RESEARCH ON TECHNOLOGICAL FACTORS AFFECTING THE PEEL STRENGTH OF ZIPPERS

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ABSTRACT. Thermoplastic adhesive bonding technology is widely used to attach zippers in the production of waterproof clothing, footwear, and leather goods, particularly waterproof sportswear. The durability of zipper bonds during use is critical to the overall quality of waterproof products. Numerous factors influence the durability of zipper bonds with waterproof materials, including the properties of the zipper tape material, the type of waterproof material, the type of adhesive, surface preparation, and bonding process parameters. In this study, an orthogonal experimental design was employed to investigate the effects of technological parameters, including temperature, bonding time, and pressure on the peel strength of two zipper samples bonded to waterproof-coated fabrics using thermoplastic polyurethane adhesive films. The peel strength of the zipper–fabric bonds was measured both after bonding and after 20 washing cycles. Using Design Expert statistical software, we analyzed the experimental data and developed mathematical models describing the relationships between the three process parameters and the peel strength of each zipper sample before and after washing. Based on these models, the optimal temperature, time, and pressure conditions were determined to ensure high peel strength of zippers bonded to waterproof-coated fabrics. 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.
KEY WORDS: zipper, zipper bonding technology, zipper peel strength

CERCETĂRI PRIVIND FACTORII TEHNOLOGICI CARE AFECTEAZĂ REZISTENȚA LA DESPRINDERE A FERMOARELOR

REZUMAT. Tehnologia de lipire cu adeziv termoplastic este utilizată pe scară largă pentru atașarea fermoarelor în producția de îmbrăcăminte, încălțăminte și articole din piele impermeabile, în special îmbrăcăminte sport impermeabilă. Durabilitatea lipirii fermoarelor în timpul utilizării este esențială pentru calitatea generală a produselor impermeabile. Numeroși factori influențează durabilitatea lipirii fermoarelor cu materiale impermeabile, inclusiv proprietățile materialului folosit la banda fermoarului, tipul de material impermeabil, tipul de adeziv, pregătirea suprafeței și parametrii procesului de lipire. În acest studiu, s-a utilizat un design experimental ortogonal pentru a investiga efectele parametrilor tehnologici, inclusiv temperatura, timpul de lipire și presiunea, asupra rezistenței la desprindere a două mostre de fermoare lipite pe țesături impermeabile folosind pelicule adezive poliuretanice termoplastice. S-a măsurat rezistența la desprindere a lipirii fermoar-țesătură atât după lipire, cât și după 20 de cicluri de spălare. Folosind software-ul statistic Design Expert, s-au analizat datele experimentale și s-au dezvoltat modele matematice care descriu relațiile dintre cei trei parametri ai procesului, precum și rezistența la desprindere a fiecărei mostre de fermoar înainte și după spălare. Pe baza acestor modele, s-au determinat condițiile optime de temperatură, timp și presiune pentru a asigura o rezistență ridicată la dezlipire a fermoarelor lipite pe țesături impermeabile. Rezultatele acestui studiu oferă o bază pentru cercetări ulterioare privind tehnologiile de aderență a fermoarelor la diferite materiale pentru a îmbunătăți calitatea produselor impermeabile.
CUVINTE CHEIE: fermoar, tehnologie de lipire a fermoarelor, rezistență la desprindere a fermoarelor

RECHERCHE SUR LES FACTEURS TECHNOLOGIQUES INFLUENÇANT LA RÉSISTANCE AU PELAGE DES FERMETURES À GLISSIÈRE

RÉSUMÉ. La technologie de collage thermoplastique est largement utilisée pour la fixation des fermetures à glissière dans la production de vêtements, de chaussures et d'articles en cuir imperméables, notamment les vêtements de sport imperméables. La durabilité du collage de la fermeture à glissière en cours d'utilisation est essentielle à la qualité globale des produits imperméables. De nombreux facteurs influencent cette durabilité, notamment les propriétés du ruban de la fermeture à glissière, le type de matériau imperméable, le type d'adhésif, la préparation de surface et les paramètres du processus de collage. Dans cette étude, un plan d'expériences orthogonal a été utilisé pour étudier les effets des paramètres technologiques, tels que la température, le temps de collage et la pression, sur la résistance au pelage de deux échantillons de fermeture à glissière collés à des tissus imperméables à l'aide de films adhésifs en polyuréthane thermoplastique. La résistance au pelage du collage fermeture à glissière-tissu a été mesurée immédiatement après le collage et après 20 cycles de lavage. À l'aide du logiciel statistique Design Expert, les données expérimentales ont été analysées et des modèles mathématiques ont été développés pour décrire les relations entre les trois paramètres du processus, ainsi que la résistance au pelage de chaque échantillon de fermeture à glissière avant et après lavage. À partir de ces modèles, les conditions optimales de température, de durée et de pression ont été déterminées afin de garantir une résistance au pelage élevée des fermetures à glissière collées sur des tissus imperméables. Les résultats de cette étude constituent une base pour des recherches ultérieures sur les technologies d'adhésion des fermetures à glissière à différents matériaux, dans le but d'améliorer la qualité des produits imperméables.
MOTS-CLÉS : fermeture à glissière, technologie de collage des fermetures à glissière, résistance au pelage des fermetures à glissière

