RESEARCH ON INFLUENCE OF SEALING PARAMETERS ON STRENGTH AND WATER RESISTANCE OF STITCH-SEALING AND WELD-SEALING SEAM

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ABSTRACT

This study presents a comparative investigation of the performance of two-seam sealing techniques stitch-sealing and ultrasonic weld-sealing applied to three-layer waterproof fabric composites used in high-performance apparel. A Box-Wilson Central Composite Design was adopted to systematically evaluate the effects of three critical sealing parameters temperature, sealing speed, and air pressure on seam thickness, tensile strength, and hydrostatic water resistance. Experimental trials were conducted both before and after 10 standardized domestic laundering cycles, following ISO 811 (hydrostatic head test) and ISO 13935-2 (grab tensile strength) protocols. Results revealed that weld-sealed joints consistently exhibited lower seam thickness and superior water resistance under all tested conditions, contributing to enhanced wearer comfort. Conversely, stitch-sealed seams demonstrated significantly higher tensile strength, particularly under high-temperature and high-pressure settings. Quadratic regression modeling indicated that temperature was the most influential parameter, with notable two-factor interaction effects observed especially between temperature and air pressure. These findings underscore the importance of optimizing sealing conditions based on end-use requirements, offering a scientific basis for the rational selection of seam sealing technologies in the manufacturing of functional waterproof garments.

KEYWORDS

Sealing Parameters, Seam Strength, Stitch-sealing, Water Resistance, Weld-sealing, 3-layer Waterproof fabric.

INTRODUCTION

In the manufacturing of performance apparel from water-repellent textiles, such as sportswear and outdoor protective garments, the integrity of the seams is of paramount importance. These joints must not only ensure waterproof integrity but also possess sufficient flexibility to maintain the fabric's inherent hand and drape. Furthermore, they must exhibit robust mechanical strength and durability to withstand the demands of their intended application and maintain functional performance over time. While stitching is currently the most dominant joining technique, manufacturers are exploring other options to meet modern demands. Among these alternatives, adhesive bonding and welding are emerging as the most prominent new methods [1,2].

Welding technologies have become integral to the fabrication of technical textiles requiring advanced functional properties. These properties include high water penetration resistance, seam durability under mechanical stress, controlled air permeability, and superior aesthetic qualities [3,4]. Among these technologies, ultrasonic welding has emerged as a particularly significant method for creating high-performance seams. Ultrasonic welding is a solid-state joining technique that utilizes high-frequency acoustic vibrations to create continuous, durable, and impermeable seams. In contrast to conventional sewing. This technique offers significant process advantages, including lower energy consumption and the elimination of consumables such as needles and thread, thereby removing associated costs and potential points of mechanical failure [5]. The technique also affords greater design flexibility, enabling the creation of variable seam widths and the lamination of multiple layers in a single pass. Crucially, by obviating the need for stitching, ultrasonic welding eliminates the needle perforations that are inherent sources of water ingress in conventional seams [6, 7]. However, for many high-performance products, the primary joint must be augmented with a sealing process to meet stringent requirements for quality and mechanical strength.

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In the conventional assembly of breathable waterproof fabrics, the use of thread necessitates a subsequent seam sealing process [8]. A waterproof sealing tape is applied to prevent water ingress through the perforations created by the sewing needle, a critical step for ensuring garment integrity [9, 10].

Despite the widespread use of both stitch-sealing and the alternative weld-sealing method, there remains a notable gap in the literature regarding a systematic, direct comparison of their performance. Specifically, research that quantitatively analyzes the influence of individual process parameters on the resultant bond strength and water resistance of these two joint types is scarce. Such an analysis is essential for identifying the optimal processing conditions for each method, which would in turn enhance manufacturing efficiency, improve product durability, and reduce costs associated with defects. Therefore, the present study was undertaken to comparatively investigate the effects of key sealing parameters on the tensile strength and water penetration resistance of stitch-sealed versus weld-sealed seams. The objective is to provide a robust scientific basis to guide the selection and optimization of the appropriate joining technology for practical manufacturing applications.

EXPERIMENTAL

Materials

Three-layer fabric: The substrate for all seam evaluations was a 3-layer fabric. The construction consists of: (i) an external face fabric, which provides primary abrasion resistance and water repellency; (ii) a central microporous functional membrane, which serves as a barrier to liquid water penetration while allowing for the transmission of water vapor (breathability); and (iii) an internal liner fabric, which protects the membrane from abrasion and provides a comfortable tactile interface for the wearer. In this study, the face fabric (layer 1) with a compound of 60% recycles polyester, 40% polyester was laminated with PU coating for water repellency ability. The more detailed properties of the fabric are presented in Table 1.

Three-layer sealing tape: For all sealing processes, a 3-layer tape with an area weight of 230 g/m² and a thickness of 0.3 mm was employed. The tape is a composite structure consisting of a 100% polyurethane (PU) adhesive layer with a melting point of 300°C, a waterproof barrier layer composed of Thermoplastic polyurethane (TPU), and a final layer composed of a jersey knit polyester made from 100% polyester backing fabric. All sealing operations were performed on a NaWon HTM 5533S seam sealing machine. The schematic illustration of the tape was demonstrated in Fig. 1(a)

Table 1. Properties of 3-layer fabric for testing stitch-sealed and weld-sealed joints.

Layer	Layer 1	Layer 2	Layer 3
Material	Woven fabric, 60% Recycled polyester, 40% Polyester; 75D x 75D (laminated with PU)	Thermoplastic polyurethane (TPU)	Woven fabric, 100% polyester
Weight [gm^{-2}]	86.2	60.0	24.8
Thickness [mm]	0.15	0.05	0.1

