Investigation of the Influence of Bonding and Thermal Ageing Duration on the Peeling Strength of Knitted Materials' Bonds

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crossref http://dx.doi.org/10.5755/j01.ms.26.2.21666

Received 17 September 2018; accepted 27 January 2019

Bonding technology namely as "sew free" technology is usually applied for joining the pieces of sportswear and leisure clothing. Influence of the thermal ageing duration on the peeling strength of woven fabric and knitted materials bonded at 150°C temperature for 10 s, 20 s, 30 s, and 40 s durations with two polyurethane films of 0.175 mm and 0.127 mm thicknesses has been investigated in this research. Based on the research results it was shown that the peeling strength of the textile bonds is dependent on material type and bonding duration, but it is not highly affected by the ageing at 45°C temperature for 150 min, 300 min, and 450 min. During concluding it may be stated that ageing at 45°C temperatures is not main factor influencing the bond quality during its exploitation in high temperature environment.
Keywords: knitted material, bonding, strength, thermal ageing, polyurethane adhesive film, SEM.

1. INTRODUCTION

In recent years, bonding technology namely as "sew free" technology is being increasingly applied in sportswear and leisure wear engineering applications [1 – 4]. The pieces of clothing could be bonded together by using thermoplastic polyurethane adhesive films which are applied between two materials surfaces with the application of high temperature and pressure for certain time duration [1, 5]. It allows the elimination of sewing for many applications, including seams, hems, etc. as well as brings both economic and aesthetic benefits [6]. The advantages of bonds may be their lower thickness and friction [7, 8], and higher plasticity compared with sewn seams [9]. Bonds have the potential advantage of design flexibility and ease of fabrication [10]. Bonded garment typically weighs less than a sewn garment due to reason that only one clothing piece seam allowance instead of two ones used for seam stitching by thread is designed for the bond formation. Bonds are less permeable to air compared to the sewn seams [11]. Adhesive technology may be also applied to perform sealing functions ensuring the waterproofness of seams [12, 13].

Adhesive bonding is a physical-chemical process. Thermally activated thermoplastic adhesive softens, melts and fills the irregularities of textile surfaces or pores inside structure [12, 13]. The strong bond, which usually is even stronger than sewn seam, is formed after cooling [2, 9]. Bond quality depends on the materials anisotropy, tensile characteristics of thermoplastic films [3], bonding parameters, textile bearing surface and structure mobility [2, 3, 14] as well as on bond peeling velocity [15].

Increased interest of the bond application influences higher demand for information concerning their properties like bond strength. One of the most important parameters influencing bond strength is bonding temperature [16, 17]. From the other side, the consideration of temperature impact in respect to ageing problem during wear, e. g. in the tropic climate, also is important. The suppliers' recommendations will rarely indicate the influence of temperature on the strength of adhesive, the temperature range over which it can be used and the expected deterioration in the physical properties (rate of ageing) when used in particular environments [10]. The performance of adhesive bonds in footwear as well as in clothing may deteriorate in storage or in wear. Many textile fibres like polyester having a wide range of applications [18] are thermoplastic, and thus heat sensitive. Polyester fibres may shrink in length or even melt on exposure to thermal conditions. Modern fabrics such as those based on microfibers with sophisticated surface finishes, e.g. "peach skin" effects, are especially sensitive to both temperature and pressure [12]. Thus, the impact of high temperature may be simulated and considered as the thermal ageing factor of both textiles and their bonds. The standard LST EN 15062 [19] describes laboratory test methods applying specified ageing conditions to simulate and to assess the deterioration of adhesive bonds which may occur as part of usual footwear worn and stored in normal practice by natural ageing. The ageing problems are also analysed in aircraft [10]. Thermoplastic elastomers (TPU) are extensively applied as an anti-vibration material in machinery, and etc. Therefore, their bonding and thermal aging properties are also important for the forecasting of their mechanical properties [20]. The aging temperature combined to the water also seems to be governing factor of the TPU degradation [21]. The importance of the aforesaid problem proves the demand for reliable research information concerning the thermal ageing of bonds as well as the procedure of its simulating and testing in clothing industry.

Thus, the aim of this research was both the simulation of textile bond thermal ageing and the evaluation of its influence on bond peeling strength.

