

RESEARCH ON OPTIMIZING PARAMETERS FOR BONDING ZIPPERS TO WATERPROOF FABRIC USING TPU ADHESIVE FILM

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ABSTRACT

The peel strength of zippers bonded to waterproof fabrics plays a crucial role in determining the durability and usability of waterproof garments. In this study, we used orthogonal experimental design to investigate the influence of technological parameters, such as temperature, time and bonding pressure on the adhesion strength of zippers to waterproof fabrics using two thermoplastic polyurethane (TPU) films. The peel strength of the zipper bonded to the waterproof fabric was determined after bonding and after 20 wash cycles. Using the Design Expert statistical software, we determined mathematical models of the relationship between the three technological parameters studied and the peel strength of each adhesive TPU film after bonding and after 20 wash cycles. From this, we determined the optimal temperature, time, and bonding pressure parameters to ensure the best peel strength of the zipper bonded to the waterproof fabric. The results of this study provide a foundation for further research on zipper adhesion technologies with different materials to improve the quality of waterproof products.

Keywords: TPU adhesive film, Peel strength, Zipper bonding.

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1. INTRODUCTION

Zippers are important accessories that are widely used in products such as clothing, footwear, handbags, backpacks, luggage, and many other technical products. In waterproof products such as protective clothing, waterproof footwear, tents, and sportswear; zippers not only allow products to be opened and closed quickly and conveniently but also serve a critical role in ensuring the

necessary sealing performance, preventing the ingress of water, dust, and other environmental factors, thereby enhancing the safety, durability, and functionality of the product [1-3].

During actual use, particularly during washing cycles, zippers and the bonded regions with the base material are subjected to the simultaneous impacts of mechanical forces, temperature, humidity, and detergent chemicals [4]. For waterproof garments, zippers are typically bonded to coated fabrics using adhesive methods rather than sewing to maintain the waterproof integrity of the product. Therefore, the peel strength of the adhesive bond between the zipper and the coated fabric becomes a critical parameter, directly influencing product quality, durability, and service life. If the sealing performance is insufficiently strong, peeling may occur during use, leading to reduced product functionality and diminished user experience [3].

In recent years, along with advances in materials science, thermoplastic polyurethane (TPU) films have been widely applied in the bonding technology of textile materials, particularly coated fabrics and laminated fabrics. TPU films offer advantages in terms of good adhesion capability, high elasticity, water resistance, and compatibility with thermoforming processes [5-9]. However, the adhesion efficiency of the bond depends not only on technological parameters such as temperature, time, and pressure but also is significantly influenced by the nature, structure, and adhesion mechanism of the adhesive film with the material surface [10, 11].

According to Palaskar [12], the adhesion mechanism between adhesive and textile materials can be explained through adhesion theories such as: mechanical adhesion, chemical adhesion, diffusion adhesion, and electrostatic

adhesion. For coated fabrics, particularly those with hydrophobic polymer coating layers, the adhesion capability of the adhesive film depends strongly on the degree of chemical compatibility between the adhesive film and the coating layer, as well as the surface energy of the material. Therefore, selecting the appropriate adhesive film type and optimizing bonding conditions are critical factors for enhancing bond strength.

Many previous studies have focused on analyzing the influence of technological parameters on the peel strength of textile material bonds [5-8,13-15]. Mikalauskaitė and Daukantienė [16] demonstrated that bonding time and thermal aging time had a significant effect on the peel strength of knitted fabric bonds, in which the degradation of bond strength depended on the properties of the adhesive material and the structure of the base material. These results indicated that the adhesive film plays a decisive role in maintaining long-term bond strength, particularly when the product is subjected to thermal effects and repeated loading during use.

Although numerous studies have been conducted on bonding textile materials and coated fabrics using TPU films, to date there remains a lack of in-depth research on the impacts of adhesive films on the peel strength of zipper bonds with waterproof fabrics, particularly under actual use conditions such as after multiple washing cycles.

Based on this context, this study investigates the impacts of thermoplastic polyurethane film combined with technological bonding parameters (temperature, time, and pressure) on the peel strength of zipper bonds with waterproof fabrics. Peel strength was measured both immediately after bonding and after 20 washing cycles to simulate actual use conditions. Based on experimental data, mathematical models were developed to determine the optimal bonding parameters, thereby contributing to improving zipper bonding technology and enhancing the quality and durability of waterproof products.

