The Effect of Different Heights and Angles of Energy Director on Interface Temperature for Ultrasonic Welding of Thermoplastics

NV Thang¹ and P Lenfeld²

1 Ph.D. Student, Faculty of Mechanical Engineering, Department of Engineering Technology, Technical University of Liberec, Czech Republic
2 Professor, Faculty of Mechanical Engineering, Department of Engineering Technology, Technical University of Liberec, Czech Republic
E-mail: petrnguyen321@gmail.com

Abstract. Besides technological parameters in the ultrasonic welding process, height and angle of energy director (ED) also affect the quality of the joint strength owing to its energy transfer and melting. This paper deals with evaluating the effect of distinct ED heights and angles of butt-joint on temperature distribution at the weld interface. Experiments were simulated using transient thermal analysis of Ansys 18 for 3D-samples made of acrylonitrile butadiene styrene (ABS) and high-density polyethylene (HDPE). The results obtained from simulation of temperature distribution in various ED heights and angles and welding amplitudes are presented and compared with each other.

1. Introduction
For bonding plastics and composites often use welding technologies. One of the most modern welding methods is ultrasonic welding technology, which has various applications in the engineering industry, especially in the automotive and textile industry, in the production of electrical appliances, in the packaging technology, etc. The main advantages of ultrasonic welding are fast, clean, efficient and repeatable process, producing a strong bond with the consumption of a very little amount of energy. To create the welded joint by ultrasonic technology requires no solvent, adhesive or external heat and the resulting joint is undetachable.

Ultrasonic plastic bonding is the joining or reforming of thermoplastics by using heat generated from high-frequency mechanical motion. This can be achieved by converting electrical energy into high-frequency mechanical motion (vibrations), which generates frictional heat at the joint area. The vibrations applied to a part under pressure/force, generate frictional heat at the interface and cause melting of the material and creating a molecular bond between the welded plastic parts. The ultrasonic welding process is described in several phases shown in Figure. 1 [1].
A whole range of welding parameters (frequency, amplitude, time, etc.) has an important effect on quality of the resulting welded joint. Besides the welding processing parameters, for proper evaluation, it was also necessary to determine the ED geometry, namely its height and angle. The energy director (see Figure. 2) was developed to provide a specific volume of material for melting, in order to achieve a good bond strength without excessive flash. When ultrasonic energy is transmitted through the part under pressure and over time, the energy concentrates at the apex of the ED. This leads to a rapid generation of heat that causes the bead to melt. The molten material flows across the joint interface, forming a molecular bond between the two welded parts [1].

In this paper, the butt joint with 60°, 75° and 90° angle included ED was used to simulate temperature distribution in ultrasonic welding at a frequency of 20 (kHz) and at amplitudes of 40, 50 and 60 microns. In addition, for each individual angle of ED, its height ranged from 0.5 to 1.75 (mm).

2. Procedure for simulation analysis

2.1. 3D Model and thermal loads
The two rectangular models having dimensions of 80*10*4 (mm) for the first one and of 80*11.2*4 (mm) for the second one are welded together. The first model with various EDs is on the top of the second one, as shown Figure. 3. The 3D model was meshed using the tetrahedral method. A transient thermal analysis was chosen to simulate for welding time of 0.8 [s] with a time increment of 0.05 [s]. The applied thermal loads were given as follows: the initial temperature of 25 °C, thermal convection to the environment with overall heat transfer coefficient $U$ (W/m²K), heat flux $\phi_q$ (W/m²) for ED
height applied as a thermal load at the interface. The properties of ABS and HDPE are presented in Table. 1.

**Table 1.** Material properties of ABS and HDPE.

| Material | Density $\rho$ (kg/m$^3$) | Specific heat capacity $C_p$ (J/kgK) | Coefficient of thermal conductivity $k$ (W/mK) | Young’s modulus (GPa) | Mechanical loss coefficient ($\zeta$) |
|----------|---------------------------|--------------------------------------|-----------------------------------------------|-----------------------|-------------------------------------|
| ABS      | 1020                      | 1386                                 | 0.23                                          | 2.0                   | 0.0138                              |
| HDPE     | 952                       | 1796                                 | 0.46                                          | 1.07                  | 0.0437                              |

2.2. Determination of values for required parameters

2.2.1. Calculation of overall transfer coefficients. The overall heat transfer coefficient $U$ per unit area can be expressed as [2]:

$$U = \frac{1}{\frac{1}{h_A} + \frac{dx_w}{k} + \frac{1}{h_B}}$$  \hspace{1cm} (1)