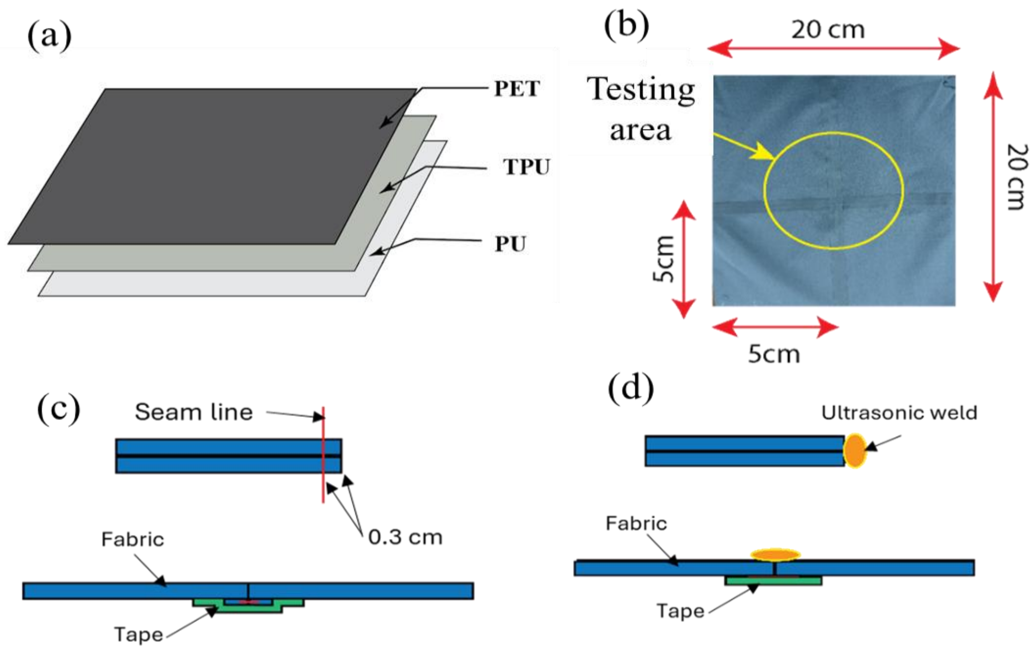

Figure 1. (a) Schematic illustration of three-layer sealing tape, (b) Position of water penetration resistance tests, (c) Schematic diagrams of stitch-sealing, (d) Schematic diagrams of weld-sealing.

In this research, both stitch-sealed and weld-sealed joints were fabricated and analyzed to facilitate a direct comparison of their efficacy in the context of waterproof jacket construction. Schematic diagrams of the stitch-sealing and weld-sealing processes are presented in Fig. 1(c) and 1 (d).

For the stitch-sealed joint, the parameters for the seam were as follows:

- Apparatus: A single-needle, edge-trimming lockstitch machine (Model: DLM-5420N-7) was utilized.
- Stitch type: The seams were constructed using a 301-lockstitch type.
- Stitch density: The stitch density was set to a range of 4–5 stitches/cm.
- Edge trim: 0.3 cm allowance from the seam line to the edge.

For the weld-sealed joint, the ultrasonic weld was utilized, the parameter for the weld were as follows:

- Apparatus: Nawon Ultrasonic Sealing Machine
- Pneumatic pressure: 0.3 MPa
- Welding Speed: 2.2 m/min
- Ultrasonic frequency: 40–42 kHz

To evaluate the performance retention of the seams after domestic laundering, specimens were subjected to 10 wash-and-dry cycles prior to tensile strength and water resistance testing. The standardized laundering parameters were as follows:

- The washing cycle is performed using an LG domestic washing machine. The wash temperature is set to 40°C, with a spin speed of 800 rpm. The duration of each cycle is 45 minutes. There is no detergent used in this process.
- The drying cycle is performed using a Whirlpool domestic tumble dryer. The drying temperature is set to 40°C with the tumble setting on low. The duration of the cycle is 40 minutes.

Experimental Design

In this study, a Design of Experiments approach was employed to investigate the influence of three critical sealing process parameters: Temperature, Sealing speed, and Air pressure - on the integrity of both stitch-sealed and weld-sealed joints. As these factors are known to have significant, interdependent relationships and exert a simultaneous influence on final joint quality, a second-order orthogonal experimental design was selected.

Specifically, a Box-Wilson Central Composite Design was utilized to structure the experimental plan. This methodology facilitates the development of empirical regression equations that model the simultaneous effects and interactions of the investigated factors. The design of the experiment and the subsequent statistical analysis of the data were carried out using Design-Expert® software (version 13.0). Alpha (α) is the axial point distance, which is a critical parameter in constructing this design. This parameter is determined by following equation [11]:

$$\alpha = 2^{k^{1/4}} \quad (1)$$

With the number of factors was k = 3, the design was configured with an axial point distance (α) of 1.68. The experimental ranges and corresponding coded levels for each parameter are detailed in Table 2.

The experimental design consisted of a total of 15 unique experimental conditions. These conditions comprised 4 factorial points, 6 axial points, and 5 central points. To ensure the reliability of the results, each of these experimental runs was replicated five times. The final response value for each condition was recorded as the arithmetic mean of the five replicates. The complete experimental matrix is detailed in Table 3.

Determination of Seam Thickness

The assessment of seam thickness serves as a quantitative indicator of the product's external appearance. The findings suggest that the application of seam tape produces flatter seams, contributing to a smoother overall seam finish. Consequently, this is expected to improve the wearer's tactile comfort by minimizing frictional forces between the body and the seam lines [12].

The thickness of the sewn-and-taped and the bonded seams was determined using a Fabric Thickness Tester, following the procedures outlined in TCVN 5071: 2007 (ISO 5084: 1996) [13].

Evaluation of Joint Water Penetration Resistance

To determine the waterproof integrity of stitch-sealed and weld-sealed joints on a three-layer fabric composite, the water penetration resistance was evaluated. Test specimens were fabricated as 20 cm × 20 cm squares, each featuring a single seam or weld line positioned centrally along the sample, as per technical standards. The water penetration resistance of all specimens was evaluated at the specific position illustrated in Fig. 1b.

The water resistance of the seams was evaluated via the Hydrostatic Head Test, in accordance with the ISO 811 standard [14]. The test was conducted by applying a constant hydrostatic pressure of 1.5 psi (equivalent to 1,055 mmH2O) to the face of the fabric for a duration of one minute. The specimen was deemed to have passed if no water penetration was observed on the seam line during the test period. The presence of any water on the reverse side indicated failure (Not pass). All tests were performed using an HTM 2225 Hydrostatic Head Tester.

Table 2. Experimental range and coded levels of investigated factors.

No.	Factor	Variability levels				
		-1.68	**-1**	**0**	**1**	**1.68**
1	X_1 - Temperature [°C]	455	480	540	600	625
2	X_2- Sealing speed [m/min]	2.2	2.5	3	3.5	3.8
3	X_3- Air pressure [Mpa]	0.03	0.04	0.045	0.05	0.06

Table 3. Experimental plan for investigating sealing factor effects.

