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Influence of Processing Parameters on Ultrasonic welding of Thermoplastic Material Using Taguchi Method

Amitkumar Makwana[1], Vipul R Patel[2]

[1]*PG Student, Department of Mechanical Engineering, Babaria Institute of Technology*
[2]*Assistant Professor, Department of Mechanical Engineering, Babaria Institute of Technology*

Abstract *—Rapid performance and the absence of filler material in Ultrasonic welding has established itself as one the most effective techniques in manufacturing industry for fusing plastic assemblies. Faster joining and reliable process for developing plastic utility has increased in past decade. In Ultrasonic welding, by applying high-frequency vibratory energy and pressure, thermoplastics materials are joined. Because of high-quality joints and low cost of Ultrasonic welding of Thermoplastic materials has become a popular process in the industry. In this research, experimental data of welding strength of acrylonitrile butadiene styrene (ABS) and Polycarbonate (PC) of material for ultrasonic welding are studied. For the investigating the significant effect of process parameters of ultrasonic welding, various welding parameters like Amplitude, Weld time and Welding Pressure and material thickness has been studied. In order to determine critical states of the welding parameters. Taguchi Orthogonal Array method is employed as Design of Experiments and analysis of variances has applied. Mathematical model was developed using Linear Regression method and experiment was validated with confirmation Test.*

Keywords- *Ultrasonic Welding, Thermoplastic Material, Process Parameters, Tensile Strength, Taguchi Orthogonal Array, ANOVA, Linear Regression Analysis.*

I. INTRODUCTION

ABS (acrylonitrile butadiene styrene) a copolymer, is made up of polymerized styrene and acrylonitrile with polybutadiene, The styrene gives the plastic a shiny and glossy impervious surface. The polybutadiene is a rubbery substance which provides toughness at even low temperatures. The nitrile makes ABS stronger than pure polystyrene. ABS has very good property of High impact resistance at low temperature, High chemical resistance to Acid and alkalis, very good toughness, shiny and glossy surface and electrical insulating properties [3]. Due to strong, tough and optically transparent characteristics Polycarbonate (PC) is widely used in engineering application. Polycarbonate material is very pliable. It can be formed at room temperature without cracking or breaking. Polycarbonate material can form small bends without application of heat. Polycarbonate has very good property of high durability, high chemical resistance to acid and alkalis, shatters resistance, lightweight, transparency, and easily machined [3].

Joining of ABS to PC has already found numerous application in automotive industry, Consumer goods, Enclosures for electrical and electronics, kitchen appliances and medical industry.

In an Ultrasonic Welding, Solid state of weld is created by holding the work-pieces together under pressure and by applying ultrasonic vibration to work-pieces [1]. It is commonly used for plastics and metals, and especially for joining dissimilar materials. In ultrasonic welding, does not require soldering materials, or adhesives, connecting bolts, and hard nails, necessary to join the materials together.

In the present research, an experimental investigation of Ultrasonic welding of dissimilar plastics between ABS & PC 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 and the output variable Welding Strength. The developed mathematical model is tested by analysis-of-variance (ANOVA) method to check its competence. This mathematical model is useful for predicting the weld strength as well as for selecting the optimum process parameters. The influence of process parameters on weld strength are discussed based on the main effect, ANOVA and S/N ratio.

II. EXPERIMENT

2.1. Experimental Setup

The experiment was carried out on pneumatic ultrasonic press USP2500. Table 1 shows the specification of Ultrasonic welding machine. The actual experimental setup is shown in figure 1. For the given Ultrasonic welding machine, welding horn was made of EN 24 (AISI 4340) material. The ideal amplitude for the Ultrasonic welding machine is 20µm peak/peak at 100% selection.

