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Facile fabrication and comparative exploration of high cut resistant woven and knitted composite fabrics using Kevlar and polyethylene

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Abstract

Composite materials offer a number of distinct advantages in a wide range of low and high technology engineering applications. Considering the fact, in this study, a facile fabrication method of highly cut resistant composite fabrics using Kevlar and polyethylene is reported. 100% Kevlar, 100% Polyethylene and 50% Kevlar/50% Polyethylene composite fabrics are fabricated by weaving and knitting techniques. These fabrics were tested for cut index, abrasion, and puncture resistance for comparative exploration. Owing to higher mechanical strength and greater number of interlacements; the woven fabrics demonstrated twice cut resistance in contrast to knitted fabrics. The surface morphology of deformed samples investigated by Scanning Electron Microscopy (SEM) also proved that the woven fabrics of all types offered much resistance towards cutting than the knitted fabrics. Moreover, it is found that greater thickness of fabrics leads to intensification of the cut resistance. Furthermore, the effect of fiber type on cut resistant property of the fabrics was also measured and it was found that the composite fabric exhibited double cut resistance than 100% Kevlar and 100% Polyethylene fabrics. The 50% Kevlar/50% Polyethylene composite woven fabric resisted up to 35 consecutive strokes of sharp steel cutter whereas the knitted fabric completely torn apart at 20 strokes only. Thus, the as synthesized 50% Kevlar/50% Polyethylene composite woven fabric exhibiting superior cut resistance property offer a judicious choice for the preparation of efficient cut resistant fabric for industrial and domestic applications.

Keywords: Cut resistance, Kevlar, Polyethylene, Composite fabric, Protective fabrics

Introduction

Several sports, domestic, and workplace activities put personnel at a danger of injuries to their arms, hands or fingers which might be harmful superficial cuts or deep lacerations. Although the injuries incurred during domestic chores are not given much attention, whereas wounds instigated at industries (Ceballos et al. 2014; van Holland et al. 2015), sports, like snowboarding, skiing etc. (Loyd et al. 2015) and medical centers (Fritzsche et al. 2012) have attracted a great deal of researchers.

The conventional protective clothing based on metallic wires, ceramics, rubber or leather were thick, bulky and rigid (Chediak et al. 1998; Stansbury 1980); thus reducing both dexterity and grip of the wearer. In spite of the fact that metallic wires absorb the impact energy and diminish the sharpness of blade, it has a detrimental effect on the comfort level of the wearer.

In present scenario, the protective clothing's are mostly based on high performance fibers. Special organic fibers such as para aramids, carbon, high molecular weight polyethylene (HMWPE) and inorganic fibers like glass are used for such purpose (LaBarre et al. 2015). To better comprehend the effect of material on the cut resistance behavior, Shin et al. (2003, 2006) and Mayo et al. (2014) characterized the cut resistance behavior of high performance multifilament yarns and single fibers. Mayo et al. reported different cut resistance behavior of organic and inorganic fibers due to their isotropic and anisotropic structure of fibers. They also highlighted the cut resistance dependency on various factors like blade sharpness, slice angle and pre-tension in the yarn. Among the various high strength polymer fibers, Kevlar and polyethylene are widely used for the manufacturing of protective materials. Kevlar is a highly crystalline poly-aramid fiber with exceptionally high strength (Lim et al. 2011) and remarkable thermal stability, widely used in stress bearing applications such as bullet proof body armor (Colakoglu et al. 2007; Jia et al. 2013), shielding for sports equipment, and fiber reinforced polymer composites in the aerospace industry. On the other hand, polyethylene (PE) is one of the most versatile and widely used thermoplastics in the world because of its toughness, near zero moisture absorption, excellent chemical inertness, low coefficient of friction, ease of processing and unusual electrical properties (Cwik et al. 2016; Golovin and Phoenix 2016; Huang et al. 2007; O'Masta et al. 2015).

