NC STATE
Wilson College of Textiles

JTATM
Journal of Textile and Apparel, Technology and Management

*Volume 13, Issue 1, 2025*

# Optimization of Sewing Parameters for Improving the Waterproof Characteristics of Seams using Box–behnken Design

Abhishek Kumar[a,b*] and Dr. Manpreet Manshahia[b]
[a]School of Design, UPES, Dehradun,
[b]Amity School of Fashion Technology, Amity University,
India

**ABSRACT**

*The available literature primarily focuses on developing alternative seaming techniques for waterproof garments to address needle holes created during stitching. However, these methods are not sustainable and present limitations, such as higher production costs, compatibility issues, adverse effects on fabric properties and user comfort. This study aims to optimize sewing parameters to improve the waterproof characteristics of seams without relying on alternative techniques. Needle size, thread size, and stitch density are the sewing parameters selected for the study. The research assesses the individual and interactive effects of these parameters on hydrostatic pressure resistance using the Box–Behnken Design (BBD) within the Response Surface Methodology (RSM) framework. The findings show that larger needle sizes reduce water resistance, which can be mitigated using higher stitch densities and larger thread sizes. Higher stitch densities also create tighter seam structures, significantly reducing water leakage. These results, validated through regression modelling and surface plot analysis, confirm that stitching effectively improves the seam's waterproof characteristics by selecting the right sewing parameters. This study provides valuable insights into optimizing traditional stitching techniques to create waterproof seams.*

*Keywords: box-behnken design, needle size, sewing parameters, stitch density, thread size, waterproof seams*

## 1. Introduction

Wearing protective garments is important to shield the wearer body from harsh external factors such as weather and chemicals [1]. Different examples of protective garments are military garments, medical garments, thermal garments, activewear, and chemical protection garments. Waterproof breathable fabrics are used in making most of these garments [2-4]. Waterproof coating or lamination are used to treat these fabrics. This additional coating layer or lamination protects the wearer from getting wet or coming into contact with harmful liquids such as water, blood, and chemicals. Apart from providing resistance from the liquid penetration, these fabrics also ensure comfort for the wearer. They allow perspiration to escape by facilitating the passage of water vapor, making the garments breathable [2-6].

The main objective of garment manufacturers is to convert two-dimensional fabrics into three-dimensional garments that hold to the shape of the human body [7-10]. These garments' overall appearance, durability, quality, and performance depend on aesthetics, seam strength, flexibility, breathability, and comfort [11-14]. The selection of appropriate seams plays an important role in the garment's overall appearance, durability, quality, and performance. It can also impact the waterproof characteristics of waterproof breathable garments [14-17]. Sewing is the traditional and most efficient method to create seams. In this process, stitching with the help of needle and thread joins different panels of the fabrics together [7-9]. However, many studies have suggested that this method is not suitable for making waterproof breathable garments. The needle holes created during the garments assembly can compromise functionality, providing passage to the liquids to penetrate inside the garments [16-19]. Most of the studies in the available literature explore alternative methods for assembling garments like the use of seam tape, adhesive bonding, and different types of welding techniques [11,16,17,20-22]. The seam tape is used widely in outdoor apparel manufacturing to confront the issue of needle holes generated during the stitching process [7,15,16,21,23]. Jana [11] suggested different emerging technologies for creating seams to assemble fabrics and accessories. Grinevičiūtė et al. [24] investigated the influence of sealing process parameters on the seam strength and resistance to water penetration of seams sealed with seam tape. Shi et al. [15] demonstrated the production of threadless seams using ultrasonic welding. Mesegul and Karabay [16] investigated using of fusible thread in bobbins to create waterproof seams. Kara and Yeşilpınar [17] conducted a comparative analysis of taped seams with different constructions. Macit and Tiber [25] examined the water permeability of ultrasonic seaming by manipulating various parameters. Hussen et al. [26] investigated the effects of ultrasonic welding parameters such as welding width, pressure force, power, and speed on hydrostatic pressure resistance.

