

Article

Influence of Fabric Characteristics on Mechanical Performances of Protective Gloves

Ali Afzal ^{1,*}, Shahbaz Ahmad ^{2,3}, Sheraz Ahmad ², Muhammad Irfan ¹, Liliana Indrie ^{4,*}, Faheem Ahmad ² and Mariana Rațiu ⁵

¹ Department of Textile Engineering, School of Engineering & Technology, National Textile University, Faisalabad 37610, Pakistan; irfan@ntu.edu.pk

² Department of Textile Technology, School of Engineering & Technology, National Textile University, Faisalabad 37610, Pakistan; shahbaz.ahmad@midassafety.com (S.A.); sheraz@ntu.edu.pk (S.A.); faheem@ntu.edu.pk (F.A.)

³ Midas Safety Inc., Toronto, ON M3B 3H9, Canada

⁴ Department of Textiles, Leather and Industrial Management, Faculty of Energy Engineering and Industrial Management, University of Oradea, Universității Str. No. 4, 410087 Oradea, Romania

⁵ Department of Mechanical Engineering and Vehicles, Faculty of Management and Technological Engineering, University of Oradea, Universității Str. No. 1, 410087 Oradea, Romania; mratiu@uoradea.ro

* Correspondence: aliafzalch89@gmail.com (A.A.); lindrie@uoradea.ro (L.I.);
Tel.: +92-322-4075177 (A.A.); +40-259-408106 (L.I.)

Abstract: In this study, high-performance gloves were developed from core–sheath yarn. Different materials were used in the core, while Kevlar fibers were used in the sheath. The filaments used in the core included glass, ultra-high-molecular-weight polyethylene (UHMWPE), and stainless steel filaments with 100D and 200D linear densities. Seamless gloves were developed from these yarns with varying characteristics to observe their effect on the performance of seamless gloves. The factors examined were the areal density (GSM) of the gloves, linear density of sheath fibers, core material, and plied structure. The mechanical behavior of the gloves was evaluated by different tests such as blade cut resistance, coupe cut resistance, tear resistance, and puncture resistance. The results demonstrated that the sheath fiber characteristics, core material type, yarn’s plied structure, and fabric’s areal density are statistically significant factors affecting the properties of gloves in relation to mechanical risk. The selection of appropriate levels of these parameters is crucial for better achievement of desired properties in workwear protection applications.

Keywords: cut-resistant gloves; high-performance gloves; Kevlar; UHMWPE; core sheath yarn; stainless steel; glass fiber



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1. Introduction

Technical/high-performance fibers are mostly used to manufacture technical products. These specialized products are used in sports, packing, agriculture, construction, hospitals, industries, automobiles, etc. [1,2]. Researchers have been pushed to produce technical textile items by ever-increasing human needs. The selection of materials, manufacturing techniques, and yarn and fabric characteristics are the major parameters which govern the performance of gloves against mechanical risks, as well as their hand performance. A glove that has improved cut protection ability without hindering hand movement is a desired solution for occupational health and safety applications [3].

Cut and needle stitch injuries have a potentially fatal danger to pathologists and surgeons. Such injuries were evaluated by the German institute of pathology from 2002 to 2007 [4]. It

was concluded that the introduction of cut-resistant gloves prevented hand injuries. Cut-resistant gloves proved to be cost-effective personal protective equipment (PPE) compared to the medical and administrative costs of such injuries [5]. The risks that are commonly faced by health care workers, butchers, and sewing professionals include needlestick and sharp cut injuries [6]. A lot of work has been carried out on cut protection, while other aspects of mechanical risks, including puncture and tear resistance, have been almost neglected as a combined focus along with cut protection [7].

High-strength fibers such as Poly Para-Phenylene Terephthalamide (para-aramid) and ultra-high-molecular-weight polyethylene (UHMWPE) are ideal materials for protective clothing. These high-performance materials have advantages over steel and other metals due to their higher strength-to-weight ratio. These fibers are flexible and exhibit high cut resistance properties. The materials' inherent cut-resistant properties significantly affect their performance and application areas. Inorganic fibers provide better cut resistance than organic fibers. This is because of two different factors: First, inorganic fibers like glass have higher hardness levels compared to organic fibers like para-aramid [8]. A blade penetrates organic fiber due to its sharpness, while it becomes dull when it comes into contact with inorganic fibers. A study reported that poly-p-phenylene benzobisoxazole (PBO) (Zylon®) has superior cut resistance compared to para-aramid (Kevlar) and UHMWPE at different cut angles [9]. Aramid, glass, and steel are considered materials with a high cut performance. Steel is used as a core filament for the commercial production of cut-resistant gloves [10]. A study reported that increasing the glass core size resulted in an increase in the tensile strength and tenacity of the yarn, whereas increasing the steel core size resulted in a decrease in the tensile strength and tenacity for the same yarn count [11]. Furthermore, composite yarns with glass cores had greater tensile strength and tenacity than composite yarns with steel cores. Changing the glass core size had an insignificant effect on the elongation at break and time to break of composite yarns. However, increasing the steel core size resulted in an increase in the yarn's elongation at break and time to break. The intrinsic properties of materials may vary the cut resistance responses for different testing standards such as ASTM F1790, ISO 13997, and BS EN 388. It has been reported that the cut resistance of steel behaved almost similarly for ASTM, ISO, and EN standards, while in contrast, glass-reinforced structures provided different results for different standards [12].

The cut resistance of hybrid yarns decreases with the increase in yarn count [13]. Core sheath structures provide better cut resistance performance than single yarns [14,15]. It was reported that dual-core hybrid yarn provided better protection against mechanical risks. Such structures may increase the fabric thickness, thereby reducing the hand performance [16]. The yarn twist has an indirect relation with the cut resistance of core sheath yarn structures [15]. The knitting structure also influences the cut performance characteristics [17]. The energy that is required to cut through the material depends on the coefficient of friction and consists of two components: the lost energy exerted by the material on the blade sides and the cutting energy at the edge of blade. These have opposite effects on the cut resistance of the material. An increase in dissipated energy increases the cut resistance. With an increase in the coefficient of friction, the cut resistance may be enhanced or reduced depending on the thickness and structure of the material [17].