Apart from material selection, researchers have found significant results by exploring the structure of fabric in different applications (Carvalho et al. 2015; Rebouillat et al. 2010; Wang et al. 2010). Background study reveals that the cut resistant fabrics were more often fabricated in knitted structures owing to the advantage of low weight, greater flexibility and wide area protection of the knitted products (Fangueiro et al. 2015). Single layered knitted fabrics provide insufficient cut resistance, which emerged the idea of stacking multiple layers. However, these concepts significantly increased weight and reduced breathability. Attempts for enhancement of cut and stab resistance was further continued by familiarizing shear thickening fluids (Decker et al. 2007; Sun et al. 2013), plasma treatments (Wu 2004) and thermoplastics (Mayo et al. 2009); however researchers found that these impeded the windowing property and significantly reduced materials flexibility (Mayo et al. 2009).

Very few researchers have come forward and carried out research using woven fabrics in the case of cut resistant fabrics specifically, despite the fact that they possess superior mechanical properties in both in-plane and transverse directions compared to knitted fabrics. It has been reported that woven fabrics based on high strength and high modulus fibers with dense structures have the advantage of shear resistance (Tien et al. 2010). Also due to interlacement of tows or yarns, woven fabrics offer high resistance to damage, superior energy absorption (Karahan et al. 2008) and remarkably high values of strain at failure in tension, and loadings (Chou and Ko 1989; Dixit and Mali 2013). With the rapid advancement in the field of textiles, woven fabrics can be fabricated to near knit shape, which could exhibit high degree of flexibility. Therefore, in the present study the comparison of cut resistance behavior of high performance knitted and woven fabrics are analyzed. 100% Kevlar, 100% PE and 50% PE/50% Kevlar composite knitted and woven fabrics were produced on electronic flat knitting machine and shuttle loom, respectively and the cut resistance behavior is clearly highlighted with a comparative analysis between knitted and woven fabrics.

Method

Yarns

High performance filament yarns of Kevlar and Polyethylene were used to produce knitted and woven fabric for a comparative study of their cut resistance behavior. DuPont Kevlar filaments (K-29) of 1000 denier with 90 GPa modulus and 3.0 GPa tenacity and Polyethylene filaments (SK60) with a molecular weight of 2×10^6, 400 deniers, 75 GPa modulus and 2.8 GPa tenacity. These filaments were purchased from a local supplier, Technical Textiles, Sialkot, Pakistan.

Fabrication

Throughout this study a number of indigenously developed knitted and woven fabrics were selected to study the effect of fabricating technique on the cut resistance property. Single jersey weft knitted fabrics and plain woven fabrics, were produced on electronic flat knitting machine and shuttle loom, respectively. For ease in comparison, gauge of knitted samples was kept constant (Fig. 1); likewise, warp density of all the woven samples (Fig. 2) was also constant. The weight of fabric in grams per square meter (GSM) was also calculated. The physical characteristics of knitted and woven samples are enlisted in Tables 1 and 2 respectively.

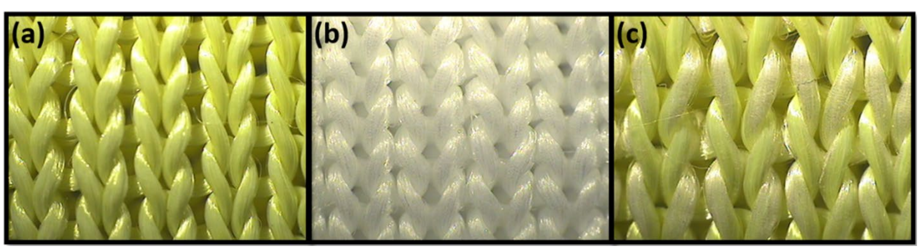

Fig. 1 Microscopic images (×40) of knitted samples **a** Kevlar, **b** polyethylene and **c** composite fabric (50% Kevlar/50% PE)

