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SCIENTIFIC ANALYSIS OF ULTRASONIC METHOD OF SEWING FABRICS AND DEVELOPMENT OF ADVANCED SEWING MACHINE

Palvannazirova Nasiba Alisher kizi
Doctoral Student

Petr Mikhailovich Butovsky
Supervisor: Ph.D. Associate Professor
Tashkent Institute of Textile and Light Industry

Agzamov M. M.
Supervisor: Ph.D. Associate Professor
Tashkent Institute of Textile and Light Industry

Abstract:
Ultrasonic welding (UW) emerges as a standout technique for efficiently joining thermoplastic materials, offering a blend of high strength and cost-effectiveness. This method, gaining traction for its advancements, demands careful consideration of application-specific requirements to unlock its full potential. This review delves into the latest strides in ultrasonic welding for fabric joining, spotlighting the influence of key parameters like duration, pressure, and vibration amplitude on joint quality. It underscores the complexity of optimizing these factors to enhance joint durability, strength, and aesthetics. Comparing ultrasonic welding to traditional methods, its advantages—such as speed, economy, and eco-friendliness—are evident, despite some material limitations. This paper presents an exhaustive analysis of ultrasonic welding's current landscape and its promising trajectory for innovation. It suggests that optimizing welding parameters and innovating energy guides could further refine joint quality, distributing energy more evenly across the weld. In summary, ultrasonic fabric welding stands out for its efficiency and reliability in joining diverse thermoplastic composites. Its track record suggests significant potential for broader application, from textiles to advanced composites, championed by its rapid processing, affordability, and strong, binder-free joints. This review not only highlights ultrasonic welding's advantages but also its adaptability and future in manufacturing, making a compelling case for its continued adoption and development.[1]

Keywords: thermoplastic composite; ultrasonic welding; energy director; dissimilar materials; bonding strength

Introduction:

Bonding of different materials is an important technological process in many industries. Particularly relevant is the task of reliably and accurately joining tissues in medical and light industrial applications.

Traditional mechanical and thermal suturing methods, such as needle suturing, have a number of significant disadvantages. Firstly, they can damage the tissue structure in the suture area, reducing its strength. Secondly, such methods often lead to changes in the colour and shape of the material. In addition, traditional suturing is a labour-intensive process that requires highly skilled personnel.[2,3]

In recent years, an alternative method of joining fabrics - ultrasonic welding - has been actively developed and implemented. This technology is based on the use of mechanical vibrations at ultrasonic frequency, which cause heating and plasticisation of materials at the point of contact without damaging the surrounding tissues.

Ultrasonic bonding has a number of advantages over traditional methods. Firstly, ultrasonic bonding does not cause changes in the colour and shape of the material, which is particularly important when working with expensive and delicate fabrics. [4]. Secondly, it simplifies and reduces the cost of the sewing process compared to traditional hand sewing.

However, despite all its advantages, the application of ultrasonic tissue joining technology is still limited. This is due to insufficient research into the optimum processing modes for different types of textile materials and product designs. In addition, there are certain difficulties in selecting and adjusting ultrasonic equipment for specific tasks [5,6].

In this respect, the study of the strength and stability of ultrasonic seams on different fabrics, as well as the search for optimal technological modes, is a very relevant direction. The results obtained will contribute to a wider implementation of this promising sewing method in industry.

Theoretical Part

Heating of materials under the action of ultrasound is confidently caused by losses of ultrasonic energy in the medium. The main heating mechanisms are viscous friction, relaxation processes, and hysteresis losses during periodic deformation of the material.

In reference [7], a schematic of the unit for stitching an ultrasonic sewing machine is diplomatically shown in the figure. The unit consists of two rollers (1,2) between which there is a layer of fabrics (3,4) with a strip of polymer (5) in between. The upper roller 2, coated with polymer and aided by spring 6, confidently presses the fabric, causing ultrasonic vibrations [8,9]. Through this process, the polymer softens and penetrates the fabric's pores, ultimately solidifying and binding the fabrics together. This method is diplomatically recognized as an effective means of fabric bonding.

