Original Research Article:
full paper

(2023), «EUREKA: Physics and Engineering»
Number 3

# OPTIMIZATION OF TECHNOLOGICAL PARAMETERS IN ULTRASONIC WELDING OF THE POLYPROPYLENE FABRIC USING TAGUCHI AND FCCCD METHODS

***Le Quang Thanh*** [1, 2, 3]
*Faculty of Mechanical Engineering*

***Nguyen Thanh Hai*** [1, 2]
*Faculty of Mechanical Engineering*

***Nguyen Huu Loc*** [1, 2] ✉
*Faculty of Mechanical Engineering*
*nhloc@hcmut.edu.vn*

[1]*Ho Chi Minh City University of Technology (HCMUT)*
*268 Ly Thuong Kiet str., District 10, Ho Chi Minh City, Vietnam, 700000*

[2]*Vietnam National University Ho Chi Minh City*
*Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam, 700000*

[3]*Ho Chi Minh City University of Transport*
*02 Vo Oanh str., District Binh Thanh, Ho Chi Minh City, Vietnam, 700000*

✉ **Corresponding author**

**Abstract**

Ultrasonic welding is a welding method that has been applied for welding nonwoven fabrics, with many advantages such as fast speed, high reliability, easy automation and especially less pollution to the environment. This paper studies the optimization of technological parameters in the welding process such as welding time, pressure, and weld shape on the breaking strength of ultrasonic welding of Polypropylene (PP) nonwovens. To evaluate the influence level and find the reasonable technological parameters domain in the paper, the Taguchi method is used in combination with the face-centered central composite design (FCCCD) response surface method. The research results have determined the regression equations used to calculate the breaking strength for each weld shape as well as the optimal domain for the main technological parameters, ensuring the breaking strength of the weld. There are different degrees of influence of technological parameters (shape of the weld zone, welding time and welding pressure) on the breaking strength of ultrasonic welds. Among them, the influence level of welding time $t$ is 45.31 %, the weld shape is Pattern 2 with the rate of 30.03 %, and the welding pressure is 24.66 %. Carrying out a verification test with the welding parameters: $t = 1.6$ s, $p = 3.1$ kgf/cm$^2$, two patterns (Pattern 2 and Pattern 3), the result of breaking strength for patterns was achieved. Pattern 2 has a difference of 1.19 % between the regression equation results and the actual experimental results, while the figure for Pattern 3 is 0.77 %. From these results, it is possible to select the appropriate technological parameters for ultrasonic welding equipment when processing products from nonwoven fabrics to ensure the highest quality and productivity.

**Keywords:** ultrasonic welding, optimization, nonwoven fabrics, breaking strength, Taguchi method, FCCCD.

**DOI: 10.21303/2461-4262.2023.002777**

## 1. Introduction

Ultrasonic welding today is widely used in many industries such as: automobile [1, 2], healthcare [3], electronics [4], packaging [5], and garment [6]. For PP plastic material, the welding process is best done in the viscoelastic state, when the bonding of the PP sheets occurs easily (**Fig. 1**). If the temperature is not high enough, the bonding of the welded product is not good. If the weld zone temperature is higher than 170 °C, then the material dripping process will take place, and the fabric will have a destruction phenomenon at the welded location [7, 8].

PP nonwoven fabric is made by blowing PP with micro-diameter components on a moving conveyor belt (**Fig. 2**). Fabric fibers are bonded together by solvents or heat to form lightweight and porous fabrics [9].

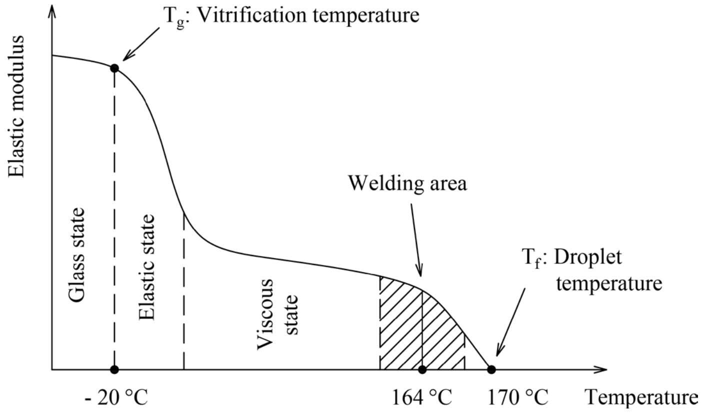



**Fig. 1.** Thermal characteristic diagram of PP

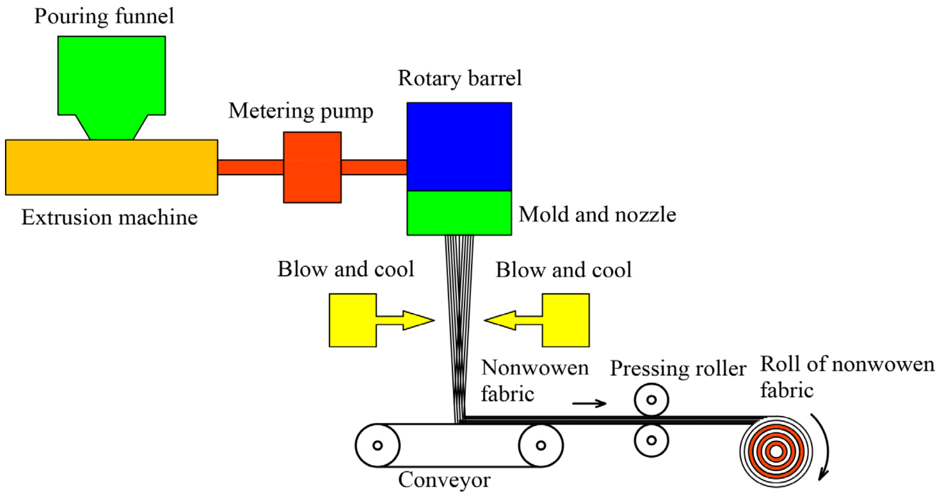



**Fig. 2.** Nonwoven fabric manufacturing process

Welding design is one of the most important requirements of ultrasonic welding [10, 11]. In recent years, research on the design of welds for sheet materials such as thin films, nonwoven fabrics has been conducted by many researchers around the world using different methods and trends.

There have been studies on analyzing the structure and properties of PP fibers during the heat-sealing process. Particularly, via thermal analysis, the crystallinity ratio of fibers was specifically calculated [12]. The test results for the breaking strength of nonwoven fabrics were determined by a tensile testing machine.

