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Strengthening Interfacial Bonding in Nanofibre Laminated Textile Composites

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***Abstract*—Textiles that use electrospun nanofibre membranes (ENMs) in laminated configurations recently achieved substantial progress in three application areas, including robotic skins, electronic sensors, and medical textiles. Research evaluates nanofibre-laminated textile bonding strength by using multiple experimental methods. The study presents the development of three different textile composites in which polyacrylonitrile (PAN) polymer was treated with electrospinning on fabric through various adhesive techniques. The testing evaluates the different nanofibre-fabric bonding methods using T-peel tests to determine their effectiveness. The direct electrospinning methods used to produce laminated textiles led to negligible or no attachment between fabric materials and ENMs. The electrospinning process led to initial ENM layer adhesion when an adhesion agent was incorporated during the process. The tested composite achieved a 60% higher strength after using adhesive pressure to create it. Research findings show that applying an adhesive agent with pressure between textile materials and ENMs produces optimal interfacial adhesion during the fabrication of laminated textile composites.**

***Keywords*—laminated composites, nanofibres, textiles, T-peel test.**

I. Introduction

Researchers have observed a significant growth in studies on textiles with diverse applications which now include the development of electronic skins for wearable electronic devices [1], [2]. Wearable health monitors and multifunctional robotic skins that replicate the properties of human skin belong to the group of innovative devices that constitute important progress in smart textile technology [3], [4].

The medical field has adopted nanofibres as highly promising materials because they provide excellent benefits for wound dressing applications [5], [6], drug delivery systems [7], [8], and tissue engineering scaffolds [9]. The nanofibre mat with porous structure display several beneficial properties such as a high surface-to-volume ratio combined with minimal weight and flexibility, which allows them to seamlessly integrate with textile technologies [10], [11].

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The combination of textile materials with nanofibres leads to laminated composite structures through research-developed integration methods. These laminated composite textiles offer multiple advantages from their two constituent materials for applications ranging from stretchable fabric skin to low-force sensors [1], noncrimping textiles [12], acoustic applications [13] and self-powered sensing textiles [14], [15] in diverse technological fields.

Composite materials depend on the level of bonding of the reinforcement elements with the matrix for both performance quality and durability [16], [17]. The interface holds an exceptional importance in nanofibre mats integrated with textile substrates, as it determines stress transfer capabilities and affects overall mechanical characteristics [18], [19]. In laminated composite textiles, robust interfacial bonding is essential, as slippage may compromise the structural integrity of nanofibre mats, which consequently deteriorates the functionality of the composite materials [20], [21].

Research on textiles strengthened through the addition of nanofibre mats has primarily examined mechanical performance and utilisation, yet provides only a limited understanding of the basis for textile-nanofibre mat bonding. The production of nanofibre mats has incorporated three different strategies: direct electrospinning onto textiles as well as pre-electrospinning with adhesive glue and weaving textile yarns. Current methodologies successfully achieve their intended objectives; however, the interfacial strength between textile substrates and nanofibre mats remains a significant knowledge gap in contemporary research.

This study implements established methods from the literature and tests a new method for developing nanofibre-reinforced laminated textiles. This investigation contributes novel insights through its systematic approach to developing three laminated composite textiles, followed by comprehensive T-peel testing and thorough examination of the component adhesive bonding strength. The methodology generates significant empirical data that advances the understanding of interfacial bonding in nanofibre-reinforced textile composites.

II. Materials and Methods

A. Materials

The fabrication of laminated textile composites reinforced with electrospun polyacrylonitrile (PAN) nanofibres required several key materials. The electrospun nanofibres were produced using polyacrylonitrile powder and N,N-dimethylformamide. Polyacrylonitrile, with an average molecular weight of 150,000 (typical) and CAS number 25014-41-9, was sourced from Sigma-Aldrich chemicals (Merck KGaA, Darmstadt, 64287, Germany). N, N-dimethylformamide (DMF), an ACS reagent (solvent) with 99.8% purity and CAS number 68-12-2, was purchased similarly from Sigma-Aldrich chemicals.

