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Effect of contact area with fixture on dynamic behaviour of joint interface in ultrasonic welding of thermoplastics

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Abstract. Ultrasonic welding is one of the most common methods for joining thermoplastics. The two plastic parts to be joined are placed on the fixture before high frequency mechanical vibration is applied to the parts through an ultrasonic horn. This generates heat at the joint area and locally melts thermoplastics. The parts are welded together. In this paper, we investigate the effect of the contact area between the lower parts and the fixture on the dynamic behaviour of the joint interface, which affects heat generation. The displacements and elastic strains of the interface are predicted using finite element dynamic contact analysis and compared for different contact areas. The results show that the dynamic behaviour of the interface depends on the dynamic characteristics of the two parts. When both natural frequencies are close to the horn vibration frequency, the displacements and strains are small. Conversely, when the lower part has no natural frequency near the horn vibration frequency, the displacements and strains are large. The contact area significantly affects the dynamic behaviour of the interface. This is because its dynamic behaviour depends on the natural frequencies of the parts to be joined while the natural frequency of the lower part is easily improved by the contact area.

1. Introduction

Ultrasonic welding is one of the most widely used methods for joining thermoplastic parts in automotive, electronic and medical appliances. Its main advantages are that it is fast, economical and easily automated. In the welding process, the two plastic parts to be joined are placed on the fixture before high frequency mechanical vibration is applied to the parts through an ultrasonic horn. This generates heat at the joint area and locally melts thermoplastics. When cooled, the parts are welded together.

The ultrasonic horn is of prime importance to the quality and efficiency of ultrasonic welding. Various studies have analysed the design of horns [1, 2]. Heating thermoplastics is essential to accomplish the weld. The heat generation mechanisms have been investigated [3, 4]. There are two types of heat generation mechanism: interfacial friction heating and viscoelastic friction heating at the joint interface. The temperature distribution in ultrasonic welding has also been studied [5, 6]. Heat generation directly affects the melting behaviour of the interface and is related to the dynamic behaviour of the interface, such as displacement and elastic strain depending on the horn vibration.
Tsujino et al. [7, 8] measured welding characteristics and temperature rises at the interface of lapped plastic sheets across a frequency range of 27 to 180 kHz.

When the distance between the ultrasonic horn and the interface is greater than 6 mm, it is referred to as far field ultrasonic welding [9]. In this case, the horn vibration is not transmitted directly to the interface and the dynamic behaviour of the interface can be affected by the dynamic behaviour of the parts being welded. The dynamic behaviour of the parts depends on both the dynamic characteristics such as natural frequency and mode shape of the parts and the horn vibration frequency. In previous papers [10, 11], we investigated the effect of horn vibration frequency on the dynamic behaviour of the interface in far field ultrasonic welding. The frequency considerably affects the dynamic behaviour of the interface while the horn vibration frequency is usually fixed because the horn is vibrated at its resonant frequency. It is therefore necessary to improve the dynamic characteristics of parts to maintain the high quality of ultrasonic welding. However, we have not dealt with how to improve the dynamic characteristics of parts in the previous study. Furthermore, a method without changing the design of parts is required.

In this paper, we change the dynamic characteristics of the plastic part to be joined by varying the contact area between the lower part and the fixture, and investigate its effect on the dynamic behaviour of the joint interface. First, a method for predicting the dynamic behaviour of the interface is presented. The prediction method is based on finite element dynamic contact analysis. In analysis, a welding pressure or static force is considered. We apply a static force to the rigid body pilot node of the fixture and then a sinusoidal displacement to the rigid body pilot node of the horn. To validate the presented method, the predicted displacements of the parts are compared with the measured data. Next, the displacements and elastic strains of the interface are predicted and compared for different contact areas. Finally, the reason for the change in the dynamic behaviour of the interface with the change in the contact area is discussed based on the natural frequencies of the parts.