Researchers also conducted some analyses on heat sealing for products made from nonwoven fabrics and the influence of bonding variables on the structure and properties of the fabric [13]. The advantage of the heat-sealing method is high speed and simplicity. The main objectives of that study were to examine the changes that take place in the fibers in the weld zone, unwelded zone, and the vicinity of the weld during welding; to understand the failures of point-linked nonwoven; and finally to suggest optimal processing conditions for heat welding based on variables such as welding area, welding size, welding temperature [14]. From there, a research was made on the strength optimization of nonwoven heat-welding. That paper dealt with the technology to overcome the shortcomings of heat welding and obtain weld seams with high strength [15]. Then, by considering the ultrasonic welding with Polyethylene (PE) and insulation fabrics, the authors described the different parameters used in ultrasonic welding for PE, Polyethylene Terephthalate (PET) fabrics and canvas (PE drawn into sheets) in both continuous and intermittent welding modes [16]. With many advantages over conventional sewing with thread, ultrasonic welding can ensure tightness and is easy to recycle because no other materials are added to the product. There is also a different view of assembly technology for garments for specialized products such as workwear, sportswear, medical protective clothing, personal protection clothing, smart clothing [17]. These products often require more functions of higher nature such as being durable for breaking strength, sealed, easy to recycle, but do not need too much in terms of aesthetics. With these perspectives, researchers analyzed the influence of factors on the ultrasonic weld properties of the nonwoven. Nonwoven fabrics with 100 % PP and 100 % PE are spun and fused, welded using ultrasonic welding machines [18]. Another consideration was a study on ultrasonic welding of the nonwoven applied in the production of surgical gowns (high-grade medical gowns) [19]. This study mainly focused on the use of ultrasonic welding for products made from nonwoven.

The factors affecting the quality of the ultrasonic weld include material type, energy region, frequency number of oscillations, amplitude of oscillation, welding pressure, welding time, holding time, welding machine power as shown by the statistics in **Table 1**.

**Table 1**

Statistics on technological parameters in research papers

| Ref. | Content of research related to ultrasonic welding | Frequency (kHz) | Amplitude (μm) | Welding pressure | Welding time (s) |
|---|---|---|---|---|---|
| [10] | Determination of optimal ultrasonic welding parameters for 3C plastic box | 20 | 43.4 | 115 kPa | 0.4 |
| [16] | Ultrasonic welding of nonwoven fabrics | 20 | 60; 70 | 30; 35; 40 psi | 360 |
| [18] | Evaluation of the influence of some ultrasonic weld seam shapes of the nonwoven | 20 | 25; 30 | 2.2 kgf/cm$^2$ | None |
| [19] | Research on ultrasonic welding for medical protective clothing products | 20 | None | 1–3 bar | None |
| [20] | Effect of welding time and weld structure | 40 | None | 2.5 MPa | 1.5; 2.5; 3.5 |
| [21] | Optimization of weld elements for ultrasonic welding of thermoplastics | 20 | 21 | 25 MPa | 0.8; 0.9; 1.4; 1.5 |

The above factors can be either independent or interdependent ones in the adjustment of the welding process [20]. Specifically, factors such as frequency, amplitude, and power of the ultrasonic source are interdependent during the welding process. In contrast, factors such as material, weld shape, welding pressure, welding time are independent ones [11].

The study used the Taguchi method combining with the face-centered central composite design method (FCCCD) to conduct experiments and obtain a quadratic regression equation to determine the relationship between such factors as welding time, welding pressure and weld shape to the breaking strength of the weld.

## 2. Materials and methods

### 2. 1. Theoretical basis

To study, the influence of each factor on the breaking strength of the weld was analyzed to find the range of values of the main parameters.

Oscillation frequency: for ultrasonic welding, the commonly used oscillation frequency is from 20 to 40 kHz. The higher the ultrasonic oscillation frequency of the equipment, the better its quality, the less noise, and the better working environment for workers. However, in terms of energy, the higher the vibration frequency, the lower the working power of the ultrasonic system, so it is necessary to choose the working frequency to best suit the actual conditions. In this study, a device with an ultrasonic frequency of 20 kHz was used from the design, the simulation to the fabrication process of the ultrasonic system, similar to the frequency applied in other studies.

Oscillation amplitude: the amplitude of oscillation at the position of the working surface of the welding die depends on the parameters of the ultrasonic system in the order from transducer, amplifier, to welding die. Depending on the design process of the amplifier and the welding die, the value of the welding amplitude will be a multiple of the oscillation amplitude generated by the transducer. The welding time for each different thermoplastic material has the most suiTable vibration amplitude parameter [20]. In this study for 70 GSM format PP nonwoven fabric, a welding amplitude of 48 μm [21] was used.

Welding time: welding time is the period during which ultrasonic waves oscillates with a certain amplitude. Careful selection of this time interval is necessary to obtain the optimum weld breaking strength [22].

By screening the designs of experiments in different welding times, combining with the reference to the studies in **Table 1**, for PP nonwoven with a 70 GSM format, the welding time from 1.2 to 2 s is satisfactory. If the welding time is less than 1.2 s, for 70 GSM-format PP nonwoven, the welding process is not sufficient to heat most of the weld area to the yield temperature. Then the weld will only stick to one part as shown in **Fig. 3, *a***, leading to the weld not ensuring the adhesion between the welding parts. In contrast, if the welding time is too long (more than 2 s), then most of the welding area will have a dripping phenomenon that makes the material unable to be bonded to return to its original state, leading to a broken weld as shown in **Fig. 3, *b***.

Welding pressure: welding pressure is the pressure exerted between the welding anvil and the welding die per unit area on the part to be welded during the welding process. The purpose of welding pressure is to keep the two parts to be welded, creating diffusion of molten material between those two parts. Depending on the welding pressure parameters, the quality of the weld will also change. To adjust the welding pressure, the air pressure of the pneumatic system for this mechanism will be adjusted. If the welding pressure from the welding die and the welding anvil on the object to be welded is small enough to create material diffusion, the nonwoven fabrics will not be able to stick together at the end of the welding process as shown in **Fig. 3, *c*, *d***.

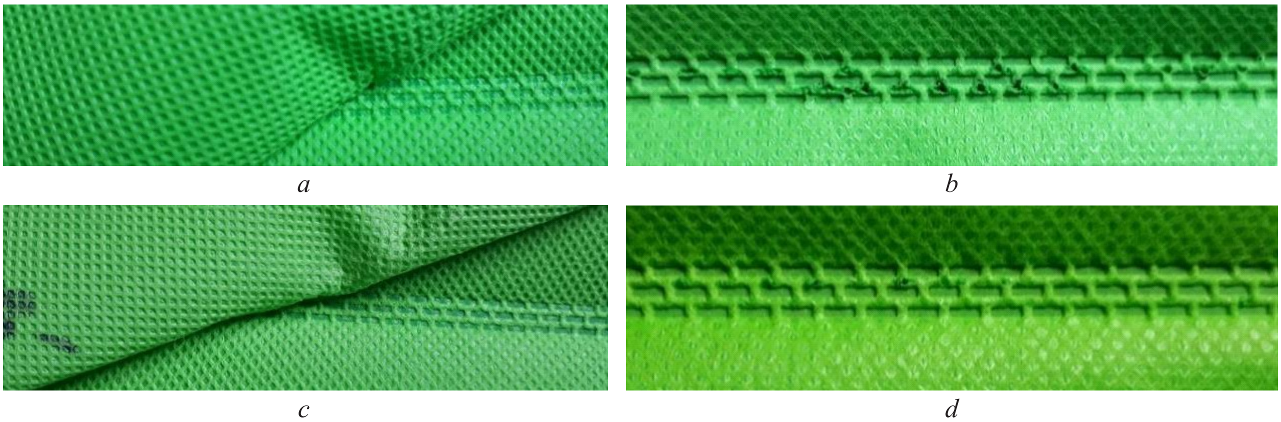


**Fig. 3.** Types of weld failure of nonwoven fabrics: *a* – unsatisfactory weld seam due to insufficient welding time; *b* – damaged welding seam due to the welding time being too long; *c* – unsatisfactory weld seam due to insufficient welding pressure; *d* – damaged welding seam due to too much welding pressure

However, if the pressure is continuously increased too high, then similar to increasing the welding time too much, the weld will also appear damaged due to too much heat (weld burn).

