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Design and Development of Horn and Slurry Circulation System in Ultrasonic Machining

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Abstract - **Traditional machining processes are unable to machine brittle materials economically. The process popularly known as Ultrasonic machining is found suitable for machining all such brittle materials like glass, ceramics, hard alloys and composites. The existing slurry circulation system is inefficient and cause lot of inconvenience for effective material removal during ultrasonic machining. Further, the new horn production is the necessity for machining of brittle materials using different work-tool combination. Horn design is performed analytically and verified using the CARD software. The horns designed were tuned and tested before employing on the machine. The modified circulation system was tested and found better and resulted into efficient slurry circulation in the machining zone. USM slurry is splashed out from sump tank because of high vibrations of tool. Acoustic head besides the new slurry circulation system has been designed and fabricated. The purpose of this work is to investigate the design of efficient horns (resonator) for the ultrasonic machining process by employing the analytical method for the design characteristics of the horn and comparing the results with those desigened using CARD software.**

Keywords – Ultrasonic Machining, Horn, Slurry System, CARD Software.

1. INTRODUCTION

The manufacturing industry is facing difficulties while machining of difficult to cut materials like super alloys, composites, ceramics, glass, and materials of brittle nature due to its applicability to remove material by indentation erosion mechanism by abrasive particles [1-2]. These materials play an increasingly important role in modern manufacturing industries, especially, in aircraft, automobile, tool, die and mould making industries. Traditional machining processes available today are unable to machine these materials economically. The Ultrasonic machining is found suitable for machining of the above materials. Crushing and grinding of abrasive grains against the work surface causes chipping of material from work piece. As the process is non-chemical and non-thermal, materials are not altered either chemically or metallurgically. Ultrasonic machining is of particular interest for the cutting of non-conductive, brittle workpiece materials such as engineering ceramics [3]. The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator.The ultrasonic machining system contains the following major components which include acoustic head, tool feed mechanism, abrasive slurry system and the generator. In this paper, the attempt is made to improve the existing USM system by modifying the existing slurry circulation system and by designing a new acoustic head horn.

2. DESIGN OF HORN

2.1 Ultrasonic Horn/Concentrator

The concentrator provides the link between the transducer and tool and its main function is to amplify the amplitude of vibration as per the requirements. This is achieved through the principle of resonance. The horn material used is a compromise between the needs of the ultrasonic and the application here it is titanium alloys, steel and stainless steel [4]. The cutting performance of ultrasonic machining equipment primarily depends on the proper design of the horn [5].

Horn is a waveguide-focusing device with a cross-sectional area, which decreases from the input (transducer) end to the output (tool) end. It amplifies the input amplitude of vibration so that at the output end the amplitude is sufficiently large for machining. The purpose of this work is to investigate the design of efficient horns for the ultrasonic machining process by employing the analytical method for the design characteristics of the horn and comparing the results with those designed using software. In the recent works, the selection of a suitable shape and corresponding dimensions of horn are usually determined by numerical simulations using finite element method [6].

In this way, the horn design can be varied quite conveniently so that a more exact resonant frequency, which matches that of the machine, can be obtained. It also helps to verify and fine-tune the horn designs based on empirical formulae. In addition, dynamic analysis can be carried out to determine the stress characteristics of the horn under operating conditions.

2.2 Design Procedure

The horn or the mechanical resonator is designed on the basis of axial vibration of an elastic member with varying cross section. Let us consider a free-free vibration of a non-uniform bar, in general as shown in fig.2 assuming-

1. Plane wave propagation in the rod along the axial direction and
2. Wave propagation along lateral directions is neglected.

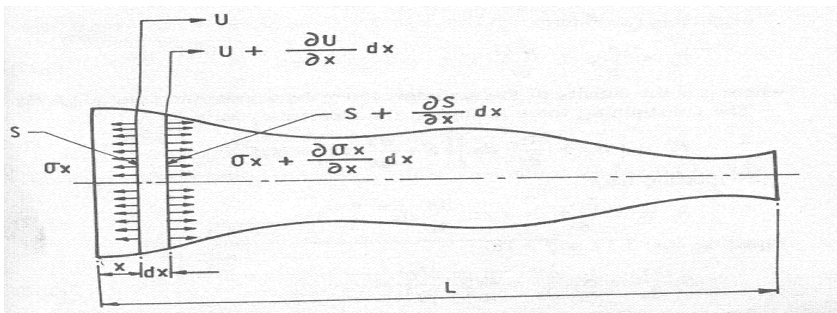


Fig. 1 Scheme of free-free vibration of non-uniform bar [7].

