DESIGN AND ANALYSIS OF SONOTRODE FOR ULTRASONIC CONSOLIDATION.

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Abstract : Additive manufacturing as an Ultrasonic Consolidation (UC) *has emerge new process of joining and machining of foil material. Due to the unique feature show as tailor made production of component for prototyping fast production with low material wastage. The process has put steps in area of space industries as well as in defense Industries. The key component of the process is ultrasonic Sonotrode so called sonotrode which uses the effect of ultrasound for joining. Proper design of sonotrode play a vital role for proper concentration of ultrasonic energy across work piece surface foil material during joining. The joining is done at temperature lower than melting point which eliminates the heat affected zones. Parameter involved in design are thickness and material of the foil to be joined, material of sonotrode based of foil material and operating frequency. This paper discusses design of different shaped sonotrode such as stepped, exponential and conical for joining of metal. First theoretical design and then based on that design FEA analysis has been done using NX Nastran software. In FEA analysis determination of natural frequency according to the mode shape and then frequency response simulation for different shape and for different material. After the proper simulation of these sonotrode, the final result around the value of 20 kHz appear at which stepped sonotrode gives maximum amplification. FEA analysis shows that maximum amplitude is achieved by the stepped sonotrode.*

1. INTRODUCTION

Rise in demand of energy in industries for production is increases day by day. So, to overcome these demand industries should developed production technologies with low cost and high efficiency [1]. Here, comes the idea of hybrid manufacturing which combines more than one process at a time and save both time and energy with great precision. Ultrasonic Consolidation is one of the hybrid manufacturing process which uses Ultrasonic Additive manufacturing with Milling machining simultaneously to provide Energy Efficient manufacturing [2].

Ultrasonic Consolidation (UC) is combination of two process first ultrasonic additive manufacturing and second is milling machining which makes it a hybrid manufacturing. Ultrasonic additive manufacturing is similar to Ultrasonic welding the only difference is in ultrasonic welding only two layers of metal are joined together while in ultrasonic additive manufacturing more than two layer are joined together up to certain thickness and then it is machined by milling as per required shape and size. Ultrasonic additive manufacturing has come to spearhead as eco-friendly joining method for joining of metals and plastic and it does not require any shielding gases like helium or argon nor it required and additional flux material which are used in conventional welding process or techniques [3].

Ultrasonic additive manufacturing comes with high mechanical joining strength with no electrical resistance between the two-joined material because the two-metal surface are join by diffusion actions removing the impurity and deposited oxide film present on the surface of the metal. Various area of UAM are battery foils, can bottom, cell phones, vacuum glasses and communication devices pats [4].

Main parts of Ultrasonic additive manufacturing are shown in figure 1. It contains mainly four parts that are a) generator b) transducer c) booster and d) sonotrode. The generator amplifies the incoming 50-60 Hz AC electrical supply to 20-40 kHz electrical energy and further the transducer converts this 20 kHz electrical energy into mechanical vibration energy of 20-40 kHz. The booster further amplifies this vibrational amplitude coming from the transducer and send it to the sonotrode and sonotrode transfer this vibrational energy to weld material, which gives a strong joining by forced diffusion at the weld interfaces [3].