Table 1. Machine Specification

Description	Value
Power Supply	220V 50Hz +20% -10%
Working Frequency	20KHz
Idle Amplitude	20µm peak/peak at 100% selection
Max. Power	2000W effective
Max. Converter Voltage	1700V effective

2.2. Welding Parameters

An experiment is designed such that, the information about the parameters affecting the process and inference of the parameter in the system can be drawn with minimum of efforts & time. The first & foremost consideration is to select the independent or confounding parameters which are to be controlled & the response parameters that are to be measured for the quality of performance of the process. The key parameters for ultrasonic welding are Amplitude, Frequency, Weld time and Pressure. It was observed that Amplitude, pressure and weld time are affecting parameters for this process. Also, Material thickness is considered as input parameter as, change in thickness of material may result in varying welding strength. The value of amplitude is taken in percentage as the ideal amplitude of machine is 20µm peak/peak at 100% selection. Below Table 2 shows the selected values of Welding parameters.

Table 2. Welding Factors & Levels

Parameter	Level 1	Level 2	Level 3
Amplitude (%) (A)	70% (14 µm)	80 % (16 µm)	90% (18 µm)
Pressure (bar) (B)	3	3.5	4
Weld Time (Sec) (C)	1.25	1.5	1.75
Thickness (mm) (D)	1.5	1.75	2.00

2.3. Methodology

In this Experimental research the test specimens were prepared according to standard EN 12814-3. The specimen selected for experiment are, ABS of 70 mm x 10 mm with 1.5, 1.75 & 2mm thickness and PC of 70 mm x 10 mm with 1.5, 1.75 & 2 mm thickness. Taguchi L_9 (3^4) method was employed as design of experiments with 4 input factors and 3 Levels. Total 18 (9x2) runs were performed with 2 replicates. During the Study, as a response parameter welding strength of ABS of PC was measured using universal tensile testing machine. Analysis of Variance (ANOVA) was used to identify the significant effect of the influencing parameters on the Welding strength of Ultrasonic welded specimen.

III. RESULTS & DISCUSSION

Total 18 runs were performed using Taguchi L_9 (3^4) design with two replicates to measure welding strength of ABS & PC joint. Statistical software MINITAB 14 was used to code the design matrix and analyze the main effects of the process parameters. The results were analyzed by employing main effects, ANOVA, and the signal-to-noise ratio (S/N) analyses. Finally, a confirmation test was carried out to compare the experimental results with the estimated results.

Table 3. Design Matrix with Experiment Result

Treatment Condition	Factors				Response Y	
	Amplitude (%) (µm)	Pressure (bar)	Time (sec)	Thickness (mm)	Trial 1 (Mpa)	Trial 2 (Mpa)
1	70% (14 µm)	3.0	1.25	1.50	9.20	9.10
2	70% (14 µm)	3.5	1.5	1.75	17.42	19.03
3	70% (14 µm)	4.0	1.75	2.00	22.48	21.79
4	80% (16 µm)	3.0	1.5	2.00	24.37	25.80
5	80% (16 µm)	3.5	1.75	1.50	20.73	21.37
6	80% (16 µm)	4.0	1.25	1.75	19.35	20.75
7	90% (18 µm)	3.0	1.75	1.75	18.53	19.87
8	90% (18 µm)	3.5	1.25	2.00	20.56	21.72
9	90% (18 µm)	4.0	1.5	1.50	24.64	25.32

3.1. S/N Ratio

In the Taguchi analysis, there are three types of quality characteristics with respect to the target design, they are 'smaller is better', 'nominal is better' and 'Larger is better'. In this study, the higher value of Welding Strength is desirable. Thus, it was categorized in the 'Larger is better' quality characteristic. All of the results were transformed into signal to noise ratio (S/N) in the last column of Table 4. S/N Ratio is calculated using below formula

$$S/N= -10\log\left[\sum_{i=1}^{n}\frac{\frac{1}{Y_i^2}}{n}\right]$$

Table 4. S/N Ratio

Treatment Condition	Response Y		Mean Response	S/N Ratio
	Trial 1	Trial 2		
1	9.20	9.10	9.150	19.2280
2	17.42	19.03	18.225	25.1879
3	22.48	21.79	22.135	26.8984
4	24.37	25.80	25.085	27.9777
5	20.73	21.37	21.050	26.4620
6	19.35	20.75	20.050	26.0264
7	18.53	19.87	19.200	25.6502
8	20.56	21.72	21.140	26.4923
9	24.64	25.32	24.980	27.9494