2. MATERIALS AND METHODS

2.1. Materials

In this study, the experimental materials consisted of one type of zipper, two types of TPU adhesive film, and three-layer waterproof fabric. The characteristics of the zipper, two types of TPU adhesive film, and three-layer waterproof fabric are provided in Tables 1, 2, and 3, respectively.

Table 1. Characteristics of zipper

No.	Characteristics	Value
1	Material composition	Polyester*
2	Weaving type	Woven
3	Warp density	313 yans/10 cm
4	Weft density	125 yans/10 cm
5	Weight	250.5g/m ²
6	Thickness	0.25mm
7	Zipper teeth width	5mm
8	Tooth density	6 teeth/1cm
9	Origin	SBS Company, China

Table 2. Characteristics of TPU adhesive films

No.	Characteristics	Type 1 film (M1 film)	Type 2 film (M2 film)
1	Material	Thermoplastic polyurethane (TPU)	
2	Thickness	75μm	50μm
3	Weight	31g/m ²	112g/m ²
4	Melting point, °C	135°C - 180°C	130°C - 170°C
5	Origin	Youyi Company, China	

Table 3. Characteristics of three-layer waterproof fabric

No.	Characteristics	Value
1	Fabric type	Waterproof coated fabric
2	Material	100% polyester
3	Weight	154g/m ²
4	Width	142cm
5	Face fabric layer	100% polyester woven basic plain weave, 100g/m ²
6	Middle layer	100% polyethylene film
7	Back fabric layer	100% polyester knit warp tricot, 25g/m ²

2.2. Methods and Equipment

The zipper sample were bonded to the coated fabric using the heat pressing method, employing two types of TPU adhesive film as shown in Table 2. The experiments were conducted according to an orthogonal experimental design with three input variables: temperature (coded as X_1), pressure (coded as X_2), and bonding time (coded as X_3). The two output variables were the peel strength of the zipper after bonding (coded as Y_1 for M1 film and Y_3 for M2 film) and the peel strength of the zipper after 20 washing cycles (coded as Y_2 for M1 film and Y_4 for M2 film).

Table 4. Table of coded technological parameters

Factor code	Variability levels									
	M1 film					M2 film				
	-1.68	-1	0	+1	+1.68	-1.68	-1	0	+1	+1.68
X ₁ - Temperature (°C)	140	150	165	175	185	125	135	150	165	175
X ₂ - Pressure (MPa)	0.18	0.25	0.35	0.45	0.52	0.18	0.25	0.35	0.45	0.52
X ₃ - Time (s)	13	18	25	32	37	6	10	15	20	24

Technological parameters including pressing temperature, pressing time, and pressing pressure were selected based on the thermal characteristics of each adhesive film type and the manufacturer's technical recommendations. The variation ranges of the technological parameters were established and coded in Table 4.

According to this experimental design, the total number of experiments (N) is calculated using the formula: $N = 2^K + n_0 + 2K$, where K is the number of input factors studied (K = 3, including X₁, X₂, and X₃), and n₀ is the number of center-point experiments (n₀ = 6). Thus, the total number of experiments performed was N = 20.

For each experiment, 10 specimens were prepared: 5 specimens were used to test the peel strength after bonding, and the remaining 5 were used to evaluate the peel strength after 20 washing cycles. The reported test results are the average values obtained from the five corresponding specimens.

The fabric and zipper sample were cut to a length of 20cm (8 inch), while the adhesive film was cut to 15cm (6 inch). The widths of the fabric and adhesive film specimens were greater than the width of the zipper to ensure complete coverage and full adhesion to the zipper surface (Figure 1). The TPU film was initially transferred onto the zipper and the coated fabric using a lightly pressed iron at 150°C for 5 seconds. The specimens were then bonded using a heat press according to the experimental design. After heat pressing, all specimens were cold-pressed for 10 seconds using a cooling plate at 10°C.