A study stated that a good puncture resistance of woven fabric was achieved by the use of a combined UHMWPE core–para-aramid sheath weft yarns compared to 100% para-aramid and para-aramid–glass combinations. The puncture resistance decreases with an increase in the ratio of the core filament. With a decrease in the core–sheath ratio, the weight and thickness of a hybrid yarn increases, which ultimately results in improved cut, abrasion, and puncture resistance properties. Para-aramid–UHMWPE yarn formed fabric

achieves high cut, abrasion, and puncture resistance and is recommended for different applications like automotive, glass, steel, and metal work [13].

From our literature review, it was observed that no study has reported the mechanical risk protection, including blade cut resistance, coupe cut resistance, tear resistance, and puncture resistance, of gloves with respect to the linear density of the sheath fibers, use of different materials as core in yarns, no. of plies in the resultant yarn, and gauge of the glove-knitting machine. The objectives of this study were to examine the influence of different materials, fiber linear densities, core yarn structures, and fabric structural parameters on the protection against different mechanical risks. This will help develop protective gloves with optimum protection properties.

2. Materials and Method

2.1. Materials

In this study, high-performance materials were used to develop sheath–core spun yarns for the development of gloves. The details of the fibers are given below in Table 1.

Table 1. Fibers used for yarn development.

Sr.	Fiber	Specifications	Supplier	Tenacity (g/D)	Elongation (%)	Tensile Modulus (g/D)
1	Kevlar®	1.5D × 51 mm and 2.25D × 51 mm	DuPont, USA	23	3.6	866
2	Steel	100D/1f and 200D/1f	Zheng Tian Garden and Craft Ltd., China	3.57	2.0	222
3	Glass	100D/200f and 200D/200f	Fulltech Fiber Glass Corp., China	6.7 and 5.6	4.8	313
4	UHMWPE	100D/75f and 200D/150f	Huvis Corporation, Korea	14	8.0	866

Kevlar® is a trademark of DuPont for Poly Para-Phenylene Terephthalamide (para-aramid), and Duraron® is a trademark of the Huvis corporation for ultra-high-molecular-weight polyethylene fiber.

2.2. Sample Preparation Methods

Initial trials were carried out to finalize the processing parameters. A ring core–sheath spun yarn process was used for the yarn development. Stainless steel (S), glass (G), and UHMWPE (P) filaments were used in the core, with the sheaths having different linear densities of Kevlar fibers (Fiber D), as shown in Table 2. The ring core–sheath spun yarn with a 100D core was made in 29.53 Tex, while the 200D core was developed in 59.05 Tex. The 29.53 Tex yarn with a 100D core was twisted in a two-ply formation to develop twisted two-ply yarn to obtain a resultant linear density of 59.05 Tex of the yarn, which is equivalent to single-ply yarn. The schematic difference between the yarn structures is shown in Figure 1.

The carded ring core–sheath spun yarn process was employed. The Toyoda Roving frame model FL-100 was used, which has 120 spindles. The input finished sliver had a count of 0.138Ne. The Jingwei F1520 ring frame was employed for yarn production and has 480 spindles, using roving of 1 Nec linear density. The spindle speeds on the ring spinning were 8000 rpm and 13,000 rpm for the 59.05 Tex and 29.53 Tex sheath–core spun yarns, respectively. The pre-tension applied on the core filament was 1.03. The main equipment used for sample development is described in Table 3.

Table 2. Design of experiment.

Sr.	Sheath Fiber Denier (Fiber D)(Denier)	Core Material (Core)	Yarn Plies (No. of Plies)	Glove Areal Density (GSM) (g/m ²)
1	Kevlar 1.5D	Steel 100D	Two-Ply	200
2	Kevlar 1.5D	Steel 200D	Single-Ply	200
3	Kevlar 2.25D	Steel 100D	Two-Ply	200
4	Kevlar 2.25D	Steel 200D	Single-Ply	200
5	Kevlar 1.5D	Glass 100D	Two-Ply	200
6	Kevlar 1.5D	Glass 200D	Single-Ply	200
7	Kevlar 2.25D	Glass 100D	Two-Ply	200
8	Kevlar 2.25D	Glass 200D	Single-Ply	200
9	Kevlar 1.5D	UHMWPE 100D	Two-Ply	200
10	Kevlar 1.5D	UHMWPE 200D	Single-Ply	200
11	Kevlar 2.25D	UHMWPE 100D	Two-Ply	200
12	Kevlar 2.25D	UHMWPE 200D	Single-Ply	200
13	Kevlar 1.5D	Steel 100D	Two-Ply	180
14	Kevlar 1.5D	Steel 200D	Single-Ply	180
15	Kevlar 2.25D	Steel 100D	Two-Ply	180
16	Kevlar 2.25D	Steel 200D	Single-Ply	180
17	Kevlar 1.5D	Glass 100D	Two-Ply	180
18	Kevlar 1.5D	Glass 200D	Single-Ply	180
19	Kevlar 2.25D	Glass 100D	Two-Ply	180
20	Kevlar 2.25D	Glass 200D	Single-Ply	180
21	Kevlar 1.5D	UHMWPE 100D	Two-Ply	180
22	Kevlar 1.5D	UHMWPE 200D	Single-Ply	180
23	Kevlar 2.25D	UHMWPE 100D	Two-Ply	180
24	Kevlar 2.25D	UHMWPE 200D	Single-Ply	180