Where:

$U$= overall heat transfer coefficient (W/m$^2$K)

$k$= thermal conductivity of the material (W/mK)

$h_A$= individual convection heat transfer coefficient for each fluid (W/m$^2$K)

$dx_w$= wall thickness (m)

A single plate exchanger with media A transfers heat to media B. Both of mediums are air with a convection heat transfer coefficient of $h_A = 50$ W/m$^2$K. The wall thickness is 4 mm and the materials used are ABS and HDPE with coefficients of thermal conductivity listed in Table. 1. The calculated values of overall heat transfer coefficient are shown in Table. 2.
Table 2. Values of overall heat transfer coefficient.

| Material | Value of U (W/m²K) |
|----------|---------------------|
| ABS      | 17.32               |
| HDPE     | 20.54               |

2.2.2. Calculation of loss moduli. Loss modulus is a measure of the viscous response of a material. It measures the energy dissipated as heat and is calculated based on Young’s modulus and mechanical loss coefficient (tan delta). The Young’s modulus is considered to be equal to [3]:

\[ E = \sqrt{\left(E'\right)^2 + \left(E''\right)^2} \]  

(2)

Where

- \( E \) = Young’s modulus (GPa)
- \( E' \) = storage modulus (GPa)
- \( E'' \) = loss modulus (GPa)

The ratio between the loss and storage modulus in a viscoelastic material is defined as the tan delta, which provides a measure of dampening in the material and can be calculated by equation (3) [3]:

\[ \tan \delta = \frac{E''}{E} \]  

(3)

Loss moduli are given by using equations (2) and (3):

\[ E'' = \frac{(E \times \tan \delta)^2}{1 + (\tan \delta)^2} \]  

(4)

The calculated values of loss modulus for ABS and HDPE are shown in Table. 3.

Table 3. Values of loss modulus.

| Material | Value of \( E'' \) (GPa) |
|----------|--------------------------|
| ABS      | 0.028                    |
| HDPE     | 0.046                    |

2.2.3. Calculation of heat fluxes

The heat generated at the joint is proportional to the square of the amplitude of the vibration. Hence, any change in the amplitude has a greater effect than a change of any other parameter [4]. In ultrasonic welding using ED, the average energy dissipated per unit time or the average internal heat generation rate can be calculated as [5]:

\[ Q_{avg} = \frac{\omega \times \varepsilon_o^2 \times E''}{2} = \pi \times f \times \varepsilon_o^2 \times E'' \]  

(5)

Where
$Q_{\text{avg}}$ = the average heating rate (W/m$^3$)

$E'$ = loss modulus of the material (Pa)

$f$ is welding frequency (Hz)

$\varepsilon_o$ = the strain amplitude, which can be written as [6]:

$$\varepsilon_o = \frac{A_0}{2*L}$$  \hspace{1cm} (6)

Where

$A_0$ = vibration amplitude applied during welding, which is ranged from 40 to 60 microns

$L$ = thickness of workpiece (m)

Heat flux is calculated according to the following equation [7]:

$$\phi_q = \frac{Q_{\text{avg}} \times V_{ED}}{A_{ED}} = \frac{Q_{\text{avg}} \times A_{ED} \times h}{A_{ED}} = Q_{\text{avg}} \times h$$  \hspace{1cm} (7)

Where

$\phi_q$ = heat flux (W/m$^2$)

$V_{ED}$ = volume of ED (m$^3$)

$A_{ED}$ = area of ED (m$^2$)

$h$ = height of ED (m)

Chuah et al., 2000 [6] determined the energy absorption ratio $r_{\text{absorb}}$ for the ABS and HDPE welded parts, which is defined as the ratio of the energy absorbed by the plastic material at the ED to that of the energy dissipated by the ultrasonic welder. The calculated values were 48.5 % for the ABS welded part and 21.1 % for that of HDPE. So, the heat flux is recalculated as (8) and the final calculated values of heat flux are listed in Table 4.

$$\phi_q = Q_{\text{avg}} \times h \times r_{\text{absorb}}$$  \hspace{1cm} (8)

Table 4. Values of heat flux.

