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Design and Numerical Analysis of Rectangular Sonotrode for Ultrasonic Welding

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Abstract

Ultrasonic welding is a fast, clean and high energy process, no flux or filler metal is required, longer tool life and greater efficiency of a weld can be achieved in just a few seconds. Limited length and thickness of weld are the main drawbacks in this process. Welding of large length and thickness materials leads the ultrasonic welding applications unlimited. The design of the components like booster and sonotrode or horn in ultrasonic welding plays a vital role to improve the length and thickness of the welds by generating uniform amplitudes. In the present work, an ultrasonic sonotrode is designed to improve the weld length with suitable uniform amplitudes on the weld bed surface. The design of sonotrode is significantly difficult to obtain the uniform amplitudes at the large weld length. Here, rectangular sonotrode with multiple slots is designed based on theoretical calculations and numerical analysis is performed to obtain the maximum possible weld lengths with uniform amplitudes at a known operating frequency. The finite element method is used to analyze the actual resonating frequency and amplitude distribution of the sonotrode and obtained the maximum weld length as 400 mm for 15 kHz frequency with 3 slots.

Keywords: Length of the weld, Magnification factor, Numerical analysis, Rectangular sonotrode, Resonating frequency, Ultrasonic welding

Introduction

Ultrasonic welding is a solid-state bonding process carried out at an ambient temperature, without the aid of electrodes or fluxes, filler material. In ultrasonic welding, the metals or thermoplastics to be welded are placed between 2 welding tips or sonotrodes, representing a driving sonotrode and a reflecting sonotrode or acoustically dead base (fixture), respectively, and are clamped under a static pressure while ultrasonic energy is induced through the driving sonotrode for a relatively short interval of time. This arrangement induces elastic vibratory energy into the weld area with the result that a weld or bond is formed between the metal or thermoplastics that are to be welded.

Typically, ultrasonic welding is classified into 2 types according to its applications, one is ultrasonic plastic welding in which vibration is perpendicular to the weld surface and another is ultrasonic metal welding in this case the vibration is parallel to the weld surface. The ultrasonic welding machine consists of 5 standard components: (a) generator (b) transducer (c) booster (d) sonotrode or horn and (e) anvil or fixture, which are shown in **Figure 1**.

A piezoelectric transducer is a primary component in ultrasonic welding which converts electrical energy to mechanical vibration which is then induced through the booster. The booster is, mostly a tapered, cylindrical device used to amplify and transform the vibration amplitude generated by the transducer to the sonotrode. Further, the sonotrode amplifies and transmits, the ultrasonic vibrations received from the booster to the components to be welded, because of the maximum amplitude needed at the sonotrode tip for welding. It can be achieved by reducing the cross-section from the top surface of the sonotrode where the booster is attached to the tip or free end of the sonotrode as depicted in **Figure 1**. As exceptionally high amplitudes in the welding of plastics are essential, also stresses on the sonotrode is significant. Therefore, while designing a sonotrode a balance between the requirement of high amplitude and low stresses is to be considered.

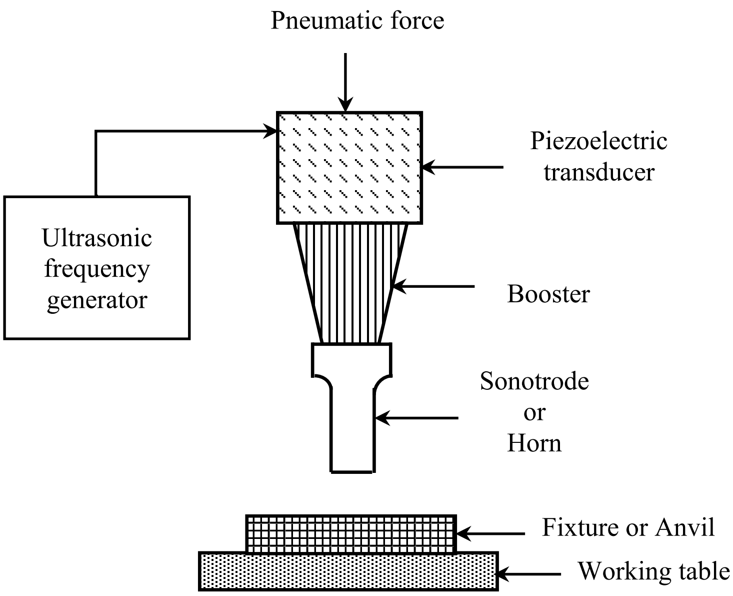

Figure 1 The schematic diagram for ultrasonic plastic welding.