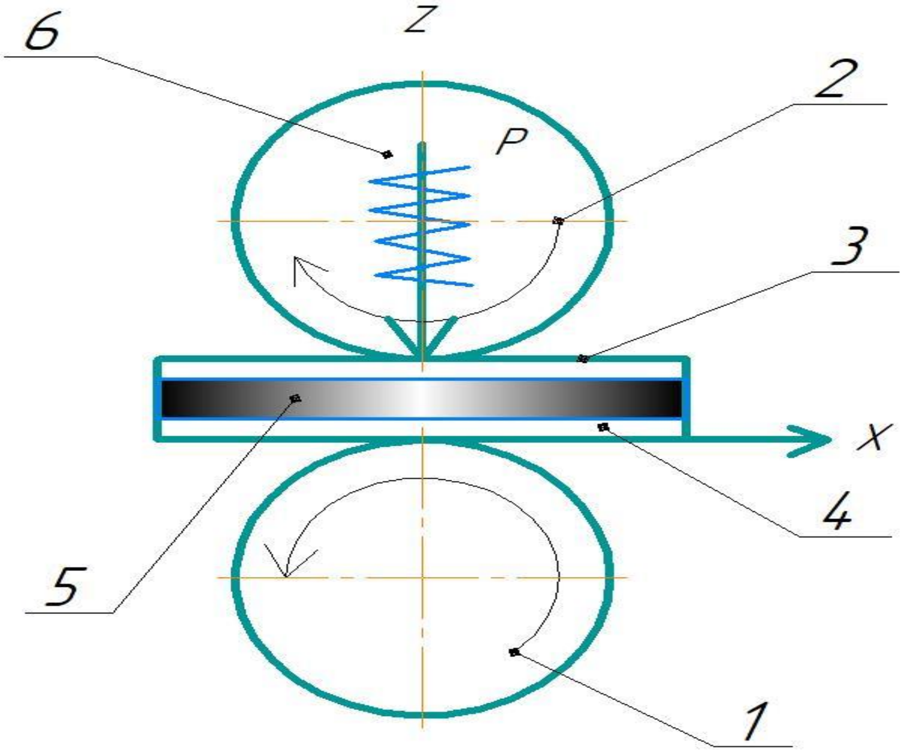

Fig. 1 Schematic diagram of the stitching unit of an ultrasonic sewing machine

The key parameters in the calculation of ultrasonic heating of a material are: radiator power W, the coefficient describing the dependence of temperature on ultrasound intensityα, material density ρ, thermal conductivity coefficient λ, heat capacity C, oscillation frequency f, Hz. [10,11]

Let us now consider the differential heat conduction equation describing the temperature distribution T(x,y,z,t) in the material under the action of ultrasound:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \alpha \cdot I(x,y,z) \cdot e^{-\beta z} \qquad (1)$$

Where I (x,y,z) is the ultrasound intensity at point (x,y,z);

$\frac{\partial^2 T}{\partial x^2}$, $\frac{\partial^2 T}{\partial y^2}$, $\frac{\partial^2 T}{\partial z^2}$- the rate of change of the temperature gradient along the corresponding coordinate;

β - ultrasound absorption coefficient of the material.

In this case, Equation (1) can be simplified by one coordinate, despite its volumetric nature.

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial z^2} + \alpha \cdot I(z,t) \cdot e^{-\beta z} \qquad (2)$$

In fact, from the equation we need to determine with α-I(z,t), since the design and frequency of oscillation and the pressing force depend on these parameters.[12]

But first let us consider in terms of energy components. the process of ultrasonic tissue welding through energy and then express the dependence of this energy on the oscillation frequency and force.

