Parametric Analysis of the Ultrasonic Welding of Aluminum to plastic (acrylic) using Design of Experiments

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Abstract:-

Ultrasonic welding is used to weld wire, thin sheet and foils of similar or dissimilar materials like polymers and metal such as magnesium, aluminum, copper, without the need for filler material producing a high-quality weld with reduced energy usage. Ultrasonic spot welding has been used to weld thin sheets of metal, fiber-reinforced composite, and polymers. The tests conducted using an ultrasonic plastic welding machine on aluminum sheets to plastic (acrylic) are taken into consideration in this work. The welded specimens were tested on universal testing machine (UTM) to evaluate the weld strength. This paper aims at optimizing ultrasonic welding parameters, characteristics, performance interface of welding joint and welding factors for different materials. The optimal welding parameters are determined by analyzing the effects of various welding parameters on the weld strength using ANOVA and S/N ratio experiments. The ideal parameters for achieving the highest tensile strength were found to be welding time 3 second, welding pressure 2 bar, and amplitude 60 μm.

Keywords:
Ultrasonic welding; energy directors; sonotrode; welding mechanism; Taguchi;

Introduction:-

Since its invention more than 50 years ago, ultrasonic welding (USW) has been used extensively in industry. In the USW process, two parts are joined by applying ultrasonic vibrations under normal pressure to the interface. For metal welding machines, the vibrations are applied parallel to the part-to-part interface [1], and for plastic welding machines, they are applied perpendicular to the part-to-part interface [2]. With the growing use of lightweight, high-performance materials like composites, welding of these materials is now accomplished efficiently with USW machines, which have strong welds, low energy consumption, and short welding times [3, 4, 5]. The joining mechanism, which disperses oxides and contaminants from the metal work piece and increases the area of pure metal contact between and bonding of the adjacent surfaces, is created by applying high frequency relative motion between the parts, which results in a weld through progressive shearing and plastic deformation for metal [6] and diffusion of molecules by melting for plastic [7].This produces a very uniform structure between the basic materials that is pore-free and distinguished by restricted inclusions and refined grains [8, 9, 10]. Sheet metal that has been coated or covered can also be joined by ultrasonic metal welding.

The results are especially useful for assessing the significance of different phenomena affecting the lap joint method that is achieved on thin sheets through the use of USW. Sonotrode energy director type determines the indentation's size and form [8, 11, 12, 13, 14]. The USW procedure may be utilized at an industrial level to assemble big components while maintaining outstanding weld quality since it permits the welding of large sections utilizing a continuous weld line [15].
i) intermolecular diffusion, ii) flow and wetting, , iii) heat transfer rate, iv) visco-elastic heating and v) Parts mechanics and vibration are the processes occurring in this process [16]. Depending on the type of weld generated, this joining technique can take several different forms, including spot, ring, line, and continuous seam welding; in our experiment, we employed spot welding.
Due to its superior fatigue life, corrosion resistance, high specific stiffness, and reduced weight as compared to metal, polymer matrix composites are being utilized more and more [17]. Thermoplastics and thermosets are matrix systems used in composites. Excellent vibration damping, reformability, fracture toughness, high damage tolerance, repairability, flexural strength, weldability, recyclability, high impact resistance, high productivity, and cost-effectiveness make thermoplastic composites the preferred material over thermoset composites [18]. Polymer structures come in two varieties: semi-crystalline and amorphous. Amorphous polymers may be welded with a broad range of amplitudes and loads. On the other hand, a large amplitude vibration is necessary for semi-crystalline polymers because a certain fraction of high frequency vibrations are internally absorbed, making it difficult to transfer ultrasonic energy to the interface [19]. Because USW uses less energy, takes less time to weld, and produces high-weld strength without the need for filler material, they are chosen over other fusion welding processes and conventional attachment methods [20]. Ultrasonic metal welding (USMW) and ultrasonic plastic welding (USPW) are the two forms of USW. From two viewpoints, the two machines differ: i) how the ultrasonic vibrations are sent to the welding zone, and ii) how the weld is produced. In USPW, pressure is delivered to the specimen interface in a normal direction while vibrations are conveyed to the specimen perpendicular to the specimen interface. The melting of material as a result of vibrational heat and molecular diffusion is the foundation of plastic welding bonding. In contrast, the vibration in the USMW case is transmitted parallel to the specimen contact, and the pressure is in the normal direction. Plastic deformation is the basis for bonding in metal welding [21, 22, 23]. The primary heating mechanisms in plastic welding are surface friction, which initiates the visco-elastic friction and welding process which takes over after the polymer's glass transition temperature is achieved and provides the most heating during the welding process [24, 25]. A sonotrode is used to apply welding pressure and mechanical vibration. The transducer that this sonotrode is attached to creates mechanical vibration, which is then amplified by a booster. The generator that the transducer is linked to produces high-frequency electrical impulses from the power source [26].
In USPW, the energy director (ED) is a crucial parameter. By concentrating ultrasonic energy at the apex, ED creates a quick heat buildup that melts the projected part and forces it to flow over the joint contact, creating a weld. It is an artificial protrusion on a resin-rich composite specimen that is positioned near the interface and lacks fiber. EDs come in a variety of forms, including