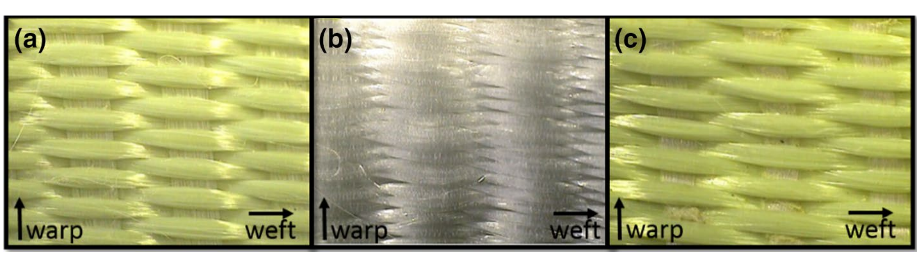

Fig. 2 Microscopic images (×40) of woven samples **a** Kevlar, **b** polyethylene and **c** composite fabric (50% Kevlar/50% PE)

Table 1 Specifications of knitted samples plain knit

	Material	Gauge	Thickness (mm)	GSM (g/m^2)
Sample 1	100% Kevlar	10/in.	1.0	610
Sample2	100% PE	10/in.	0.7	300
Sample3	50/50% Kevlar/PE	10/in.	1.1	500

Table 2 Specifications of woven samples plain weave

	Warp	Weft	Warp density	Weft density	Thickness (mm)	GSM (g/m^2)
Sample 1	Kevlar	Kevlar	10/in.	36/in.	0.9	444
Sample 2	Polyethylene	Polyethylene	10/in.	59/in.	0.8	318
Sample 3	Kevlar	Polyethylene	10/in.	47/in.	1.1	347

Characterization

The surface deformation of cut Kevlar and polyethylene filaments was characterized by field emission-scanning electron microscopy (FE-SEM, JEOL JSM-6700F) with a very thin coating of Platinum at accelerating voltage of 15 kV. Blade cut resistance test was performed on SATRA STM 611 Circular blade cut resistance tester. This test was performed in longitudinal and transverse direction with 5 N load. For each direction, an average of five readings was taken. Five different knitted and woven cut resistant fabric samples made of Kevlar, Polyethylene and Kevlar/PE were chosen and tested for cut resistance as per BS EN 388. In the BS EN 388 test method the cut resistance is demonstrated in terms of cut index value. Cut index is defined as the ratio of number of cycles of a circular blade required to cut through the sample to the mean cycles required to cut through a reference cotton fabric (Standard 2003). Abrasion resistance was performed on Martindale Abrasion Tester M235. Pressure of 9 kPa was applied on the specimen. Four samples of each specimen were tested, and an average value was reported. Testometric M250 3CT was used to analyze the puncture resistance. Circular specimens with a minimum of 40 mm diameter were prepared. An average of four readings was recorded with 100 mm/min stylus speed.

Results and discussion

To understand the cut behaviour of the fabrics, FE-SEM was used and the images of cut woven and knitted composite fabrics are presented in the Fig. 3. For all specimen, the filaments seem distorted and sheared after cutting (Fig. 3a–d). However the cutting behaviour of knitted and woven fabrics was different as shown in Fig. 3a, b. The knitted samples are smoothly cut apart where as, woven samples are resistant to cutting. This is associated with the poor on-axis mechanical properties of knitted fabric composites in comparison to the woven fabric composites, due to low fibre volume fraction and less orientation of fibres to the wale or course direction (Pandita et al. 2002). It is visible from the image that the cutting action also creates fibrils at or near the cutting point.

Cut resistance is an important property of protective textiles against various mechanical forces (Fan 2005). It is influenced by numerous factors, such as blade sharpness, slice angle (Shin et al. 2006), yarn count, fabric construction and fabric thickness (Hou et al.