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INTRODUCTION

Zippers are essential accessories widely used in products such as clothing, footwear, handbags, backpacks, suitcases, and many other everyday applications. They allow products to be opened and closed quickly and conveniently, replacing traditional fastening methods such as buttons or laces, thereby enhancing user convenience [1]. In addition, for products such as protective clothing, waterproof footwear, tents, or technical garments, zippers ensure the necessary sealing performance to protect users from external factors such as water, dust, or chemicals. As a result, they contribute significantly to product protection, safety, and functionality [2, 3]. During product use, particularly during washing, zippers are subjected to substantial mechanical and environmental impacts [4]. The adhesion strength between the zipper and the material surface is a key factor influencing both product quality and durability. In waterproof products, zippers are typically bonded rather than sewn. Therefore, if the adhesive layer between the zipper and the material is insufficiently strong, peeling may occur, leading to reduced product functionality and diminished user experience [3].

In recent years, advances in materials science and the increasing use of coated and laminated fabrics in functional apparel have promoted the widespread adoption and development of zipper bonding technologies. However, several challenges remain, including bonding along deep curves, ensuring elasticity and flexibility at seam regions, and overcoming material incompatibility issues [5]. When evaluating the quality of zipper bonding in products, properties such as tensile strength, peel strength, appearance, elasticity, and air permeability are commonly assessed [3, 6]. To date, several studies have investigated the influence of technological parameters on the peel strength of bonded components [7–11]. Maryna Yatsenko *et al.* developed mathematical models describing the relationships between roller temperature, bonding time, and roller pressure on the adhesion strength of leather. In this study, the leather surfaces were treated with different chemicals, and a heat-sensitive adhesive was used to bond the leather layers. The authors identified the optimal bonding parameters for each type of surface treatment [7]. The study conducted by Gerda Mikalauskaite *et al.* examined the influence of peel speed on the peel strength of adhesive joints and on the seam strength of knitted and woven fabrics made from polyamide and polyester. Three types of single-layer thermoplastic polyurethane films were used to bond the fabric samples. The results indicated that peel speed had a significant effect on the peel strength of the adhesive joints, while it had no influence on seam strength [8]. Živilė Jakubčionienė *et al.* investigated the bond strength of four different types of woven, knitted, and laminated fabrics to determine the most suitable bonding method for each fabric type. The fabric layers were bonded using a thermoplastic polyurethane film at a temperature of 180 °C and a pressing time of 30 s [9]. The effect of temperature on the structure of polyester/elastane knitted materials and their adhesive peel strength was evaluated in the study by Virginija Daukantienė *et al.* The authors found that 150°C was the optimal bonding temperature for most of the textiles examined [10]. Gita Busilienė *et al.* investigated the spatial behavior of knitted fabrics composed of 93% polyester and 7% elastane. The fabrics were bonded using two TPU films with thicknesses of 75 µm and 150 µm. The results showed that the changes occurring before and after cyclic fatigue loading were mainly determined by the type of thermoplastic film, while the orientation of the knitted fabric pieces in the bonded seam had no significant effect [11]. In addition, several authors have examined the influence of technological parameters on the bond strength between interlining and fabric in garment production [12–14].

Overall, the above-mentioned studies focus on the technological factors affecting the bonding of textile materials. Fabrics and waterproof coated fabrics are commonly bonded using the thermoforming method with TPU films [8–11]. However, to date, no research has been conducted on the influence of technological parameters on the peel strength of zippers bonded to waterproof coated fabrics.

In this study, we investigated the influence of technological parameters, including temperature, time, and pressure on the peel strength of two zipper samples bonded to waterproof coated fabrics using thermoplastic polyurethane adhesive film. An orthogonal experimental design was employed to establish the testing plan. The peel strength of the bonded zippers was measured both immediately after bonding and after 20 washing cycles. Experimental data were processed using Design Expert statistical software to develop mathematical models describing the relationship between the three technological parameters and the peel strength of each zipper sample in both testing conditions. Based on these models, the optimal bonding temperature, time, and pressure were determined to achieve the highest peel strength. The results provide a scientific basis for improving zipper bonding technology and enhancing the quality of waterproof products.

