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The experimental investigation and optimization of the effects of ultrasonic welding parameters on weld quality

Hüseyin Gezer[a*], Cihan Kaboğlu[b], Yunus Can Koser[c]

[a]*Sanver Engineering and Automation, Minarelicavus, Nilufer, Bursa, Turkiye*
(ORCID: 0000-0002-6418-0632), huseyin.gezer@sanvermuhendislik.com
[b]*Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Metallurgical and Materials Engineering, Bursa, Türkiye*
(ORCID: 0000-0002-6249-0565), cihan.kaboglu@btu.edu.tr
[c]*Sanver Engineering and Automation, Minarelicavus, Nilufer, Bursa, Turkiye*
(ORCID: 0009-0004-6685-1315), yunuscankoser@gmail.com

Abstract

Ultrasonic welding is a widely used industrial process for joining plastics and metals, especially dissimilar materials. In this process, the workpieces are held together under pressure and joined using high-frequency ultrasonic acoustic vibrations. Achieving the desired weld quality is crucial for the overall integrity of the final product. Therefore, investigating and optimizing the effects of ultrasonic welding parameters on weld quality is of significant importance. This study presents an experimental investigation aimed at understanding and optimizing the impact of various ultrasonic welding parameters on weld quality. An experimental study was conducted to analyze the effects of ultrasonic welding parameters such as amplitude, pressure, and time on weld quality. The Taguchi method was employed to minimize the number of experiments and determine the optimal combination of welding parameters that maximize the desired weld quality characteristics. The Taguchi experimental design method is a statistical approach that allows for the consideration of multiple factors simultaneously while achieving the most optimal result with fewer experiments. According to this method, a series of experiments were designed based on the L9 orthogonal array. The tensile test results of the samples obtained from the experiments were evaluated as the response variable to determine the weld quality. The results were statistically analyzed using Minitab software to identify the significant factors affecting weld quality and their interactions. The data revealed that the best weld strength was achieved at 4 bar pressure, 1 second processing time, and 90 Hz amplitude. Additionally, a correlation between the increase in these parameters and weld quality was established. In conclusion, this study demonstrated that the Taguchi method could be effectively applied to optimize ultrasonic welding parameters to achieve high-quality welds. The findings contribute to the advancement of ultrasonic welding technology, providing a basis for developing efficient and reliable welding processes for various applications and material combinations.

Keywords: Ultrasonic Welding, Welding Parameters, Taguchi, Pressure, Frequency.

1. Introduction

Ultrasonic welding is a versatile and efficient process widely used in various industries for joining different materials, offering advantages such as speed, precision, and cleanliness in the welding process. High-frequency vibrations, generated by a generator, are transmitted to a component called a horn or sonotrode. The sonotrode amplifies these vibrations. The amplified vibration waves are then transferred to the material's welding surface. As the surface temperature increases, the material softens or melts. Once the materials reach a softened or molten state, the welding process is completed by applying pressure for specific durations to form a strong and durable weld. The basic components of an ultrasonic welding machine include an ultrasonic generator that converts electrical energy into ultrasonic vibrations, a sonotrode that amplifies the vibrations and transmits them

* Corresponding author
E-mail addresses: *huseyin.gezer@sanvermuhendislik.com*
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to the workpiece, a robotic arm equipped with a pressure control valve to apply compressive force during welding, and a fixture that supports the workpiece during the welding process. A schematic representation of the ultrasonic welding process is provided below.