semicircular, triangular, rectangular, and numerous [27]. USPW can also be achieved without ED. Numerous welding parameters and procedure-related elements influence or govern the quality of ultrasonic welding. Vibration amplitude, welding frequency power, vertical displacement during welding energy, welding pressure, and weld duration are also crucial welding characteristics [28, 29]. Weld time, welding pressure, and vibration amplitude are the factors that have the most effects on welding quality [30, 31]. The amount of vibration amplitude and weld pressure applied directly correlate with the rate of heat production [32].Factors influencing a successful USW are:- i) welding frequencies, ii) material consideration, iii) joint design impact, iv) tooling and fixtures, v) welding parameters. The main issues that industries deal with are when it comes to ultrasonic welding the weld's poor quality and strength. It is crucial to choose parameters that have a big impact on the weld's strength because they have a big impact on the bond formation's quality and strength. The aim of this research is to determine the ideal parameter levels and their interactions that would result in the highest weld strength when welding aluminum to plastic (acrylic) utilizing Taguchi's design of experiments approach.

2. Material and methodology

2.1 Material

The material used for this research study are aluminum sheet and acrylic thermoplastic (poly(methyl methacrylate) which also named as PMMA) which is transparent.

2.2 Specimen preparation for Welding

Aluminum were selected as material, the specimen was prepared from aluminum sheet of thickness 0.5mm. It is of rectangular shape and the dimensions are length (L) = 100 mm, width (W) = 25 mm and thickness (T) = 0.5 mm.

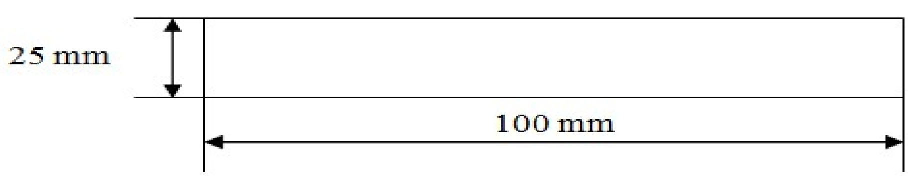

Figure 1: Schematic of specimen.

2.3 Welding procedure:

We used an ultrasonic plastic welding equipment of the YASKAWA welder to conduct the experiment employing flat surface joint design, spot welding method, and lap joint, as illustrated in Figure 2. This welder's characteristics include a maximum force of 3000 N, a maximum power supply of 2000 W, and a frequency of 34.932 kHz. During the experiment, a

10-mm-diameter stepped titanium horn was utilized. Since the sonotrode comes into touch with components close to the joint region, near field welding has been envisaged.

The welding parameters which we able to vary are weld time, amplitude and weld pressure. Wooden fixture was clamped on the table. Both specimens kept in lap joint position for the welding. Welding parameters are set on controller screen as design by Taguchi approach. Run the program for specimen 1 and remove the welded specimen, cleaning the fixture, and similarly same procedure was repeat for all remaining specimens. By following above mentioned procedure, the total of 27 numbers of specimens was welded. The real welded samples that were utilized for joining are displayed in Figure 3. The weld strengths were measured using universal testing equipment at CIPET, Chandrapur.