The average effect of the factors at each level is shown in the table 5 & 6. From the table 5 it is determined that for the given set of condition, Medium amplitude 80%, high pressure 4 bar, Medium time 1.5 sec and high thickness 2.00 mm are the optimum values. Same can be observed from Fig 2 & 3 the main effects plot for SN ratio and means respectively. Also the Time has Rank 1 which indicates Time is the significant parameter in this process.

Table 5. Response Table for Signal to Noise Ratio – Larger is better

Level	Amplitude	Pressure	Time	Thickness
1	23.77	24.29	23.92	24.55
2	26.82	26.05	27.04	25.62
3	26.70	26.96	26.34	27.12
Delta	3.05	2.67	3.12	2.58
Rank	2	3	1	4

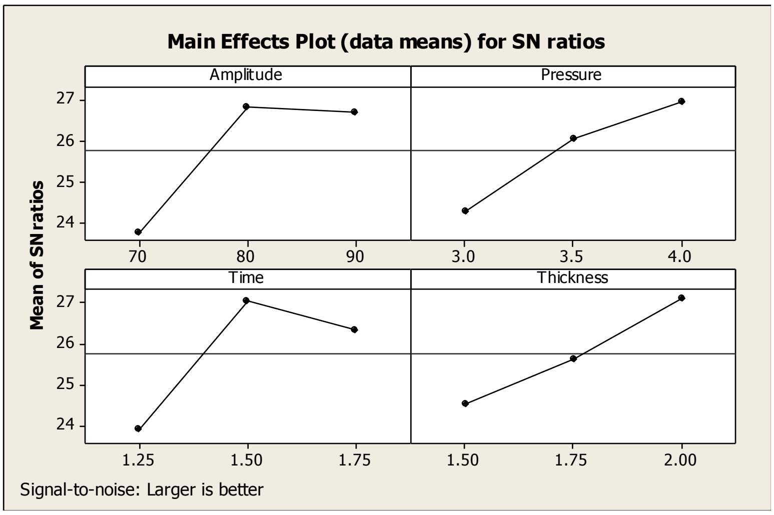

Figure 2. Main Effects Plot for SN Ratios

Table 6. Response Table for Means

Level	Amplitude	Pressure	Time	Thickness
1	16.50	17.81	16.78	18.39
2	22.06	20.14	22.76	19.16
3	21.77	22.39	20.80	22.79
Delta	5.56	4.58	5.98	4.39
Rank	2	3	1	4

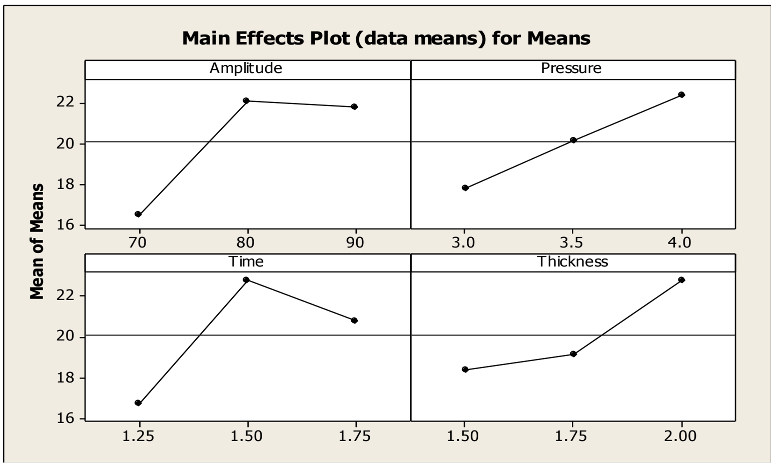

Figure 3. Main Effects Plot for Means

3.2. Analysis of Variance (ANOVA)

The purpose of the analysis of variance (ANOVA) is to investigate which parameters significantly affected the process. In order to perform ANOVA, the total sum of square, SS_T is calculated using following formula:

$$SS_T = \sum_{i=1}^{N} y_i^2 - C.F.$$

Where,

C.F. = Correction Factor

y_i = Response parameter (Welding Strength) of the i runs

N = Number of runs

Value of N is considered 18 (9x2) as each specimen was tested two times.