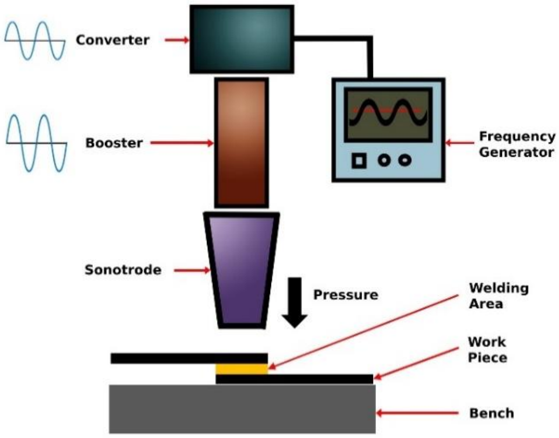

Fig. 1. Schematic representation of the ultrasonic welding process

The most significant advantages of the ultrasonic welding process include the absence of additional materials such as adhesives and solvents, making it a clean process; the application of heat to a very small area, thus minimizing thermal deformation of the part; operation at lower temperatures compared to other welding processes; and the speed of the process. However, the method also has certain limitations. These include its applicability only to materials that can be softened or melted, its use with thin to medium-thickness materials, the necessity for properly designed horns and anvils for effective welding, and the need for optimal determination of operating parameters. In the literature review conducted within this scope, some key studies addressing ultrasonic welding and its parameters are presented below.