The woven fabric used in this investigation was model 21502/45_PN, featuring plain interlacing with a width of 150±1.5 centimetres and a weight of 150±17 grammes per square metre. The fabric structure comprised warp and weft components constructed of 28 Tex linen. This material was obtained from AB 'Linas', S. Kerbedzio Street 23, LT-35114 Panevezys, Lithuania. The fabric adhesive used was a solvent-free formulation, Art. 639820, obtained from Gutermann GmbH, situated at Landstrasse 1, DE-79261 Gutach-Besigau, Germany.

B. Fabrication of nanofibre laminated fabric composites

The fabrication process began with the preparation of the PAN solution, by which PAN powder was incorporated into the DMF solvent at a concentration of 10% wt / wt. This mixture underwent continuous agitation for 8 hours utilising a Thermo Scientific™ Cimarec+™ Stirring Hotplate (USA) at 80°C, with ambient conditions maintained at 22±1°C and 60% relative humidity. The stirring speed was regulated at 800 rpm. Subsequently, the solution was kept at room temperature for 1 hour to facilitate the elimination of air bubbles and achieve solution stability, similarly as mentioned in [22].

The textile compound required exact trimming of the fabric in specific dimensions that corresponded to the circumference of the drum (30 cm by 45 cm) with the weft direction as the longer edge. The RC-5000 rotating drum collector with dimensions of 140 mm in in diameter by 300 mm length from Shenzhen Tongli Tech Co Ltd., Shenzhen, China received this fabric material. The precise application of the fabric adhesive was carried out on the substrate (~210 g/m²) by hand methods following the principles while weight measurements determined the amount of adhesive before and after application.

The electrospinning of PAN nanofibres was conducted at 22±1°C utilising a Fisherbrand™ Single Syringe Pump system (Danbury, CT 06811, USA) in conjunction with the prepared rotating drum assembly. The apparatus used a 10-ml plastic syringe (lure lock) fitted with an 18 Ga needle. The operational parameters encompassed a 20 kV voltage potential, a flow rate of 1 ml / h, and an 18 cm separation between the tip of the syringe and drum collector centre. The drum collector maintained a constant rotational velocity of 1200 rpm (approximate tangential velocity of 8.8 m/s).

Before the T-peel test, all specimens underwent conditioning at 22±1°C and relative humidity below 60% for 48 hours, according to ISO 139:1973 (Textiles—Standard atmospheres for conditioning and testing). To facilitate the collection of PAN nanofibre mats, aluminium foil (45 cm × 5 cm, 35 µm thickness) sourced from Vireo.de, Merseburg (06217), Germany, was placed on the adhesive layer, thereby enabling subsequent collection of nanofibre collection whilst preventing direct interaction between adhesive and nanofibre components.

C. T-peel test of nanofibre laminated fabric composites:

The T-peel test followed ASTM D1876 (Standard Test Method for Peel Resistance of Adhesives - T-Peel Test). The test specimens were cut precisely along the fibre orientation to obtain dimensions of 25 millimetres wide and

100 millimetres long. The PPT Group UK Ltd (as Mecmesin) Multi-Test 2.5-i tensile testing machine measured the adhesive strength with its 25 N sensor. The testing machine adjusted its elongation speed to 100 mm/min following ASTM D1876 standards. Figure 1 presents a visual representation of the samples prepared for the T-peel test, where L denotes the adhesive length of the sample, W represents the specimen width, and l indicates the distance between the grips.

