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Evaluation of the Mechanical Parameters of Ultrasonically Welded Textile Composite Structures for Protective Footwear

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Abstract
Textile materials are used in protective footwear due to their good mechanical and hygienic properties and to provide thermal insulation. This work presents a technological process of designing ultrasonically welded composite structures characterised by various densities of welding spots. The study involved three variants of composite structures made of three layers. The composite structures developed were tested in terms of mechanical properties and were statistically analysed in terms of the effects of welding spot density and reinforcing nonwoven thickness on the protective parameters. Inserts made of ultrasonically spot-welded textile composite structures may offer protective footwear users greater comfort in terms of mechanical resistance. The evaluation method proposed may be a useful tool in assessing textile composite structure inserts for protective footwear.

Key words: *protective footwear, composite structures, insole, ultrasonically welding.*

Introduction

A wide range of textile composite structures are employed in personal protective equipment (PPE) to improve user comfort. In the case of protective footwear, such materials are typically implemented as liners and contoured inserts or insoles. However, to date, research and development work in this area has mostly focused on the design of composite structures for casual footwear [1, 2].

Recent years have seen the rapid development of innovative PPE. Indeed the Long Term PPE Perspective of the European Union until 2020 recommends the design of functional solutions for protective footwear in the form of support textiles not integrated with the footwear itself, such as insoles, liners, and socks with antifungal, antibacterial, and hygienic properties, characterised by a short service life [3, 4].

Other important functional features of support textiles (insoles or inserts) for protective footwear are mechanical properties and thermal insulation, which can be obtained by modifying the composite structure. The most common technologies involve the lamination of two or more nonwoven layers with different adhesives, including hot-melt adhesives [5-7]. Patents [8] and [9] describe composite structures obtained by joining two outer spunbond layers with an interior melt-blown layer (SMS), made of polypropylene or polypropylene and polyethylene, by means of a roll mill. Another configuration of such nonwovens is SSMMS [10]. Nevertheless it should be noted that the production of SMS composite structures and laminates entails several technologies for the manufacture of nonwovens and a separate technology for their bonding. Lang and Schmalz [11] developed a different method for producing nonwoven composite structures in which the elementary fibres of the various composite structure layers were hydroentangled. In a similar way, nonwoven composite structures may be produced by means of the needle-punching and stitching of the layers. However, in such composite structures the fibre diameter is too large for protective applications. A number of textile materials have been developed for socks and insoles intended for protective footwear and characterised by improved mechanical properties as well as very good antimicrobial features [12-14]. Textile materials are used in protective footwear due to their good mechanical and hygienic properties. The type of fibres used, their morphological structure, and physical and mechanical properties, as well as the design of the end product affect the transport of heat and moisture away from the skin of the foot and outside the footwear, as has been shown in many works [6, 15-19]. Indeed many authors have reported that support textiles (socks, liners, and inserts or insoles) significantly influence the overall comfort of footwear use [13, 20]. The widespread current methods of adhesive bonding of textile materials (both hydrophobic and hydrophilic) that employ synthetic adhesives impair the outward transport of heat and moisture [7, 12, 21-22]. Optimum functional properties of footwear inserts may be obtained by using combinations of polyester or polyamide fibres with fibres exhibiting high water sorption capacity (natural fibres or artificial cellulose fibres). According to the literature, of importance is appropriate design of the textiles with an optimised arrangement of hydrophobic and hydrophilic fibres in the structure of the product [23, 24].

Composite structures for protective footwear inserts may also be made by ultrasonic welding, which is a widely used, economical, and time-efficient technology, However, it must be optimised in terms of the distribution of welding spots to ensure appropriate bonding strength between the layers. This work presents a technological process of designing ultrasonically welded composite structures with superior mechanical strength, characterised by various densities of welding spots.

The objective was to analyse the effects of welding density on the mechanical parameters of composite structures to be used as support textiles (inserts) in protective footwear.

