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Process Condition Optimization for Plastic–Membrane Welding by a Ultrasonic Welding

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Abstract

Ultrasonic welding has come into prominence with the increase in demand for micro-welding techniques by increase in small precision components. This study designs and fabricates a 40 kHz horn used for plastic welding by applying the finite element analysis. An experimental set-up was constructed for ultrasonic welding. The radiation time, pressure, and voltage were set as the process parameters applied to plastic–membrane welding. A universal testing machine was used to measure the bond between the plastic and the membrane. The correlation between the process parameters and the bonding force was identified by the design of experiments. Consequently, an optimal process condition was determined.

Keywords: Optimization, Ultrasonic welding, Strength, Ansys, Process condition

INTRODUCTION

Many of the world's leading manufacturers in the auto, semiconductor, and shipbuilding industries are developing and utilizing more and more heterogeneous materials. Accordingly, the welding techniques for different kinds of materials are highlighted. Ultrasonic and friction welding using vibration or friction are used more than ever. Ultrasonic welding is safer and more precise than conventional welding; hence, it rapidly diffuses. However, studies on the main components of ultrasonic welding parts or the welding process for heterogeneous materials are not sufficient. Moreover, environmental regulations, such as those for volatile organic chemicals (VOCs), which target volatile organic compounds and lead, and restriction of hazardous substrates (RoHS) have been initiated in Europe and implemented among many advanced countries in the world. Such regulations restrict carbon emissions and reflect increasing interest in energy saving. Unlike conventional fusion welding, ultrasonic welding does not need a separate heat source, filler metal, and welding rod nor emit hazardous light or material. Therefore, ultrasonic welding emerges as an alternative welding technique from both economic and environmental perspectives. [1] This study designed a 40 kHz ultrasonic horn, then fabricated. A longitudinal ultrasonic welding system was constructed to evaluate the welding between the vent and the membrane and the welding strength through the experiment. Consequently, a process condition with the optimal welding strength was derived. The finite element analysis program was applied to the theoretical design of the ultrasonic horn to analyze and verify the ultrasonic welding mechanism. An impedance analysis was conducted to verify the design. The vent and the membrane were welded by a longitudinal ultrasonic wave using a transducer and the fabricated welding device. The reliability of the proposed welding process condition was verified by measuring the strength of the weld interface in a compression experiment.

DESIGN AND SIMULATION OF THE PIN MAP OBJECTS AND METHOD OF THE STUDY

Objects

The vent in Fig. 1 and the membrane in Fig. 2 were bonded by ultrasonic welding. The functions of the vent and the membrane included raising the air permeability of the electronic enclosure and maintaining the balance between the internal and external pressures, thereby preventing the ingress of pollutants. As air pollution becomes more serious because of auto vehicles, many countries tend to apply stricter environmental regulations concerning exhaust gas. The spread of electrical vehicles is also not optional any more. Accordingly, a process technique for the vent, which is one of the commonly applied electrical parts, must be developed.