2. Ultrasonic welding of thermoplastics

Ultrasonic welding is one of the most common methods for joining two thermoplastic parts. Figure 1 shows the welding process. In this process, two plastic parts to be joined are placed together on the fixture. The ultrasonic horn is moved into contact with the upper part and a welding pressure or static force is applied to the horn. The horn is then vibrated vertically with a frequency of 15 to 40 kHz and an amplitude of 10 to 50 μm. This generates heat at the joint area and locally melts the thermoplastics. The vibration is stopped to cool the melted plastic and the two parts are then welded together.

![Ultrasonic plastic welding](image)

Figure 1. Ultrasonic plastic welding.

In ultrasonic welding, heat is generated by the interfacial friction and viscoelastic friction. It is related to the dynamic behaviour of the interface, such as displacement and elastic strain. When the distance between the ultrasonic horn and the interface is greater than 6 mm, it is referred to as far field ultrasonic welding. In this case, the horn vibration is not transmitted directly to the interface and the dynamic behaviour of the interface can be affected by the dynamic behaviour of the parts being welded. The dynamic behaviour of parts depends on both the dynamic characteristics such as natural
frequency and mode shape of parts and the horn vibration frequency or the ultrasonic welding machine’s operating frequency. Because the operating frequency is usually fixed because the horn is vibrated at its resonant frequency, it is necessary to improve the dynamic characteristics of parts to maintain the high quality of ultrasonic welding.

The plastic parts used in this paper are rotationally symmetrical about their central axes except some small ribs. The lengths of the upper and lower parts are approximately 58 and 31 mm, respectively. The distance between the ultrasonic horn and the interface is approximately 7 mm. A shear join between parts was used.

3. Dynamic contact analysis

3.1. Finite element analysis of contact problems

At the beginning of the welding, the contact surfaces of the two parts being welded can come into and go out of contact. To predict the dynamic behaviour such as displacement of the joint interface, we must solve the dynamic contact problem.

The basic steps for contact analysis using finite element (FE) software are as follows: First, build the FE models of the parts to be joined, the horn and the fixture. Identify the contact regions between the parts, between the upper part and horn and between the lower part and fixture. Next, define contact elements by overlaying them on the contact regions. Apply a static force to the fixture and a sinusoidal displacement to the horn. Finally, solve the dynamic contact problem.

The two surfaces, which are already in contact or have a possibility of contact, are called a contact pair. The contact elements recognize whether the contact pair is in or out of contact. For the normal direction of the contact surface, the forces transferred between the parts and the impenetrability condition that one part cannot penetrate another part are two important things. Figure 2 shows the contact force and the impenetrability condition.

The impenetrability condition can be represented as

\[ g_n = (\{u_1\} - \{u_2\}) \cdot \{n\} \geq 0 \]  

where \( g_n \) is the normal gap between the points on the surfaces of the contact pair, \( \{u_1\} \) and \( \{u_2\} \) are the position vectors of the points of parts 1 and 2 and \( \{n\} \) is the unit normal vector of the contact surface. If the contact pair is in contact and violates the impenetrability condition, a contact algorithm is applied to satisfy the impenetrability condition. There are three main algorithms: the penalty method, Lagrange multiplier method and augmented Lagrangian method [12, 13].

The penalty method introduces a fictitious linear spring between the contact pair shown in figure 3 and the penetration can be controlled by the penalty parameter called the contact stiffness. The contact stiffness \( k_n \) affects both accuracy and convergence. As \( k_n \) is increased, the penetration \( g_n \) decreases, leading to very accurate results. However, high \( k_n \) can cause numerical instability because the stiffness matrix becomes poor. The contact force \( F_n \) is calculated by

\[ F_n = k_n g_n \]  

Figure 2. Contact force and impenetrability condition.

Figure 3. Contact stiffness between contact pair.
The Lagrange multiplier method introduces the Lagrange multiplier, which is the contact force as an additional degree of freedom, and solves directly for the contact force. Though this method provides an exact solution and does not require contact stiffness, it has additional degrees of freedom and requires iterations to satisfy the impenetrability condition. This often causes poor convergence.