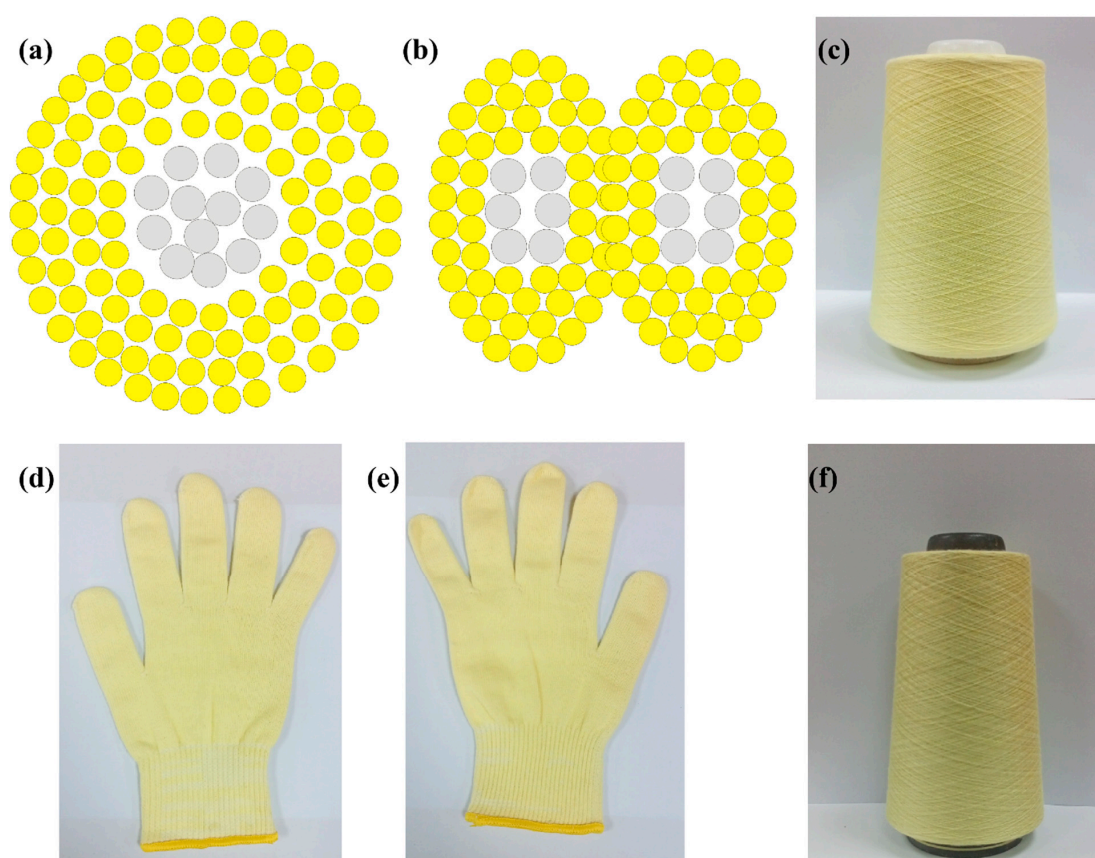
**Figure 1.** (a) Schematic diagram of ring sheath–core single-ply core-spun yarn. (b) Schematic diagram of two-ply core-spun yarn. (c) Glass core-spun yarn with Kevlar sheath. (d) Glove structure's technical face. (e) Glove structure's technical back. (f) Steel core-spun yarn with Kevlar sheath.

Table 3. List of equipment used for sample development.

Sr.	Equipment	Model	Manufacturer
1	Ring core spinning	F1520	Jingwei, China
2	Two-for-one twister machine	373	Murata, Japan
3	Glove-knitting machines	N-SFG	Shima Seiki, Japan

The gloves were developed using seamless glove-knitting machines by Shima Seiki, model N-SFG; we used 13 gauges and 15 gauges to develop gloves with areal densities (GSM) of 180 g/m² and 200 g/m², respectively, in a single jersey design. The machine has 88 needles.

2.3. Characterization

The equipment and testing protocols that were used for characterization to evaluate the performance of the developed samples are described in Table 4.

Table 4. Characterization equipment with standard protocol used.

Sr.	Characterization	Equipment	Test Standard
1	Blade cut resistance	TDM-100 tester, RGI	ASTM F1790:2015
2	Coupe cut resistance	Coup test XP, Sodemat	EN388:2016
3	Tear resistance	Tenso Lab4, Mesdan	EN388:2016
4	Puncture resistance	Instron 5565	EN388:2016

To measure the performance of gloves, the ASTM F1790 and EN 388 test methods were used [18]. The blade cut resistance was measured with a TDM-100 Tomodynamometer cut resistance tester using a sharp linear blade at a 20 mm distance. The sample was tested against three different weight loads, with five repetitions each. The results are recorded in units of Newton per millimeter (N/mm). The test method used to measure the cut resistance using a circular blade is known as the coupe cut resistance. Sodemat Coup test expert version, CT3-051, France, was employed. The coupe cut resistance is measured as the number of cycles that are completed by a circular rotating cutting blade moving in a linear direction with 50 mm displacement at a constant speed under a standard 5 N contact force to cut through a sample vs. the control sample. Its unit is no. of cycles. The circular blade was replaced with a new one after each sample test to avoid the risk of a blunt blade. The coupe cut index is calculated using the number of rotations of the circular blade that are required to cut the sample and the mean rotations of the blade that are required to cut the standard sample as per the following equation:

$$I_n = \frac{(C_n + T_n)}{C_n}$$

where I_n is the coupe cut index, C_n is the average rotation of the circular blade before and after the cut of the test sample, and T_n is the rotations that are required to cut the test sample.

The tear resistance is defined as the force that is required to tear the fabric. It was measured on a Tenso Lab4 Tensile strength tester model 2512E, Mesdan, Italy. A fabric sample was taken from the palm portion of a glove in 100 mm × 50 mm dimensions. The slit should be made with a shrill blade at straight and vertical angles to fabric sample. Five tests were performed for each sample. The test results are reported in Newton.

The puncture resistance is defined as the force that is required to pierce the fabric with a thin pin. A rounded sample of a minimum 40 mm radius was selected without seams and other assistance. Puncture testing was performed on an Instron 5565 load testing frame

using a 100 N load cell and controlled with Bluehill 2 software. A probe displacement rate of 10 mm/min was used. The results are recorded in Newton force.

