# Finite Element Analysis of Ultrasonic Machinie Tool

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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 machine, finite element analysis, stress analysys,*** *Resonant.*

## I. INTRODUCTION

The FE method for practical use and by the 1970s it was being used by large industries such as aerospace, automotive, defense and nuclear industries at large, mainframe computers. However, with rapid advancements in computational power and the reduced cost of FE software, FEA is now widely used. The FE method works by modeling a structure using a mesh of elements connected together using nodes. The elements can have simple as complex material properties applied to characterise the behavior of the structure under analysis. Boundary and load conditions can be simulated on the nodes or elements of the mesh and a variety of analytical results can be calculated depending on the type of analysis requested by the user and the parameters the uses is interested in. Several modeling techniques can be used to analyse a structure in using a 2D or 3D modeling domain, the choice of which depends using the FE methods and FEA is now considered to be an essential tool in the arsenal of an engineer especially for design or troubleshooting.

## II. DESIGN PROCESS FOR ULTRASONIC TOOL.

1 micron amplitude is supplied by the transducer at one end of the rod then the displacement at the other end is 1 micron, this however in reality never occurs due to slight internal losses. Also, gain is dependent on the rate of change in cross- sectional area from the base of the component, where the input is supplied to the tip. A reduction in cross-sectional area from the base to the tip increases gain and an increase in cross-sectional area reduce gain. Many components profiles exist such as conical, exponential, stepped or combination of each to magnify or reduce amplitude at the tip of the component.

## III. DESIGN CONSIDERATION FOR USM TOOL

For the experimental cutting tool tuned to the longitudinal mode of vibration at 30 kHz frequency, material Alloy Steel (High Carbon High Chromium Alloy Steel) and work-piece Glass. An increase in gain would allow a large range of amplitude to be investigated. To increase the vibration amplitude of the tool and for simplicity for tuning and comparison studies two symmetric circular cuts were taken from both uniform rod along the longitudinal axis to reduce the cross sectional area from the base to the tip, as shown in fig: 1.1

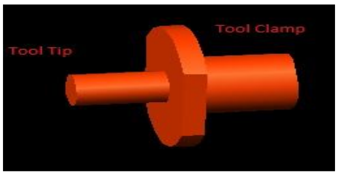

Fig 1.1 Symmetric circular cuts through a uniform rod

## IV. TUNING THE ULTRASONIC TOOL

Only the longitudinal length was multiplied by the constant to tune the tool whilst the diameter remained constant. To tune the ultrasonic tool the geometry of the tool was created in ABAQUS and then the program executed to determine natural frequencies. The longitudinal mode of the tool was identified and the resonant frequency recorded. Afterwards the length of the tool was rescaled by multiplying the length by the constant as calculated which was the ratio of the calculated output frequency to the desired frequency. The analysis was the resubmitted and the longitudinal mode identified to determine if it was operating at the driving frequency.

## V. STRESS ANALYSIS USING FEA

After the tool had been tuned to resonance a forcing was applied to the base of the tool as indicated in Equation 15 where F is the force, A the amplitude of the transducer (8 microns), ω the natural frequency and t the time.

$$F = A \sin \omega t \qquad \text{(Equation....1)}$$

A steady state dynamics direct step was included in the FE analysis after the frequency step to analysis stress and displacement of the tool due to the applied loading at the longitudinal mode of vibration. The stress distribution in the tool can be plotted using the Von-mises and Hencky criteria as shown in Eq: 1 below where $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses and $\sigma_o$ is the yield stress.

$$(\sigma_1 - \sigma_2)^2 + (\sigma 2 - \sigma_3)^2 + (\sigma 3 - \sigma_1)^2 = 2\,\sigma_o^2 \qquad \text{(Equation....2)}$$