Also, correction factor is calculated using following formula: $C.F. = \frac{T^2}{N}$

Where, T = Total of the response (Welding Strength)

Mean Square (Variance) which is produced by dividing Sum of Square by Degree of freedom of factors.

F Value, which is the ratio produced by dividing the Mean Square for the Model by the Mean Square for Error

Below Table 7 shows the result of Analysis of Variance.

Table 7. Analysis of Variance

Symbol	Factors	Degree of Freedom	Sum of Square	Mean Square	F Ratio	% Contribution
A	Amplitude	2	117.5022	58.751	95.304	32.32%
B	Pressure	2	62.8435	31.422	50.971	17.28%
C	Time	2	111.5897	55.795	90.508	30.69%
D	Thickness	2	66.1028	33.051	53.615	18.18%
	Error	9	5.548	0.616		1.53%
	Total	17	363.5864	21.387		100.00%

From the ANOVA results it was observed that Amplitude and time are the most significant factors affecting the ultrasonic welding of ABS and PC. The percentage contribution for both Amplitude and time are 32.32% and 30.69% respectively. Thus, it can be concluded that Amplitude and time are the statistically significant parameter.

3.3. Linear Regression Model

A linear regression model aims to develop a relationship between two or more decision variables and response variable. To derive a relation between Amplitude, Pressure, Time, Thickness and Welding strength multiple linear regression model was developed using Minitab 14 software

The final equation for the Welding strength can be given by the following equation:

$$Y = -44.4 + 0.263*Amplitude + 4.58*Pressure + 8.03*Time + 8.79*Thickness$$

In order to validate the developed regression equation, normal probability plot of the residuals is generated through MINITAB software 14.0

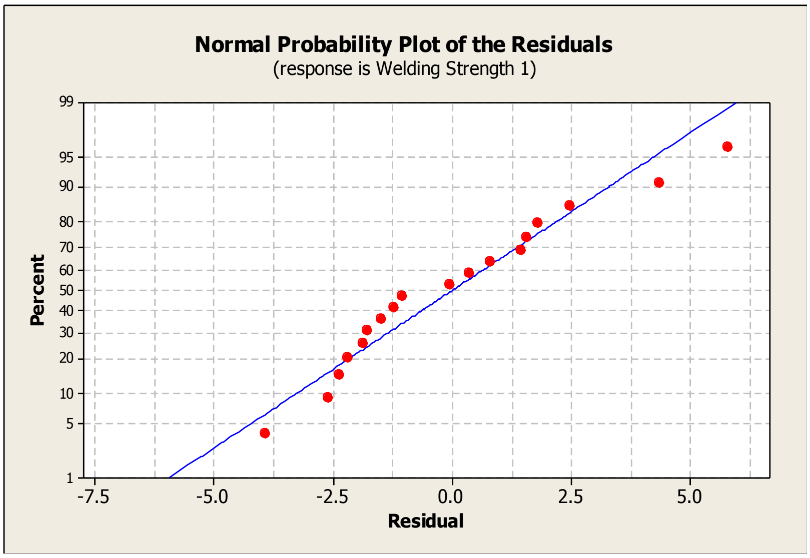

Figure 4. Normal Probability Plot of the Residuals

Normal probability plot of the residuals for Welding strength is shown in figure 4. It is observed that the residuals follows a straight line and there are no unusual patterns or outliers. As a result, the assumptions regarding the residual were not violated and the residuals are normally distributed

Table 8. Analysis of Variance of Linear Regression

Source	DF	Seq SS	MS	F	P
Regression	4	252.421	63.105	7.38	0.002
Residual Error	13	111.165	8.551		
Total	17	363.586			
S = 2.92424		R-Sq = 69.4 %		R-Sq (adj) = 60.0%	

Table 8 shows the analysis of variance of linear regression for Welding Strength. The P- value of Regression equation indicates that the regression model is significant. The coefficient of determination (R^2) which indicates the goodness of fit for the model so the value of R^2 =60.0% indicates that the model is significant.