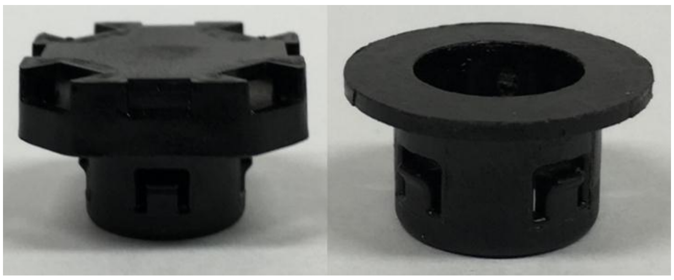


Figure 1: Vent

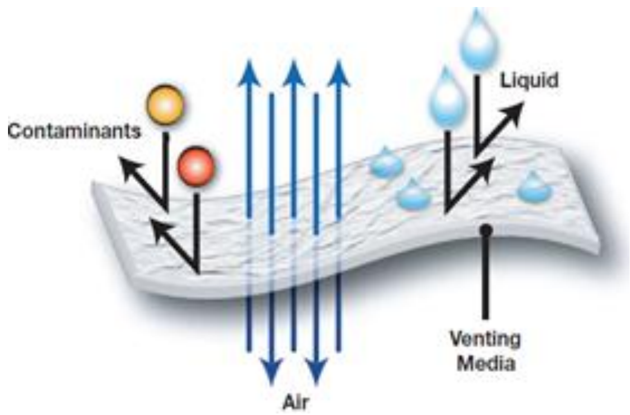
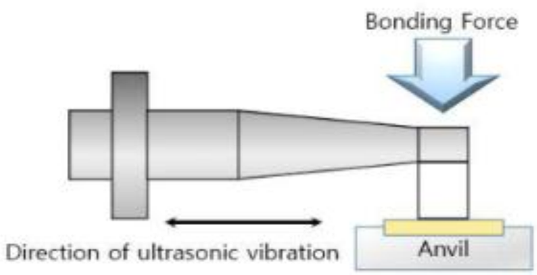


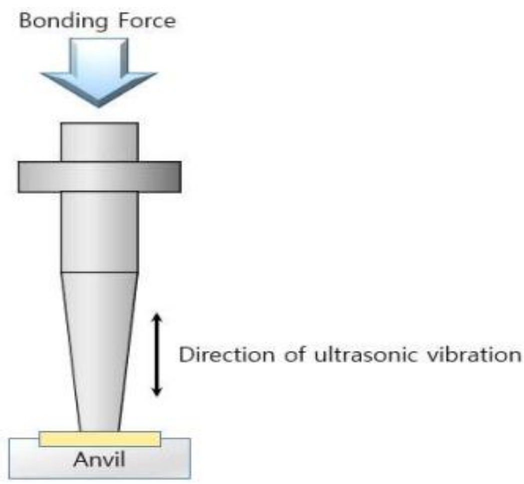
Figure 2: Membrane

Ultrasonic welding

An ultrasonic wave is a high-frequency wave over 20 kHz that offers a wide variety of applications, such as welding, cleaning, measuring, testing, and cutting. Ultrasonic welding joins heterogeneous metals or thermoplastics by applying transverse or longitudinal ultrasonic vibrations. In the case of plastics, longitudinal vibrations generate viscoelastic heat to melt plastics, thereby forming a weld junction. In the case of metals, transverse vibrations remove oxide film and impurities from the weld interface, thereby forming a solid-state weld junction by diffusion. Although ultrasonic welding is applied in different ways, each application needs a very similar welding equipment operation and configuration. The transverse ultrasonic welding of Fig. 3(a) applies vertical pressure and transverse vibration to welded items. This welding process is completed within 1 s; hence, it is advantageous in speed. However, the weld interface is not wide enough, and is much affected by the assembly state. Accordingly, transverse welding is not suitable for processes that demand a high level of reliability, and is usually applied to the metal welding process. Fig. 3(b) shows longitudinal ultrasonic welding, which is mainly applied to plastic bonding. Longitudinal welding applies a vertical ultrasonic wave to welded items, such that the vibration of a horn and the load have the same direction. This method requires a simple system configuration and minimizes the change of process parameters, thereby achieving high stability. In contrast, the vibration cannot be uniform and the weld interface has stains if the welding area is wider than the deposited area of the tool horn by more than half of the wave length.



(a) Schematic of the transverse welding system



(b) Schematic of the longitudinal welding system

Figure 3: Ultrasonic welding method

This study conducted ultrasonic welding using a longitudinal ultrasonic horn (Fig. 4). This process is a solid-state welding of materials using the vibrations generated from an ultrasonic horn while the radiation surface generating the vibrations applies a pressure to the surface of the specimen to be welded.