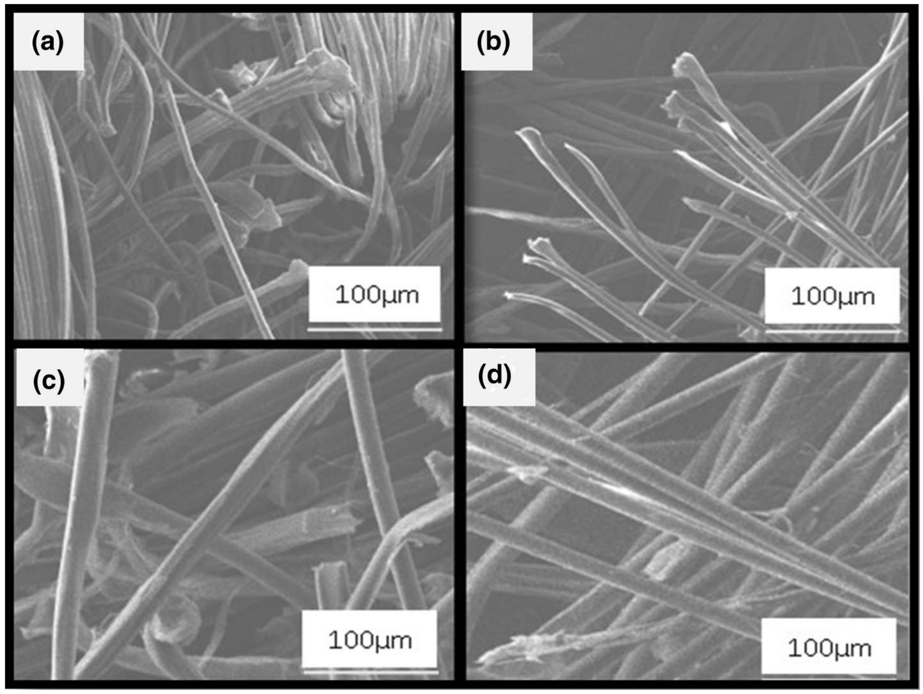

Fig. 3 SEM images of composite fabrics **a** cut woven fabric **b** cut knitted fabric **c**, **d** fibrillated yarns

2013; Thi et al. 2009). The samples were conditioned at 21 °C and 65% R.H. before testing and the results are given in Figs. 4 and 5. Comparing the effect of type of material used, it can be noted that, composite fabric (Kevlar/PE) showed significantly higher cut resistance followed by 100% Kevlar fabric. The similar trend is observed in both knitted and woven fabrics. This can be attributed to the higher thickness of composite fabric, as given in Tables 1 and 2. Within a composite structure; desirable mechanical properties such as stiffness, elongation and tensile strength are achieved in both axial and transverse direction (Dixit and Mali 2013). Enhanced mechanical properties in both the directions lead to higher cut resistance of composite fabrics. However, 100% Kevlar fabrics exhibited higher level of cut resistance as compared to 100% PE fabrics which can be attributed to its higher modulus, yarn count and slightly higher stiffness of the Kevlar

