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Thermal Analysis on ABS & HDPE Materials of Bonding Strength by Ultrasonic Welding

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Abstract - Ultrasonic plastic welding has received significant attention in the past few years, and has become more reliable and suitable for a wide range of applications. In recent years, technique has been extensively used due to the advent of component miniaturization and improvements in producing lightweight components. There are a number of advantages for ultrasonic plastic welding, including greater efficiency and speed, longer tool life, higher accuracy and no filler or flux needed to be used. Thus the technique can be viewed as being environmentally friendly

In this work effect of various parameters on weld strength have been studied. Welding of 0.5 mm thickness Acryl nitride Butadiene-Styrene (ABS) and High Density Polyethylene (HDPE).plates were successfully welded by 20 kHz ultrasonic welding system. This experiment was carried to find out the optimum parameter for maximum strength. In order to determine critical states of the welding parameters, analysis of variances has applied while optimization of the parameters affecting the joint strength has achieved with centre composite method of the Response Surface Methodology. This study involves modeling of experimental data of joint strength of ABS & HDPE material for ultrasonic welding on welding parameters (welding pressure, welding time, and amplitude. Results are compared with Analytical values.

Keywords - Ultrasonic Welding, Thermoplastic Material, Process Parameters, JOINT Strength, Full Factorial Method, ANOVA, Response Surface.

1. INTRODUCTION

1.1 HISTORY

The use of ultrasonic in some form may be found in nearly every industry today whether it is high powered applications such as Ultrasonic welding or low powered applications such as imaging, non-destructive testing and cleaning. Ultrasonic pertains to acoustic frequencies above the audible range of the human ear, which is approximately 20,000 cycles per second. Ultrasonic Welding (USW) may be comparable to other attachment processes that involve fusion through such methods of application of heat via flame or hot tool, electrical current, electrical arc or adhesives. Many of these processes involve surface preparation and processes additives such as fluxing agents and filler materials. Ultrasonic welding has existed since the early 1950s. However, the first patent regarding an ultrasonic welding machine was not granted until the 1960s because it was not believed by the “patent supervisor” that there existed a machine that could make a metallurgical bond without the use of heat or filler materials. Early machines where, inefficient, expensive and quite large, while today’s machines are much more efficient This increase in efficiency may be manly contributed to a change in the methods of creating ultrasonic vibrations. Early converters transformed electrical energy to mechanical vibrations with the use of ferromagnetic materials. A current was induced in this magneto astrictive material, which created a periodic alternating magnetic field, therefore causing a dimensional change in the material. Today however, ultrasonic welders produced oscillations through piezoelectric ceramics. Re-alignment of dipoles inside the elementary cells of the piezoelectric ceramic causes an incremental change in volume In the present research, an experimental investigation of Ultrasonic welding of dissimilar plastics between ABS & PC has been carried out. Response surface methodology (RSM) is employed to develop mathematical relationships between the welding process parameters namely Amplitude, Pressure and Weld time 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 and interaction plots

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2. EXPERIMENT

2.1 EXPERIMENTAL SETUP

The welding was carried out using a conventional ultrasonic plastic welding machine (2,500 W, 20 kHz). The specification of the machine is shown in the table 1. The actual experimental setup is as shown in Fig1 with the data acquisition system. A horn made of titanium alloy was used for this study and an anvil made of steel with serrations at the top surface. The parameters that can be varied in this setup are the weld pressure, weld time, and the amplitude of vibration. These factors are selected as the variables for this study. The area of horn that comes into contact has serrations similar to the top surface of the anvil for gripping the work piece well. The specimen (0.5 mm ABS &HDPE sheet) was prepared as per standard for testing shear strengths of the joint by tensile loading. A universal testing machine was used to determine the weld strengths. The temperature at the interface of the specimen was monitored in real time using a data acquisition system. The data acquisition system includes sensors (thermocouple), a terminal block, DAQ card, and analyzing software. An SWG 36 Alumal–Cromal (type K) thermocouple is used in this study which can measure temperatures from -180°C to +1,300°C. It has a high accuracy of 1.5°C on each side from -40°C to +375°C