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial z^2} + q \qquad (3)$$

Where q is the specific power of internal heat sources (W/m3) associated with the absorption of ultrasonic energy in the material.

The ultrasonic power absorbed in a unit volume of material can be expressed as:

$$q = 2 \cdot \alpha \cdot I \qquad (4)$$

The intensity of the ultrasonic wave is represented by 'I' in watts per square metre (W/m^2), while the ultrasound absorption coefficient is represented by 'α' in metres to the power of negative one (m^{-1}) [13].

The amplitude of the vibrational velocity v of the medium particles and the acoustic impedance Z determine the intensity of the ultrasonic wave:

$$I = 0.5 \cdot \rho \cdot v^2 \cdot Z \qquad (5)$$

where ρ is the density of the medium,

Z = ρ*c (c is the speed of sound in the medium).

The amplitude of the vibrational velocity of particles v is related to the amplitude of displacement A and the cyclic frequency of oscillations ω:

$$v = \omega \cdot A = 2\pi \cdot f A \qquad (6)$$

The amplitude of the displacement A is related to the amplitude of the force F acting on the material by the ultrasonic tool and the stiffness of the material k:

$$A = \frac{F}{k} \qquad (7)$$

Thus, the intensity of ultrasound can be expressed through the frequency of oscillation f and the amplitude of the force F:

$$I = \frac{2\pi^2 \cdot f^2 \cdot F^2 \cdot \rho}{k^2 \cdot Z} \qquad (8)$$

Substituting the expression for the intensity I into the heat conduction equation(2), we obtain:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial z^2} + 4\pi^2 \cdot \alpha \cdot f^2 \cdot F^2 \cdot \frac{\rho}{\left(k^2 \cdot Z\right)} \qquad (9)$$

This equation relates the temperature change in the material to the oscillation frequency f and the amplitude of the force F acting from the ultrasonic roller, as well as to the thermophysical properties of the material (ρ, c, λ) and acoustic characteristics (α, Z, k).[14].

Since the design force is considered for the point , and still the two cylinders have contact , and they press on the fabric so we determine the distribution of force at each point using the Hertz-Bilyaev equation :

R- Cylinder radii

E- Moduli of elasticity of the cylinder materials

Using Hertz's theory for contact between two bodies, we can calculate:

Radius of the contact pad a:

$$a = \left(\frac{3FR}{4E}\right)^{\frac{1}{3}} \qquad (10)$$

where $E^* = \left[\frac{1 - \mu 1^2}{E1} + \frac{1 - \mu 2^2}{E2}\right]^{-1}$ is the reduced modulus of elasticity

$\mu 1, \mu 2$ - Poisson's ratios of materials

Maximum contact pressure p_0:

$$p_0 = \frac{F}{\pi a^2} \qquad (11)$$

Pressure distribution p(r) along the radius of the contact site:

$$p(r) = F\left(0.5\left(\frac{3FR}{4E}\right)^{\frac{2}{3}} - x\right)\sqrt{1 - \frac{R^2}{\left(\frac{3FR}{4E}\right)^{\frac{2}{3}}}} \qquad (12)$$

where r is the current radius within $0 \le r \le a$

Thus, knowing the geometrical and mechanical parameters of the cylinders and the applied force, we can calculate the contact interaction parameters, including the pressure distribution. In fact, we can consider how the temperature is distributed across the joint. [15,16]

Equation (9) for heat conduction will now be solved, taking into account the internal heat source caused by ultrasonic oscillations.