The sonotrode is generally either a solid cylindrical metal rod or rectangular block with a regular or variable, longitudinal, or transverse cross-section in shape. The length of the sonotrode depends on the frequency, wavelength, speed of propagation of ultrasound of the material. The maximum achievable amplitude of ultrasonic vibration depends mainly on the properties of the material and the shape of the sonotrode. In practice, the sonotrodes are made of titanium, stainless steel, and aluminum alloys or powdered metals. The most common sonotrode profiles are stepped cylindrical, exponential, Gaussian, and Bezier. Based on the fundamentals of the ultrasonic welding process, the design and analysis of horns follow a design procedure that includes a selection of material, frequency, determination of the sound propagation velocity in the selected material, calculation of the theoretical dimensions [1-3]. Roopa Rani and Rudramoorthy [4] fabricated 5 different aluminum horn profiles, tested and tuned to the operating frequency. Experimentally proved that the parts welded by Bezier horn produce 3 times stronger joint than Gaussian horn and 1.5 times stronger joint than Catenoidal sonotrode. Similarly, ultrasonic plastic welding conical sonotrodes offer better performance than other sonotrode profiles. In [5,6] it is experimentally estimated that for 20 kHz and 40 kHz horns the lower the frequency higher the weldability. The shape optimization of acoustic horns is performed using metaheuristic algorithms [7], but in which mesh size and geometry smoothing techniques are not considered. These 2 techniques play a vital role in the horn design and it shows an impact on the welding strength of the specimens. Lin *et al.* [8] proposed and studied the performance of a longitudinal step-type ultrasonic horn with the adjustable location of the piezoelectric stack. Grabalosa *et al.* [9] studied the effects of dimensions and wear on its performance of a stepped horn. The optimized dimensions of the horn dimensions are tabulated for an operating frequency of 30 kHz ± 250 Hz. A regressive work published on the design and analysis of horns [10-16] . Kumar *et al.* [17] carried out an analysis of slotted block sonotrode for maximizing vibration amplitude uniformity. It is identified that block sonotrodes with longitudinal slots reduces the transverse coupling and achieves uniform high amplitude at the welding face of the rectangular sonotrode. A method to obtain uniform amplitudes at the working surface of the stepped wide-blade sonotrode is presented in [18] for 15 kHz frequency and concluded that the uniformity of amplitude depends on the change in the shape of the sonotrode. Hung *et al.* [19] developed an optimization procedure for making ultrasonic sonotrodes for plastic welding. The sonotrodes are fabricated from the obtained optimization procedure and experimentally verified and compared with original sonotrodes. A rectangular sonotrode can be used in various applications ranging from thermoforming to abrasive polishing process to improvise the conventional processes [20-22].

Very few researchers have been studied the effect of dimensions and influence of the number of slots on rectangular horns in terms of its performance and uniform amplitude [17,23,24]. From the literature survey, cylindrical sonotrodes in ultrasonic welding offer a small weld pool i.e., spot welding. To compensate for the limited applications of cylindrical sonotrodes, rectangular sonotrodes are designed.

It helps in obtaining a continuous weld pool and larger weld areas. Very recently, a composite horn with the combination of conical and cylindrical shape is considered in [25], this composite shape forms a quasi-periodic phononic crystal structure. This structure improves the uniformity for the sonotrode amplitude distribution and gains to increase the weld surface at the end of the sonotrode. The general trend observed in ultrasonic welding is that the lengths and areas of weld decrease with increasing frequency of the sound. Also, at higher frequencies, it becomes difficult to balance the setup and operate the welding process due to the increased vibration. With increased frequencies, the amplitudes of the vibration also increase, due to which the weldability of the ultrasonic set up also diminishes. Hence, at 15 kHz frequency, the weldability of the ultrasound is greater and thus one can obtain greater lengths of the weld. At 15 kHz, the amplitude of vibration is also lesser and therefore the welding operation can be carried out with ease and efficiency. The welding time at this frequency ranges within a fraction of seconds and the weld obtained is neat, clean and strong. In the present paper, the design and analysis of rectangular sonotrode are considered. The effect of change in dimensions of the sonotrode at an operating frequency of 15 kHz is analyzed.

Materials and methods

Materials

The design of the sonotrode depends on the material of the sonotrode, frequency of the ultrasonic machine, size, shape, and material of the parts to be welded. The designed rectangular sonotrode must resonate at a specified ultrasonic frequency; its design parameters must be determined to satisfy the desirable vibration characteristics. The schematic diagram of the rectangular sonotrode is shown in **Figure 2**.

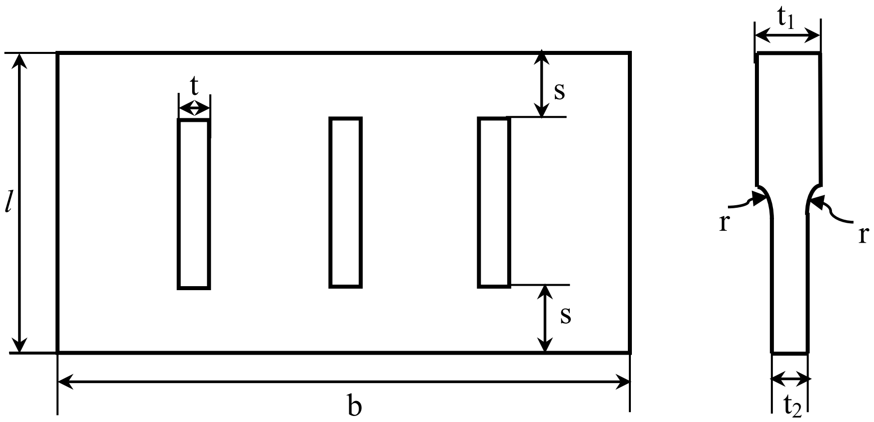

Figure 2 Schematic diagram of rectangular sonotrode.