It has been observed that ultrasonic welding achieves the most effective results for small parts with material thicknesses ranging from approximately 0.1 mm (100 micrometers) to several millimeters, particularly under high-volume production conditions. Considering production costs and part precision, ultrasonic welding has been identified as the most cost-effective and suitable joining method [1]. Elangovan et al. [2] investigated welding parameters such as welding pressure, welding time, and vibration amplitude in the ultrasonic welding of 0.2 mm thick copper. It was observed that other joining methods damaged the part due to its small size. A suitable experimental design based on Taguchi's methodology was conducted to investigate the effects of different welding parameters on weld strength and to obtain the optimal parameters. Analysis of variance (ANOVA) and signal-to-noise ratio analyses were used for this purpose. In another study combining the Response Surface Methodology (RSM) and Genetic Algorithm (GA), an effective methodology was developed to determine the optimal welding conditions that maximize the strength of joints produced by ultrasonic welding. RSM was used to develop an effective model for predicting weld strength by combining process parameters such as pressure, welding time, and amplitude. It was observed that as amplitude and pressure increased, weld strength also increased [3]. Wagner et al. [4] demonstrated the applicability of ultrasonic welding in joining multi-material structures such as lightweight metals and fiber-reinforced polymer (FRP) composites. In a study conducted in 2013, different welding horn profiles for ultrasonic welding of thermoplastics were characterized in terms of displacement amplitude and von-Mises stresses using modal and harmonic analyses. Experimental results showed that welds made using a Bezier horn profile exhibited high interface temperatures and higher strength compared to welds made with other horn profiles [5]. In a doctoral thesis by Al-Sarraf, Z. S. [6], a lateral drive ultrasonic welding machine capable of joining thin metals was designed and studied. The thesis investigated the design and parameters of the ultrasonic welding machine, focusing on its ability to join thin metals effectively. Another study examined the effects of ultrasonic welding parameters on the microstructure and mechanical properties of different joints. Experiments were conducted at various clamping pressures and energy levels to investigate the microstructure, mechanical properties, and bond quality of the welds. It was found that increasing clamping pressure allowed achieving nearly the same weld strength at relatively low energy levels in a short time. As welding energy increased, it was observed that the microstructure deteriorated due to increased temperature from continuous application of ultrasonic power, leading to recrystallization along the weld interface [7]. In 2015, Nikoi R. et al. [8] conducted an experimental analysis on the effect of ultrasonic welding on the weld strength of polypropylene composite samples. The impact of three process parameters—welding time, air pressure, vibration amplitude, and the amount of glass fiber in the composite—on the tensile-shear strength of weld joints was investigated. To reduce the number of tests and costs, a response surface methodology was employed in the experimental design, considering the above four parameters at three levels. It was observed that the best results, with a maximum breaking force of approximately 2.30 kN, were achieved when the air pressure, vibration amplitude, welding time, and glass fiber content were 1.5 bar, 32 microns, 0.4 seconds, and 10%, respectively. Panda M. R. [9] introduced a numerical and experimental approach in a master's thesis to study the parametric effects of ultrasonic welding. A numerical model was proposed to evaluate the heat generation during welding due to deformation and frictional heating. According to the study, the higher thermal conductivity of aluminum compared to steel and the application of thermal load to the center of the weld result in a greater temperature distribution in the workpiece. A statistical study of parameters in ultrasonic welding of plastics revealed that welding time significantly affects welding outcomes and subsequently welding pressure. It was found that holding time does not significantly contribute to welding results, as pressure is necessary during a specific duration (welding time) to develop close contact between the surfaces to achieve a strong bond. Ultrasonic welding of acrylonitrile butadiene styrene (ABS) samples was found to be easier compared to high-density polyethylene (HDPE) material. Under the same experimental conditions, ABS samples exhibited greater bond strength than HDPE components [10]. In a study investigating the effect of welding parameters on the tensile strength of ultrasonic spot welded aluminum to steel, a 3-factor, 3-level experimental design was implemented. According to the results, compressive force and vibration amplitude do not significantly affect tensile strength. However, vibration duration, despite being near the significance threshold, significantly impacts tensile strength. Interaction among welding parameters can significantly influence tensile strength. An artificial neural network optimized with Genetic Algorithm was used to construct an analytical model, and complementary experiments and analyses were conducted to validate the analytical model [11]. Satpathy, M. P. and Sahoo, S. K. [12], conducted experimental and numerical studies on ultrasonic welding of different metals. They proposed and accurately modeled a new type of booster and horn in this study. The Finite Element Method (FEM) modal analysis module was used to analyze the effects of different step lengths and filler radii on the natural frequency. Dynamic analysis was also performed to find the stress distribution in both parts under repeated loading conditions. In 2018, Chinnadurai, T. [13], conducted experimental research on the behavior of polypropylene during ultrasonic welding. The morphology of weld and non-weld regions of polypropylene samples was analyzed using Scanning Electron Microscopy (SEM). It was found that weld strength and joint integrity were higher with increased vibrations, indicating higher interfacial strength when the tendency for gap formation decreased. Shahid, M. B. et al. [14], examined the effect of process parameters on the bonding strength of Cu and Ni foils in ultrasonic welding. In this study, a series of weld qualities were introduced, and welding parameters were optimized for bond quality using optical microscopy and nanoindentation based on these qualities. Different types of failures based on microscopic images of broken samples were correlated with weld quality. A correlation between welding parameters and welding characteristics (such as bond density and post-weld thickness) was developed to provide insights into their interdependencies. Raza, S. F. et al. [15], presented the optimization of welding factors for ultrasonic welding of similar thermoplastic acrylonitrile butadiene styrene (ABS/ABS) and polypropylene (PP/PP) using Taguchi experimental design (L-8). Bhudolia, S. K. et al. [16], reviewed the detailed progress made by the scientific and research community in ultrasonic welding of thermoplastic composites to date. The focus of this study is to review the recent advancements in ultrasonic welding technique from thermoplastic composites to different materials. Various ultrasonic welding modes and their process parameters, such as welding time, welding pressure, amplitude, types of energy directors (EDs) affecting weld quality, and the advantages and disadvantages of ultrasonic welding compared to other joining techniques, were summarized. In 2022, an optimization of ultrasonic welding process parameters was conducted using a experimental design approach to increase the welding strength of 3C power boxes. In this study, Taguchi methods were employed to examine the optimal process parameters for achieving high welding strength in a plastic power box. The most significant control factor affecting welding strength was amplitude, followed by welding pressure, holding time, and trigger position. The optimal process parameters were determined as 43.4 µm amplitude, 115 kPa welding pressure, 0.4 seconds holding time, and 69.95 mm trigger position. Finally, verification experiments were conducted to validate these optimal process parameters [17]. In the study conducted by Şeker et al. [18], low carbon steel sheet material and automation steel fittings were welded using the MIG welding method and the effect of different protective welding gas flow rates on weld penetration was investigated. Other welding parameters of the test samples were kept constant and welding was performed at 8 different gas flow rates. As a result of the measurements, weld penetration was examined and the gas flow rates that provided optimum welding penetration values for both the sheet material and the fitting were determined.

