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EFFECT OF ULTRASONIC WELDING PARAMETERS ON WELD STRENGTH OF THERMOPLASTIC MATERIALS USING TAGUCHI METHOD

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Abstract

The ultrasonic welding process is not only a well-known industrial joining process but it has also been a dynamic research area. Materials ranging from metals to non-metals are easily welded using this welding technique. Some research has already been carried out but the more extensive analysis is needed on ultrasonic welding of thermoplastics. Ultrasonic welding is a promising joining technique for thermoplastic composites based on the low amplitude and high-frequency vibrations transversally applied to surfaces to be welded. Its main features are the high speed of the process (welding times ranging from a fraction of a second to a few seconds) and the fact that no foreign material is needed at the welding interface. In this investigation, experimental data of the weld strength of Polypropylene (PP) is studied. The study has been carried out for understanding the significant effects of welding parameters such as Pressure, Amplitude, Thickness ratio and Weld time on weld strength of Polypropylene. In order to optimize the welding parameters, the Taguchi method is implemented and the significantly affecting process parameters are identified and ranked using analysis of variance (ANOVA) method. Also, a mathematical model is developed using Linear Regression Method. The outcome of this study helps us to identify the significant parameters affecting the weld strength of Polypropylene.

Keywords: Ultrasonic welding, Thermoplastics, Weld strength, Taguchi method, ANOVA, Linear Regression Method.

1. Introduction

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 behaviour is therefore dependent on the geometry of the part, and also on the ultrasonic absorption characteristics of the material. The closer the source of the vibrations is to the joint, lesser the energy that is lost through absorption [19]. Ultrasonic welding is used in almost all major industries in which thermoplastic parts are assembled in high volumes such as automotive, medical, electronic and packaging.

In the present research, an experimental investigation of Ultrasonic welding of Polypropylene (PP) material has been carried out. Linear regression method is employed to develop mathematical relationships between the welding process parameters namely Amplitude, Pressure, Weld time and Thickness ratio and the output variable Weld Strength. The developed mathematical model is verified by analysis of variance (ANOVA) method to check its adequacy. This mathematical model is helpful for predicting the weld strength as well as for choosing the optimum process parameters. The influence of process parameters on weld strength is discussed based on the main effect, ANOVA and S/N ratio.

2. Experimental Procedure

The experiments were conducted on the ultrasonic plastic welding machine. The welding is carried out on Polypropylene material. In ultrasonic welding, the generator changes standard electrical power (120-240 volts, 50/60 Hz) 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].

2.1. 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 the 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× 365mm
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

2.2. 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. The first and foremost consideration is to choose the control 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 [17].

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 2. 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

2.3. Methodology

In this experimental work, the test specimen selected for the experiment is of 90 mm × 20 mm with a thickness ratio of 0.33, 0.5 and 1. Taguchi L9 ($\mathbf{3^4}$) orthogonal array is employed as the design of experiment with 4 control variables and 3 levels. Total 18 (9×2) runs were performed with 1 sample. The response parameter weld strength was measured using a polymer tensile testing machine. Analysis of Variance (ANOVA) was applied to identify the significant effect of welding parameters on weld strength of Polypropylene (PP).

3. Results and Discussion

Total 18 runs were performed using Taguchi L9 (3^4) orthogonal array with 1 replicate to measure the weld strength of Polypropylene. Statistical software MINITAB 17 was used to design the matrix and analyze the main effects of processing parameters. The results were evaluated by employing the main effect plot, ANOVA, signal-to-noise ratio (SNR) analysis and linear regression method.

Polypropylene:

Table 3. Result Table for Polypropylene

Ex. No.	Factors				Weld Strength
	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

3.1 Signal-to-noise Ratio (SNR)

In Taguchi Method, there are three types of quality characteristics with respect to the target design. These quality characteristics are 'Smaller is better', 'Nominal is better' and 'Larger is better'. In this study, the higher value of the weld strength is desired, hence 'Larger is better' type quality characteristic is selected.

Table 4. Signal-to-noise Ratio

Treatment Condition	Mean Response	SNR
1	15.20	23.5334
2	14.00	23.0580
3	19.45	23.5910
4	36.60	23.4986
5	10.05	20.0433
6	12.55	21.6197
7	21.00	21.5255
8	14.50	21.2140
9	9.65	19.5545

Table 5. Response Table for Signal-to-noise Ratio

Level	Amplitude	Pressure	Weld Time	Thickness Ratio
1	20.76	22.85	22.12	21.04
2	21.72	21.44	22.04	22.07
3	23.39	21.59	21.72	22.77
Delta	2.63	1.41	0.40	1.72
Rank	1	3	4	2

From table 5, it is observed that for the given set of condition amplitude of 37 µm, the pressure of 2 bar, weld time of 2 seconds and the thickness ratio of 1 are the optimum values. Also, the amplitude has rank 1 which indicates that it is the most significant parameter in controlling the weld strength.