EXPERIMENTAL

Materials

In this study, the experimental materials consisted of waterproof coated fabric, TPU adhesive film, and two types of zippers. The specifications of the zippers, adhesive film, and fabric are provided in Tables 1, 2, and 3.

Table 1: Characteristics of types of zippers

No.	Characteristics	Value
1	Material composition	Polyester*
2	Weave type	Woven
3	Warp density	337 yarns/10 cm
4	Weft density	137 yarns/10 cm
5	Weight	213.5 g/m^2
6	Thickness	0.2 mm
7	Zipper teeth width	3 mm
8	Teeth density	9 teeth/1 cm
9	Origin	SBS Company, China
10	Code	M1

** The second type of zipper is impregnated with waterproof PU resin (Coded M2).*

Table 2: Characteristics of adhesive film

No.	Characteristics	Value
1	Material	Thermoplastic polyurethane (TPU)
2	Weight	31 g/m^2
3	Thickness	25 µm
4	Melting point	110°C–140°C
5	Origin	Youyi Company, China

Table 3: Characteristics of waterproof fabric

No.	Characteristics	Value
1	Material	100% polyester
2	Weave type	Woven plain
3	Warp density	310 yarns/10 cm
4	Weft density	310 yarns/10 cm
5	Waterproof coating	Polyurethane
6	Weight	138 g/m^2
7	Origin	Maxport Company, Vietnam

Methods and Equipment

To design the experiment, we applied an orthogonal experimental planning method with three input variables: temperature (coded as X_1), pressure (coded as X_2), and time (coded as X_3). The two output variables were the zipper peel strength after bonding (coded as Y_1 for sample M1 and Y_3 for sample M2), and the zipper peel strength after 20 washing cycles (coded as Y_2 for sample M1 and Y_4 for sample M2). Based on (i) the findings from the literature review on the physical and mechanical properties of the adhesive film used, and (ii) the reference thermoplastic bonding technologies currently applied in several garment manufacturing factories, we established the variation ranges of the technological parameters and coded them as shown in Table 4.

Table 4: Table of coded technological parameters

Factor Code	Variability levels				
	-1.68	-1	0	+1	+1.68
X_1-Temperature (°C)	108	115	125	135	142
X_2-Pressure (MPa)	0.18	0.25	0.35	0.45	0.52
X_3-Time (s)	13	18	25	32	37

According to this experimental design, the total number of experiments (N) is calculated using the formula:

$$N = 2^K + n_0 + 2K, \quad (1)$$

where K is the number of input factors studied (K = 3, including X_1, X_2, and X_3), and n_0 is the number of center-point experiments (n_0 = 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 samples were cut to a length of 20 cm, while the adhesive film was cut to 15 cm. 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.

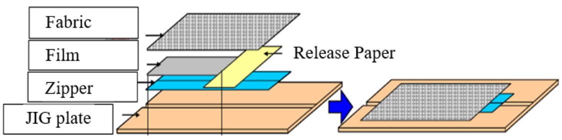

Figure 1. Test specimen preparation specifications

The peel strength of the zipper bonds was tested using a tensile testing machine in accordance with ISO 17708:2018. During testing, the free ends of the zipper and the coated fabric were clamped in the upper and lower grips of the machine. The specimens were peeled at a constant speed of 100 mm/min under room temperature conditions. The peel strength, Y (N/cm), was calculated using the formula:

$$Y = \frac{F}{A} \quad (2)$$

where F is the average peeling force (N), obtained from the recorded force–displacement curve, and A is the average width of the test specimen (cm).

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 samples 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.

RESULTS AND DISCUSSIONS

The peel strength results of the two zipper samples after bonding and after 20 washing cycles are presented in Table 5 and illustrated in Figures 2 and 3.

Table 5: Experimental results of peel strength of two zipper samples after bonding and after washing