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2. EXPERIMENTAL

2.1. Materials

Investigations were performed with commercially available woven fabric W1 and knitted fabrics K1, Ks1, Ks2, Ks3, Ks4, and Ks5 suitable for sportswear or leisure wear production. The characteristics of the investigated textiles are presented in Table 1. Textile thickness was measured according to the standard EN ISO 5084 [22]. Textile area density was determined according to the standard LST EN 12127 [23]. Determination of number of threads per unit length of woven fabric was carried out according to the standard LST EN 1049 [24], and the number of stitches per unit length of knitted materials was determined according to the standard EN ISO 14971 [25].

Textiles were bonded with commercially available thermoplastic polymeric resin polyurethane (PU) dry films T1 and T2 of 8 mm width suitable for fabric-to-fabric substrates (Table 1).

2.2. Bond peeling strength testing methodology

Thermoplastic adhesive films are reactivated by heat to ensure excellent coating uniformity. For the purpose to ensure reliable bond between textile substrates, the bonding parameters should be controlled: pressure, temperature, and duration. Thus, bonding conditions were adjusted by taking into account the recommendations of thermoplastic film producer as well as the previous investigations [16, 17, 26, 27]. The film T1 was applied for the bonding of the textile specimens' Ks1, Ks2, Ks3, Ks4, and Ks5, and the film T2 – for bonding of W1, K1, and Ks1 textiles. W1 and K1 textiles were chosen for the comparison of bond peeling strength between woven and knitted fabrics. Ks1 textile bonds were tested for both T1 and T2 adhesive film cases intending to illustrate the influence of the film type on bond peeling strength. The investigation of the textile bonds Ks1_T1, Ks2_T1, Ks3_T1, Ks4_T1, and Ks5_T1 characterised the behaviour of polyester knitted fabrics' bonds containing different amount of the elastane fibre which varied from 4 % up to 20 % (Table 1).

The pairs of 20 mm × 80 mm lengthwise textile samples were bonded with 8 mm × 50 mm adhesive tapes by applying the pressing device GTK DEA 25R at 5.6 kPa pressure at 150 °C temperature for the different bonding duration t (10 s; 20 s; 30 s; and 40 s).

The lengthwise textile specimens were chosen by taking into account the construction instructions commonly being applied in the clothing industry which consider that clothing pieces should be placed warp/wale direction during their cutting from textile materials. Even if one of the previous publications [3] states, that the orientation of knitted materials pieces in bonded seams does not have any significant effect, whereas the other research study [17] reveals that the fabric orientation in the bond makes significant influence on the peeling strength of the lengthwise specimens bonded at both 150 ℃ and 160 ℃ temperatures. Additionally, based on the published research works it may be concluded that, the selected bonding temperature (150 ℃) does not exceed the glass transition temperature (T_g = 226 °C) of polyester fibres refereed in the researches had been published by other scientist (https://us.setaram.com), previously. There were shown, that the characteristics of a pristine adhesive bond kept well below its glass transition temperature should remain stable for extended periods of time [10]. Therefore, it may be assumed that the chosen bonding temperature is optimal for the current investigation.

Samples were conditioned in standard atmosphere conditions (65 ± 4 % RH and 20 ± 2 ℃ temperature) for 24 hours before bond peeling strength testing according to the standard LST EN ISO 139 [28]. Then the samples were exposed to 45 ± 5 ℃ temperature in the oven chamber E5CN for the thermal ageing durations: t_h = 150 min, 300 min, and 450 min. Expose of the textile bonds to the high temperature for certain duration may be considered as their ageing being standardized in the standard LST EN 15062 [19] suitable for the adhesives for leather and footwear materials. Whereas, this type of standard for textile adhesive bonds is missing; thus, the bond ageing temperature was selected as average value (45 ± 5 °C) between two temperatures which falls within the limits of ageing temperature for leather and footwear materials adhesives as well as the average temperature of both ageing in warm air cabinet with forced ventilation capable at (50 ± 2 ℃) temperature and moist ageing in glass container at (40 ± 2 ℃) temperature according to the standard LST EN 15062 [19]. Temperature of the tropic climate zones also was assumed [29].

