This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization

Mehrdad Hossein Alizadeh[a], Mehdi Kamali Dolatabadi[a] , Saeed Shaikhzadeh Najar[b], Reza Eslami-Farsani[c]

[a] Department of Textile Engineering, Islamic Azad University Tehran, Iran

[b] Department of Textile Engineering, Amirkabir University of Technology Tehran, Iran

[c] Faculty of Materials Science and Engineering, K. N. Toosi University of Technology, Tehran, Iran

Corresponding author: orreskamalimehdi@yahoo.com, mehdi.kamali.dolatabadi@gmail.com

Abstract

One method of producing thermoplastic composites is using the co-air-textured yarn technique. Such composite materials are subjected to various loading conditions during their life cycle. For the efficient use of these materials in high-performance applications, their behavior under impact loading should be well understood. This is because polymer composites are sensitive to impact loading. Accordingly, one of the main objectives of the present research was to optimize the parameters to achieve the best energy absorption of Kevlar® /polypropylene weft-knitted hybrid composites under high-velocity impact. The kinetic energy absorption was evaluated using the experimental testing data of the composites. In this study, production parameters such as blend ratio, stitch length, knitting structure, melting time, molding pressure, molding temperature and blending quality were optimized via the response surface method (RSM) to obtain the best specific energy absorption of the composites. The results showed that the desired energy absorption occurred when the absorbed energy on the areal density of the composite had the maximum value. The results also showed that the blend ratio of Kevlar/PP (1:2), a higher blending quality, a higher stitch length, the use of the full-milano knitting structure, a longer molding time (20 min), a higher molding pressure (300 kg/cm^2) and a lower molding temperature (160 °C) delivered the best performance in terms of specific energy absorption.

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

Keywords: Specific energy absorption, High-velocity impact, Co-air-textured yarn, Weft-knitted, Thermoplastic composite

1. Introduction

Fiber-reinforced polymer composites (FRPCs) are widely used for their protective structures, especially those with high-performance fibers (Priyanka et al., 2019). When FRPCs are to be used for light ballistic protection or soft armor, weak fiber–matrix adhesion is required to allow the fibers to undergo maximum deformation (Cheeseman & Bogetti, 2003). In this case, thermoplastic polymers have an advantage over thermosetting matrices, which are known for their high stiffness and low deformation (Zaera, 2011).

One method to produce a thermoplastic composite is to prepare the thermoplastic matrix in the form of fiber and then mix it with the reinforcing fibers to produce hybrid yarns. Recently, due to the advantages of this method, some researchers have turned to it to develop a new generation of composites, such as biocomposites or eco-composites. In this method, the possibility of wetting the reinforcing agent can be increased, while the uniformity of blending can also be achieved (Atiqah et al., 2019; Selver et al., 2016; Wiegand & M€ader., 2017).

Nowadays, much research has been devoted to knitted fabric-reinforced thermoplastic composites. It should be noted that the nonconsolidated plain (planar) knitted fabrics can be easily fabricated by using commingled yarns or by using co-knitting (Czigany & Karger-Kocsis, 2001). Knitted fabric-reinforced composites can be considered as a type of textile structure-reinforced composites. The unique interlocked loop structure gives the knitted fabric many advantages: excellent stretchability and drapability, which makes it very adaptable to any complex shape without wrinkling. The desired shape can be obtained by knitting with the help of modern knitting machines. These advantages imply that the knitted fabric-reinforced

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

composites have the following properties, among others: good drapability, desirable impact resistance, reasonable interlaminar properties, good formability, high production rate and short production time (Zaixia et al., 2006).

According to a review article by Safri et al. (2014), lowvelocity impacts occur at a velocity of less than 10 m/s, medium-velocity impacts occur between 10 m/s and 50 m/s, high-velocity impacts (ballistic) have a velocity range from 50 m/s to 1000 m/s and hyper-velocity impacts range from 2 km/s to 5 km/s. The most important parameters affecting the ballistic capacity of a target plate appear to be the projectile (size, shape, density and hardness), the target plate (hardness/strength, ductility, microstructure and thickness) and the actual impact conditions (such as impact velocity, angle of attack and projectile attitude). Several factors such as the ratio of the target thickness to the projectile diameter, the shape of the projectile nose and the materials involved are known to contribute to penetration mechanisms.