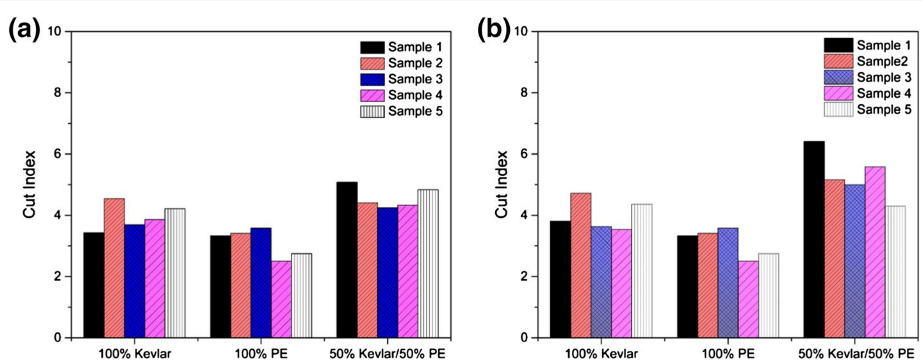

Fig. 4 Cut index as a function **a** − 45° and **b** + 45° for knitted samples

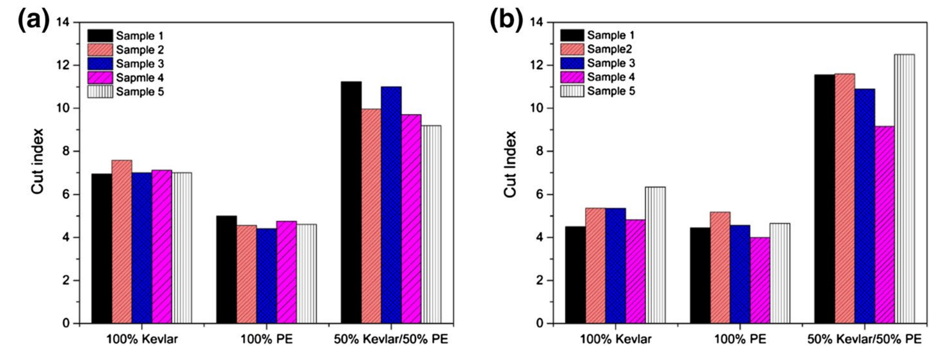

Fig. 5 Cut index as a function **a** – 45° and **b** + 45° for woven samples

fabric. The coarser the yarn, greater is its weight, which leads to increase in cut resistance index value of fabric samples (Ertekin and Erhan Kirtay 2015). However, the change in direction of cutting does not have significant influence on the cut resistance index values (Figs. 4, 5).

Comparative analysis of cut resistance

Evaluating the effect of fabric structure on the cut resistance property, it is evident from Fig. 6a and b that woven fabrics tend to resist that cutting action more as compared to knitted fabric. The cut indices values of woven fabrics are exceptionally high in contrast to knitted fabrics. This is due to very high strength and compact structure of woven fabrics. Cut resistance is highly dependent on the internal friction of fabric, which is greater in woven samples because of more number of interlacements. Greater cut resistance of woven fabrics owes to the fabric tightness. As in case of plain weave, greater number of interlacement points enhances the tightness of fabric. Furthermore, increasing the warp density (threads per unit space) would also result in higher cut resistance as the yarns take up the cutting force. Higher the work of deformation means higher cut resistance (Rameshkumar 2014).

The cutting behavior of these samples was also evaluated by cutting them with a sharp steel cutter. Numbers of strokes were recorded to determine the level of cut resistance as shown in Figs. 7 and 8. The fabric samples were hold tightly with masking tape on