Table 1. The characteristics of investigated textile materials and thermoplastic adhesive films

Code	Content	Structure	Density along direction, cm^{-1}		Thickness, mm	Area density, g/m^2
			Warp/Wale	Weft/Course		
Textile materials						
W1	100 % Polyester	Plain woven	42.0 ± 2.3	57.0 ± 4.1	0.28 ± 0.01	150.6 ± 2.1
K1	100 % Polyester	Interlock	18.0 ± 1.0	16.0 ± 0.6	0.56 ± 0.02	113.2 ± 4.9
Ks1	96 % Polyester,4 % Elastane	Interlock	22.0 ± 0.5	18.0 ± 0.5	0.90 ± 0.02	251.6 ± 2.0
Ks2	84 % Polyester, 16 % Elastane	Plain jersey	33.0 ± 0.5	21.0 ± 0.5	0.69 ± 0.02	218.8 ± 2.0
Ks3	90 % Polyester,10 % Elastane	Plain jersey	28.0 ± 0.5	14.0 ± 0.5	0.59 ± 0.01	235.5 ± 1.8
Ks4	87 % Polyester, 13 % Elastane	Warp knitted	27.0 ± 0.5	22.0 ± 0.5	0.63 ± 0.01	254.0 ± 4.0
Ks5	80 % Polyester, 20 % Elastane	Warp knitted	47.0 ± 0.5	30.0 ± 0.5	0.47 ± 0.01	218.0 ± 2.1
Thermoplastic adhesive films						
Code	Content	Thickness, mm			Melting point, °C	
T1	Polyurethane (PU)	0.175			90 – 100	
T2	Polyurethane (PU)	0.127			95	

For a thin, 10 – 200 μm adhesive layer, tensile forces will be dominant [10], thus the destructive examination was performed with computerized CRE-type tension machine H10KT (TINIUS OLSEN) to evaluate the influence of both bonding and ageing durations on the bond peeling strength. Peeling speed was kept at 50 mm/min. The strength F (N/mm) was calculated from the typical peeling curves. The number of samples in each group varied from 5 up to 6. The variation coefficient was determined being within the limits of 2.3 % and 14.0 %.

The changes in textile bond morphology before and after thermal ageing was controlled by applying SEM method realized with QUANTA200FEG. This method was suggested also by previous researches as being suitable to explain the obtained strength values of the bonds [2].

3. RESULTS AND DISCUSSION

The dependencies between the bond peeling strength F and bonding duration t of the investigated textile bonds are presented in Fig. 1. These curves may be significantly approximated by the polynomial equation, in exception the samples Ks2_T1 (R^2 = 0.4500) and Ks4_T1 (R^2 = 0.7834) (Fig. 1). The determination coefficient R^2 varied from 0.4500 for bond Ks2_T1 up to 0.9886 for bond Ks3_T1.

Aforesaid results show, that the values of bond peeling strength F (Fig. 1) have decreased by 25.2 % and by 34.6 % for two interlock knitted fabrics' K1 and Ks1 samples, respectively, using the thinner film T2, supposedly, due to too long duration for the penetration of melted adhesive into knitted structure (Fig. 1). T2 film application for W1 woven fabric bonding influenced the significant increase in bond peeling strength (81.7 %) while increasing the bonding duration from 10 s up to 40 s. This evidences, that longer duration is needed for the penetration of adhesive into tighter structure of W1 woven fabric than of knitted fabrics. Bond peeling strength of the bonds of polyester knitted fabrics containing different elastane amount which varies from 4 % up to 20 % (Table 1) and thicker adhesive film T1 has increased from 19.8 % (Ks5_T1) up to 320.8 % (Ks3_T1), dependently on textile structure, after increase in bonding duration up to 40 s. It is worth mention, that very high increase in bond peeling strength (101.2 %) was also determined for Ks2_T1 knitted fabric. Both Ks2 and Ks3 knitted fabrics were of the plain knitted structure.

The maximal bond peeling strength (6.12 N/mm) has been determined for the polyester knitted fabric without elastane fibre K1_T2 for 10 s bonding duration. Both density and thickness of K1 fabric was one of the minimal (Table 1) between investigated textiles. Thus, it may be assumed, that it absorbs melted adhesive more regularly and deeper than other textiles being under testing.