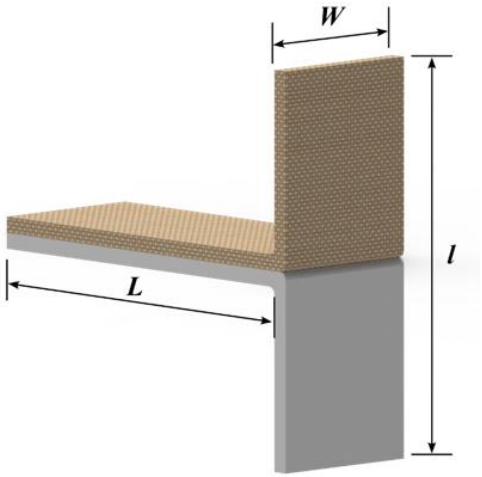

Fig.1. Illustration of the T-peel test specimen.

The investigation comprised three distinct groups of specimens. The first group, designated as S1, consisted of samples in which nanofibres were directly electrospun onto the fabric substrate. The second group, denoted S2, incorporated specimens where adhesive was applied to the fabric prior to the electrospinning process, with nanofibres subsequently deposited directly on the adhesive-treated fabric. The third group, classified as S3, used nanofibres initially collected on aluminium foil, which were subsequently adhered to the fabric using an equivalent amount of adhesive glue. These samples were subjected to pressure application (~600 N/m²) for a duration of 24 hours to ensure optimal bonding.

III. Results and Discussion

The S1 group of samples, which consisted of nanofibres electrospun directly onto the fabric, demonstrated no adhesion between the fabric and the electrospun nanofibres. Figure 2 illustrates the sample from the S1 group after 24 hours at room temperature.

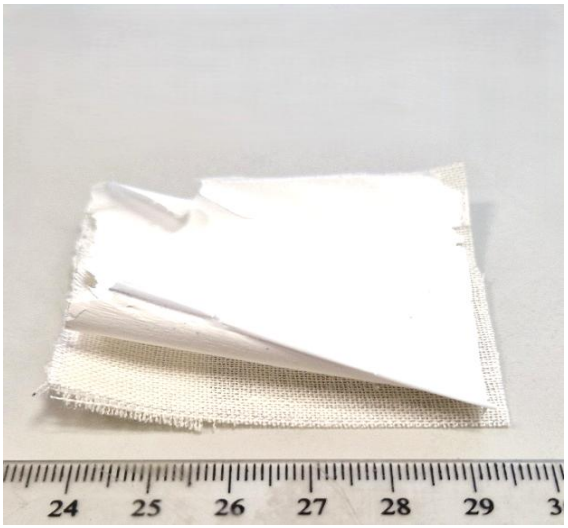

Fig. 2. S1 group sample after 24 hours of exposure to room temperature.

The samples collected from groups S2 and S3 did not lose cohesive properties. Groups S2 and S3 used adhesive materials that led to their stability but in group S1 the electrospun nanofibres reached the collector while staying solid and wrapped it without sticking to the fabric.

Opposite phenomena was observed by [13], which could be attributed to the collection of nanofibres at a reduced distance and their deposition onto the textile in a semi-solid state, as evidenced by the presence of beads in the morphology. Nevertheless, in both this investigation and other published work, the adhesive strength between textile substrates and nanofibre mats remains largely unexplored.

The test results of the T-peel experiments demonstrate that the bond strength between interfacial layers shows different levels for the S2 and S3 samples (Fig. 3). S3 specimens fabricated consisting of pre-collected nanofibres and adhesive application under pressure treatment exhibited high bonding strength through their peak force of 4.3 ± 0.1 N followed by stable bonding at 3.13 ± 0.13 N. The bonding strength of the S2 specimens showed reduced performance when adhesive was applied before direct electrospinning because the initial peak force reached 2.7 ± 0.1 N and then stabilised at 2.16 ± 0.1 N.

