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BLOCK HORN DESIGN AND ANALYSIS FOR ULTRASONIC PLASTIC WELDING

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ABSTRACT

Ultrasonic horns are tuned components designed to vibrate in a longitudinal mode at ultrasonic frequencies. Reliable performance of such horns is normally associated with the amplitude of vibration, uniformity of vibration amplitude at the working surface and the avoidance of modal participation by non-tuned modes at the operating frequency. In order to maximise vibration amplitude uniformity, standard slotting configurations are included in the horn design. The slot position in the horn is optimised using finite element method and Taguchi design of experiments. Modal and harmonic analysis of the horn is done using ANSYS software package. It is observed that slotted block horn with optimised slot position vibrates in longitudinal mode with uniform displacement amplitude across the face of the sonotrode which is desirable

Keywords: *Ultrasonic plastic Welding, Block horn design and Optimization.*

1. Introduction

Use of engineering plastics in structural and non structural applications is increasing rapidly. Among the many processes available for joining of thermoplastics, ultrasonic welding (USW) is one of the preferred processes. Ultrasonic welding is gaining popularity as the process is fast and efficient with weld times being less than a second. Ultrasonic welding has got applications in pharmaceutical, automobile, medical, consumer appliances etc.

The ultrasonic plastic welding machine consists of power supply (generator), transducer, booster, horn (sonotrode), control system and fixture to hold the components to be welded. The 60 Hz electrical power supply will be converted to high frequency electrical power supply and is fed to the transducer. The piezoelectric transducer will convert the high frequency electrical power supply into mechanical vibrations. The booster then transforms the vibration amplitude delivered by the transducer to the value required by the horn. The horn further amplifies the ultrasonic vibration and then transmits to the components being welded.

In USW, the parts to be welded are held together under pressure and are then subjected to ultrasonic vibrations usually 20 KHz. The resulting alternating stresses generate heat in the plastic and by providing energy directors in the component to be welded, the heat generated can be localised at the joint where heat generation is by inter- molecular friction.

The design and manufacture of sonotrode is very important for the ultrasonic welding to take place. The material used for manufacturing sonotrode should have high fatigue strength and low acoustic losses.

Block horns must have longitudinal slots in order to reduce the transverse coupling due to the Poisson effect. Without such slots the horn will either have very uneven amplitude across the face or may even resonate in a non axial manner. Although slots help to improve the face amplitude uniformity, additional horn refinements are often necessary to further improve the uniformity, depending on the particular application. Unfortunately, the required slots can introduce additional problems, although these can be reduced through careful design.

2. Literature Review

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 elements of the ultrasonic system – sonotrode must have the required dynamic properties, which must be determined already in design phase.

Nad [1] had carried out horn design for ultrasonic machining technologies. He analysed the dynamic properties of various horn designs like cylindrical, tapered and exponential. The effect of sonotrode dimensions on natural frequencies and mode shape is analysed by using finite element method. The importance of proper design of sonotrode shape is emphasised. The dynamical properties of different geometrical shapes of ultrasonic horns are presented.

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Dependence of fundamental modal properties (natural frequencies, mode shapes) of various sonotrode shapes for various geometrical parameters is analyzed. Modal analyses of the models are determined by the numerical simulation using finite element method (FEM) design procedures. 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 comparable parameters like modal frequencies, slenderness ratio and amplification factors of the various sonotrode shapes were studied and presented leading to the selection of a suitable shape and corresponding geometrical dimensions of the sonotrode with required dynamical properties.

The vibration performance of ultrasonic block horns has been investigated by Cardoni and Lucas [2]. Block rectangular horns are large components designed to vibrate in longitudinal mode at low frequency, and their reliable performance is normally associated with amplitude of vibration, uniformity of amplitude and avoidance of modal participation by non- tuned modes at operating frequency. In order to maximise vibration amplitude uniformity, standard slotting configurations was included in the horn design. The role of additional fine slots and castellation was studied with reference to two distinct ultrasonic applications involving a similar block horn. The modes were classified using experimental data from 3D laser Doppler vibrometer measurements and finite element analysis. They suggested that block horn must incorporate long slots to ensure pure longitudinal motion of the blades and fine slots or castellation in the block horns can provide an effective design solution by improving the uniformity of amplitude.