No.	x_1	x_2	x_3	X_1 [°C]	X_2 [m/min]	X_3 [Mpa]
1	1	1	-1	600	3.5	0.04
2	1	-1	1	600	2.5	0.05
3	-1	1	1	480	3.5	0.05
4	-1	-1	-1	480	2.5	0.04
5	-1.68	0	0	455	3	0.045
6	1.68	0	0	625	3	0.045
7	0	-1.68	0	540	2.2	0.045
8	0	1.68	0	540	3.8	0.045
9	0	0	-1.68	540	3	0.03
10	0	0	1.68	540	3	0.06
11	0	0	0	540	3	0.045
12	0	0	0	540	3	0.045
13	0	0	0	540	3	0.045
14	0	0	0	540	3	0.045
15	0	0	0	540	3	0.045

Determination of Joint Tensile Strength

The tensile strength of the joints was determined using a monotonic tensile test. The procedure involved subjecting the seam specimen to a continuous, unidirectional tensile load until catastrophic failure occurred. The tensile strength was defined as the maximum force (in Newtons, N) that the specimen could withstand before rupture.

Tensile testing was conducted on a Mesdan Lab Strength Tester, following the grab test method outlined in the ISO 13935-2 standard [15]. Specimen preparation was carried out in accordance with the TCVN 1748-91 standard [16].

RESULTS AND DISCUSSION

Results of Seam Thickness For Stitch-Sealed and Weld-Sealed Joints

The appearance on the surface fabric and the cross - sectional images of the stitch-sealing and weld-sealing reveals distinct topographical differences between the two seam types (Fig. 2 from a to d). The weld-sealed joints exhibit a smooth, flat, and uniform surface profile. Conversely, the stitch-sealed seams, which involve applying tape over a line of stitching, present a noticeably uneven and raised profile. This surface irregularity is the primary factor contributing to the greater overall thickness measured in the stitch-sealed specimens.

Table 4 presents a comparison of seam thickness [mm] between two joining techniques: stitch-sealing and weld-sealing. The findings from experiments 5 and 6 reveal that joint thickness exhibits a decreasing trend with an increase in temperature. In contrast, experiments 7 and 8 demonstrated that a higher speed correlated with an increase in joint thickness. In experiments 9 and 10, while an increase in hot air pressure led to a reduction in joint thickness, this change was negligible.

The preliminary optimal parameters for achieving the minimum stitch-sealed joint thickness (1.21 mm) were determined from experiment 1 with the following Temperature of 600 °C, Sealing speed of 3.5 m/min, and Air pressure of 0.04 Mpa. While the preliminary optimal parameters for achieving the minimum weld-sealed joint thickness (0.56 mm) were determined from experiment 2 with the following Temperature of 600 °C, Sealing speed of 2.5 m/min, and air pressure of 0.05 Mpa.

Furthermore, the data consistently shows that in all experimental conditions, the weld-sealing joints were thinner than the stitch-sealing joints. This finding suggests that the reduced seam thickness achieved through the weld-sealing method is a key factor affecting wearer comfort.

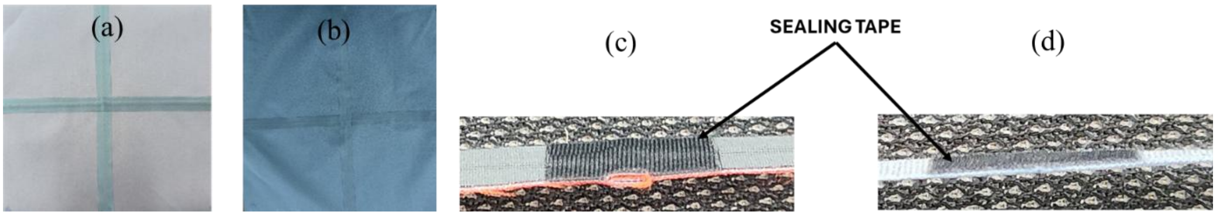

Figure 2. Appearance of (a) Stitch-sealing on fabric, (b) Weld-sealing on fabric, cross-sectional images of (c) Stitch-sealing (d) Weld-sealing

Table 4. Thickness of stitch-sealed and weld-sealed joints of testing specimens

No	X1 [°C]	X2 [m/ min]	X3 [MPa]	Thickness [mm] *Stitch-sealing*	Thickness [mm] *Weld-sealing*
1	1	1	-1	1.21 ± 0.01	0.72 ± 0.01
2	1	-1	1	1.47 ± 0.01	0.56 ± 0.01
3	-1	1	1	1.45 ± 0.01	0.64 ± 0.01
4	-1	-1	-1	1.28 ± 0.01	0.66 ± 0.01
5	-1.68	0	0	1.35 ± 0.01	0.71 ± 0.01
6	1.68	0	0	1.27 ± 0.01	0.61 ± 0.01
7	0	-1.68	0	1.28 ± 0.01	0.60 ± 0.01
8	0	1.68	0	1.37 ± 0.01	0.79 ± 0.01
9	0	0	-1.68	1.39 ± 0.01	0.78 ± 0.01
10	0	0	1.68	1.37 ± 0.01	0.60 ± 0.01
11	0	0	0	1.26 ± 0.01	0.69 ± 0.01
12	0	0	0	1.27 ± 0.01	0.69 ± 0.01
13	0	0	0	1.27 ± 0.01	0.70 ± 0.01
14	0	0	0	1.28 ± 0.01	0.71 ± 0.01
15	0	0	0	1.27 ± 0.01	0.70 ± 0.01

Table 5. ANOVA for quadratic model of stitch-sealed seams' thickness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0796	9	0.0088	41.53	0.0004	significant
X_1	0.0032	1	0.0032	15.02	0.0117	
X_2	0.0041	1	0.0041	19.01	0.0073	
X_3	0.0002	1	0.0002	0.9388	0.3771	
X_1X_2	0.0337	1	0.0337	158.42	< 0.0001	
X_1X_3	0.0058	1	0.0058	27.02	0.0035	
X_2X_3	0.0003	1	0.0003	1.44	0.2833	
X_1^2	0.0037	1	0.0037	17.47	0.0087	
X_2^2	0.0067	1	0.0067	31.39	0.0025	
X_3^2	0.0202	1	0.0202	94.73	0.0002	
Residual	0.0011	5	0.0002			
Lack of Fit	0.0009	1	0.0009	17.30	0.0141	significant
Pure Error	0.0002	4	0.0000			
Cor Total	0.0807	14				

Due to the experimental results, to optimize the thickness of the stitch-sealed seam, the effect of the sealing process parameters was analyzed. The ANOVA results are shown in Table 5. The results of ANOVA indicate that the interaction between temperature [°C] and speed [m/min] is the dominant influence on the thickness of the stitch-sealed seam throughout the entire process. The main factors X_1 – temperature [°C] and speed [m/min] - X_2 are important; these factors should be considered during the sealing process to ensure the thickness of the stitch-sealed seam is desirable. The interaction plot of the temperature and speed to the thickness of the stitch-sealed seam was demonstrated in Fig 3.