By qualitatively observing many experiments in different welding times, for PP nonwoven fabric with a 70 GSM format, the satisfactory welding pressure should be selected in the range from 2.5 kgf/cm$^2$ to 3.5 kgf/cm$^2$. With a fixed mechanical system (pneumatic cylinder size, mold size), the pneumatic pressure adjustment levels at the pressure regulator valve are at the following levels: 2.5, 3, and 3.5 kgf/cm$^2$. Static pressure is applied stably during one cycle of ultrasonic welding by means of a pressurized valve system.

Welding pattern: the shape of the ultrasonic weld is also a critical factor affecting the weld strength. In addition, the shape of the weld also affects the aesthetics of the product, so it is considered an essential factor in the production of nonwoven fabric by ultrasonic welding.

In this article, the most popular weld patterns in practice were researched and selected with the area ratio of welding area to surrounding area to conduct analysis and selection of the suiTable patterns.

The study conducted ultrasonic welding of samples of PP nonwoven fabric in a 70 GSM format with dimensions according to ISO 9073-3:1989 with a width of 200 mm in welding modes:

frequency of 20 kHz, amplitude of 48 μm, welding time of 1.6 s, and welding pressure of 3 kgf/cm$^2$ to obtain welding patterns with the shape as in **Table 2** [21].

With the chosen patterns, to evaluate the breaking strength, experiments were conducted with seven repeated tests where $n = 7$. The test results are presented in **Table 2**.

With the above patterns, to evaluate the breaking strength, experiments were conducted with seven repeated tests where $n = 7$. The test results are presented in **Table 3**.

The output parameter is the breaking strength *F*, which is the maximum breaking force in newtons (*N*) that the test piece can withstand at break (ISO 5082:1982).

From the dimensions of the welds, the ratio areas for weld shapes from Pattern 1 to Pattern 6 are shown in **Table 3**.

**Table 2**

Types of ultrasonic welding patterns after welding with different anvils

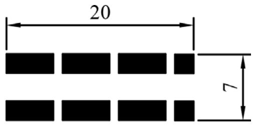
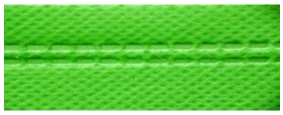
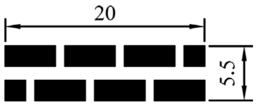
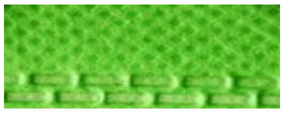
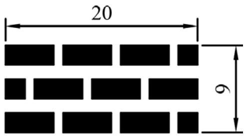
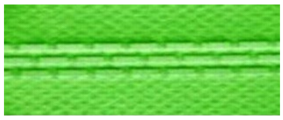
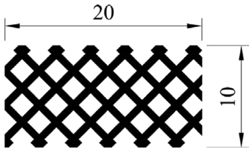
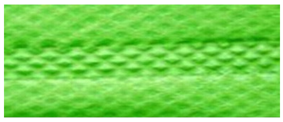
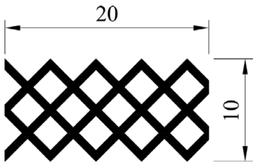
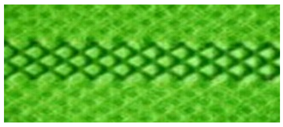
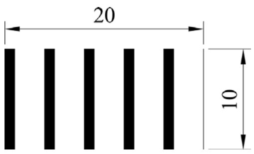
| Patterns | Designed welding anvil patterns | Welding patterns |
|---|---|---|
| Pattern 1 |  |  |
| Pattern 2 |  |  |
| Pattern 3 |  |  |
| Pattern 4 |  |  |
| Pattern 5 |  |  |
| Pattern 6 |  |  |

**Table 3**

Welding area parameters with a length of 20 mm

| Patterns | Welding area (mm$^2$) | Surrounding area (mm$^2$) | Area ratio (%) | Breaking strength, *F* (N) |
|---|---|---|---|---|
| Pattern 1 | 68 | 140 | 49 | 194.17 |
| Pattern 2 | 68 | 110 | 62 | 241.57 |
| Pattern 3 | 102 | 180 | 57 | 226.42 |
| Pattern 4 | 97 | 200 | 49 | 192.05 |
| Pattern 5 | 77.5 | 200 | 39 | 188.14 |
| Pattern 6 | 50 | 200 | 25 | 187.56 |

Based on the data of **Table 3**, a graph was built as shown in **Fig. 4**, which reveals that there is a dependence of the breaking strength *F*, (N) on the area ratio (%) of the welding area according to the shape of the weld pattern.

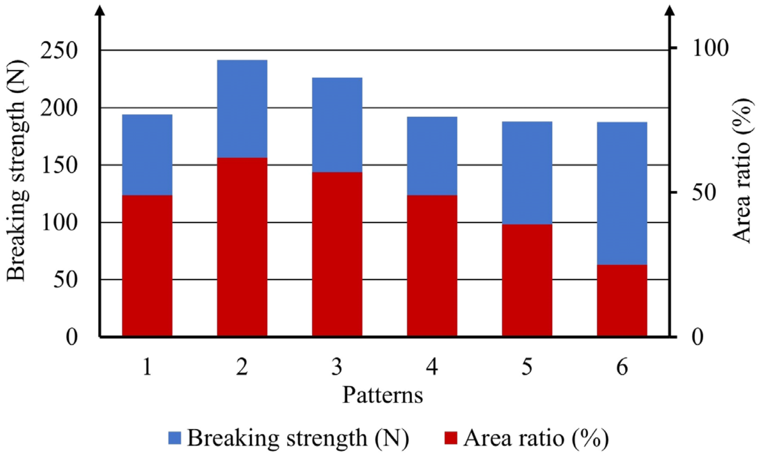



**Fig. 4.** Dependence of breaking strength *F*, (N) on weld area ratio

Using Minitab, it is possible to obtain the dependence of the breaking strength *F*, (N) on the percentage of weld area (area ratio) according to the shape of the weld pattern. The quadratic regression has the following form:

$$F = 159 + 3.67r - 0.1444r^2 + 0.0017r^3, \quad (1)$$

where *F* is the breaking strength, *r* is the percentage (area ratio) of the weld area to the surrounding area of the weld shapes.

From **Fig. 4** and **Table 3**, Pattern 2 has the highest strength, followed by Pattern 3. To optimize weld strength, the weld designs according to Pattern 2 and Pattern 3 were the research focus and implemented in the next steps of this paper.

When conducting the experiment, the first step is to determine the number of replicate experiments *n* needed. In this study, after the initial series of experimental results, the number of repeated experiments was determined as $n = 7$ repetitions.

Choosing the degree of the regression equation and the range of values of the factors: with the factors affecting the breaking strength of the weld seam being analyzed above, separate experiments for factors such as welding time, welding pressure were conducted, and results are presented in graph form so that the influence of each factor on the breaking strength of the weld seam can be observed as shown in **Fig. 5, 6**.