Factors			Zipper M1					Zipper M2				
			Sample code	Peel strength, N/cm		Difference between Y_1 and Y_2		Sample code	Peel strength, N/cm		Difference between Y_3 and Y_4	
X_1 (°C)	X_2 (MPa)	X_3 (s)		Y_1	Y_2	N/cm	%		Y_3	Y_4	N/cm	%
135	0.45	32	M1.1	14.02±1.56	11.02±0.53	3.00	21.40	M2.1	11.39±0.34	10.95±2.18	0.44	3.86
115	0.45	32	M1.2	10.51±2.78	9.94±0.67	0.58	5.52	M2.2	9.65±0.69	8.24±1.77	1.41	14.61
135	0.25	32	M1.3	11.76±1.46	9.57±2.12	2.19	18.62	M2.3	10.44±0.91	8.99±1.5	1.45	13.89
115	0.25	32	M1.4	10.38±1.92	8.83±0.89	1.55	14.93	M2.4	9.10±0.16	6.43±1.06	2.67	29.34
135	0.45	18	M1.5	13.02±0.39	10.83±0.60	2.18	16.74	M2.5	11.36±1.22	11.18±0.10	0.18	1.58
115	0.45	18	M1.6	10.74±0.97	11.14±0.89	-0.40	-3.72	M2.6	9.12±2.27	7.61±1.03	1.50	16.45
135	0.25	18	M1.7	14.60±1.64	14.14±1.01	0.46	3.15	M2.7	11.00±1.41	10.96±1.32	0.03	0.27
115	0.25	18	M1.8	8.03±1.06	7.19±1.75	0.84	10.46	M2.8	8.84 ±4.32	4.34±2.09	4.51	51.02
125	0.35	25	M1.9	12.90±0.74	12.25±1.04	0.67	5.19	M2.9	10.24±1.58	9.73±1.26	0.52	5.08
125	0.35	25	M1.10	12.52±1.9	9.98±1.13	2.54	20.29	M2.10	12.19±0.43	9.34±1.42	2.85	23.38
125	0.35	25	M1.11	11.12±1.21	10.41±1.31	0.72	6.47	M2.11	11.07±0.64	9.48±1.41	1.60	14.45
125	0.35	25	M1.12	11.73±2.93	11.73±1.76	0.00	-0.09	M2.12	9.56±1.1	6.91±1.41	2.66	27.82
125	0.35	25	M1.13	10.44±0.84	9.49±1.61	0.95	9.10	M2.13	8.56±0.46	6.93±0.90	1.64	19.16
125	0.35	25	M1.14	11.10±0.54	8.41±1.02	2.69	24.23	M2.14	15.08±1.5	14.73±0.52	0.36	2.39
142	0.35	25	M1.15	17.30±0.62	13.11±0.87	4.18	24.16	M2.15	11.43±0.26	11.43±1.81	0.00	0.00
108	0.35	25	M1.16	10.25±0.87	10.11±1.31	0.14	1.37	M2.16	10.99±1.3	9.00±0.65	1.99	18.11
125	0.52	25	M1.17	13.47±0.76	11.10±0.33	2.36	17.52	M2.17	11.81±1.71	12.33±1.62	-0.52	-4.40
125	0.18	25	M1.18	6.13±2.22	6.71±1.86	-0.58	-9.46	M2.18	7.32±1.59	5.64±0.62	1.68	22.95
125	0.35	37	M1.19	14.93±1.6	14.73±1.04	0.20	1.34	M2.19	11.36±0.7	9.16±0.94	2.20	19.37
125	0.35	13	M1.20	8.97±1.38	9.25±1.43	-0.27	-3.01	M2.20	6.91±1.42	6.09±1.26	0.82	11.87

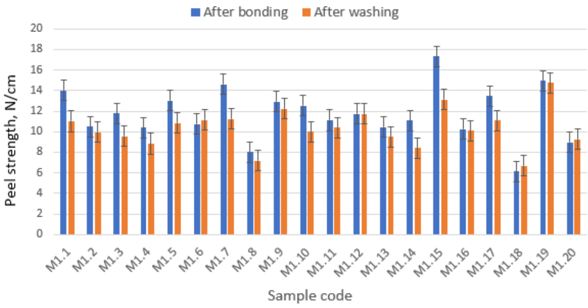

Figure 2. Peel strength graph after bonding and after washing of M1 zipper

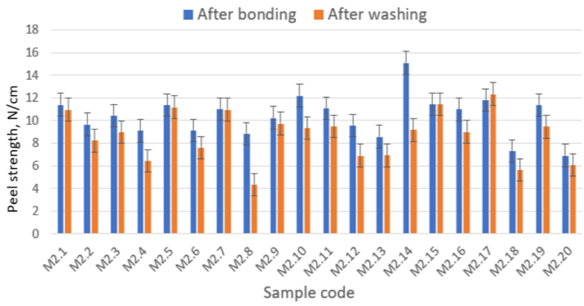

Figure 3. Peel strength graph after bonding and after washing of M2 zipper

According to the data in Table 5, there is a statistically significant difference in the peel strength after bonding and after washing between the two zipper samples ($p < 0.05$, *p(two-tailed)* = 0.001 < 0.05). In both cases, sample M1 exhibited higher peel strength than sample M2. The average peel strength after bonding for sample M1 was 11.70 N/cm, compared with 10.37 N/cm for sample M2. Similarly, the average peel strength after washing for sample M1 was 10.50 N/cm, higher than the 9.00 N/cm recorded for sample M2. These results indicate that the waterproofing treatment of zippers with PU resin solution reduces the peel strength when the same bonding technological parameters are applied. The standard deviations of the peel strength measurements for both samples M1 and M2 were relatively high, reflecting considerable variability in the test results. Notably, the standard deviation of sample M2 was greater than that of sample M1, suggesting larger fluctuations in the peel strength values of the PU-treated zipper sample.