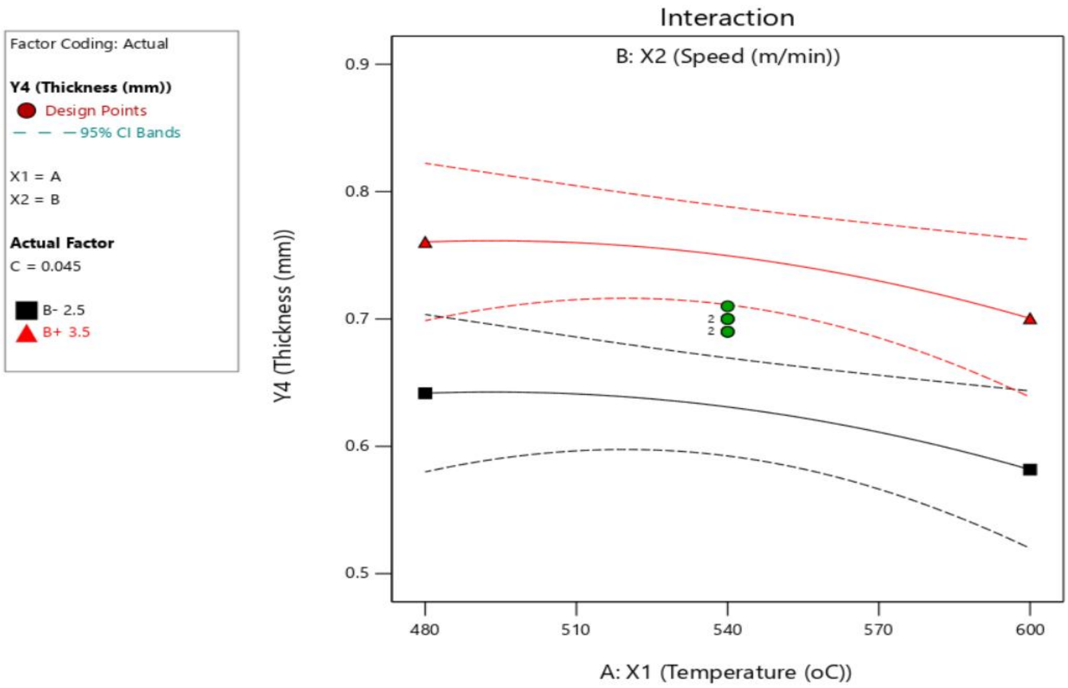

Figure 3. Interaction plot of stitch-sealing thickness - Y1 [N] at different levels of Temperature - X1[°C] and Sealing speed – X2 [m/min].

Table 6. Water penetration resistance results before and after 10 washing 10 cycles at stitch-sealing and weld-sealing areas

No.	X1	X2	X3	Before washing		After washing [10 cycles]	
	[°C]	[m/min]	[MPa]	*Stitch-sealing*	*Weld-sealing*	*Stitch-sealing*	*Weld-sealing*
1	1	1	-1	P	P	P	P
2	1	-1	1	P	P	P	P
3	-1	1	1	P	P	NP	P
4	-1	-1	-1	P	P	P	P
5	-1.68	0	0	P	P	P	P
6	1.68	0	0	P	P	P	P
7	0	-1.68	0	P	P	P	P
8	0	1.68	0	NP	NP	NP	NP
9	0	0	-1.68	NP	NP	NP	NP
10	0	0	1.68	NP	NP	NP	NP
11	0	0	0	P	P	P	P
12	0	0	0	P	P	P	NP
13	0	0	0	P	P	P	P
14	0	0	0	P	P	NP	P
15	0	0	0	P	P	P	P

P-Pass & NP – Not pass

Results of Joint Water Penetration Resistance for Stitch-Sealing and Weld-Sealing

The water resistance of the seams was evaluated under a hydrostatic pressure of 1.055 mmH_2O for a duration of one minute. The results in Table 6 indicate that when process parameters such as air pressure [Mpa] were at their highest or lowest levels, and speed [m/min] was at its maximum, both the stitch-sealing and weld-sealing joints failed to meet the required water resistance. This was observed in both pre-wash conditions and after 10 washing cycles**.**

Experiments 3, 12, and 14 show that the water resistance of both stitch-sealing and weld-sealing joints decreased after 10 washing cycles. This demonstrates that the water resistance of the joint may be affected by usage (simulated by the washing process in this study).

Based on the average results across the experiments, the weld-sealed joints consistently yielded better water resistance than the stitch-sealing joints.

Table 7. Tensile strength results of stitch-sealing and weld-sealing

No.	X_1	X_2	X_3	Tensile strength [N]	
	[°C]	[m/ min]	[MPa]	*Stitch-sealing*	*Weld-sealing*
1	1	1	-1	452.4 ± 75.6	336.8 ± 21.4
2	1	-1	1	490.2 ± 104.8	327.4 ± 15.2
3	-1	1	1	369.4 ± 101.2	331.6 ± 11.0
4	-1	-1	-1	446.0 ± 117.0	337.6 ± 15.4
5	-1.68	0	0	303.0 ± 48.3	335.8 ± 8.8
6	1.68	0	0	402.6 ± 74.1	352.4 ± 19.7
7	0	-1.68	0	293.2 ± 49.2	342.4 ± 22.2
8	0	1.68	0	336.0 ± 63.2	338.6 ± 13.8
9	0	0	-1.68	323 ± 112.6	288.6 ± 32.8
10	0	0	1.68	345.6 ± 79.1	302.6 ± 16.9
11	0	0	0	274.0 ± 63.2	270.2 ± 11.1
12	0	0	0	292.6 ± 17.1	304.4 ± 14.9
13	0	0	0	295.0 ± 19.2	302.8 ± 15.0
14	0	0	0	297.8 ± 18.3	305.0 ± 14.6
15	0	0	0	291.3 ± 18.4	303.5 ± 15.2

Results of Tensile Strength of Stitch-Sealing and Weld-Sealing

Analysis of sealing process parameters on joints tensile strength

The experimental results for tensile strength are presented in Table 7, revealing distinct trends for the two joining methodologies. For stitch-sealed joints, an increase in temperature (Experiments 5 and 6), speed (Experiments 7 and 8), and air pressure (Experiments 9 and 10) consistently resulted in an enhanced the strength of the stitch-sealed joints. Conversely, for the weld-sealed joints, while increasing temperature (Experiments 5 and 6) and air pressure (Experiments 9 and 10) improved the strength of the weld-sealed seam, an increase in speed (Experiments 7 and 8) led to a reduction in the tensile strength of the joint.