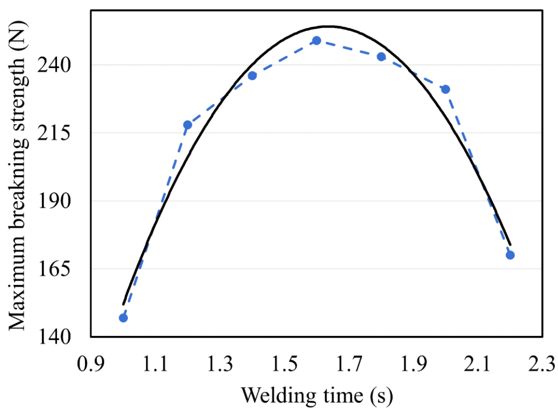



**Fig. 5.** Effect of welding time on breaking strength *F*, (N)

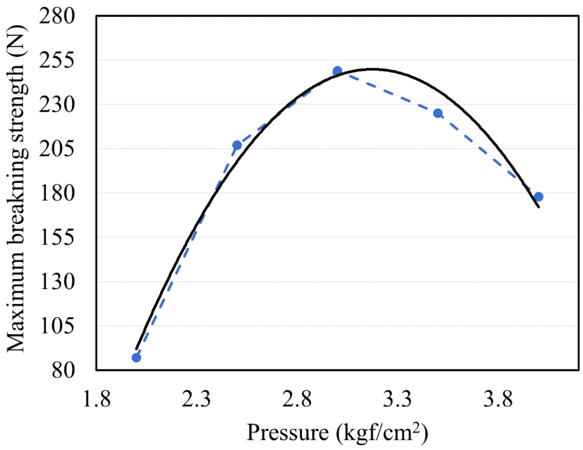



**Fig. 6.** Effect of welding pressure on breaking strength *F*, (N)

For welding time factor, the second-degree regression equation has the form:

$$F_1 = -421.4 + 825.8t - 252.4t^2. \quad (2)$$

For welding pressure, the second-degree regression equation has the form:

$$F_2 = -902.2 + 725.7p - 114.3p^2. \quad (3)$$

Based on the graphs from the experimental values for the input factors in **Fig. 5**, **6**, it is clear that the application of the regression model in the form of 2$^{nd}$ degree polynomials is suiTable for the experimental model. The general form of a polynomial of the second degree with two factors:

$$y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ii} x_i x_j. \quad (4)$$

**2. 2. Equipment for creating samples for experimentation**

A vertical ultrasonic welding machine with ultrasonic system having the working size of $w = 200$ mm, with additional sensors to measure technological parameters, is a device to conduct prototyping of experiments by the axial welding method (**Fig. 7**). The ultrasonic welding technology parameters include the maximum power of 2 kW, frequency of 20 kHz. The welding and holding time can be adjusted from 0.2 to 4 s, and the pneumatic pressure acting on the weld line of the maximum machine is 5 kgf/cm$^2$.

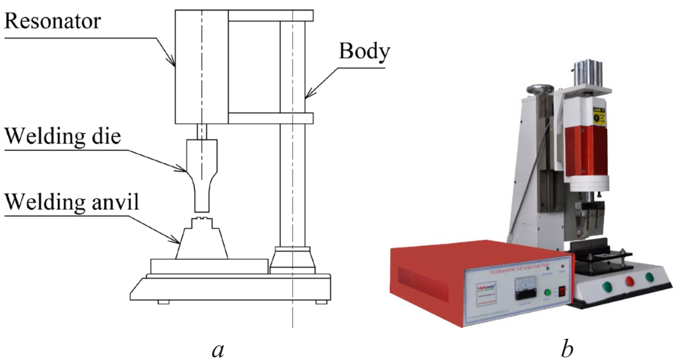



**Fig. 7.** Vertical welding machine: *a* – scheme; *b* – welding machine

For nonwoven fabric welding, the welding anvil detail, in addition to being a product support part, also has an important function of shaping the connection between two fabrics when welding.

In order to shape the weld seam, the contact part of the upper welding anvil must be machined to different types of Pattern shapes.

Experimental model: to evaluate the breaking strength of two pieces of PP nonwoven fabric, the study applied the standards to test the weld breaking strength of two pieces of nonwoven fabric with the size of the sample test being 200 mm. The samples for testing the breaking strength of the weld seam are described in **Fig. 8, *a*, *b***. The study welded the samples in different welding modes and then checked the breaking strength of the weld seam on the universal testing machine model Instron 3369 as in **Fig. 9**.

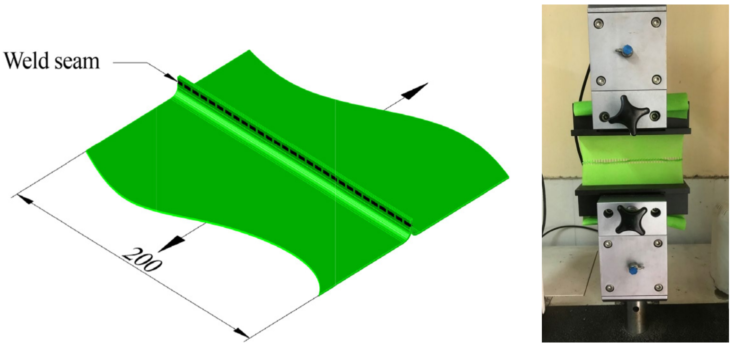



**Fig. 8.** Breaking testing: *a* – sample for experiment; *b* – breaking testing

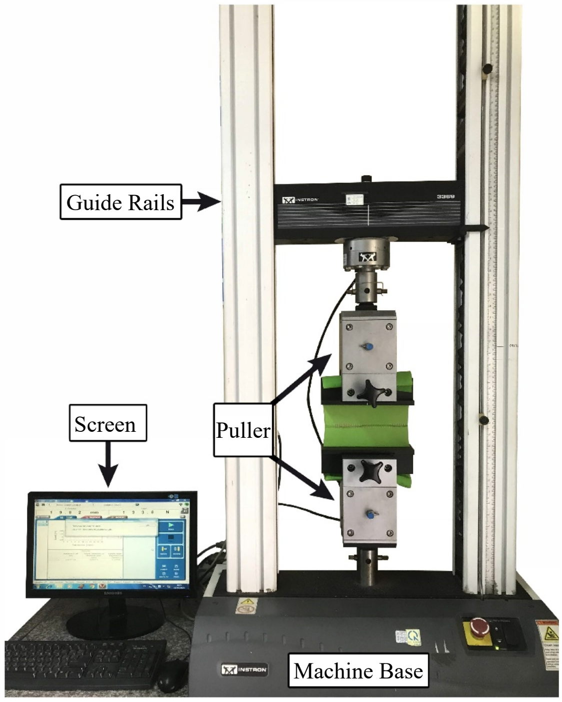
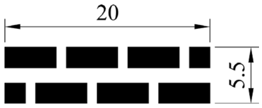
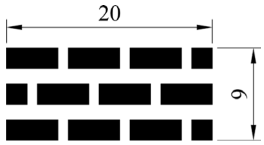
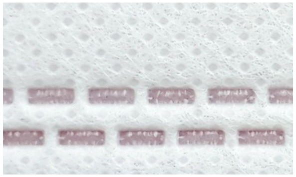
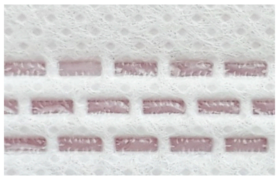



**Fig. 9.** The universal testing machine model Instron 3369

Within the limitations of the study, two weld patterns in **Table 4** were selected.