The alternative methods to create waterproof seams have their limitations. Using seam tape to cover the needle holes and improve the resistance to water penetration can lead to discomfort and affect fabric draping and bending resistance [7,16]. The welding techniques require the application of heat over the thermoplastic materials to create seams. This results in the reduction of fabric strength and seam strength in comparison to traditional sewing. The welding process also requires intensive energy consumption to generate the required heat [16,26]. The bonding process requires the use of chemical or liquid adhesives. It presents challenges in achieving adequate bond strength and preserving fabric integrity, breathability, and resistance to washing and staining. Chemical adhesives also raise environmental concerns due to the potential release of harmful substances [16.27,28].

J T A T M

The ability of seams to resist water penetration is affected by the needle holes created during stitching. The impact of these needle holes on the resistance to water penetration may depend on the sewing parameters such as needle size, thread size, and stitch density. Existing studies have mainly focused on exploring alternative methods of stitching to mitigate the concerns related to seam leakage caused by needle holes. However, these alternative techniques have their limitations. There is no available literature that studies the effect of these parameters on the waterproof characteristics of seams. This study aims to address this gap in research by answering the following research questions:

*RQ1.* How does needle size affect the waterproof characteristics of seams?
*RQ2.* How does thread size affect the waterproof characteristics of seams?
*RQ3.* How does stitch density affect the waterproof characteristics of seams?
*RQ4.* How do interaction effects among needle size, thread size, and stitch density influence the overall water resistance of seams?

## 2. Materials and methods

This study investigates the influence of sewing parameters on the waterproof characteristics of stitched seams using the Box–Behnken Design (BBD) framework within the Response Surface Methodology (RSM) framework. RSM is a tool for examining the relationship between response and explanatory variables in statistics while reducing resource usage as well as lab work [29-33]. The RSM procedure consists of two steps. The first step involves using a fractional factorial design to determine the factors and their interactions significantly impacting the result as an initial screening. This step establishes the range of control variables for additional research and helps determine the steepest ascent or descent direction. In the second step, specialized experimental designs like Central Composite Design (CCD) or Box-Behnken Design (BBD) carry out the response surface regression [33-37]. BBD was used for this study because this approach requires fewer experimental trials while evaluating multiple variables and their interactions than CCD. It makes it more convenient and economical for scenarios involving the same number of factors (k < 5) [37-39]. In addition, this design is rotatable, indicating that the model displays a consistent distribution of scaled prediction variance throughout the experimental area [33].

A single fabric type is selected for this study to focus the analysis on how sewing parameters impact the waterproof characteristics of the seams. A fabric made of polyester with a thermoplastic polyurethane (TPU) membrane is selected. Table I lists the physical characteristics of the fabric selected for this study.

J T A T M

**Table I: Physical properties of fabric (Source: Authors own work)**

| | |
|---|---|
| Fiber Content | 92% Polyester + 8% Spandex |
| Membrane | Thermoplastic Polyurethane (TPU) |
| Areal Density, g/m$^2$ | 135 |
| Thickness, mm | 0.258 |
| Warp Density, Ends/Inch (EPI) | 95 |
| Weft Density, Picks/Inch, (PPI) | 74 |
| Resistance to Water Penetration, cm $H_2O$ | 273 |

Seams are made following ASTM D6193 standard [40] and seam class SS. The layers of fabric are superimposed and sewn together using stitch type 301 on a Juki DDL-8100E single needle lockstitch machine. 100% polyester thread is selected over cotton threads for this study. Cotton threads are hydrophilic, absorbing water and potentially skewing results when assessing the relationship between thread size and waterproof characteristics of the seam [2,41].

Needle size, thread size, and stitch density are the sewing parameters selected as control factors for BBD. The experimental design levels are detailed in Table II. The ranges for each factor are determined based on initial investigations, with needle size and thread size varying from size 8 to 14 (blade diameter = 60 nm to 90 nm) and 21 to 27 Tex, respectively, while stitch density in Stitches/ Inch (SPI) ranged from 8 to 12. Each factor is assigned a code: low (-1), medium (0), and high (1). Employing the Box-Behnken design necessitated 12 design points along with 3 center runs, making a total of 15 trials. Consequently, 15 sets of specimens with superimposed seams are prepared for the hydrostatic test. Table III presents the BBD design matrix alongside the actual experimental results of the responses.