To demonstrate the method and simplify the solution, a one-dimensional case without explicit time variation (stationary state) and with simplified boundary conditions will be assumed. This allows us to exclude the temporal part of the equation and focus solely on the spatial temperature distribution caused by the ultrasonic heat source. Our approach is confident in its ability to effectively solve this problem while also being diplomatic in acknowledging the assumptions made. However, the equation includes a time derivative, which suggests a non-stationary process. Nevertheless, we can still use a simplified solution method. We will assume that the heat source is constant and uniformly distributed in the material, and exclude the time dependence. This approach is a confident and effective way to solve the problem at hand while maintaining accuracy:

$$\frac{d}{dz}\left(\lambda\frac{dT}{dz}\right)+Q=0 \tag{13}$$

The constant Q is derived from the internal heat source:

$$Q=\frac{4\pi^2\alpha f^2F^2\rho}{k^2Z} \tag{14}$$

For further simplification, we assume that (λ) is constant, then the equation simplifies to:

$$\lambda\frac{d^2T}{dz^2}+Q=0 \tag{15}$$

We integrate it twice over z to get the general solution for T(z)

After integrating the equation, we obtain the general solution for the temperature T(z) in the form:

$$T(z)=\frac{Qz^2}{2\lambda}+C_1z+C_2 \tag{16}$$

where C_1 and $C_2$are integration constants, which are determined from the boundary conditions of the problem. (λ) is the thermal conductivity of the material, and (Q) is a constant related to the internal heat source caused by ultrasonic welding.

To determine the constants C_1 and C_2, specific values were substituted to show that C1 is 0.1 and C2 is zero, and the general equation is as follows:

$$T(z)=\frac{4\pi^2\alpha f^2F^2\rho z^2}{2\lambda k^2Z}+0{,}1z \tag{17}$$

This solution demonstrates how the temperature change in the material depends on the coordinate z , given the ultrasonic crosslinking parameters and the thermophysical properties of the material.

Substituting the numerical values we can find equation (14) considering that the required melting temperature of plastic is 1200C and optimising the data for a roller with a diameter of 30mm and a width of 1mm of cotton fabric with a thickness of 2mm we obtain a frequency equal to 23452Hz and a squeezing force of 43N.

Experimental part:

To investigate the efficiency of ultrasonic crosslinking of textile materials, experiments on joining cotton, silk and polyester fabric samples were carried out on a laboratory ultrasonic welding unit. [17]

To determine the optimal modes of ultrasonic welding and to evaluate the strength characteristics of the obtained joints, fabric samples of 100% cotton, 100% polyester with dimensions of 100×50±1 mm were taken.

Cross-linking of fabric samples was carried out on a laboratory unit using ultrasound. The following modes were worked out (Table 1):

Table 1 Tissue stitching modes at various frequencies from 20-50kHz in 5kHz steps

Fabric	**Pressing forces, N**
Cotton	100,200,300,400,500
Polyester	100,200,300,400,500

- The ultrasonic oscillator generator had a power range of 100, 150, and 200 W, covering the capabilities of the equipment used.
- The welding pressure was varied between 0.2 and 0.4 MPa, in line with recommendations for ultrasonic welding of textile materials.
- The pulse duration of ultrasonic exposure was kept at 1.0 s, which is the optimal duration determined through preliminary experiments.

2. To control the quality of welds, all specimens were visually inspected under natural and artificial light. Additionally, microscopic inspection of the joint zone structure was performed with 50x magnification (USB microscope). Defects, pores, thread breaks were recorded.

3. mechanical tests of welded joints of textile materials were carried out on a tensile machine RMI-250 at a constant speed of movement of the active gripper of 50 mm/min. During the tests, the breaking force of the specimens was recorded.[5]

Statistical processing of the test results included:

Calculation of the average value of breaking force $\mathbf{F}_{cp}$ for each fabric type and ultrasonic welding mode based on all obtained values (n=30 for one mode).[18]