Experimental

Structure and characterisation of materials

The study involved three variants of composite structures made of the following layers:
- an outer layer in contact with the foot, made of a knitted polyester spacer fabric (the first layer);
- a middle layer made of a polypropylene melt-blown nonwoven (the second layer);
- an outer layer in contact with the footwear, made of a polypropylene reinforcement nonwoven, one- or two-ply (the third layer).

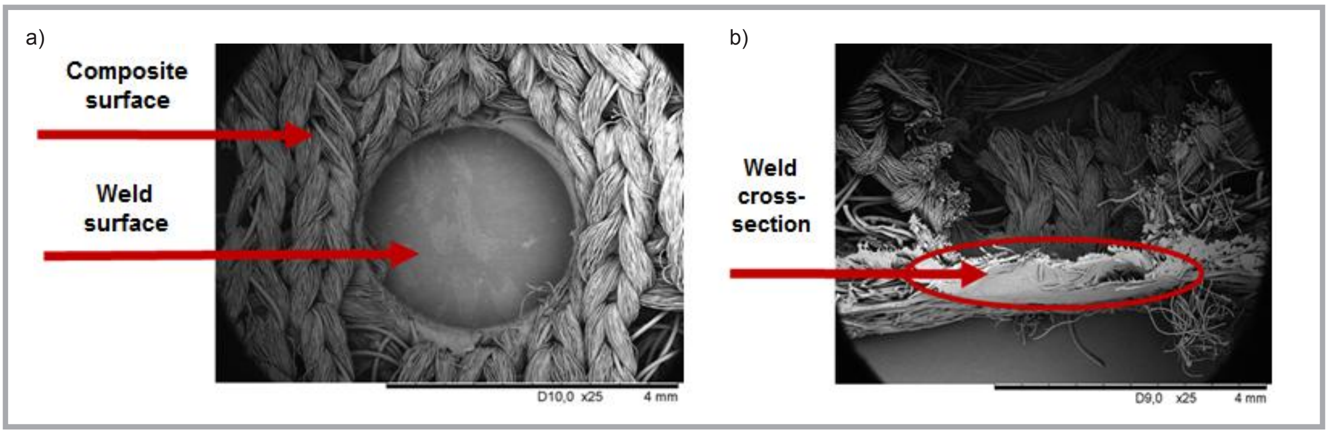


***Figure 1.** Weld surface morphology a), Weld cross-section b) (SEM images).*

Four spacer fabric variants (*Bowi*-Styl, Poland) differing in microfilament height were used in the first layer, in contact with the user's foot, The second (middle) layer was made of a polypropylene melt-blown nonwoven (CIOP-PIB, Poland). The third layer (the outer layer in contact with the footwear) was made of a one- or two-ply polypropylene reinforcing nonwoven (Filter Service, Poland). The main function of this layer was to impart rigidity and an appropriate shape to the protective footwear inserts. Material characteristics of the spacer fabrics, melt-blown nonwoven, and reinforcing nonwoven are given in ***Table 1***.

***Table 1.** Material characteristics of composite structure layers.*

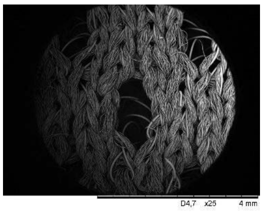
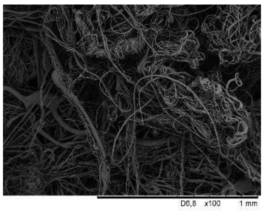
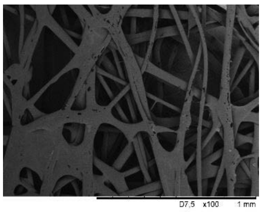
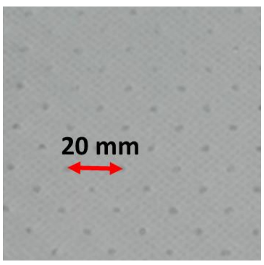
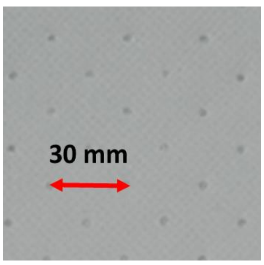
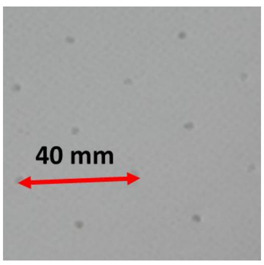
First layer (Outer, in contact with the foot)				Second layer (Middle)	Third layer (Outer, in contact with the footwear)
Type of textile					
Knitted fabric				Nonwoven	Nonwoven
					