**Table II: Experimental design levels for BBD (Source: Authors own work)**

| Variables | Needle size | Thread size, tex | Stitch Density, SPI |
|---|---|---|---|
| **-1** | 8 | 21 | 8 |
| **0** | 11 | 24 | 10 |
| **1** | 14 | 27 | 12 |

**Table III: The BBD with experimental values of the hydrostatic pressure test (Source: Authors own work)**

| Standard run order | Needle size | Thread size, tex | Stitch Density, SPI | Hydrostatic Pressure Test, cm $H_2O$ |
|---|---|---|---|---|
| **1** | 8 | 21 | 10 | 40.5 |
| **2** | 14 | 21 | 10 | 20 |
| **3** | 8 | 27 | 10 | 48 |
| **4** | 14 | 27 | 10 | 28 |
| **5** | 8 | 24 | 8 | 43 |
| **6** | 14 | 24 | 8 | 23 |
| **7** | 8 | 24 | 12 | 46 |
| **8** | 14 | 24 | 12 | 26 |
| **9** | 11 | 21 | 8 | 30 |
| **10** | 11 | 27 | 8 | 37 |
| **11** | 11 | 21 | 12 | 30.5 |
| **12** | 11 | 27 | 12 | 40 |
| **13** | 11 | 24 | 10 | 33.5 |
| **14** | 11 | 24 | 10 | 35 |
| **15** | 11 | 24 | 10 | 36.5 |

J T A T M

The resistance to water penetration is assessed using the hydrostatic pressure test following the AATCC-127 dynamic test method [42]. Specimens measuring 10 cm x 10 cm are securely clamped onto the testing apparatus with the surface to be evaluated and exposed to the water. A pressure gradient of 60 mbar/min is applied. The hydrostatic pressure is noted when water droplets breached the seams. This process is conducted three times for each sample, and the average hydrostatic pressure is calculated.

Minitab software is used to perform RSM simulations, which involve conducting ANOVA and generating a regression equation. Additionally, main effects plots, interaction plots, and surface plots are generated using Minitab to visualize the data and analyze the relationship between the variables.

## 4. Results and discussion

### 4.1 Analysis and validation of regression model for hydrostatic pressure test

The ANOVA analysis presented in Table IV indicates that the quadratic regression model is highly significant, as evidenced by the F-value of 97.3 and a probability value (P = 0.000 < 0.05). As shown in Table IV, the goodness-of-fit results confirm the model's adequacy, with a determination coefficient suggesting that the model can predict 99.43% of the variability in the response. This level of predictability is deemed satisfactory within the range of experimental variables. Additionally, there is substantial agreement between the predicted values of the hydrostatic pressure test and the experimental data, as shown in Table IV.

**Table IV: ANOVA results of the quadratic regression model for the hydrostatic pressure test of the seams (Source: Authors own work)**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | R-sq | R-sq(adj) |
|---|---|---|---|---|---|---|---|
| Model | 9 | 952.296 | 105.811 | 97.30 | 0.000 | 99.43% | 98.41% |
| Linear | 3 | 949.313 | 316.438 | 290.98 | 0.000 | | |
| Needle Size | 1 | 810.031 | 810.031 | 744.86 | 0.000 | | |
| Thread Size | 1 | 128.000 | 128.000 | 117.70 | 0.000 | | |
| Stitch Density | 1 | 11.281 | 11.281 | 10.37 | 0.023 | | |
| Square | 3 | 1.358 | 0.453 | 0.42 | 0.749 | | |
| Needle Size*Needle Size | 1 | 0.519 | 0.519 | 0.48 | 0.520 | | |
| Thread Size*Thread Size | 1 | 0.923 | 0.923 | 0.85 | 0.399 | | |
| Stitch Density*Stitch Density | 1 | 0.058 | 0.058 | 0.05 | 0.827 | | |
| 2-Way Interaction | 3 | 1.625 | 0.542 | 0.50 | 0.700 | | |
| Needle Size*Thread Size | 1 | 0.063 | 0.063 | 0.06 | 0.820 | | |
| Needle Size*Stitch Density | 1 | 0.000 | 0.000 | 0.00 | 1.000 | | |
| Thread Size*Stitch Density | 1 | 1.562 | 1.562 | 1.44 | 0.284 | | |
| Error | 5 | 5.438 | 1.088 | | | | |
| Lack-of-Fit | 3 | 0.938 | 0.313 | 0.14 | 0.928 | | |
| Pure Error | 2 | 4.500 | 2.250 | | | | |
| Total | 14 | 957.733 | | | | | |
| Significant at the 5% level. | | | | | | | |