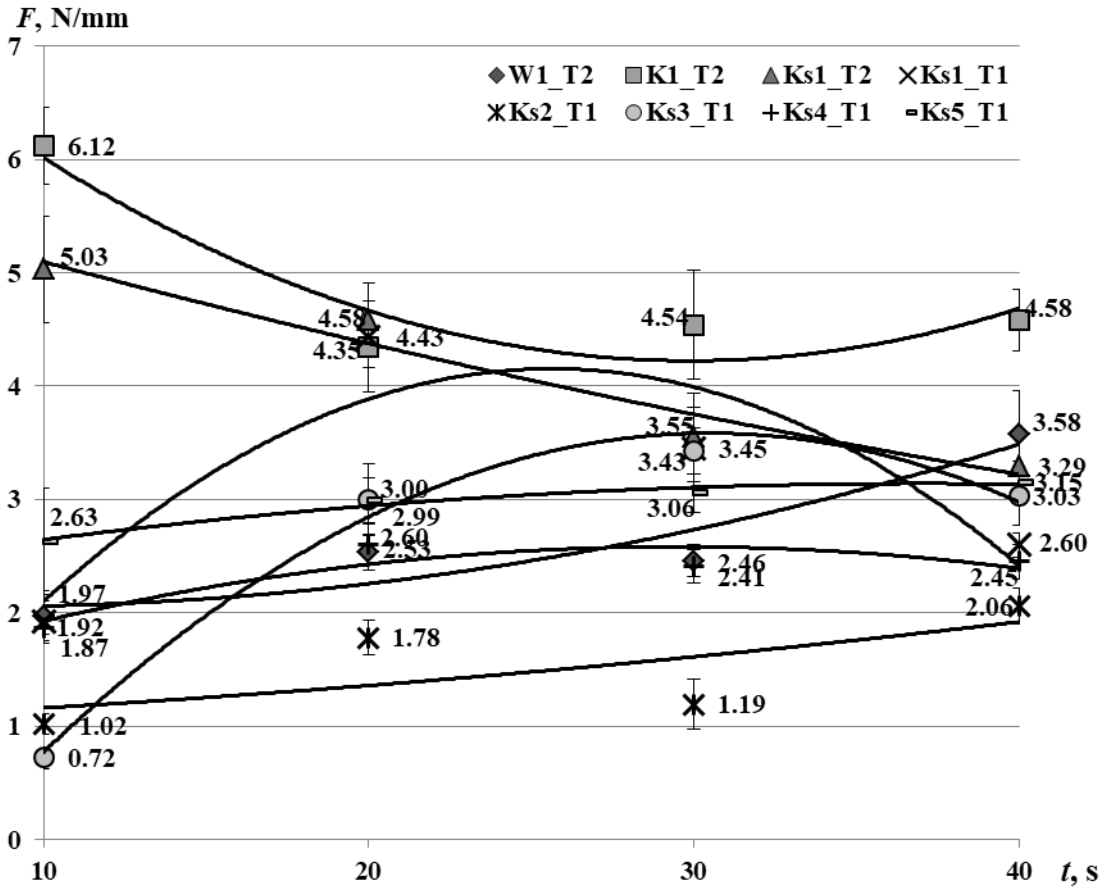


Fig. 1. Dependencies between bond strength F and bonding duration t for the ageing duration t_h of 0 min