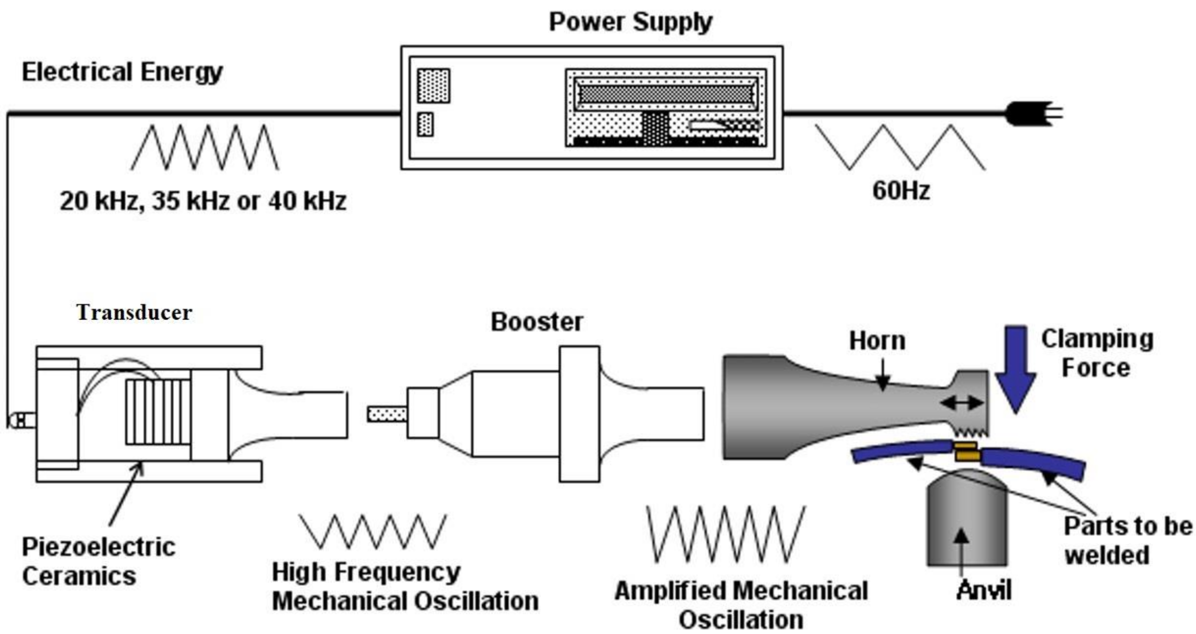


Figure 1: Main Component of Ultrasonic Additive Manufacturing

2. LITERATURE REVIEW

Study of Horn with Aluminium and Stainless steel and their FEM analysis by modal analysis is done by K. H. W. Seah et al [6], it was found that no frequency change occur by adding tool to horn or by making it hollow tube. S. Amini et al [8], had done FEM analysis with horn material as Aluminium and workpiece material as Inconel 718, Al7075 and Ck 45 for Ultrasonic Assisted turning. A dynamic analysis of sonotrode with different shape like conical, stepped and exponential is done by M. NAd [7]. For designing sonotrode the main thing is resonant frequency and after that correct resonant length. Sonotrode performance is depend on amplification factor. Length of sonotrode is defined by governing equation of longitudinal vibrations.

Many researches have been conducted on the ultrasonic welding but only few research have been done on Ultrasonic additive manufacturing. The main advantage of ultrasonic additive manufacturing is that it can joined mostly ductile material like Aluminium alloy which cannot be easily machined by subtractive manufacturing.

In this study, sonotrode are design with different material like Aluminium, Steel and Titanium for different shapes like Stepped, Exponential and conical. After mathematical design they are analyzed using modal analysis using NX Nastran 9.0 software and from analysis the suitable design with specific material and shape is tested.

3. SONOTRODE DESIGN FOR ULTRASONIC ADDITIVE MANUFACTURING

3.1 Process for sonotrode design

Major criteria in Sonotrode design is selection of sonotrode material. It depends on foil material and its thickness. The geometrical dimension, strength and weight also play an important role in sonotrode design. It is preferable that the material of sonotrode must have higher hardness than the foil material. Shape of sonotrode on amount of amplitude amplification are stepped, exponential and conical shapes are used by researchers. Sometime on the process demand the shape of sonotrode can be modified by using more than one shape at same time or mixture of different shape. Selection of shape of sonotrode depends on amount of Amplitude amplification required. As, stepped shape widely used due to its high Amplitude amplification but on other hand as amplification ratio increases stress concentration also increases dur to sudden change in area [5].

The design of sonotrode is most important for the quality and manufacturing. The function of the sonotrode is to magnify the amplitude of mechanical vibration and concentrate the energy on the smaller cross section. The amplitude of an ultrasonic vibrator is 4-10 μm and required amplitude for effective ultrasonic joining has to be more than 10-100 μm. Therefore, incoming amplitude from transducer required additional magnification which is done by sonotrode. The amplification principle of the sonotrode is that the vibration energy through a cross section remains unchanged, therefore smaller the cross section larger the density [6].

3.2 Analytical sonotrode design

Many shapes of sonotrode are being used in the industries. For the same diameter ratio between its both end of the cross-section, the amplitude magnification is in descending order of the stepped shape, exponential shape and conical shape. For circular cross section, the amplitude magnification is equal to ratio of the diameter square for a stepped shape, and for exponential and circular it is equal to diameter ratio and proportional to diameter ratio. From the manufacturing point of view these can be arranged in ascending order, as conical shape, stepped shape and exponential shape respectively. In stepped shape a fillet is used to prevent stress concentration due to abrupt change of cross-section.

For sonotrode design primary step is to calculate the resonance length of the sonotrode from the formula derived from Webster's horn equation, (1) and then after to determine other dimensions and shape of the sonotrode on the basis of Frequency analysis such as modal and natural frequency analysis. The resonance length is equal to half wavelength of the system [7]. Table 1, shows dimension formulation of different shape of sonotrode based on formula (2).

