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PARAMETRIC INFLUENCE OF ULTRASONIC PLASTIC WELDING ON WELD STRENGTH OF ACRYLIC, POLYCARBONATE AND POLYPROPYLENE MATERIALS

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Abstract: Ultrasonic welding is the most widely used and fastest known welding technique for joining of thermoplastic materials. The process uses high frequency vibrational energy to produce low amplitude mechanical vibrations. These vibrations cause generation of heat at joint interface of the parts being welded, the heat generated is sufficient for melting of the thermoplastic materials and after cooling weld formation takes place. The fundamental aim of this study is to investigate the effect of welding parameters such as amplitude, pressure, weld time and thickness ratio on weld strength of thermoplastic materials. The thermoplastic materials such as Acrylic, Polycarbonate and Polypropylene are selected for this study. An experimental model based on full factorial design is selected and experiments are performed as per Design of Experiment. The significantly affecting process parameters are identified and ranked using analysis of variance (ANOVA) method. The outcome of this study is to identify the weld strength obtained in different thermoplastic materials for a selected range of process parameters.

Keywords: *Ultrasonic welding, Thermoplastic materials, Weld strength, Full factorial design, ANOVA, Design of Experiment.*

1. Introduction

Plastics are the most important part of everyday life; products made from plastics range from complex biomedical parts to disposable items. One of the important reasons for the great popularity of plastics in industries is the wide range of properties exhibited and their ease of processing. Plastics offer many advantageous characteristics such as high strength, high toughness, flame retardant characteristics, good rigidity and durability. These properties when combined with other features like excellent insulation properties, corrosion resistant properties and light weight make them prime material for industrial applications namely, automotive, aerospace, medical and other domestic appliance industries [16]. In today's era, the use of engineering plastics has cropped up in various industries, therefore, joining of these materials becomes a vital manufacturing operation. Processes of bonding plastic parts fall into two major categories, mechanical fastening and joining.

Fastening implicates the use of a foreign body to mechanically connect distinct parts. Screws, rivets, bolts, clamps are typical illustration of mechanical fasteners. In the case of joining, the parts are secured without foreign bodies. Glues, welding techniques and solvent are common examples of joining processes. Bonding uses chemical reactions to create a permanent joint. Examples of bonding include adhesives and solvent. Welding fuses the two parts together by non-chemical means. Among all the available joining techniques this paper focuses, particularly on ultrasonic welding [3]. Ultrasonic welding is a favorable technique for joining thermoplastic materials based on the low amplitude and high-frequency vibrations longitudinally or transversally applied to surfaces to be welded. Its main features are the high speed of the process and the fact that no foreign material is needed at the welding interface for either carbon or glass fiber reinforced composites [13].

2. Concept of Ultrasonic Plastic Welding

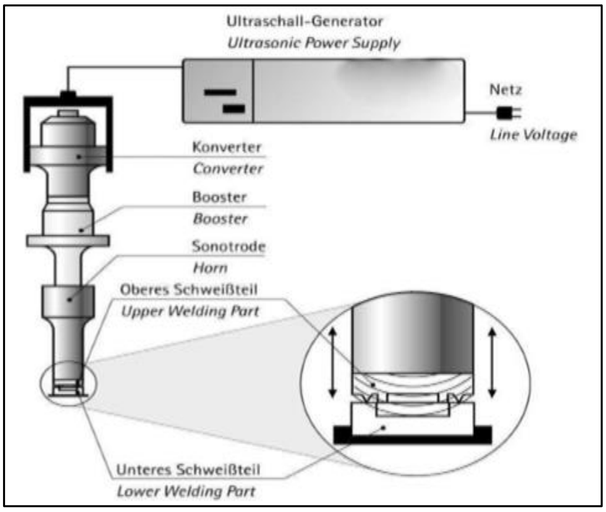

Fig. 1. Principle of Ultrasonic Welding [3]