Composition [Percentage share of fibre type]					
Polyester [100%]				Polypropylene [100%]	Polypropylene [100%]
Mass per unit area, g/m^2					
204.4	282.0	305.9	272.5	90	70
Thickness, mm					
2.22	3.41	2.85	3.93	1.07	0.46
Microfilament height, mm				**Average fibre thickness, mm**	
2	3	2.5	4	0.02	0.5

***Table 2.** Images of composite structures with various weld spacing patterns.*

Intervals between welds		
20 mm	**30 mm**	**40 mm**
		

Processing procedure

Layers of the composite structures were ultrasonically spot-welded using an ultrasound welding machine developed as part of the project implemented at CIOP-PIB (Maskpol, Poland). Welds were spaced evenly every 20, 30 or 40 mm, all of which had a diameter of 2.5 mm. ***Table 2*** shows images of the composite structures with variously spaced welds.

The weld surface morphology and cross-section acquired by means of scanning electron microscopy (SEM) are shown in ***Figure 1***.

Table 3 gives metrological characteristics of the composite structure variants developed.

SEM images of weld cross-sections revealed a regular surface, indicating good bonding of all layers of the composite structures in the process of ultrasonic welding.

Testing methods

The composite structures developed were tested in terms of mechanical properties which are significant from the point of view of the requirements of protective footwear. The parameters evaluated included bending stiffness, abrasion resistance, and tear resistance (bonding strength) of the composite structure layers. Prior to measurements, all samples were conditioned at (23 ± 2) °C and relative air humidity of (50 ± 5) % for 24 h.

Bending stiffness testing

The present authors designed a procedure for testing the bending stiffness of flat items at a constant angle [14, 25-28]. The sample tested was placed on the horizontal plane of the testing apparatus. A metal ruler was placed on the sample so that its "0" marking coincided with the transverse side of the sample and edge of the apparatus. The sample with the ruler was moved until the end of the sample came in contact with the diagonal plane of the apparatus. The length of sample overhang was read from the ruler with an accuracy of 1 mm. The results were evaluated within a reference system developed by the present authors, where the lower the bending modulus, the less rigid the material. The interpretation of results is shown in ***Table 4***.

Abrasion resistance testing

Abrasion resistance was tested on Martindale apparatus pursuant to Standard PN-EN ISO 20344:2012 [29], with 25.600 abrasive cycles for dry samples and 12.800 for wet samples. Since the original method was dedicated for the assessment of individual fabrics, and the composite structures studied consisted of three layers, it was necessary to develop a new procedure for the interpretation of abrasive defects [30]. For this purpose, the percentage degree of material wear was assessed visually both for dry- and wet-abraded samples according to the guidelines specified in ***Table 5***.

Tear resistance testing

Tear resistance was tested pursuant to Standard PN-EN 1392:2007 [31]. In order to determine the tear resistance of individual layers, (20 ± 2) mm of adjacent layers was mounted in the jaws of a universal tester (Instron, Great Britain). Subsequently the ends of the samples were peeled at a rate of (100 ± 10) mm/min. Tear resistance was defined as the mean tear force per unit of width expressed in N/mm and calculated according to ***Equation (1)***:

$$\text{tear resistance} = \frac{\text{mean tear force [N]}}{\text{sample width [mm]}} \qquad (1)$$

Results equal to or greater than 0.4 N/mm were accepted as satisfactory.