Overall, the stitch-sealed seams exhibited a superior average bond strength (490 N) compared to the weld-sealed seams (352 N).

Modeling and analysis of stitch-sealed joint strength (Y1)

To quantitatively analyze the relationship between the sealing process parameters—Temperature (X1), Speed (X2), and Air pressure (X3)—and the tensile strength of stitch-sealed seams (Y1), a quadratic regression model was established as follows:

$$Y_1 = 290.11 + 29.88X_1 + 13.37X_2 + 5.65X_3 + 15.35X_1X_2 + 41.98X_1X_3 - 1.92X_2X_3 + 38.86X_1^2 + 28.75X_2^2 + 18.91X_3^2 \quad (1)$$

From (1), the linear effects of the process parameters (Xi) on tensile strength (Y_1) are evaluated by their corresponding coefficients (a_i). The largest absolute coefficient, $a_1 = +29.88$, corresponds to temperature (X_1), identifying it as the most significant linear factor. The positive sign indicates that increasing the temperature leads to a substantial increase in the bond strength of stitch-sealed seams. The coefficient $a_2 = +13.37$ suggests that speed (X_2) also has a positive linear effect on tensile strength. In contrast, the much smaller coefficient for air pressure ($a_3 = +5.65$) implies its linear influence on the seam strength is negligible compared to that of temperature and speed.

The interaction effects between two parameters (X_{ij}) are assessed via the a_{ij} coefficients. The large positive coefficient for the temperature-pressure interaction ($a_{13} = +41.98$) is particularly noteworthy, indicating a strong synergistic interaction between temperature (X_1) and air pressure (X_3). The positive signifies that to maximize tensile strength (Y_1), a simultaneous increase in both temperature and pressure is required. A similar, though less pronounced, synergistic interaction is observed between temperature and speed (X_1X_2), as shown by its positive coefficient ($a_{12} = +15.35$), suggesting that a concurrent increase in these two parameters also enhances bond strength.

Based on this analysis and corroborated by 3D response surface plots, Fig.4 (a) – (c), and interaction plots, Fig.5 (a) – (c), optimizing the bond strength of stitch-sealed seams necessitate operating in a high-temperature, high-pressure regime while adjusting the speed accordingly. However, it is critical to calibrate these parameters appropriately to prevent seam degradation, as excessive temperature or pressure could lead to bond failure.

Table 8. Fit statistics values of sealing process parameters and stitch-sealed seam tensile strength

Std. Dev.	73.56	**R^2**	0.5964
Mean	347.47	**Adjusted R^2**	-0.1299
C.V. %	21.17	**Predicted R^2**	-50.5134
		Adeq Precision	2.6264

Table 9. ANOVA for quadratic model of stitch-sealed joint strengt

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	39992.59	9	4443.62	0.8211	0.6253
A-X1	4960.08	1	4960.08	0.9165	0.3824
B-X2	915.92	1	915.92	0.1692	0.6978
C-X3	255.38	1	255.38	0.0472	0.8366
AB	628.33	1	628.33	0.1161	0.7471
AC	3956.55	1	3956.55	0.7311	0.4316
BC	8.57	1	8.57	0.0016	0.9698
A^2	18701.83	1	18701.83	3.46	0.1221
B^2	8888.35	1	8888.35	1.64	0.2562
C^2	8627.16	1	8627.16	1.59	0.2624
Residual	27058.46	5	5411.69		
Lack of Fit	26708.27	1	26708.27	305.07	< 0.0001
Pure Error	350.19	4	87.55		
Cor Total	67051.05	14			