Choosing the form of the design matrix of experiments: In this study, the Taguchi method was used, and the response surface method was the face-centered central composite design (FCCCD) [23, 24]. The Taguchi method with the L18 design matrix with three factors as in **Table 6** (**Fig. 10, *a***): two shapes of weld seam Pattern were selected (Pattern 2 and Pattern 3), the other two factors have three levels of values. The advantage of the L18 design matrix (column *N* **Table 6**) is that nine experiments per one pattern, if rearranged, correspond to nine experiments according to the response surface method, which is FCCCD (column $N'$ **Table 6** and **Fig. 10, *b*, *c***). From the quadratic regression equation, it is possible to find the domain of technological parameters to ensure that the breaking strength reaches the highest value or is within the given value range.

**Table 4**
Two types of weld patterns to be the experiments

| Patterns | Pattern 2 | Pattern 3 |
|---|---|---|
| Welding anvil patterns |  |  |
| Weld patterns |  |  |

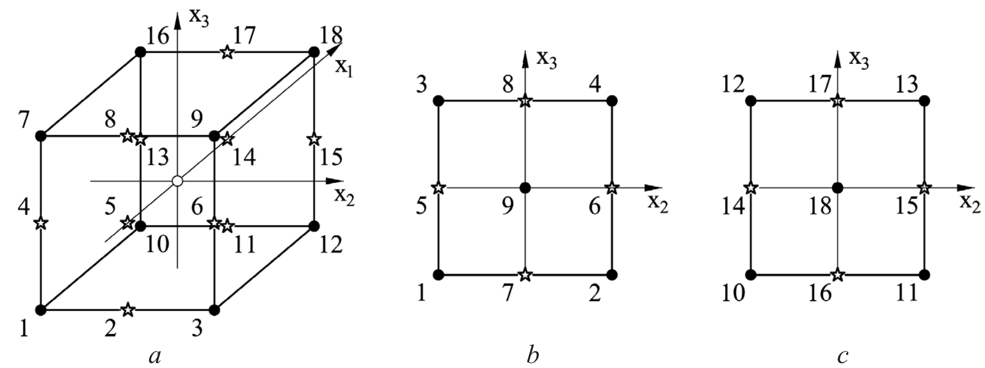



**Fig. 10.** Design of experiments:
*a* – Taguchi method L18; *b* – FCCCD for Pattern 2; *c* – FCCCD for Pattern 3

**3. Results and discussions**

The experiments with the factor values according to the Taguchi method are presented in **Table 5**.

The order of experiments according to column *N* with one factor having two levels of values and two factors having three levels of values (eighteen experiments) is displayed in **Table 6**.

**Table 5**
Factor levels

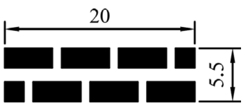
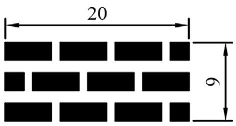
| Factors | Symbol | | Intervals | Level of factors | | |
|---|---|---|---|---|---|---|
| | | | | Taguchi method | | |
| | Uncoded | Code | | 1 | 2 | 3 |
| | | | | FCCCD method | | |
| | | | | –1 | 0 | 1 |
| Pattern of weld seam | *D* | $x_1$ | None |  |  | None |
| Welding time (s) | *t* | $x_2$ | 0.4 | 1.2 | 1.6 | 2.0 |
| Welding pressure (kgf/cm$^2$) | *P* | $x_3$ | 0.5 | 2.5 | 3.0 | 3.5 |

**Table 6**
Matrix design L18 with $N = 2 \cdot 3^2 = 18$ and three factors

| *N* | *N′* | Coded levels | | | Coded levels | | | Uncoded value | | | Breaking strength, *F*, (N) | *S*/*N* ratio | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $x_1$ | $x_2$ | $x_3$ | $x_1$ | $x_2$ | $x_3$ | *D* | *t* | *p* | | | |
| 1 | 1 | 1 | 1 | 1 | –1 | –1 | –1 | Pattern 3 | 1.2 | 2.5 | 160.52 | 47.17 | 160.52 |
| 2 | 5 | 1 | 1 | 2 | –1 | –1 | 0 | Pattern 3 | 1.2 | 3.0 | 207.52 | 47.94 | 207.52 |
| 3 | 3 | 1 | 1 | 3 | –1 | –1 | 1 | Pattern 3 | 1.2 | 3.5 | 182.74 | 47.48 | 182.74 |
| 4 | 7 | 1 | 2 | 1 | –1 | 0 | –1 | Pattern 3 | 1.6 | 2.5 | 228.31 | 46.56 | 228.31 |
| 5 | 9 | 1 | 2 | 2 | –1 | 0 | 0 | Pattern 3 | 1.6 | 3.0 | 249.54 | 47.05 | 249.54 |
| 6 | 8 | 1 | 2 | 3 | –1 | 0 | 1 | Pattern 3 | 1.6 | 3.5 | 236.55 | 46.22 | 236.55 |
| 7 | 2 | 1 | 3 | 1 | –1 | 1 | –1 | Pattern 3 | 2.0 | 2.5 | 212.91 | 41.58 | 212.91 |
| 8 | 6 | 1 | 3 | 2 | –1 | 1 | 0 | Pattern 3 | 2.0 | 3.0 | 225.28 | 44.99 | 225.28 |
| 9 | 4 | 1 | 3 | 3 | –1 | 1 | 1 | Pattern 3 | 2.0 | 3.5 | 204.69 | 43.05 | 204.69 |
| 10 | 10 | 2 | 1 | 1 | 1 | –1 | –1 | Pattern 4 | 1.2 | 2.5 | 119.97 | 45.47 | 119.97 |
| 11 | 14 | 2 | 1 | 2 | 1 | –1 | 0 | Pattern 4 | 1.2 | 3.0 | 177.83 | 46.99 | 177.83 |
| 12 | 12 | 2 | 1 | 3 | 1 | –1 | 1 | Pattern 4 | 1.2 | 3.5 | 142.14 | 45.94 | 142.14 |
| 13 | 16 | 2 | 2 | 1 | 1 | 0 | –1 | Pattern 4 | 1.6 | 2.5 | 187.77 | 45.22 | 187.77 |
| 14 | 18 | 2 | 2 | 2 | 1 | 0 | 0 | Pattern 4 | 1.6 | 3.0 | 223.52 | 45.31 | 223.52 |
| 15 | 17 | 2 | 2 | 3 | 1 | 0 | 1 | Pattern 4 | 1.6 | 3.5 | 198.05 | 44.01 | 198.05 |
| 16 | 11 | 2 | 3 | 1 | 1 | 1 | –1 | Pattern 4 | 2.0 | 2.5 | 182.48 | 47.17 | 182.48 |
| 17 | 15 | 2 | 3 | 2 | 1 | 1 | 0 | Pattern 4 | 2.0 | 3.0 | 184.35 | 47.94 | 184.35 |
| 18 | 13 | 2 | 3 | 3 | 1 | 1 | 1 | Pattern 4 | 2.0 | 3.5 | 158.55 | 47.48 | 158.55 |

Using Minitab software to process experimental results, it is possible to obtain the ANOVA analysis results (**Table 7** and **Fig. 11**).