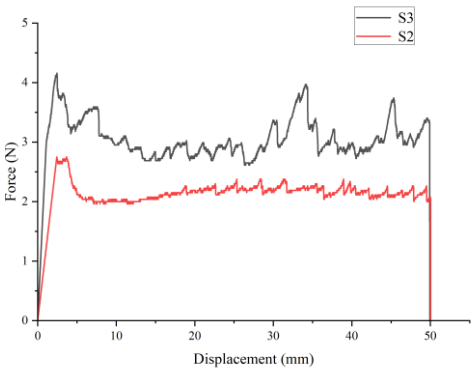

Fig. 3. Representative force displacement curves from T-peel testing of the nanofibre-laminated textiles of groups S2 and S3.

Peak load peel strength measurement for S3 samples produced 172 ± 4 N/m while the steady-state delamination phase exhibited 125.2 ± 5.2 N/m. The peel strength measurements for the S2 samples reached peak values of 108 ± 4 N / m, after which they showed steady-state delamination at 86.4 ± 4 N/m. The pressure-assisted bonding approach creates interfaces that demonstrate a strength at least 60% greater than that of electrospinning onto adhesive-treated fabric under direct conditions.

Both force-displacement curves exhibit characteristic serrated patterns because of the way nanofibre-fabric interfaces fail progressively across the woven structure surface. S3 sample shows maximum force variability because they have more nanofibres properly bound to the fabric base. These cyclic variations in the measurements align with the fabric weaves because the nanofibres establish contact with the natural peaks and valleys on the textile surface.

Laboratory tests on the specimens after failure display additional information on failure behaviours (Figure 4). The S3 specimens maintained better fibres on the fabric surface which confirms that the interfacial bonding achieved superior results. The pressure treatment used during the fabrication improved overall bonding between the nanofibre mat and the fabric structures because it allowed deeper adhesive penetration. The adherence to fabric surfaces turned out to be weaker in the S2 specimens as compared to the S3 because direct electrospinning on the adhesive-treated fabric creates suboptimal fibre-matrix interaction.

Fig. 4. Specimens from group S3 after T-peel testing.

The S3 fabrication method produced superior peak force results of approximately 60% compared to S2 because effective processing parameters enable strong interfacial bonding. The enhancement stems from two important characteristics: the uniform pressure distribution during bonding and the protective effect aluminium foil provides to nanofibre mats before adhesive application.

The total strength measurements between the S2 and S3 test samples have essential value for improving manufacturing methods of nanofibre-laminated textile composites. The pressure-assisted bonding technique (S3) proves advantageous for applications that require strong interfacial strength due to its particular importance in wearable electronic devices and medical textiles.

The steady-force plateau following the initial peak in both specimen types creates favourable conditions for long-term performance calculations in real-life applications. The pressure-assisted bonding approach enables the S3 samples to maintain a steady force level of 3.13 ± 0.13 N as the displacement increases, indicating that the method produces a well-distributed robust bond throughout the entire surface of the composite. Uniform structure is of particular importance for strain sensors and protective clothing because they need consistent textile performance. A similar phenomenon of adhesive-assisted bonding was demonstrated in other textile composite applications [12]. However, while direct comparison of adhesive strength values is not possible since they were not measured in previous studies, similar bonding strategies have been successfully employed for different purposes. For example, in hybrid textile composites, adhesive bonding has been shown to enhance structural integration and mechanical properties, though through different mechanisms and for different applications.

The structural integrity of nanofibres in S3 specimens showed significant improvement with pressure-assisted bonding, demonstrating preservation of the structure of the nanofibre network. This structural preservation plays a vital role in maintaining composite functionality across all performance domains, including electrical functionality and mechanical properties. The observed failure mechanism exhibited progressive detachment of the nanofibres rather than sudden delamination, indicating an energy-absorbing process that contributes to the durability of the product.

IV. Conclusions

The paper analysed the interfacial bond strength of a nanofibre laminated textile composite through three separate fabrication techniques. The experimental results from direct electrospinning failed to establish a meaningful bond between fabric and nanofibre mat (S1). The application of adhesive before electrospinning in Method S2 produced the strongest bond with a peak peel strength of 108 ± 4 N/m. Pressure-assisted bonding of pre-collected nanofibres (S3) served as the most successful method by achieving a peak peel strength of 172 ± 4 N/m, which exceeded the S2 method by 60%.