Results

Laboratory test results

Bending stiffness results

Figure 2 shows bending stiffness results for the composite structure variants studied.

Table 3. *Basic metrological characteristics of the composite structure variants developed.*

Variant designation	First layer of composite (in contact with the foot)	Second layer of composite (in the middle)	3 First layers of composite (in contact with the footwear)		Basic metrological characteristics		
					Welding density, mm	Thickness, mm	Mass per unit area, g/cm^2
1-D-1 I	Knitted spacer fabric with 2 mm high microfilaments	Melt-blown nonwoven	Reinforcing nonwoven	1-ply	20	3.53	404.6
1-D-1 II					30	3.8	399.4
1-D-1 III					40	3.87	389.5
1-D-2 I				2-ply	20	3.92	454.2
1-D-2 II					30	4.15	467.9
1-D-2 III					40	4.35	517.9
2-D-1 I	Knitted spacer fabric with 3 mm high microfilaments			1-ply	20	3.24	484.8
2-D-1 II					30	3.95	459.4
2-D-1 III					40	4.3	451.4
2-D-2 I				2-ply	20	3.38	551.7
2-D-2 II					30	4.15	532.5
2-D-2 III					40	4.69	517.9
3-D-1 I	Knitted spacer fabric with 2.5 mm high microfilaments			1-ply	20	4.6	484.5
3-D-1 II					30	4.55	469.7
3-D-1 III					40	5.04	460.8
3-D-2 I				2-ply	20	4.8	548.6
3-D-2 II					30	5.04	549.7
3-D-2 III					40	5.43	549.8
4-D-1 I	Knitted spacer fabric with 4 mm high microfilaments			1-ply	20	5.36	462.0
4-D-1 II					30	5.62	463.7
4-D-1 III					40	5.8	460.8
4-D-2 I				2-ply	20	5.2	552.6
4-D-2 II					30	5.82	521.3
4-D-2 III					40	6.3	508.4

Table 4. *Interpretation of bending stiffness results for the composite structure material [25].*

Bending stiffness results, kPa	Interpretation
Modulus ≤ 1500	Positive result
Modulus > 1500	Negative result