3. Results and Discussion

Minitab statistical software ver. 17 was used to analyze the data. A response surface regression analysis was performed. The factors and interactions with p -values above α -level (0.05) were considered non-significant and therefore removed from the analysis. The analysis of variance and model summary analysis are given in Tables 5 and 6, respectively, for all the test methods.

Table 5. Analysis of variance table for all test methods.

Source	Blade Cut Resistance			Coupe Cut Resistance			Tear Resistance			Puncture Resistance		
	DF	Adj SS	p -Value	DF	Adj SS	p -Value	DF	Adj SS	p -Value	DF	Adj SS	p -Value
Model	8	215,887,008	0.000	10	2556.62	0.000	9	234,769	0.000	5	16,867	0.000
Linear	4	198,685,642	0.000	5	2538.54	0.000	5	229,133	0.000	3	14,369	0.000
Fiber D				1	2.34	0.026	1	315	0.053			
Plies	1	21,281,667	0.000	1	14.28	0.000	1	495	0.019			
GSM	1	17	0.992	1	7.58	0.001	1	8251	0.000	1	6017	0.000
Core	2	177,403,958	0.000	2	2514.35	0.000	2	220,072	0.000	2	8352	0.000
2-Way Interaction	4	17,201,367	0.000	5	18.07	0.000	4	5636	0.000	2	2499	0.000
Fiber D*GSM				1	3.29	0.011						
Fiber D*Core				2	8.89	0.001	2	3474	0.000			
Plies*Core	2	13,466,458	0.000									
GSM*Core	2	3,734,908	0.001	2	5.89	0.006	2	2162	0.000	2	2499	0.000

Table 6. Model summary of all test methods.

	Blade Cut Resistance	Coupe Cut Resistance	Tear Resistance	Puncture Resistance
S	408.80	0.61	8.42	10.00
R-sq	98.85%	99.81%	99.58%	90.36%
R-sq(adj)	98.24%	99.67%	99.31%	87.68%
R-sq(pred)	97.06%	99.36%	98.76%	82.85%

As per the results shown in the ANOVA in Table 5, it was observed that the yarn core and glove areal density (GSM) had a statistically significant effect on all the tested properties. In contrast, the number of yarn plies had significant effects on the blade cut, coupe cut, and tear resistance properties. In addition, the effect of the fiber linear density was found to be significant for the coupe cut and tear resistance properties only. The R-square values obtained for all response parameters were high, which explains why most of the variations in the test results are explained by the input factors (Table 6). Figure 2 shows the main effect plots of the fitted mean values for all test types. It was observed that the number of plies had indirect relationships with the blade cut, coupe cut, and tear resistance properties. The highest indirect relation effect was observed for the blade cut resistance, followed by a sharp slope down to the tear resistance and coupe cut resistance results. In contrast, the glove areal density (GSM) showed indirect relationships with all the

tested properties. The highest effect was observed for tear resistance, followed by puncture resistance, coupe cut resistance, and blade cut resistance in order. Furthermore, an indirect relationship was observed between the fiber linear density and tear resistance, while a direct relationship was observed with the coupe cut resistance results. The influence of the core materials was also found to be significant and sharp for different material types. The glass core provided the best results for coupe cut resistance, while the steel core showed the best results with regard to the blade cut resistance properties. The tear and puncture resistance properties were found to be high using a UHMWPE core.

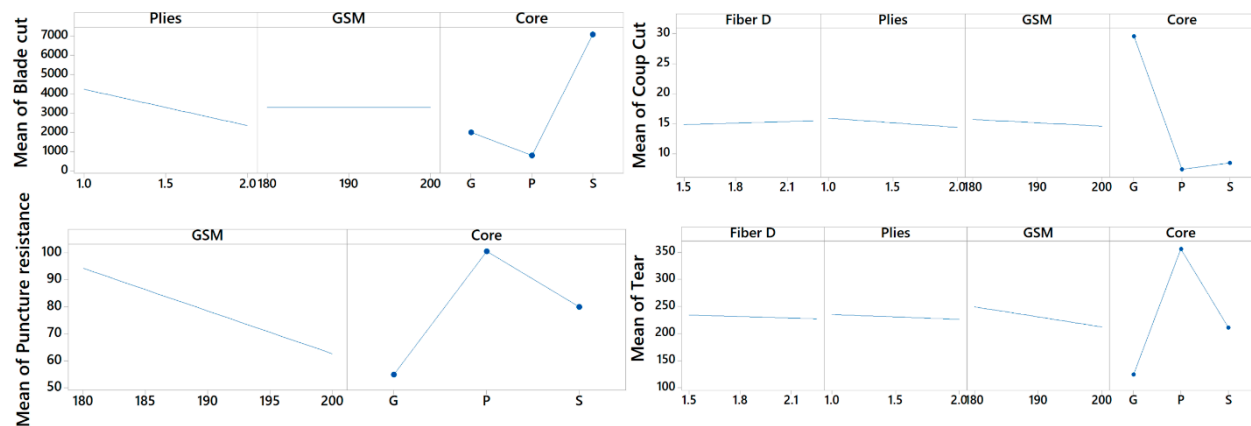


Figure 2. Main effect plots of fitted means for all response parameters.

3.1. Blade Cut Resistance

The ANOVA results suggested that the core material and number of plies have significant linear inverse relationships with the blade cut resistance values, while a non-significant direct linear relationship was found for the machine gauge (GSM). The reason may lie in the fact that the material hardness and ductility are the prevailing factors governing the blade cut resistance results. The ductility and material hardness properties play vital roles in the blade cut resistance performance. The ductility helps in the formation of a loop upon the application of applied forces during cutting, which may resultantly consume applied energy to resist cuts in the structure. Organic materials have lower levels of hardness compared to inorganic materials, which means that steel cores have shown the highest blade cut resistance, followed by glass and UHMWPE core-spun yarn structures. Furthermore, it is easier to cut finer filaments than a coarser filament, which is observed in the reduction in blade cut resistance with respect to plies, where the filament diameter reduces in double-ply yarns [19]. In addition, blade slippage is more predominant in the case of single-ply cores than double-ply core-spun yarn structures, leading to a decrease in the blade cut resistance with the increase in the number of plies in core-spun yarn.