Literature review underscores the necessity of examining and optimizing ultrasonic welding parameters during production. Current information indicates that factors such as pressure, amplitude, frequency, and time significantly influence the quality of ultrasonic welding. Systematic adjustment of these parameters is crucial to ensure optimal mechanical properties, integrity, and reliability of welded joints. Understanding the interaction among these factors helps mitigate potential issues and enhances process control, forming the basis for improving product quality across various industrial applications.

2. Material and Method

The necessary experiments were conducted using an ultrasonic welding machine produced by Sanver Engineering and Automation within the scope of this study. The ultrasonic welding machine is seen in the figure below.

Fig. 2. Ultrasonic welding machine

The most critical parameters identified to affect the efficiency of ultrasonic welding are pressure representing the clamping force during welding, welding process time, amplitude, and three different types of plastic materials. In our study, ultrasonic welding was applied to the painted surfaces of bumpers with different colors. All three bumper types (Type 1: White, Type 2: Black, Type 3: Red) are made of the same material composition, a blend of Polypropylene (PP) and Ethylene Propylene Diene Monomer (EPDM). However, during the ultrasonic welding process on the painted surfaces, it was observed that the color differences had an impact on the welding quality and performance. This may be due to the varying pigment structures or thicknesses of the paints, which could influence the transmission of ultrasonic energy and its interaction with the material. In this context, an L9 (3^4) orthogonal Taguchi experimental design was conducted with 4 factors at 3 levels each. The factors and levels are shown in the table below:

Table 1. Test factors and levels

	Levels		
Factors	1	2	3
Pressure (bar)	2.5	3	4
Process Time (sn)	0.5	0.75	1
Amplitude (Hz)	70	80	90
Material Type	Type-1	Type-2	Type-3

In the defined experimental parameters, 9 welding processes have been completed. Images of the obtained samples are provided below.

Fig. 2 Sample welding images

To determine the ideal welding parameters, tensile strength was used as the output parameter. The materials used in the welding were subjected to tensile testing, and their tensile strengths were obtained. The tensile test was conducted according to ASTM D638 standard, which is commonly used to test the tensile properties of plastics, including molded and welded samples. The sample size should be ASTM D638 Type I, with a thickness of 3.2 mm (1/8 inch) and a gauge length of 50 mm (2 inches). In our study, welded samples were prepared by cutting them to the desired dimensions according to this standard. During the test, the specimen is loaded with opposing forces acting on opposite faces, both aligned along the same axis, attempting to pull the specimen apart. The machine continues to apply stress until the specimen fractures. Load and elongation data are recorded throughout the test using appropriate software and data acquisition systems. The data obtained from the tensile test results are provided in the table below.

Table 2. Tensile test results

Sample No	Elongation (mm)	Rupture Force (N)	Tensile Stress $\sigma_ç$ (MPa)	Rupture Stress σ_k (MPa)
1	1.283	774	18.61	18.51
2	1.357	802	19.28	18.99
3	1.506	865	20.79	20.36
4	1.455	878	21.11	20.91
5	1.577	932	22.40	22.16
6	1.588	912	21.92	21.51
7	1.586	957	23.00	22.60
8	1.625	960	23.08	22.84
9	1.731	994	23.89	23.56

According to the results of the tensile test, the maximum tensile strength was obtained with a force of 994 N in sample number 9, while the lowest maximum tensile force was found to be 774 N in sample number 1. The maximum elongation was measured at 1.731 mm in the number 9 sample. The lowest rupture stress recorded was 18.51 MPa in sample number 1.