**Table 7**
ANOVA analysis results

| Number | Levels | Factor | | | Optimal set |
|---|---|---|---|---|---|
| | | *D* | *t* | *p* | |
| 1 | 1 | 46.46 | 44.22 | 45.02 | |
| 2 | 2 | 44.73 | 46.83 | 46.44 | |
| 3 | 3 | None | 45.73 | 45.32 | D1p2t2 Pattern 2; $t = 1.6$ s; $p = 3$ kgf/cm$^2$ |
| Delta | | 1.73 | 2.61 | 1.42 | |
| % affect | | 30.03 | 45.31 | 24.66 | |
| Rank | | 2 | 1 | 3 | |

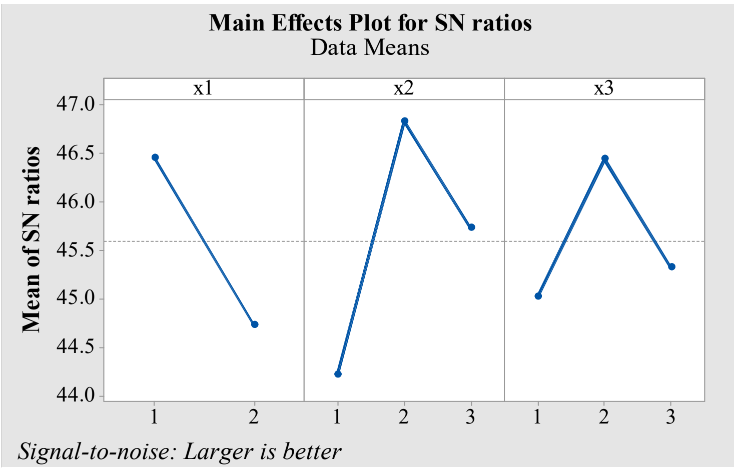



**Fig. 11.** The influence of the parameters on the breaking strength of the weld seam

Obviously, the factors that most affect the breaking strength are welding time (at 45.31 %), shape of weld seam (Pattern 2) (at 30.03 %), and welding pressure (at 24.66 %).

The research used the FCCCD response surface method with three levels of welding time and welding pressure values to obtain a quadratic regression model and find the optimal technological parameter domain. Each type of weld according to Pattern 2 and Pattern 3 was performed with the order of experiments in columns $N'$ in **Table 6**: Pattern 2 with $N'$ from 1 to 9 (**Fig. 10, *b***) and Pattern 3 with $N'$ from 10 to 18 (**Fig. 10, *c***). The number of repeated tests is $n=7$ repetitions, the results are as in **Table 6**.

Processing the experimental results, analyzing, and evaluating the regression equation on Minitab, the regression equation for the influence of the parameters on the breaking strength for each type of weld Pattern was obtained as follows (**Table 8**).

**Table 8**
The regression equations

| Form | The breaking strength (N) | |
|---|---|---|
| | The shape of weld seam – Pattern 2, $F_2$ | The shape of weld seam – Pattern 3, $F_3$ |
| Coded form | $256.06+15.94x_2+4.07x_3-$ $-39.77x_2^2-20.89x_3^2-8.16x_2x_3$ | $223.49+14.25x_2+0.93x_3-$ $-42.95x_2^2-29.54x_3^2-10.41x_2x_3$ |
| Uncoded form | $1822+1051.7p+550.5t-$ $-159.09p^2-130.6t^2-40.82pt$ | $-2134.3+1142.5p+749.2t-$ $-171.8p^2-184.6t^2-52.03pt$ |

For Pattern 2, ANOVA analysis was conducted on Minitab to show that the coefficients of the above regression equations were significant ($p$-value<0.05) (as displayed in **Table 9**), and goodness-of-fit was $R\text{–}Sq=90.04$ %. All $VIF=1$ means coefficients are not correlated and multicollinearity does not exist in the regression model.

Experimental results are presented in the form of curves and contour lines as shown in **Fig. 12**.

**Table 9**
ANOVA analysis for Pattern 2

| Term | Coef | SE Coef | T-Value | P-value | VIF |
|---|---|---|---|---|---|
| Constant | 252.06 | 2.53 | 99.74 | 0.000 | – |
| *p* | 15.94 | 1.38 | 11.51 | 0.000 | 1.00 |
| *t* | 4.07 | 1.38 | 2.94 | 0.005 | 1.00 |
| *p*p* | –39.77 | 2.40 | –16.59 | 0.000 | 1.00 |
| *t*t* | –20.89 | 2.40 | –8.71 | 0.000 | 1.00 |
| *p*t* | –8.16 | 1.70 | –4.82 | 0.000 | 1.00 |

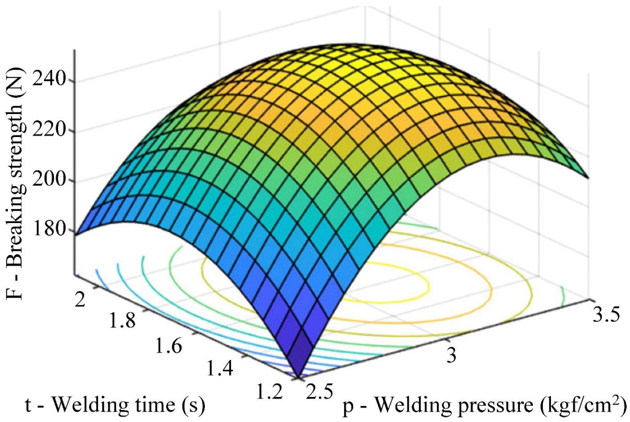



**Fig. 12.** Effect of welding time and welding pressure on the breaking strength of Pattern 2

For Pattern 3, An ANOVA analysis was conducted on Minitab to reveal that the coefficients of the above regression equations were significant (except *t*) (as in **Table 10**), and goodness-of-fit was $R\text{–}Sq = 92.02$ %.

Experimental results are presented in the form of curves and contour lines as shown in **Fig. 13**.