Webster's horn equation

$$\frac{\partial^2 u(x,t)}{\partial x^2} + \frac{\partial u(x,t)}{\partial x}\frac{\partial}{\partial x}(\ln S_x) = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2}, \qquad (1)$$

From Webster's horn equation,

$$C_l = \sqrt{E/_d} \quad , \lambda = \frac{C_l}{F} \qquad (2)$$

Where, C_l = Sound propagation speed (m/s)

E = Young's Modulus of Material (GPa)

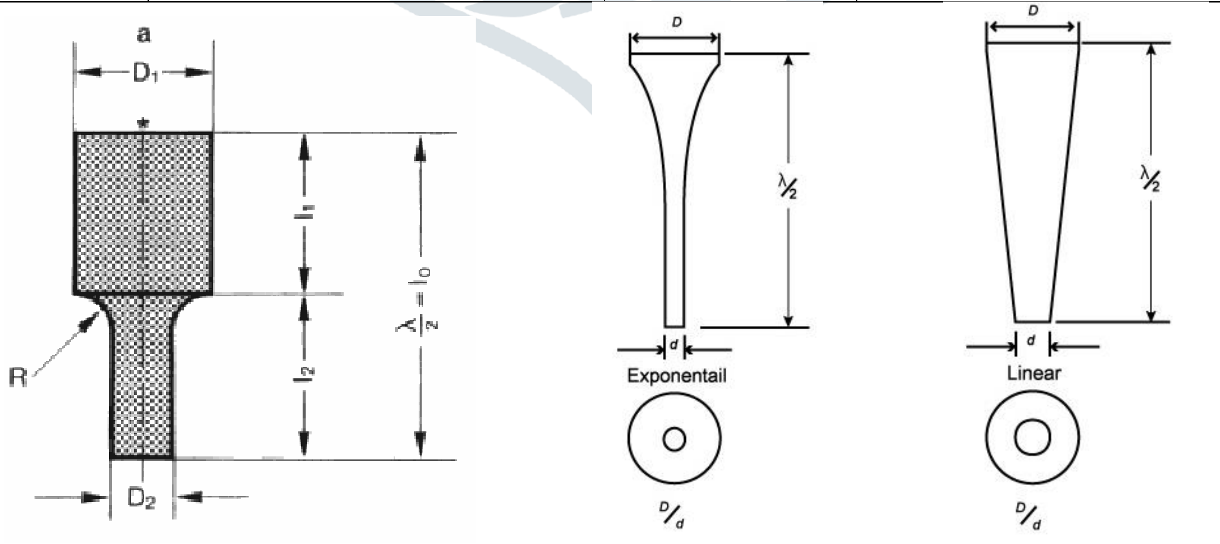
d = Density of material (kg/m^3)

F = Operating frequency (kHz)

λ = wavelength (mm)

Table 1: Dimension formulation on the basis of wave equations

Shape	Length	Amplification ratio	other
Stepped	$L = \frac{\lambda}{2}$	$(\frac{D_1}{D_2})^2$	$L_1 = \frac{1.5}{k_u}$, $L_2 = \frac{1.6}{k_u}$ and $k_u = \frac{2\pi}{\lambda}$
Exponential	$L = \frac{C_l}{2F} \text{ x } \sqrt{1 + (\frac{\ln\frac{D_1}{D_2}}{\pi})^2}$	$\frac{D_1}{D_2}$	
Conical	L = 1.1 x Length of Exponential shape sonotrode	$\frac{D_1}{D_2}$	



(a) (b) (c)

Figure 2: Above figures (a), (b) and (c) shown the stepped, exponential and conical shape of sonotrode with detail nomenclature.

3.3 RESONANCE LENGTH OF SONOTRODE'S

For the resonance length of sonotrode the equation varies from with different shape of sonotrode which is shown in table 1. These equations depend on different parameters shown in table 2 [10,11]. On the basis of parameter shown in table 2 the resonance length of sonotrode shapes with different material are calculated as shown in table 3.

Table 2: Parameters of sonotrode design

Parameter	Symbol	Unit	Parameter	Symbol	Unit
Sound Propagation velocity	C_l	m/s	Input diameter of sonotrode	D_1	mm
Wavelength	λ	mm	Output diameter of sonotrode	D_2	mm
Length	L	mm	Input amplitude of sonotrode	ξ_1	μm
Frequency	F	kHz	Output amplitude of sonotrode	ξ_2	μm
Transformation ratio	K_t				

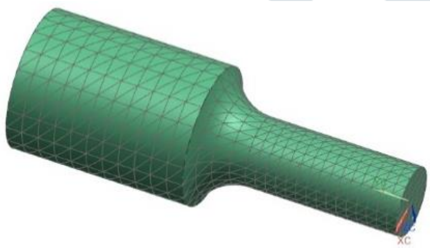
Table 3: Resonance length of Sonotrode for different material for 20 kHz frequency.