A new horn for high displacement amplification was developed by Wang et al [3]. The design is based on cubic Bezier curve. The horn profile was optimised using a nondominated sorting genetic algorithm and finite element analysis. Performance of the horn was evaluated by experiments. Bezier horn is able to absorb more electrical power since its electrical impedance at the working frequency is low. Due to this the displacement amplitude of Bezier horn is 71% higher than the traditional catenoidal horn with the same length and end diameters. Moreover the maximum Von Mises stress of the Bezier horn is much lower than that of the catenoidal horn. Therefore Bezier horn is suitable for the applications where high displacement amplification and low stress concentration are required.

The modal analysis of an ultrasonic block horn using electronic speckle pattern interferometry (ESPI) to measure three mutually orthogonal components of surface vibration response was presented by Graham et al. [4]. Slotted block horns are used in many high power ultrasonic tools, to achieve a uniform vibration amplitude across a wide output face. Finite element analysis is an established method for designing tuned block horns and for the prediction and design of horns with a well isolated tuned operating mode.

The computational and experimental modelling of the vibration performance of five different horn profiles: Cylindrical, Gaussian, Catenoidal, Stepped and Bezier were carried out by Rooparani and Rudramoorthy [5].It was observed that the stepped and Bezier horns have high displacement amplitude and a corresponding higher temperature during welding. Tensile testing of the welded specimens showed that a higher interface temperature leads to stronger welded joints. The Von Mises stress of the stepped horn and the Bezier horn are more than the other profile horns. The stepped and Bezier horn profile is found suitable for welding semi crystalline polymers and for welding components in the far field owing to its high displacement amplitude at the tip/face.

Sherrit et al. [6] presented a variety of novel horn designs which overcome some of the limitations in usual design procedure. The horn length primarily determines the resonance frequency. In many applications it would be useful to reduce the resonance frequency. However, this would require device lengths of the order of fraction of a meter which may be impractical. In addition, manufacturing a horn requires the turning down of stock material from larger outer diameter to the horn tip diameter which is both time consuming and wasteful. They suggested a new horn design with reduced overall length of the resonator but maintain or increase the acoustic length.

Novel high-frequency ultrasonic transducers have been developed by Wang et al [7] for microelectronics packaging. By use of finite element method (FEM), the dynamic characteristics of components are investigated. The resonance frequency, vibration displacement nodes and rule of ultrasonic energy transmission are acquired by making modal and harmonic analysis. Through optimum design by considering the piezoelectric effect, the dimensions of ultrasonic transducer have been gained.

Design of a rotary ultrasonic milling tool using finite element method (FEM) was done by Kuo [8]. The harmonic piezoelectric vibrations of the ultrasonic milling system are simulated by FEM to shed light on the frequency and amplitude of the vibration as well as stress distribution. Results of the study show that the use of FEM in dynamic simulation of ultrasonic milling is feasible. In addition, increase in tool length will result in increase in mass and resonance amplitude but decrease in resonance frequency.

From the literature review it is clear that proper design and analysis of horn is very important for the ultrasonic welding. Numerical method using finite element analysis is widely used for the design and analysis of horn. Although the groove and slot have been widely utilized for horn design to achieve high uniformity, their effects on displacement uniformity have not analyzed thoroughly. In this work, slotted block horn is designed in a systematic way to increase the displacement uniformity, and the effects of the slot on uniformity are analyzed using finite element method and the Taguchi design of experiments (DOE).

3. Design of Sonotrode

The component which has to be welded has been selected first. The photograph of the component to be welded is shown in the figure 1.

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 material for sonotrode is selected as Aluminium. For a machine frequency 'f' of 20 KHz, the half wave length 'λ/2' is found to be 130 mm. The properties of Aluminium and velocity of sound 'C' are given in table 1.

Fig 1. Component to be welded

Table 1: Properties of Aluminium alloy

Property	Value
Density (ρ)	$2.74*10^3$ Kg/m^3
Young's modulus (E)	74.5 GPa
Poisson's ratio (μ)	0.33
Velocity of sound C= √E/ρ	5215 m/s
Wavelength λ= c/f	260 mm

The breadth and width of the horn is fixed as 118 mm and 65 mm according to the dimensions of the component to be welded. Initially horn is designed without slot and finite element analysis is done in ANSYS. It was observed that without slot, the horn will vibrate in non longitudinal mode as shown in figure 2.Then the slotted block horn is modelled in Pro Engineer and it is shown in figure 3.