Table 1: ultrasonic machine specifications

S.NO	DESCRIPTION	VALUES
1	INPUT POWDER	2500W
2	OUTPUT FREQUENCY	20KHZ
3	MAXIMUM AMPLITUDE	50µm
4	MAXIMUM FORCE	300N
5	STROKE LENGTH	100mm

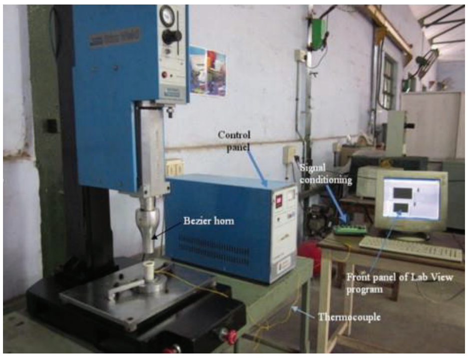

Fig 1 experimental setup

2.2. Welding Parameters

There are mainly two types of factor that affect any process one is the controlled and another is uncontrolled one. Here in the USW, the controlled factors are welding time, welding pressure, input power, frequency, amplitude etc. The uncontrolled factors are that factors which can’t be controlled during process. In this paper, the uncontrolled factors were neglected and controlled factors were selected for study. It has noted that most affecting parameters were welding time, welding pressure and amplitude of sonotrode. Here all three factors were considered. Each of the factors with three levels has taken as shown in table 2.

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Table 2: Factors and levels for the experiments

Factors	Level 1	Level 2	Level 3
Pressure (bar)	1.5	2	2.5
Amplitude (μm)	40	45	50
Welding Time (s)	2	2.25	2.50

2.3 Methodology

In this research work the specimen has prepared according to ASTM standard . The specimen selected for the experiment is ABS material having (80 × 50 mm) and 0.5 mm thickness. Total 9 run have identified Values applying design of experiment with 3 input parameters and 3 levels. Here the joint strength has measured by universal testing machine as one output parameter. During the tensile testing, ductile fracture has observed at weld interface for most of the welded samples. Analysis of variance (ANOVA) has used to identify significant effect of parameters and regression analysis have to follow to optimize parameter values for maximum joint strength.

3. Result and discussion

Identified 29 runs to experiment, using centre composite technique of response surface method. Designs of experiment have performed and corresponding joint strength have recorded. The data acquisition system includes sensors (thermocouple), a terminal block, DAQ card, and analyzing software. An SWG 36 Alumal–Cromal (type K) thermocouple is used in this study which can measure temperatures. Experimental results are shown in below Table 3.

Table 3: Experimental results

Ex. No.	Welding Pressure (bar) A	Amplitude (μm) C	Welding Time (sec) B	Response							
				Interface Temperature (°C)				Joint Strength (MPa)			
				Trials			Average	Trials			Average
				1	2	3		1	2	3	
1	1.5	40	2	105	112	106	107.66	1.58	1.80	1.87	1.75
2	1.5	45	2.25	102	106	110	106	2.09	2.31	2.22	2.21
3	1.5	50	2.50	85	98	102	95	3.32	2.60	2.24	2.72
4	2	40	2.	115	106	112	111	2.09	2.45	2.09	2.18
5	2	45	2.25	102	116	108	108.66	4.26	3.32	2.31	3.29
6	2	50	2.50	103	105	110	106	1.44	1.95	2.24	1.87
7	2.5	40	2	90	95	105	96.66	3.65	3.33	2.60	2.72
8	2.5	45	2.25	117	110	102	109.66	3.22	2.42	1.92	1.87
9	2.5	50	2.50	125	115	122	120.66	1.44	1.80	1.58	1.60

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Welding strength was calculated by using basic physics.

