ISSN 2348 - 2249

Volume-2, Issue-3, July-September, 2014

International Journal for Multi Disciplinary Engineering and Business Management

(IJMDEBM)

A Study on the Tool Geometry and Stresses Induced in Tool in Ultrasonic Machining Process Applied for the Tough and Brittle Materials

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Abstract – The objective of the present study is to investigate the tool geometry and stresses induced in tool in ultrasonic machining process applied for the tough and brittle materials. Generally, the sonotrodes are made of metals that have high fatigue strengths and low acoustic losses. The most important aspect of sonotrode design is a sonotrode resonant frequency and the determination of the correct sonotrode resonant wavelength. Ultrasonic vibrations have been harnessed with considerable benefits for a variety of production applications, for example, ultrasonic cleaning, plastic welding, etc. and has proved to offer advantages in a number of other applications. These applications include the automotive, food preparation, medical, textile and material joining and mainly applications in manufacturing industries. Significant increasing in performance and qualitative improvements are achieved by using ultrasonic vibrations in machining technological processes.

Keywords – Ultrasonic, Sonotrode, Wavelength, Brittle, Acoustic, Resonant

I. INTRODUCTION

The use of ultrasound phenomenon is becoming increasingly used feature in many industrial applications. Ultrasonic vibrations have been harnessed with considerable benefits for a varietyof production applications, for example, ultrasonic cleaning, plastic welding, etc. and has proved to offer advantages in a number of other applications. These applications include the automotive, food preparation, medical, textile and material joining and mainly applications in manufacturing industries. Significant increasing in performance and qualitative improvements are achieved by using ultrasonic vibrations in machining technological processes.

Applications of ultrasonic vibration energy in machining technologies are realized by two different approaches. The first approach, called as an ultrasonic machining, is based on abrasive principle of material removal. The tool which is shaped in the exact configuration to be ground in workpiece and it is attached to a vibrating horn. The second approach is based on the conventional machining technologies – ultrasonic assisted machining. The ultrasonic vibrations are transmitted directly on cutting tools, respectively directly to a cutting process. These techniques are used for high precision machining application for non-brittle materials and difficult-to-cut materials machining such as hardened steels, nickel-based alloys, titanium and aluminium-SiC metal matrix composites. The repetitive high frequency vibro-impact mode brings some unique properties and improvements into metal cutting process where the interaction between the work piece and the cutting tool is transformed into a micro-vibro-impact process. Generally, in all manufacturing systems using ultrasonic vibrations, the electromechanical transducer acts as the source of mechanical oscillations, transforming the electrical power received from the generator into mechanical vibrations. The electromechanical transducers are based on the principle utilizing magneto-strictive or effects.

The electromechanical transducers generate the vibration with resonant frequency fres ≈ 20 kHz and more. The amplitude of the resulting ultrasonic vibrations is inadequate for realization of the cutting process. To overcome this problem, the amplifying wave guided elements of the ultrasonic machining equipments are connected to the electromechanical transducer enabling to achieve the necessary size of amplitude. The wave-guide focusing device known as ultrasonic horn (also known as concentrator, sonotrode or tool holder) is fitted onto the end of the transducer. Ultrasonic horn transfers the longitudinal ultrasonic waves from the transducer end to the toe end with attached the cutting tool and it amplifies the input amplitude of vibrations so that at the output end the amplitude is sufficiently large to perform of required machining process.

The equipment primarily depends on the well taken design of the sonotrode. The sonotrode is the only part of the ultrasonic machining system which is unique to each process. They are used in various shapes and sizes, according to the application, but like other components should be resonant at the operating frequency. The sonotrode material used is a compromise between the needs of the ultrasonics and the application – titanium alloys, steel, stainless steel. As was mentioned earlier, the shape of ultrasonic horn depends on technological process for which will be used. The most frequently used shapes of ultrasonic horns are: cylindrical, tapered, exponential and stepped. To achieve optimal performance of ultrasonic machining system is necessary to take into account all relevant effects and parameters that affect the dynamics of the system. One of the most important

ISSN 2348 - 2249
Volume-2, Issue-3, July-September, 2014
International Journal for Multi Disciplinary Engineering and Business Management
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elements of the ultrasonic system sonotrode, must have the required dynamic properties, which must be determined already in design phase. The dynamical analysis of various shapes of sonotrodes is presented.