Assuming the stress distribution lies in-plane along the cross-section of the blade where no traverse movement exists implies that there is only one principal stress, $\sigma_2$, acting in one direction always and no shear stress and using Eq: 2

$$\sigma_1, \sigma_3 = 0$$

$$(0 - \sigma_2)^2 + (\sigma_2 - 0)^2 + 0 = 2\,\sigma_o^2$$

$$\sigma_2^2 = 2\,\sigma_0^2$$

$$\sigma_2 = \sigma_0 \qquad \text{(Equation....3)}$$

as shown in Eq 2 the Von Mises stress will be the same as the maximum principal stress in the longitudinal direction in the wave guides when excited in the longitudinal mode. Maximum stress limits in components must always be considered in any design and for ultrasonic cutting tool ideally the maximum stress must lies in the elastic region of the material at a safety factor typically of 4 or greater for operational safety. The maximum allowable stress in an ultrasonic component when designed can therefore be considered to the yield stress of the material divided by the safety factor as denoted in Eq:4

$$\sigma_{max} = \sigma_{yield} / \text{Safety Factor} \qquad \text{(Equation …4)}$$

## VI. MATERIAL SELECTION FOR ULTRASONIC TOOL

Material selection for ultrasonic components is critical to ensure the tool operate correctly. Material factor such as high strength and high toughness are specified for the design of ultrasonic components especially ultrasonic tool where the components experience extreme loading conditions. Minimising heat generation during operation is often a design specification for ultrasonic tool to restrict burning at the cut interface that can ruin the substrate material, and materials with low internal friction co-efficients are required to minimise temperature rise during operation. However, in some processes such as ultrasonic cutting of glass products a slight temperature increase is sometimes an advantage and for soft materials can locally melt the material at the interface which can often produce a cut surface that is visually appearing to the eye. Ideally during operation an acoustic loss factor zero is prefect as there will be no energy losses due to heat or noise and all energy supplied will be transformed into mechanical vibration but in reality every ultrasonic component will experience acoustic losses and energy will be lost in the system. Often the quality factor is used to characterise the effectiveness of the ultrasonic components and a high mechanical Q is often advantageous for ultrasonic components design. The mechanical Q or quality factor can be calculated using Eq.5, where Q is the quality factor and $\Phi$ is the acoustic loss available from material table.

$$Q = 1/\Phi \qquad \text{(Equation....5)}$$

Many materials have high quality factor but it is also critical when selecting a material for component design to consider the acoustic impedance, z, of the material which can be determine from Eq: 6 where c is the speed of sound in the material and $\rho$ is the density.

$$Z = c\,\rho \qquad \text{(Equation....6 )}$$

When several ultrasonic components are connected, usually by using threaded studs where one component is tightened against another, the acoustic impedance should be matched as closely as possible to ensure transfer is maximised between joining components and to ensure the vibration is transferred effectively between one component and the next.

## VII. EXPERIMENTAL ULTRASONIC TOOL

In the investigation Alloy steel (High carbon, High Chromium steel) is used for the ultrasonic tool, used in the experimental cutting trials due to its high strength, high toughness, corrosion resistance, durability and low acoustic loss (or high mechanical Q). The material properties for alloy steel are tabulated in table 1.A finite Element model of the ultrasonic tool was made using the FE package ABAQUS and using the procedure described previously to resonate in the longitudinal mode at 30 kHz.

| Alloy Steel (High carbon, High Chromium steel) | |
|---|---|
| Density | 7.8gm/cm$^3$ |
| Hardness (Vicker's) HRB | 168 |
| Ultimate Tensile Strength | 765 MPa |
| Yield Strength | 529 MPa |
| Young's Modulus | 84.2 GPa |
| Poisson Ratio | 0.321 |
| Fatigue Strength | 114 MPa |
| Specific Heat Capacity | 0.359 Kj/Kg$^o$C |
| Thermal Conductivity | 4.5 W/mK |

Table 1 Material properties of Alloy Steel (High carbon, High Chromium steel)

## VIII. BOUNDARY CONDITIONS AND LOADS

Boundary conditions are the conditions existing at the physical boundary of the domain. In stress analysis problem they refer to displacements or rotation and forces/ moment conditions. Since the upper part of the ultrasonic tool is fixed in the horn therefore no longitudinal movements and no rotational movements are allowed. The boundary conditions were imposed to finite element model by freezing all degrees of freedom of motion at one end (ENCASTRE; U1=U2=U3=UR1=UR2=UR3=0). The same condition was applied to the work piece which was holded at the base. The load applied on the tip of the ultrasonic tool is 100 MPa in the longitudinal direction direct to the work piece. During machining operation pressure is also applied on the sides wall of the ultrasonic tool that is approximately half the force applied on the tip i.e. 50MPa. This happens because the abrasive particles get stuck in the gap between tool and work piece hole and due to this effect the hole diameter generated is always bigger than the required hole diameter. The force is transferred to the abrasive and these abrasives strike with the work piece to remove the material by erosion effect. These are 6586 tetrahedral elements were generated for the studies to ultrasonic tool and 12858 tetrahedral elements were generated for the studies to the glass work-piece. In which 21 tetrahedral elements are come on the surface of the tip of USM tool. The maximum stresses are generated in this part.