An elementary section taken at a distance x from one end of thickness will be subjected to different stress gradient which will produce a strain in the elementary strip as,

Strain= $\dfrac{[U+(\partial U/\partial x)dx]-U}{dx}=\dfrac{\partial U}{\partial x}=\dfrac{\sigma_x}{E}$

where U is the displacement of section x and x is the stress level on the section at x of area S

Hence, $\sigma_x = E\dfrac{\partial U}{\partial x}$

(1)

Due to vibration, the elementary strip shall be acted upon by an accelerating force as,

$$F_a=\frac{\rho}{g}\frac{\left(S+\frac{\partial S}{\partial x}\right)dx+S}{2}dx\frac{\partial^2 U}{\partial t^2}$$

(2)

Neglecting ∂x^2 term,

$$F_a=\frac{\rho}{g}Sdx\frac{\partial^2 U}{\partial t^2}$$

where ρ is the density of the material and g is the acceleration due to gravity.

The constraining force acting on the elementary strip is

$$F_c=\left(\sigma_x+\frac{\partial \sigma_x}{\partial x}dx\right)\left(S+\frac{\partial S}{\partial x}dx\right)-\sigma_x S$$

Neglecting ∂x^2 term,

$$F_c=S\frac{\partial \sigma_x}{\partial x}dx+\sigma_x\frac{\partial S}{\partial x}dx$$

(3)

from eqs. (2) and (3)

$$S\frac{\partial \sigma_x}{\partial x} + \sigma_x \frac{\partial S}{\partial x} = \frac{\rho}{g} S \frac{\partial^2 U}{\partial t^2} \quad (4)$$

Substituting the values of σ_x and $\frac{\partial \sigma_x}{\partial x}$, from eqs. (1) and (4)

$$SE\frac{\partial^2 U}{\partial x^2} + E\frac{\partial U}{\partial x}\frac{\partial S}{\partial x} = \frac{\rho}{g} S \frac{\partial^2 U}{\partial t^2} \quad (5)$$

Now the displacement equation for angular frequency w can be written as

$$U = A\sin(wt) + B\cos t(wt)$$

From which

$$\frac{\partial^2 U}{\partial t^2} = \omega^2 U$$

Which again on substitution in eq. (5) gives

$$\frac{\partial^2 U}{\partial x^2} + \frac{1}{S}\frac{\partial U}{\partial x}\frac{\partial S}{\partial x} + \frac{\omega^2}{c^2} U = 0 \quad (6)$$

where

$c = \sqrt{\frac{Eg}{\rho}}$ =Velocity of sound in the material.

where,

E = young's modulus and ρ = Density of a material

Case study

For uniform cylindrical rod,

As, $\left(\frac{\partial S}{\partial x}\right) = 0$

From eq. (6)

$$\frac{\partial^2 U}{\partial x^2} + \frac{\omega^2}{c^2} U = 0$$

The solution, which is given by

$$U = A\sin\left(\frac{\omega}{c} x\right) + B\cos t\left(\frac{\omega}{c} x\right)$$

Putting the boundary values as U =0 at x=L

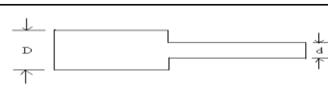
$$L = \frac{n\pi}{\omega}\sqrt{\frac{Eg}{\rho}} \qquad \text{(Where n=1, 2, 3…)}$$

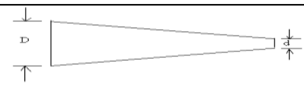
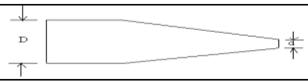
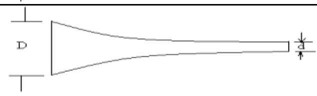
First fundamental resonant frequency is given by,

$$f_1 = \frac{1}{2L}\sqrt{\frac{Eg}{\rho}} \quad (7)$$

To obtain maximum vibration at two extreme ends of the rod, the length should be half the wavelength. As the amplitude at both the ends are equal giving a gain value of the amplitude amplification as 1 and in ultrasonic application there must be some gain for the amplification of the amplitude of vibration from the transducer end to the required level at the tool end.