| Amplitude (µm) | Value (W/m$^2$) | Material | ABS | HDPE |
|----------------|-----------------|----------|-----|------|
|                |                 | Height of ED |     |      |
| 40             | $\phi_q$        | h = 0.5 (mm) | 10500. 4 | 16406. 9 |
|                |                 | h = 1 (mm)   | 21000. 8 | 32813. 7 |
|                |                 | h = 1.5 (mm) | 31501. 2 | 49220. 6 |
|                |                 | h = 1.75 (mm)| 36751. 4 | 57424. 0 |
|                |                 | h = 0.5 (mm) | 7735.2 | 12086. 2 |
|                |                 | h = 1 (mm)   | 15470. 3 | 24172. 4 |
| 50             |                 | h = 1.5 (mm) | 23205. 5 | 36258. 5 |
|                |                 | h = 1.75 (mm)| 27073. 0 | 42301. 6 |
| 60             |                 | h = 0.5 (mm) | 10500. 4 | 16406. 9 |
|                |                 | h = 1 (mm)   | 21000. 8 | 32813. 7 |
|                |                 | h = 1.5 (mm) | 31501. 2 | 49220. 6 |
|                |                 | h = 1.75 (mm)| 36751. 4 | 57424. 0 |
|                |                 | h = 0.5 (mm) | 7735.2 | 12086. 2 |
|                |                 | h = 1 (mm)   | 15470. 3 | 24172. 4 |
|                |                 | h = 1.5 (mm) | 23205. 5 | 36258. 5 |
|                |                 | h = 1.75 (mm)| 27073. 0 | 42301. 6 |

$\phi_q$ = heat flux (W/m$^2$)

$V_{ED}$ = volume of ED (m$^3$)

$A_{ED}$ = area of ED (m$^2$)

$h$ = height of ED (m)
3. Results and discussion

The simulation process was carried out on the 3D model with ED to determine temperature distribution, as well as maximum interface temperature (MIT) at the apex of ED, as shown in Figure 4. Figure 5, 6 showed values of MIT for ABS and HDPE, respectively, which depended on welding amplitude, height and angle of ED. It could be seen in Figure 5 that the highest value was 570.2 (°C) at welding amplitude of 60 (μm) with ED height and angle of 1.75 (mm) and 60 (°), respectively. Whereas the smallest value was 79.5 (°C) at welding amplitude of 40 (μm) with ED height and angle of 0.5 (mm) and 90 (°), respectively. Thus, it clearly showed that increasing welding amplitude caused a strong increase in the value of MIT. In terms of the percentage difference in MIT, the greatest value between welding amplitude of 40 (μm) and 60 (μm) was about 113 (%) at ED height and angle of 1.75 (mm) and 60 (°), respectively. The smallest value was approximately 86 (%) at ED height and angle of 0.5 (mm) and 90 (°), respectively. In contrast, the value of MIT slightly decreased with increasing ED angle; namely, the greatest percentage difference in MIT was almost 29.4 (%) between ED angle of 60° and 90° at welding amplitude of 60 (μm) and ED height of 1.75 (mm). The smallest value was 6 (%) between ED angle of 75° and 90° at welding amplitude of 40 (μm) and ED height of 0.5 (mm). On the other hand, value of ED height was moved from 0.5 (mm) to 1.75 (mm), causing a significant increase in MIT; namely, the greatest percentage difference in MIT was approximately 225 (%) between ED height of 0.5 (mm) and 1.75 (mm) at welding amplitude of 60 (μm) and ED angle of 60°. The smallest value was about 14 (%) between ED height of 1.5 (mm) and 1.75 (mm) at welding amplitude of 40 (μm) and ED angle of 90°.

Figure 4. Temperature distribution at the weld interface in workpiece model with ED.

Figure 5. The maximum temperature at the weld interface for ABS.
Similarly, the data in Figure 6 indicated that the highest value was 285.6 (°C) at welding amplitude of 60 (μm) with ED height and angle of 1.75 (mm) and 60 (°), respectively. Whereas the smallest value was 49.9 (°C) at welding amplitude of 40 (μm) with ED height and angle of 0.5 (mm) and 90 (°), respectively. Hence it clearly showed that when rising welding amplitude, it caused a strong rise in the value of MIT. In terms of the percentage difference in MIT, the greatest value between welding amplitude of 40 (μm) and 60 (μm) was almost 103 (%) at ED height and angle of 1.75 (mm) and 60 (°), respectively. The smallest value was about 63 (%) at ED height and angle of 0.5 (mm) and 90 (°), respectively. On the other hand, it can be observed that value of MIT slightly declined with increasing ED angle: namely, the greatest percentage difference in MIT was 28 (%) between ED angle of 60° and 90° at welding amplitude of 60 (μm) and ED height of 1.75 (mm). The smallest value was about 3.6 (%) between ED angle of 75° and 90° at welding amplitude of 40 (μm) and ED height of 0.5 (mm). It also revealed that rise of ED height from 0.5 (mm) to 1.75 (mm) caused a significant rise in MIT: namely, the greatest percentage difference in MIT was about 211 (%) between ED height of 0.5 (mm) and 1.75 (mm) at welding amplitude of 60 (μm) and ED angle of 60°. The smallest value was approximately 12 (%) between ED height of 1.5 (mm) and 1.75 (mm) at welding amplitude of 40 (μm) and ED angle of 90°.

