Analysis of Different Shaped Sonotrodes used for Plastic Welding

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Abstract-- For proper concentration of ultrasonic energy across work piece surface during welding, geometry of horn plays a vital role. The issues involved in the study of design are horn material and shape, frequency and amplitude of vibration. This paper discusses on design of different shaped acoustic horns like conical, stepped and exponential for ultrasonic welding of plastics. First, the theoretical dimensions of different shaped horn are calculated and compared with the dimensions obtained through commercial horn design software CARD®. Correspondingly, the magnification factors attainable for both cases for all horn shapes have been compared. The said discussion is a part of research work intended to study the joint strength of Acrylic and Polycarbonate joints under various welding parameters.

Keyword-- Ultrasonic plastic welding, Horn, Frequency, Amplitude

I. INTRODUCTION

Ultrasonic welding, one of the most widely used welding methods for joining thermoplastics, uses ultrasonic energy at high frequencies (20 – 40 kHz) to produce low amplitude (1 – 25 µm) mechanical vibrations. The vibrations generate heat at the joint interface of the parts being welded, resulting in melting of the thermoplastic materials and weld formation after cooling. Ultrasonic welding is the fastest known welding technique, with weld times typically between 0.1 and 1.0 seconds.

In addition to welding, ultrasonic energy is commonly used for processes such as inserting metal parts into plastic or reforming thermoplastic parts to mechanically fasten components made from dissimilar materials.

When a thermoplastic material is subjected to ultrasonic vibrations, sinusoidal standing waves are generated in the material. Part of this energy is dissipated through intermolecular friction, resulting in a build-up of heat in the bulk material, and part is transmitted to the joint interface where boundary friction causes local heating. Optimal transmission of ultrasonic energy to the joint and subsequent melting behavior is therefore dependent on the geometry of the part and also on the ultrasonic absorption characteristics of the material.

In Ultrasonic plastic welding, function of the acoustic horn is to magnify the amplitude of mechanical vibrations or to accumulate the energy on the smaller cross section. In general, the amplitude produced by an ultrasonic vibrator is 4 – 10 µm. However, the amplitude required for effective ultrasonic machining has to be more than 10-100 µm (Amin et al. 1995). The amplitude of a vibrator has to be magnified by an acoustic horn. The principle of amplification of the acoustic horn is that the vibration energy through a cross section remains unchanged, therefore the smaller the cross section, the larger the energy density. The amplitude through the small section is magnified neglecting the losses during energy transfer (Kremer D et. al. 1981).

II. HORN DESIGN FOR ULTRASONIC PLASTIC WELDING

A welding horn, also known as a Sonotrode is an acoustical tool that transfers the mechanical vibrations to the work piece and is custom-made to suit the requirements of the application. The molecules of a horn expand and contract longitudinally along its length so the horn expands and contracts at the frequency of vibration.

The amplitude of the horn is determined by the movement from the longest value to the shortest value of the horn face in contact with the part (i.e. peak-to-peak movement). Horns are designed as long resonant bars with a half wavelength. By changing the cross sectional shape of a horn, it is possible to give it a gain factor increasing the amplitude of the vibration it receives from the transducer – booster combination. Three common horn shapes are the stepped, exponential and conical in plastic welding industry.
Stepped horns consist of two sections with different but uniform cross-sectional areas. The transition between the sections is located near the nodal point. Due to the abrupt change in cross-section in the nodal plane, step horns have a very high stress concentration in this area and can fail if driven at excessive amplitude. Gain factors up to 9:1 can be attained with step horns.

Conical horns have a cross-sectional area that changes conically with length. The smooth transition distributes the stress over a greater length thus offering lower stress concentrations than that found in step horns. They generally have lower gain factors so are used for applications requiring low forces and low amplitudes.

Exponential horns have a cross-sectional area that changes exponentially with length. It is same as conical horn but produced more gain than conical horn.

### III. THEORETICAL LENGTH OF DIFFERENT SHAPED HORN

Basic horn design equations are represented as equation 1 and equation 2 in terms of particle displacement $\xi$:

$$\frac{1}{c^2} \frac{\partial^2 \xi}{\partial t^2} - \frac{1}{s} \frac{\partial s}{\partial x} \frac{\partial \xi}{\partial x} - \frac{\partial^2 \xi}{\partial x^2} = 0$$

And in terms of particles velocity $v$, and implying harmonic motion,

$$\frac{\partial^2 v}{\partial x^2} + \frac{1}{s} \frac{\partial s}{\partial x} \frac{\partial v}{\partial x} + \frac{\omega^2}{c^2} v = 0$$

Where $x$ is the distance from one end of horn to the reference position, in meters; $s$ the cross section area of the horn at distance $x$, in square meters; $\omega$ the angular frequency; and $c$ the velocity of sound in the medium of horn in meters per second.