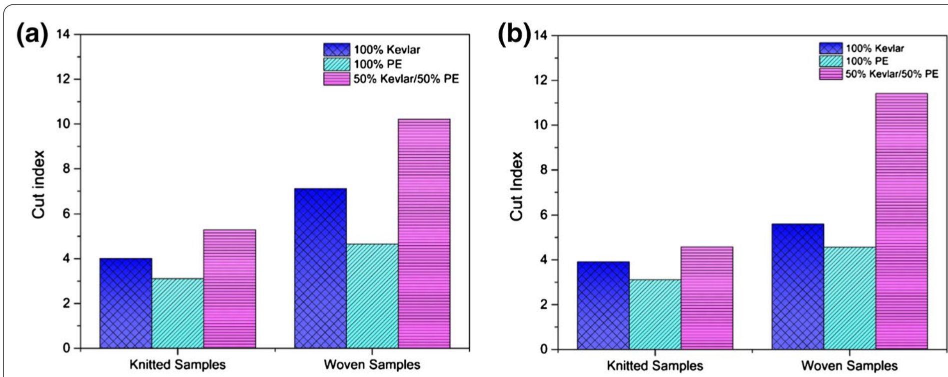

Fig. 6 Comparison of knitted and woven samples **a** + 45° and **b** – 45°

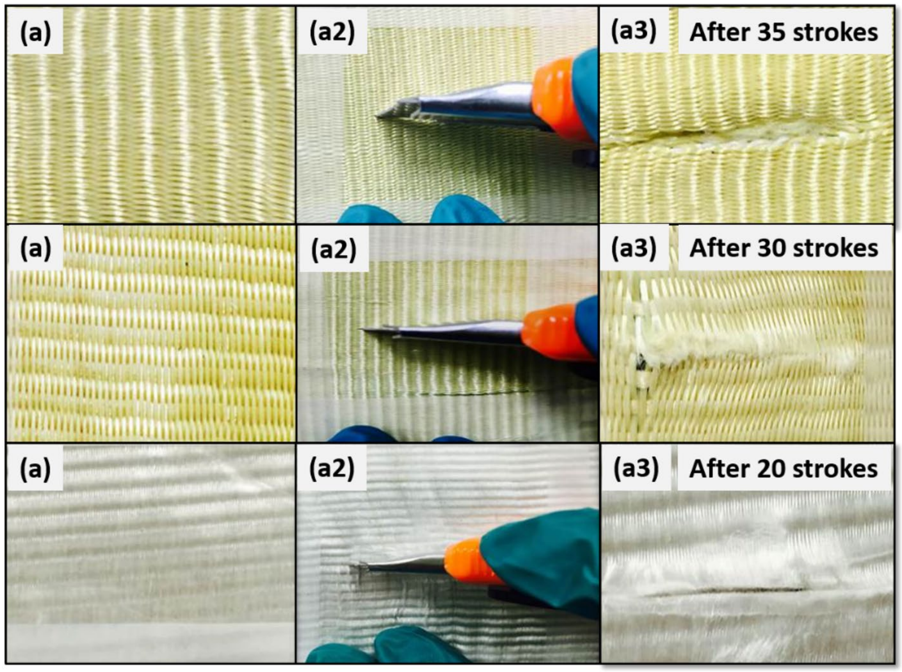

Fig. 7 Cutting behavior of woven samples with sharp steel cutter **a** composite fabric **b** Kevlar **c** polyethylene

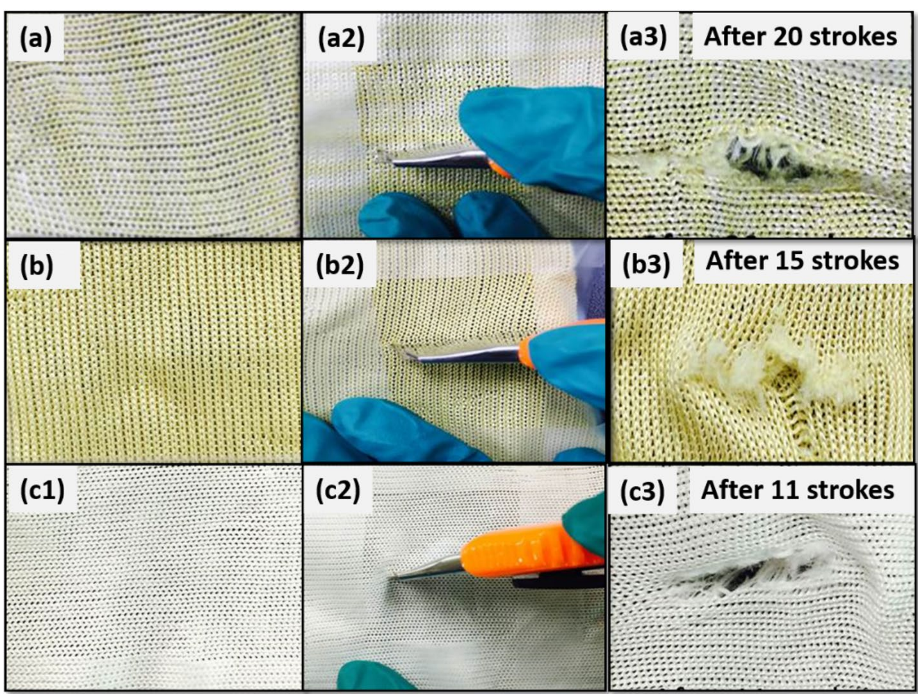

Fig. 8 Cutting behavior of Knitted samples with sharp steel cutter **a** composite fabric **b** Kevlar **c** polyethylene

four sides. The woven composite fabric could resist up to 35 strokes with no breakage of weft yarns. Else it was difficult to cut such high performance fabrics with the cutter. This resulted in fraying off and distortion of the fabric. Whereas the knitted fabric was torn apart completely at 20 strokes. Similar trend was observed in 100% Kevlar and 100% PE knitted and woven fabrics.