According to the following three reasons were attributed to the variation in values of MIT:

- The first and second reason – when increasing welding amplitude and value of ED height, caused an increase in MIT. This is explained as follows: according to equations (5)-(7), the value of heat flux was proportional to the value of welding amplitude and ED height. As a result, rising these values caused a strong rise in the rate of heat energy transfer through the surface of ED.

- The third reason – smaller ED angle concentrated more viscoelastic heat. This created higher temperature at the weld interface. Thus the value of MIT slightly dropped with rising ED angle.

![Figure 6. The maximum temperature at the weld interface for HDPE.](image)
Figure 7. Comparison of maximum temperature at the weld interface between ABS (left) and HDPE (right).

Figure 7 clearly showed that values of MIT of ABS were always greater than that of HDPE. The greatest percentage difference in MIT was approximately 100 (%) between ABS and HDPE at welding amplitude of 60 (µm) with ED height and angle of 1.75 (mm) and 60 (°), respectively. In contrast, the smallest value was about 60 (%) between ABS and HDPE at welding amplitude of 40 (µm) with ED height and angle of 0.5 (mm) and 90 (°), respectively. As known, ABS is an amorphous polymer and HDPE is a semi-crystalline one. In amorphous polymers, the molecules are randomly oriented, allowing the vibrational energy to pass through them easily, with little attenuation. Therefore, they transmit ultrasonic vibrations more efficiently. Whereas semi-crystalline polymers tend to absorb vibrations due to their orderly molecular structure [1,5]. Furthermore, Chuah [8] determined value of energy absorption ratio for ABS being almost 2.5 times greater than that for HDPE. This resulted in increasing value of heat flux of ABS in comparison with that of HDPE.

4. Conclusion
This paper indicated that ED height, as well as welding amplitude strongly affected the interface temperature for ultrasonic welding of thermoplastics, viz increasing welding amplitude and ED height strongly increased MIT. Whereas the effect of ED angle on the interface temperature was less. With increasing ED angle, the value of MIT slightly decreased. The simulation figure of temperature distribution showed that the maximum interface temperature was found at the apex of ED, where the energy was concentrated. Ultrasonic welding of amorphous polymers is more suitable than that of semi-crystalline ones due to their ability to effectively transfer ultrasonic vibrations. In other words, energy absorption ratio for ABS was higher than that for HDPE. Hence values of MIT of ABS were always greater than that of HDPE.

The further research directions will be fabrication of the test samples with different energy directors by using injection moulding and then be welded under various welding conditions. Subsequently, the obtained results will be used to evaluate the effect of the main factors on the joint strength and the resulting dimension of workpiece after welding. In addition, the experimental temperature distributions during welding process will be measured by using thermocouples positioned at different points on the workpiece and the obtained results will be compared with the ANSYS simulation results.

5. References
[1] Guide to Ultrasonic Plastics Assembly, https://www.dukane.com/us/Documents/DesignGuides
[2] Overall Heat Transfer Coefficient, http://www.engineeringtoolbox.com/overall-heat-transfer-coefficient-d_434.html
[3] Menard K 2008 Dynamic Mechanical Analysis: A Practical Introduction (Florida: CRC Press) p 218
[4] Ultrasonic Welding. http://www.solvay.com/en/binaries/Ultrasonic-Welding_EN-199453.pdf
[5] Troughton M 2008 Handbook of Plastics Joining: A Practical Guide (New York: William Andrew Inc.) p 600
[6] Potente H 1984 Ultrasonic welding: principles and theory Materials and Design 5 228–234
[7] Suresh K S, “Studies on temperature distribution in various joint designs and design of horns for ultrasonic welding of thermoplastics,” Ph.D. dissertation, Dept. Mech. Eng., Anna Univ., Chennai, India, 2007
[8] Chuah Y, Chien L, Chang B et al. 2000 Effects of the shape of the energy director on far-field ultrasonic welding of thermoplastics Polymer Engineering and Science 40 157–167

Acknowledgments
This publication was written at the Technical University of Liberec with the 117/2200 financial institutional support of the Department of Engineering Technology/Faculty of Mechanical Engineering.