Table. 1 Classical solution for standard tapers [4].

Type of horn	Shape	Gain (N=D/d)
Stepped		a = $(D/d)^2 = N^2$

Conical		a = D/d a < N
Stepped-conical		a = D/d a > N
Exponential		a = D/d = N

Sound magnification using stepped horn can be as high as 25000, while exponential horn is limited to D/d. For example, with D/d = 100; exponential horn magnifies sound 100 times, while stepped horn magnifies it to 10000 times. Typically, **length of the horn = ½ wavelength of used frequency**.
In this work, two different materials are used for making horn are aluminum and steel. Table 2 shows the elastic constants and propagation velocities of horn materials.

Table. 2 Elastic constants and propagation velocities for some solids at 20^0C [6].

Material	Density ρ (gm/cm^2)	Young's modulus E (kg/mm^2)	shear modulus (kg/mm^2)	Poisson' ratio μ	Wave speed c in rod (m/sec)
Aluminum	2.7	7100	2640	0.34	5080
Mild Steel	7.8	21000	8200	0.28	5170

2.2.1 Analytical Design

The calculation to determine the dimension of the horn is described in this subsection. Sample calculation for aluminium horn is shown.

1. Aluminum

Data: - Young's modulus (E) = 70 G Pa, Density (ρ) = 2710 Kg/m3, Poisson's ratio (η) = 0.35, Frequency of vibrations (n) = 20 KHz, Assuming D = 27 mm and d =10 mm.
The velocity of sound (C) in a material is given by,

$$c = \sqrt{\frac{Eg}{\rho}}$$

$$C = \sqrt{\frac{7.136 X 9.81 X 10^{\wedge}9}{2710}}$$

C = 5082.498 m/s
Since the velocity of sound can also be calculated by,
C = n λ
Where, n = frequency and
λ = Wavelength of sound wave
∴ λ = C/ n
= 5082.498 / 20000
= 0.254 m
To obtain maximum vibration at two extreme ends of the rod, the length should of half the wavelength. i.e. L = λ/2
∴ L = 0.254/2
= 0.127 m

$\therefore$ **L = 127 mm**

and hence the gain can be given as,

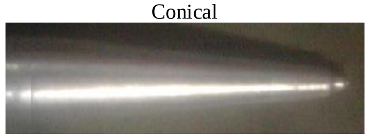
N = D/d
= 27/10
$\therefore$ **N = 2.70**

A similar procedure was used to determine the required value of L and N for mild steel and EN 8 steel horn design.

2.2.2 Design of Horn using software (CARD)

CARD software uses the quantitative techniques for design of acoustic resonators with low to moderate complexity. The software is useful to design the new resonator or for analyzing the existing resonators. Resonator dimensions can be selected for automatic tuning, or the resonator can be manually tuned. Resonators up to three half-waves long can be analyzed. CARD calculates various acoustic parameters, including tuned length, tuned frequency, gain, node location, maximum stress, stored energy, loss, overall quality factor (Q), and weight. While calculating the stress, the software considers the effect of stress concentrations at radii and slot ends. The output graphically displayed the calculated amplitude, stress, and loss distributions at each point along the length of the resonator. Horns of three different materials were designed using CARD software. The horn of aluminum, mild steel and EN8 alloy steel with their designed parameters are shown in table 3.
The horn designed using software was compared with the analytically obtained design parameters. Accordingly the horns were fabricated and tuned subsequently before fixing in the acoustic head.

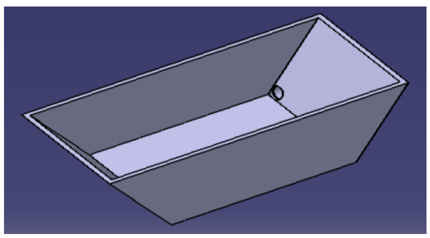
Table. 3 Comparison of horn design.