A universal testing machine (UTM) is used to test the weld strength of all welded specimen using tension test at strain rate (tension speed) of 5mm/min and the technical specification as shown Table 1

Table 1: Technical Specification of UTM :-

Capacity	10 kN	Load Cells available	10kN, 250N
Maximum cross head travel	1100mm	Testing speed range	0.001 to1000 mm/min
Maximum cross head speed at 5kN	500 mm/min	Jog speed	0.001 to1000 mm/min
Return speed	0.001 to750mm/min	Frame stiffness	100 kN/mm

Figure 2: Ultrasonic welding robot setup.

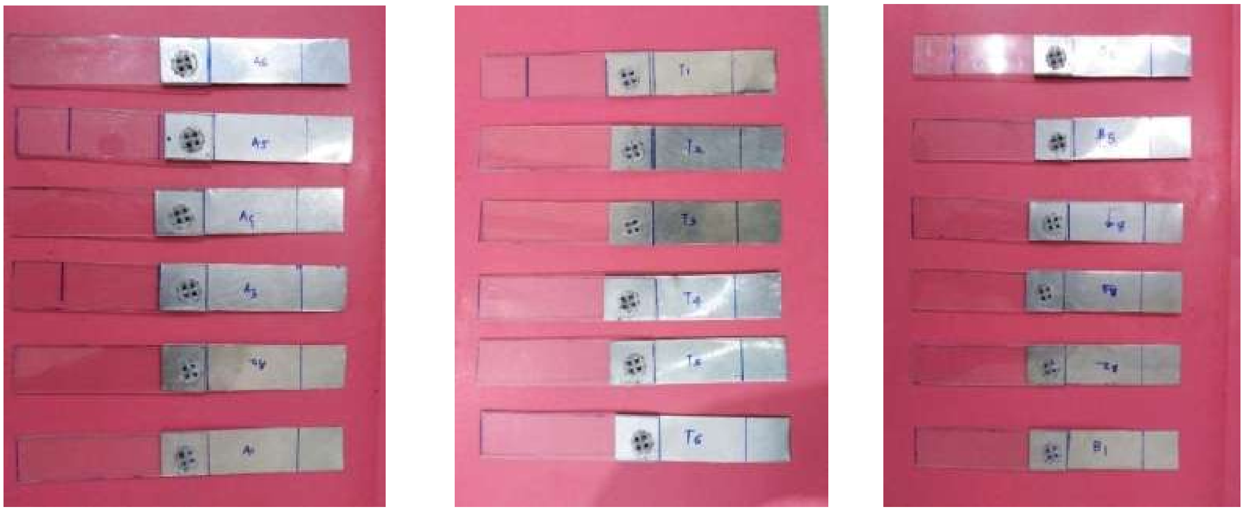

Figure 3: Welded Specimen

2.4 Test Parameters

The welding experiment was carried out in a lab setting, and the parameters that were investigated were the amplitude (30–50 µm), welding time (3–4 seconds), and welding pressure % (2–3 bar). MINITABTM version 19 was used to execute the design of experiments (DOE). Three parameters and three levels were used in the welding testing. The L27 orthogonal array technique employed in this study consists of 27 rows and 3 columns. The factors and levels of the trial are shown in Table 2. Table 3 displays the results of 27 tests with three repeats for various factor permutations in the L27 orthogonal array. Tensile strength was calculated and shown in Table 3 for each set of weld settings. The S/N ratio is mainly separated into three groups for quality features in Taguchi analysis: smaller is better, higher is better, and nominal is best. The higher levels of welding strength were approved. Thus, the "Greater is better" S/N ratio was chosen for the analysis. The following formula was used to calculate the S/N ratio:

$$\frac{S}{N} = -10 * \log 10\left(\frac{\sum(Y^2)}{n}\right) \qquad (1)$$

Table 2: The Levels and Factors

Factor	Level 1	Level 2	Level 3
Welding Pressure (bar)	2	2.5	3
Welding Time (sec)	3	3.5	4
Amplitude (µm)	40	50	60