Final Equation: Joint Strength = +5.39 +0.12 * A +0.088 * B +0.39 * C -0.21 * A^2 -0.62 * B^2 -0.073 * C^2 +0.024 * A* B +0.14 * A * C -0.39 * B * C

By using this above equation joint strength is calculated at different parameters

1. Joint strength = +5.39 +0.12 *(1.5) +0.088 *(2) +0.39 *(40) -0.21 * $(1.5)^2$ -0.62 *$(2)^2$ -0.073 * $(40)^2$ +0.024 * (1.5)* (2) +0.14 * (1.5) * (40) -0.39 * (2) * (40) = **1.75 MPa**

2. Joint Strength = +5.39 +0.12 * 1.5 +0.088 * 2.5 +0.39 * 45 -0.21 * $(1.5)^2$ -0.62 * $(2.5)^2$ -0.073 * $(45)^2$ +0.024 * 1.5* 2.5 +0.14 * 1.5 * 45 -0.39 * 2.5 * 45 =**2.21 MPa**

3. Joint Strength = +5.39 +0.12 * 1.5 +0.088 * 2.50 +0.39 * 50 -0.21 * 1.5^2 -0.62 * 2.50^2 -0.073 * 50^2 +0.024 * 1.5* 2.50 +0.14 * 1.5 * 50 -0.39 * 2.50 * 50 =**2.72MPa**

4. Joint Strength = +5.39 +0.12 * 2 +0.088 * 2 +0.39 * 40 -0.21 * 2^2 -0.62 * 2^2 -0.073 * 40^2 +0.024 * 2* 2 +0.14 * 2 * 40 -0.39 * 2 * 40 =**2.18MPa**

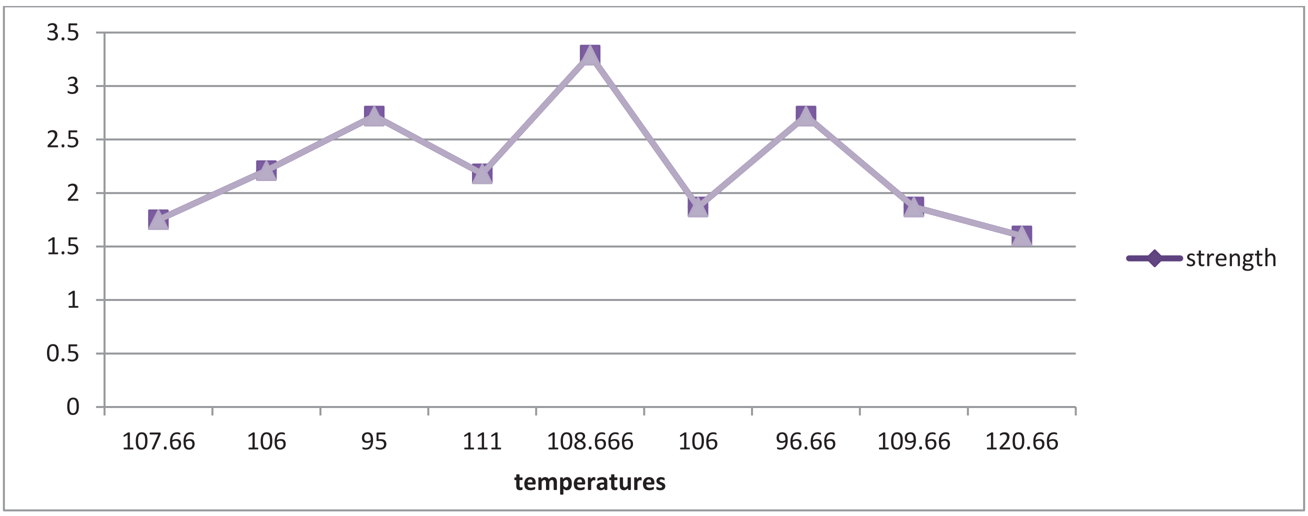
5. Joint Strength = +5.39 +0.12 * 2 +0.088 * 2.25 +0.39 * 45 -0.21 * 2^2 -0.62 * 2.25^2 -0.073 * 45^2 +0.024 * 2* 2.25 +0.14 * 2 * 45 -0.39 * 2.25 * 45 =**3.29MPa**

6. Joint Strength = +5.39 +0.12 * 2 +0.088 * 2.50 +0.39 * 50 -0.21 * 2^2 -0.62 * 2.50^2 -0.073 * 50^2 +0.024 * 2* 2.50 +0.14 * 2 * 50 -0.39 * 2.50 * 50 =**1.87MPa**