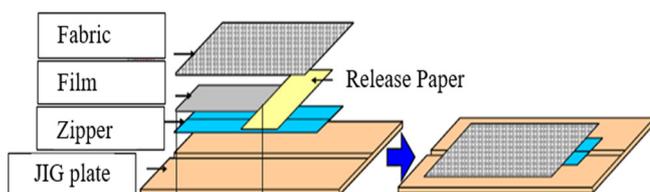


Figure 1. Test specimen preparation specifications

The bonded samples were conditioned under standard environmental conditions before conducting mechanical testing. The peel strength of the bond between the zipper and the fabric was determined using a universal tensile testing machine in accordance with ASTM D903-98(2025). During testing, the free ends of the zipper and fabric were clamped in the two grips of the machine. The samples were peeled using the 180° peel method at a constant speed of 100 mm/min under room temperature conditions. The peel strength was determined from the average peeling force obtained from the force-displacement curve and was expressed in units of N/cm. For each experimental condition, 5 replicate specimens were tested, and the reported results are the average values to ensure statistical reliability. The peel strength results of the two TPU adhesive film samples were compared to evaluate their impacts on the adhesion capability between the zipper and the three-layer waterproof fabric. The differences in peel strength were analyzed and correlated with the material properties as well as the adhesion mechanism of each adhesive film type.

The test specimens were washed under conditions simulating the real-life laundering of garments. Specifically, the specimens were washed in a household washing machine using 50 grams of common detergent for each wash. Each washing cycle lasted 45 minutes, with a washing temperature of 40°C and a spin speed of 800 rpm. After each cycle, the specimens were dried at 60°C for 20 minutes before proceeding to the next washing cycle.

Experimental data were processed using Design Expert software, which enabled the establishment of mathematical models and the analysis of the simultaneous effects of the studied factors on the peel strength after bonding and after washing. Based on these models, the optimal values of the three technological parameters (temperature, pressure, and time) were

determined to ensure the highest peel strength after bonding and after washing for each zipper sample.

To verify the validity of these optimal values, zipper sample were bonded to the coated fabric using the optimized temperature, pressure, and time. The objective was to obtain the highest peel strength after washing (Y_2 and Y_4), as this parameter is critical for assessing product durability during actual use. The peel strength of the bonded samples was then measured and compared with the values predicted by the mathematical models. This comparison provided an evaluation of the reliability and suitability of the identified optimal technological parameters.

Subsequently, SEM analysis was conducted to observe the distribution of the adhesive film within the bonded interfaces of the zipper and the coated fabric. The SEM images helped clarify the influence of the technological factors on the peel strength. SEM imaging of the cross-sections of the specimens was performed using the JSM-IT200 microscope.

3. RESULTS AND DISCUSSIONS

3.1. Results of peel strength testing of two types of TPU adhesive films

The peel strength results after bonding and after washing of M1 film and M2 film according to the experimental design are presented in Tables 5 and 6 and illustrated in Figures 2 and 3.

Table 5. Experimental test results of peel strength after bonding and after washing of M1 film

Factors			Sample code	Peel strength, N/cm		Difference between Y_1 and Y_2	
X_1 (°C)	X_2 (MPa)	X_3 (s)		After bonding Y_1	After washing Y_2	N/cm	%
170	0.45	32	M1.1	17.52 ± 1.04	16.13 ± 5.77	1.39	7.92
150	0.45	32	M1.2	10.63 ± 1.12	9.21 ± 2.15	1.43	13.43
170	0.25	32	M1.3	14.53 ± 1.12	13.70 ± 2.53	0.83	5.74
150	0.25	32	M1.4	11.49 ± 1.80	4.96 ± 1.74	6.53	56.80
170	0.45	18	M1.5	12.83 ± 1.38	8.85 ± 2.32	3.98	31.02
150	0.45	18	M1.6	9.11 ± 0.76	4.09 ± 1.38	5.02	55.11
170	0.25	18	M1.7	11.78 ± 1.42	5.20 ± 1.25	6.59	55.90
150	0.25	18	M1.8	8.29 ± 1.81	4.55 ± 0.85	3.74	45.12
165	0.35	25	M1.9	11.74 ± 2.03	8.68 ± 1.87	3.06	26.04
165	0.35	25	M1.10	12.98 ± 0.46	8.69 ± 1.33	4.29	33.04