Table 3: Experimental results

Expt. No.	Welding Pressure (bar)	Welding Time (sec)	Amplitude (μm)	Tensile Strength ($N/mm2$)
1	2	3	40	17.116
2	2	3	40	16.956
3	2	3	40	17.785
4	2.5	3	50	17.994
5	2.5	3	50	16.932
6	2.5	3	50	17.375
7	3	3	60	16.901
8	3	3	60	17.698
9	3	3	60	17.052
10	3	3.5	40	17.997
11	3	3.5	40	18.838
12	3	3.5	40	19.425
13	2	3.5	50	19.995
14	2	3.5	50	19.982
15	2	3.5	50	19.598
16	2.5	3.5	60	20.253
17	2.5	3.5	60	19.835
18	2.5	3.5	60	20.922
19	2.5	4	40	17.768
20	2.5	4	40	17.246
21	2.5	4	40	18.496
22	3	4	50	16.958
23	3	4	50	17.287
24	3	4	50	17.693
25	2	4	60	19.831
26	2	4	60	18.135
27	2	4	60	18.285

3. Results and Discussion

Taguchi's experimental design was systematically applied to enhance the process parameters for ultrasonic welding of 0.5 mm thick plastic (acrylic) to metal. Figure 4 displays the major effect plot for the S/N ratios for tensile strength, whereas Figure 5 displays the main impact plot for the means for tensile strength. As seen in Figure 4, the optimal experimental parameters for maximum tensile strength are welding pressure of 2 bar, welding duration of 3.5 seconds, and amplitude of 60 μm. With a delta value of 1.09, welding time has the most effect on welding performance, followed by welding pressure (0.41) and amplitude (0.37), as Table 3 demonstrates. Figure 5 displays the residual plots for tensile strength. Figure 5 displays the residual plot for tensile strength, which was produced with MINITABTM 19 software and provides information on the reproducibility of testing results. The testing data's tendency is closer to the middle value, as the residuals' normal probability map illustrates. Although the residuals are severe at the lesser error, statistical assessment indicates that the replies are acceptable. Tensile strength interaction graphs with respect to three factors are shown in Figure 6.The ANOVA results for the response are shown in Table 6. Table 6 demonstrates that the factors of welding time, welding pressure, and amplitude have a substantial influence on the response (tensile strength). Table 6's Column 8 displays the influence (p) of each element on the total deviation of the tensile strength result. Table 6 demonstrates that, when taken into account independently, the welding time, welding pressure, and amplitude all have no (zero) impact on the variation in the tensile strength result. The % contribution to the tensile strength is displayed in Table 6's column 4. The most important variable, welding time, contributes the highest percentage (66.68%) to the tensile strength, followed by welding pressure (10.45%) and amplitude (7.91%). Thus, the welding time is an important control component to take into account when determining the incidence of tensile strength, which is followed by welding pressure and amplitude. It should be kept in mind that the optimal combination of components and their levels chosen from the response analysis (weld strength) is the set of elements that generates the process's central tendency (process average).

Table 4. Response Table for Signal to Noise Ratios - Larger is better

Level	Welding Pressure (bar)	Welding Time (sec)	Amplitude (µm)
1	25.38	24.76	25.07
2	25.33	25.86	25.18
3	24.98	25.07	25.44
Delta	0.41	1.09	0.37
Rank	2	1	3

Table 5. Response Table for Means

Level	Welding Pressure (bar)	Welding Time (sec)	Amplitude (µm)
1	18.63	17.31	17.96
2	18.54	19.65	18.20
3	17.76	17.97	18.77
Delta	0.87	2.34	0.81
Rank	2	1	3