7. Joint Strength = +5.39 +0.12 * 2.25 +0.088 * 2 +0.39 * 40 -0.21 * 2.25^2 -0.62 * 2^2 -0.073 * 40^2 +0.024 * 2.25* 2 +0.14 * 2.25 * 40 -0.39 * 2 * 40 =**2.72MPa**

8. Joint Strength = +5.39 +0.12 * 2.25 +0.088 * 2.25 +0.39 * 45 -0.21 * 2.25^2 -0.62 * 2.25^2 -0.073 * 45^2 +0.024 * 2.25* 2.25 +0.14 * 2.25 * 45 -0.39 * 2.25 * 45 = **1.87MPa**

9. Joint Strength = +5.39 +0.12 * 2.5 +0.088 * 2.50 +0.39 * 50 -0.21 * 2.5^2 -0.62 * 2.50^2 -0.073 * 50^2 +0.024 * 2.5* 2.50 +0.14 * 2.5 * 2.50 -0.39 * 2.50 * 50 =**1.60MPa**



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From the above graph is weld strength with respect to temperature in this graph weld strength is maximum at 3.29MPa at temperature 108.666°c

3.1 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, SST 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. = 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 shows the result of Analysis of Variance.

Table 4: 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 HDPE. 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.

3.2. ANALYSIS OF BONDING STRENGTH:

3.2.1 EXPERIMENTATION AND DATA COLLECTION:

The below table 4 the different parameters are taken with different levels in this process to weld the materials used in ultrasonic welding

Table 5: parameters and their levels of experiment

SYMBOLS	PROCESS PARAMETERS	LEVELS		
		LOW	MEDIUM	HIGH
V	Voltage (Volt)	220	230	240
I	Current (amp)	10.4	10.8	11.6
P	Pressure (MPa)	1.5	2	2.5

3.2.2 EXPERIMENTAL RESULTS:

The below table 5 is consolidated design of experiment done by different parameters

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Table 6: Consolidated design of experiment table

EXPERIMENT NO	Voltage (v)	Current (amp)	Pressure (MPa)	Strength (10^6N/m^2)
1	220	10.4	1.5	1.75
2	220	10.8	2	2.21
3	220	11.6	2.5	2.72
4	230	10.4	1.5	2.18
5	230	10.8	2	3.29
6	230	11.6	2.5	1.87
7	240	10.4	1.5	2.72
8	240	10.8	2	1.87
9	240	11.6	2.5	1.60

In this work, the controllable factors taken are Voltage (V), Current (I) and pressure (P). Since they affect strength and welding operation and these factors are controllable in the ultrasonic welding process, they are considered as a controllable factor.

3.2.3Analysis of means and response graph for strength:
The analysis of each controllable factor is studied and the main effect of the same is obtained in table. Main effect of each factor at individual level i.e. at low, medium and high level is equal to the mean of strength of all experiments with the factor at individual level.

(a) The main effect of voltage on strength at various levels calculated as follows

L = (1.75+2.21+2.72)/3 =2.22 (10^6N/m^2)

M = (2.18+3.29+1.87)/3 =**2.44** (10^6N/m^2)

H = (2.72+1.87+1.60)/3 =2.06 **(**10^6N/m^2)

(b)The main effect of current on strength at various levels calculated as follows

L = (1.75+2.18+2.72)/3 =2.21 (10^6N/m^2)

M = (2.21+3.29+1.87)/3 =**2.45**(10^6N/m^2)

H = (2.72+1.87+1.60)/3 = 2.06(10^6N/m^2)

(c) The main effect of pr ure on strength at various levels calculated as follows

L = (1.75+3.29+1.60)/3 = 2.21 (10^6N/m^2)

M = (2.21+1.87+2.72)/3 = **2.26**(10^6N/m^2)

H = (2.72+2.18+1.87)/3 =2.25(10^6N/m^2)

Table 7: Responses for strength

Symbols	Controlled factors	Strength(10^6N/m^2)		
		Low	Medium	High
V	Voltage	2.39	**2.44**	2.06
I	Current	2.21	**2.45**	2.43
P	Power	2.21	**2.26**	2.25