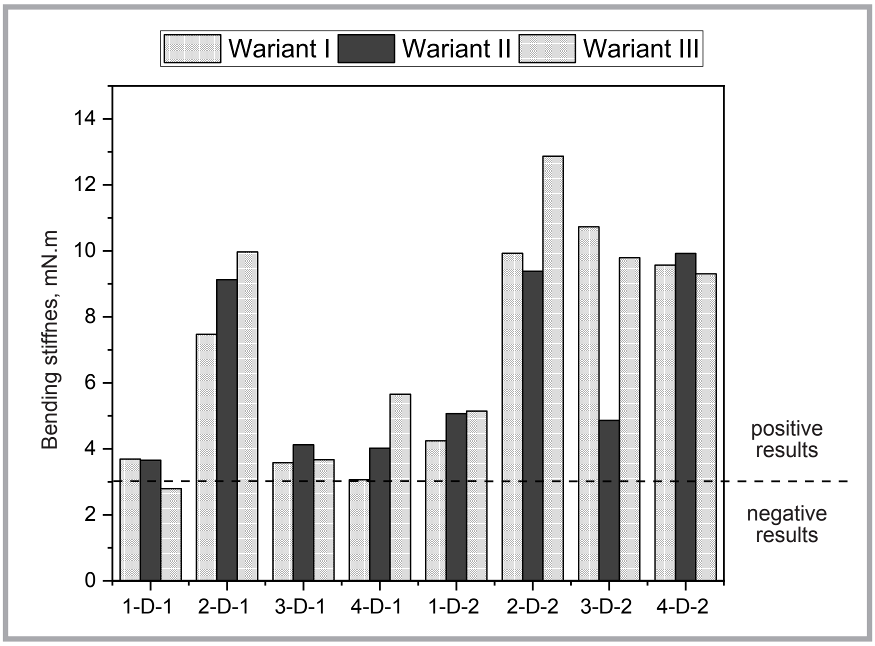


Figure 2. *Bending stiffness results for composite structure variants studied.*

Table 5. *Evaluation of percentage abrasive wear of composite structure materials for use in protective footwear [30].* ***Note:*** ** No composite structure samples corresponding to these criteria were obtained in tests. It is not possible to assign the percentage wear to the number of cycles from the standard. The percentage consumption of the sample surface was estimated by converting the area consumed to not used, according to own method. Percentage estimation was also made to obtain mathematical data necessary for statistical analysis.*

Percentage wear	Example image of abraded sample	Description of abrasion wear
0%*		Neither surface of the spacer fabric reveals damage
10%		Individual damaged fibres in a few spots on the top layer of the knitted spacer fabric
20%		Individual damaged fibres visible across the surface of the knitted fabric
30%		The entire surface of the top layer of the knitted spacer fabric worn, individual microfilaments ruptured
40%		The entire surface of the top layer of the knitted spacer fabric worn, individual defects in polyester microfilaments
50%		The entire surface of the top layer of the knitted spacer fabric worn, numerous defects in polyester microfilaments
60%		The entire surface of the top layer of the knitted spacer fabric worn, defects in polyester microfilaments on 60% of the area of the sample
70%		The entire surface of the top layer of the knitted spacer fabric worn, defects in polyester microfilaments on 70% of the area of the sample
80%		The entire surface of the top layer of the knitted spacer fabric worn, defects in polyester microfilaments on 80% of the area of the sample
90%*	Not applicable	The entire surface of the top layer of the knitted spacer fabric worn, defects in polyester microfilaments on 90% of the area of the sample
100%*	Not applicable	The entire surface of the top layer of the knitted spacer fabric worn; defects in polyester microfilaments affect the entire area of the sample

Abrasion resistance

Table 6 gives detailed results of abrasion testing for the composite structure variants developed.

Tear resistance

Figure 3 shows tear resistance results for composite structure layers.

Statistical analysis results

The results obtained were statistically analysed in terms of the effects of the welding spot density and reinforcing nonwoven thickness (one or two-ply) on the protective parameters.

The results were subjected to two-way ANOVA with *a posteriori* bootstrapping (1000 replicates). Post-hoc comparisons were made using the Bonferroni test. A 95% confidence interval (±2 *SD*) was determined for the mean variable values. The results exhibited a normal distribution. Analysis was performed using the software SPSS Statistics v. 23.0.

Table 7 shows descriptive statistics for the mechanical parameters (abrasion resistance, bending stiffness, tear resistance) for the composite structure variants developed.

Table 8 shows ANOVA statistics for the effect of the welding spot density on mechanical parameters in dependence on the number of plies in the reinforcing nonwoven layer.

Discussion of research results

The aim of the work presented was to analyse the impact of different densities of welding points on the mechanical parameters of composites in terms of their use in protective footwear as a suport of textiles in the form of inserts. The tests had a utilitarian purpose and concerned the evaluation of materials currently used in protective footwear in a ready-made product (insoles). Appropriate mechanical properties of this type of product constitute an essential condition for durability and associated comfort of use of the footwear. For a full assessment of the mechanical properties of a point – welded product, the method of joining the layers should be evaluated. Therefore the work used an innovative approach to research inserts for protective footwear using non-standard methods based on techniques used in the assessment of personal protective equipment. The assumption was the utilitarian evaluation of the product and the development of a research methodology which would allow to assess the suitability of new types of inserts based on ultrasonically welded textile composite structures. It should be emphasised that, so far, evaluation of the durabilty of insoles for protective footwear has not been conducted in this sense.