The significance levels of the coefficients, determined by the p-values, indicate the interaction effects between each independent variable. The lack-of-fit p-value 0.928 suggests no significant lack-of-fit at the $\alpha$ = 0.05 significance level, rendering the model acceptable. The regression equation in uncoded form illustrates the relationship among the variables, explaining the resistance to water penetration by seams. The regression model for the hydrostatic pressure test is expressed in Equation 1 (in terms of uncoded factors):

$$\begin{aligned}\text{Hydrostatic Pressure } (\text{cm } H_2O) = {} & 22.5 - 2.77 \text{ Needle Size} + 2.81 \text{ Thread Size} - 1.28 \text{ Stitch Density} \\ & - 0.0417 \text{ Needle Size*Needle Size} - 0.0556 \text{ Thread Size*Thread Size} \\ & - 0.031 \text{ Stitch Density*Stitch Density} + 0.0139 \text{ Needle Size*Thread Size} \\ & + 0.0000 \text{ Needle Size*Stitch Density} \\ & + 0.1042 \text{ Thread Size*Stitch Density}\end{aligned} \tag{1}$$

## 4.2 Effect of various sewing parameters on the resistance to water penetration of the seams

Factorial plots are employed to investigate the main effects and interactions of factors, encompassing needle size, thread size, and stitch density, on resistance to water penetration (Figures 1 and 2). The main effects plot illustrates the individual influence of each factor on hydrostatic pressure. Interaction plots are employed to explore the effects of different factors combined to influence hydrostatic pressure. Surface plots are generated to visualize the variation of hydrostatic pressure across different levels of multiple factors (Figure 3).