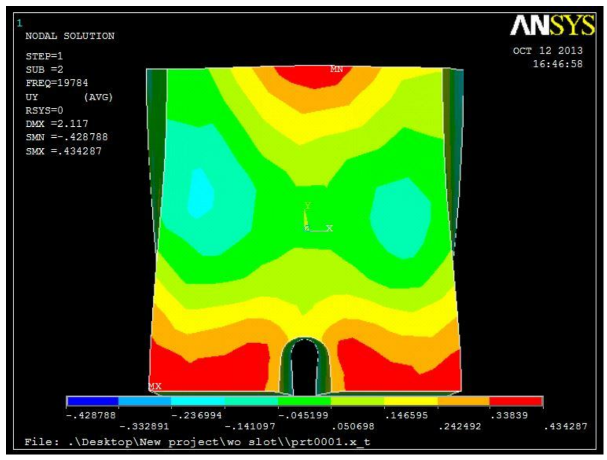

Fig 2. Non longitudinal mode of vlbration for horn design without slot

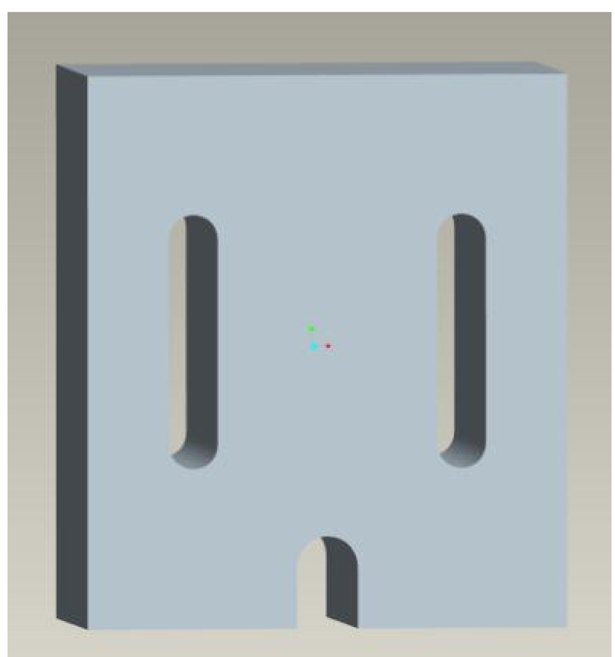

Fig 3. 3D model of slotted horn

4. Finite Element Analysis of the Horn

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 elements of the ultrasonic system – sonotrode must have the required dynamic properties, which must be determined already in design phase. Numerical method using finite element analysis is widely used for the design and analysis of horn. Finite element analysis (FEA) is a computer-based method for analyzing and improving resonator performance. In FEA, the resonator is simulated as a computer model. The computer simulation model consists of a large number of small elements that represent (approximately) the shape of the resonator. Each element can be described mathematically by a set of equations. The solution to this set of equations yields a prediction of the resonator's performance- i.e., the natural frequencies at which the resonator will vibrate and the amplitudes and stresses associated with each of these frequencies. After the performance has been predicted, the resonator's dimensions or materials can be changed within the FEA model in order to improve the performance.

4.1 Modal Analysis

Modal analysis is an important tool in the analysis, diagnosis, design and control of vibration. The 3D model of horn profiles are modelled in Pro Engineer and are saved as parasolid (xt) file. Then it is imported to ANSYS for modal analysis. The model was meshed using Solid tetra 10 node 187 element with a fine mesh size of 3 and material properties (Table 1) are specified. Mode extraction is carried out in the frequency range 17–21 KHz using Block Lanchoz option. Five mode shapes are extracted in the given frequency range with pre stress results turned on. Two or more modes, close to the axial mode will result in modal coupling, which reduces the efficiency of the horn and is to be avoided. The longitudinal or axial mode is the required mode shape.

4.2 Harmonic Analysis

Harmonic analysis of horn is to determine the displacement and stresses experienced by the horn in the given frequency range. The displacement amplitude available at the transducer end is 15 µm (specified by the equipment manufacturer). The booster amplifies it to 23.4 µm. The displacement at the booster end is given as the input or the forcing function to the horn for performing the harmonic analysis. The sonotrode resonant frequency corresponding to the longitudinal mode of vibration obtained from the modal analysis is given as the frequency range. Since the horn is fastened to the horn booster its lateral and rotational movement is constrained and only longitudinal or axial movement is allowed. The axial movement of the horn is responsible for the welding of the components. For a given machine frequency and horn geometry the maximum amplitude available at the horn end is determined. In the present study it is assumed that whatever amplitude is produced by the horn is available for welding. How much of this amplitude is utilized for welding depends on the material being welded and the weld configuration (near or far welding). The nodal solutions 'displacement' and 'stresses' are obtained as the post processor results.