3. Results and Discussion

Below is the table showing the defined parameters and the results of the tensile tests based on these parameters.

Table 3. Rupture forces depending on test parameters

Experiment	Pressure (bar)	Process Time (sn)	Amplitude (Hz)	Material Type	Rupture Force (N)
1	2.5	0.5	70	Type-1	774
2	2.5	0.75	80	Type -2	802
3	2.5	1	90	Type -3	865
4	3	0.5	80	Type -3	878
5	3	0.75	90	Type -1	932
6	3	1	70	Type -2	912
7	4	0.5	90	Type -2	957
8	4	0.75	70	Type -3	960
9	4	1	80	Type -1	994

The obtained data were analyzed using the Minitab program to determine the optimal operating parameters. The analysis method selected was 'larger is better'. This method was chosen to maximize the rupture strength. The Taguchi experimental design and method can be viewed as follows in the Minitab program.

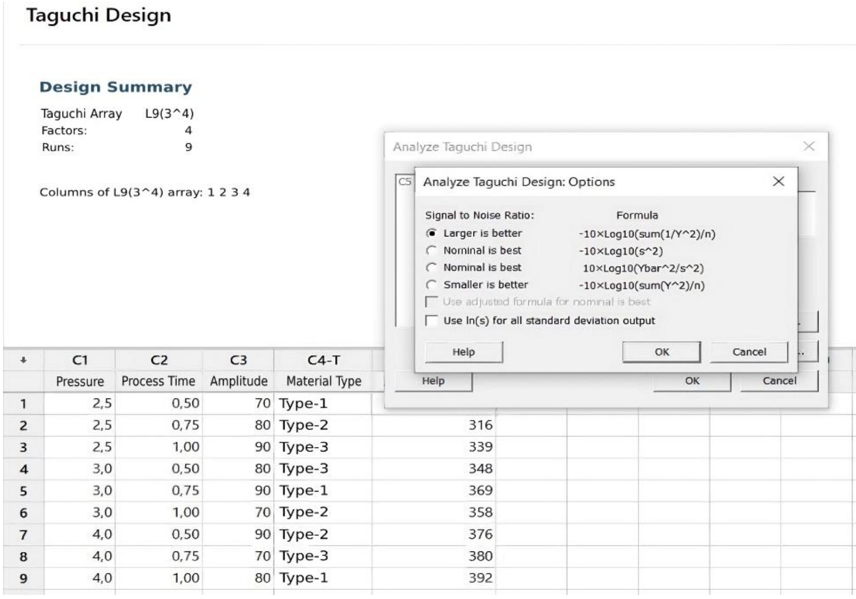

Fig. 3. Minitab Taguchi design and method

After the necessary definitions, the analysis was conducted. According to the analysis results, signal-to-noise ratio values and graphical representation are provided as follows.