The technology of bonding three textile layers of different chemical composition and structure by means of ultrasonic spot welding presented leads to multi-functional textile composite structures. The composite structures contain knitted spacer fabrics with a pronounced 3D structure. Such textiles are composed of two outer layers with a specially designed spacing volume. Such a structural arrangement leads to additional elasticity. According to Wollina and Heide [32-36], the fibres most frequently used in knitted spacers are polyamide, polyester, viscose, cellulose (lyocell), and cotton. Heide reported that knitted spacer fabrics ensure high breathability and mechanical strength. By combining different textile products (woven and knitted fabrics and nonwovens), one can achieve an integrated assembly exhibiting superior physical and mechanical properties as compared to those of the constituent materials. Strong and durable bonding of layers may be achieved by a number of techniques. The present authors used ultrasonic spot welding with the objective of determining whether the density of welding spots had a significant effect on the protective parameters of the resulting composite structures intended for protective footwear inserts [37]. An integrated material assembly was obtained by combining three textiles (a 3D knitted fabric and two nonwovens). Subsequently the structures studied were tested pursuant to standards harmonised with Directive 89/686/EEC [22] and current criteria for evaluation of casual footwear.

The tests showed that the thickness of the composite structures and their mass per unit area depend on that of the knitted spacer fabric and welding density (***Table 3***). The greatest thickness was recorded for composite structures in which the external layer in contact with the foot was 3 or 4 mm thick. The composite structure thickness was also slightly higher for those variants containing a two-ply reinforcing layer (in contact with the footwear). In the case of composite structures with one-ply reinforcing layers, those with a welding density of 40 mm (variant III) were thicker by approx. 10% than those with a welding density of 20 mm (variant I). In the case of composite structures with two-ply reinforcing layers, the difference between welding densities of 20 mm and 40 mm was approx. 20%. The welding density did not significantly affect the mass per unit area. The lowest surface density was found for the composite structures with spacer fabric No. 1. In the case of composite structures containing a spacer fabric with 2 mm high microfilaments, the mass per unit area was approx. 400 g/cm^2 for a one-ply reinforcing layer and 450 g/cm^2 for a two-ply layer. For the other composite structures, the surface density amounted to approx. 450 g/cm^2, with the ones containing two-ply reinforcing layers exceeding 500 g/cm^2.

Statistical analysis of the test results revealed that the density of ultrasound welding spots influenced the mechanical parameters of the protective composite structures studied. Bending stiffness was significantly ($p < 0.05$) affected both in variants with one- and two-ply reinforcing layers. The bending stiffness of materials with two-ply reinforcing nonwovens