The geometric parameters of the sonotrode which are given in **Figure 2** are given below:
l = Length of the sonotrode
b = Width of the sonotrode or length of the weld
t_1 = Upper surface thickness of the sonotrode
t_2 = Lower surface thickness of the sonotrode
t = Thickness of the slot
s = Distance of slot from the top end of the sonotrode
r = Fillet radius at the step

Theoretical calculations

In the present work, an aluminum alloy (Al-6061-T6) is considered. The material properties like density and Young's modulus of Al-6061-T6 alloy are 2700 kg/m^3 and 70 GPa, respectively. The length of the acoustic sonotrode is considered as half-wavelength of the resonant frequency [1].

$$l = \frac{\lambda}{2} \tag{1}$$

here,

$$\lambda = \frac{c}{f}$$

The wave velocity (c) of solid in terms of density and Young's modulus is [1]:

$$c = \sqrt{\frac{\mathrm{E}}{\rho}} \tag{2}$$

here,

$$c = \sqrt{\frac{70 \times 10^9}{2700}} = 5091.75 \text{ m/s}$$

$f = 15$ kHz (Assumed)

From Eq. (2);

$$\lambda = \frac{5091.75}{15000} = 0.33945 = 339.45 \text{ mm}$$

therefore, $l = \dfrac{339.45}{2} = 169.72 \cong 170$ mm

The length of the sonotrode can be related to the number of slots in the sonotrode by using the following relation (Derks, P.L.L.M., 1984).

$$l = \frac{c}{2f} + 2\mathrm{s} - \left(\frac{2}{\mathrm{k}}\right)\tan^{-1}\left\{\left(1 + \frac{\mathrm{nt}}{\mathrm{b} - \mathrm{nt}}\right)\tan(\mathrm{ks})\right\} \tag{3}$$

here, c = Speed of propagation of ultrasound through the material
k = Wave number = $\dfrac{2\pi f}{c}$
n = Number of slots

The actual resonant length considerably differs (i.e., ±10 - 20 mm) from half-wavelength obtained from Eq. (1) [26]. The number of slots (n) of a sonotrode can be found by replacing the length of the sonotrode obtained from half-wavelength (l) with actual resonant length (l') in Eq. (3) as follows:

The number of slots obtained by varying the actual resonant length from 10 to 15 % of the length of the sonotrode obtained from the half-wavelength and keeping constant values of thickness of the slot as 10 mm and distance of slot from the top end of the sonotrode as 35 mm.

$$\mathrm{n} = \frac{\mathrm{b}}{\left\{\dfrac{\mathrm{t} \times \tan(\mathrm{ks})}{\tan\left\{\left(\dfrac{c}{2f} + 2\mathrm{s} - l'\right)\dfrac{\mathrm{k}}{2}\right\} - \tan(\mathrm{ks})} + \mathrm{t}\right\}} \tag{4}$$

The geometrical parameters considered in this paper for rectangular sonotrode and corresponding obtained slots are tabulated in **Table 1**.

Table 1 Design specifications of sonotrode.

The actual resonant length of the sonotrode (mm)	Width of the sonotrode or length of the weld (mm)	Upper surface thickness (mm)	Lower surface thickness (mm)	Fillet radius at the step (mm)	Number of slots
168	100	20	5	7.5	0
164	200	25	8	8.5	2
164	300	40	10	15	3
166	400	50	12	19	3

The model calculation for the number of slots of 400 mm length of the weld is given below.

For $\mathrm{k} = \dfrac{2 \times \pi \times f}{c} = \dfrac{2 \times \pi \times 15000}{5091.75} = 18.501$

$$\tan(\mathrm{ks}) = \tan(18.5 \times 0.035) = 0.756\ \mathrm{rad}$$

Substituting all the values in Eq. (4), we get;

$$\mathrm{n} = \frac{0.4}{\left\{ \dfrac{0.01 \times 0.756}{\tan\left\{ \left(\dfrac{5091.75}{(2 \times 15000)} + (2 \times 0.025) - 0.166 \right) \dfrac{18.5}{2} \right\} - 0.756} + 0.01 \right\}} = 2.74 \cong 3$$

Now, the theoretical magnification of this design can be calculated using the following relation [23];

$$\begin{aligned} \text{Magnification factor} &= \frac{\text{Input area}}{\text{Output area}} \\ &= \frac{\text{Upper surface thickness} \times \text{Width of the sonotrode}}{\text{Lower surface thickness} \times \text{Width of the sonotrode}} \\ &= \frac{50 \times 400}{12 \times 400} = 4.167 \end{aligned} \tag{5}$$

Modeling of rectangular sonotrode

The design of rectangular sonotrode cross-section is modeled in a computer-aided 3-dimensional interactive application (CATIA V5) based on the theoretical calculations. The shape of the rectangular sonotrode is designed with a cross-section of rectangular in the transverse direction and exponential in the longitudinal direction [23]. In this work, sonotrode with the plane surface at the booster side is considered as the sonotrode can be attached to the booster using different methods such as soldering, brazing, screwing etc. [27]. The isometric view of the sonotrode with 400 mm weld length in the transverse direction is shown in **Figure 3**. The width and thickness at the upper and lower ends are the main constraints to the design of sonotrode. In the design process, the screw attached to the sonotrode is not considered because of its lightweight there is no effect on resonance frequency.

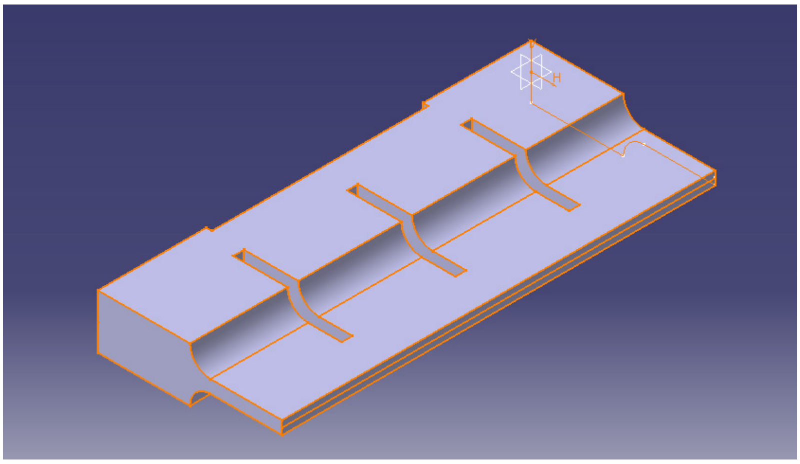

Figure 3 Design of sonotrode with 400 mm weld length.