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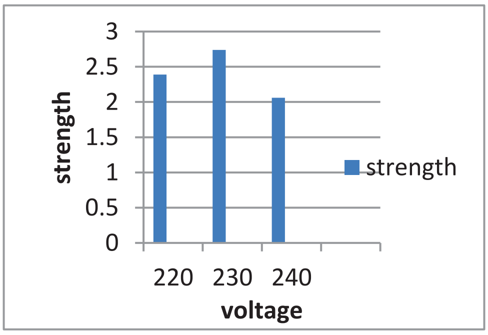
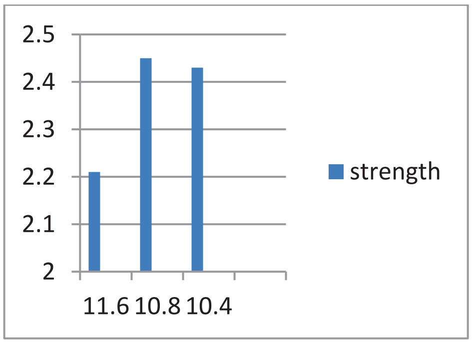
The value obtained from the response table are plotted to visualize the effect of three parameters. From the means response graph observation finding are illustrated as follows-

(a) Level III for voltage (V2) =2.44(10^6N/m^2) indicated as the optimum situation in terms of strength.
(b) Level II for current (I2) =2.45(10^6N/m^2) indicated as the optimum situation in terms of strength.
(c) Level III for voltage (P2) =2.26(10^6N/m^2) indicated as the optimum situation in terms of strength.

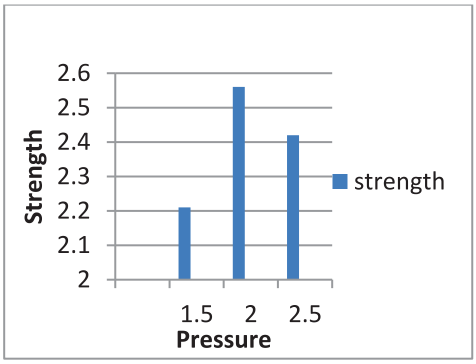
Main effect plot for Strength



(a) Strength v/s voltage



(b) Strength v/s Current



(c) S ngth v/s pressure

Confirmation of experiment

For maximum strength the combination of optimum parameters (V2, I2, P2).It means high voltage, medium current and high pressure. For this combination **V2=230v, I2=10.8 amp** and **P2= 2 MPa, the** strength is **3.29 (10^6N/m^2)**

3.2.4 MODELLING OF PARAMETERS

To generalize the result, the modeling of input parameters (Voltage, Current and Pressure) and output parameters (Strength) is done using REGRESSION MODELING and Mat lab software R2011b. Now the Formula of strength in terms of voltage, Current, and Pressure

Strength = (Voltage) $^{0.5514}$* (Current) $^{0.1431}$* (Pressure) $^{1.5115}$

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Table 8: Experimental results & Result from Mathematical modeling