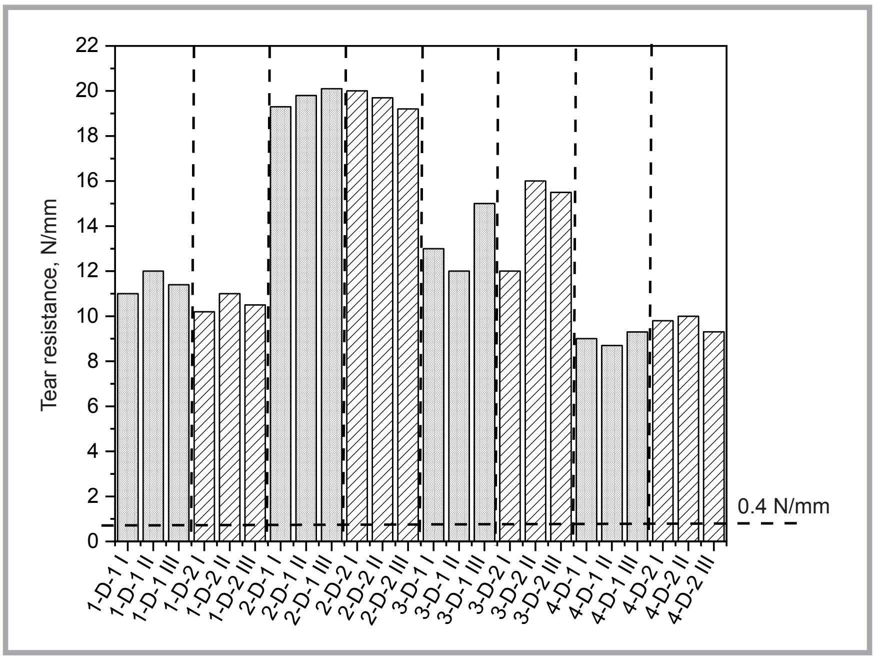


Figure 3. *Tear resistance of composite structure layers.*

Table 6. *Abrasion resistance of composite structures containing an outer knitted spacer fabric with a filament height of 2 mm, 3 mm, 2.5 mm & 4 mm.*

Cycle No.	Designation												
	1-D-1 I	1-D-1 II	1-D-1 III	2-D-1 I	2-D-1 II	2-D-1 III	3-D-1 I	3-D-1 II	3-D-1 III	3-D-1 I	4-D-1 I	4-D-1 II	4-D-1 III
25.600 dry	40%	50%	50%	50%	20%	20%	70%	70%	50%	70%	60%	50%	50%
12.800 wet	10%	20%	20%	20%	20%	20%	50%	40%	40%	50%	50%	30%	30%
	1-D-2 I	1-D-2 II	1-D-2 III	2-D-2 I	2-D-2 II	2-D-2 III	3-D-2 I	3-D-2 II	3-D-2 III	3-D-2 I	4-D-2 I	4-D-2 II	4-D-2 III
25.600 dry	30%	40%	40%	40%	40%	50%	40%	30%	30%	40%	30%	30%	30%
12.800 wet	20%	20%	20%	40%	20%	10%	20%	20%	20%	20%	20%	20%	20%

Table 7. Descriptive statistics of mechanical parameters for the composite structure variants developed. ***Note:*** *N – number of measurements, M – average, Me – median, SD – standard deviation, Min – minimal value, Max – maximal value.*

Mechanical parameters		Composite structure variant			N	M	Me	SD	Min	Max
		Designation	Welding spot density	Reinforcing nonwoven plies						
Abrasion resistance, %	Dry	2-D-1 I	20	1	3	50.00	50.00	30.00	20.00	80.00
		2-D-1 II	30	1	3	30.00	30.00	10.00	20.00	40.00
		2-D-1 III	40	1	3	26.67	30.00	5.77	20.00	30.00
	Wet	2-D-1 I	20	1	3	23.33	20.00	15.28	10.00	40.00
		2-D-1 II	30	1	3	16.67	20.00	5.77	10.00	20.00
		2-D-1 III	40	1	3	16.67	20.00	5.77	10.00	20.00
Bending stiffness, mN.m		2-D-1 I	20	1	3	5.35	5.19	0.30	5.16	5.70
		2-D-1 II	30	1	3	4.51	3.62	1.88	3.23	6.67
		2-D-1 III	40	1	3	5.83	5.22	1.13	5.14	7.13
		2-D-2 I	20	2	3	7.87	7.78	7.63	8.20	0.30
		2-D-2 II	30	2	3	7.01	6.65	6.60	7.79	0.67
		2-D-2 III	40	2	3	9.16	9.70	7.82	9.95	1.16
Tear resistance, N		2-D-1 I	20	1	3	5.60	5.70	0.26	5.30	5.80
		2-D-1 II	30	1	3	6.67	6.70	0.15	6.50	6.80
		2-D-1 III	40	1	3	4.83	4.80	0.25	4.60	5.10
		2-D-2 I	20	2	3	5.87	5.80	5.70	6.10	0.21
		2-D-2 II	30	2	3	7.07	7.00	6.90	7.30	0.21
		2-D-2 III	40	2	3	5.77	5.90	5.30	6.10	0.42

Table 8. ANOVA statistics showing the effect of the welding spot density on mechanical parameters in dependence on the number of plies in the reinforcing nonwoven layer. ***Note:*** *N – part of sample, M – medium, Ja – SD median – standard deviation, Min/Max – minimum/maximum, F (2, 26) – ANOVA statistics with degrees of freedom, p – ANOVA condition, η^2 – foreign power (eta).*