Abrasion resistance is affected by various factors such as yarn twist, elastic recovery, linear density (Saville 1999) elongation percentage and stiffness (Palaniswamy and Mohamed 2006). From Fig. 9, it is clear that 100% PE has elevated abrasion resistance as compared to 100% Kevlar. This can be attributed to its greater elongation percentage and low co-efficient of friction. As a matter of fact, the abrasion resistance increases with the increase in elongation percentage but the co-efficient of friction has inverse relation with the abrasion resistance property. The abrasion resistance of composite fabric is moderate.

Comparative analysis of abrasion resistance

With respect to its structure, abrasion resistance also depends on the fabric geometry (Abdullah et al. 2006) and co-efficient of friction (Manich et al. 2001). Significant difference is not seen as illustrated in Fig. 10, in abrasion resistance of knitted and woven samples. Slight difference may be accredited to the elasticity in knitted samples and comparatively greater GSM than the woven samples.

Puncture resistance is greatly influenced by the material strength (Ulbricht et al. 2003) and cross-section of yarns. Greater the cross-section more will be the puncture resistance (El Messiry 2014). As shown in Fig. 11a and b, puncture resistance of 100% Kevlar is remarkably higher than composite fabric and 100% PE. The reason may be the greater cross-section of yarns and greater tensile strength of Kevlar. Puncture resistance of a material is also dependent on windowing property of a material. Polyethylene is slippery, owing to lower co-efficient of friction, hence it allows stylus or sharper objects to pass through the material.

Comparative analysis of puncture resistance

The puncture resistance of knitted samples is higher in contrast to woven samples (Fig. 12). This may be accredited to the greater GSM of knitted samples. It can also be because of the flexibility in the knitted structures which resist the penetration of sharper objects and hence reduce the windowing effect caused by the stylus.