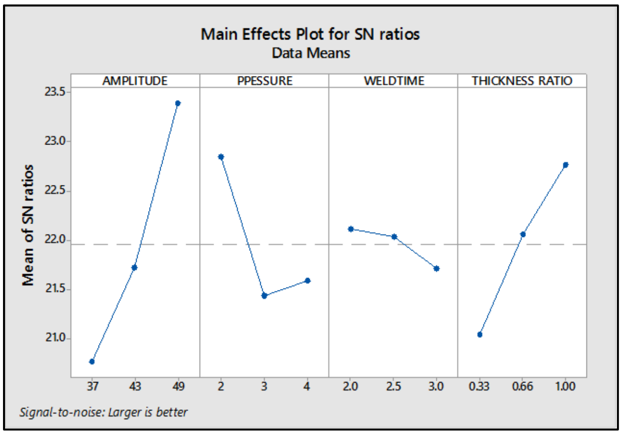

Fig. 3. Main Effects Plot for SNR

Table 6. Response Table for Means

Level	Amplitude	Pressure	Weld Time	Thickness Ratio
1	10.97	13.97	12.86	11.52
2	12.35	11.92	12.89	12.73
3	14.79	12.22	12.36	13.86
Delta	3.81	2.04	0.53	2.34
Rank	1	3	4	2

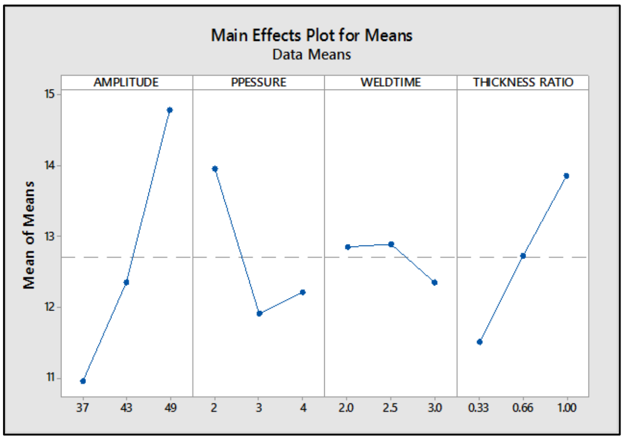

Fig. 4. Main Effects Plot for Means

3.2. Analysis of Variance (ANOVA)

The relative effect of the different factors can be obtained by the decomposition of variance which is commonly called Analysis of Variance (ANOVA). ANOVA is also helpful for estimating the error variance for the factor effects and variance of the prediction error.

From the table 7, it can be concluded that amplitude and thickness ratio are the most significant factors affecting the weld strength of the Polypropylene material. The percentage contribution of amplitude and thickness ratio is 56.82% and 21.33% respectively.

Table 7. Analysis of Variance

Sr. No	Factors	DOF	Sum of Square	Mean Square	F Ratio	% Contri.
A	Amplitude	1	21.8123	21.8123	25.16	56.82
B	Pressure	1	4.5588	4.5588	5.26	11.88
C	Weld Time	1	0.3651	0.3651	0.42	0.95
D	Thickness Ratio	1	8.1867	8.1867	9.44	21.33
	Error	4	3.4671	0.8668		9.03
	Total	8	38.3900	35.7897		100.00

3.3. Linear Regression Model

Linear Regression Model between amplitude, pressure, weld time, thickness ratio and weld strength was developed by using MINITAB 17 software. The regression equation is given as follows:

$$\ln(UTS) = 1.581 + 0.02523\times A - 0.0728\times B - 0.0463\times C + 0.2960\times D \quad (1)$$

Where,

A- Amplitude
B- Pressure
C- Weld time
D- Thickness ratio

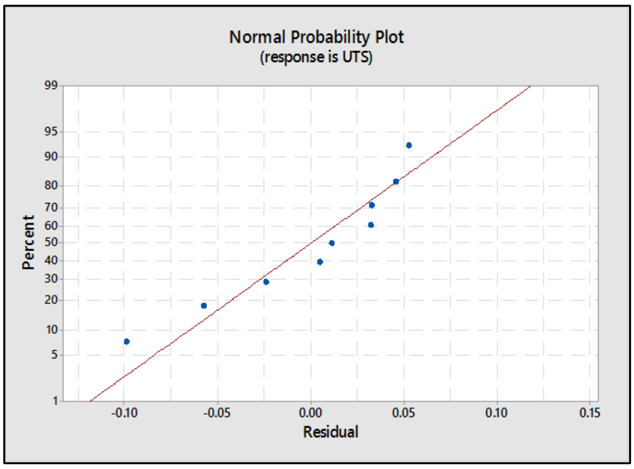

Fig. 5. Normal Probability Plot of the Residuals

Fig. 5 shows the Normal Probability Plot of Residuals for Welding Strength.

4. Conclusion

In this study, an experimental investigation of Ultrasonic Welding parameters is performed. The following conclusion can be drawn from the experimental results:

- ANOVA analysis shows that amplitude and thickness ratio are the most significant parameters contributing the weld strength. The percentage contribution of amplitude and thickness ratio are 56.82% and 21.33% respectively.
- It was observed from Taguchi response table for SNR and Mean data that amplitude has rank 1 and thickness ratio has rank 2 which implies that amplitude and thickness ratio are the most significant factors which contribute the weld strength.
- For Polypropylene material, pressure and weld time are the least significant factors.

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