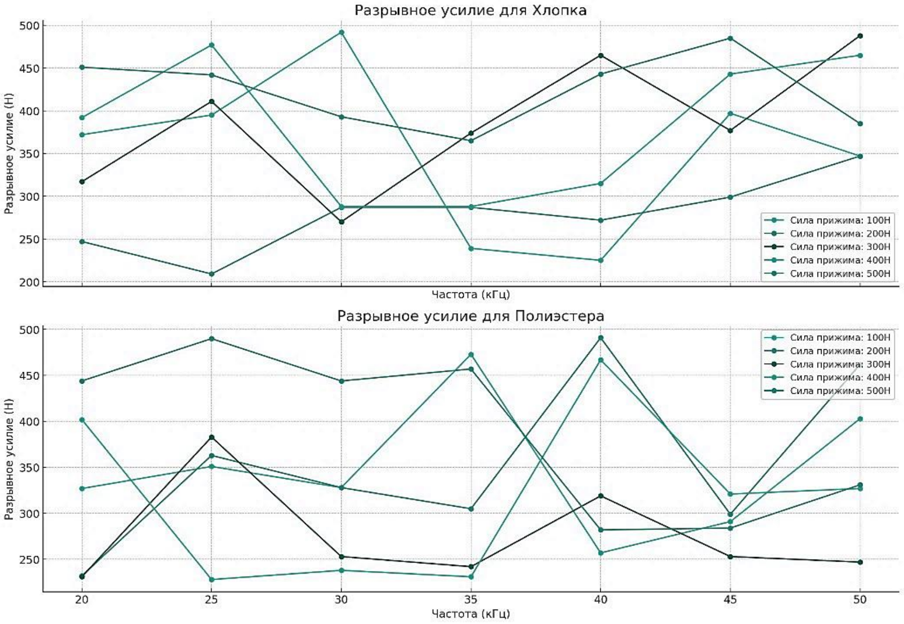

Fig.2- Analysis of the influence of ultrasonic welding frequency and pressing force on the breaking force of cotton and polyester fabrics

Calculation of the standard deviation σ, characterising the scatter and error of measurements.[19].

Construction of confidence interval for the mean value at 95% significance level.

Comparison of the obtained data using two-sample Student's t-test.

All calculations were performed using OriginPro 2019 package. The results showed significant differences between joint strengths depending on fabric type and welding modes.

The results of the tests are summarised in Table 2:

Table 2 **Results of tests**

Fabric	**Ultrasonic modes**	**F_{cp}, N**	**σ, N**	**ΔF_{cp}, N**
Cotton	100 Watt; 0,2 MPa	788	31	±6
Silk	150 Watt; 0,3 MPa	619	54	±9
Polyether	200 Watt; 0,4 MPa	1207	83	±15

Note: **F_{cp}** the limits of the 95% confidence interval of the mean value of the breaking force

F_{cp}- the main result - average weld strength, [N]

σ- statistical parameter showing reproducibility, [N]

ΔF_{cp}- calculate the confidence interval for measured values with consideration for errors and random factors that affect variation, using [N] as the unit of measurement.

The obtained data confirm with a high degree of reliability the dependence of strength characteristics of ultrasonic joints on the nature of the welded fabric and welding mode. (Fig. 2)