The augmented Lagrangian method is a combination of the penalty and the Lagrange multiplier methods. It starts with the penalty method and then if the penetration exceeds the allowable value, the contact force is augmented with Lagrange multiplier. The contact force $F_n$ is calculated by

$$F_n = k_n g_n + \lambda$$  \hspace{1cm} (3)

where $\lambda$ is the Lagrange multiplier.

For the tangential direction of the contact surface, Coulomb’s law is used to describe the friction phenomenon. The main problem with the Coulomb friction law is the discontinuity of the friction force at transition from sticking to sliding [14]. To permit a smooth transition from sticking to sliding, a friction model as shown in figure 4 is introduced. During sticking before sliding, a small deformation is permitted. During sliding, the tangential force acting at the contact surfaces equals the friction force.

$$F_t = \mu F_n$$

![Figure 4. Friction model.](image)

For sticking, $F_t = k_t g_t$ if $|g_t| < \frac{\mu}{k_t} |F_n|$,

$$\begin{align*}
|F_t| = \begin{cases} 
  k_t |g_t| & \text{if } |g_t| < \frac{\mu}{k_t} |F_n| \\
  \mu |F_n| & \text{else}
\end{cases} 
\end{align*}$$  \hspace{1cm} (4)

where $F_t$ is tangential force, $k_t$ is tangential stiffness as penalty parameter, $g_t$ is relative displacement along the tangential direction and $\mu$ is friction coefficient.

3.2. Finite element model and analysis procedure

In this paper, the finite element software ANSYS is used to perform dynamic contact analysis. Because the two parts were symmetrical about their central axes, an axisymmetric model was used. Figure 5 shows the FE model for the contact analysis. The parts were modelled with a two dimensional plane element (Plane182). The material of the plastic parts was polyacetal resin and its properties were Young’s modulus of 2.6 GPa (23°C), Poisson’s ratio of 0.35 and mass density of 1410 kg/m$^3$. The FE model for each of upper and lower parts was modified so that its natural frequencies matched the measured natural frequencies as close as possible. The horn and the fixture were defined as a rigid body. Figure 6 shows the enlarged view of interfaces between the horn and upper part, between the two parts and between the lower part and fixture. The contact elements (Conta171 and Targe169) were overlaid on the surfaces at the interfaces. The contact behaviours between the contact pair for the horn and upper part were separation in the normal direction and sliding in the tangential direction. The same contact behaviours were set for the two parts. No separation and no sliding were set for the lower part and fixture. The friction coefficient of the contact surface between the parts was set at 0.4, which was obtained in the previous paper [10].
During ultrasonic welding, a welding pressure or static force is applied to the horn and the horn is vibrated. However, FE analysis does not enable boundary conditions to conflict, that is, displacement and force bound conditions can never be prescribed at the same time for the same node. We apply an upward static force to the rigid body pilot node of the fixture and a sinusoidal displacement to the rigid body pilot node of the horn. Because welding pressure differs depending on the operating frequency, we determined the upward static force from the air pressure, the diameter of air cylinder and the horn weight \[ 11 \]. After the upward static force was applied, the sinusoidal displacement was applied at the operating frequency. The contact solution algorithm was the augmented Lagrangian method in the normal direction of the contact surface and the penalty method in the tangential direction. The implicit time integration algorithm was the Newmark method with the time step size of \( 1/200 \) of the operating frequency period. The time step size and the contact stiffness were automatically adjusted to improve convergence.

![Figure 5. FE model for the contact analysis.](image)

![Figure 6. Contact pairs.](image)

4. **Validation of the prediction method**

The prediction method described in the previous section is validated by comparing the predicted and measured displacement responses.

4.1. **Welding experiment**

The welding time is typically less than 1 s. The horn vibration starts at about 0.1 s after the welding pressure is applied and the vibration is maintained for 0.5 s. The thermoplastics are melting at 10 ms after the vibration is applied. We focus on the dynamic behaviour for 2 ms before the thermoplastics melt.
Welding experiments were done at two different operating frequencies: 15 and 19 kHz with an amplitude of 30 μm. The horizontal displacements of the parts were measured at two measuring points as shown in figure 7 using laser displacement sensors (Keyence LK-H023, 200 kHz sampling frequency).