The results obtained enable fundamental understanding for better manufacturing methods of nanofibre-laminated textile composites. The bonding process developed in this study presents a dependable method to create strong interfacial bonds that is crucial for applications in wearable electronics, in addition to medical textiles and other advanced textile applications requiring superior mechanical reliability. In future, researchers could optimise pressure settings alongside studies on the longevity of the interface in different environmental situations.

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References

[1] X. You, J. He, N. Nan, X. Sun, K. Qi, Y. Zhou, W. Shao, F.Liu and S. Cui, "Stretchable capacitive fabric electronic skin woven by electrospun nanofiber coated yarns for detecting tactile and multimodal mechanical stimuli," J. Mater. Chem. C, vol. 6, no. 47, pp. 12981–12991, 2018, doi: 10.1039/C8TC03631D

[2] H. Jin, Md O. G. Nayeem, Md O. G. Nayeem, S. Lee, N. Matsuhisa, D.Inoue, T. Yokota, D. Hashizume and T. Someya, "Highly durable nanofiber-reinforced elastic conductors for skin-tight electronic textiles," ACS Nano, vol. 13, no. 7, pp. 7905–7912, 2019, doi: 10.1021/acsnano.9b02297

[3] J. S. Meena, S. Bin Choi, S.-B. Jung, and J.-W. Kim, "Electronic textiles: new age of wearable technology for healthcare and fitness solutions," Mater. Today Bio, vol. 19, no. December 2022, p. 100565, 2023, doi: 10.1016/j.mtbio.2023.100565

[4] B. Baye and T. Tesfaye, "The new generation fibers: a review of high performance and specialty fibers," Polym. Bull., vol. 79, no. 11, pp. 9221–9235, 2022, doi: 10.1007/s00289-021-03966-6

[5] G. Anusiya and R. Jaiganesh, "A review on fabrication methods of nanofibers and a special focus on application of cellulose nanofibers," Carbohydr. Polym. Technol. Appl., vol. 4, no. November, p. 100262, 2022, doi: 10.1016/j.carpta.2022.100262

[6] E. J. Jang, R. Patel, and M. Patel, "Electrospinning Nanofibers as a Dressing to Treat Diabetic Wounds," Pharmaceutics, vol. 15, no. 4, 2023, doi: 10.3390/pharmaceutics15041144

[7] E. R. Radu, S. I. Voicu, and V. K. Thankur, "Polymeric membranes for biomedical applications," Polymers (Basel)., vol. 15, no. 3, pp. 1–28, 2023, doi: https://doi.org/10.3390/polym15030619

[8] S. Baek, H. Park, Y. Park, H. Kang, and D. Lee, "Development of a lidocaine-loaded alginate/CMC/PEO electrospun nanofiber film and application as an anti-adhesion barrier," Polymers (Basel)., vol. 12, no. 3, 2020, doi: 10.3390/polym12030618

[9] L. Bauer, L. Brandstäter , M. Letmate, M. Palachandran, F. O. Wadehn,C. Wolfschmidt, T. Grothe, U. Güth and A. Ehrmann, "Electrospinning for the Modification of 3D Objects for the Potential Use in Tissue Engineering," Technologies, vol. 10, no. 3, 2022, doi: 10.3390/technologies10030066

[10] J. V. Sanchaniya, I. Lasenko, V. Gobins, and A. Kobeissi, "A Finite Element Method for Determining the Mechanical Properties of Electrospun Nanofibrous Mats," Polym., vol. 16, no. 6, p. 852, 2024, doi: 10.3390/polym16060852