The interaction terms of the core material with the no. of plies and machine gauge were found to be significant, with p -values below the α -level (0.05); therefore, the machine gauge was also considered a significant factor, despite its higher p -value as a linear interaction (Table 6). The interaction of the core with plies was found to have a direct relationship with the blade cut resistance, which explains why with the increase in the no. of plies, different materials behave differently. In other words, the coefficient of friction changes, hence causing a loss of the energy exerted by the material on the blade sides [20]. It was also observed that the machine gauge and core material type have direct relationships with the blade cut resistance. This effect is explained based on the core sheath ratio, which is a significant factor influencing the cut-resistant properties.

The surface plots of the material properties vs. blade cut resistance are shown in Figure 3. The results suggested that gloves made with two-ply core-spun yarn offer low cut

resistance compared to single yarn. The horizontal blade cut resistance increases with the increase in the gloves' GSM for glass and UHMWPE cores, while it reduces for steel-core glove structures. It was also observed that the steel core provided the highest value of cut resistance, followed by glass and UHMWPE in order. A good selection of manufacturing parameters with respect to blade cut resistance would be to use a steel core, with a single-ply yarn glove knitted with a lower fabric areal density. The regression equations developed for the blade cut resistance for different cores are as follows:

$$\text{Blade cut resistance (Glass)} = -4994 - 1438 \text{ Plies} + 48.1 \text{ GSM} \quad (1)$$

$$\text{Blade cut resistance (UHMWPE)} = 1156 - 313 \text{ Plies} + 0.6 \text{ GSM} \quad (2)$$

$$\text{Blade cut resistance (Stainless Steel)} = 22140 - 3900 \text{ Plies} - 48.5 \text{ GSM} \quad (3)$$

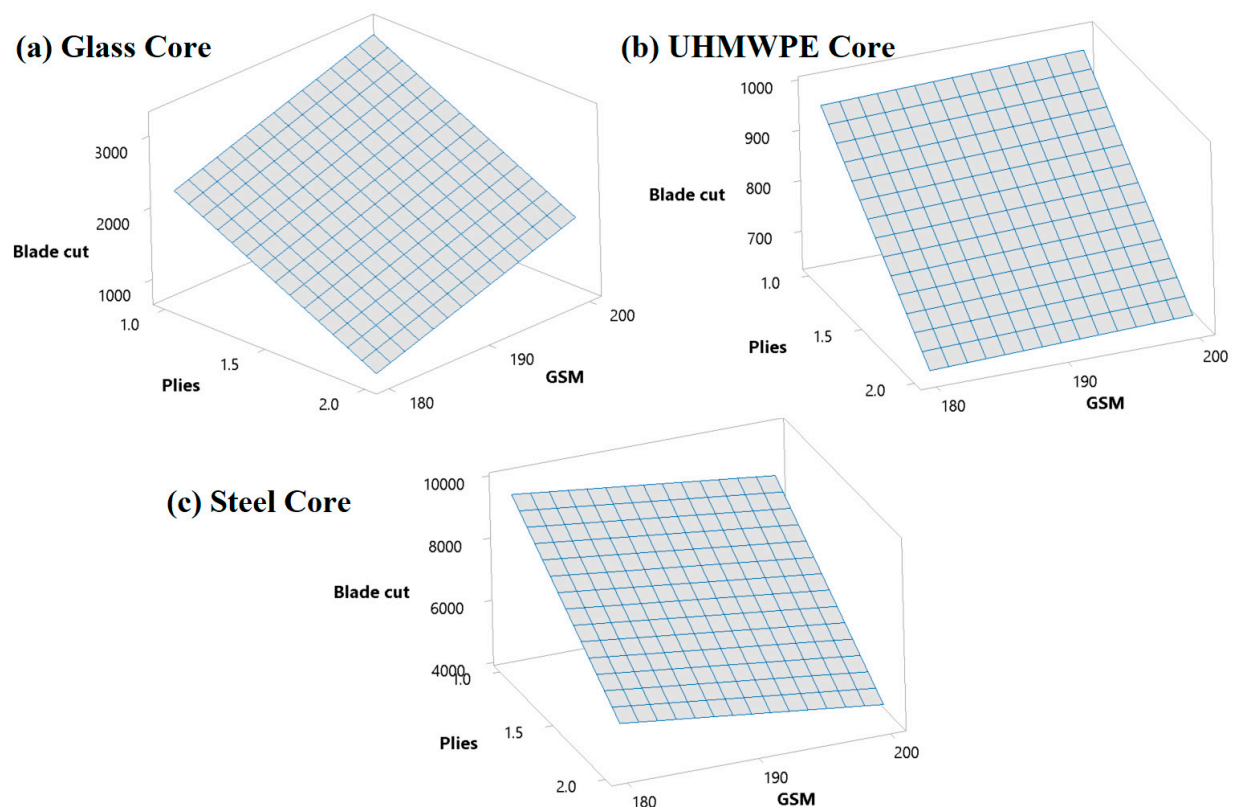


Figure 3. Response surface plots for blade cut resistance.

3.2. Coupe Cut Resistance

The ANOVA results suggested that the sheath fiber denier, core material, number of plies, and machine gauge have significant linear relationships with the coupe cut resistance values. The interaction terms of the sheath fiber denier with the machine gauge and core material were also found to be significant, with p -values below the α -level (0.05). In addition, the interaction of the machine gauge and core material were also found significant for coupe cut-resistant properties.

The fiber denier as a linear term and its interaction terms with the machine gauge and core type were found to be in direct relationships with the coupe cut resistance results. The coupe cut resistance increases with increases in the sheath fiber denier. Meanwhile, the number of plies and machine gauge were found to be in indirect relationships with the coupe cut results. Finer sheath fibers cover the core filament better than coarser fibers and therefore impart their contribution towards cut-resistant properties. The increase in the

number of plies employs finer filaments, which are easier to cut compared with coarser filaments. The dense fabric structure reduces the slippage of yarns and hence reduces the blade slippage, which thereby reduces the coupe cut resistance values.