3.3. Determination of Optimal condition and Prediction of Performance

The optimal condition is the optimal parameters settings which yield the optimum performance. From the results of Response table for S/N Ratio & ANOVA, the optimal condition is obtained which yield the optimum performance. The optimal condition is obtained by identifying the levels of significant control parameters which yield the highest S/N ratios and a parameter level corresponding to the maximum average S/N ratio is called optimal level performance for that parameter and overall it is called optimal condition. Below table 9 shows the Optimal condition which needs to validated against Confirmation test.

With the help of optimal conditions, the optimum performance will be predicted with the help of following equation:

$$Y_{Opt} = T + \sum_{i=1}^{k}(Ti - T)$$

Where,
Y_{Opt} = Predicted optimum performance
T = Total mean of all experimental runs
Ti = Mean of all experimental runs at optimum level for factor i
K = Number of factors

Table 9. Optimal Condition for Validation

Treatment Condition	Amplitude (%) (µm) (A)	Pressure (bar) (B)	Time (sec) (C)	Thickness (mm) (D)
19	80% (16 µm)	4.0	1.5	2.00
20	80% (16 µm)	3.5	1.75	2.00
21	80% (16 µm)	3.0	1.75	1.75
22	80% (16 µm)	3.5	1.5	1.5

3.4 Confirmation Test

Confirmation experiment is the last and important step in the Taguchi process as it is the direct proof of the methodology. If the predicted and the observed values are close to each other then the used model is adequate for describing the effect of parameters on quality characteristics and if there is a large difference in observed values and predicted values then the used model is inadequate.

Below table 10 shows the values of confirmation test against predicted values and linear regression model values.

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Table 10. Comparison of Linear Regression Vs Taguchi Predict Vs Confirmation Test

Treatment Condition	Amplitude (%) (µm) (A)	Pressure (bar) (B)	Time (sec) (C)	Thickness (mm) (D)	Linear Regression Model	Taguchi Predict	Confirmation Test
19	80% (16 µm)	4.0	1.5	2.00	24.585	29.6617	26.637
20	80% (16 µm)	3.5	1.75	2.00	24.3025	25.4433	23.974
21	80% (16 µm)	3.0	1.75	1.75	19.815	19.4883	18.964
22	80% (16 µm)	3.5	1.5	1.5	17.9	23.0183	20.743

IV. CONCLUSION

In the present paper, experimental investigation of ultrasonic welding process parameter validation has been performed on ABS & PC material. The following conclusions can be drawn from the experimental investigation carried out within given condition of experiment.

- ANOVA analysis results shows that amplitude and time are statistically significant parameters for the ultrasonic welding process of ABS and PC samples as the percentage contribution of time and amplitude 30.69 % and 32.32% respectively.
- From the Taguchi response table for S/N ratio and mean data, Time factor has Rank 1 and Amplitude has Rank 2 which indicates that Time and Amplitude are the most significant parameters for process.
- Mathematical model developed using linear regression analysis and Taguchi Predict values validates the confirmation test.
- It was observed that Pressure and Thickness are less contributing factors for given sets of conditions for this experiment. A linear relationship of Pressure and Thickness with welding strength was observed. With increase in Pressure and increase in Thickness, welding strength increases.
- Optimized welding strength of 26.637 MPa was observed with 80% of amplitude and pressure of 4 bar and 1.5 sec of Weld time and 2.00 mm Thickness.
- Thus, it can be concluded that Time and Amplitude are the most significant parameters for the given set of condition for this experiment.

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