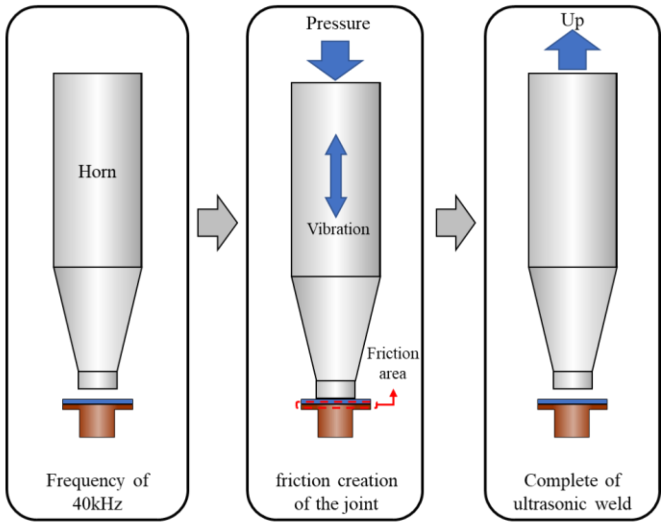


Figure 4: Schematic diagram of the ultrasonic welding process

SIMULATION AND RESULTS ULTRASONIC HORN DESIGN

Ultrasonic horn shape

The main functions of an ultrasonic horn were to amplify the vibrations to the desired level of a user and transfer the vibration energy from a transducer to a workpiece. As shown in Fig. 5, the ultrasonic horn was designed as a step horn with a high amplitude ratio and easy fabrication. The step was processed to have a round shape to prevent damage and a degraded stability caused by excessive misalignment, which is a typical disadvantage of step horns.

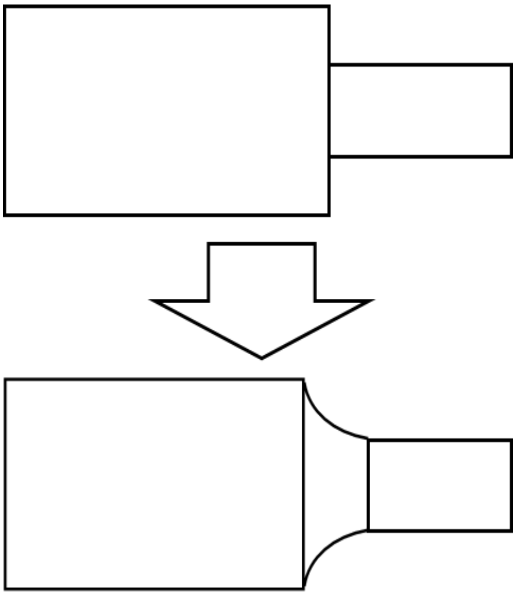


Figure 5: Step horn shape

Ultrasonic horn materials

The ultrasonic horn materials must be determined depending on the workpiece material and the horn weight. Hardness and rigidity should be mainly considered in choosing the materials. The horn is recommended to have a higher hardness than the workpiece. The ultrasonic horn volume increases when the ultrasonic transducer vibrates, which also increases the transfer loss of the ultrasonic vibration inside the material. Moreover, the amplitude at the output of the ultrasonic horn often does not reach a desired level if the cross-sectional ratio of the ultrasonic horn is not reduced. The typical materials of an ultrasonic horn used in the ultrasonic machine are titanium alloy and aluminum alloy. This study also applied titanium alloy and aluminum alloy to the finite element analysis. Table 1 presents the mechanical properties of the horn material.

Table 1: Mechanical properties of the horn material

Material	Mechanical properties		
	Density (㎏/㎥)	Young's Modulus (㎫)	Poisson's Ratio
Titanium	4,620	96,000	0.36
Aluminium	2,770	71,000	0.33

Modal analysis of the ultrasonic horn

ANSYS 16.2 was the commercial software used for the finite element analysis herein. The free–free boundary condition was applied to the modal analysis. The ultrasonic transducer material was aluminum, whereas that of the ultrasonic horn was titanium. Fig. 6 illustrates the designed horn shape. Table 2 presents the horn dimension.

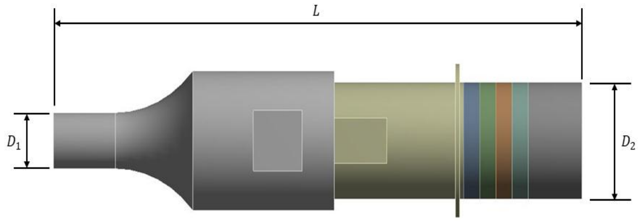
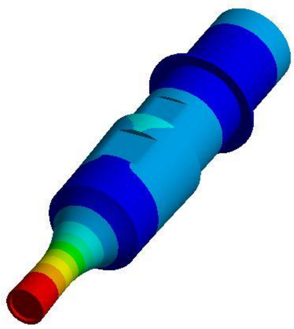