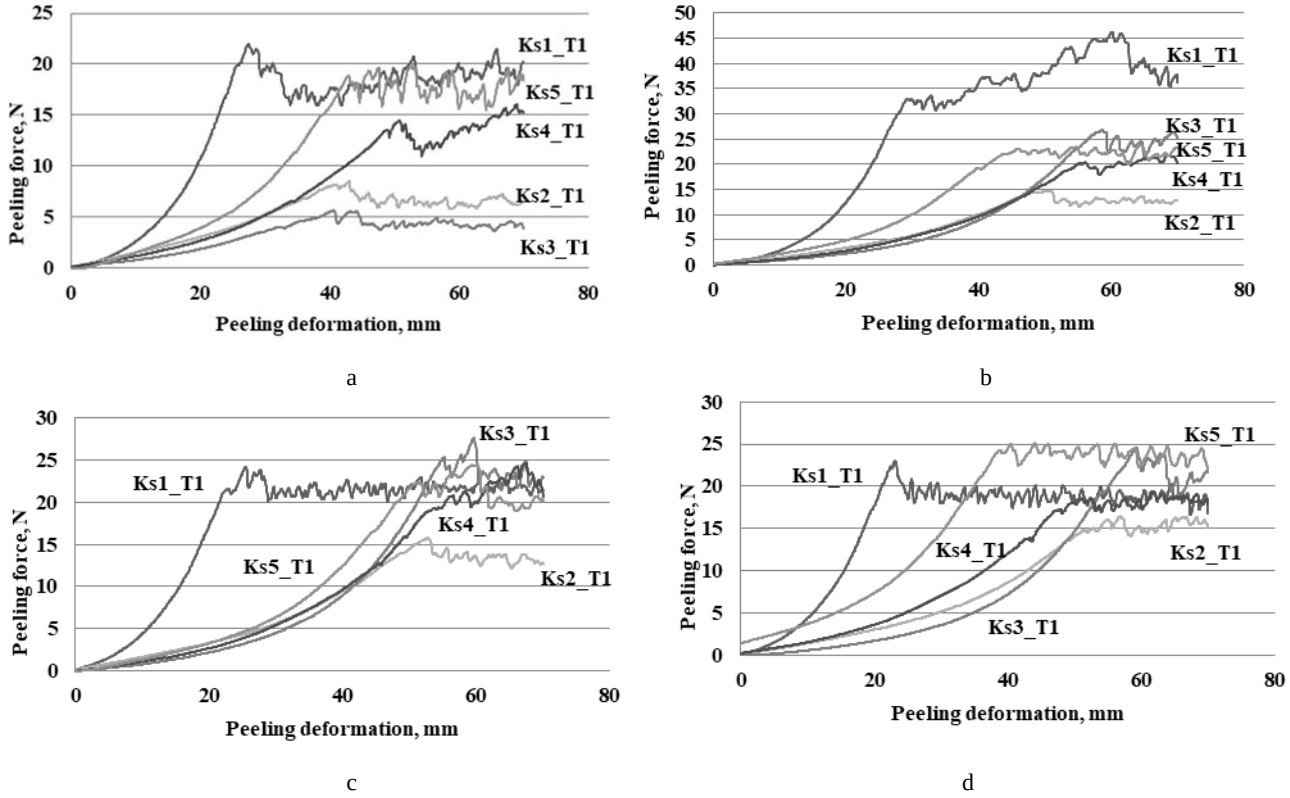


Fig. 2. The peeling curves of the investigated textile bonds for bonding duration: a – 10 s; b – 20 s; c – 30 s; d – 40 s

And, the thinner (0.127 mm) polyurethane adhesive film (T2) is optimal for the formation of the strong cohesive bond between two layers of textile fabric K1. High bond peeling strength was determined for both K1_T2 and Ks1_T2 (5.03 N/mm) bonds laminated with the film T2 of lower thickness (0.127 mm) for 10 s bonding duration. Thus, while making comparison analysis between two investigated cases Ks1_T2 and Ks1_T1 of the same polyester interlock knitted fabric which contains 4 % of elastane fibre, but uses the adhesive polyurethane films T2 and T1 of the different thicknesses − (0.127 mm) and (0.175 mm), respectively, it may be concluded, that higher amount of melted adhesive is not necessary for the formation of the sufficiently strong adhesive bond for 10 s duration (Fig. 1). Adhesive film thickness influences the different impact of bonding duration on bond peeling strength. The peeling strength of Ks1_T2 bond decreased in 34.6 % after increase in bonding duration from 10 s up to 40 s due to too deep absorption of T2 film melted adhesive into textile structure.

The bond Ks1_T1 is much weaker than one of Ks1_T2 bond for 10 s bonding. When using the thicker (0.175 mm) film T1 peeling strength increases increasing bonding duration from 20 s up to 40 s, and resembling it to the values of the peeling strength have been determined for this fabric's bonds being laminated with T2 thinner (0.127 mm) film. Ks1 fabric is the thickest and the long bonding duration had been applied to it has influenced the deep penetration of adhesive into textile structure influencing, supposedly, stronger mechanical adhesion within the knitted fabrics' structure, but weaker cohesion within adhesive interlayer [6, 30] when using thinner adhesive film.

The minimal increase (19.8 %) in the peeling strength due to increasing the bonding duration up to 40 s was determined for Ks5_T1 sample while comparing it with other ones of the polyester knitted fabrics containing elastane fibre being under investigation. The fabric Ks5 is the thinnest and of the highest density as well as it contains highest amount of elastane fibre (20 %). While analysing the influence of bonding duration had been changed from 10 s up to 40 s on the peeling strength for the bonds laminated from two substrates of polyester knitted fabrics containing elastane (Fig. 1) being under investigations applying the thin film T1, it worth to mention that the bond peeling strength increases significantly, i. e. from 19.8 % for Ks5_T1 up to 320.8 % for Ks3_T1. And, the first step of the bonding duration increase by 10 s makes the significant influence on the peeling strength which has increased from 39.0 % Ks4_T1 up to 316.7 % Ks3_T1. Later, during increasing the bonding duration up to 30 s the changes in the values of peeling strength varies within the measurement errors limits with the increasing tendency, but afterwards had been applied increasing of the bonding duration up to 40 s has influenced the decrease in the values of peeling strength for the aforesaid bonds. Thus, it may be concluded that the bonding duration which approximately equals to both 20 s and 30 s may be considered as being optimal for the adhesive bonding of the polyester knitted fabrics containing elastane fibre being under investigations. The tendency of the knitted fabric bonds' peeling strength's increase due to increase in bonding duration may be explained by loose knitted structure which effectively absorbs the melted adhesive into the pores between yarns and fibres influencing the

formation of thin adhesive layer between two layers of textile fabric (Fig. 4).