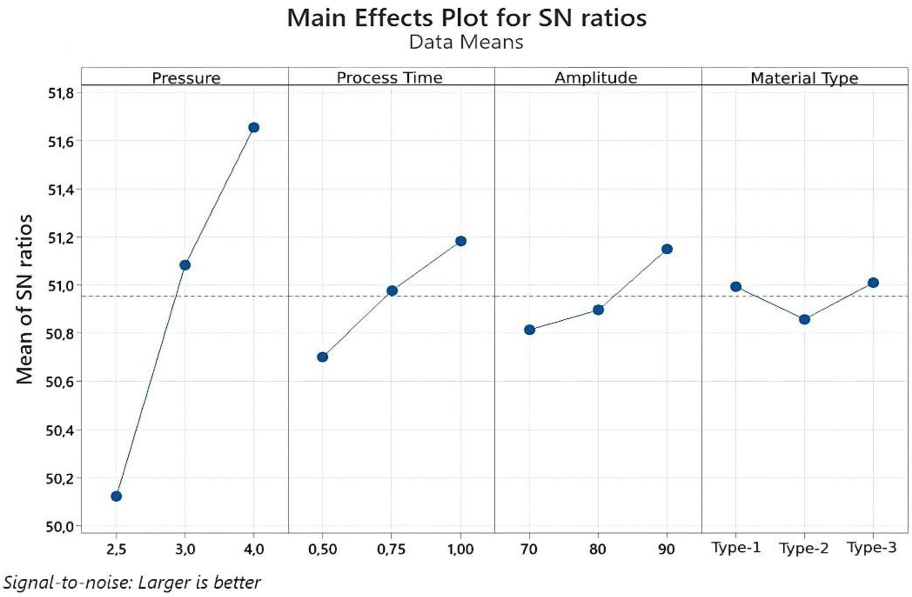

Fig. 4. Signal-to-noise plot

In the signal-to-noise ratio table, it is observed that the values for pressures of 3 bar and 4 bar are above average, while 2.5 bar pressure is insufficient for this welding method. In terms of process time, the most ideal duration is found to be 1 second, although 0.75 seconds can also be used. Regarding the amplitude parameter, the only usable value above average is determined to be 90 Hz. Finally, while Type-1 and Type-3 materials are ideal for welding under these parameters, it is observed that Type-2 material cannot be welded effectively. Following statistical analyses, an ANOVA analysis was conducted to determine the model quality. The R-squared value of 92% indicates that the model quality is adequate.

4. Conclusion

In this study, the effect of ultrasonic welding parameters on weld quality was investigated. The parameters examined were pressure, processing time, amplitude, and material type. A Taguchi experimental design with 4 factors and 3 levels was employed to conduct experiments. Tensile tests were performed on the obtained samples to determine their rupture strengths. Statistical analyses were conducted using Minitab software to identify the optimal operating parameters. It was found that for achieving the highest rupture strength, the optimal parameters were 4 bar pressure, 1 second processing time, and 90 Hz amplitude. Type-1 and Type-3 materials showed the best welding results under these parameters. As expected, the results revealed a significant correlation between pressure, processing time, and weld quality. Lower pressure and processing time values were associated with lower weld quality, emphasizing the importance of careful selection and optimization of these parameters to achieve robust welds. Furthermore, the results indicated that amplitude values of 70 Hz and 80 Hz were not sufficiently effective for this process, and Type-2 material exhibited lower weld quality under these parameters. During ultrasonic welding, the varying quality of welds observed in car bumpers with different paint layers can be attributed to the thermal properties of the color pigments. White reflects more light and heat, leading to less heating of the material during the welding process and minimal thermal degradation of the paint layer. This results in a more uniform and stronger weld. Black paint, on the other hand, absorbs more heat, causing excessive heating in the welding area, which leads to the degradation of the paint layer and a weaker weld. Red paint, absorbing a moderate amount of heat, produces intermediate results. This indicates that the thermal conductivity and absorption characteristics of the paint pigments significantly impact the quality of ultrasonic welding.

The study contributes to the literature by systematically establishing an understanding for selecting welding parameters to determine ideal weld quality. Our research findings align with those of Demir A. [19], who investigated the effects of ultrasonic welding and welding parameters on tensile strength in thermoplastic materials. Comparisons indicate that welding quality improves up to a certain point with increased pressure, amplitude, and processing time. These findings are consistent with existing literature on the impact of ultrasonic welding on tensile strength, emphasizing the crucial role of optimizing welding parameters in enhancing tensile strength. The data obtained enable practitioners to select appropriate parameters for achieving optimal tensile strength in ultrasonic weld connections, thereby contributing to manufacturing processes. The study's outcomes may serve as a basis for future research exploring differences in material properties, additional parameters, or novel approaches to improve welding quality. Furthermore, investigating the effects of these parameters on mechanical properties other than rupture strength can lead to a more comprehensive understanding of the welding process. Ultimately, this study significantly enhances our understanding of ultrasonic welding parameters, facilitating the optimization of the process for industrial applications.

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