Figure 4 shows the effects of the fiber linear densities, yarn plies, and fabric GSM on the cut resistance by coupe tests of different core materials. The effect of a glass core material was observed to be higher than those of steel and UHMWPE core materials, which is in accordance with the literature [21]. The reason lies in the fact that glass is a hard and brittle inorganic material which resists incision forces better than the other used materials. As this test method involves cutting with a circular rotating blade, stretching of the material may not occur. In such a case, a material's resistance against a cut is more effectively ensured by glass due to its hard structure compared with steel filament. The graphical trends clearly show that the cut resistance increases with the increase in fiber denier. As a thick fiber is more resistant to cuts, better cut resistance values are obtained for thicker sheath fibers. Gloves made with two-ply yarns have lower coupe cut resistances compared to single yarn. This is also consistent with the trend for sheath fibers. The thicker material absorbs more energy and is more resistant to cuts than thinner filaments [14]. The coupe cut resistance decreases with the increase in the fabric's GSM. With an increase in areal density, the yarn slippage gaps reduce, and hence, the material will easily be cut. A good coupe cut resistance property will be achieved by using a core sheath yarn with a glass core with coarser Kevlar sheath fibers in a single-ply yarn, which should be used to develop a low-areal-density glove structure. The regression equations developed for the coupe cut resistance for different cores are as follows:

$$\text{Coupe cut resistance (Glass)} = 59.1 - 15.77 \text{ Fiber D} - 1.542 \text{ Plies} - 0.1727 \text{ GSM} + 0.0988 \text{ Fiber D} \times \text{GSM} \quad (4)$$

$$\text{Coupe cut resistance (UHMWPE)} = 63.6 - 18.37 \text{ Fiber D} - 1.542 \text{ Plies} - 0.2877 \text{ GSM} + 0.0988 \text{ Fiber D} \times \text{GSM} \quad (5)$$

$$\text{Coupe cut resistance (Stainless Steel)} = 62.6 - 19.67 \text{ Fiber D} - 1.542 \text{ Plies} - 0.2638 \text{ GSM} + 0.0988 \text{ Fiber D} \times \text{GSM} \quad (6)$$

3.3. Tear Resistance

The ANOVA results explain the significant linear relationships of the number of plies, machine gauge, and core material with the tear resistance of glove structures. The interaction terms of the core material with the sheath fiber denier and machine gauge were also found to be significant, with p -values below the α -level. The effect of the sheath fiber denier, number of plies, machine gauge, and core material were found to be in indirect relationships with the tear resistance of the glove structures.

Figure 5 shows the effects of the sheath fiber linear densities, yarn plies, and fabric GSM on the tear resistance. Gloves made using two-ply core-spun yarns have inferior tear resistance to single-ply core-spun yarn. The tear resistance also increases with an increase in the fiber denier for UHMWPE-core and steel-core spun yarn glove structures, while it decreases for glass-core spun yarn structures. The reason lies in the smooth and slippery surface of the glass filament, which allows the sheath fiber to slip to form a bundle formation, which thereby increases the tear strength values. As the finer fibers are more flexible and can better group together in a bundle formation, this result is opposite to what was obtained for steel- and UHMWPE-core yarns. The highest tear strength was obtained for UHMWPE core-spun yarn gloves, followed by steel cores and glass cores in order. The reason lies in the mechanical behavior of the core material, where bending and elongation properties influence the tear resistance values. Glass, being a rigid material, resists bending, which means that the destruction of its structure occurs, which thereby reduces the tear resistance values. The GSM has a visible impact on the tear resistance, which increases with the decrease in GSM. The reason lies in the fact that at a lower areal density, more

space will be available for the yarn to form a bundle formation by slippage during tear force application, which thereby enhances the tear resistance values, which is in accordance with previous results [14]. The regression equations developed for the tear resistance for different cores are as follows:

$$\text{Tear resistance (Glass)} = 429 - 55 \text{ Fiber D} - 9.08 \text{ Plies} - 0.987 \text{ GSM} \quad (7)$$

$$\text{Tear resistance (UHMWPE)} = 952.4 + 11.33 \text{ Fiber D} - 9.08 \text{ Plies} - 3.175 \text{ GSM} \quad (8)$$

$$\text{Tear resistance (Stainless Steel)} = 463.6 + 14.67 \text{ Fiber D} - 0.9.08 \text{ Plies} - 1.4 \text{ GSM} \quad (9)$$