Material	Type of Horn	Analytical Design		Software Design	
		Length (Lc) (mm)	Gain (N)	Length (Lc) (mm)	Gain (N)
Aluminum	Conical 	127	2.70	134.9	2.78
Mild steel	Stepped 	118.32	2.74	119.1	3.71
EN8	Stepped-conical 	130.14	2.74	149.3	2.50

3. DESIGN OF SLURRY CIRCULATION SYSTEM

The role of abrasive slurry is prime in mechanism of material removal in ultrasonic machining. It acts as a coolant for the horn, tool and workpiece, supplies fresh abrasive to the cutting zone and removes debris from the cutting area [8]. Higher slurry concentration is preferred when the higher MRR is desired. But this might cause the instability and reduced material removal if the abrasive particles are more than threshold. The saturation occurs when the

volume of the slurry is 30 to 40% of abrasive/water mixture. The shape of the grain in the slurry plays very important role. The edge of the abrasive particle removes the metal. So if more than one edge is in touch with the work-piece simultaneously, more metal will be removed at a time. The liquid used for making slurry is not less important. The most common abrasive materials used are aluminium oxide, silicon carbide, boron carbide, etc [7].
The slurry concentration has significant effect, as the concentration increases from zero, the metal removal rate also increases. An optimum concentration is achieved and with that maximum metal removal rate. After this any increase in concentration fails to effect further increase in the metal removal rate. The metal removal rate increases with an increase in the rate of flow of slurry in the interface of the work and the tool. It attains a maximum value corresponding to a particular flow rate called optimum flow rate. There is no further increase in the metal removal rate with any increase in the flow rate. The reason can be analyzed as follows. With lower flow rates the abrasive grains remain in the cutting zone for longer period. Due to the impact of the tool, the cutting edges of the grains become blunt and thus less effective in removing the metal any more. The slurry temperature also affects the machining rate. It is mainly due to cavitation effect. The metal removal rate is maximum at 50^{o}C. It is due to the fact that the vapor pressure of water at this temperature causes optimum cavitation.



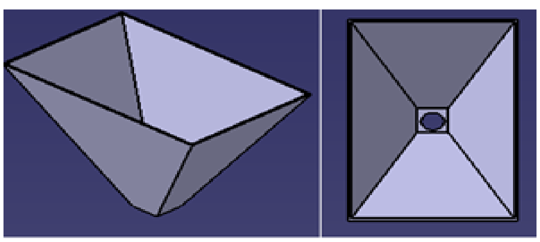


Fig. 2 Previous slurry tank Fig. 3 Modified slurry tank

The previous slurry circulating system had certain drawbacks. The output of the upper tank was a small hole provided at one of the corner, which lead to the reduced concentration of the slurry, as most of the slurry was not able to flow within the tank. The dimensions of the storage tank were such that clearance between the shaft of the motor and sides of the tank was larger; hence only little amount of slurry was coming in the whirl of the motor. Also, the height of the storage tank was little more and hence motor was not able to lift the slurry settled at the bottom. The pipe connecting the two tanks has a small diameter increasing the chances of trapping the abrasive particles into pipe. Hence, it was required to redesign both the tanks in order to get proper mixing of slurry and water and also, to get the uniform flow rate.

In view of the above drawbacks, the new slurry tank has been designed as shown in fig. 3. The new slurry system tank is fabricated and installed in the system. It is tested for slurry circulation and better slurry circulation is found compared to old slurry tank.

4. CONCLUSIONS

The design of horn concentrator plays an important role in providing a resonance state in USM to maximize the material removal rate. The design of the conical, stepped and straight conical horns made of aluminum, mild steel and EN8 using the empirical estimates proved to be successful and this validated using the empirical equations, since the horns could be tuned to the ultrasonic machine. The calculations done on the various horn designs shows that the frequencies obtained by simulation are quite close to the expected frequency of 20 kHz.

The slurry acts as a coolant for the horn, tool and work piece, supplies fresh abrasive to the cutting zone and removes debris from the cutting area. The tool may crack from joint if inadequate supply of slurry is there. It also provides a good acoustic bond between the tool, abrasive and work piece, allowing efficient energy transfer. During operation in USM slurry is splashed out from sump tank because of high vibrations of tool. Hence proper care was taken for fixing the tank so that the slurry concentration and slurry flow rate ensure higher MRR.

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