**Table 10**

ANOVA analysis for Pattern 3

| Term | Coef | SE Coef | T-Value | P-value | VIF |
|---|---|---|---|---|---|
| Constant | 223.49 | 2.45 | 91.26 | 0.000 | – |
| *p* | 14.25 | 1.34 | 10.62 | 0.000 | 1.00 |
| *t* | 0.93 | 1.34 | 0.70 | 0.490 | 1.00 |
| *p***p* | –42.95 | 2.32 | –18.49 | 0.000 | 1.00 |
| *t***t* | –29.54 | 2.32 | –12.72 | 0.000 | 1.00 |
| *p***t* | –10.41 | 1.64 | –6.33 | 0.000 | 1.00 |

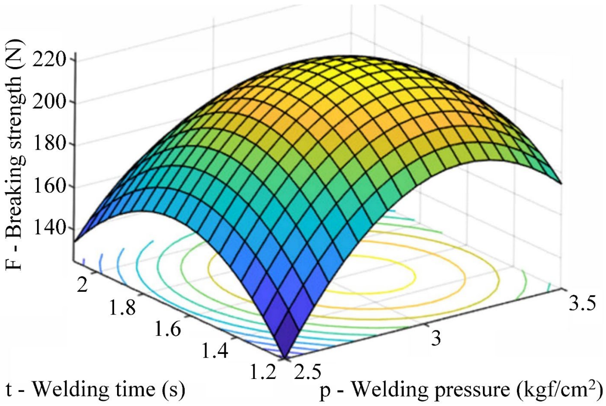
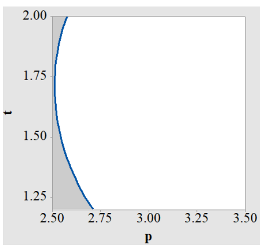
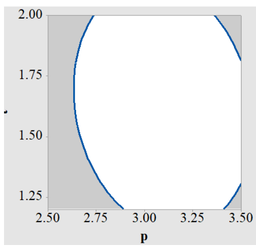
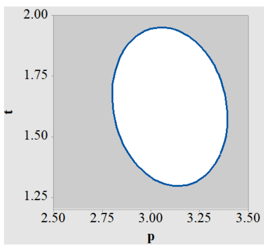
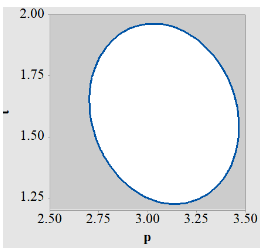
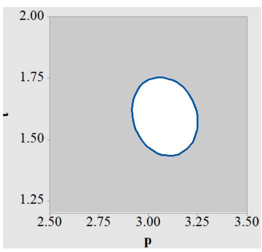
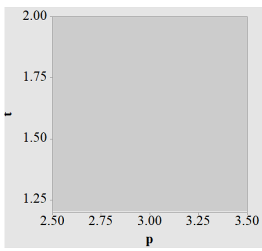



**Fig. 13.** Effect of welding time and welding pressure on the breaking strength of Pattern 3

An analysis for the domain of technological parameters was performed to ensure that the breaking strength reached the lowest given values of 200 N, 220 N, and 240 N, which is given in **Table 11**.

**Table 11**

Technological parameters value ranges corresponding to breaking strengths

| Breaking strength, *F*, (N) | ≥200 N | ≥220 N | ≥240 N |
|---|---|---|---|
| Pattern 2 |  |  |  |
| Pattern 3 |  |  |  |

Using Minitab software with defined regression equations, the optimal breaking strength values of the patterns are presented in **Table 12**.

**Table 12**
Values of breaking strength corresponding to types of welding specimens

| Pattern | Welding time (s) | Welding/pressure (kgf/cm$^2$) | Maximum breaking strength (N) |
|---|---|---|---|
| 2 | 1.62 | 3.1 | 253.73 |
| 3 | 1.60 | 3.1 | 224.67 |

Carrying out the test again with the test samples having the welding parameters of $t = 1.6$ s, $p = 3.1$ kgf/cm$^2$, two weld shapes, the study obtained the results of the breaking strength as shown in **Table 13**.

**Table 13**
Values of breaking strength corresponding to types of welding specimens

| Pattern | $F_1$, (N) | $F_2$, (N) | $F_3$, (N) | $F_4$, (N) | $F_5$, (N) | $F_6$, (N) | $F_7$, (N) | $F_m$, (N) |
|---|---|---|---|---|---|---|---|---|
| 2 | 250.13 | 260.84 | 247.38 | 243.32 | 257.34 | 246.46 | 249.53 | 250.71 |
| 3 | 230.54 | 231.43 | 223.72 | 233.69 | 220.25 | 219.21 | 225.06 | 226.77 |

Compared with the regression equation results (**Table 11**) of Pattern 2 and Pattern 3, the difference between the regression equation and the experimental results are 1.19 % and 0.77 %.

Based on the recommended welding temperature for PP materials, with welding frequency of 20 kHz, welding amplitude of 48 µm, welding time from 1.2 to 2 s, welding pressure from 2.5 to 3.5 kgf/cm$^2$, the welding temperature is in the region to the right of the viscoelastic state but not to the $T_f$ droplet temperature region.

From these results, it is possible to select appropriate technological parameters for ultrasonic welding equipment when processing products from nonwoven fabrics to ensure the highest quality and productivity. For example in **Table 11**, Pattern 2 has the breaking strength greater than 240 N, it is possible to choose welding pressure parameters to minimize the welding time and pressure, particularly around 1.35 s and 23.5 kgf/cm$^2$, to achieve the highest machine productivity.

The study only focused on optimizing the breaking strength of ultrasonic welds of PP nonwovens. Other materials and types of nonwoven fabrics may have different influence technological parameters and the range of values for these parameters is different; therefore, further research may be required to determine these parameters. Moreover, other factors such as the size of nonwoven fabrics, the type of ultrasonic welding equipment, and the production process may affect the optimal technological parameters.

In summary, the study provides valuable insights into optimizing technological parameters for ultrasonic welding of PP nonwoven fabrics. With these presented methods and equipment, further research can be made to validate the findings in different contexts with different materials.

## 4. Conclusions

The study optimized the main technological parameters using the Taguchi method combining with the FCCCD response surface method to determine the appropriate breaking strength as required. The experimental process to determine the maximum breaking strength of the ultrasonic welding of the nonwoven reaches about 79 % of the breaking strength of the nonwoven material.

There are different degrees of influence of technological parameters (shape of the weld zone, welding time and welding pressure) on the breaking strength of ultrasonic welds. Among them, the influence level of welding time $t$ is 45.31 %, the weld shape is Pattern 2 with the rate of 30.03 %, and the welding pressure is 24.66 %.

A regression equation was used for the selected types of welding patterns, thereby determining the optimal technological parameter areas suiTable for the requirements of the weld strength.

For Pattern 2, the highest breaking strength was obtained at 253.73 N where $t = 1.62$ s and welding pressure $p = 3.1$ kgf/cm$^2$. For Pattern 3, the highest breaking strength was obtained at 224.67 N where $t = 1.6$ s and welding pressure $p = 3.09$ kgf/cm$^2$. Carrying out a verification test with welding parameters: $t = 1.6$ s, $p = 3.1$ kgf/cm$^2$, two patterns (Pattern 2 and Pattern 3), the result of breaking strength for patterns was achieved. Pattern 2 has a difference of 1.19 % between the regression equation results and the actual experimental results, while the figure for Pattern 3 is 0.77 %.

The research is the basis for using other methodologies to optimize the technological parameters of the ultrasonic welding process with the aim of creating welds with breaking strength and productivity that meet actual requirements. From there, a technological process for ultrasonic welding method for nonwoven fabrics can be developed. Depending on the manufacturer's requirements for the productivity and breaking strength of the welded products, a reasonable set of technological parameters will be applied to the production process.

**Conflict of interest**

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

**Financing**

The study was performed without financial support.

**Data availability**

Manuscript has no associated data.