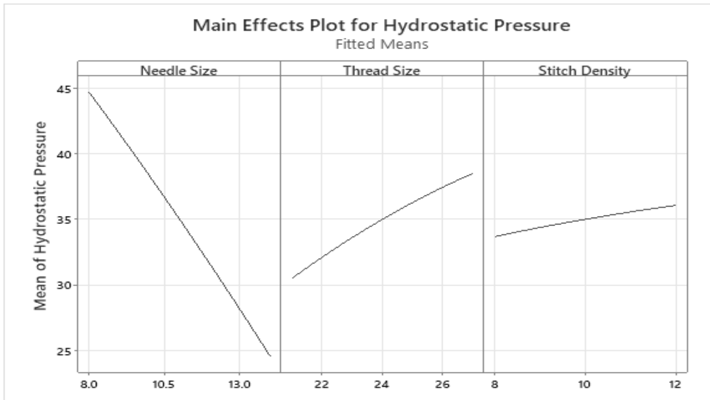


**Figure 1: Main effects plot for hydrostatic pressure (cm $H_2O$) (Source: Authors own work)**

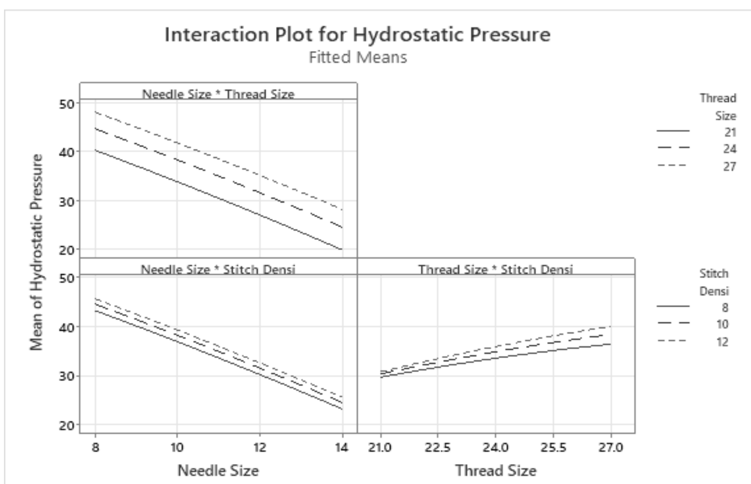


**Figure 2: Interaction plot for hydrostatic pressure (cm H2O) (Source: Authors own work)**

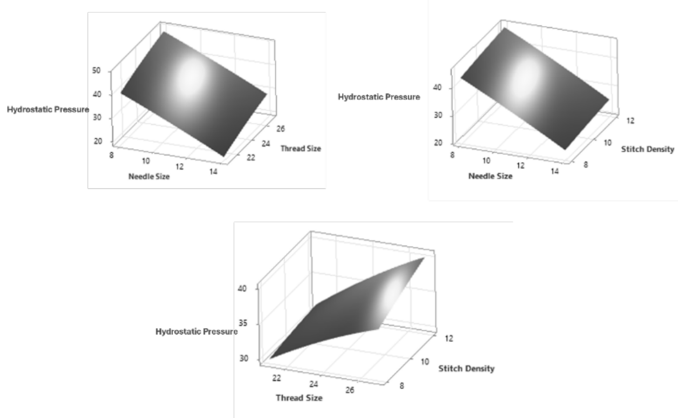


**Figure 3: Surface plots for the effects of design variables on hydrostatic pressure (cm H2O) (Source: Authors own work)**

**Effect of needle size on the resistance to water penetration**

The main effect plot (Figure 1) shows that the resistance to water penetration decreases as the needle size increases from 8 to 14. The result indicates a clear negative relationship. The interaction plot (Figure 2) suggests that stitch density and thread size influence the relationship between needle size and resistance to water penetration. Using size 14 needles in combination with 8 SPI and 21 Tex thread significantly reduces resistance to water penetration. As the needle size increases, bigger holes are created in the fabric during stitching. Water can pass through these holes, making the fabric less resistant to water seeping through. Larger needle sizes reduce the resistance to water penetration mainly due to this. The gaps between the stitches are larger when the stitch density is low, making the fabric structure more open. When the thread size is small, they are less likely to fill the perforations created by the stitched seams. This increases the effect of larger needle sizes, as the perforations created by the needle are less likely to be filled or sealed by the stitching, further reducing resistance to water penetration. This mechanism is supported by the patterns seen in the surface plots (Figure 3). The resistance to water penetration diminishes with increasing needle size while stitch density and thread size remain constant; this can be seen in these plots as a downward slope.

J T A T M

**Effect of thread size on the resistance to water penetration**

Larger thread sizes are positively correlated with hydrostatic pressure, indicating higher resistance to water penetration. (Figure 1). The interaction plot (Figure 2) suggests that the interaction between 27 Tex thread and 12 SPI leads to enhanced water resistance. Larger thread sizes have a greater capacity to fill the perforations made by needles. This filling effect reduces the potential for water to penetrate through the seam. The interaction between thread size and stitch density further enhances this effect. While higher stitch density means more perforations, it also means more thread material is distributed along the seam. When larger threads are combined with higher stitch density, the threads compress against each other more tightly, creating a denser barrier along the seam. This compressing effect reduces the vulnerable points where water might penetrate, resulting in improved water resistance. On the contrary, the interaction between 21 Tex thread and needle size 14 reduces water resistance. When needle size increases while thread size remains small, the thread does not adequately fill the perforations created by the needle, leading to increased water penetration. These findings are consistent with the pattern observed in the surface plots (Figure 3).