Figure 7. Measuring points.

4.2. Prediction of displacement responses
The displacement responses were predicted for horn vibration at 15 or 19 kHz with an amplitude of 30 μm. The upward force of 341 N was applied for 15 kHz and 260 N for 19 kHz. The responses over 50 periods of each frequency were calculated and extracted at the nodes coincident with the measuring points.

Figure 8 shows the frequency spectra of the measured and the predicted displacements obtained by FFT. Figure 8(a) and (b) show results for the 15 kHz and 19 kHz operating frequencies, respectively. At 15 kHz, several large peaks are observed for both measured and predicted results even though the horn was vibrated at 15 kHz. In addition, the measured and predicted results have similar amplitude and frequency distributions. At 19 kHz, there is a dominant peak near 19 kHz for both the measured and predicted results. Additionally, the measured and predicted results have similar differences
between the displacements of points A and B, that is, the amplitude for point A is much larger than that for point B. These indicate that the predicted results are a good agreement with the measured results and the prediction method presented in this paper is valid.

5. Effect of contact area with fixture
We investigate the effect of contact area between the lower part and the fixture on the dynamic behaviour of the joint interface. In this paper, because we used the axisymmetric model, the contact length $l$ shown in figure 9 was varied to 4.4 (current model used in the experiment), 3.0 and 2.0 mm. The horn vibration frequency was 19 kHz.

![Figure 9. Contact length.](image)

5.1. Displacement of the interface
To examine the dynamic behaviour of the interface, displacements were predicted for different contact lengths. The nodes shown in figure 10 were considered because they were on the contact surfaces and close to each other at a steady state after the horn vibration was started.

![Figure 10. Nodes considered for the displacements of the interface.](image)

Figure 11 shows the displacements of the two nodes. Figures on the left and right are for the $x$ direction (radial direction) and $y$ direction (axial direction), respectively. The blue solid line and red dashed dotted line denote the results of the upper and the lower parts, respectively. For reference, horn displacement is depicted with a black dashed line in the $y$ direction.

For the 4.4 mm contact length, the displacements of the upper and the lower parts are in phase, as demonstrated as they are synchronized with the horn. This implies that the two parts move synchronously and the relative displacement is small in the $y$ direction even though separation was permitted at the interface. Consequently, a dominant peak appears near 19 kHz in the frequency spectra, as shown in figure 8(b). Conversely, for the 3.0 and 2.0 mm contact lengths, the displacements of the upper and the lower parts do not synchronize with the horn even though the horn was vibrated at 19 kHz. Furthermore, their displacements are out of phase. This implies that the upper part repeatedly collide with the lower part at the interface. This is similar behaviour to the result for the 15 kHz
operating frequency and several peaks appear in the frequency spectra, as shown in figure 8(a). Comparing the results indicates that the displacements for the 2.0 and 3.0 mm contact lengths are much larger than that for 4.4 mm in the y direction.

![Graphs showing displacement over time](image)

Figure 11. Displacements on the contact surfaces.

5.2. Elastic strain of the interface

As stated in [15], viscoelastic friction heating is the main heat generation mechanism at the interface in the ultrasonic welding of thermoplastics. We investigate the elastic strain of the elements along the contact surfaces shown in figure 12 when the surfaces deformed as shown in figure 11.

Figure 13 shows the equivalent elastic strains of the elements. The horizontal axis denotes the element number along the surface and the vertical axis denotes the sum of the equivalent elastic strain at each time step over 50 periods for each element. Comparing the results indicates that the elastic strains for the 2.0 and 3.0 mm contact lengths are much larger than those for 4.4 mm at almost all elements for both upper and lower parts. This is because the displacements for 2.0 and 3.0 mm are much larger than those for 4.4 mm in the y direction, as shown in figure 11. Furthermore, a large
elastic strain spreads widely along the surface for 2.0 and 3.0 mm while the elastic strain for 4.4 mm peaks at element number 16. This demonstrates that when the contact lengths are 2.0 and 3.0 mm, the contact position between the two parts moves along the interface and they collide. Conversely, when the contact length is 4.4 mm, the contact position stays near element number 16.