Table 6 .Analysis of Variance for Tensile Strength

Source	DF	Seq SS	Contri-bution	Adj SS	Adj MS	F-Value	P-Value
Welding Pressure (bar)	2	4.1009	10.45%	4.1009	2.0504	6.99	0.005
Welding Time	2	26.1706	66.68%	26.1706	13.0853	44.58	0.000
Amplitude (µm)	2	3.1053	7.91%	3.1053	1.5527	5.29	0.014
Error	20	5.8705	14.96%	5.8705	0.2935		
Lack-of-Fit	2	0.0004	0.00%	0.0004	0.0002	0.00	0.999
Pure Error	18	5.8701	14.96%	5.8701	0.3261		
Total	26	39.2473	100.00%				

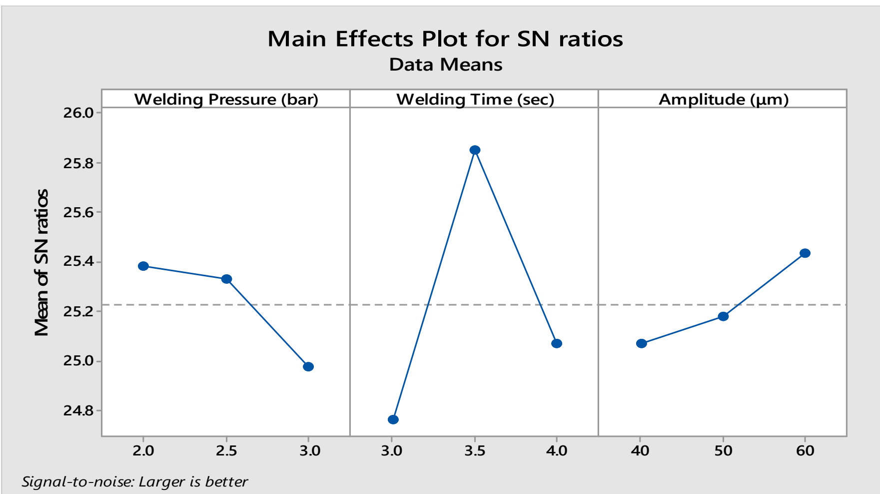

Figure 4: Main effect plot for S/N ratio Tensile Strength

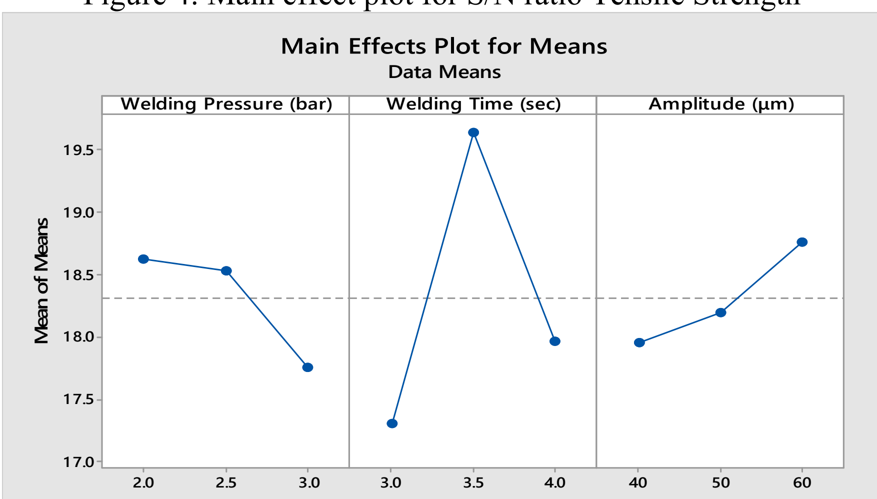

Figure 5: Main effect plot for Means Tensile Strength

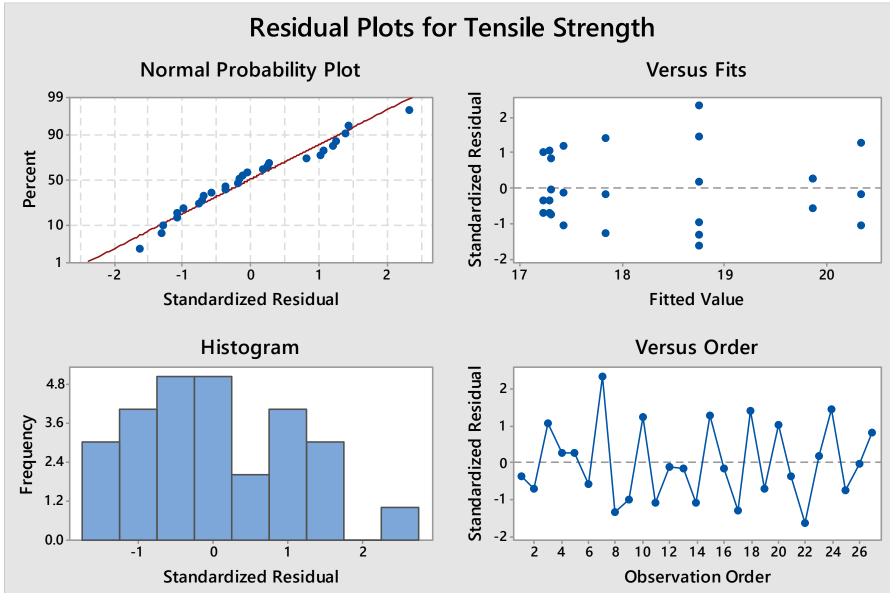

Figure 6: Residual plots for Tensile Strength

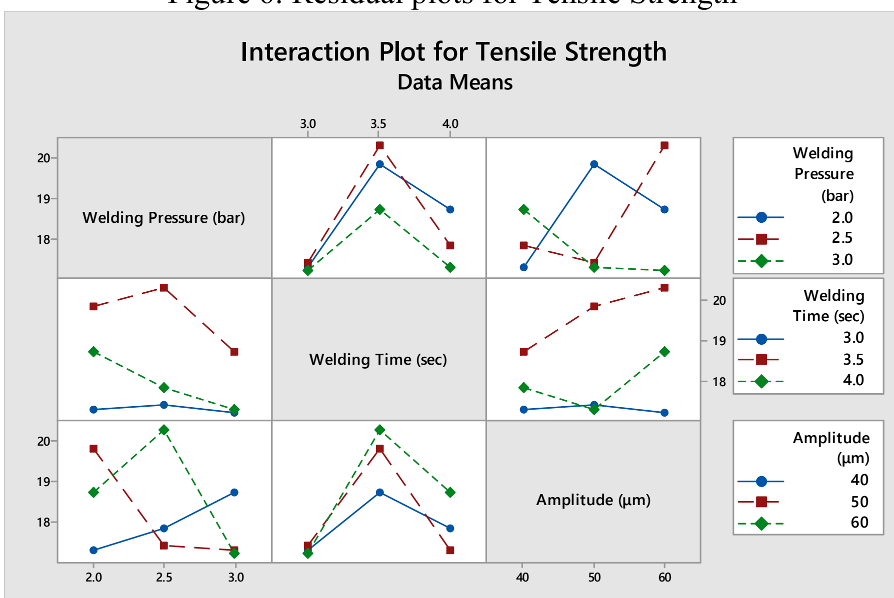

Figure 6: Interaction plots for Tensile Strength

4. Conclusions.

The ultrasonic welding equipment was used to examine the weld strength of aluminum to acrylic plastic under various conditions. The study and experimental results led to the following conclusions.

1. Research was done on the variables that affect ultrasonic plastic welding when combining acrylic plastic to aluminum. Weld strength variation was minimized and weld strength was maximized with the optimal parameter combinations.

2. It is discovered that include welding time, welding pressure and amplitude have a substantial influence on the response (weld strength).
3. The ANOVA findings indicate that the most significant contributing component, welding time, accounts for 66.68% of the tensile strength, followed by welding pressure (10.45%) and amplitude (7.91%) for the parameters under investigation.
4. The ideal parameters for achieving the highest tensile strength were found to be welding time 3 second, welding pressure 2 bar, and amplitude 60 μm.

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Conflict of interest

To the best of their knowledge, the authors hereby declare that there are no conflicts of interest in any of the connections and/or interests discussed in this paper.

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