Results and discussion

Numerical analysis

In the present study, the finite element technique is used for numerical implementation using ANSYS to validate the proposed slotted rectangular sonotrode designs obtained from theoretical calculations. **Figure 4** shows the proposed methodology of numerical analysis for a rectangular sonotrode. Here, 2 types of analyses such as modal and harmonic analysis are considered from these analyses resonance frequency and output displacements are obtained, respectively.

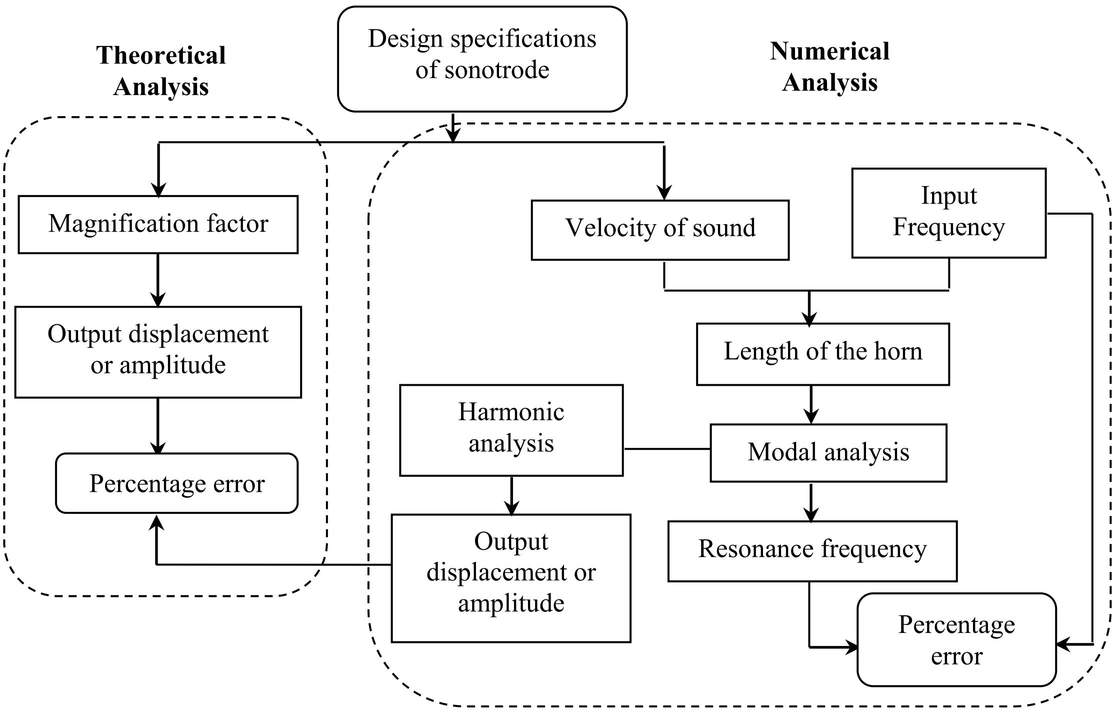

Figure 4 Flowchart for the methodology of theoretical and numerical analysis.

Modal analysis

The designed rectangular sonotrodes with slots from theoretical calculations are analyzed to obtained resonating frequency using modal analysis in ANSYS. The sonotrode with 100 mm weld length has a longitudinal length of 168 mm, which is very close to the theoretically derived length of the sonotrode from half-wavelength i.e., 170 mm. This design not required any slots because of its shorter transverse length. Hence a longitudinal vibration at the desired frequency could be obtained without the use of slots. From **Figure 5**, it is observed that the sonotrode resonates longitudinally at a frequency of 14,996 Hz, which is very close to the desired operating frequency of 15,000 Hz.

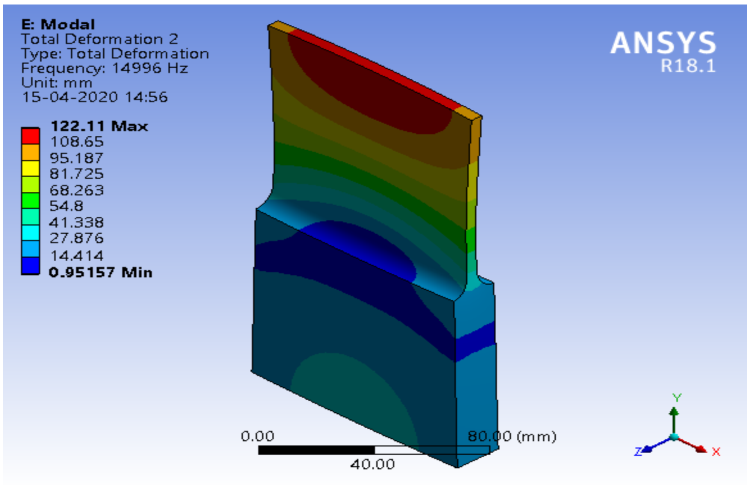

Figure 5 Modal analysis of sonotrode with 100 mm weld length.

The sonotrode with a 200 mm weld length has a longitudinal length of 164 mm. This design required 2 slots due to the increased weld length. In this design, sonotrode resonates longitudinally at a frequency of 14,987 Hz as shown in **Figure 6**.