**Effect of stitch density on the resistance to water penetration**

The main effect plot (Figure 1) illustrates a positive correlation between stitch density and resistance to water penetration. As stitch density increases from 8 to 12 SPI, there is a corresponding increase in resistance to water penetration. This indicates that higher stitch densities contribute to better resistance against water. Furthermore, the interaction plot (Figure 2) suggests that maintaining 8 SPI reduces resistance to water penetration as needle size increases from 8 to 14. The interaction between thread size and stitch density suggests that increasing thread size from 21 Tex to 27 Tex in conjunction with 12 SPI enhances resistance to water penetration. These observations are consistent with the pattern observed in surface plots (Figure 3). The observed increase in hydrostatic pressure with higher stitch density can be attributed to stitch density increasing, and the number of stitches per unit length rises, leading to a tighter and more compact seam structure. This denser structure forms a barrier that limits water flow through the seams, improving the resistance to water penetration. The relationship between needle size and fabric can be explained by the fact that larger holes in the fabric caused by an increase in needle size might weaken the seam's ability to resist water penetration. A low stitch density makes the larger needle holes more prominent, which reduces resistance. Higher stitch density and thicker threads produce a more compact physical barrier against water. The larger thread's ability to fill gaps and higher stitch density, minimizing the amount of space available for water to pass through, improves seam's waterproof characteristics.

## 5. Conclusion

The study employed the BBD within the framework of RSM to analyze the effects of sewing parameters on the waterproof properties of seams. The results indicated that needle size, thread size, and stitch density significantly influenced the hydrostatic pressure resistance of seams, with distinct effects observed for each parameter. It is found that increasing the needle size from 8 to 14 reduced water resistance due to the formation of larger needle holes, which facilitated water penetration. The adverse impact of needle sizes was mitigated by the combined use of 27 Tex threads and 12 SPI, resulting in a more impenetrable seam structure. Increasing the thread size resulted in better filling of the needle holes while higher stitch densities created a more compact seam structure, further reducing water ingress and improving waterproof performance. Interaction effects among these parameters also played a crucial role in determining overall seam water resistance. The surface plots visually substantiated these findings, reinforcing the validity of the regression model.

These findings provide valuable insights for producing functional garments where water resistance is crucial. Manufacturers can achieve waterproof seams by optimizing sewing parameters without using alternative seaming technologies that may compromise garment integrity and sustainability. Future research can examine the long-term durability of these optimized seams under different environmental conditions, further improving the functionality of waterproof breathable garments.

## References

[1] Radhakrishnan, S. and Kumari, D. (2017). Seams for Protective Clothing–An Overview. *World Journal of Textile Engineering and Technology*, Vol. 3, 16-23.

[2] Troynikov, O., Nawaz, N. and Watson, C. (2017). Durability of vapor-permeable waterproof textile materials used in sailing protective apparel. *Textile Research Journal*, *88*(24), 2825–2840. https://doi.org/10.1177/0040517517732079