165	0.35	25	M1.11	13.12 ± 1.34	8.39 ± 1.87	4.73	36.03
165	0.35	25	M1.12	12.94 ± 2.48	5.60 ± 1.98	7.34	56.71
165	0.35	25	M1.13	11.63 ± 1.70	7.97 ± 1.67	3.65	31.42
165	0.35	25	M1.14	14.68 ± 2.61	7.97 ± 2.52	6.71	45.72
185	0.35	25	M1.15	16.04 ± 3.63	16.63 ± 3.01	-0.59	-3.69
140	0.35	25	M1.16	9.52 ± 1.15	4.82 ± 1.14	4.70	49.38
165	0.52	25	M1.17	13.66 ± 0.91	11.48 ± 1.66	2.19	16.00
165	0.18	25	M1.18	11.99 ± 0.66	6.22 ± 0.34	5.77	48.15
165	0.35	37	M1.19	14.86 ± 1.77	13.65 ± 2.03	1.21	8.16
165	0.35	13	M1.20	8.94 ± 1.73	4.50 ± 1.66	4.44	49.64

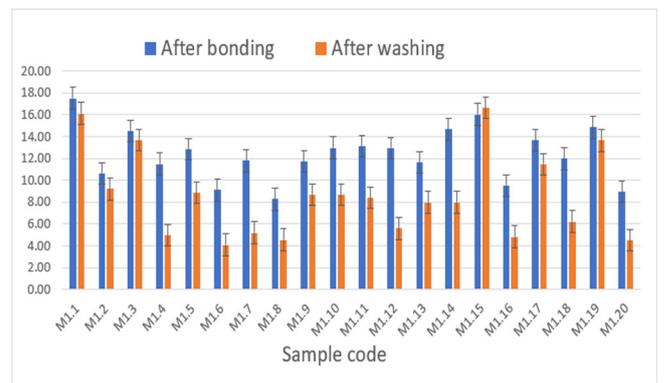


Figure 2. Peel strength comparison of M1 film after bonding and after washing

Table 6. Experimental test results of peel strength after bonding and after washing of M2 film

Factors			Sample code	Peel strength, N/cm		Difference between Y_3 and Y_4	
X_1 (°C)	X_2 (MPa)	X_3 (s)		After bonding Y_3	After washing Y_4	N/cm	%
165	0.45	20	M2.1	14.73 ± 1.48	12.85 ± 1.02	1.89	12.81
135	0.45	20	M2.2	11.54 ± 1.34	6.83 ± 1.81	4.71	40.82
165	0.25	20	M2.3	16.31 ± 0.67	13.14 ± 1.30	3.17	19.46
135	0.25	20	M2.4	11.10 ± 1.86	10.01 ± 0.99	4.74	42.75
165	0.45	10	M2.5	13.51 ± 0.76	8.35 ± 1.89	5.16	38.21
135	0.45	10	M2.6	11.62 ± 1.63	6.14 ± 1.99	5.49	47.20
165	0.25	10	M2.7	14.86 ± 1.23	10.01 ± 1.06	4.85	32.62
135	0.25	10	M2.8	12.23 ± 1.03	7.56 ± 1.43	4.67	38.22
150	0.35	15	M2.9	12.76 ± 0.82	5.98 ± 1.70	6.78	53.15
150	0.35	15	M2.10	12.95 ± 1.56	7.57 ± 1.05	5.38	41.57
150	0.35	15	M2.11	13.61 ± 2.60	7.43 ± 1.97	6.18	45.39
150	0.35	15	M2.12	13.44 ± 2.76	6.55 ± 0.88	6.89	51.27

150	0.35	15	M2.13	12.23 ± 1.76	8.82 ± 0.90	3.40	27.83
150	0.35	15	M2.14	11.30 ± 1.30	6.75 ± 2.41	4.55	40.24
175	0.35	15	M2.15	15.98 ± 1.09	12.92 ± 3.44	3.06	20.42
125	0.35	15	M2.16	12.42 ± 0.82	6.27 ± 2.71	6.14	49.47
150	0.52	15	M2.17	12.32 ± 1.15	8.44 ± 1.43	3.88	31.47
150	0.18	15	M2.18	11.50 ± 0.84	7.66 ± 1.02	3.84	33.43
150	0.35	24	M2.19	11.45 ± 1.67	7.44 ± 1.81	4.01	35.05
150	0.35	6	M2.20	12.40 ± 1.72	8.98 ± 1.30	3.42	27.57