**Acknowledgement**

We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

**References**

[1] de Leon, M., Shin, H.-S. (2022). Review of the advancements in aluminum and copper ultrasonic welding in electric vehicles and superconductor applications. Journal of Materials Processing Technology, 307, 117691. doi: https://doi.org/10.1016/j.jmatprotec.2022.117691

[2] Unnikrishnan, T. G., Kavan, P. (2022). A review study in ultrasonic-welding of similar and dissimilar thermoplastic polymers and its composites. Materials Today: Proceedings, 56, 3294–3300. doi: https://doi.org/10.1016/j.matpr.2021.09.540

[3] Boz, S., Küçük, M. (2021). The analysis of the ultrasonic welding performance for the medical protective clothing. Tekstil ve konfeksiyon. doi: https://doi.org/10.32710/tekstilvekonfeksiyon.811584

[4] Hunstig, M., Schaermann, W., Broekelmann, M., Holtkaemper, S., Siepe, D., Hesse, H. J. (2020). Smart Ultrasonic Welding in Power Electronics Packaging. CIPS 2020; 11th International Conference on Integrated Power Electronics Systems. Available at: https://ieeexplore.ieee.org/document/9097722

[5] Long, Z., Ju, J., Chen, Z., Kireeva, M., Liu, X., Ye, S. (2022). A novel ultrasonic transducer with multiple vibrations in microelectronic packaging. Sensors and Actuators A: Physical, 341, 113582. doi: https://doi.org/10.1016/j.sna.2022.113582

[6] El-Barbary, A. F. M. (2021). The Effect of using Ultrasonic In Sewing Leather Garments. International Design Journal, 11 (4), 347–358. Available at: https://digitalcommons.aaru.edu.jo/cgi/viewcontent.cgi?article=1466&context=faa-design

[7] Karimi, F., Soltani, P., Zarrebini, M., Hassanpour, A. (2022). Acoustic and thermal performance of polypropylene nonwoven fabrics for insulation in buildings. Journal of Building Engineering, 50, 104125. doi: https://doi.org/10.1016/j.jobe.2022.104125

[8] Wu, W., Urabe, K., Hirogaki, T., Aoyama, E., Sota, H. (2020). Investigation of Production of Nanofiber Nonwoven Fabric and its Thermal Properties. International Journal of Automation Technology, 14 (2), 264–273. doi: https://doi.org/10.20965/ijat.2020.p0264

[9] Wang, W., Feng, L., Song, B., Wang, L., Shao, R., Xia, Y. et al. (2022). Fabrication and application of superhydrophobic nonwovens: a review. Materials Today Chemistry, 26, 101227. doi: https://doi.org/10.1016/j.mtchem.2022.101227

[10] Kuo, C.-C., Tsai, Q.-Z., Li, D.-Y., Lin, Y.-X., Chen, W.-X. (2022). Optimization of Ultrasonic Welding Process Parameters to Enhance Weld Strength of 3C Power Cases Using a Design of Experiments Approach. Polymers, 14 (12), 2388. doi: https://doi.org/10.3390/polym14122388

[11] Raza, S. F., Khan, S. A., Mughal, M. P. (2019). Optimizing the weld factors affecting ultrasonic welding of thermoplastics. The International Journal of Advanced Manufacturing Technology, 103 (5-8), 2053–2067. doi: https://doi.org/10.1007/s00170-019-03681-7

[12] Chand, S., Bhat, G. S., Spruiell, J. E., Malkan, S. (2001). Structure and properties of polypropylene fibers during thermal bonding. Thermochimica Acta, 367–368, 155–160. doi: https://doi.org/10.1016/s0040-6031(00)00672-9

[13] Bhat, G. S., Jangala, P. K., Spruiell, J. E. (2004). Thermal bonding of polypropylene nonwovens: Effect of bonding variables on the structure and properties of the fabrics. Journal of Applied Polymer Science, 92 (6), 3593–3600. doi: https://doi.org/10.1002/app.20411

[14] Warner, S. B. (1989). Thermal Bonding of Polypropylene Fibers. Textile Research Journal, 59 (3), 151–159. doi: https://doi.org/10.1177/004051758905900304

[15] Fedorova, N., Verenich, S., Pourdeyhimi, B. (2007). Strength Optimization of Thermally Bonded Spunbond Nonwovens. Journal of Engineered Fibers and Fabrics, 2 (1), 155892500700200. doi: https://doi.org/10.1177/155892500700200104

[16] Ghosh, S., Reddy, R. (2009). Ultrasonic sealing of polyester and spectra fabrics using thermo plastic properties. Journal of Applied Polymer Science, 113 (2), 1082–1089. doi: https://doi.org/10.1002/app.30050

[17] Jana, P. (2011). Assembling Technologies for Functional Garments – An Overview. Indian Journal of Fibre & Textile Research, 36, 380–387. Available at: https://nopr.niscpr.res.in/handle/123456789/13232.

[18] Kayar, M., Mistik, S. I., Inan, D. (2015). Analysing effect of the factors on ultrasonic seam tensile properties of nonwoven fabrics by Nested Anova Design. International Journal of Clothing Science and Technology, 27 (6), 803–817. doi: https://doi.org/10.1108/ijcst-05-2014-0066

[19] Eryuruk, S. H., Karagüzel Kayaoglu, B., Kalaoglu, F. (2017). A study on ultrasonic welding of nonwovens used for surgical gowns. International Journal of Clothing Science and Technology, 29 (4), 539–552. doi: https://doi.org/10.1108/ijcst-05-2016-0048

[20] Arabaci, U., Özdemir, U. (2022). Influence of The Welding Time on The Structure and Mechanical Properties of Vibration Welded PPT20 Polymers. Contemporary Multidisciplinary Technical Research, 8, 169–180. Available at: https://avesis.gazi.edu.tr/yayin/5eecf1f7-7b7b-4872-a771-b2a222226de2/contemporary-multidisciplinary-technical-research

[21] Nguyen, T., Thanh, L. Q., Loc, N. H., Huu, M. N., Nguyen Van, A. (2020). Effects of Different Roller Profiles on the Microstructure and Peel Strength of the Ultrasonic Welding Joints of Nonwoven Fabrics. Applied Sciences, 10 (12), 4101. doi: https://doi.org/10.3390/app10124101

[22] Shi, W., Little, T. (2000). Mechanisms of ultrasonic joining of textile materials. International Journal of Clothing Science and Technology, 12 (5), 331–350. doi: https://doi.org/10.1108/09556220010377869

[23] Loc, N., Hung, T. Q. (2021). Optimization of Cutting Parameters on Surface Roughness and Productivity when Milling Wood Materials. Journal of Machine Engineering, 21 (4), 72–89. doi: https://doi.org/10.36897/jme/144426

[24] Nguyen, H. L., Tran, V. T. (2022). Applying FCCCD Response Surface Method in Studying the Cutting Power of Wood Materials. Solid State Phenomena, 329, 25–31. doi: https://doi.org/10.4028/p-kjkk7u

*Received date 10.01.2023*
*Accepted date 16.03.2023*
*Published date 25.05.2023*



***How to cite:*** *Le, Q. T., Nguyen, T. H., Nguyen, H. L. (2023). Optimization of technological parameters in ultrasonic welding of the polypropylene fabric using Taguchi and FCCCD methods. EUREKA: Physics and Engineering, 3, 97–111. doi: https://doi.org/10.21303/2461-4262.2023.002777*