool has fixed 0,0 in all degree of freedom as tool is griped on the machine from this surface and a harmonic force 4.2 kg is applied on the bottom surface as it is striking at the work piece at a harmonic frequency of 20000 Hz. The variation of stress in x,y and z directions with the increase of frequency is shown in figs. 4-6.



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NODAL SOLUTION

STEP=1
SUB =450
FREQ=20000
REAL ONLY
EPTOZ      (AVG)
RSYS=0
DMX =.150E-10
SMN =-.339E-10
SMX =.486E-11
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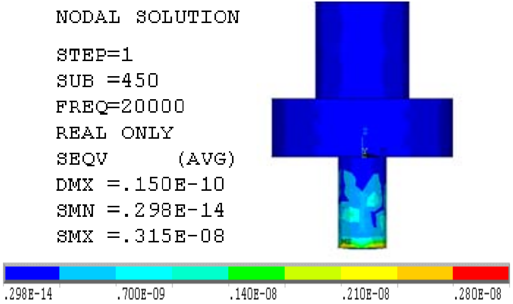
Fig. 2 Strain produced in the tool

A rigorous solution to the problem of the propagation of the high amplitude vibrations in a rod of finite length with changing cross section presents mathematical difficulties.



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NODAL SOLUTION

STEP=1
SUB =450
FREQ=20000
REAL ONLY
SEQV       (AVG)
DMX =.150E-10
SMN =.298E-14
SMX =.315E-08
```

Fig. 3 Von mises stress produced in the tool

Hence, several simplifying assumptions are made for technical calculations to make the problem mathematically tractable.

1.The velocities of the particles over the whole area of a cross section are constant.

2. The material for the horn is homogeneous and isotropic.