When ultrasonic vibrations are passed through thermoplastic materials stationary sine waves are generated. Part of this energy is dissipated through intermolecular friction, which increases the heat in the bulk material, and part is transmitted to the joint interface where boundary friction causes localize heating. Optimal transmission of ultrasonic energy to the joint and successive melting behavior is therefore dependent on the geometry of the part, and also on the vibration absorption characteristics of the material. In order to minimize the loss of energy through absorption the source should be as close as possible to the joint. When the distance between the welding horn and the joint is less than 0.64 cm the process is known as near field welding. This process is mostly suitable for crystalline and low stiffness material as they have high energy absorption characteristics. Similarly, when the distance is greater than 0.64 cm then the process is known as far field welding. This is suitable for amorphous and high stiffness materials, which have low energy absorption capacity.[19]

3. Experimental Procedure

The experiments were conducted on the ultrasonic plastic welding machine. The welding is carried out on three different materials Acrylic, Polycarbonate and Polypropylene. In ultrasonic welding, the generator changes standard electrical power into electrical energy at the frequency at which the system is designed to operate. The high-frequency electrical energy produced by the generator is sent through a cable to the transducer which changes the electrical energy into vertical low-amplitude mechanical motion or vibration. These vibrations are then transmitted to a booster which is used to increase or decrease the amplitude of the vibration. The booster changes the amplitude of the vibration going into the horn so that the desired result is appropriate for the specific application. The vibrations are then transmitted to a horn of the proper size and shape to best deliver the vibrational energy to the workpiece. This mechanical vibration is used to produce the friction between the adjacent layers. Depending on its shape, the horn may further increase the amplitude of the vibration [15].

3.1. Advantages of Ultrasonic Welding

Ultrasonic welding is one of the most popular welding techniques used in industry and has various advantages which are listed as follows:

- It is fast, economical, easily automated, and well-suited for mass production
- Production rates up to 60 parts per minute being possible.
- It produces consistent, high-strength joints with compact equipment.
- Welding times are shorter than in any other welding method, and there is no need for elaborate ventilation systems to remove fumes or heat.
- The process is energy efficient and results in higher productivity with lower costs than many other assembly methods.
- Tooling can be quickly changed, in contrast to many other welding methods, resulting in increased flexibility and versatility.
- It is commonly used in the healthcare industry because it does not introduce contaminants or sources of degradation to the weld that may affect the biocompatibility of the medical device.

3.2. Experimental Setup

The experiment was carried out on Pneumatic Ultrasonic Welding Machine UPWM 1800. Table 1 shows the specifications of Ultrasonic Welding Machine. The actual experimental setup is shown in Fig. 2. Welding horn used in setup was made up of Titanium (Grade 5) material. The maximum amplitude of the Ultrasonic Welding Machine is of 55 μm peak/peak at 100% selection.

Fig. 2. Experimental Setup

Table 1. Specifications of Ultrasonic Welding Machine

Sr. No.	Parameter	Range
1	Model No.	UPWM 1800
2	Closing force(max)	7854 N
3	Generator	UPWM 1800
4	Ultrasonic output power	1800 W
5	Frequency	20 kHz
6	Max stroke	100 mm
7	Working table	375 mm × 365 mm
8	Horn	Titanium Grade- 5 Density= 4470 kg/m³ E= 115 GPa
9	Max pressure	10 bar
10	Max weld time	10 sec
11	Ultrasonic transducer capacity	2500 W
12	Ultrasonic booster capacity	1:1.5

4. Design and Manufacturing of Horn

4.1. Selection of Horn Material

Horn materials are usually high-strength aluminium alloy, titanium, or hardened steel. Aluminium offers various advantages such as excellent acoustic properties, easily machinable, cheap and readily available. Titanium has good surface hardness, fatigue strength and excellent acoustic properties. However, it offers certain drawbacks such as it is costly and hard to machine. The basic requirement for selection of horn materials is high fatigue strength and low acoustic losses. The other materials can be used but at the risk of high-power losses. By considering the basic requirements of horn materials, in this study Titanium Grade 5 of exponential type profile is selected as horn material.