In the ballistic impact, the kinetic energy of the projectile is dissipated and absorbed by the target in several ways upon impact. The main energy-absorbing mechanisms during ballistic impact are as follows: kinetic energy absorbed by the moving cone that forms on the back of the target, shear plugs of the projectile in the target, energy absorbed due to the tensile failure of the primary yarns, energy absorbed due to the elastic deformation of the secondary yarns, energy absorbed due to cracks in the matrix and delamination and the frictional energy absorbed during penetration. The ballistic impact performance of composite laminates is dependent on the mechanical properties of the reinforcement/matrix and physical properties of the impacting projectile and the target. Mechanical properties of the target include the elastic modulus, tensile strength, fracture strain and laminate configuration. Projectile properties also include mass and shape. Thickness and size are the target parameters that can affect ballistic impact. A ballistic impact is generally a low mass and high-velocity impact caused by a

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

propulsive source. The ballistic limit of a target is defined as the maximum velocity of a projectile at which complete perforation occurs with a zero exit velocity (Naik & Shrirao, 2004; Patil & Naik, 2018).

The ballistic impact behavior of bio- and eco-composites has also been studied recently (George et al., 2018; Loganathan et al., 2019; Salman et al., 2017; Vijaykumar, 2018).

Naik et al. (2004) studied the ballistic impact behavior of typical plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites. Naik et al. (2004) also carried out parametric studies related to the ballistic impact behavior of woven fabrics. It was found that for identical ballistic impact conditions, the ballistic limit is higher for the E-glass/epoxy compared to the T300 carbon/epoxy. For the E-glass/epoxy, the energy absorbed by the secondary yarn deformation and the tensile failure of the primary yarn are the main energy absorption mechanisms. For the T300 carbon/epoxy, the main energy-absorbing mechanisms are secondary yarn deformation and shear plugging.

On the strength of their studies on the ballistic performance of aramid fabric/polypropylene (PP) composite laminates (CL) and plain-layered aramid fabric (AF) impact samples, Carrillo et al. (2012) reported that the addition of a thermoplastic PP matrix increases the ballistic performance (the ballistic limit and perforation threshold energy) of the CL targets compared to the AF targets with a similar areal density.

Sevkat et al. (2012) studied the ballistic performance of hybrid and non-hybrid composite plates (plain-woven IM7graphite/toughened epoxy and woven S2-glass-IM7-graphite fibers/toughened epoxy hybrid composites). They introduced the hybridization of the graphite composite by using glass fabrics to improve the ballistic limit.

Leong et al. (1998), Chou and Wu (1992), Ramakrishna and Hull (1993), Dabiryan et al. (2019) and Pandita et al. (2002) studied the effect of some parameters on the low-velocity absorbing energy weft-knitted composites of different materials. They generally reported that 2D and 3D weft-knitted composites have the highest absorbing impact energy at low-impact velocity compared to weaving and other types of composites.

Dimeski et al. (2011) studied the ballistic properties of polyethylene composites based on bidirectional and unidirectional fibers. They reported that when a projectile impacted a ballistic fabric, the risk of yarn breakage was highest at the intersections of warp and fill.

Li et al. (2017) studied on the simulation and modeling of dynamic puncture in a more complex problem due to the full consideration of the tightness of the fabric and the sharp profile of the puncture and presented a numerical simulation of complicated dynamic puncture behavior based on the roles of expansion and stress wave transmission on the deformation. They showed that the dynamic puncture damage critically depends on the elastic modulus of yarns and the distance between yarns; the distance between yarns affects the dynamic puncture strength more significantly. Dynamic puncture stress increases nonlinearly with elastic modulus and decreases linearly with yarn spacing. The results also show that the weave density can be increased to improve the dynamic puncture strength more significantly.

Mounting evidence in the literature suggests that the available experimental data on aramid/thermoplastic matrix composites is limited. In addition, aramid/PP systems have not been studied in detail, although PP is inexpensive and has low adhesion to the aramid fiber, which is desirable for soft armor. Although the low-velocity impact performance of weft-knitted composites has been studied, not much has been done regarding the high-velocity impact performance of weft-knitted composites made from air-textured yarn. In fact, to the best of the authors' knowledge, the energy absorption of weft-knitted hybrid composites of Kevlar® and PP co-air-textured yarns during high-velocity impact has not been reported. In this study, the effects of production parameters, namely blend ratio, stitch length, type of the knitting

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

method, melting time, molding pressure, melting temperature and blend quality, were simultaneously optimized via the response surface method (RSM) to obtain the optimum specific energy absorption of the composites during high-velocity impact.