3. There is no change in the material properties of horn along the length of the horn.

4. To solve the meshed tool with the specified boundary conditions the generated equations are solved .The variation of strain produced at different nodes along x,y and z directions is shown in figures 7-9 along x,y and z respectively.

The fig.10 presents the detailed tool geometry used in the experimentation work.

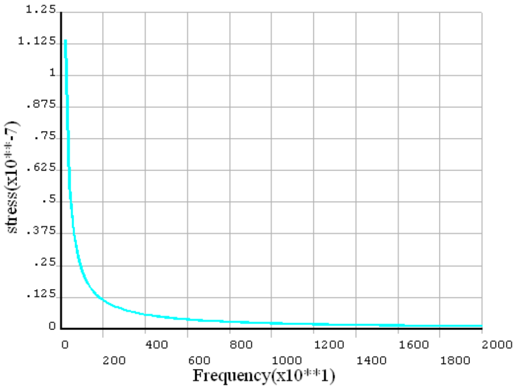


Fig. 4 Variation of stress in x direction with increasing frequency

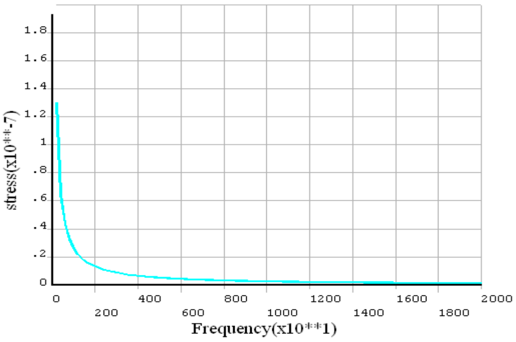


Fig. 5 Variation of stress in y dir’n with increasing frequency

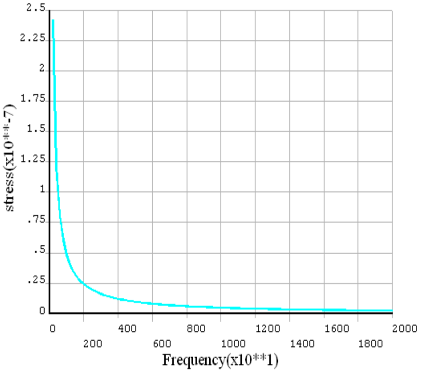


Fig. 6 Variation of stress in z dir’n with increasing frequency

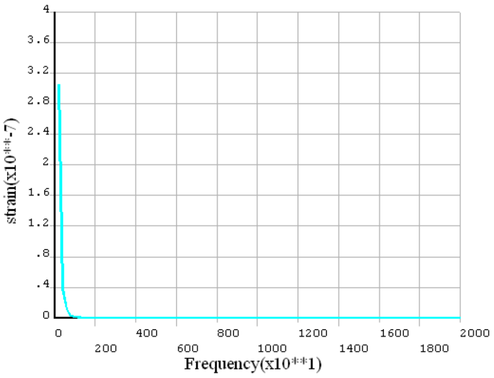


Fig. 7 Variation of strain in x dir’n with increasing frequency

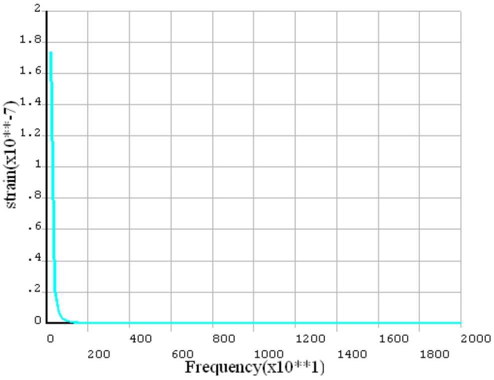


Fig. 8 Variation of strain in y dir’n with increasing frequency

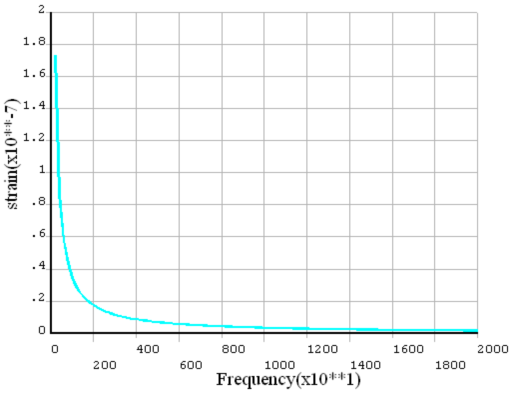


Fig. 9 Variation of strain in z dir’n with increasing

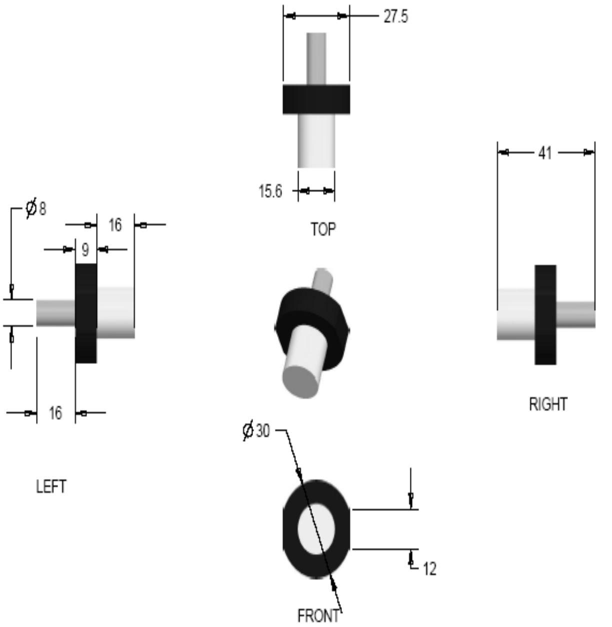


Fig. 10 Detailed drawing of the tool geometry frequency

B. Prediction of Nozzle Behavior