#### 3.1 Calculation for stepped horn

By solving Equation 1 and getting the length of horn from equation 3; where value of $l_i=70$mm

$$l = l_i + \frac{c}{4f}$$

$c$ is the sound propagation velocity through horn materials. $f$ is frequency at input diameter $D_i$.

And its amplitude magnification $M$ is calculated by:

![Figure 1. Stepped Shaped horn](image)

**Figure 2.** Length of stepped shape horn by using CARD software

$$M = \frac{A_1}{A_2} = \left( \frac{D_1}{D_2} \right)^2$$

#### 3.2 Calculation for Exponential horn

By solving Equation 1 and getting the length of horn from equation 5;

$$l = \frac{c}{2f} \sqrt{1 + \left( \frac{\ln(D_1 / D_2)}{\pi} \right)^2}$$

Where $D_1$ and $D_2$ are the diameters of the input end and output end, respectively; $f$ is frequency at input diameter $D_1$; $c$ is the sound propagation velocity through horn materials.

And its amplitude magnification $M$ is calculated by:

$$M = \left( \frac{D_1}{D_2} \right)$$
3.3 Calculation for conical horn

3.3.1 Area Decreasing with Increasing $x$

Figure 1 depicts the profile of a conical horn with area decreasing with increasing $x$. By solving Equation 1 and getting the length of horn from equation 7:

$$\tan \frac{\omega \ell}{c} = \frac{\omega c (D_1 - D_2)}{c^2 (D_1 - D_2)^2 + \omega^2 \ell^2 D_1 D_2}$$

(7)

Where $D_1$ and $D_2$ are the diameters of the input end and output end, respectively; $\omega$ (Resonance frequency) $= 2\pi f$, $c$ is the sound propagation velocity through horn materials.

And its amplitude magnification $M$ is calculated by:

$$M = \left| \frac{D_1}{D_2} \cos \frac{\omega \ell}{c} - \frac{c (D_1 - D_2)}{\omega D_2} \sin \frac{\omega \ell}{c} \right|$$

(8)

IV. RESULTS AND DISCUSSION

4.1 Analysis of conical shaped horns

In order to calculate the dimension of horn by CARD software, the inputs required are diameter of horn $D_1$
and $D_2$ and material properties. Similar practice is required for calculations using theoretical equations. In either cases diameter $D_1$ is assumed arbitrarily considering the least size matching with booster on machine setup. Diameter $D_2$ is the required diameter of the weld joint. However the diameter ratios are according to the ratios used for commercial horns. The input and Output parameters are listed in Table 1.

**TABLE 1. Values of Different shaped Horn**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension By CARD software(mm)</th>
<th>From Theoretical equation(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_1$</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$D_2$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Material</td>
<td>A2024 –T3 aluminum alloy</td>
<td>A2024 –T3 aluminum alloy</td>
</tr>
<tr>
<td>$D_1/D_2$</td>
<td>3:1</td>
<td>3:1</td>
</tr>
<tr>
<td>Frequency</td>
<td>20KHz</td>
<td>20KHz</td>
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<tr>
<td>Outputs for Conical shaped horn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>142</td>
<td>140</td>
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<tr>
<td>Magnification</td>
<td>3.33</td>
<td>2.84</td>
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<td>Outputs for Stepped shaped horn</td>
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<tr>
<td>L</td>
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<td>134</td>
</tr>
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<td>Magnification</td>
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<td>9</td>
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<tr>
<td>Outputs for Exponential shaped horn</td>
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<td>L</td>
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<td>135</td>
</tr>
<tr>
<td>Magnification</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Values of magnification calculated by using Equation (4, 6, 8) and by using CARD software are given in Table 1.

Figure 6, 7 & 8 give the values of amplifications by taking the ratio of amplitude at diameter $D_1$ to amplitude at diameter $D_2$ by using CARD software.
V. CONCLUSIONS

From the above discussion it is evident that under the condition of same area ratio between its two ends cross sections the amplitude magnification of them is in descending order for the stepped shape, exponential shape and conical shape respectively. A stepped shape horn produces larger amplitude, since it will have larger vibration stress. Stress distribution results show that for ultrasonic plastic welding, conical shaped horn and exponential shaped horn are better than any other shape of horn. Same as the computation for an exponential shape horn is easiest among three different shapes. Also the horn of exponential shape has better amplitude than conical shaped horn. But due to difficulty in machining it is rarely used in practice where its machining cost is justified. Although the computation for conical horn shape is most difficult, it is easy to manufacture and also has almost same amplitude as exponential shape horn. Therefore, conical shaped horn is extensively used in industry. However, it can be clearly observed that both values calculated by CARD software are slightly exceeding the values by theoretical equations. From above results one can conclude that magnification of horn by using CARD software and by using theoretical equation is closer. Hence CARD software may be useful tool for horn design.

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VII. REFERENCES

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