Analysis of the typical peeling curves of the knitted fabrics with different per cent elastane fibre being under investigations (Fig. 2) has shown that the lowest amplitude of peeling force oscillation is determined for 40 s bonding duration (Fig. 2 d), supposedly, due to even distribution of the melted adhesive polymer in the space between two textile substrates being under investigations. The bonding duration of 40 s also seems being optimal for the thickest interlock knitted fabric Ks1 which demonstrates the high oscillation in peeling force for both 10 s and 20 s bonding durations (Fig. 2 a and b) as well as introduces not very high increase in the bond peeling strength (35.4 %) due to bonding duration increase comparing with the knitted fabrics containing elastane being under investigations.

The relationships between bond peeling strength F and ageing duration t_h for the investigated textile bonds are presented in Fig. 3. Summary of the empirical coefficients (a, b and c) and determination coefficients (R^2) of the polynomial equation ($y = ax2 + bx + c$) which is presented in Table 2 prove the significance of aforesaid relationship, in exception the cases being marked in the grey-coloured squares.

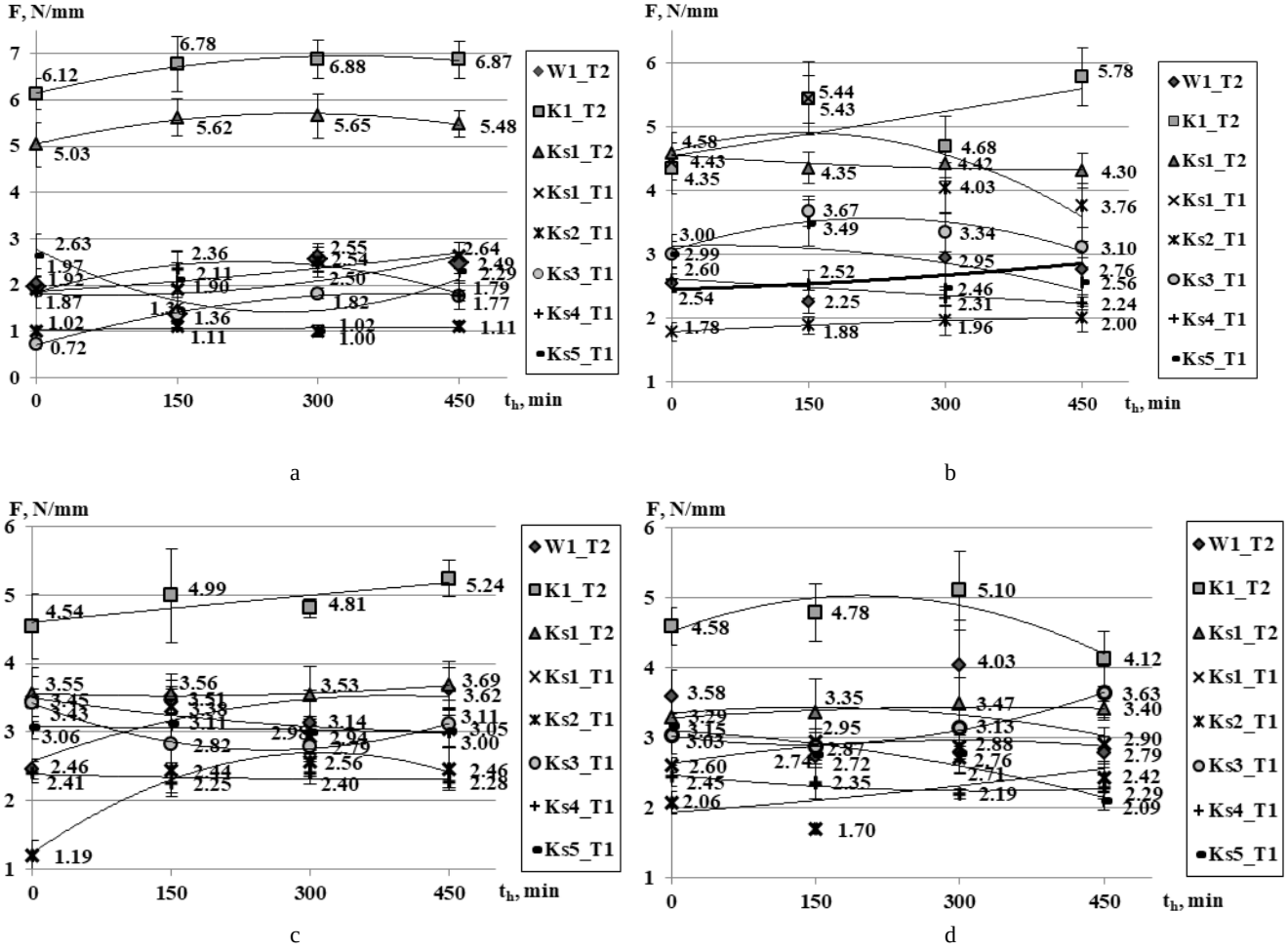


Fig. 3. The dependencies between peeling strength F and thermal ageing duration t_h for: a – 10 s bonding duration; b – 20 s bonding duration; c – 30 s bonding duration; d – 40 s bonding duration

Table 2. Summary of empirical coefficients (a, b and c) and determination coefficient (R^2) of the polynomial equation ($y = ax^2 + bx + c$)

Coefficients	Bond type							
	W1_T2	K1_T2	Ks1_T2	Ks1_T1	Ks2_T1	Ks3_T1	Ks4_T1	Ks5_T1
10 s bonding duration								
R^2	0.4938	0.9746	0.9737	0.846	0.2000	0.9930	0.9665	0.7006