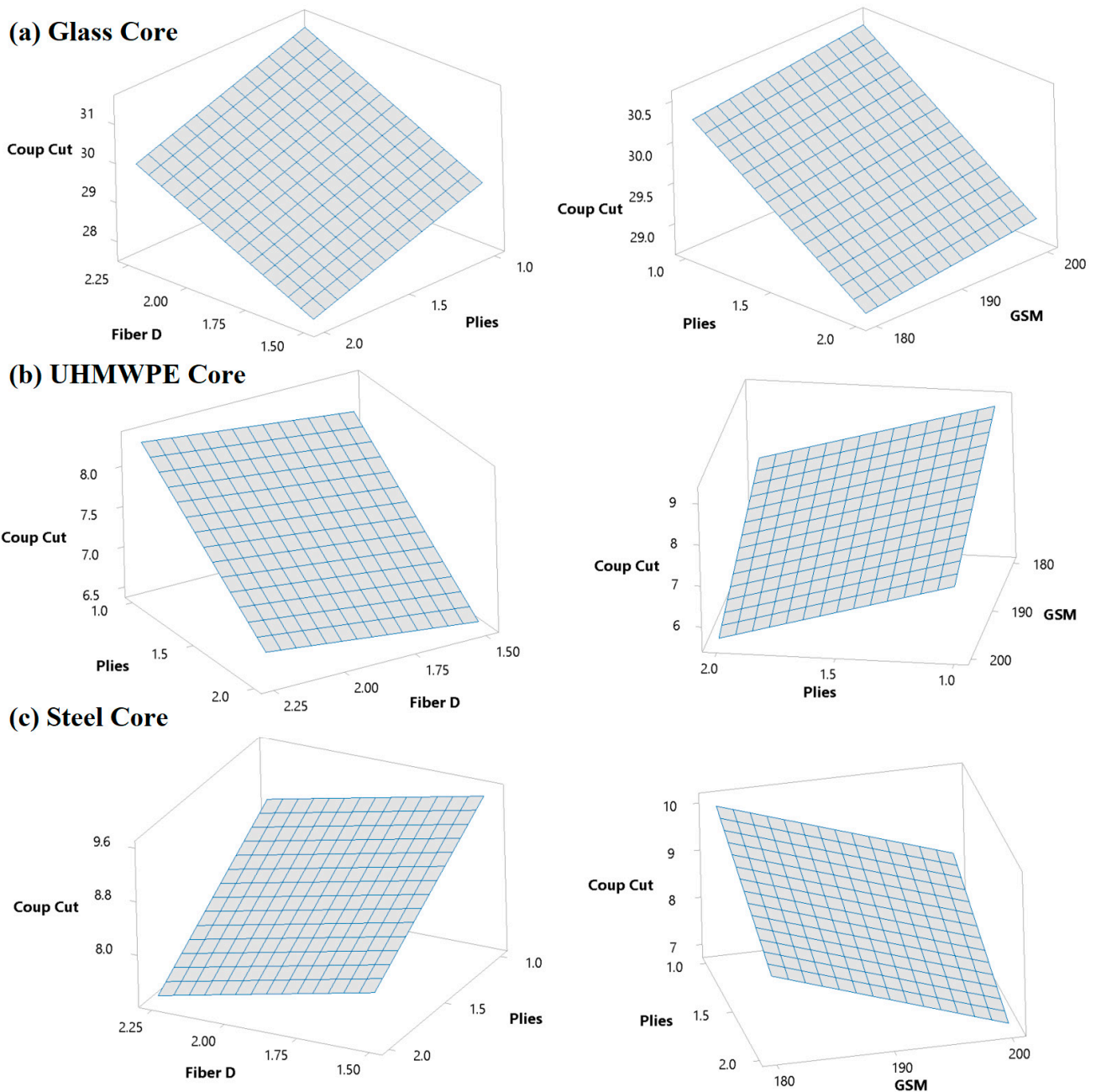


Figure 4. Response surface plots for coupe cut resistance vs. material properties.

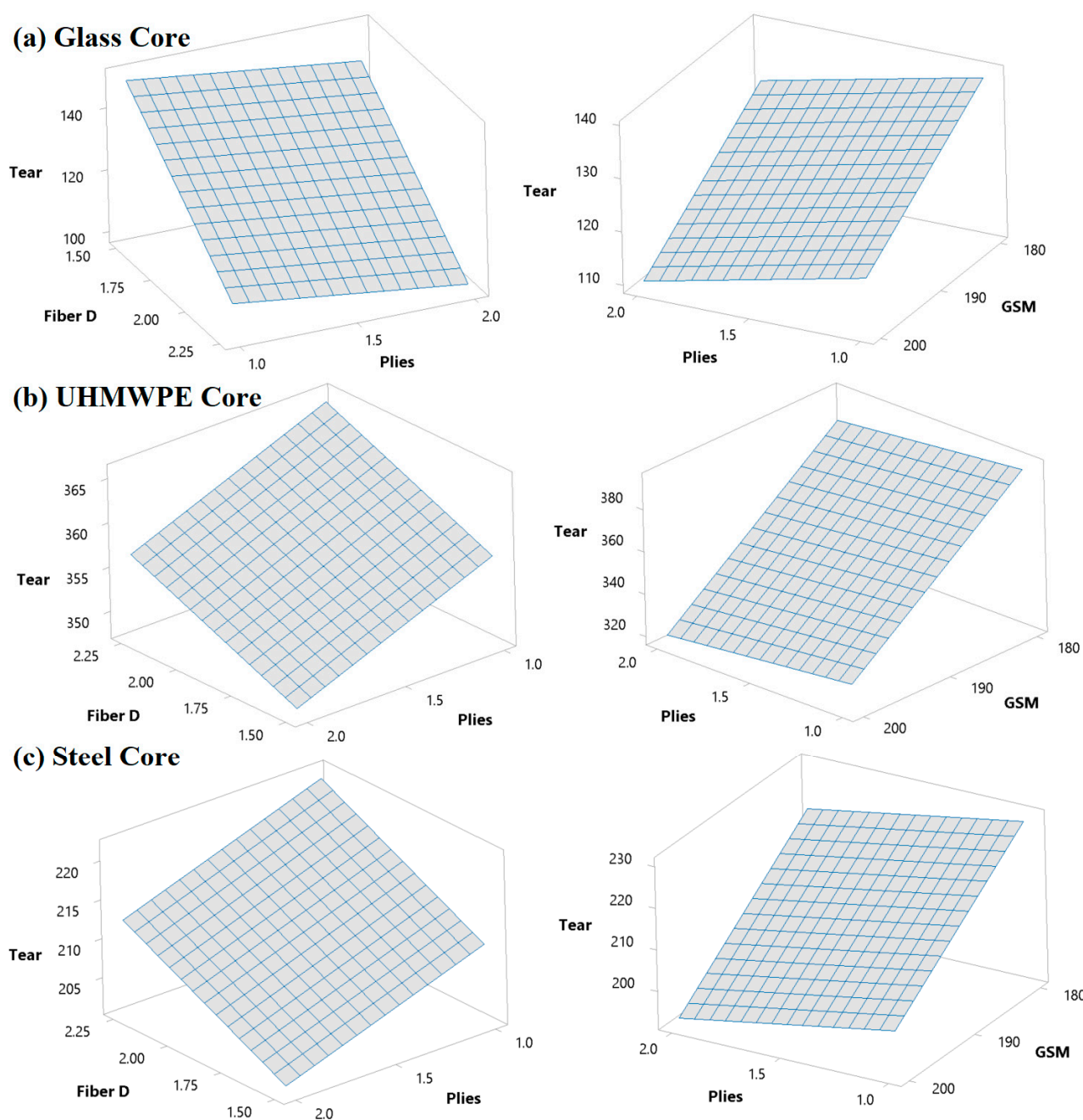


Figure 5. Response surface plots for tear resistance vs material properties.