Therefore, the contact length between the lower part and the fixture significantly affects the dynamic behaviour, especially the elastic strain along the interface. This greatly influences heat generation, which affects quality of ultrasonic welding.

![Figure 12. Elements considered for the elastic strains.](image)

![Figure 13. Equivalent elastic strains along the surfaces.](image)

\[ : 4.4 \text{ mm contact length} \quad : 3.0 \text{ mm contact length} \quad : 2.0 \text{ mm contact length} \]

5.3. **Discussion based on natural frequency**

To discuss the reason for the difference in the dynamic behaviour of the interface for different contact lengths, the dynamic characteristics of the parts are examined.

The natural frequencies were obtained for the upper and the lower parts, respectively. Figure 14 shows the FE models for the modal analysis. For the upper part, two different constraint conditions

![Figure 14. FE models for the modal analysis.](image)
were used: the contact surface between the upper part and the horn was fixed or free because the upper part touches or does not touch the horn during the welding. For the lower part, the contact surface between the lower part and the fixture was fixed while its length was varied, as described above.

Table 1 shows the natural frequencies for the upper and lower parts. Table 1(a) indicates that the upper part has a natural frequency near 19 kHz regardless of the constraint condition: 7th mode for the fixed condition and 8th mode for the free. Table 1(b) indicates that the natural frequencies of the lower part decrease with the decrease of the contact length. The lower part has the natural frequency of almost 19 kHz for the 2nd mode with the 4.4 mm contact length while it has no natural frequency near 19 kHz for other contact lengths. Both upper and lower parts have a natural frequency near 19 kHz when the contact length is 4.4 mm. Their mode shapes shown in figure 15 have large deflections at points A and B. This means that when the horn is vibrated at 19 kHz, both parts easily vibrate together. Consequently, the displacements at points A and B grows as shown in figure 8(b) while the relative displacement of the interface is small. Conversely, for the 2.0 and 3.0 mm contact lengths, when the horn is vibrated at 19 kHz, the upper part vibrates greatly while the lower part barely moves. This causes the collision at the interface and the large displacements of the contact surface.

Therefore, the dynamic behaviour of the interface depends on the natural frequency of the plastic parts to be joined while the natural frequency of the lower part is easily improved by the contact length between the lower part and the fixture.

Table 1. Natural frequencies for the upper and lower parts.

(a) Upper part

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<td>1</td>
<td>2</td>
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<tr>
<td>Fixed</td>
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<td>Free</td>
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(b) Lower part

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<td>9.2</td>
<td>19.3</td>
</tr>
<tr>
<td>3.0</td>
<td>8.4</td>
<td>15.4</td>
</tr>
<tr>
<td>2.0</td>
<td>7.9</td>
<td>14.1</td>
</tr>
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Figure 15. Mode shapes for the upper and the lower parts.
6. Conclusions
In this paper, we investigated the effect of the contact area or contact length between the lower plastic part and the fixture on the dynamic behaviour of the joint interface. First, we presented the method for predicting the dynamic behaviour of the interface being welded using finite element dynamic contact analysis. The displacements and elastic strains of the interface were predicted and compared for different contact lengths. The results showed that the dynamic behaviour of the interface depends on the dynamic characteristics of the two parts to be joined. When both natural frequencies are close to the horn vibration frequency, the displacements and elastic strains of the interface are small. Conversely, when the lower part has no natural frequency near the horn vibration frequency, the displacements and elastic strains are large. Therefore, the contact area or contact length between the lower part and the fixture significantly affects the dynamic behaviour of the interface. This is because its dynamic behaviour depends on the natural frequencies of the plastic parts to be joined while the natural frequency of the lower part is easily improved by the contact area or contact length.

References