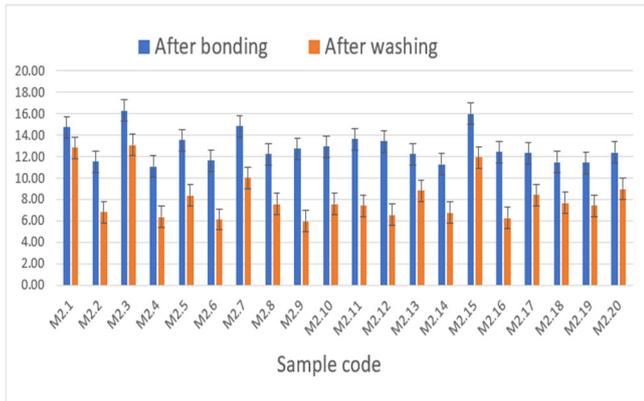


Figure 3. Peel strength comparison of M2 film after bonding and after washing

According to the technical requirements of sportswear brands, the minimum peel strength required is 13.34N/cm for both after bonding and after washing conditions to ensure the durability and reliability of zipper bonds during actual use in athletic apparel. For M1 film, the experimental results showed that several technological conditions achieved peel strength after bonding (Y_1) reaching and exceeding the threshold of 13.34N/cm, particularly at combinations of medium-to-high temperature and pressure parameters. This demonstrates that M1 film has the capability to form good initial bonds with the coated fabric and zipper. However, not all experimental conditions met this standard, indicating that the peel strength after bonding of M1 film still strongly depends on the technological parameters. After washing, only a few M1 film maintained peel strength ≥ 13.34 N/cm, while most of the remaining samples decreased below the required threshold. Nevertheless, compared with M2 film, M1 film exhibited better capability in maintaining peel strength after washing, with a lower average reduction and several conditions giving post-washing values approaching the standard. This indicates that M1 film has the potential to meet actual use requirements if properly optimized in terms of temperature, pressure, and bonding time.

For M2 film, the results indicated that most peel strength values after bonding (Y_3) only approached or were lower than 13.34N/cm, and only a very small number of conditions achieved the required threshold. After washing, the majority of M2 film showed peel strength significantly lower than the standard, with large reductions, exceeding 40 - 50% in many cases. This suggests that the bonds of M2 film may fail to meet the long-term durability requirements under washing conditions, even when the initial bond strength is at an acceptable level.

3.2. The influence of washing on the peel strength of the M1 film

According to the data in Table 5, the washing process had a significant influence on the peel strength of the bond between M1 film and the waterproof fabric. In general, the peel strength after washing (Y_2) decreased compared with after bonding (Y_1) for most experimental conditions. Specifically, among the 20 experimental conditions, only one sample (M1.15) recorded a slight increase in peel strength after washing compared with after bonding, with an increase of 0.59N/cm (equivalent to 3.69%). In addition, some samples such as M1.1, M1.3, and M1.19 showed small reductions, below 1.5N/cm (equivalent to less than 10%), indicating relatively stable bonds after washing under these technological conditions. For the majority of the remaining samples, the peel strength after washing decreased significantly. The reductions ranged from 0.83N/cm (5.74%) in sample M1.3 to 7.34N/cm (56.71%) in sample M1.12, demonstrating the clear adverse effect of the washing process on the bond strength under these technological conditions. At the center point condition ($X_1 = 165^\circ\text{C}$, $X_2 = 0.35\text{MPa}$, $X_3 = 25\text{s}$), the replicate samples M1.9 to M1.14 showed reductions in peel strength after washing ranging from 26.04% to 56.71%, reflecting relatively large variability in the experimental results, even when applying the same set of technological parameters. This indicates that the peel strength after washing depends not only on the bonding technological parameters but is also influenced by other factors such as the distribution of the adhesive film, the degree of surface wetting, and the microstructure of the bonded region.

Overall, the results indicated that the washing process caused significant degradation in the peel strength of the M1 film, with typical reductions in the range of 8 - 56%. Therefore, evaluating and optimizing peel strength after washing is especially necessary to ensure the durability and reliability of waterproof products during actual use.

3.3. The influence of washing on the peel strength of the M2 film

Also according to the data presented in Table 6, it can be observed that the washing process caused a significant and adverse influence on the peel strength of the bond between M2 film and the waterproof fabric. Across all 20 experimental conditions, all samples recorded reductions in peel strength after washing (Y_4) compared with after bonding (Y_3), indicating that the bonds of M2 film are less stable when subjected to washing cycles. Specifically, the reductions in peel strength of M2 film ranged over a relatively wide range, from 1.89N/cm (12.81%) in sample M2.1 to 2.89N/cm (51.27%) in sample M2.12. The majority of samples showed reductions exceeding 30%, reflecting the significant impact of the washing process on the adhesion capability of the bonds. In particular, samples M2.6, M2.9, M2.11, M2.12, and M2.16 recorded very large reductions, ranging from 45% to over 53%, indicating that the bond strength was severely weakened after washing under the corresponding technological conditions.