3D histogram of average joint strength with coloured values

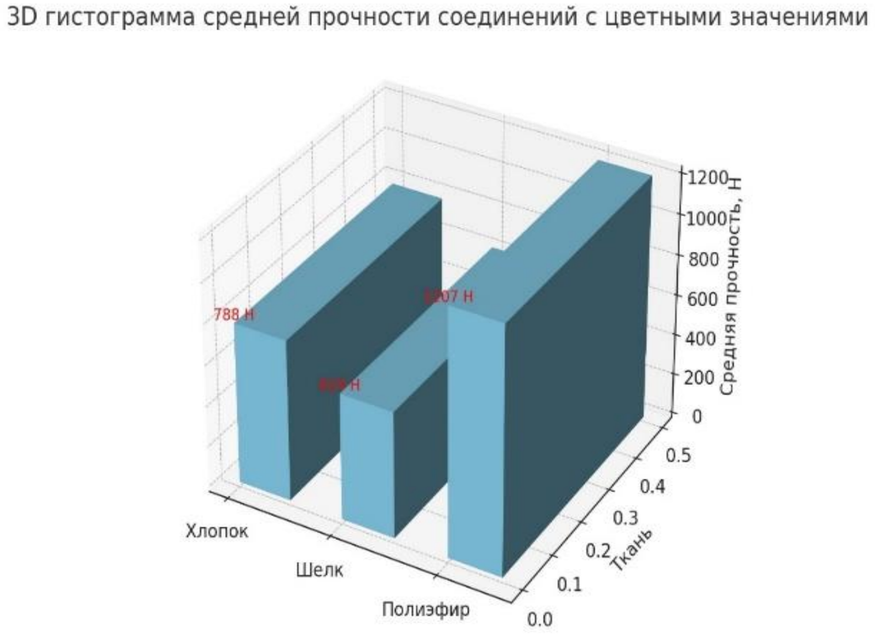

Fig.3- Analysis of reproducibility and confidence intervals of strength of welded joints of fabrics at ultrasonic welding

For visual comparison of the obtained data on ultrasonic seam strength of different fabrics, a histogram was constructed in OriginPro programme.

The X axis shows the type of fabric: cotton, silk and polyester.

The Y axis shows the parameter - the average value of breaking force $\Delta\mathbf{F}_{cp}$ characterising the strength of the welded joint.

For each type of fabric on the histogram, there is a bar whose height is proportional to the value of $\Delta\mathbf{F}_{cp}$ .That is, the higher the bar, the greater the force required to break the ultrasonic suture of the given fabric.

Thus, it is visualized that polyester yarn joints have the highest strength (column of highest height).[8] The cotton and silk fabric seams showed comparable but slightly lower strength values. The histogram clearly demonstrates the effectiveness of ultrasonic welding process for all the materials investigated and also the difference in seam strength for different types of fabrics.[20]

Analyses of the results are given in the following paragraphs:

1. High efficiency of ultrasonic welding method for joining textile materials of different nature has been experimentally confirmed. The method makes it possible to obtain strong, reliable seams without damaging the structure of yarns.

2. It is established that the maximum strength of the joint is achieved when welding polyester fibres. This material provides the breaking force of the seam at an average of 1207 N. (Fig. 4.)

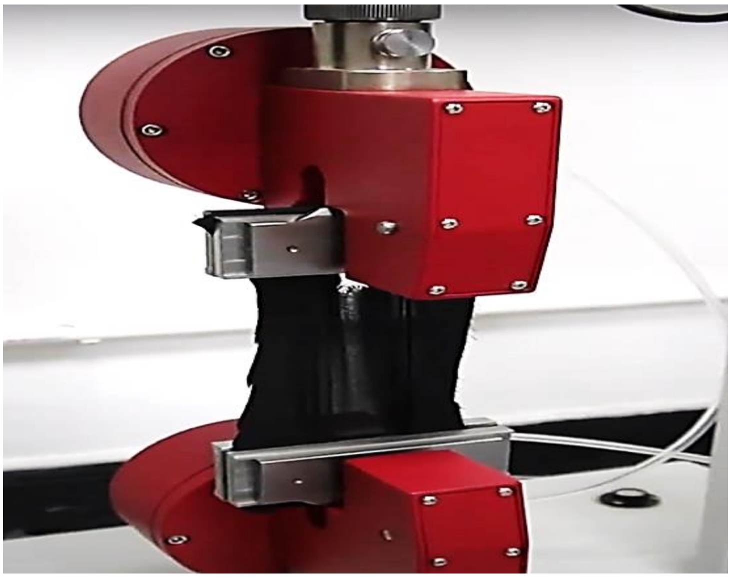

Fig.4 Bursting force of the seam with 1207 N force on the bursting machine.