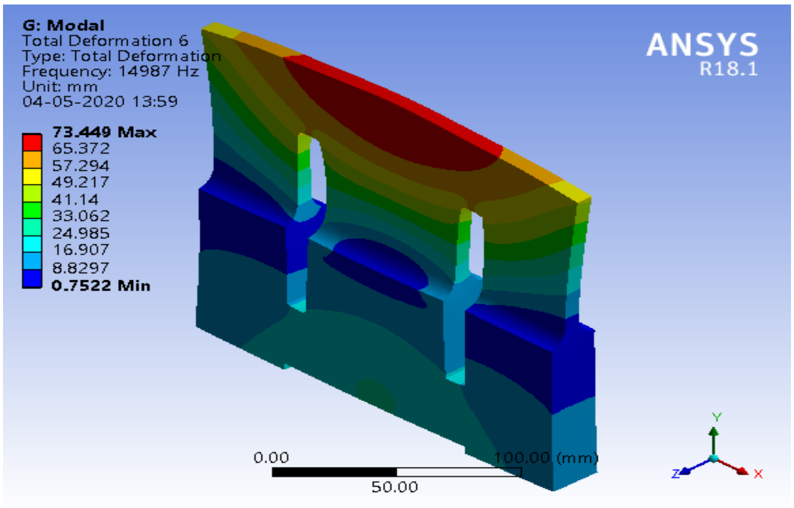

Figure 6 Modal analysis of sonotrode with 200 mm weld length.

The sonotrode of 300 mm weld length has a longitudinal length of 164 mm and the number of slots is 3. **Figure 7** shows the longitudinal frequency at this length is 14,985 Hz.

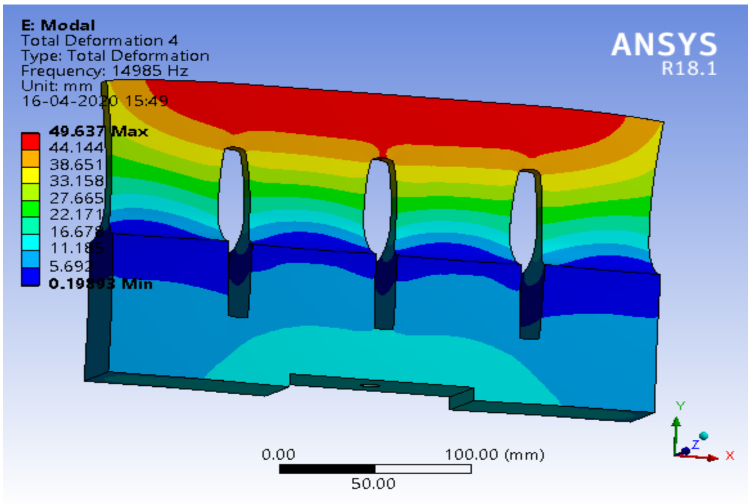

Figure 7 Modal analysis of sonotrode with 300 mm weld length.

Similarly, the sonotrode with 400 mm weld length has a longitudinal length of 166 mm and 3 slots. The longitudinal frequency of 14,942 Hz obtained from modal analysis for this design is shown in **Figure 8**.

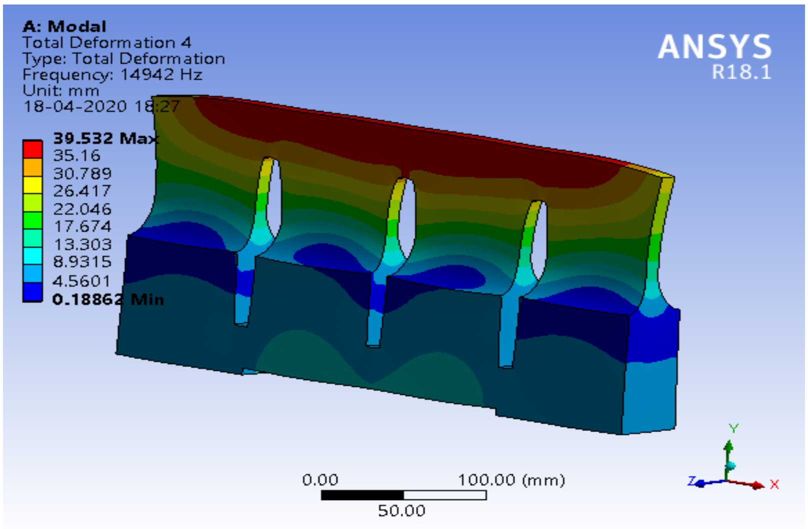

Figure 8 Modal analysis of sonotrode with 400 mm weld length.

Harmonic analysis

Harmonic analysis with the input vibration of 30 µm, rectangular sonotrode output displacement or amplitude at the known operating frequency of 15 kHz is determined and identified the resonance occurrence possibility in this frequency range. To magnify the vibration amplitude, a step is provided at the central cross-section in the design. At this junction, the amplitude gets magnified by a factor called magnification factor which depends upon the input area (upper surface of the sonotrode) of the cross-section of the sonotrode and the weld area (lower surface of the sonotrode). The outputs obtained from the harmonic analysis are shown in **Figure 9**. The maximum amplitude for this design is 126.73 µm.