At the center point condition ($X_1 = 150^\circ\text{C}$, $X_2 = 0.35\text{MPa}$, $X_3 = 15\text{s}$), the replicate samples M2.9 to M2.14 exhibited reductions in peel strength after washing in the range of 27.83% to 53.15%. The high degree of variability in the results under the same set of technological parameters suggests that the stability of M2 film after washing remains limited, while simultaneously reflecting the sensitivity of this material system to the impacts of water, heat, and detergent chemicals.

Overall, the results indicated that M2 film experienced more pronounced adverse effects from the washing process compared with M1 film, with typical reductions in peel strength in the range of 20 - 50%. Therefore, for M2 film, the evaluation and optimization of peel strength after washing are especially critical to ensure the durability and reliability of waterproof products during actual use.

3.4. The influence of temperature, pressure and time on the peel strength

The experimental data were processed using Design Expert software, resulting in mathematical models describing the relationship between the three technological parameters and the peel strength after bonding Y_1 and the peel strength after washing Y_2 of M1 film, which were developed as follows:

$$Y_1 = 11.99 + 3.29X_1 + 0.25X_2 + 2.69X_3 + 1.72X_1X_2 + 1.15X_1X_3 + 0.09X_2X_3 + 0.93X_1^2 - 0.38X_2^2 - 0.72X_3^2 + 2.63X_1X_2X_3 + 2.37X_1^2X_2 - 0.35X_1^2X_3 + 2.34X_1X_2^2; R^2 = 0.9393 \quad (1)$$

$$Y_2 = 6.12 + 5.91X_1 + 2.48X_2 + 3.11X_3 + 0.97X_1X_2 + 4.39X_1X_3 + 1.26X_2X_3 + 4.65X_1^2 + 1.57X_2^2 + 1.27X_3^2 - 4.31X_1X_2X_3 - 1.53X_1^2X_2 + 5.81X_1^2X_3 - 2.08X_1X_2^2; R^2 = 0.9763 \quad (2)$$

The statistical significance of regression models 1 and 2 was evaluated according to Fisher's criterion. The results showed that the calculated Fisher values (F_{est}) of the regression models were all lower than the tabulated Fisher value (F_{tab}) at the significance level of 0.05. Specifically, for Y_1 , $F_{est} = 0.743 < F_{tab} = 5.050$ ($\alpha = 0.05$); for Y_2 , $F_{est} = 1.019 < F_{tab} = 5.050$ ($\alpha = 0.05$). This confirms that the developed second-order mathematical models are suitable and statistically significant, and are appropriate for analyzing the influence of temperature, pressure and time on the peel strength of the zipper after bonding and after washing. The correlation coefficients of the obtained regression models are all greater than 0.94, demonstrating the strong correlation between the peel strength of the zipper and the three investigated technological parameters.

Similar to M1 film, for the M2 film, mathematical models describing the relationship between the three technological parameters and the peel strength after bonding Y_3 and the peel strength after washing Y_4 were developed, as follows:

$$Y_3 = 13.14 + 3.00X_1 + 0.09X_2 - 0.09X_3 - 2.59X_1X_2 + 2.82X_1X_3 + 0.14X_2X_3 + 2.59X_1^2 + 0.02X_2^2 - 0.52X_3^2 - 0.98X_1X_2X_3 - 4.27X_1^2X_2 + 3.21X_1^2X_3 + 3.15X_1X_2^2; R^2 = 0.8988 \quad (3)$$

$$Y_4 = 7.83 + 4.35X_1 + 0.41X_2 - 0.11X_3 - 0.20X_1X_2 + 5.16X_1X_3 + 2.31X_2X_3 + 2.88X_1^2 + 1.15X_2^2 + 1.10X_3^2 + 1.29X_1X_2X_3 - 2.15X_1^2X_2 + 7.49X_1^2X_3 + 1.22X_1X_2^2; R^2 = 0.9308 \quad (4)$$