20 s bonding duration								
R^2	0.3496	0.4752	0.7313	0.6125	0.9993	0.7771	0.9580	0.4663
30 s bonding duration								
R^2	0.6867	0.7058	0.8334	0.7711	0.9674	0.9901	0.1632	0.4802
40 s bonding duration								
R^2	0.0765	0.8004	0.8212	0.8258	0.3813	0.9950	0.8562	0.8917

Increase in the bond peeling strength for majority of the bonds being under investigations was determined after application of the first stage of thermal ageing (150 min) for all bonding durations being under evaluation (Fig. 3). On the other hand, these changes for the majority of the bond cases being under investigation vary within the measurement errors' limits when changing the bonding duration from 150 min up to 450 min. It may be noticed an exceptional case, that the impact of thermal ageing on the peeling strength of the polyester K1 knitted fabric's bond laminated applying the thicker adhesive film T2 is most significant comparing with the one of the other textiles' bonds being under investigations. Through, the case of the longest bonding duration (40 s) for the aforesaid bond K1_T2 (Fig. 3 d) negotiates the importance of the thermal ageing on peeling strength.

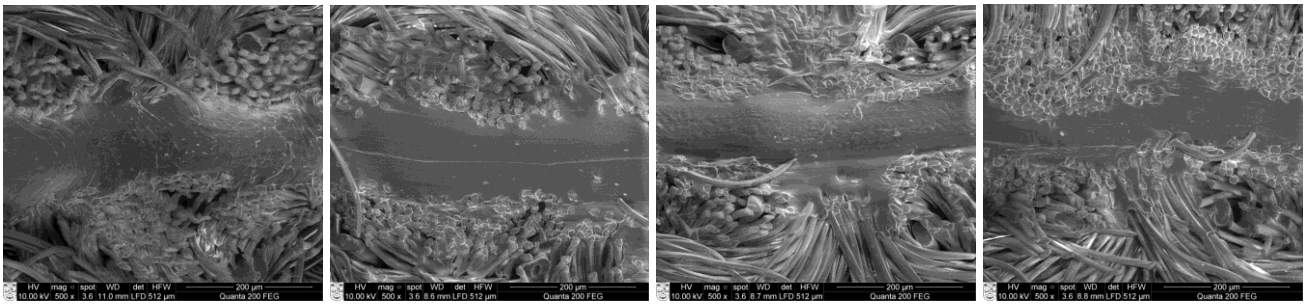
Also, it is interesting to notice that the bonds being bonded from two substrates of the polyester knitted fabric K1 with the thicker adhesive film T2 was strongest among all adhesive bonds being under investigation independently on both bonding and thermal ageing durations. For aforesaid case, the maximal peeling strength (6.88 N/mm) was determined for 10 s bonding duration, independently on ageing duration, and the minimal one (4.12 N/mm) – for both 40 s bonding and 450 min thermal ageing in the oven chamber durations.