The modal and harmonic analysis were done in ANSYS and different mode shapes are obtained. It was observed that at some frequencies the horn is vibrating in non longitudinal mode even if the slots are provided as shown in figure 4. But at a particular frequency the horn is vibrating in longitudinal mode, even though the vibration amplitude is not uniform across the face of the sonotrode as shown in figure 5.

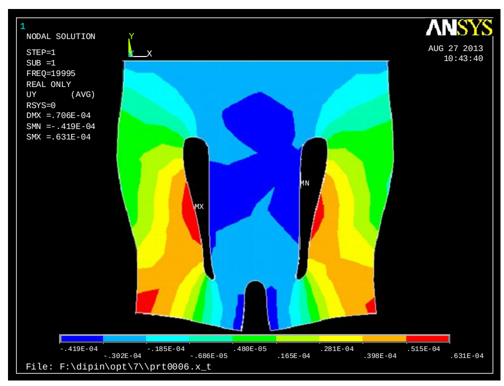

Fig 4. Non longitudinal mode of vibration

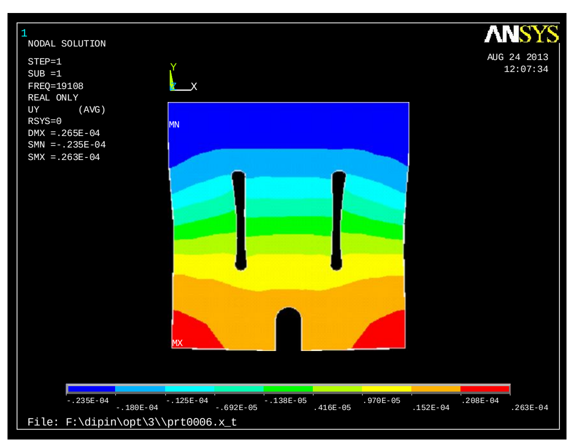

Fig 5. Longitudinal mode of vibration wih non uniform displacement amplitude

5. Optimization of Slot Position

It was observed that by providing slots in the horn design longitudinal mode of vibration can be obtained which is desirable. But in order to have uniform displacement amplitude across the face of the sonotrode optimisation of slot position is required.

For the optimisation of slot position the design variables are taken as X_1, X_2, X_3, X_4 and X_5 as shown in figure 6. Optimisation was done in Minitab software using Taguchi's method. The problem is designed as 5 variables and 2 levels. The values of two levels assigned for five variables are given in table 2.

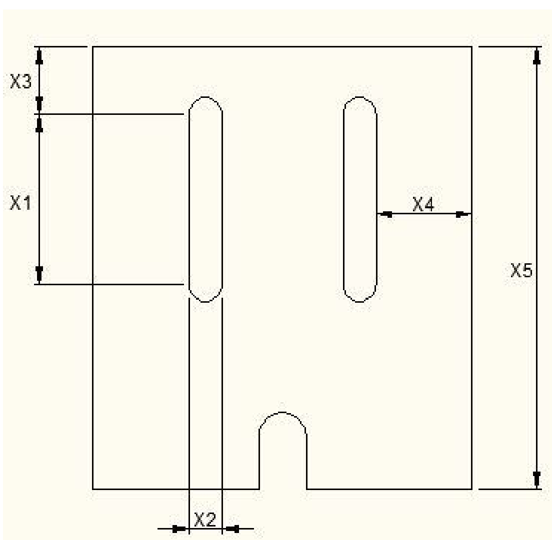

Fig 6. Design Variables

Table 2: Design variables and corresponding levels

Design Variables	Levels
X_1	50-60 mm
X_2	8- 12 mm
X_3	10- 40 mm
X_4	20-30 mm
X_5	125-135 mm

The L12 array is selected and modelling and finite element analysis was done for the 12 combinations. From the finite element analysis the resonant frequency and displacement at the end of sonotrode are obtained. Table 3 shows the L12 orthogonal array design. Then the design variables are plotted against displacement and frequency as shown in figures 7 and 8.