Mechanical parameters		Reinforcing layer ply		Welding spot density			Post-hoc test	*F*(2, 6)	*p*	η^2
				20	30	40				
Abrasion resistance, %	Dry	1	M	50.00	30.00	26.67	–	1.39	*NS*	0.32
			SD	30.00	10.00	5.77				
	Wet	1	M	23.33	16.67	16.67	–	0.44	*NS*	0.13
			SD	15.28	5.77	5.77				
Bending stiffness, mN.m		1	M	5.35	4.51	5.83	30 < 20. 40	4.82	$p < 0.05$	0.52
			SD	0.30	1.88	1.13				
		2	M	7.87	7.01	9.16	30 < 20. 40	5.52	$p < 0.05$	0.65
			SD	0.30	0.67	1.16				
Tear resistance, N		1	M	5.60	6.67	4.83	30 > 20. 40	48,70	$p < 0.001$	0.94
			SD	0.26	0.15	0.25	20 > 40			
		2	M	5.87	7.07	5.77	30 > 20. 40	18.12	$p < 0.001$	0.86
			SD	0.21	0.21	0.42	20 > 40			

was higher by approx. 50% as compared to one-ply nonwovens. The highest bending stiffness was found for composite structure variants with spacer fabric no. 2 (amounting to more than 7 and 10 mNm for variants with one- and two-ply reinforcing nonwovens, respectively). In the case of composite structures incorporating spacer fabric No. 2, the bending stiffness also depended on the welding density. The highest bending stiffness was recorded for composite structure variant III. On the other hand, the bending stiffness did not exceed 5 mNm for spacer fabric No. 1, no matter whether for one- or two-ply reinforcing layers.

The tear test of the composite structure layers revealed a statistically significant ($p < 0.001$) effect of the welding density on this parameter, both for variants containing one- and two-ply reinforcing nonwovens. The highest tear force, exceeding 18 N/mm, was found for the composite structure variant containing spacer fabric No. 2. In turn, the lowest tear force, 8 N/mm was recorded for the composite structure containing spacer fabric No. 4.

The tests did not reveal a statistically significant effect of the welding density on dry or wet abrasion resistance for the variant containing a one-ply reinforcing layer. According to the criteria adopted herein, damage estimated as more than 50%, that is, complete wear of the spacer surface and damage to filaments, was observed for the following variants: 2-D-1 I, 3-D-1 II, and 4-D-1 I. Lesser damage, in the form of 30-40% wear of the structure, was found for variants 1-D-1 II and III, 3-D-1 III, as well as 4-D-1 II. In the other cases, the top layer of the knitted spacer fabric was completely worn, while the filaments were damaged slightly. Wet abrasion led to some rupture of microfilaments (10-20%) in composite structure variants 3-D-1 I and 4-D-1 I.

The tests conducted indicate that both the material composition and structure of composite structure inserts for protective footwear may be optimised. The beneficial composite structure variant should contain a knitted spacer fabric with 3 mm high microfilaments, a melt-blown nonwoven, and a one-ply reinforcing nonwoven with the welding spots arranged at 30 mm intervals.

Conclusions

Inserts made of ultrasonically spot-welded textile composite structures may offer protective footwear users greater comfort in terms of mechanical resistance. These properties may be improved by optimising the density of welding spots with a given diameter, as well as by their regular spacing during the welding process. The evaluation method proposed, taking into consideration three parameters critical to footwear use (abrasion, layer tear, and bending stiffness), may be a useful tool in assessing textile composite structure inserts for protective footwear.

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37. Application of the utility model of the Protective footwear insole application no. W.127975 [WIPO ST 10 / C PL127975U] to the Patent Office of the Republic of Poland on 2019-01-21, Applicant: Central Institute of Protection Work – National Research Institute, PSO Maskpol Spółka Akcyjna, Łódź Technical University.

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