To study the flow behavior of abrasive slurry coming out of the nozzle a standard taper nozzle was considered for simulation using ANSYS CFX module. The geometry of nozzle is shown in figure 1 inlet pressure of fluid is 3bar, inlet diameter is 25mm, outlet diameter is 10mm and the overall length of 75 mm was considered out of which 30mm is taper part and 45mm is straight part. The outside air pressure was considered to be 1 atm. From the fig. 11 the red region shows the region of maximum velocity and fig.14 is between distance from the outlet and velocity of fluid is obtained which shows the region of peak velocity and it is found to be 20.624 m/sec at a distance of 1mm from outlet.

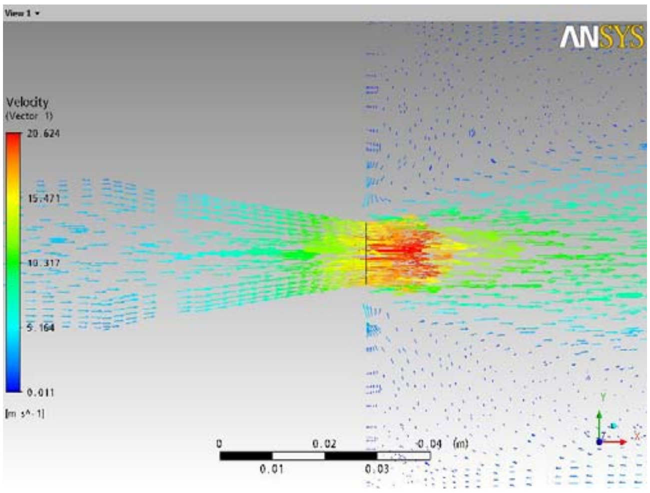


Fig. 11 velocity vector

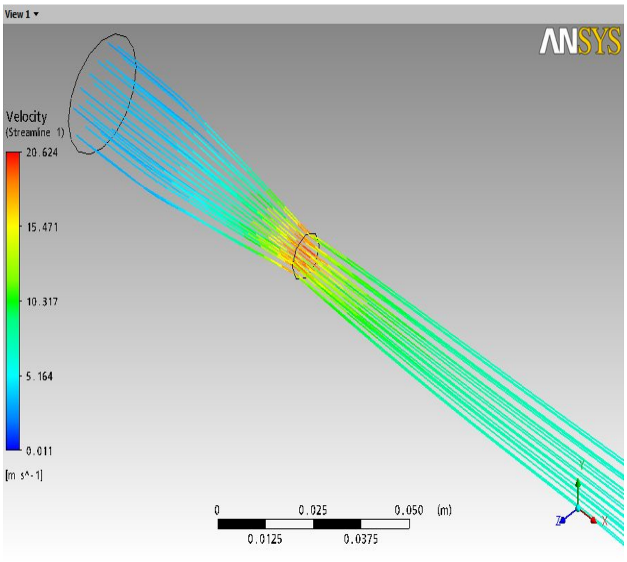


Fig. 12 velocity streamline

The region of minimum velocity is represented by blue arrows and it is found to be 0.011m/sec as shown in figure 12. It is found that if we place the nozzle at a distance of around 10mm from the cutting zone the efficiency of the nozzle will be maximum . It can also be experimentally validated and the results can be compared with the simulated results. The pressure variations inside the nozzle are shown in figure 13.

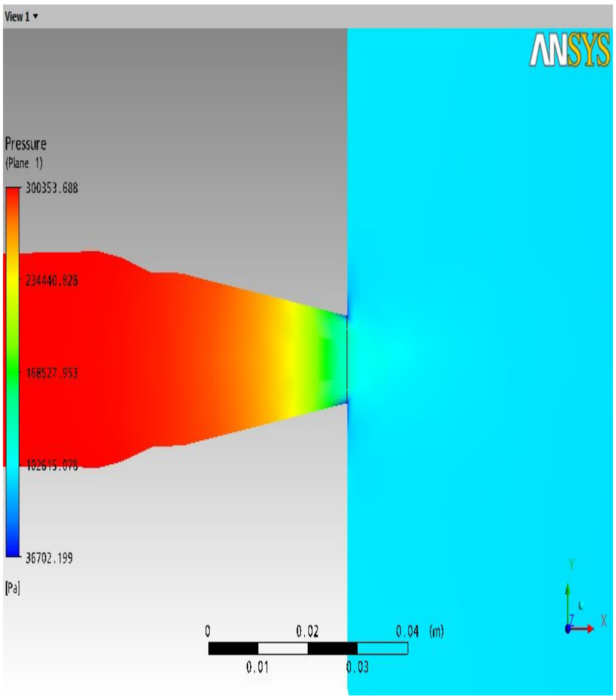
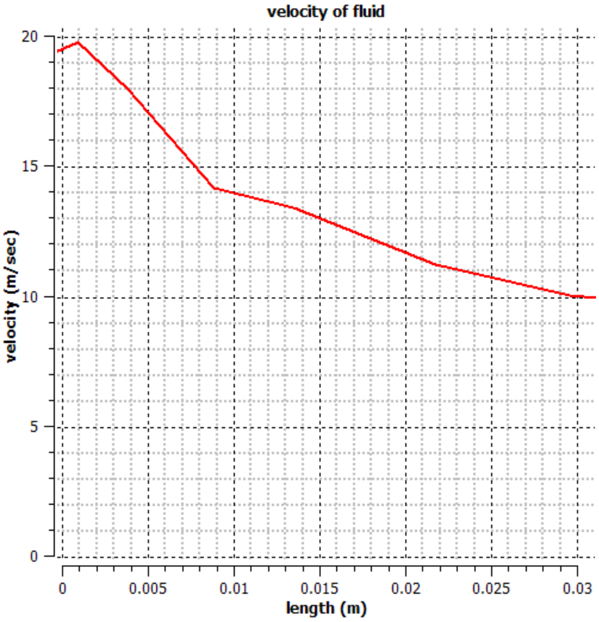


Fig. 13 Pressure distribution inside the nozzle



Fig, 14 Velocity of the fluid from the outlet of nozzle

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