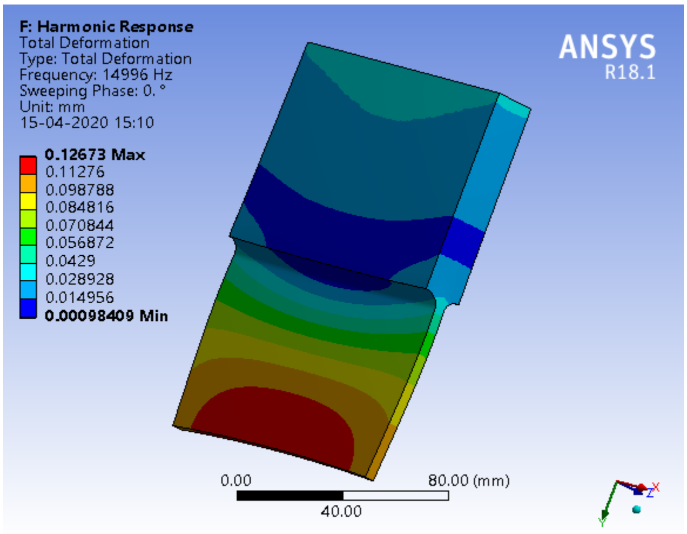

Figure 9 Harmonic analysis of sonotrode with 100 mm weld length for deformation.

The von Mises stresses in the design are shown in **Figure 10**. It can be observed that the maximum stress is concentrated in the middle of the sonotrode. This is because of the change in the cross-sectional area at this junction, which leads to an increase in stress concentration. Due to this, the stresses near the input surface and weld surface of the sonotrode are minimal. Thus, when the sonotrode comes in contact with the workpieces or the equipment, the damage occurring to the sonotrode at these surfaces should be minimum. The maximum and minimum stresses in this sonotrode are observed to be 164.39 MPa and 2.974 GPa, respectively.

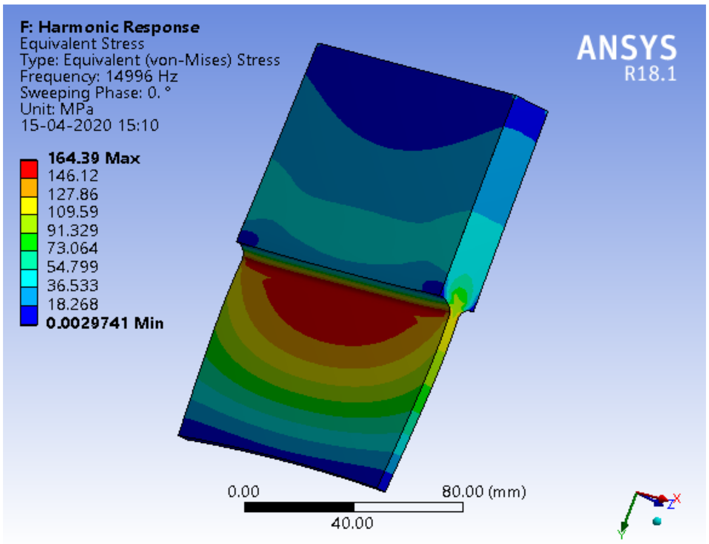

Figure 10 Harmonic analysis of sonotrode with 100 mm weld length for stresses.

The maximum deformation of 200 mm weld length for an input vibration of 30 µm is 102.54 µm as shown in **Figure 11**.

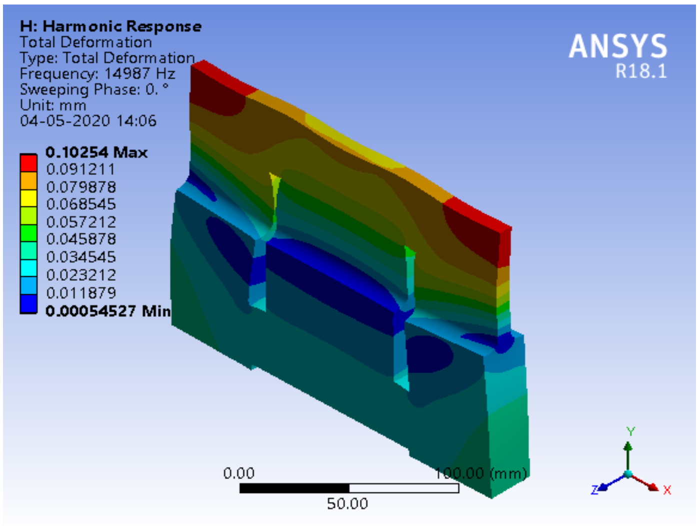

Figure 11 Harmonic analysis of sonotrode with 200 mm weld length for deformation.

The maximum stress in this sonotrode is observed as 234.76 MPa as shown in **Figure 12**. It can be observed that the maximum stress is concentrated in the middle of the sonotrode. Hence the design is safe for operation.

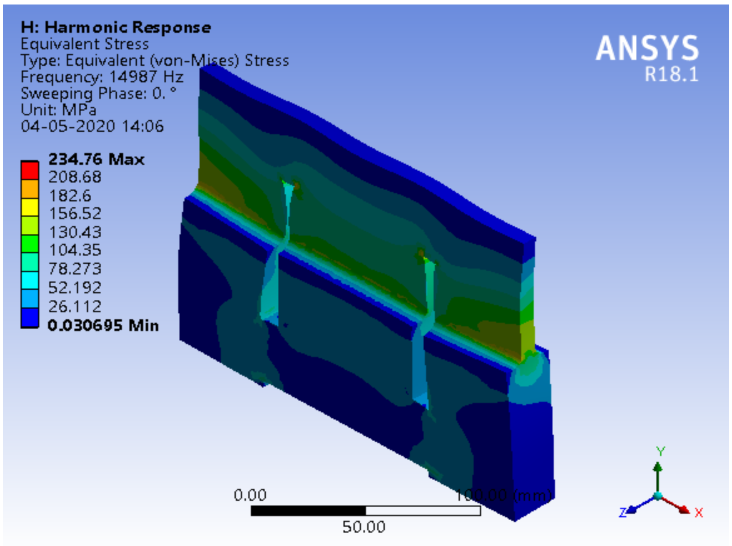

Figure 12 Harmonic analysis of sonotrode with 200 mm weld length for stresses.