Figure 6: Step horn shape

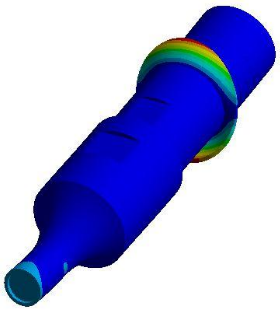
Table 2: Horn dimension

Classification	Dimension (mm)
D_1	12.0
D_2	25.0
L	132.0

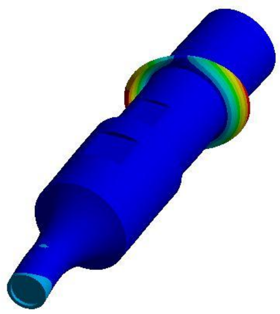
The horn directly transferred vibrations in the longitudinal mode to the workpiece for ultrasonic vibration-based welding. The vibration mode of the ultrasonic horn must generate a longitudinal vibration with the maximum amplitude at the output of the horn. The longitudinal vibration mode and the natural frequency of the real horn were verified by applying a modeled horn to the finite element analysis. The results were applied to the resonance design of the ultrasonic horn. The finite element analysis considered the difference of real boundary conditions by allowing approximately 1 kHz difference for the designed resonance frequency. The generator provided 40 kHz excitation frequency; hence, the analysis range of the natural frequency was set to 35–45 kHz. Fig. 7 presents the modal analysis results of the ultrasonic horn. As shown in Fig. 7(a), the 4th mode had a longitudinal vibration. The nearby frequency and the resonance frequency must be separated in the ultrasonic horn design to prevent the mode switching or overlapping between the excitation frequency and the frequency of its adjacent mode, which may distort the longitudinal vibrations or reduce the uniformity and amplification of the amplitude. Table 3 provides the frequency analysis results of each mode.



(a) Mode1



(b) Mode2



(c) Mode3

Figure 7: Vibration mode shape for the ultrasonic horn

Table 3: Natural frequency in the 35–45 kHz range

Mode	Frequency (Hz)
1	39009
2	43398
3	43488

Ultrasonic horn fabrication and resonance frequency analysis

Fig. 8 shows the ultrasonic horn fabricated based on the finite element analysis result.

Figure 8: BLT ultrasonic horn

The resonance frequency of the fabricated ultrasonic horn was measured, and the HP 4194A impedance analyzer was used. The measurement range was set to 39.0–42.0 kHz to conduct the impedance measurement. The mode analysis with the longitudinal vibrations using the finite element method produced 39.0 kHz. The resonance frequency was measured to be 40.2 kHz by the impedance analyzer. The two values showed a difference of 1.2 kHz. Moreover, a 0.5% difference from the real resonance frequency of 40 kHz was confirmed, which indicated the adequacy of the ultrasonic horn design. Fig. 9 depicts the resonance frequency of the ultrasonic horn obtained using the impedance analyzer.

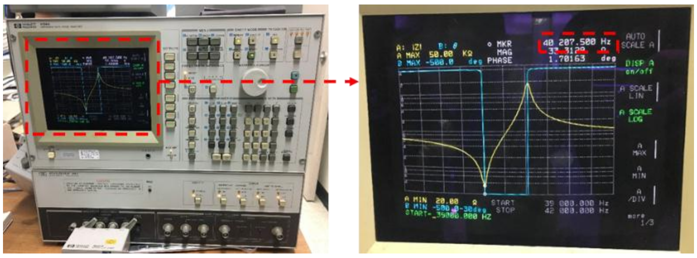


Figure 9: Result of Impedance analysis

ULTRASONIC WELDING EXPERIMENT AND WELDING STRENGTH MEASUREMENT

Experimental setup

The experimental setup of this study consisted of a generator, a servo motor, a load cell, and an indicator. The generator input an excitation frequency into the ultrasonic horn; the servo motor made the vent; the membrane applied pressure to the ultrasonic horn; the load cell measured the pressure applied to the ultrasonic horn; and the indicator output the pressure measurement. Fig. 10 shows a schematic diagram of the ultrasonic welding system.