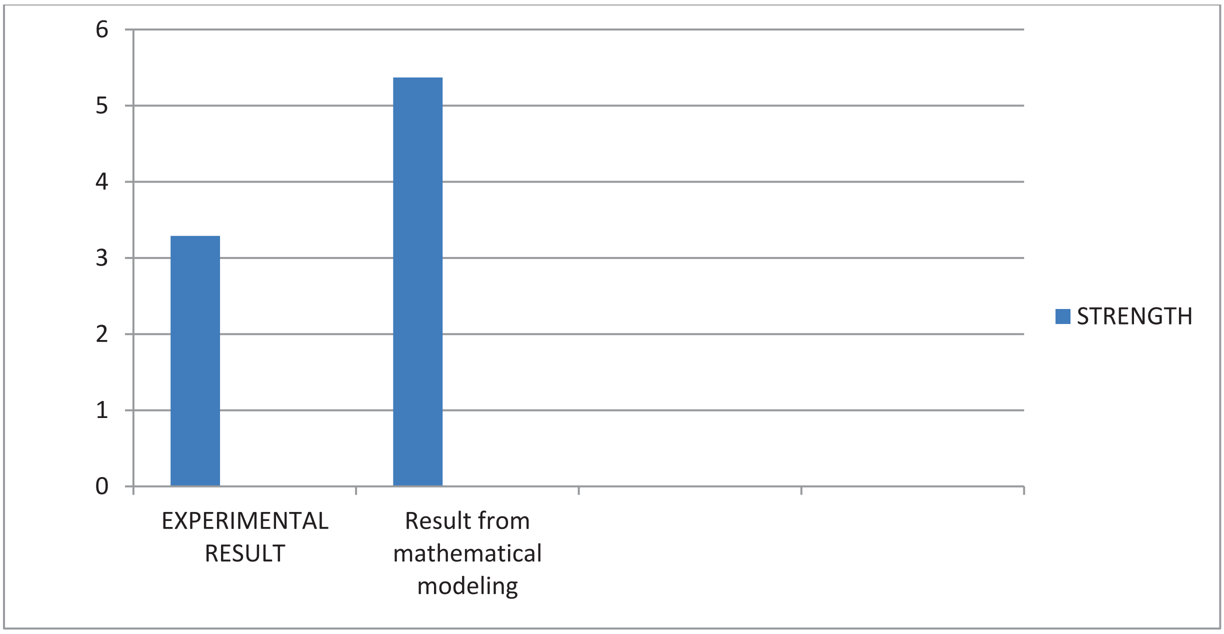
Strength	
Experimental result	Result from mathematical modeling
1.75	2.86
2.21	3.77
3.22	4.30
2.18	4.57
3.29	**5.37**
2.76	5.01
2.72	3.81
1.87	5.28
1.60	2.67

Comparison of result for maximum strength

1. Strength = $(220)^{0.5514}*\ (10.4)^{0.1431}*\ (1.5)^{1.5115}$ = 2.86
2. Strength = $(220)^{0.5514}*\ (10.8)^{0.1431}*\ (2)^{1.5115}$ =3.77
3. Strength = $(220)^{0.5514}*\ (11.6)^{0.1431}*\ (2.5)^{1.5115}$ =4.30
4. Strength = $(230)^{0.5514}*\ (10.4)^{0.1431}*\ (1.5)^{1.5115}$ =4.57
5. Strength = $(230)^{0.5514}*\ (10.8)^{0.1431}*\ (2)^{1.5115}$ =5.37
6. Strength = $(230)^{0.5514}*\ (11.6)^{0.1431}*\ (2.5)^{1.5115}$ =5.01
7. Strength = $(240)^{0.5514}*\ (10.4)^{0.1431}*\ (1.5)^{1.5115}$ =3.81
8. Strength = $(240)^{0.5514}*\ (10.8)^{0.1431}*\ (2)^{1.5115}$ =5.28
9. Strength = $(240)^{0.5514}*\ (11.6)^{0.1431}*\ (2.5)^{1.5115}$ =2.67

RESULTS	Experimental result	Result from mathematical modeling
LEVEL	V2I2P2	V2I2P2
STRENGTH($10^6 N/m^2$)	3.29	5.37

Comparison of results



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From the graph is between experimental results and results from mathematical modeling from this results the weld strength is maximum at V2I2P2

3.2.5. Welding Heat Input:

Formula

The below mathematical formula is used in mechanical engineering to calculate how much heat for welding.

Q = (A x V x 60)/TS

TS = (L/S) x60

Substitute

Q = (V x A x S)/L

Where

L=length in mm

S=weld time in sec

A-welding current in amps

V-voltage in volts

Q= joules/mm

In the field of mechanical engineering, while working with heat transfer, sometimes it's important to analyze welding heat to finish a particular job. The above formula & step by step calculation may be useful for users to understand how the values are being used in the formula to find the heat input, however, when it comes to online for quick calculations, this welding heat calculator helps the user to perform & verify such mechanical engineering heat transfer calculations as quick as possible.