3.4. Puncture Resistance

The ANOVA results demonstrated that the core material and machine gauge have significant linear relationships with the puncture resistance values, while non-significant relationships were found for the sheath fiber denier and number of plies. The two-way interaction of the machine gauge with the core material showed significant effect on the puncture resistance, with a p -value below the α -level. It was also observed that the machine gauge has an indirect relationship with the puncture resistance.

Figure 6 shows the interaction effect of the machine gauge and core material on the puncture resistance properties. An indirect effect of the machine gauge on puncture resistance values can be observed. The reason may lie in the modulus and elongation properties of the constituent materials. As polyethylene has the highest modulus and largest elongation percentage values, the material may become stretched upon the application of

puncture forces, hence absorbing the applied stresses without failure. In contrast, glass is a brittle material and has a lower modulus, and its elongation properties are destructed upon puncture forces and allows the needle to pass through. Another reason is that glass is smooth, and its glossy surface allows it to slip more easily, which allows for the penetration needle to go through the fabric structure [14]. The highest level of puncture resistance values was obtained for UHMWPE-core materials, followed by steel- and glass-core materials in order. On the other hand, the fabric areal density increased by increasing the loop length, which allowed the needle to pass through, hence decreasing the puncture resistance values. Better puncture resistance properties will be obtained for a protective glove developed with a UHMWPE core at a lower fabric areal density. The regression equations developed for the puncture resistance for different cores are as follows:

$$\text{Puncture resistance (Glass)} = 176 - 0.637 \text{ GSM} \quad (10)$$

$$\text{Puncture resistance (UHMWPE)} = 670.5 - 3 \text{ GSM} \quad (11)$$

$$\text{Puncture resistance (Stainless Steel)} = 291.3 - 1.113 \text{ GSM} \quad (12)$$

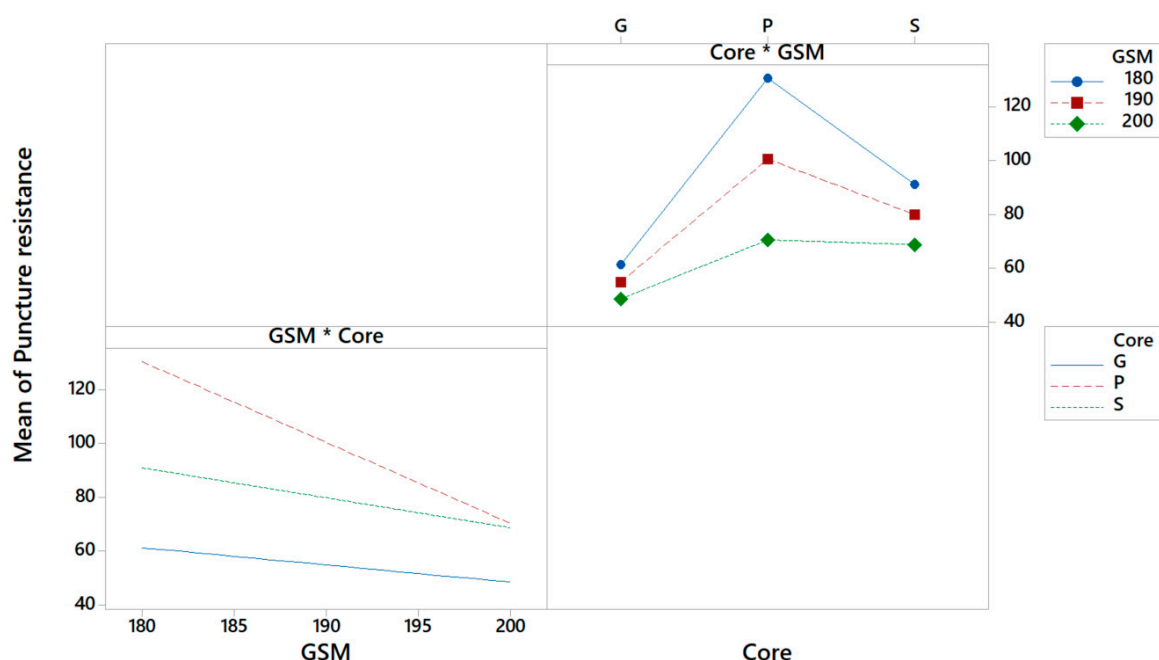


Figure 6. Interaction plot for puncture resistance with material properties.

4. Conclusions

In this study, seamless knitted gloves were developed with different materials and processing parameters to evaluate the effects of the sheath fiber linear density, no. of plies, core material type, and fabric GSM on the cut, tear, and puncture resistance properties. The results demonstrated that the effect of the sheath fiber denier was significant for the coupe cut and tear resistance properties. An increase in sheath fiber denier increases the coupe cut resistance values, while it decreases the tear resistance properties. The results demonstrated that the number of plies of core significantly affects the blade cut, coupe cut, and tear resistance properties as an indirect relation, while no effect was observed for the puncture resistance. Gloves made with single-ply yarns have better cut and tear protection compared to gloves made with two-ply yarns. The effect of the fabric areal density (GSM) was also found to be statistically significant on the blade cut, coupe cut, tear, and puncture resistance properties. An increase in fabric GSM increases the blade cut

resistance, while it reduces the coupe cut, tear, and puncture resistance properties. The steel core can be appropriately used for blade cut resistance applications, a glass core is suitable for coupe cut resistance, while a UHMWPE core provides good results for tear and puncture resistance properties.

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Conflicts of Interest: Author Shahbaz Ahmad was employed by the company Midas Safety Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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