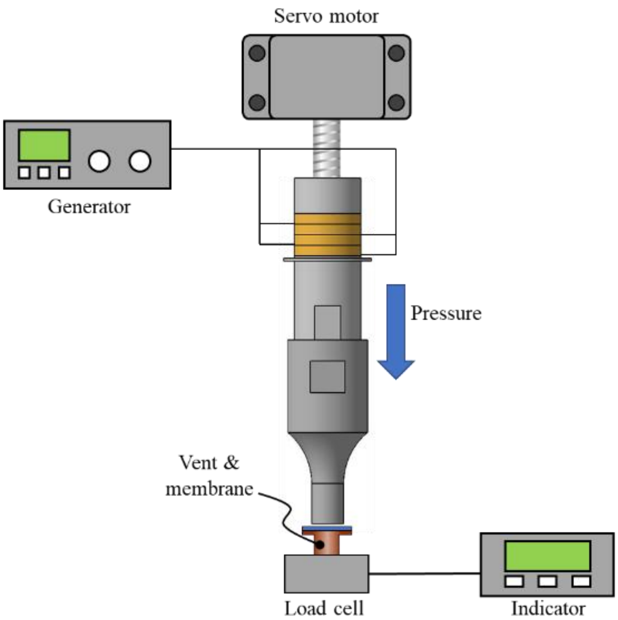


Figure 10: Schematic diagram of the ultrasonic welding system

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Experimental method and process condition

The pressure pushing down the workpiece, the radiation time input into the ultrasonic horn, and the output were determined using the process parameters to weld the vent and the membrane. The horn vibration may damage the workpiece if the pressure applied to the workpiece is too strong. In contrast, the membrane may deviate if the pressure is too weak. Accordingly, an appropriate pressure is essential. In addition, the membrane could be damaged or cut during welding if the radiation time is set to be too long. The vent and the membrane cannot be joined if the output voltage is weak. Thus, suitable radiation time and output are also very important factors of the process design. In ultrasonic welding, a vent is fixed to a jig, and a membrane is put on the vent. A horn connected to a servo motor is moved vertically downward by a control panel. Pressure is applied with the output surface of the ultrasonic horn and the workpiece being butted with each other. The pressure generated by the servo motor is measured using the load cell and the indicator. In this state, the generator sets the radiation time and the output voltage, which are input into the ultrasonic horn. Fig. 11 shows the ultrasonic welding system and its components.

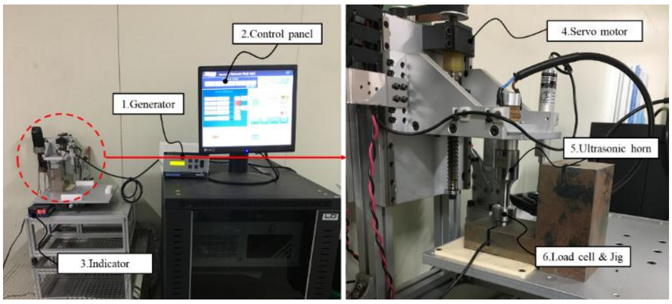


Figure 11: Ultrasonic welding system

The Box–Behnken method was used in the experiment to set the process condition and the experimental procedure. The pressure pushing down the workpiece by the ultrasonic horn, radiation time, and power were set as the three factors. A total of 30 rounds, including two iterations, were conducted in the experiment. Table 4 presents the condition of the designed experiment.

Table 4: Experiment condition

Factor	Level		
	Low	Middle	High
Pressure (kgf)	10	15	20
Time (s)	0.2	0.4	0.6
Power (V)	630	650	670

Weld junction strength measurement

The strength of the vent–membrane junction was measured by the universal testing machine (UTM) shown in Fig. 12. For the measurement, a pin-type jig smaller than the vent diameter was fabricated, and a compressive test was conducted. The welded vent was fixed to the jig, and the membrane was compressed using the pin at the speed of 5 mm/min until the weld junction of the vent and the membrane deviated, where the maximum load was measured. Table 5 provides the process condition in the experimental procedure based on the design of experiments (DOE) and the measurements of the welding strength obtained by the UTM.