The effect of relevant sonotrode dimensions on natural frequencies and mode shapes is analyzed by finite element method (FEM). The mutual comparisons of the comparable parameters of the various sonotrode shapes are presented. The main aim of this paper is to present generally valid results leading to the selection of suitable shape and corresponding geometrical dimensions of sonotrode with required dynamical properties**.**

II. THE SONOTRODE OR TOOL HOLDER DESIGN

Generally, the sonotrodes are made of metals that have high fatigue strengths and low acoustic losses. The most important aspect of sonotrode design is a sonotrode resonant frequency and the determination of the correct sonotrode resonant wavelength. The wavelength should be usually integer multiple of the half wavelength of the sonotrode. The resonant frequency of sonotrode, which has simple geometrical shape can by determined analytically (cylindrical shape). For complicated geometrical shape, the resonant frequency is usually determined numerically using finite element method. The required performance of sonotrode is assessed by an amplification factor,

The required performance of sonotrode is assessed by an amplification factor

$$\vartheta = \left|\frac{A_1}{A_0}\right|, \tag{1}$$

Where A0 – amplitude of input end of sonotrode,A1 – amplitude of output end of sonotrode. The basic requirement for the size of the amplification factor is

$$\vartheta > 1. \tag{2}$$

The analytical solution of the free sonotrode vibrations. The governing equation of longitudinally vibrating sonotrode with variable circular cross-section S(x), which is valid for 1D continuum (thin elastic bar), is expressed in the form

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c_p^2\left[\frac{1}{S(x)}\frac{\partial S(x)}{\partial x}\frac{\partial u(x,t)}{\partial x} + \frac{\partial^2 u(x,t)}{\partial x^2}\right], \tag{3}$$

where x – coordinate in the longitudinal direction,
u(x, t) – longitudinal displacement of cross-section,
S(x) = π(r(x))2 – cross-section area,
r(x) – radius of circular cross-section,
cp = E/ρ – velocity of the longitudinal waves in 1D continuum,
E – Young's modulus of sonotrode material,
ρ – density of sonotrode material

The free sonotrode vibration of cylindrical shape (r(x) = r) is described by wave equation

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c_p^2\frac{\partial^2 u(x,t)}{\partial x^2}. \tag{4}$$

The solution of equation (4) is supposed in the form u(x, t) = U(x)T(t). Then partial differential equation (4) is divided into following two ordinary differential equations

$$\frac{\mathrm{d}^2 U(x)}{\mathrm{d}x^2} + \frac{\omega_0^2}{c_p^2}U(x) = 0, \tag{5}$$

$$\frac{\mathrm{d}^2 T(t)}{\mathrm{d}t^2} + \omega_0^2 T(t) = 0, \tag{6}$$

where ω0 – natural angular frequency.
Introducing the following non-dimensional quantities
• non-dimesional coordinate in the longitudinal direction:

$$\xi = \frac{x}{l_0};\ \xi \in \langle 0; 1\rangle, \tag{7}$$

• non-dimesional longitudinal displacement of cross-section:

$$\Psi(\xi) = \frac{U(x)}{l_0}, \tag{8}$$

The first of equations (5), we obtain non-dimensional equation

$$\frac{\mathrm{d}^2\Psi(\xi)}{\mathrm{d}\xi^2} + \beta^2\Psi(\xi) = 0 \tag{9}$$

and its solution

$$\Psi(\xi) = A\cos(\beta\xi) + B\sin(\beta\xi), \tag{10}$$

where β = ω0/cpl0 – frequency parameter,
l0 – sonotrode length.