The Influence of Washing on the Peel Strength of Zipper

Also, according to the data presented in Table 5 and Figures 2 and 3, washing had a significant effect on reducing the peel strength of both zipper samples bonded with coated fabric ($p < 0.05$, *p(two-tailed)* = 0.000 < 0.05). For sample M1, only three test conditions—M1.6, M1.18, and M1.20—showed an increase in peel strength after washing, and even then, the increase was small, less than 0.6 N/cm (equivalent to 9.5%) compared with the values before washing. For the remaining M1 samples, the peel strength after washing decreased by values ranging from 1.4 N/cm (M1.16) to 4.18 N/cm (M1.15). The maximum reduction reached 24.4%, with an average decrease of 10.26% (Figure 2). Compared with sample M1, the reduction in peel strength due to washing was more pronounced for sample M2. The average decrease in peel strength of sample M2 was 13.45%. Only one test condition, M2.17, showed a slight increase in peel strength after washing (0.52 N/cm, equivalent to 4.40%). All other M2 specimens experienced reductions in peel strength, with changes ranging from negligible values up to 4.5 N/cm, and the maximum reduction reaching 51.02% (Figure 3).

Thus, when using the same TPU adhesive film to bond the same coated fabric with different types of zippers, the effect of washing on adhesion strength varied considerably. The M2 zipper sample, which had been impregnated with a waterproof PU resin, exhibited a greater reduction in peel strength compared with the M1 zipper sample. Overall, the adhesion strength between the zipper and the fabric decreased after washing cycles. Therefore, evaluating and optimizing peel strength after washing is essential to ensure the durability and quality of waterproof products during actual use.

The Influence of Temperature, Pressure and Time on the Peel Strength of Zipper M1

The experimental data processed using Design Expert software yielded mathematical models describing the relationship between the three technological parameters and the peel strength of the M1 zipper. These models were evaluated based on Fisher's criterion, where the calculated Fisher values (Fest) must be lower than the tabulated value (Ftab). The obtained results satisfied this condition, with Fest ranging from 1.734 to 3.462, which is less than Ftab = 4.0012. This confirms that the developed mathematical models are statistically significant and suitable for analyzing the influence of temperature, pressure, and time on zipper peel strength.

$Y_1 = 11.64 + 3.52X_1 + 3.67X_2 + 2.98X_3 - 0.78X_1X_2 – 1.44X_1X_3 + 0.45X_2X_3 + 2.01X_1^2 – 1.97X_2^2 + 0.18X_3^2 + 3.98X_1X_2X_3 – 8.44X_1^2X_2 – 8.44X_1^2X_3 – 1.75X_1X_2^2$ (1), $R^2 = 0.9628$.

$Y_2 = 10.39 + 1.50X_1 + 2.20X_2 + 2.74X_3 – 2.50X_1X_2 – 1.76X_1X_3 + 0.70X_2X_3 + 0.93X_1^2 – 1.77X_2^2 + 1.32X_3^2 + 4.71X_1X_2X_3 – 4.38X_1^2X_2 – 10.36X_1^2X_3 + 0.86X_1X_2^2$ (2), $R^2 = 0.8629$.

The equations indicate that all three factors (temperature, pressure, and time) affect the peel strength of the zipper both after bonding and after washing. An example of the relationship between the peel strength of zipper M1 after bonding and the technological parameters is illustrated by the 3D surface plots in Figures 4–6.

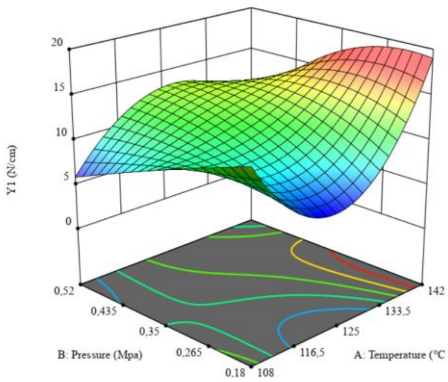

Figure 2. 3D plot illustrating the influence of temperature and pressure on the peel strength after bonding of the M1 zipper