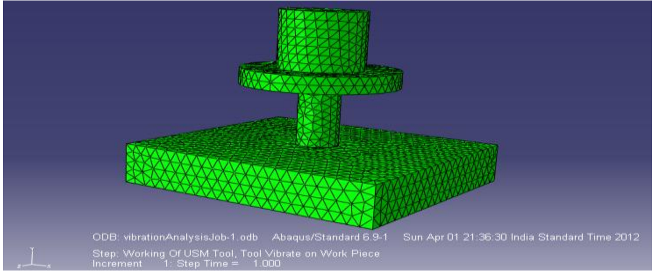

Fig: 2 Modal in ABAQUS with boundary condition

## IX. RESULTS

By analysis of the results obtained for the defining and submitting a job where the load applied was represented using a sinusoidal force function as equation using data of table 1., the maximum stress, tool displacement were determined. Fig:3 illustrate using contour plots, the locations of maximum stresses and displacement for the 30 kHz tool when excited in the longitudinal mode.

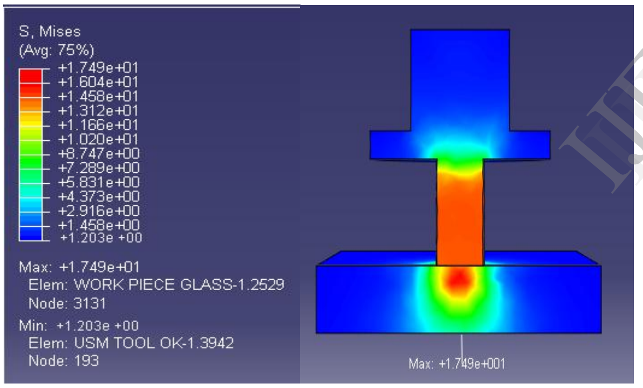

Fig: 3 Contour plot of the deformed shape for the tuned 30 kHz ultrasonic machine tool maximum principal stress in the longitudinal direction

The maximum stress was generated on the tip of the work piece the value of the stress is shown in the table the value is approximately 17.49 Mpa. It observed that stress is decrease when we move in the upward along longitudinal direction. Same way the maximum stress is generated under the tip of the tool at the work piece. These load and conditions (parameters) was used to remove the material from the work piece with the help of erosion effect. The vibration force was transferred in to the abrasive slurry due to the vibration these abrasive particles strike with work-piece and the material start erode.

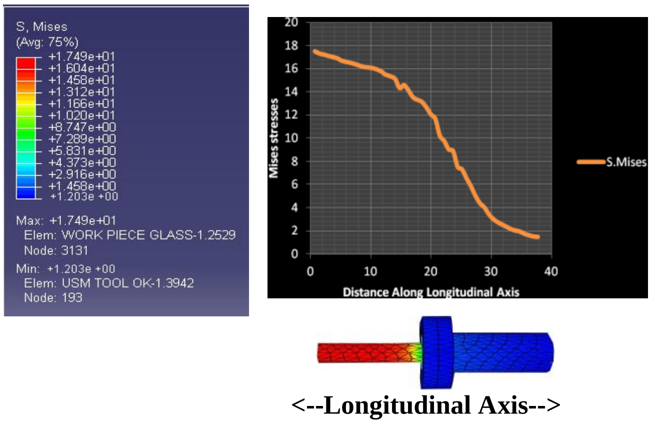

Fig: 4 Present the principal stress in the longitudinal direction and Mises stress for the 30kHz.