Both sides of sonotrode have the posibility of motion in the axial direction. To the input side is attached electromechanical transducer which generates ultasonic axial vibrations and to the output end is attached vibrating tool. Then the boundary conditions for free vibration of sonotrode are supposed as a free-free edge on both sides in the form

$$\left.\frac{\mathrm{d}\Psi(\xi)}{\mathrm{d}\xi}\right|_{\xi=0} = 0, \qquad \left.\frac{\mathrm{d}\Psi(\xi)}{\mathrm{d}\xi}\right|_{\xi=1} = 0 \tag{8}$$

Then, after application of boundary conditions (8) into solution (7), the following modal
parameters of sonotrode are obtained
• natural frequency (in [Hz]) of the kth mode shape

$$f_{0k} = \frac{k}{2l_0}\sqrt{\frac{E}{\rho}},$$

• non-dimensional wave length of the kth mode shape

$$\lambda_k = \frac{2\pi}{\beta_k} = \frac{2}{k},$$

where βk is kth root of characteristic equation and k = 1, 2, . . .

In order to achieve the desired effect on ultrasonicmachining, only the first twomode shapes of sonotrode are used, i.e. for k = 1 so-called "half wave" shape and k = 2 "wave" shape (Fig. 1). As it is seen, the analytical determination of mode shapes and the natural frequencies of cylindrical shape of sonotrode are relatively simple. Analytical determination of these parameters for non-cylindrical shapes is more complicated. Therefore, to the determination of modal properties for more complicated geometrical sonotrode shapes, the numerical method (FEM) is better to use.

ISSN 2348 - 2249
Volume-2, Issue-3, July-September, 2014
International Journal for Multi Disciplinary Engineering and Business Management
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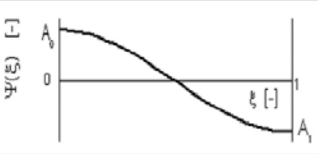
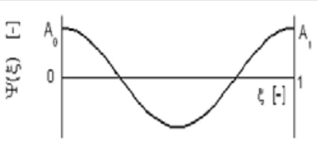
Name of Shape	Parameters	Mode Shape of Sonotrode Vibration
λ/2 – "*half wave*" shape	$k=1$ $\lambda_1=2$ $f_{01}=\frac{1}{2l_0}\sqrt{\frac{E}{\rho}}$ $\vartheta_1=1$	
λ – "*wave*" shape	$k=2$ $\lambda_2=1$ $f_{02}=\frac{1}{l_0}\sqrt{\frac{E}{\rho}}$ $\vartheta_2=1$	

Fig:1 Mode shapes of cylindrical sonotrode vibrations

The dynamical analysis of the various geometrical shapes of sonotrodes as one of the most important elements of the ultrasonic machining systems is presented in this paper. The main dynamic characteristics (natural frequencies and amplification factors) of sonotrode in the resonant state were studied according to the geometric shape and dimensions. The efficiency and performance of ultrasonicmachining systems depends on specific design and the relatively large number of parameters. Selection of a geometric shape of the sonotrode depends on technological operation for which the sonotrode will be used. The value of resonance frequency and amplitude amplification factor on the output side of sonotrode are fundamental requirements for the selectionof appropriate sonotrode shape. The cylindrical sonotrode shape was used as a comparative geometric shape to the expressing of results of other sonotrode shapes. Generally, it can be said that the geometrical shapes and dimensions of the sonotrodes affect the stiffness and mass distribution. With the changing of the cross section towards to the output side of sonotrode, the amplification factor ϑ is changing in the whole interval of cross-section changing ($\vartheta i > 1.0$ for increasing cross section, ($\vartheta i < 1.0$ for growing cross section). In addition to changes in cross section, significant effect on the amplification factor has also slenderness ratio. For the increasing cross-section and growing slenderness ratio of sonotrode, the amplification factor decreases. For the interval in which the cross-section increases, the amplification factor increases in dependency on the growing of slenderness ratio. Dependency of the natural frequencies on the slenderness ratio changes and cross section changes of sonotrodes . The specific case of sonotrode shape is the stepped shape. For this case of sonotrode shape are valid the same conclusions as in the cases of tapered and exponential sonotrode shapes.