Shape and Material	Titanium Ti6Al4V	Aluminium Alloy	Steel
Stepped shape	L = 111.35 mm L_1 = 53.2 mm L_2 = 56.75 mm	L = 109.8 mm L_1 = 52.45 mm L_2 = 56 mm	L = 128 mm L_1 = 61.14 mm L_2 = 65.22 mm
Exponential shape	L = 118 mm	L = 109.8 mm	L = 119.4 mm
Conical Shape	L = 129.8 mm	L = 120.78 mm	L = 131.34 mm

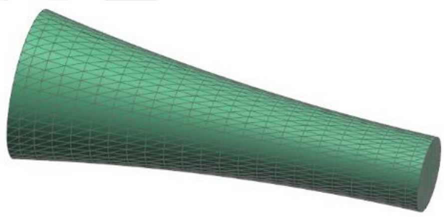
4. FEA ANALYSIS

For prediction of vibration behavior of the sonotrode FEA play vital role in both design and ultrasonic assembly before manufacturing [12] In sonotrode design two analysis required they are modal analysis and Frequency response analysis. From modal analysis the natural frequency of sonotrode is obtained. Modal analysis is primary stage of sonotrode analysis which give its own vibrational frequency and information on limit of use of frequencies to work, help in implementing in terms of time and cost of designing, manufacturing and use of sonotrodes.

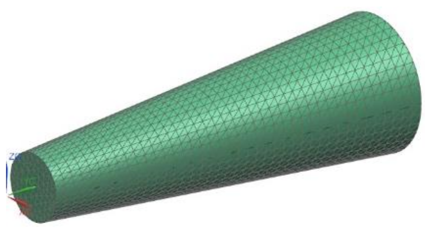
Result obtained from modal analysis are damped free hence the vibration tendency can be specified with tolerances of about 500-600 kHz. Sometime due to material parameter introduction as input in FEA may occur as error.in FEA analysis 3D mesh element is taken in all shape analysis. The 3D mesh for different shape are shown below in figure 3. The table 3 shows the number of Element and Node for different shape and material of sonotrode.



(a) Mesh of Stepped Shape



(b) Mesh of Exponential Shape



(c) Mesh of Conical Shape

Figure 3: Meshing of different shape sonotrode

Table 2: Meshing data of sonotrodes

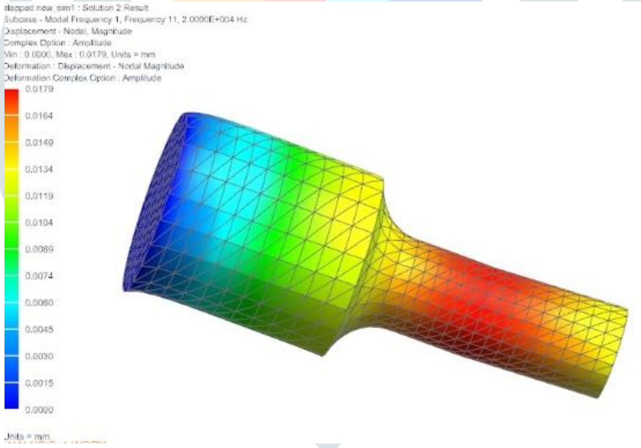
Mesh	Element Family	Material	Shape	Element	Node
3d_mesh	Tetra10	Aluminum_6061	Stepped	3822	6599
3d_mesh	Tetra10	Aluminum_6061	Exponential	6233	10696
3d_mesh	Tetra10	Aluminum_6061	Conical	14523	23212
3d_mesh	Tetra10	Steel Alloy	Stepped	2629	4737
3d_mesh	Tetra10	Steel Alloy	Exponential	7951	13527
3d_mesh	Tetra10	Steel Alloy	Conical	17795	28362
3d_mesh	Tetra10	Titanium_Ti-6AL-4V	Stepped	4370	7511
3d_mesh	Tetra10	Titanium_Ti-6AL-4V	Exponential	7221	12294
3d_mesh	Tetra10	Titanium_Ti-6AL-4V	Conical	15490	24784

After messing of sonotrode the Eigenvalue analysis is done for finding natural frequency and followed by modal frequency response for finding maximum amplitude of the sonotrode. Table 4, shows the detail of solver used for simulation in NX NASTRAN software. Whereas, table 5 show the natural frequency sonotrode which are under operating frequency.