The statistical significance of regression models 3 and 4 was also evaluated according to Fisher's criterion. The results showed that the calculated Fisher values (F_{est}) of the regression models were all lower than the tabulated Fisher value (F_{tab}) at the significance level of 0.05. Specifically, for Y_3 , $F_{est} = 1.13 < F_{tab} = 5.050$ ($\alpha = 0.05$); for Y_4 , $F_{est} = 3.66 < F_{tab} = 5.050$ ($\alpha = 0.05$). This confirms that the developed second-order mathematical models

Table 7. Test results of M1 and M2 films using optimal technological parameters

TPU films	After bonding, experimental results	After bonding, calculated according	Difference		After washing, experimental results	After washing, calculated according	Difference	
			N/cm	%			N/cm	%
M1	18.53±1.92	19.82	-1.29	-6.98	16.55±1.78	17.22	-0.67	-4.06
M2	17.77±2.06	17.467	0.30	1.71	14.97±2.19	15.452	-0.48	-3.22

are suitable and statistically significant, and are appropriate for analyzing the influence of temperature, pressure and time on the peel strength of the zipper after bonding and after washing. The correlation coefficients of regression models 3 and 4 are all greater than 0.9, demonstrating the strong correlation between the peel strength of the zipper and the three investigated technological parameters.

Based on the obtained mathematical models, we determined the optimal technological parameters to ensure the best peel strength after bonding and the best peel strength after washing of M1 film and M2 film. Specifically:

- (i) Y_1 reached 19.82N/cm at a bonding temperature of 176°C, a bonding pressure of 0.45MPa, and a pressing time of 29 s;
- (ii) Y_2 reached 17.22N/cm at a bonding temperature of 179°C, a bonding pressure of 0.49MPa, and a pressing time of 24s;
- (iii) Y_3 reached 17.47N/cm at a bonding temperature of 178°C, a bonding pressure of 0.30MPa, and a pressing time of 13s;
- (iv) Y_4 reached 15.45N/cm at a bonding temperature of 170°C, a bonding pressure of 0.28MPa, and a pressing time of 23s.

All peel strength values after bonding and after washing obtained for both TPU films reached a minimum of 15.45N/cm, considerably higher (achieving 115.82%) than the requirement for zipper bond strength of many sportswear brands, which is 13.34N/cm. In actual production and product use, the peel strength of the zipper after washing is of greater concern because it directly determines the functional quality of the product. Therefore, priority should be given to selecting the optimal solution to maximize the peel strength of the zipper after washing, specifically the optimal values of Y_2 and Y_4 .

3.5. Verification and explanation of optimal results

The M1 and M2 films were used to bond the zipper to the coated fabric using the optimal technological parameters determined to achieve the highest peel

strength after washing. Specifically, the M1 film was bonded at a temperature of 179°C, a pressure of 0.49MPa, and a pressing time of 24s; while the M2 film was bonded at a temperature of 170°C, a pressure of 0.28MPa, and a pressing time of 23s. The peel strength test results of the obtained specimens are presented in Table 7.

According to the data in Table 7, the experimental peel strength of adhesive M1 film showed good agreement with the values predicted by mathematical models (1) and (2). The difference between the experimental values and the calculated values did not exceed 7%, and the peel strength after washing was quite high, reaching 124.07% compared with the requirement of 13.34N/cm. The peel strength of M2 film gave satisfactory results, with the difference between the experimental values and the values predicted by mathematical models (3) and (4) not exceeding 3.22%. In addition, the standard deviation of the experimental results for both TPU films was relatively small, especially for M1 film, indicating good stability and reliability of the obtained mathematical models.

The high peel strength of the zipper bonds with the waterproof fabric using two types of TPU films can be explained through the SEM images of the cross-sections of the zipper bonds shown in Figures 4 and 5.

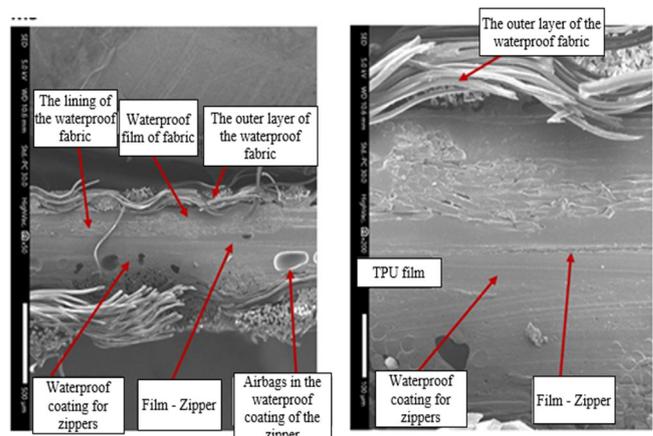


Figure 4. SEM image showing the overall cross-section of specimen M1: (a) the distribution of adhesive film; (b) produced under optimal technological parameters