Fig. 3. Titanium (Grade 5) Welding Horn

Table 2. Specifications of Welding Horn

Sr. No.	Parameter	Value
1	Material	Titanium Grade 5
2	Modulus of elasticity	115 GPa
3	Density	4470 kg/m³
4	Input frequency	20 kHz
5	Big end diameter	39 mm
6	Small end diameter	25 mm
7	Input resonant length	130 mm

5. Design of Experiments

Every experimenter has to plan and conduct experiments to obtain enough and relevant data so that he can infer the science behind the observed phenomenon. A well-planned set of experiments, in which all parameters of interest are varied over a specified range, is known as Design of experiment [17]. The first and foremost consideration is to choose the control or independent parameters which are to be controlled and the response parameters that are to be measured. The control parameters selected for this study are Amplitude, Pressure, Thickness ratio and Weld time as it was observed that these parameters greatly influence the weld strength of thermoplastic material.

For this experimental work, we have selected 4 control factors having 3 levels. According to Genichi Taguchi, for experiment having 4 factors and 3 levels, L9 orthogonal array is suitable where 9 indicates the number of experiments to be carried out. Hence, we have selected L9 orthogonal array for this experiment.

Table 3. Welding Factors and Levels

Parameter	Level 1	Level 2	Level 3
Amplitude (µm)	49	43	37
Pressure (bar)	2	3	4
Weld Time (sec)	2	2.5	3
Thickness Ratio	0.33	0.66	1

5.1. Results and Discussion

Total 27 runs were performed using Taguchi L9 (3^4) orthogonal array with three replicates to measure the weld strength of Acrylic, Polycarbonate and Polypropylene. Statistical software MINITAB 17 was used to design the matrix and analyze the main effects of processing parameters. The plots in fig. 4, fig. 5 and fig. 6 depict the effect of amplitude, pressure, weld time and thickness ratio on weld strength of Acrylic, Polycarbonate and Polypropylene materials respectively. The results obtained by performing the designed experiment on these materials are tabulated as follows:

A. Acrylic:

Table 4. Result Table for Acrylic Material

Ex. No.	Factors				Weld Strength (MPa)
	Amplitude (μm)	Pressure (bar)	Weld Time (sec)	Thickness Ratio	
1	49	2	2.0	0.33	30.65
2	49	3	2.5	0.66	45.75
3	49	4	3.0	1.00	54.00
4	43	2	2.5	1.00	46.75
5	43	3	3.0	0.33	46.50
6	43	4	2.0	0.66	29.90
7	37	2	3.0	0.66	54.10
8	37	3	2.0	1.00	32.55
9	37	4	2.5	0.33	28.40

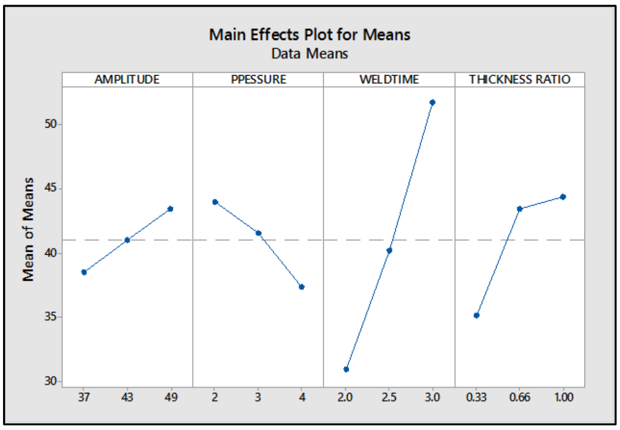

Fig. 4. The main effect plot of Acrylic material

Amplitude:
It was noticed that the weld strength increases linearly with an increase in amplitude. Higher amplitude offers higher weld strength for Acrylic. The maximum weld strength is obtained at an amplitude of 49μm. The percentage contribution of amplitude is about 4.06%.

Pressure:

In the case of Acrylic, the weld strength increases with a decrease in pressure. The maximum weld strength is obtained at a pressure of 2bar. The contribution of pressure in weld strength is about 7.29%.

Weld time:

It was observed that weld time is the most significant factor contributing to maximize the weld strength. As the weld time increases the weld strength increases significantly. The percentage contribution of weld time is about 70.97%.