3. The samples made of cotton and silk fabric showed comparable performance - 788 N and 619 N respectively. This is 60-65% of the seam strength of polyester.(Fig.5)

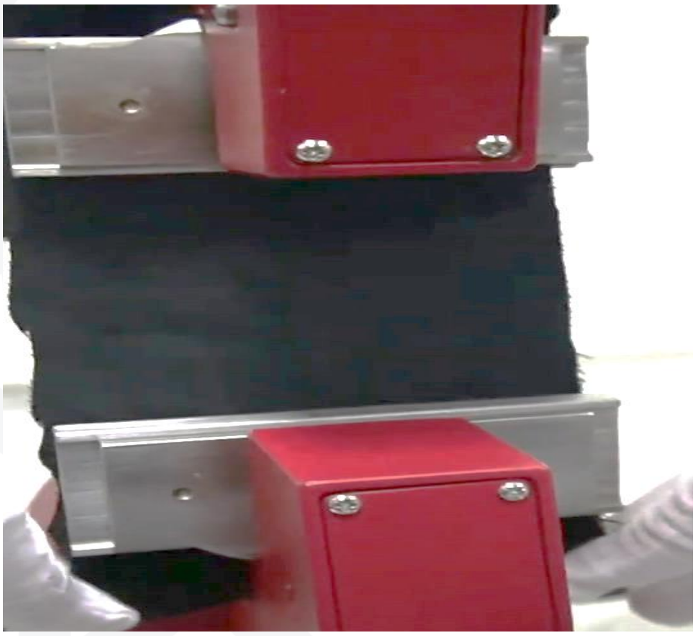

Fig.5 - Tearing of fabric on a tearing machine

5. The rational mode parameters for different materials are selected based on their pressure. It has been observed that the strength of seams increases with higher compression force.

Conclusion:

Hence, fabric type and modes are critical factors in determining the quality of ultrasonic joints. These findings can be utilized to optimize the welding process.

In recent years, the textile industry has confidently sought and implemented alternative methods of joining fabrics. Ultrasonic welding is one such method. This approach has been adopted diplomatically, acknowledging the benefits of traditional methods while exploring new possibilities. This method offers significant advantages over traditional techniques such as sewing or glue joining. It is faster, does not require thread or glue, and allows for the creation of hermetic joints. This is especially important for producing garments and technical textiles used in fields such as medicine, where sterility and water resistance are necessary. Ultrasonic welding technology enables the joining of complex materials, including mixed and synthetic fibers, providing high strength and seam durability without damaging the fabric structure. This opens up new horizons for designers and manufacturers, allowing the development of innovative products with improved functional characteristics. Furthermore, it is important to note that the environmental impact of ultrasonic welding is minimal. Considering the growing emphasis on environmental safety and sustainability, it is imperative to avoid using adhesives and filaments that may contain harmful substances. Ultrasonic welding is a highly effective method that reduces production waste and increases resource efficiency, making it a crucial aspect of modern environmentally-oriented manufacturing. Research and development in ultrasonic welding is an ongoing process. Our team is confident that future innovations will expand its applications, including the creation of new types of composite materials, improved joint quality and reliability, and the development of more efficient and customized equipment. We believe that our continued efforts in this field will lead to significant breakthroughs and benefits for our industry and beyond. These advancements will not only contribute to technological progress in the textile industry but also enhance the competitiveness of products in the global market.

In conclusion, ultrasonic textile welding is a highly promising area that combines innovative technologies, environmental safety, and the potential to create high-quality, functional, and aesthetically pleasing textile products. Further research and development in this area will undoubtedly open up new opportunities for improvement and diversification. It is important to note that this conclusion is based on the information provided, and additional context about the content of the article may be necessary to draw more definitive conclusions. To create a comprehensive conclusion, I require information on the main theses discussed in the article, the key research findings, and the specific aspects that the authors wish to highlight. This will enable me to produce a thorough and meaningful text that meets your requirements. Please provide additional information about the article to enable me to fulfil your request.

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