III. Rotary Ultrasonic Machining (RUM)

USM is used for machining hard and brittle materials to complex shapes with good accuracy and reasonable surface finish. 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. Working is not hazardous. Power consumption is about 0.1-Watt hour/mm3 for glass and about 5.0-Watt hour/mm3. However, in USM, the slurry has to be fed to and removed from the gap between the tool and the work piece. Because of this fact, there are some disadvantages of this method.

The material removal rate slows down considerably and even stops as penetration depth increases. 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 phenomenon. 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.

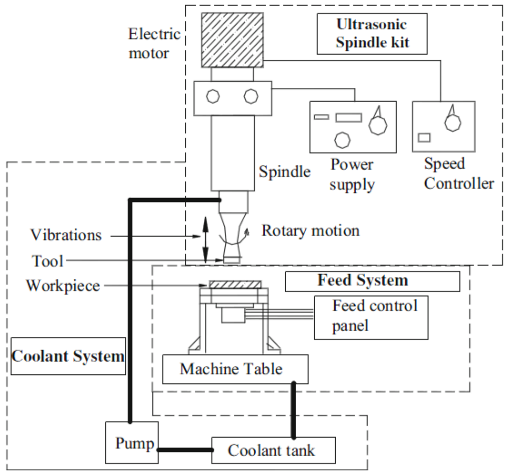


Fig.2 Presentation of USM process

IV. Mathematical Modelling

A rigorous solution to the problem of the propagation of the low-amplitude vibrations in a rod of finite length with reducing cross section presents mathematical difficulties. Hence, several simplifying assumptions are made for technical calculations to make the problem mathematically tractable.

1. A plane wave is propagated in the rod, that is, the stresses and the velocities of the particles over the whole area of a cross section are constant.
2. The transverse compression of the rod is neglected, as it is not taking part in the cutting operation.
3. The slurry acts as a coolant for the horn, tool, and workpiece, supplies fresh abrasives to the cutting zone and removes debris from the cutting area.
4. The material for the horn is homogeneous and isotropic. There is no change in the material properties of horn along the length of the horn.

V. Stresses in the Horn with Rotation

The displacement obtained for the rotary horn is related to the stress components. The variation of components of stresses along the z-axis at r=0.4047 mm. This figure indicates that the axial stress is the maximum stress, and it is responsible for a major part of the stresses developed in the horn domain while the other three stress components approach zero values over most of the horn length. The components of stresses starts with zero value at the transducer end and rises to a first peak due to stress concentration at the hole tip. The second higher peak value is obtained at the middle portion of the horn where the sudden change in the area of the horn domain occurs. The peak effective stress value for the horn at

ISSN 2348 - 2249
Volume-2, Issue-3, July-September, 2014
International Journal for Multi Disciplinary Engineering and Business Management
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250 rpm is about 500 MPa, which is below the allowable limit. The variation of stress components along the axis at a radius of 5 mm is plotted . Here it is observed that the axial stress is well below the allowable endurance strength of the horn material. The maximum peak value of axial stress is about 510 MPa, which is just below the maximum allowable endurance strength of the horn material. The variation of stress components along radius at axial length equal to 0 mm is plotted.