Thickness ratio:

In this work, the different thickness ratios (0.33, 0.66 and 1) are selected. It can be noted that the thickness ratio is the second most significant factor which affects the weld strength. The percentage contribution of thickness ratio is about 14.16%.

B. Polycarbonate:

Table 5. Result Table for Polycarbonate Material

Ex. No.	Factors				Weld Strength (MPa)
	Amplitude (μm)	Pressure (bar)	Weld Time (sec)	Thickness Ratio	
1	49	2	2.0	0.33	29.70
2	49	3	2.5	0.66	23.35
3	49	4	3.0	1.00	19.00
4	43	2	2.5	1.00	26.00
5	43	3	3.0	0.33	25.21
6	43	4	2.0	0.66	20.45
7	37	2	3.0	0.66	27.80
8	37	3	2.0	1.00	26.00
9	37	4	2.5	0.33	28.00

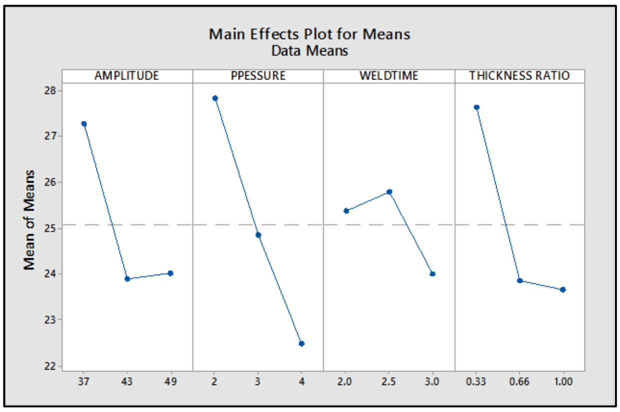

Fig. 5. The main effect plot of Polycarbonate material

Amplitude:
In the case of Polycarbonate, the weld strength is maximum at low amplitude. The maximum weld strength is obtained at an amplitude of 37 μm. The percentage contribution of amplitude in maximizing weld strength is about 15.79%.

Pressure:

In the case of Polycarbonate, the weld strength is maximum at minimum operating system pressure. In this setup, the minimum operating system pressure is 2 bar. The percentage contribution of pressure in weld strength is about 42.78%.

Weld time:

It was observed that weld time is the least significant factor contributing to maximize weld strength. The maximum weld strength is obtained at 2.5 sec. The percentage contribution of weld time is about 2.85%.

Thickness ratio:

Among all the selected control factors for polycarbonate material, thickness ratio is the second most significant factor. The percentage contribution of thickness ratio is about 23.34%. The maximum weld strength is obtained at a thickness ratio of 0.33.

C. Polypropylene:

Table 6. Result Table for Polypropylene Material

Ex. No.	Factors				Weld Strength (MPa)
	Amplitude (µm)	Pressure (bar)	Weld Time (sec)	Thickness Ratio	
1	49	2	2.0	0.33	15.02
2	49	3	2.5	0.66	14.22
3	49	4	3.0	1.00	15.12
4	43	2	2.5	1.00	14.96
5	43	3	3.0	0.33	10.05
6	43	4	2.0	0.66	12.05
7	37	2	3.0	0.66	11.92
8	37	3	2.0	1.00	11.50
9	37	4	2.5	0.33	9.50

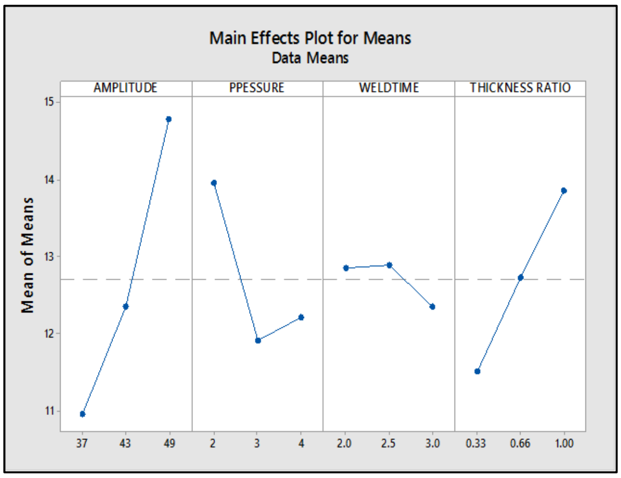

Fig. 6. The main effect plot of Polypropylene material

Amplitude:

It was noticed that the weld strength is maximum at an amplitude of 49 µm. As compared to other control factors amplitude is the most significant factor. The percentage contribution of amplitude is about 54.50%.