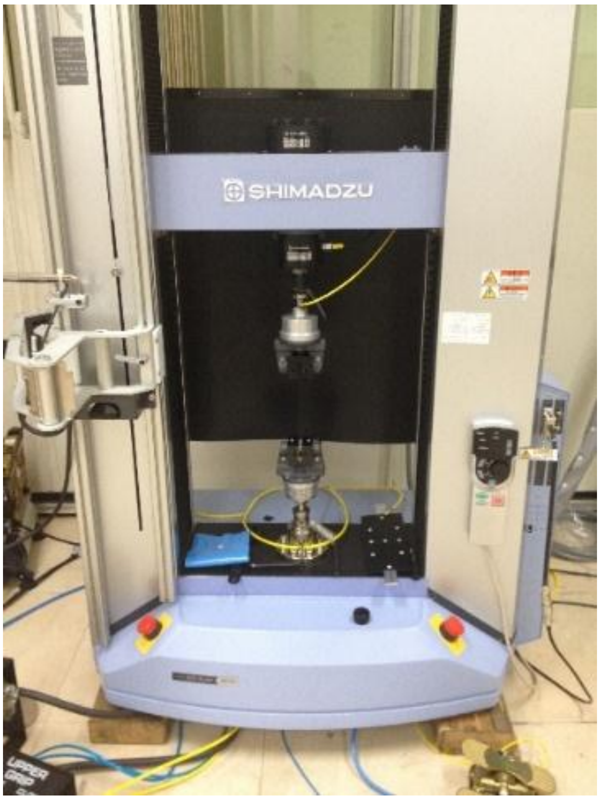


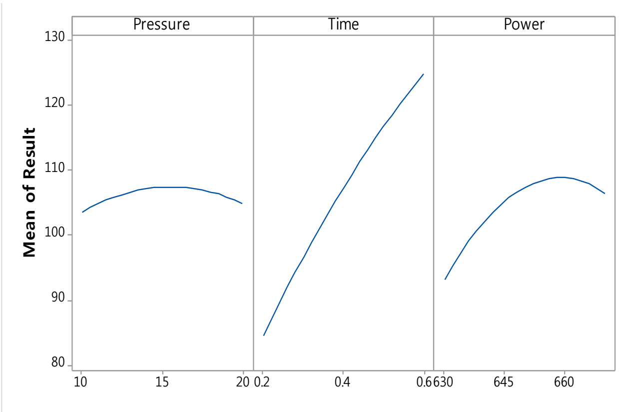
Figure 12: Universal testing machine

Table 5: Experimental conditions and results

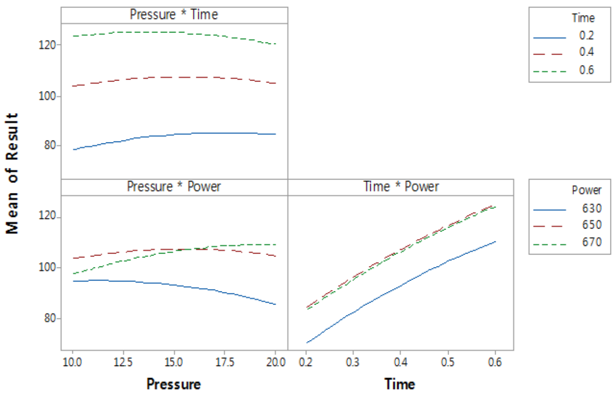
Std Order	Run Order	Pressure (kgf)	Time (s)	Power (V)	Result (N)
13	1	15	0.4	650	96.4
19	2	20	0.6	650	111.6
30	3	15	0.4	650	98.1
7	4	10	0.4	670	96.8
22	5	10	0.4	670	86.9
⋮					
11	26	15	0.2	670	84.9
21	27	20	0.4	630	82.7
1	28	10	0.2	650	84.0
15	29	15	0.4	650	119.4
18	30	10	0.6	650	127.6

Experimental results for the welding strength

The welding strength measurements obtained by the UTM were analyzed using Minitab. Fig. 13(a) shows a graph of the main effects on the welding strength. The pressure variation had little effect on the welding strength, while the radiation time and the power had a significant effect. The longer the radiation time of the ultrasonic wave, the higher the welding strength. However, the membrane may be broken when the radiation time increases. Accordingly, the process condition needs to be set to 0.6 s or below. Moreover, the welding strength was the highest when the power was between 650 and 670. Fig. 13(b) shows no intersection among factors, which indicates that no interaction existed among them.