J T A T M

[4] Kumar, A., Manshahia, M. and Aggarwal, J. (2023). A Review of Development of Waterproof Breathable Garments. *Journal of the Textile Association, 83*,5, 348-354.
[5] Kumar, A. and Manshahia, M. (2024). The rise of sustainable approaches in development of waterproof breathable fabrics for garment: a systematic literature review. *International Journal of Clothing Science and Technology*. https://doi.org/10.1108/ijcst-01-2024-0015
[6] Porav, A. V. (2011). Gore-Tex and Sympatex Textile Waterproofing. *Annals of the University of Oradea Fascicle of Textiles-Leatherwork, 12*(1), 160-165.
[7] Kara, Ş. and Yeşilpinar, M.S. (2012). A research on the waterproofness of seam lines of protective clothes. *5th European Conference on Protective Clothing, Valencia, Spain*, 32.
[8] Jeong, W. Y. and An, S. K. (2003). Seam characteristics of breathable waterproof fabrics with various finishing methods. *Fibers and Polymers*, *4*(2), 71–76. https://doi.org/10.1007/bf02875440
[9] Dobilaitė, V., Jucienė, M. and Mackevičienė, E. (2013). The influence of technological parameters on quality of fabric assemble. *Materials Science*, *19*(4). https://doi.org/10.5755/j01.ms.19.4.2482
[10] Chen, D. and Cheng, P. (2019). Investigation of factors affecting the seam slippage of garments. *Textile Research Journal, 89*(21–22), 4756–4765. https://doi.org/10.1177/0040517519838068
[11] Singh, P. A., Manshahia, M., & Das, A. (2022). Study on tactile comfort characteristics of School uniforms. *Journal of the Textile Association*, *83*(1), 427-430.
[12] Jana, P. (2011). Assembling technologies for functional garments – an overview. *Indian Journal of Fibre & Textile Research, 36(4)*, 380-387.
[13] Bulut, Y. and Sular, V. (2012). Manufacturing and sewing performance of polyurethane and polyurethane/silicone coated fabrics. *Materials and Manufacturing Processes*, *28*(1), 106–111. https://doi.org/10.1080/10426914.2012.700148
[14] Choudhary, A. K. and Goel, A. (2013). Effect of some fabric and sewing conditions on apparel seam characteristics. *Journal of Textiles*, *2013*, 1–7. https://doi.org/10.1155/2013/157034
[15] Sülar, V., Meşegül, C., Kefsiz, H. and Seki, Y. (2014). A comparative study on seam performance of cotton and polyester woven fabrics. *The Journal of The Textile Institute*, *106*(1), 19–30. https://doi.org/10.1080/00405000.2014.899079
[16] Shi, H., Wang, J., Chen, X., Luo, S. and Zhang, L. (2016). Research on the seam performance of waterproof clothing based on continuous ultrasonic welding technology. *International Journal of Clothing Science and Technology*, *28*(2). https://doi.org/10.1108/ijcst-03-2015-0036
[17] Mesegul, C. and Karabay, G. (2020). Usage of fusible sewing threads to improve the waterproof property of seam. *Materials Science*, *26*(4), 498–504. https://doi.org/10.5755/j01.ms.26.4.24147
[18] Kara, S. and Yeşilpınar, S. (2021). Comparative study on the properties of taped seams with different constructions. *Fibres and Textiles in Eastern Europe*, *29*(2(146)), 54–60. https://doi.org/10.5604/01.3001.0014.6082

J T A T M

[19] Ashour, S., Gabr, G. and Megeid, Z.M.A. (2017). Investigating the effect of Joining Techniques on Waterproof and Comfort Properties. *International Journal of Scientific & Engineering Research*, *8*(11), 1319-1327.

[20] Oh, H., Oh, K. W. and Park, S. (2019). A study of the improvement of foam material sealing technology for Wetsuits. *Fashion and Textiles*, *6*(1). https://doi.org/10.1186/s40691-019-0181-5

[21] Di, J., Perwuelz, A. and Gueguen, V. (2001). The surface energy of PET fabrics coated with silicone. *Journal of the Textile Institute*, *92(Part 1 No. 2)*, 184-192.

[22] Sakthivel, S., Hamza, A.Z. and Kiruthika, S.D. (2013). Application of waterproof breathable fabrics. *The Indian Textile Journal*, *124(1)*, 63-68.

[23] Jevšnik, S., Eryürük, S. H., Kalaoğlu, F., Kayaoğlu, B. K., Komarkova, P., Golombikova, V. and Stjepanovič, Z. (2016). Seam properties of ultrasonic welded multilayered textile materials. *Journal of Industrial Textiles*, *46*(5), 1193–1211. https://doi.org/10.1177/1528083715613632

[24] Vlad, L., Stan, M. and Buhai, C. (2013) 'The optimization of the assemblies applied to products made of waterproof fabrics', *Tekstil ve Konfeksiyon*, 23(2), 273-279.

[25] Grinevičiūtė, D., Valasevičiūtė, L., Narvilienė, V., Dubinskaitė, K. and Abelkienė, R. (2014). Investigation of sealed seams properties of moisture barrier layer in firefighters clothing. *Materials Science*, *20*(2). https://doi.org/10.5755/j01.ms.20.2.3396

[26] Macit, A. Ş. and Tiber, B. (2021). Evaluation of some physical performance properties of ultrasonic seaming, conventional seaming and sealing adhesive tape on waterproof polyester knitted fabrics with polyurethane. *Textile Research Journal*, *92*(3–4), 498–510. https://doi.org/10.1177/00405175211038857

[27] Hussen, M. S., Kyosev, Y. K., Pietsch, K., Rothe, S. and Kechi, A. (2021). Effect of ultrasonic welding process parameters on hydrostatic pressure resistance of hybrid textiles for weather protection. *Textile Research Journal*, *92*(15–16), 2553–2568. https://doi.org/10.1177/004051752098 8124