The stress distribution along the radial length is linear and it is nearly zero value at the transducer end. The variation of stress components along radius at z=45 mm. The maximum axial stress is obtained in this region, as there is sudden change in the area. The maximum stress value in this area is 500 MPa, which is below the allowable endurance strength (520 MPa) of the horn material. It is also shown that the nature of the curve is linear along radius at a section where z=45 mm. The variation of stress components along radius at axial length equal to 130 mm is plotted. As the tool end of the horn is free to move, stress is decreased, and it approaches zero for the circumferential and shear stress, the 3D stress surface plot for the stress distribution over the whole horn length. It is plotted by taking radial length as a X-axis, axial length as a Y-axis and the stress component on the Z-axis. The 3D stress surface plot is created using SURFER software. The 3D stress surface plot for the radial stress (σrr). The stress distribution is nearly zero at the transducer end and it is maximum where the sudden change in the horn area occurs at the middle of the horn. The maximum (σrr) obtained at the middle of the horn by the present FEM model is well below the maximum allowable stress.

This work has covered the design of a horn for rotary ultrasonic machining using the finite element method. The amplitude of vibration and the stress components induced within the horn domain are calculated and the conclusions of the present work are as follows:

A mathematical model for the determination of displacement within the horn used in rotary ultrasonic machining is developed. The components of stresses within the horn domain are found to be within the allowable stress.

The amplification factor is more for rotary USM over conventional USM without horn rotation for the same material properties and the boundary conditions.

The first peak value for the stress components are obtained near the top of the horn because of the hole concentration in that region.

The maximum stresses are obtained at the middle surface of the horn where the area changes suddenly but it is well within the maximum allowable stress for the horn material.

The stresses at the bottom surface of the horn are nearly zero because the horn is free to move at that end.

Rotary ultrasonic machining (RUM) is one of the machining processes for advanced ceramics. Edge chipping (or chamfer), commonly observed in RUM of ceramic materials, not only compromises geometric accuracy but also possibly causes an increase in machining cost. In this paper, a three-dimensional finite element analysis (FEA) model is developed to study the effects of three parameters (cutting depth, support length, and pretightening load) on the maximum normal stress and von Mises stress in the region where the edge chipping initiates. Two failure criteria (the maximum normal stress criterion and von Mises stress criterion) were used to predict the relation between the edge chipping thickness and the support length. Furthermore, a solution to reduce the edge chipping is proposed based upon the FEA simulations and verified by experiments.

This paper presents an investigation into the edge chipping during RUM of ceramics. A possible solution to reduce the edge chipping thickness was proposed based on FEA simulations and then validated by experiments. The main conclusions are:

- As the cutting depth increases, the maximum values of the maximum normal stress and the von Mises stress increase.
- The effects of pre tightening load on the maximum values of the maximum normal stress and the von Mises stress are not significant.
- There exists a critical support length. As the support length increases before reaching the critical length, the maximum values of the maximum normal stress and the von Mises stress decrease slightly. When the support length exceeds the critical length, there are sharp decreases in the maximum values of the maximum normal stress and the von Mises stress.
- The edge chipping thickness can be reduced by increasing the support length.

Engineering ceramics have significant applications in different industries such as; automotive, aerospace, electrical, electronics and even martial industries due to their attractive physical and mechanical properties like very high hardness and strength at elevated temperatures, chemical stability, low friction and high wear resistance. However, these interesting properties plus low heat conductivity make their machining processes too hard, costly and time consuming. Many attempts have been made in order to make the grinding process of engineering ceramics easier and many scientists have tried to find proper techniques to economize ceramics' machining processes. This paper proposes a new diamond plunge grinding technique using ultrasonic vibration for grinding Alumina ceramic (Al_2O_3). For this purpose, a set of laboratory equipments have been designed and simulated using Finite Element Method (FEM) and constructed in order to be used in various measurements. The results obtained have been compared with the conventional plunge grinding process without ultrasonic vibration and indicated that the surface roughness and fracture strength improved and the grinding forces decreased.