The outputs obtained from the harmonic analysis are shown in **Figure 13**. The maximum deformation for 300 mm weld length for an input vibration of 30 µm is 113.5 µm. Even though, the weld length increases from 100 to 300 mm here, in the figure the maximum deformation occurred at the end of the tip.

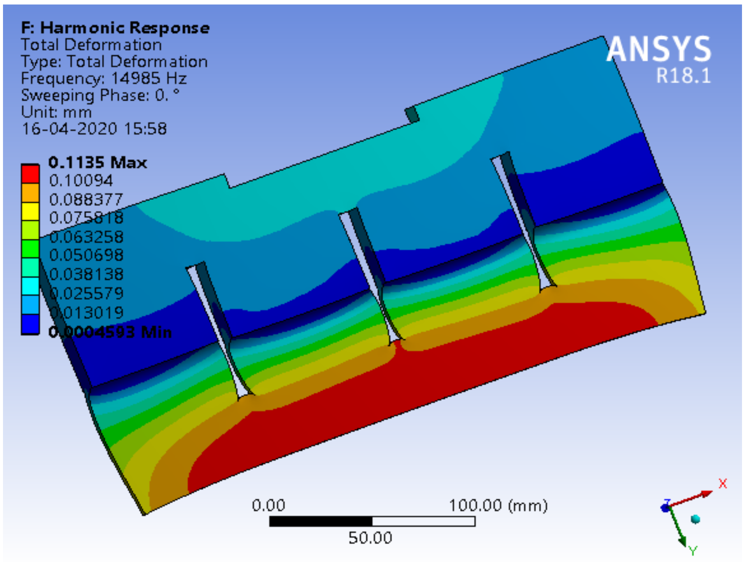

Figure 13 Harmonic analysis of sonotrode with 300 mm weld length for deformation.

The maximum stress in this sonotrode is observed to be 217.93 MPa. The von Mises stresses for 300 mm weld length are shown in **Figure 14**. The design is safe because the maximum stress is concentrated in the middle of the sonotrode.

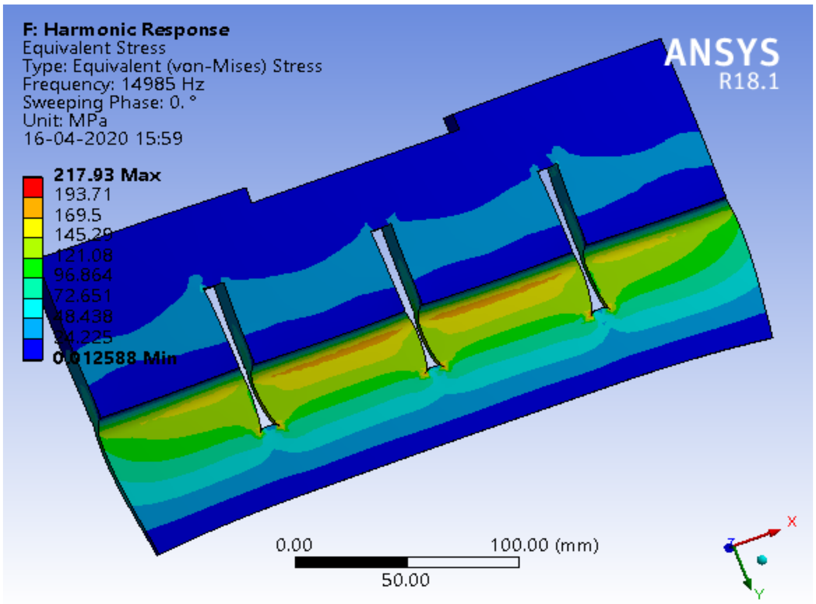

Figure 14 Harmonic analysis of sonotrode with 300 mm weld length for stresses.

The maximum deformation in the sonotrode is shown in **Figure 15**. It can be observed that the maximum deformation for 400 mm weld length rectangular sonotrode for an input vibration of 30 µm is 120.66 µm.

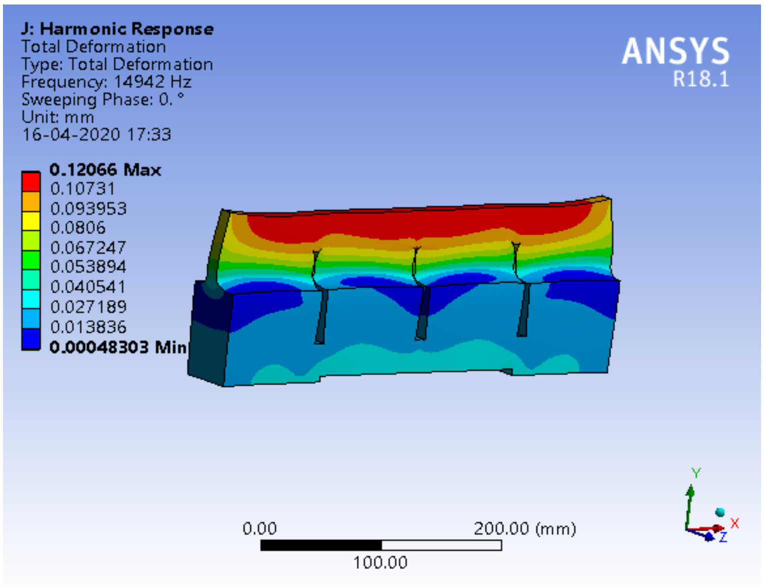

Figure 15 Harmonic analysis of sonotrode with 400 mm weld length for deformation.