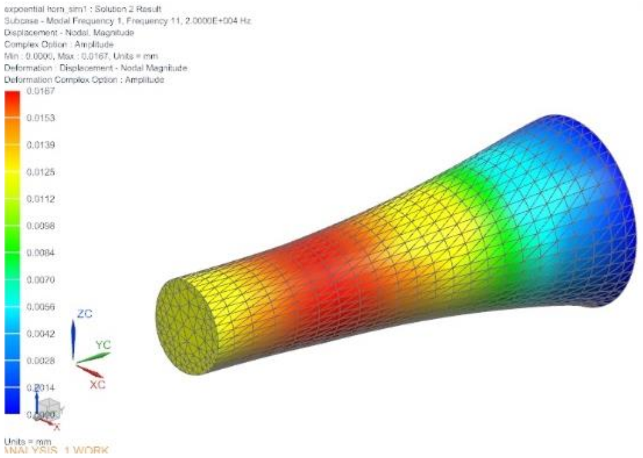
Table 3: Detail of Software

Solver:	NX NASTRAN
Analysis Type:	Structural
Solution Type:	1. SOL 103 Real Eigenvalues
	2. SOL 111 Modal Frequency Response

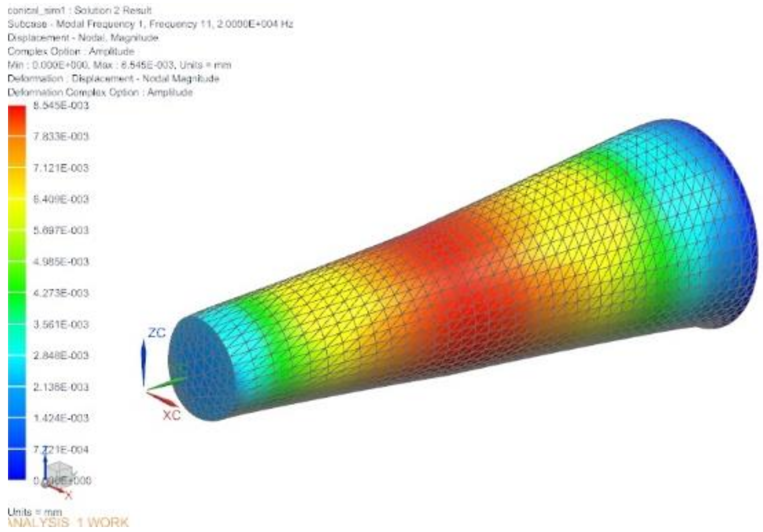
The result of frequency response analysis is shown below. With different material and shape of sonotrodes.