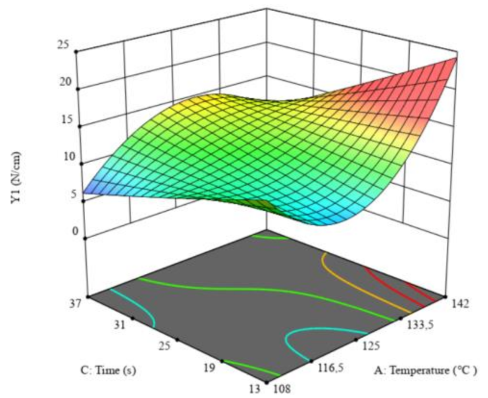

Figure 5. 3D plot illustrating the influence of temperature and time on the peel strength after bonding of the M1 zipper

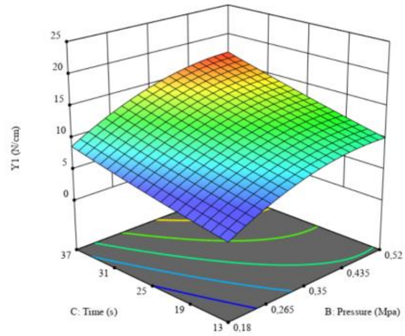

Figure 6. 3D plot illustrating the influence of pressure and time on the peel strength after bonding of the M1 zipper

Based on the obtained mathematical models, we determined the optimal technological parameters to ensure the peel strength of the M1 zipper bonded to the coated fabric. Specifically:

(i) Y_1 reaches 18.94 N/cm at a bonding temperature of 140 °C, a bonding pressure of 0.37 MPa, and a pressing time of 18 s; and

(ii) Y_2 reaches 17.65 N/cm at a bonding temperature of 140 °C, a bonding pressure of 0.35 MPa, and a pressing time of 16 s.

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 the optimal solution that maximizes the peel strength after washing.

The Influence of Temperature, Pressure and Time on the Peel Strength of Zipper M2

Similar to the M1 zipper, the experimental data for the M2 zipper were processed using Design Expert software, and mathematical models describing the relationship between the three technological parameters and the peel strength were established. The adequacy of the models was verified using Fisher's criterion, according to which the calculated values (Fest) must be lower than the tabulated value (Ftab). The obtained results satisfied this requirement, with Fest ranging from 0.765 to 3.334, all below Ftab = 4.0012.

$Y_3 = 11.11 + 0.22X_1 + 2.24X_2 + 2.23X_3 + 0.17X_1X_2 - 0.48X_1X_3 + 0.31X_2X_3 + 0.19X_1^2 - 1.45X_2^2 - 1.88X_3^2 + 0.19X_1X_2X_3 - 5.17X_1^2X_2 - 6.27X_1^2X_3 + 3.96X_1X_2^2$ (3), $R^2 = 0.5844$;

$Y_4 = 9.53 + 1.22X_1 + 3.34X_2 + 1.54X_3 - 1.05X_1X_2 - 1.79X_1X_3 + 0.10X_2X_3 + 0.49X_1^2 - 0.73X_2^2 - 2.09X_3^2 + 1.98X_1X_2X_3 - 5.21X_1^2X_2 - 4.11X_1^2X_3 + 5.98X_1X_2^2$ (4), $R^2 = 0.6638$.

The correlation coefficients of mathematical models 3 and 4 for the M2 zipper are lower than those of models 1 and 2 for the M1 zipper. This indicates a weaker relationship between the investigated technological parameters and the peel strength of the M2 zipper. This finding is consistent with the higher standard deviation observed in the peel strength results of the M2 samples compared with those of the M1 zipper (Table 5). An example of the relationship between the peel strength of the M2 zipper after bonding and the technological parameters is illustrated by the 3D plots shown in Figures 7–9.

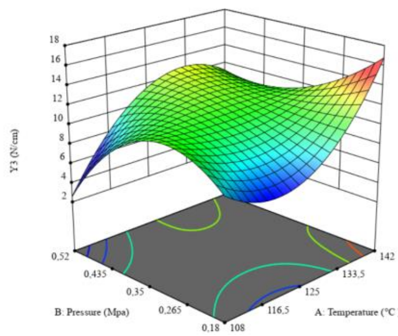

Figure 7. 3D plot illustrating the influence of temperature and pressure on the peel strength after bonding of the M2 zipper

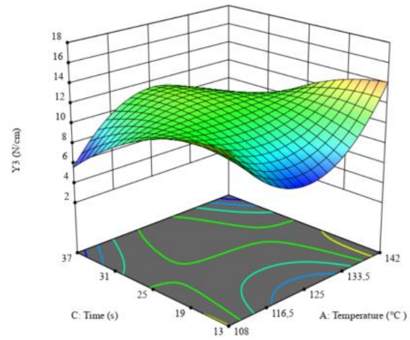

Figure 8. 3D plot illustrating the influence of temperature and time on the peel strength after bonding of the M2 zipper