SEM images for Ks1_T1 control (Fig. 4 a) and thermally aged (Fig. 4 b) samples were analysed to introduce the influence of both bonding t and thermal ageing t_h duration on textile bond morphology. Ks1_T1 bond was chosen due to the notification while analysing the results presented in Fig. 1, that the peeling strength of the aforesaid bond was approximately equal to an average value within the range of ones have been determined for other bonds being under investigations (Fig. 1).

And, the maximal duration of the thermal ageing (t_h = 450 min) influences small changes in the morphology's images of the analysed textile bonds as there are some evidences for immigration of PU adhesive between fibers of upper and lower surfaces at higher ageing times (450 min) (Fig. 4 b).

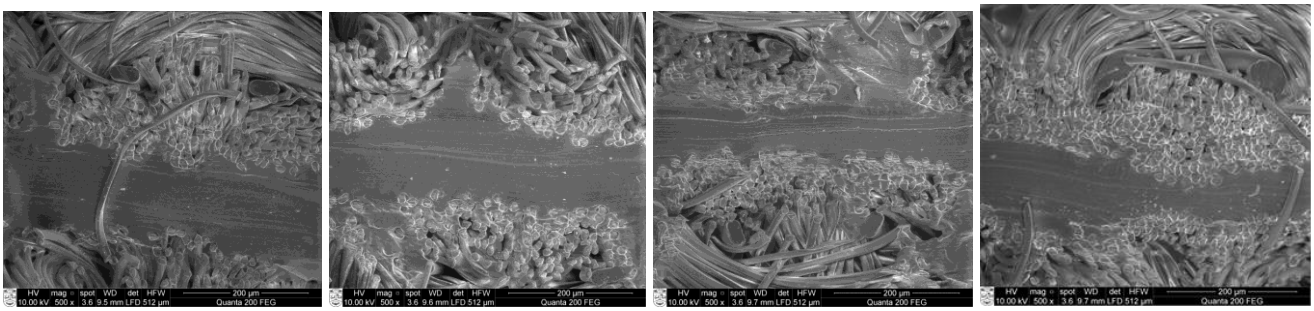
4. CONCLUSIONS

1. In the current contribution, bond peeling strength testing has been used to study the influence of both bonding and thermal ageing duration on bond quality. The following findings were derived from this experimental study:
   – the peeling strength of textile bonds was dependent on structure of the textiles being under investigations; the peeling strength of the polyester knitted fabric K1 samples bonded with the thinner adhesive film T2 was highest compared with other polyester textiles being under investigations;



Ks1_T1 t = 10 s; t_h = 0 min | Ks1_T1 t = 20 s; t_h = 0 min | Ks1_T1 t = 30 s; t_h = 0 min | Ks1_T1 t = 40 s; t_h = 0 min

a



Ks1_T1 t = 10 s; t_h = 450 min | Ks1_T1 t = 20 s; t_h = 450 min | Ks1_T1 t = 30 s; t_h = 450 min | Ks1_T1 t = 40 s; t_h = 450 min

b

Fig. 4. SEM images of the textile bonds (Ks1_T1) laminated for 10 s; 20 s; 30 s; and 40 durations t for control: a – not exposed by thermal ageing; b – exposed by 450 min ageing duration t_h samples

– the increase in bonding duration *t* from 10 s up to 40 s influences the increase in peeling strength *F* for the knitted fabrics containing elastane fibre, but it tends to be decreased for knitted fabric without elastane, if compared with the case of 10 s bonding temperature;

– the comparison of the textiles' bonds for the woven and knitted materials without elastane fibres had shown that the increase in the bonding temperature increased the bond peeling strength of the woven fabric W1 and decreased for knitted fabric K1 if compared with the case of 10 s bonding temperature;

– the influence of the ageing at 45 °C temperature on the peeling strength was very small for the different ageing durations applying all bonding durations.

2. Thus concluding finally, it should be stated that the ageing duration at 45 °C temperature is not that factor which makes significant influence on the textile bonds quality during their exploitation, for example, in the tropic climate zones. Longer thermal ageing duration also is not relevant for the simulation of clothing exploitation as the wearer would not be able to endure the temperatures higher than 45 °C for 450 min and longer. Thus, for the future investigations the major focus should be concentrated on the estimation of bonding temperature influence on the mechanical properties of textile materials applying the methods of both differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA). Choosing the bonding temperature which influences the increase in bond peeling strength [10, 17] the destruction of the thermoplastic fibres that compiles knitted fabric, should be avoided, which may weaken the material itself.

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