It is observed that maximum stress is generated on the tip of the tool, the maximum stress value at the tip of a tool is 17.49 MPa, The value of the stresses is decrease gradually from tip to the end along longitudinal axis. The minimum value of stress is 1.203 MPa at the other end of the tool. In the tool stress diagram different colours show the change in the stress value. For example from the 0.5 mm distance the value is 16.24 MPa it shows with the help of red colour. At the distance 15 mm from the tip of tool the value of stress is 13.85 MPa is shown with the light yellow colour. At distance 25 mm from the tip of tool the value of stress is 8.56 MPa it is shown by the sky-blue colour. The minimum stress value is at 38mm from the tip of the tool the value is 1.25 MPa and it is shown with the blue colour.

The FE analysis the maximum stress location along the longitudinal axis of the ultrasonic tool was predicted by plotting the principal stress in the longitudinal direction or the Mises stress along a path of node along the centre of the tool at the excited natural frequency.

The nodal displacement can also be determined along the same nodal path Fig: 6.8 present the nodal displacement, principal stress in the longitudinal direction and Mises stress for the 30 kHz for work piece Glass.

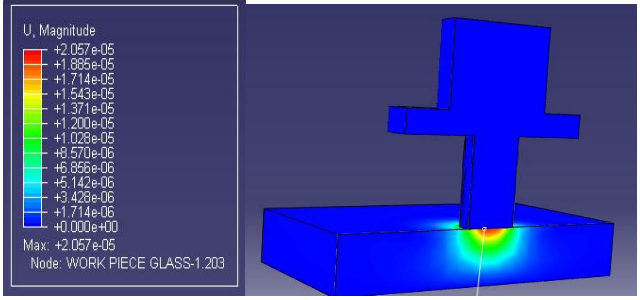

Fig:5 Contour plot of the deformed shape for the work piece Glass

Similarly, the nodal displacement can also be determine along the same nodal path for the work-piece (Glass) is shown in Fig: 6.9 present the nodal displacement, principal stress in the longitudinal direction and Mises stress for the 30 kHz

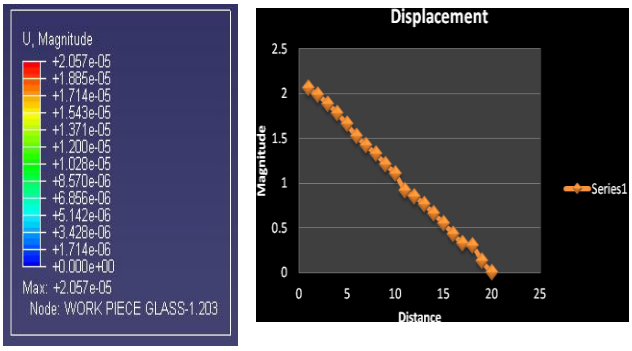

Fig: 6 Present the nodal displacement in the longitudinal direction and Mises stress for the 30kHz

At the just below of the tip of ultrasonic tool the maximum stresses is generate, Because the Ultrasonic tool is vibrate and the maximum vibration is transfer at this point, and this vibration is transfer in to the abrasive particle, when these particles are strike with the work piece the material will remove by erosion, the maximum stresses is generate under the tip of tool is +2.05e-05 (0.00205 MPa).

## CONCLUSIONS

The ultrasonic tool design process has been introduced and explained in detail in this section with an introduction to FEA based ultrasonic tool analysis. The finite element model was developed with an aim to predict the stresses generated, tool deformations and strains under different operating conditions for example: tip diameter, ultrasonic amplitude, cutting orientation, ultrasonic tool material properties. FEA was used to design ultrasonic tool resonant in the longitudinal mode at 30 kHz for use in experimental work.

The theory of the longitudinal vibration of uniform rods used to calculate the tuned length of a 30 kHz uniform alloy steel rod has been discussed. The calculated lengths of the uniform Alloy steel rod were then modelled using the FE modelling package ABAQUS using tetrahedral elements to determine the resonant natural frequency of the longitudinal mode.

A 30 kHz alloy steel tool for experimental process trials was designed using FEA. A defining and submitting a job was performed on the ultrasonic tool from the initial design concept and tuned to the driving frequency of the transducer to resonate in the longitudinal mode of vibration. The tip displacement, maximum stress and its location along the longitudinal axis in the ultrasonic tool was determine using the FE procedure.. The stress results were analysed for the maximum vibration output of the transducers considering a safety factor of 4 during operation to ensure the stress levels did not exceed the yield point of the tool material.

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