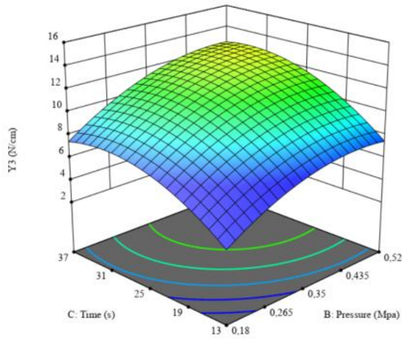

Figure 9. 3D plot illustrating the influence of pressure and time on the peel strength after bonding of the M2 zipper

Similar to sample M1, the optimal technological parameters for zipper M2 were identified to achieve the maximum peel strength after bonding and after washing. Specifically:

(i) Y_3 reached a maximum value of 18.66 N/cm at a temperature of 140 °C, a pressure of 0.18 MPa, and a bonding time of 16 s; and

(ii) Y_4 reached a maximum value of 18.32 N/cm at a temperature of 142 °C, a pressure of 0.21 MPa, and a bonding time of 20 s.

Verification and Explanation of Optimal Results

The M1 and M2 zippers were bonded to the coated fabric using TPU film under the optimal technological parameters determined to achieve the highest peel strength after washing. Specifically, the M1 zipper was bonded at a temperature of 140 °C, a pressure of 0.35 MPa, and a pressing time of 16 s; while the M2 zipper was bonded at a temperature of 142 °C, a pressure of 0.21 MPa, and a pressing time of 20 s. The peel strength test results of the obtained specimens are presented in Table 6.

Table 6: Test results of specimens made by optimal technological parameters

Zipper samples	Result (N/cm)							
	After bonding, experimental results	Calculated according to equations 1 and 3	Difference N/cm	Difference %	After washing, experimental results	Calculated according to equations 1 and 3	Difference N/cm	Difference %
M1	18.65±0.87	18.94	-0.29	1.55	18.38±0.86	17.65	0.73	3.98
M2	16.10±0.90	18.66	-2.56	15.88	15.92±1.02	18.32	-2.40	-15.08

According to the data in Table 6, the experimental peel strength of the M1 zipper shows good agreement with the values predicted by mathematical models (1) and (2). The difference between the experimental and calculated values does not exceed 4%, which is consistent with the high correlation coefficients of these models. The peel strength of the M2 zipper bonded to the fabric using the optimal technological parameters also gives satisfactory results; however, the difference between the experimental values and those predicted by mathematical models (3) and (4) reaches up to 16%. This corresponds to the lower correlation coefficients of models (3) and (4). Additionally, the standard deviation of the experimental results for both zipper samples is relatively small, especially for sample M1, indicating good stability and reliability of the measurements. These findings further confirm the positive effect of impregnating the zipper with PU resin solution on enhancing peel strength.

SEM cross-sectional images of the M1 zipper specimens produced under the optimal technological conditions, along with those of a specimen exhibiting poor peel strength (specimen M1.8 in Table 5), are presented in Figures 10–13.

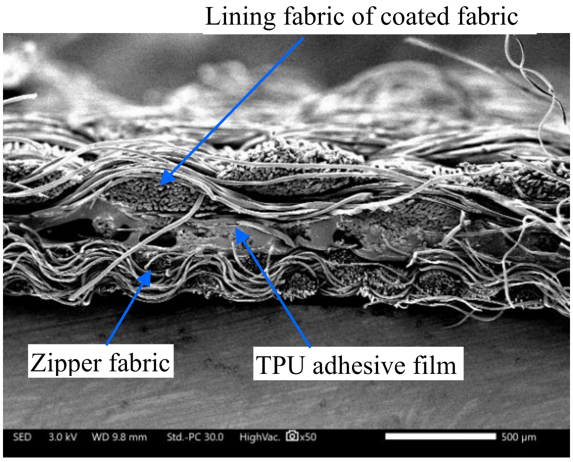

Figure 10. SEM image showing the overall cross-section of specimen M1.8 produced using suboptimal technological parameters