Table 9: heat input for welding results

S.NO	Voltage(volts)	Current(amps)	Weld time(sec)	Heat input(joules/mm)
1	220	10.4	2	193.734
2	220	10.8	2.25	226.525
3	220	11.6	2.50	270.332
4	230	10.4	2	202.711
5	230	10.8	2.25	236.822
6	230	11.6	2.50	282.627
7	240	10.4	2	211.525
8	240	10.8	2.25	247.118
9	240	11.6	2.50	294.665

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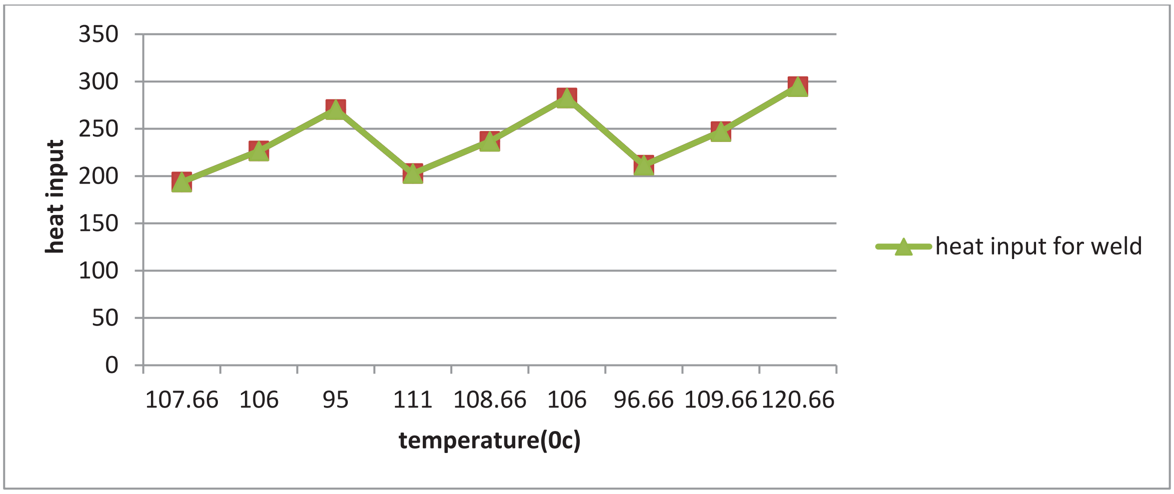
Calculation

1. Q=(V x A x S)/L=(220*10.4*2)/2.36=193.734
2. Q=(V x A x S)/L=(220*10.8*2.25)/2.36=226.525
3. Q=(V x A x S)/L=(220*11.6*2.50)/2.36=270.332
4. Q=(V x A x S)/L=(230*10.4*2)/2.36=202.711
5. Q=(V x A x S)/L=(230*10.8*2.25)/2.36=236.822
6. Q=(V x A x S)/L=(230*11.6*2.50)/2.36=282.627
7. Q=(V x A x S)/L=(240*10.4*2)/2.36=211.525
8. Q=(V x A x S)/L=(240*10.8*2.25)/2.36=247.118
9. Q=(V x A x S)/L=(240*11.6*2.50)/2.36=294.66

Graph between welding heat input and temperature



From the above graph heat input in welding varies different temperature. From this study welding strength is maximum at 108.66°c and the heat input at this temperature is 236.822 j/mm

3.2.5 Modeling of experimental data of joint strength

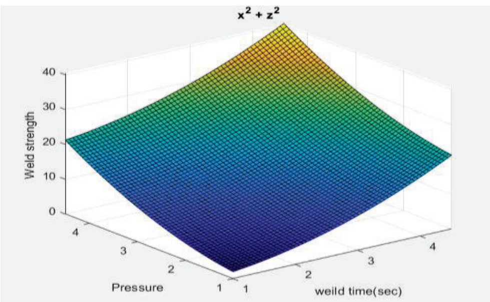


Fig 3.2.5(a) Response surface, Effect of pressure and weld time on weld strength

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From the fig 3.2.5(a) shows the effect of pressure and weld time on weld strength by using the response surface methodology