(a) Main effects plot for result



(b) Interaction plot for result

Figure 13: Main effect and interaction diagrams

Table 6 shows the response surface analysis results. The significance probability (P value) for the design variable was below 0.05, which indicated a significant difference. Fig. 14 shows the residual analysis. The normal probability plot displays the points in a straight line; hence, the normality could be identified, and the homoscedasticity is shown by the random distribution of each value. Moreover, no trend existed according to the order of the observed values. Consequently, the analysis result model turned out valid.

Table 6: Response surface analysis results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure	1	7.29	7.29	0.08	0.777
Time	1	6532.68	6532.68	70.71	0.000
Power	1	700.93	700.93	7.59	0.010
Power * Power	1	418.62	418.62	4.53	0.050
Pressure	1	7.29	7.29	0.08	0.777

S	R-sq	R-sq(adj)
0.285165	92.78%	92.48%

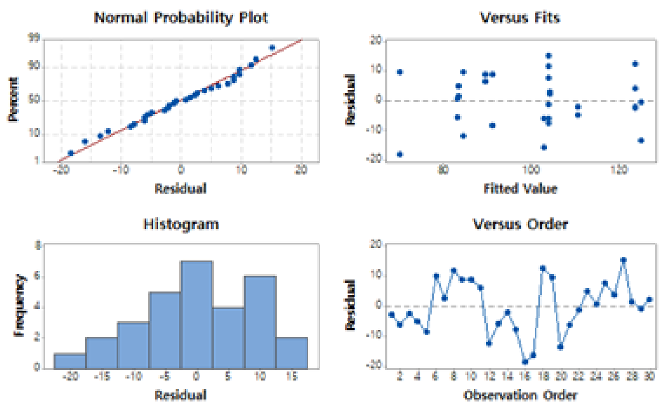


Figure 14: Residual plots for the result

As shown in Fig. 15, a response optimizer was used to derive the process condition ensuring the maximum welding strength. A pressure of approximately 15.8 kgf, a radiation time of 0.6 s, and a power of 660 V were the process conditions that produced 126.5 N as the maximum estimation of the welding strength. The derived optimal condition was applied to the weld experiment and the strength measurement. Table 7 presents the measurement results. The strength measurements were approximately 14% higher than the estimated 126.5 N. The difference between the estimation and the measurement was attributable to the dimensional error caused by the mold process of the vent and the difference of the welding strength caused by the irregular roughness of the weld interface.

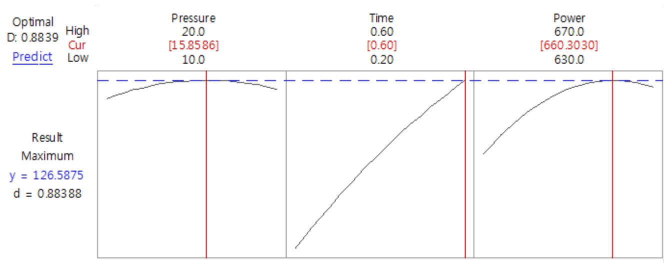


Figure 15: Response optimization result

Table 7: Measurements of the welding strength for the optimization condition

Specimen No.	Strength (N)
1	166.0
2	118.9
3	148.7
AVG	144.5

CONCLUSION

This study designed an ultrasonic horn with 40 kHz vibration, welded the vent and the membrane using a longitudinal ultrasonic wave, and conducted an experiment to measure the welding strength. The correlation between the welding strength and the process condition was analyzed by the DOE based on the experimental results. The significance was identified, and an optimized process condition was derived. The following conclusions are obtained:

(1) An experimental set-up for 40 kHz ultrasonic welding was configured. The process parameters were set, and the Box–Behnken method was used to determine an experiment plan before the welding process. A compressive test for the welded vent was conducted to measure the welding strength.

(2) The relationship between the welding strength and the process parameters was analyzed using the DOE. The main effect plot showed the influences of the process parameters on the welding strength. No interaction was observed.

(3) A response optimizer was used to derive an optimal process condition. Specimens were fabricated, and the welding strength was measured. The maximum estimation and the real measurement showed an approximately 14% difference, which was attributable to the dimensional error of the vent and the irregular roughness of the weld interface.

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