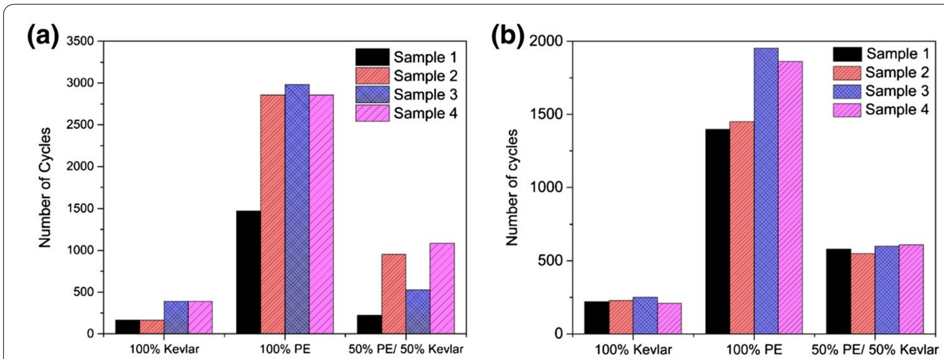

Fig. 9 Abrasion resistance of individual samples **a** Knitted and **b** Woven

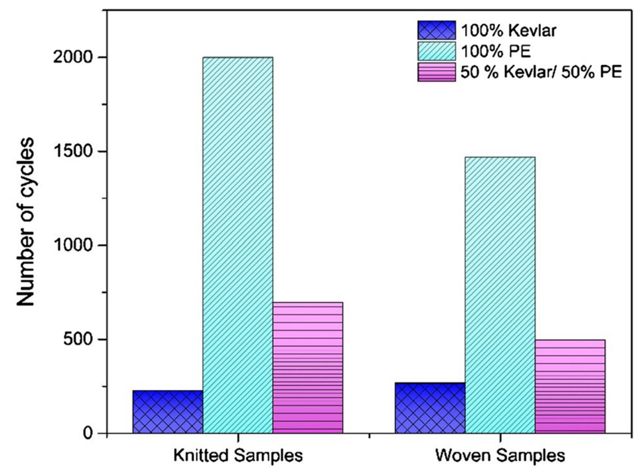

Fig. 10 Comparison of abrasion resistance of knitted and woven samples

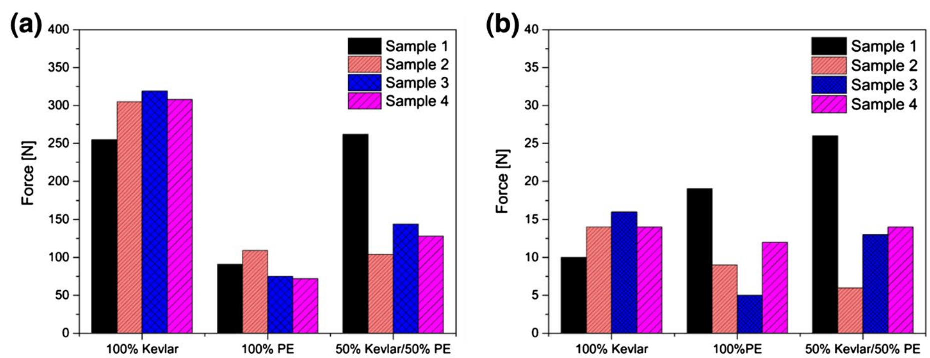

Fig. 11 Puncture resistance of individual samples **a** Knitted and **b** Woven

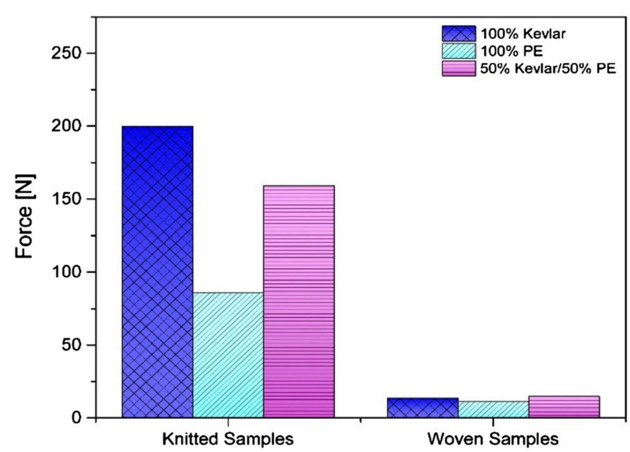

Fig. 12 Comparison of puncture resistance knitted and woven samples

Conclusion

Knitted and woven cut resistant fabrics were fabricated indigenously from Kevlar and Polyethylene, and a 50/50% composite of them in order to compare their cut resistant properties. The cut index, abrasion resistance, and puncture resistance properties were measured for comparative analysis. It is concluded that the woven fabric possess better cut resistance property compared to the knitted fabric of same gauge. Composite woven samples (Kevlar/PE) show highest cut resistance index compared to both pure Kevlar and PE. Moreover, it is seen that cut resistance depends on the thickness of fabric. By increasing the thickness of the fabric, the cut resistance property was increased. In view of the superior cut resistance behavior of woven composite fabric, it can be considered as the substantial choice for the sportswear, industrial and domestic applications.

Authors' contributions
AAM, MHP and SHJ designed, planned and carried out the work. Moreover, they have also done the data analysis, interpretation and presentation part. IAS finalized the final draft. SA contributed in the data analysis of some test results. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

Ethics approval and consent to participate
Not applicable.

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