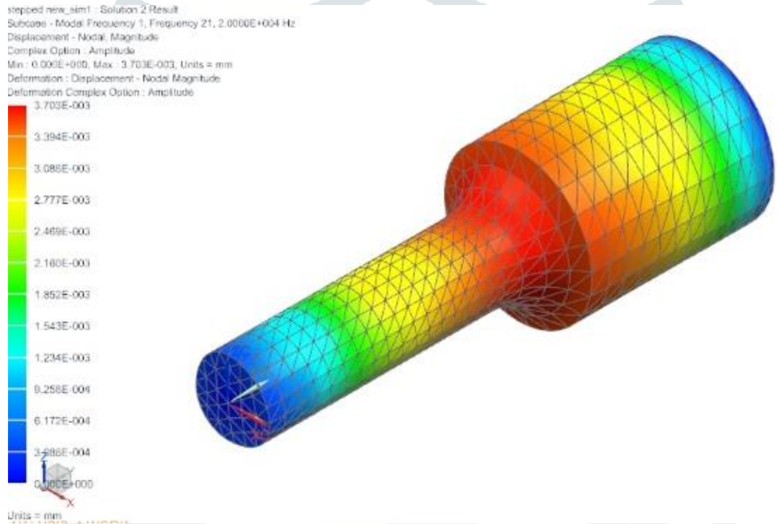
(a) Aluminium stepped sonotrode



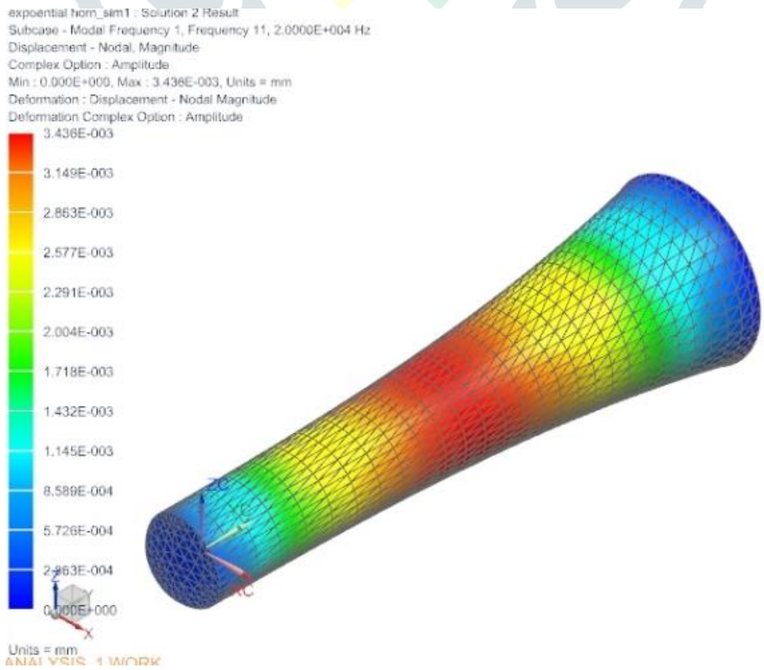
(b) Aluminium Exponential Sonotrode



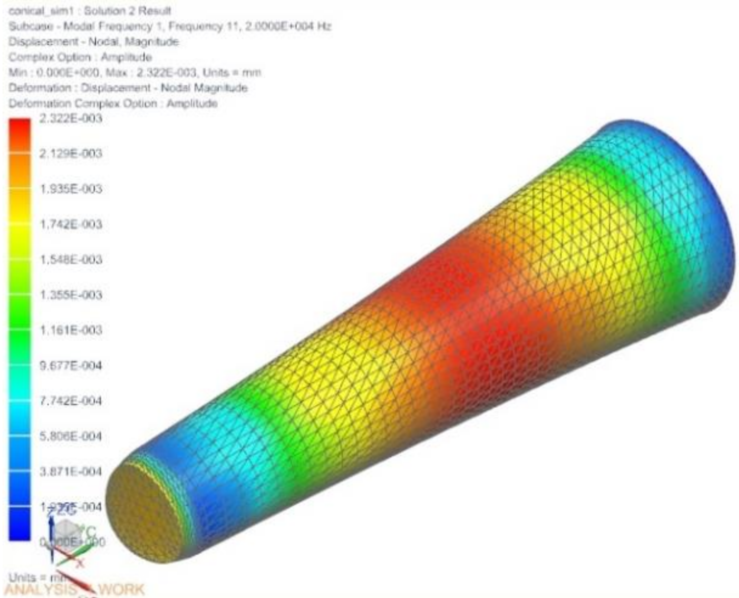
(a) Aluminium Conical sonotrode



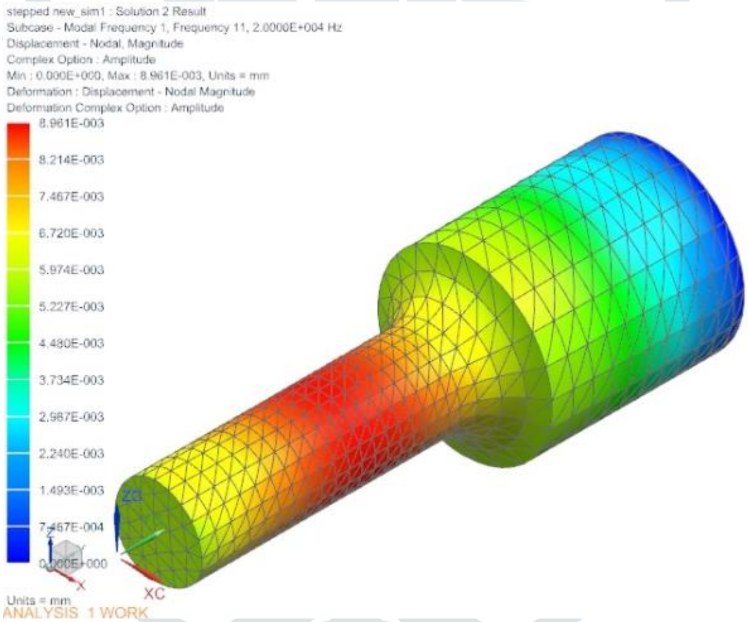
(d) Steel Alloy Stepped Sonotrode



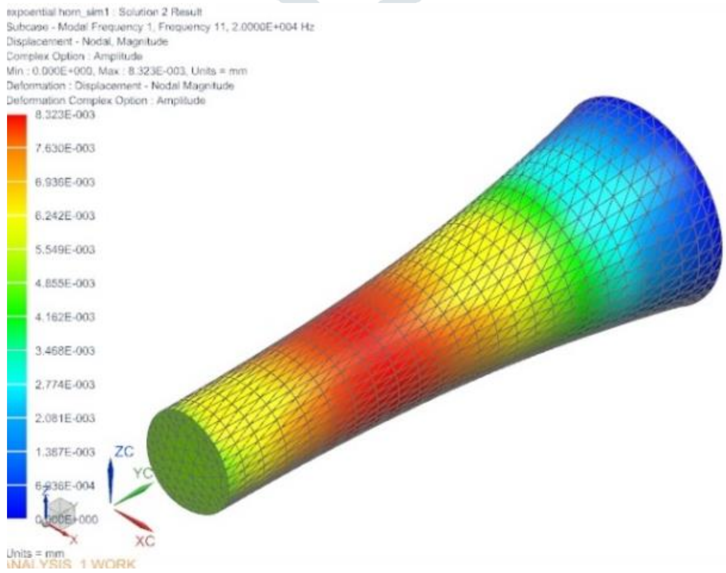
(e) Steel Exponential Sonotrode



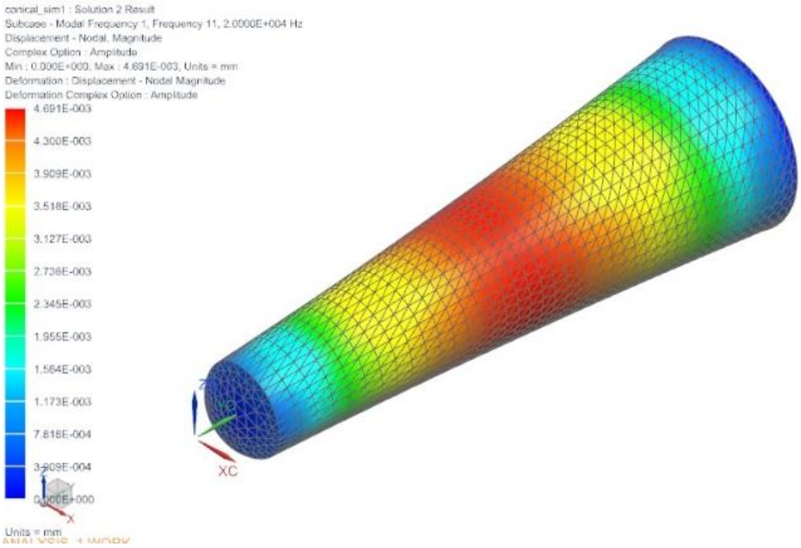
(f) Steel Conical sonotrode



(g) Titanium Stepped sonotrode



(h) Titanium Exponential sonotrode



(i) Titanium Conical Sonotrode

Figure 4: Frequency response of sonotrode with different shape and material

Table 4: Natural frequency of Sonotrodes

Material \ Shape	Stepped	Exponential	Conical
Aluminum_6061	6795	7759	8163
Steel Alloy	5539	5288	5576
Titanium_Ti-6AL-4V	5399	6882	7442

5. RESULT

From above FEA analysis of different shape and for different material, the maximum displacement is achieved in Stepped shape sonotrode due to sudden change in shape. For the material most preferable material is Titanium, since it is hardest among all with low density. But it is very costly so next to line is Steel Alloy which can be used as sonotrode material shown in figure 5. The following graph show maximum displacement of stepped sonotrode for steel material as shown in figure 6.