[11] J. V. Sanchaniya, I. Lasenko, V. Vijayan, H. Smogor, V. Gobins, A.Kobeissi and D. Goljandin, "A Novel Method to Enhance the Mechanical Properties of Polyacrylonitrile Nanofiber Mats: An Experimental and Numerical Investigation," Polymers (Basel)., vol. 16, no. 7, p. 992, Apr. 2024, doi: 10.3390/polym16070992

[12] J. V. Sanchaniya, I. Lasenko, S. P. Kanukuntla, A. Mannodi, A. Viluma-gudmona, and V. Gobins, "Preparation and Characterization of Non-Crimping Laminated Textile Composites Reinforced with Electrospun Nanofibers," Nanomaterials, vol. 13, no. 13, p. 1949, 2023, doi: 10.3390/nano13131949

[13] M. Kucukali-Ozturk, E. Ozden-Yenigun, B. Nergis, and C. Candan, "Nanofiber-enhanced lightweight composite textiles for acoustic applications," J. Ind. Text., vol. 46, no. 7, pp. 1498–1510, 2017, doi: 10.1177/1528083715622427

[14] X. Guan, B. Xu, M. Wu, T. Jing, Y. Yang, and Y. Gao, "Breathable, washable and wearable woven-structured triboelectric nanogenerators utilizing electrospun nanofibers for biomechanical energy harvesting and self-powered sensing," Nano Energy, vol. 80, no. July 2020, p. 105549, 2021, doi: 10.1016/j.nanoen.2020.105549

[15] L. Liu, W. Xu, Y. Ding, S. Agarwal, A. Greiner, and G. Duan, "A review of smart electrospun fibers toward textiles," Compos. Commun., vol. 22, no. August, p. 100506, 2020, doi: 10.1016/j.coco.2020.100506

[16] S. Budhe, M. D. Banea, S. de Barros, and L. F. M. da Silva, "An updated review of adhesively bonded joints in composite materials," Int. J. Adhes. Adhes., vol. 72, no. October 2016, pp. 30–42, 2017, doi: 10.1016/j.ijadhadh.2016.10.010

[17] R. Hsissou, R. Seghiri, Z. Benzekri, M. Hilali, M. Rafik, and A. Elharfi, "Polymer composite materials: A comprehensive review," Compos. Struct., vol. 262, no. December 2020, pp. 0–3, 2021, doi: 10.1016/j.compstruct.2021.113640

[18] I. Lasenko, J. V.Sanchaniya, S. P. Kanukuntla, Y. Ladani, A. Viluma-Gudmona, O.Kononova, V. Lusis, I. Tipans and T. Selga, "The mechanical properties of nanocomposites reinforced with PA6 electrospun nanofibers," Polymers (Basel)., vol. 15, no. 3, 2023, doi: 10.3390/polym15030673

[19] K. M. F. Hasan, P. G. Horváth, and T. Alpár, "Potential fabric-reinforced composites: a comprehensive review," J. Mater. Sci., vol. 56, no. 26, pp. 14381–14415, 2021, doi: 10.1007/s10853-021-06177-6

[20] F. Adekunle and A. F. M. Seyam, "The Effect of Adhesive Quantity on Adhesion Quality and Mechanical Characteristics of Woven Kevlar Fabric-Reinforced Laminated Structures," J. Compos. Sci., vol. 8, no. 12, 2024, doi: 10.3390/jcs8120505

[21] Y. Zhou, M. Fan, and L. Chen, "Interface and bonding mechanisms of plant fibre composites: An overview," Compos. Part B Eng., vol. 101, pp. 31–45, 2016, doi: 10.1016/j.compositesb.2016.06.055

[22] J. V.Sanchaniya, I. Lasenko, S. P. Kanukuntla, H. Smogor, A. Viluma-Gudmona, A.Krasnikovs, I. Tipans and V.Gobins, "Mechanical and Thermal Characterization of Annealed Oriented PAN Nanofibers," Polymers (Basel)., vol. 15, no. 15, 2023, doi: 10.3390/polym15153287