A new grinding technique applying ultrasonic vibration along the radius of the grinding wheel was proposed. A compact ultrasonic unit composed of an ultrasonic transducer, acoustic horn and their respective holders was designed and constructed and then installed on a dynamometer surface to measure the normal and tangential grinding forces. During horizontal grinding, the work piece was vibrated ultrasonically at the resonant frequency in the vertical

ISSN 2348 - 2249
Volume-2, Issue-3, July-September, 2014
International Journal for Multi Disciplinary Engineering and Business Management
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direction. Performance of the unit, including the percent reduction in the normal and tangential grinding force and also improvement in the surface roughness and fracture strength has been investigated. The results described below has been confirmed the validity of the proposed new grinding technique, and demonstrated that the designed and constructed unit performed well.

VI. Results and Discussion

The results can be summarized as follows:

1. The ultrasonic machining process is very useful for the machining of extremely brittle materials like glass, ceramics etc. This is because the tool does not directly touching the work piece during machining.
2. The ultrasonic machining process is finding extensive applications for conducting as well non-conducting work materials
3. The harder the abrasive particles resulting in more material removal rate. The use of aluminium oxide and silicon carbide is recommended for soft materials.
4. The use of boron carbide is recommended for hard work materials. This is because the more material removal rate is obtained using the boron carbide. However the machining cost gets increased.
5. The results of the grinding test showed that the surface roughness of Alumina work pieces was improved by 8% when ultrasonic vibration was applied.
6. The assistance of ultrasonic vibration in the grinding operation reduced the total grinding force. For Alumina (Al2O3), particularly, the reduction reached about 22%.

REFRENCES

[1] Amin, S. G., Ahmed, M. H. M., Youssef, H. A., Computer-aided design of acoustic horns for ultrasonic using finite-element analysis, Journal of Materials Processing Technology 55 (1995) 254–260.

[2] Amini, S., Soleimanimehr, H., Nategh, M. J., Abudollah, A., Sadeghi, M. H., FEM analysis of ultrasonic-vibration-assisted turning and the vibratory tool, Journal of Materials Processing Technology 201 (2008) 43–47.

[3] Babitsky, V. I., Kalashnikov, A. N.,Meadows, A.,Wijesundara, A. A. H. P., Ultrasonically assisted turning of aviation materials, Journal of Materials Processing Technology 132 (2003) 157–167.

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

[5] Seah, K. H. W., Wong, Y. S., Lee, L. C. Design of tool holders for ultrasonic machining using FEM, Journal of Materials Processing Technology 37 (1993) 801–816.

[6] Wang, F., Zhao, Z., Zhang, D., Wu, Y., Development of novel ultrasonic transducers for microelectronics packaging, Journal of Materials Processing Technology 209 (2009) 1 291–1 301.

[7] Kremer D, Ghabrial SM, Moisan A (1981) The state of the art of ultrasonic machining. Ann CIRP 30:107–110.

[8] Gilmore R (1991) Ultrasonic machining: a case study. J Mater Process Technol 28:139–148

[9] Pei ZJ, Ferreira PM (1999) An experimental investigation of rotary ultrasonic face milling. Int J Mach Tool Manuf 39:1327–1344.

[10] Yadava V, Jain VK, Dixit PM (2002) Thermal stresses due to electric discharge machining. Int J Mach Tools Manuf 42(8): 877–888.

[11] D. Prabhakar, P. M. Ferreira, M. Haselkorn, “An experimental investigation of material removal rates in rotary ultrasonic machining,” Transactions of the North American Manufacturing Research of SME 10, pp. 211–218, 1992.

[12] Y. Wu, T. Kondo, M. Kato, “A new center-less Grinding Technique Using a Surface Grinder,” Journal of Material Processing Technology, 162-163, pp. 709-717, 2005.

[13] S. G. Amin, M. H. M. Ahmed, H. A. Youssef, “Computer-aided design of acoustic horns for ultrasonic machining using finite-element analysis,” Journal of Material Processing Technology, pp. 55, 254- 260,1995.