Table 3: L12 Orthogonal array Design

X_1	X_2	X_3	X_4	X_5
50	8	10	20	125
50	8	10	20	125
50	8	40	30	135
50	12	10	30	135
50	12	40	20	135
50	12	40	30	125
60	8	40	30	125
60	8	40	20	135
60	8	10	30	135
60	12	40	20	125
60	12	10	30	125
60	12	10	20	135

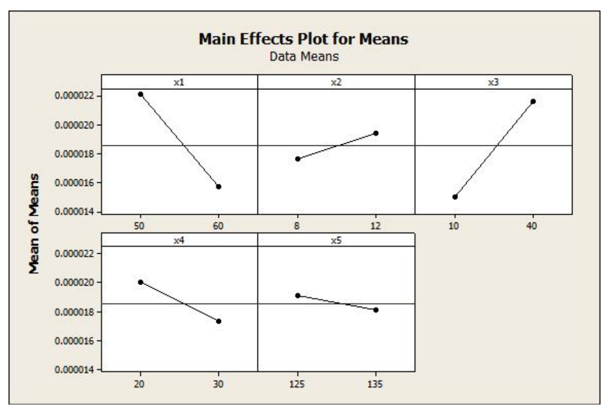

Fig 7. Design variables plotted against displacement

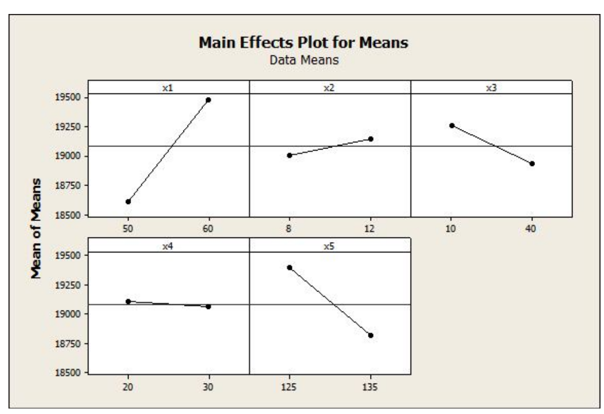

Fig 8. Design variables plotted against frequency

Figures 7 and 8 illustrates the main effects plot for means and delta values can be calculated by subtracting lowest mean value from the highest. A higher delta value for a parameter indicates that it affects the results more significantly than the other parameters. From the graph of design variables plotted against displacement it is observed that X_1 and X_3 are the major factors affecting the displacement. Because the displacement is influenced most significantly by the factors X_1 and X_3, it appears that the uniformity can be controlled effectively by adjusting the dimensions of X_1 and X_3. By varying these factors and keeping other variables as constant, optimization of slot position was done by trial and error method.

The optimum dimensions of the slot which gives high uniform displacement are given in table 4. The result obtained from the harmonic analysis of the horn with optimized slot position is shown in figure 9. It can be seen that the horn is vibrating in longitudinal mode with uniform displacement amplitude across the face of the sonotrode.

Table 4: Optimized values of slot dimensions

X_1 (mm)	X_2 (mm)	X_3 (mm)	X_4 (mm)	X_5 (mm)
50	12	40	20	135

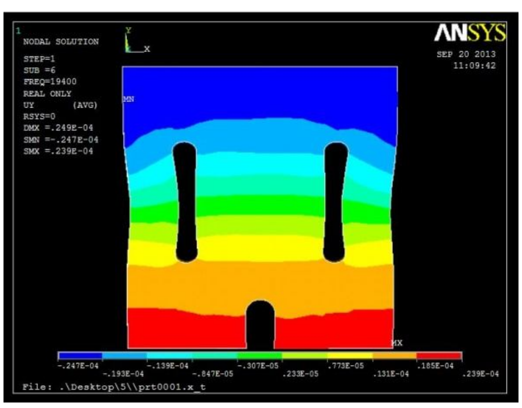

Fig 9. Longitudinal mode of vibration with uniform displacement amplitude

6. Conclusion

The design and manufacture of sonotrode is very important for the ultrasonic welding to take place. For large sized horns in order to have uniform amplitude across the face longitudinal slots are to be provided. Without such slots the horn will either have very uneven amplitude across the face or may even resonate in a non axial manner. Although slots help to improve the face amplitude uniformity, additional horn refinements are often necessary to further improve the uniformity, depending on the particular application. Optimization of slot position can be done by design of experiments. Optimising the slot position such that only the longitudinal mode is available in the given frequency range is the key to a successful horn design.

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