Pressure:

In the case of Polypropylene, the maximum weld strength is obtained at 2 bar. The contribution of pressure is about 12.60% for maximizing the weld strength.

Weld time:

It was observed that weld time is the least significant factor contributing to weld strength. The maximum weld strength is obtained at 2.5 sec. The percentage contribution of weld time is about 1.28%.

Thickness ratio:

The thickness ratio is the second most significant factor contributing to weld strength. The maximum weld strength is obtained at a thickness ratio of 1. The percentage contribution of thickness ratio is about 23.39%.

5.2. ANOVA Analysis

ANOVA analysis helps us to find the percentage contribution of input parameters on weld Strength of Acrylic, Polycarbonate and Polypropylene material. The results of ANOVA analysis are tabulated as follows:

A. Acrylic:

Table 7. Percentage Contribution of Process Parameter for Tensile Strength for Acrylic material

Source of Variation	% Contribution
Amplitude	4.06
Pressure	7.29
Weld Time	70.97
Thickness Ratio	14.16
Error	3.52
Total	100.00

B. Polycarbonate:

Table 8. Percentage Contribution of Process Parameter for Tensile Strength for Polycarbonate material

Source of Variation	% Contribution
Amplitude	15.79
Pressure	42.78
Weld Time	2.85
Thickness Ratio	23.34
Error	15.25
Total	100.00

C. Polypropylene:

Table 9. Percentage Contribution of Process Parameter for Tensile Strength for Polypropylene material

Source of Variation	% Contribution
Amplitude	54.50
Pressure	12.60
Weld Time	1.28
Thickness Ratio	23.39
Error	8.24
Total	100.00

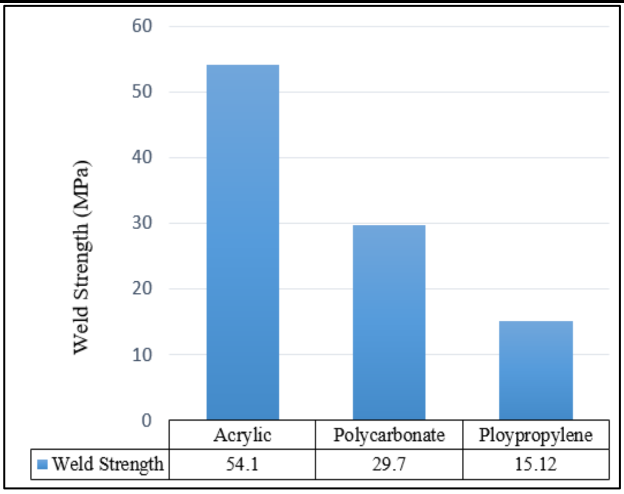

Fig. 7. Weld Strength Comparison

We can observe from the fig. 7 that the weld strength of Acrylic is more as compared to Polycarbonate and Polypropylene materials.

6. Conclusion

In this experimental work, various ultrasonic plastic welding parameters like Amplitude, Pressure, Weld time and Thickness ratio have been evaluated to investigate their influence on the weld strength. Based on the result obtained, the following conclusions can be drawn:

The weld time is the most significant control factor which affects the weld strength of the thermoplastic material. Meanwhile, it was also observed that amplitude is also equally significant.

- Increasing the weld time, the weld strength of Acrylic is improved.
- Similarly, for Polycarbonate pressure is the most significant control factor.
- For Polypropylene, amplitude is the most significant control variable.

We also observed that weldability of Polypropylene is more as compared to Polycarbonate and Acrylic materials.

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