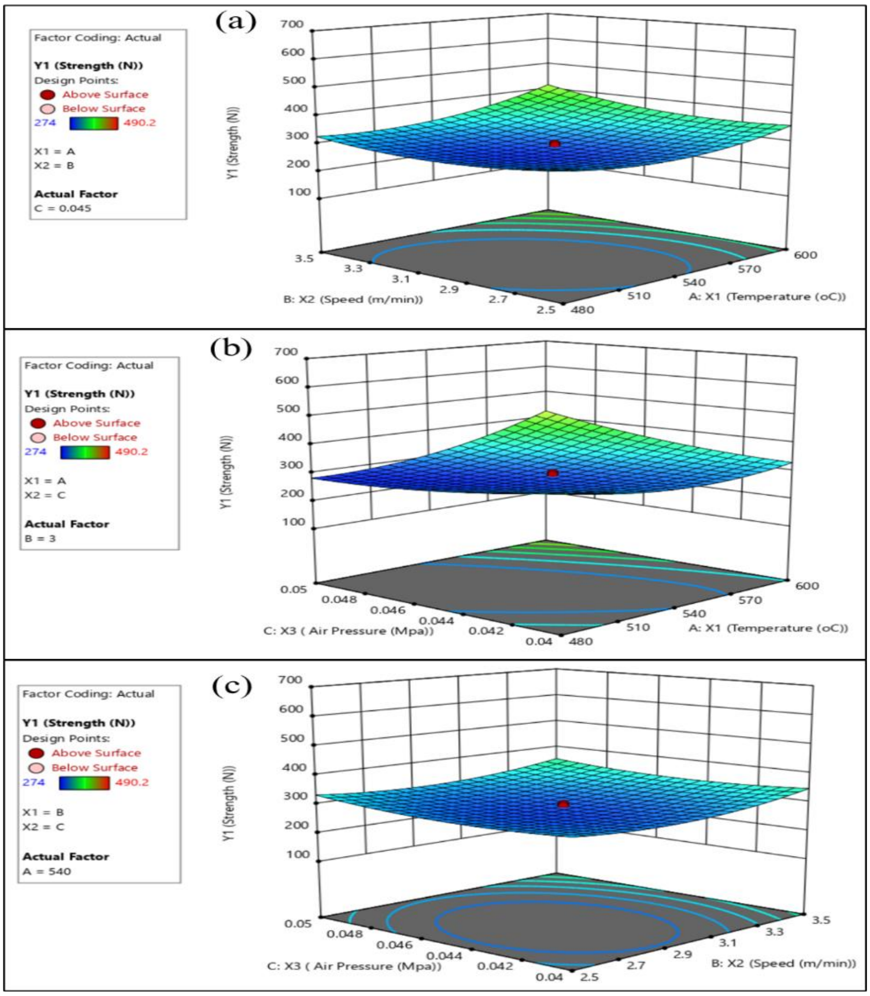

Figure 4. 3D-graph response of stitch-sealing tensile strength Y1 [N] at different levels of: (a) Temperature - X1 [°C] and Sealing speed - X2 [m/min], (b) Temperature - X1 [°C] and Air pressure - X3 [MPa], and (c) Sealing speed - X2 [m/min] and air pressure - X3 [MPa].

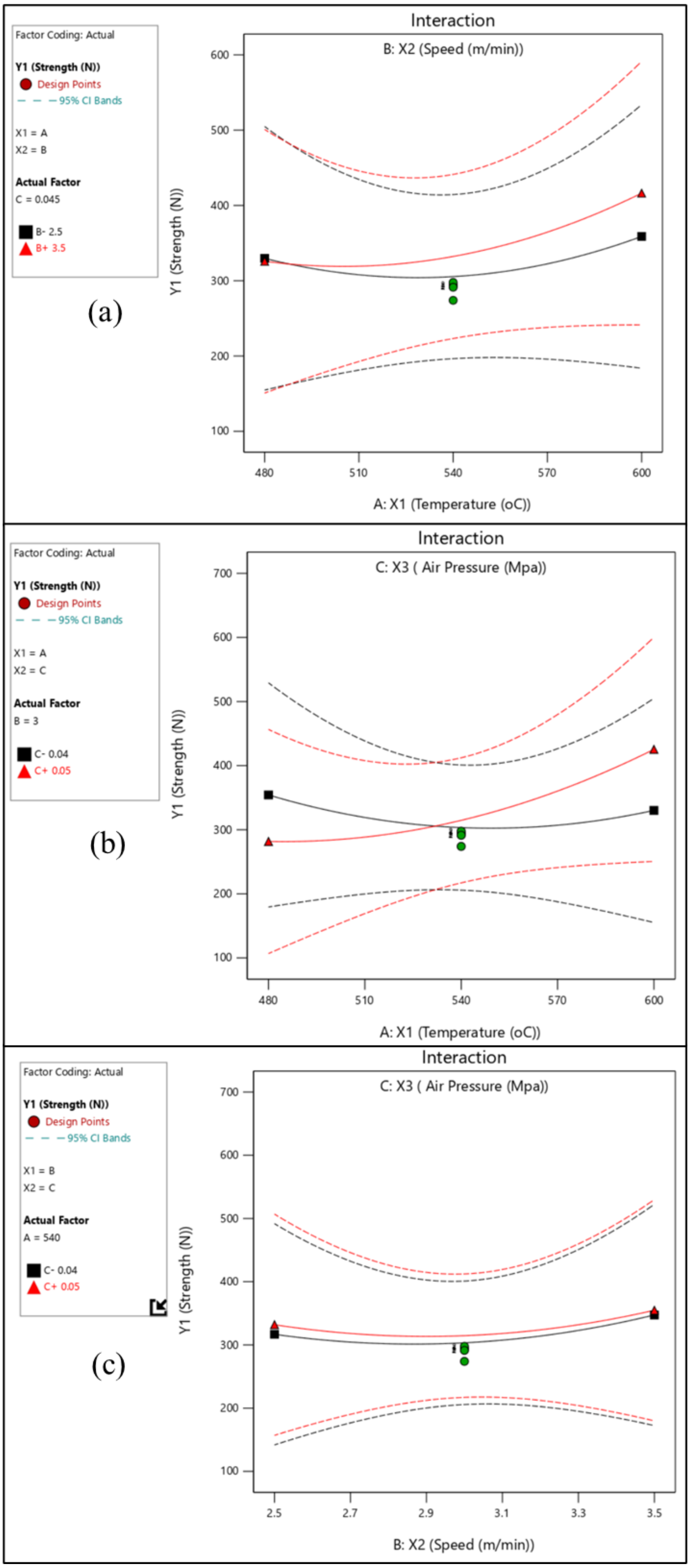

Figure 5. Interaction plot of stitch-sealing tensile strength Y_1 [N] at different levels of (a) Temperature - X_1[°C] and Sealing speed – X_2 [m/min], (b) Temperature - X_1[°C] and Air pressure – X_3 [Mpa], (c) Sealing speed – X_2 [m/min] and Air pressure – X_3 [Mpa].

Table 10. Fit statistics value of the relationship of the sealing process parameters to the weld-sealed seam tensile strength

Std. Dev.	13.64	**R^2**	0.8792
Mean	318.65	**Adjusted R^2**	0.6618
C.V. %	4.28	**Predicted R^2**	0.5141
		Adeq Precision	5.7596

Table 11. ANOVA for quadratic model of weld-sealed joint strenght

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	6775.52	9	752.84	4.04	0.0691
A-X1	137.78	1	137.78	0.7402	0.4289
B-X2	7.22	1	7.22	0.0388	0.8516
C-X3	98.00	1	98.00	0.5265	0.5006
AB	144.06	1	144.06	0.7740	0.4193
AC	9.32	1	9.32	0.0501	0.8318
BC	90.26	1	90.26	0.4849	0.5172
A^2	3711.62	1	3711.62	19.94	0.0066
B^2	3262.30	1	3262.30	17.53	0.0086
C^2	0.8821	1	0.8821	0.0047	0.9478
Residual	930.66	5	186.13		
Lack of Fit	17.93	1	17.93	0.0786	0.7931
Pure Error	912.73	4	228.18		
Cor Total	7706.18	14			

Modeling and analysis of weld-sealed joint strength (Y2)

In the experiments to analyze the effect of sealing parameters on the weld-sealed seam tensile strength, the C.V. value of 4.28% is generally considered very low, indicating that the variation in the data is small compared to the mean value (318.65). This implies that the experiments are highly repeatable and precise.