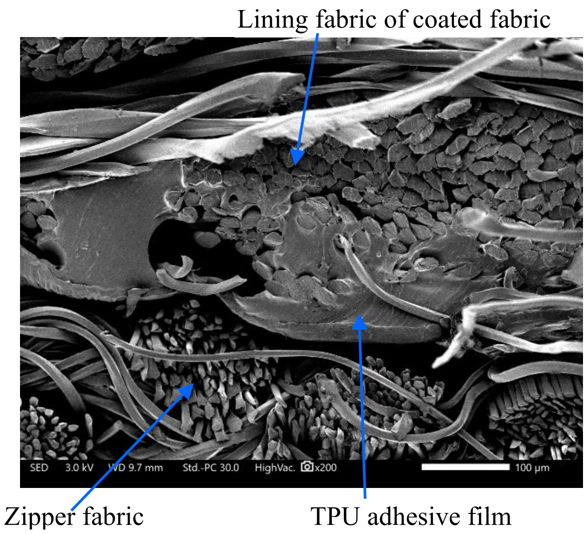

Figure 11. SEM image showing the distribution of adhesive film in specimen M1.8 produced using suboptimal technological parameters

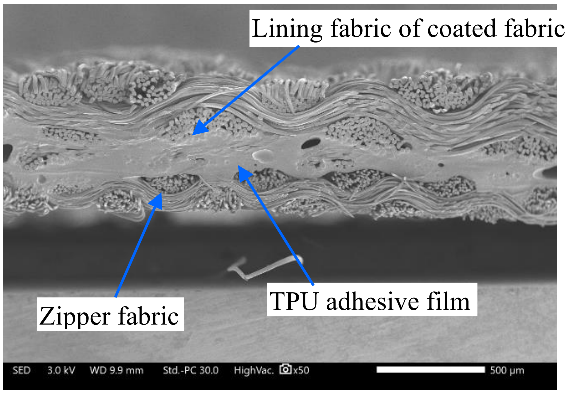

Figure 12. SEM image showing the overall cross-section of specimen M1 produced under optimized technological parameters

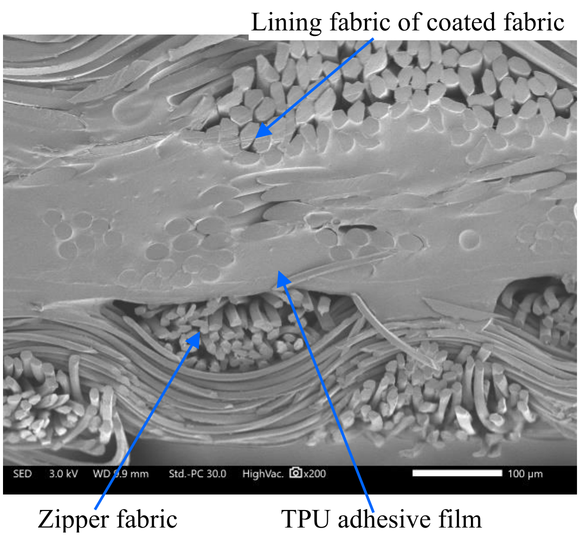

Figure 13. SEM image showing the distribution of adhesive film in specimen M1 produced under optimized technological parameters

The SEM images in Figures 10 and 11 show that in specimen M1.8 the bond structure is loose, with gaps present between the adhesive film and the fabric surface layers on both sides – the zipper and the waterproof fabric. The fabric fibers also appear to be separating, and gaps between the adhesive and fibers indicate poor adhesion. This poor bonding is primarily due to low temperatures and short pressing times, which prevent the hot-melt adhesive film from properly melting and penetrating the fabric fibers. Low pressure may also contribute to the loose bond, but temperature remains the dominant factor. These observations are consistent with the experimental results.

In contrast, the SEM images of specimen M1 produced under optimized technological parameters (Figures 12 and 13) show a well-formed bond. At higher temperatures, the hot-melt adhesive melts thoroughly, and the application of high pressure ensures deep penetration into the material, particularly into the fabric surface of the zipper strip. As a result, a tight bond is formed, with fabric fibers integrated into the adhesive 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.

CONCLUSIONS

The washing process has a significant impact on the peel strength of zippers bonded to waterproof coated fabrics using TPU adhesive film. Therefore, it must be carefully considered when establishing the technological parameters for zipper bonding. In this study, factors such as temperature, time, and pressure were shown to affect the adhesion strength of both zipper samples according to second-order mathematical models. The optimal bonding parameters determined here demonstrated high reliability, ensuring elevated peel strength of the zippers both immediately after bonding and after washing. The achieved peel strength values were approximately 1.4 times higher than the minimum requirement of 13.34 N/cm for sportswear applications. Results from practical testing and SEM analysis confirm that the developed mathematical models and optimized technological solutions can be applied in industrial production. These findings provide a solid foundation for further studies on the influence of technological parameters on the peel strength of zippers and materials in various types of waterproof products.

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