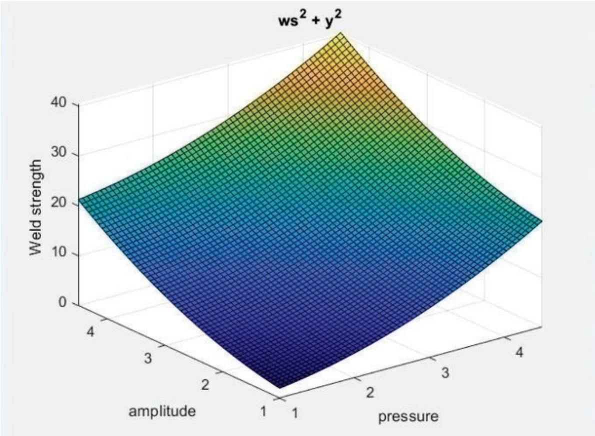

Fig 3.2.5(b) Response surface, Effect of amplitude and pressure on weld strength

From the fig 3.2.5(b) shows the effect of pressure and amplitude on weld strength by using the response surface methodology

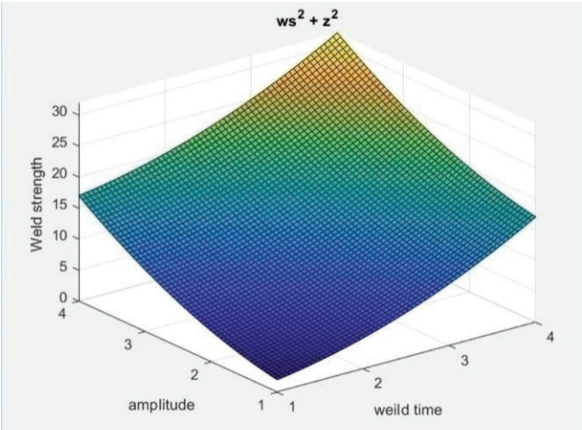

Fig 3.2.5(c) Response surface, Effect of amplitude and weld time on weld strength

From the fig 3.2.5(C) shows the effect of amplitude and weld time on weld strength by using the response surface methodology

4. DISCUSSIONS

The specimens used in this work were made of Acryl nitride Butadiene-Styrene (ABS) and High Density Polyethylene (HDPE). The experiment is done at three levels i.e., level 1, level 2 and level 3 respectively. The experimental factors are pressure, amplitude and weld time. This experiment is carried on at 3 levels where each factor is applied to other factors in 3 different ways. The above table shows the results obtained from the experiment. In this investigation weld at 2 bar weld pressure, 2.50 sec weld time and amplitude 45 welding pressure is maximum 3.29(10^6N/m^2).while compare to others weld strengths hence these parameters are preferable for this process and also by using REGRESSION MODELING and Mat lab software R2011b we can proved weld strength at V2I2P2 is prefer for welding process and also response surface methodology also used to find the different parameters are effecting on weld strength In this investigation calculating the how much heat for welding occurred in these process with respect to temperature.

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5. CONCLUSION

- Experimental and analytical thermal analysis on ultrasonic welding process parameter improvement have been performed on Acryl nitride Butadiene-Styrene (ABS) and High Density Polyethylene (HDPE)
- In this study, RESPONSE SURFACE METHODOLOGY (RSM) has revalidated to predict the most weld strength of welds created by USW
- From the outcomes, it was discovered that the welding strength mainly depends on value of amplitude and then on amount of weld pressure also weld time
- Beyond 2 bar, the weld strength again start decreasing for constant value of amplitude and weld time. This is because increase in pressure reduces the relative motion between surfaces and that leads to reduced area of contact and so reduced strength.
- Optimized weld strength has observed to be maximum 3.29 MPa at 2 bar weld pressure; 2.50 sec weld time and amplitude of 45 μm. Results of present investigation have been valuable to choose ideal welding condition, at which the most extreme weld quality can accomplish to enhance weld capacity of nonmetallic material and rate of creation.
- From the a above results we observed that welding strength is is maximum at temperature 108.66^{0c} and heat is generated at that welding point is 236.822 j/mm

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