Similarly, a quadratic regression model was developed to elucidate the relationship between the process parameters and the tensile strength of weld-sealed joints (Y_2):

$$Y_2 = 297.18 + 4.98X_1 - 1.19X_2 + 3.5X_3 + 7.35X_1X_2 - 2.04X_1X_3 + 6.23X_2X_3 + 17.31X_1^2 + 17.42X_2^2 - 0.19X_3^2 \quad (2)$$

According to (2), the largest absolute linear coefficient is a_1 = +4.98, corresponding to temperature (X_1), which suggests it is the most influential linear factor. The positive value indicates a direct relationship where higher temperatures increase the tensile strength of the weld-sealing. The coefficient a_3 = +4.93 also shows a positive linear effect of air pressure (X_3) on bond strength. In contrast, the coefficient a_2 = -1.19 is negative, indicating an inverse linear relationship for speed (X_2); that is, decreasing the speed promotes higher tensile strength. However, the magnitudes of these linear coefficients are minor compared to the quadratic coefficients for temperature (a_1^2 = +17.31) and speed (a_2^2 = +17.42). This finding suggests that the tensile strength of weld-sealed seams (Y_2) is not predominantly governed by the linear effects of individual parameters but rather by the non-linear (quadratic) effects of temperature and speed.

Regarding interaction effects, the positive coefficient a_{12} = +7.35 indicates a synergistic interaction between temperature (X_1) and speed (X_2), implying that a concurrent increase of both is beneficial for tensile strength. Likewise, the interaction between speed and air pressure (X_2X_3) is also synergistic (a_{23} = +6.23). Conversely, the coefficient for the temperature-pressure interaction (a_{13} = -2.04) is negative, indicating an antagonistic relationship. This suggests that to increase tensile strength, one parameter must be increased while the other is decreased (e.g., increasing temperature while decreasing pressure, or vice-versa).

In conclusion, the analysis, in conjunction with 3D response surface plots, Fig. 6 (a) – (c), and interaction plot, Fig. 7 (a) – (c), indicate that optimizing the tensile strength for weld-sealed joints requires setting temperature and speed at their optimal extreme levels within the experimental domain.

The analysis reveals that the optimal sealing parameter sets for achieving maximum tensile strength differ significantly between the two joining methods. For stitch-sealing, the highest tensile strength was achieved under conditions of high temperature, low speed, and high pressure (as demonstrated in Experiment 2). In contrast, the optimal tensile strength for weld-sealing was obtained at a very high temperature, while maintaining both speed and pressure at intermediate levels (Experiment 6).

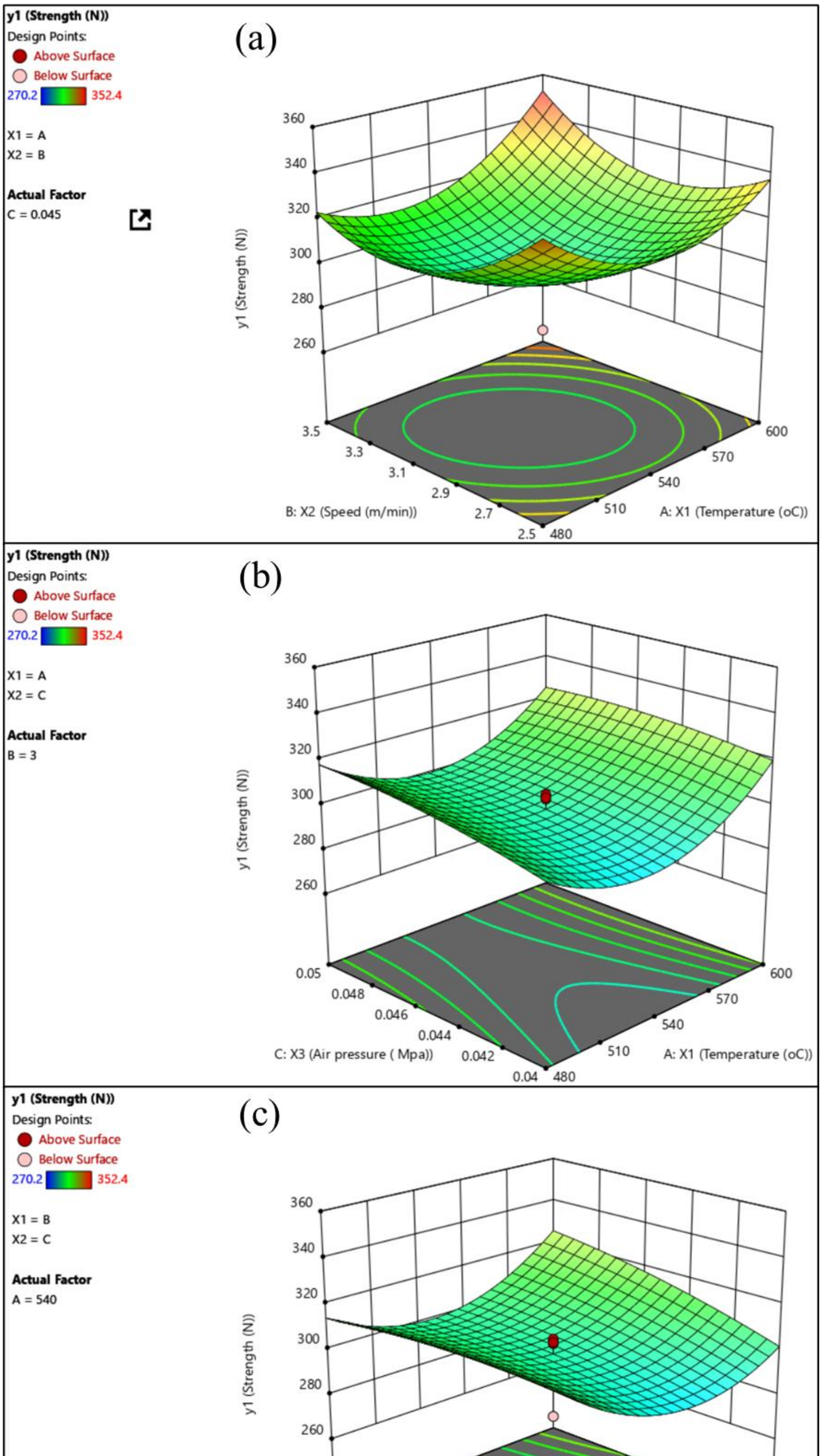

Figure 6. 3D-graph response of weld-sealing tensile strength Y1 [N] at different levels of (a) Temperature - X1 [°C] and Sealing speed - X2 [m/min], (b) Temperature - X1 [°C] and Air pressure - X3 [Mpa], and (c) Sealing speed - X2 [m/min] and Air pressure - X3 [MPa].