The maximum stress in this sonotrode is observed to be 254.67 MPa. The maximum stress is concentrated in the middle of the sonotrode as shown in **Figure 16**. Hence, the design is safe for operation.

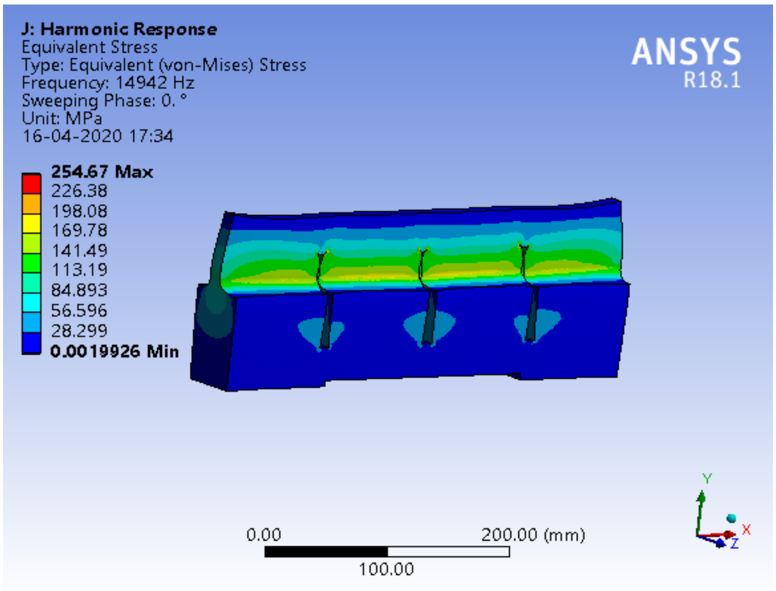

Figure 16 Harmonic analysis of sonotrode with 400 mm weld length for stresses.

The percentage of errors of assumed and obtained frequency from numerical analysis are given in **Table 2**. In all the cases of weld lengths considered, the frequency percentage error is below 0.4 %, which means the geometric parameters along with the number of slots considered are reliable for fabrication and experimentation. The maximum dimensions of a rectangular sonotrode obtained from this analysis are 400×166×31 mm^3 (length of the weld × length of the sonotrode × average thickness). From which, the total weight of the sonotrode for the aluminum alloy is 5.62 kg. This is very much acceptable as the commercial sonotrode for the 15 kHz frequency machines are ranging from 0.5 - 20 kg [28].

Table 2 Frequency percentage error.

Length of weld (mm)	Assumed frequency (Hz)	Obtained frequency (Hz)	Percentage error
100	15,000	14,996	0.0267
200	15,000	14,987	0.0867
300	15,000	14,985	0.1
400	15,000	14,942	0.3867

The magnification factors obtained from the theoretical and harmonic analysis are analyzed. **Figure 17** shows that the deviation of magnification factors is very much less and the percentage error of amplitude magnification factors are in the allowable range. This amplitude magnification is crucial for obtaining the desired weld joint. Therefore, in terms of magnification factor also the designed rectangular sonotrodes are recommended for further analysis.

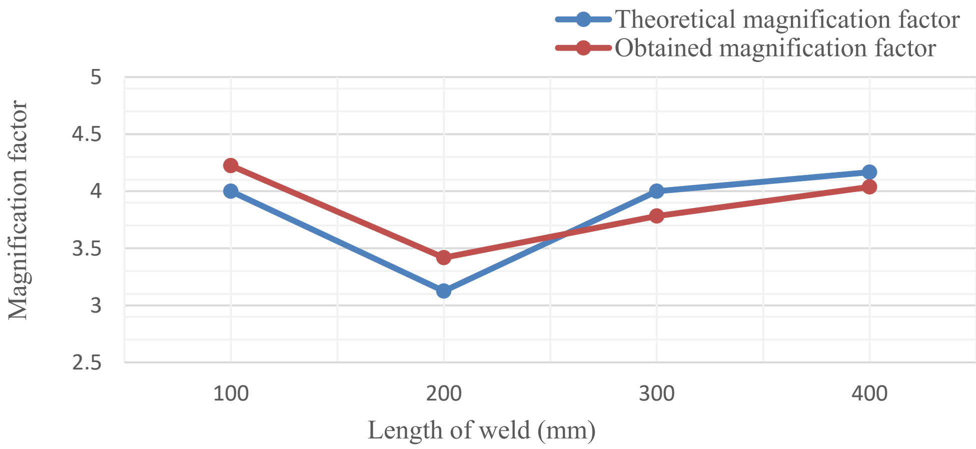

Figure 17 Magnification factors.

Conclusions

In the present work, rectangular sonotrodes with different weld lengths have been designed to obtain the maximum possible weld lengths at uniform amplitudes in ultrasonic welding for a known operating frequency of 15 kHz. Aluminium 6061 - T6 alloy material is used for the design of sonotrode because of its reliable acoustic properties. Sonotrodes with weld lengths varying from 100 to 400 mm have been designed using CATIA software based on the theoretical analysis. Later, these designs are analyzed for their performance and safety in ANSYS Workbench. The increase in the weld length of the sonotrode deviates the amplitude distribution within the sonotrode. To overcome this non-uniform amplitude distribution, longitudinal slots are provided in the sonotrodes. Slots obstruct the vibration traveling in directions other than longitudinal direction. Slots also provide the advantage of weight reduction, making it possible to design sonotrodes with larger dimensions.

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