[28] Jakubčionienė, Ž., Masteikaitė, V., Kleveckas, T., Jakubčionis, M. and Kelesova, U. (2012). Investigation of the strength of textile bonded seams. *Materials Science*, *18*(2). https://doi.org/10.5755/j01.ms.18.2.1922

[29] Mikalauskaitė, G. and Daukantienė, V. (2019). Investigation of the influence of bonding and thermal ageing duration on the peeling strength of knitted materials' bonds. *Materials Science*, *26*(2), 225–232. https://doi.org/10.5755/j01.ms.26.2.21666

[30] Ferreira, S., Bruns, R., Ferreira, H., Matos, G., David, J., Brandão, G., Da Silva, E., Portugal, L., Reis, P. D., Souza, A. and Santos, W. D. (2007). Box–Behnken design: An alternative for the optimization of analytical methods. *Analytica Chimica Acta, 597*(2), 179–186. https://doi.org/10.1016/j.aca.2007.07.011

[31] Box, G. E. P. and Wilson, K. B. (1951). On the experimental attainment of optimum conditions. *Journal of the Royal Statistical Society: Series B (Methodological), 13*(1), 1–38. https://doi.org/10.1111/j.2517-6161.1951.tb00067.x


J T A T M

[32] Sun, Y., Li, T., Yan, J. and Liu, J. (2010). Technology optimization for polysaccharides (POP) extraction from the fruiting bodies of *Pleurotus ostreatus* by Box–Behnken statistical design. *Carbohydrate Polymers, 80*(1), 242–247. https://doi.org/10.1016/j.carbpol.2009.11.018
[33] Myers, R. H., Montgomery, D. C. and Anderson-Cook, C. M. (2016). *Response surface methodology: Process and product optimization using designed experiments*. John Wiley & Sons.
[34] Hikelmann, K. and Kempthorne, O. (2007). *Design and analysis of experiments: Introduction to experimental design*. A John Wiley & Sons, Inc.
[35] Khuri, A. I. (2006). *Response surface methodology and related topics*. World Scientific eBooks. https://doi.org/10.1142/5915
[36] Montgomery, D. C. (2017). *Design and analysis of experiments*. John Wiley & Sons.
[37] Tong, L. I., Chang, Y. C., & Lin, S. H. (2011). Determining the optimal re-sampling strategy for a classification model with imbalanced data using design of experiments and response surface methodologies. *Expert Systems with Applications, 38*(4), 4222–4227. https://doi.org/10.1016/j.eswa.2010.09.087
[38] Wu, L., Yick, K.-l., Ng, S.-p. and Yip, J. (2012). Application of the Box–Behnken design to the optimization of process parameters in foam cup molding. *Expert Systems with Applications*, *39*(9), 8059–8065. https://doi.org/10.1016/j.eswa.2012.01.137
[39] Manohar, M., Joseph, J., Selvaraj, T. and Sivakumar, D. (2013). Development of models using genetic programming for turning Inconel 718 with coated carbide tools. *International Journal of Design and Manufacturing Technology*, *4*(1). https://doi.org/10.34218/ijdmt.4.1.2013.30320130401001
[40] Manshahia, M. and Das, A. (2014). Thermo-physiological comfort of compression athletic wear. *Indian Journal of Fibre & Textile Research*, *39*(2), 139–146.
[41] ASTM International. (2016). *ASTM D6193: Standard practice for stitches and seams*. https://www.astm.org/d6193-16r20.html
[42] Ghezal, I., Moussa, A., Marzoug, I. B., El-Achari, A., Campagne, C., & Sakli, F. (2022). Investigating waterproofness and breathability of a coated double-sided knitted fabric. *Coatings, 12*(10), 1572. https://doi.org/10.3390/coatings12101572
[43] AATCC. (2017). *Test method for water resistance: Hydrostatic pressure* (AATCC TM127). American Association of Textile Chemists and Colorists. https://members.aatcc.org/store/tm127/535/

J T A T M