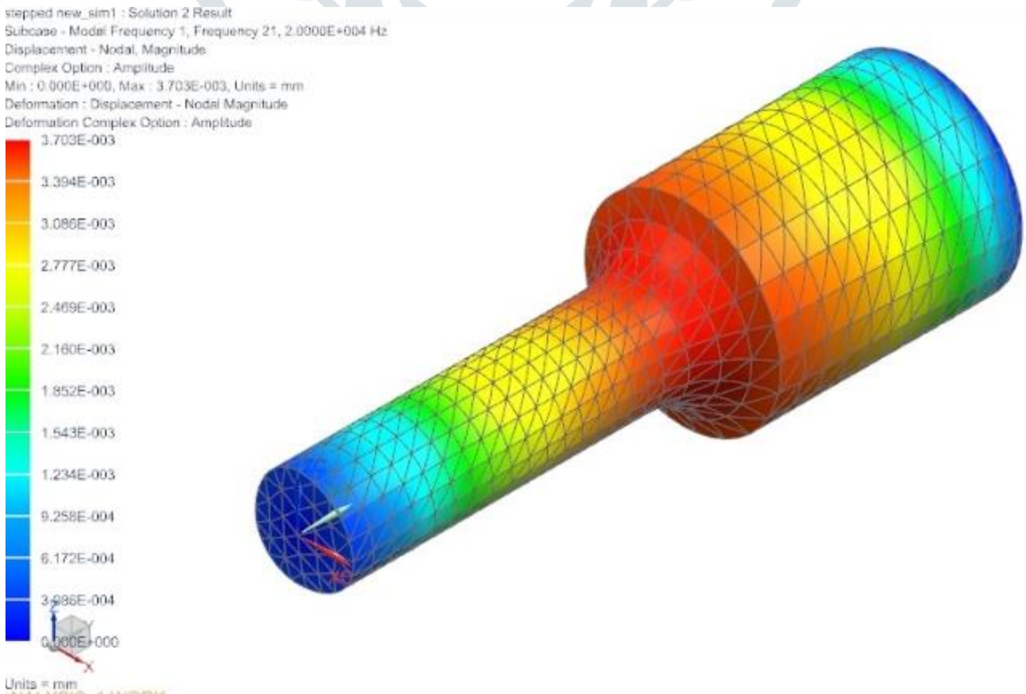


Figure 5: Frequency Response of Steel Stepped Shape Sonotrode

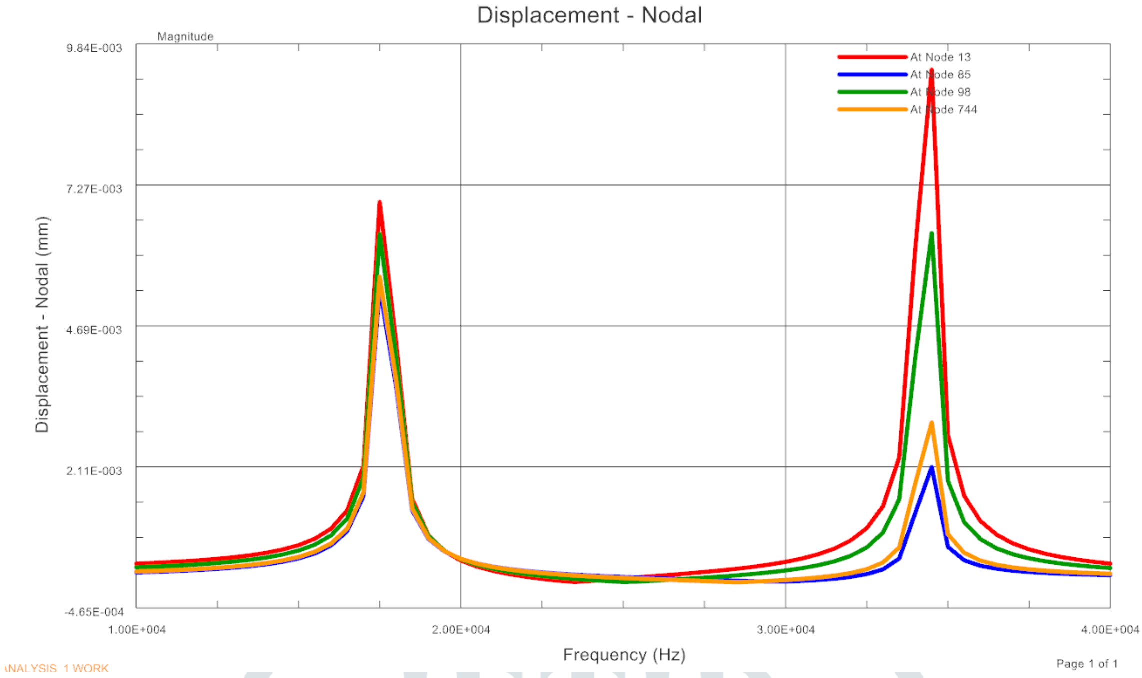


Figure 6: Displacement Vs Frequency of Steel Steeped shape Sonotrode

6. CONCLUSION

The paper presents the design of a sonotrode used in joining or joining of sheet material by using integrated CAD-CAE software. There are number of parameter are taken into consideration for the effectiveness of energy transfer in the joining area. Among these parameters the important factor is design of sonotrode. Maximum efficiency can be achieved by making sonotrode in resonance state with transducer. Determination of resonant frequency and wavelength is required for sonotrode design. FEA analysis is most important stage of element design that makes ultrasonic processing systems. Dynamic Characteristics of the sonotrode in the state of resonance were studied as function of geometrical shape and dimension. Analyzing their own vibration modes, gives information on the use of frequencies to work with positive implication in term of time and cost of designing sonotrode.

The sonotrode was designed for a frequency of 20 kHz FEA analysis confirms that the sonotrode is vibrated longitudinally close to 20 kHz, which insure uniformity of vibration amplitude of the sonotrode to work surface.

7. ACKNOWLEDGMENT

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8. REFERENCES

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