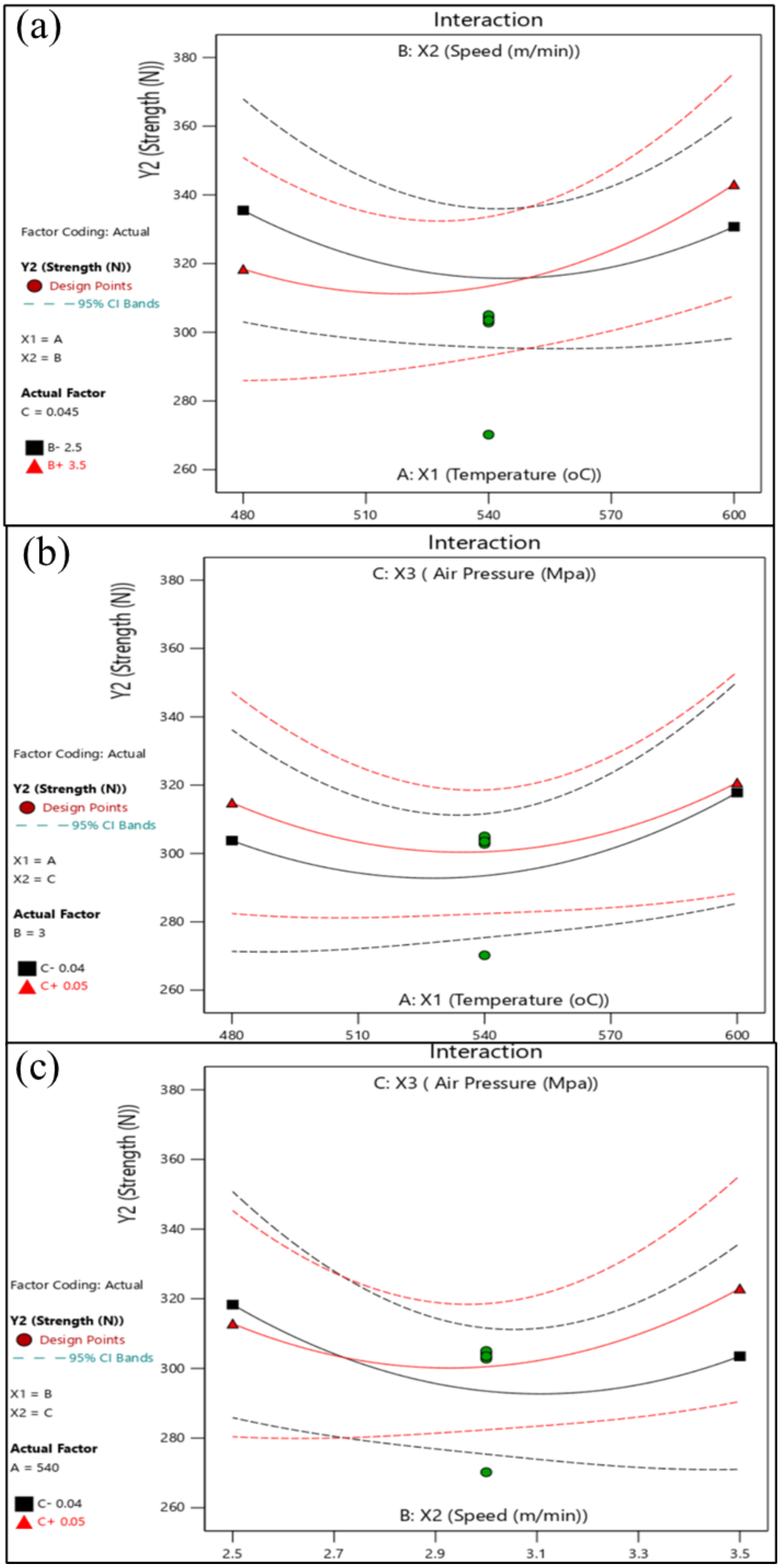

Figure 7. Interaction plot of weld-sealing tensile strength - Y1 [N] at different levels of (a) Temperature - X1 [°C] and Sealing speed – X2 [m/min], Temperature - X1 [°C] and Air pressure – X3 [Mpa], and (c) Sealing speed – X2 [m/min] and Air pressure – X3 [MPa].

This comparative analysis indicates that, from the perspective of optimizing bond strength, the weld-sealing process offers superior process stability and repeatability for large-scale manufacturing compared to the stitch-sealing method.

CONCLUSION

This study provided a systematic comparison between stitch-sealing and ultrasonic weld-sealing techniques applied to three-layer waterproof fabrics commonly used in high- performance apparel. Through the application of Box-Wilson Central Composite Design, the effects of key sealing parameters temperature, sealing speed, and air pressure were evaluated in relation to seam thickness, hydrostatic water resistance, and tensile strength. Ultrasonic weld-sealing consistently produced thinner seams and demonstrated superior water resistance, particularly after repeated laundering, indicating greater long-term waterproof integrity and enhanced wearer comfort. Stitch-sealing outperformed in terms of tensile strength, making it more suitable for applications demanding high mechanical durability. Among all variables, temperature had the most dominant influence on joint performance, followed by sealing speed and air pressure. Significant two-factor interactions, especially between temperature and air pressure, further contributed to joint integrity.

Based on these findings, the application of the jointing methodologies can be optimal due to the aim of the application. For applications where absolute waterproof integrity is the primary objective (medical protective garments or high-performance rainwear), the ultrasonic weld-sealing technique is superior, with the sealing parameter of higher sealing temperatures and moderate speeds to ensure hydrostatic resistance. Conversely, for applications where mechanical durability is paramount (industrial workwear), the stitch-sealing method is recommended, with moderate temperature and higher pressure for sealing parameters.

Future studies should explore the sealing performance across various fabric types and real-world usage conditions. Additionally, integrating simulation-based modeling and techno-economic analysis will enhance process optimization and industrial scalability.

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