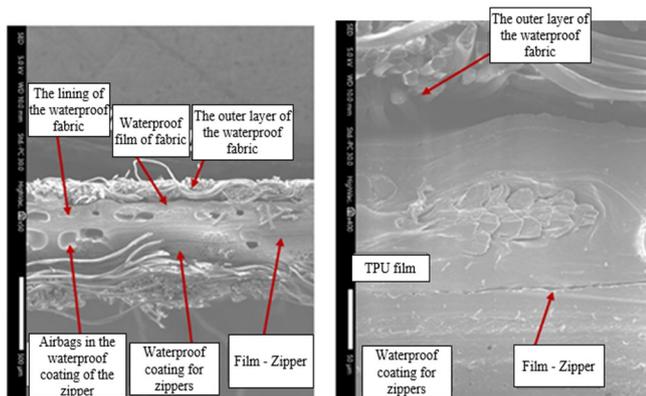


Figure 5. SEM image showing the overall cross-section of specimen M2: (a) the distribution of adhesive film; (b) produced under optimal technological parameters

The SEM images of specimens M1 and M2 produced under the optimal technological parameters (Figures 5 and 6) show that well-formed bond structures were achieved. At high temperatures, the adhesive film melts thoroughly, and under the application of high pressure, the adhesive penetrates deeply into the material (the back fabric layer) and bonds with both the adhesive layer (the middle layer) that joins the fabric layers of the waterproof fabric. The molten adhesive film also bonds well with the waterproof coating layer of the zipper. As a result, tight bonds are formed, with fabric fibers integrated into the adhesive layer and no visible gaps between the fibers and the adhesive film. This structural integrity explains the high peel strength observed experimentally between the zipper strip and the coated fabric.

3.6. Comparison of the two types of TPU films

The research results indicated that both M1 and M2 film exhibited high peel strength after bonding and after washing when technological parameters were optimized. However, notable differences remain between the two TPU films regarding adhesion capability and after washing stability. For M1 film, both peel strength values after bonding (Y_1) and after washing (Y_2) reached high levels, showing good adhesion with the waterproof fabric and stable bond structure under washing conditions. Notably, the Y_2 value is relatively close to Y_1 , confirming that M1 film maintains good adhesion strength after water exposure and washing, making it suitable for products demanding long-term durability. In contrast, M2 film also achieved high peel strength after bonding (Y_3); nevertheless, the peel strength after washing (Y_4) is lower than that of M1 film. This suggests that the bond stability of M2 film under humid conditions and washing is inferior, resulting in considerable reduction in peel strength after washing.

Overall comparison shows that, although both adhesives meet the requirements for peel strength after bonding, M1 film demonstrates a clear advantage in terms of strength after washing, which is a critical factor determining the quality and durability of the product under actual use conditions. Therefore, M1 film is considered more suitable for applications requiring wash resistance and long-term stability, while M2 film may be appropriate for applications with less exposure to water or washing cycles.

4. CONCLUSIONS

The washing process has a significant impact on the peel strength of zippers bonded to waterproof coated fabrics using TPU adhesive film. Therefore, this factor must be carefully considered when establishing the technological parameters for the zipper bonding process. In this study, factors such as temperature, time, and pressure were demonstrated to affect the adhesion strength of both TPU adhesive film samples through second-order mathematical models. The obtained mathematical models all showed statistical significance and high adequacy. The results indicated that temperature is the dominant factor, while pressure and pressing time play supporting roles in ensuring effective melting and penetration of the adhesive film into the fabric fiber structure. The optimal technological parameters were determined for the two TPU film to achieve the highest peel strength after bonding and after washing. The obtained peel strength values were all higher than the minimum requirement of 13.34N/cm for sportswear applications. Results from practical testing and SEM analysis confirm that the developed mathematical models and optimized technological solutions can be effectively applied in industrial production. Adhesive M1 film demonstrated better capability to maintain peel strength after washing compared with adhesive M2 film. Therefore, for manufacturing waterproof garments from the zipper sample and coated fabric used in this study, adhesive film M1 should be used to enhance product quality.

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