2. Materials and methods

The materials used in this study were air-textured Kevlar/PP yarns according to the method developed by Hosseinalizadeh et al. (2019). Considering the knitting and composite machine conditions, the highest and lowest blending quality was selected for the fabrication of the weft-knitted hybrid thermoplastic composites. The blending ratio consisted of a one-ply Kevlar filament and two/four-ply PP filament, which were designated as 1:2 and 1:4, respectively. The specifications of the fibers used are listed in Table 1. The weft-knitting technique was used to fabricate the preforms from the air-textured Kevlar/PP yarns. The weft-knitted structure was produced on the TEXTIMA flat knitting machine and is commonly referred to as rib 1:1 and Full-milano (Table 2). To obtain the PP composites reinforced with Kevlar fibers, the preforms were processed on the GOTECH hot-pressing machine. To sinter the PP fibers, one layer of the preforms (as shown in Table 3) was placed in the hot-pressing machine for three trials per category. In order to optimize the composite performance, possible conditions on two levels were considered. For this purpose, a temperature of 160 °C and 170 °C, pressure of 200 kg/cm^2 and 300 kg/cm^2, and pressing time of 10 min and 20 min were applied according to Table 3.

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

Table 1. Fiber specifications.

Material	Company	Number of filaments	Strand linear density (den)	Filament linear density (den)	Bulk density (g/cm^3)	Shape of cross-section
Kevlar® roving	Dupont (USA)	1000	1500	1.5	1.44	Circular
Polypropylene filament yarn	Behkosh (Iran)	72	350	4.9	0.91	Circular

Table 2. Variables and their corresponding values[a].

Index	x_1	x_2	x_3	x_4	x_5	x_6	x_6	x_7
Variable Level	Blend ratio [Kevlar®:PP] (Strand No.)	Stitch length	Knitting structure	Molding time (min)	Molding pressure (kg/cm^2)	Molding temperature (°C)	Molding temperature (°C)	Blending quality (–)[b]
Low (1)	1:2	3	Full-milano	10	200	160	160	2
High (2)	1:4	4	Rib 1×1	20	300	170	170	1

[a] Values were adjusted via pretests on the process.

[b] These values represent the blending quality: 1: high blending quality and 2: low blending quality (Hosseinalizadeh et al., 2019).

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

Table 3. Sample description and the process parameters considered in this study.

Samples category	x_1 Blend ratio [Kevlar®:PP]	x_2 Stitch length	x_3 Knitting structure	x_4 Molding time (min)	x_5 Molding pressure (kg/cm^2)	x_6 Molding temperature (degree)	x_7 Blending quality (–)[a]
1	1:2	3	Full-millano	10	200	160	1
2	1:2	3	Full-millano	10	300	160	2
3	1:2	3	Full-millano	20	200	170	1
4	1:2	3	Full-millano	20	300	170	2
5	1:2	3	Rib 1×1	10	200	170	2
6	1:2	3	Rib 1×1	10	300	170	1
7	1:2	3	Rib 1×1	20	200	160	2
8	1:2	3	Rib 1×1	20	300	160	1
9	1:2	4	Full-millano	10	200	170	2
10	1:2	4	Full-millano	10	300	170	1
11	1:2	4	Full-millano	20	200	160	2
12	1:2	4	Full-millano	20	300	160	1
13	1:2	4	Rib 1×1	10	200	160	1
14	1:2	4	Rib 1×1	10	300	160	2
15	1:2	4	Rib 1×1	20	200	170	1
16	1:2	4	Rib 1×1	20	300	170	2
17	1:4	3	Full-millano	10	200	170	2
18	1:4	3	Full-millano	10	300	170	1
19	1:4	3	Full-millano	20	200	160	2
20	1:4	3	Full-millano	20	300	160	1
21	1:4	3	Rib 1×1	10	200	160	1
22	1:4	3	Rib 1×1	10	300	160	2
23	1:4	3	Rib 1×1	20	200	170	1
24	1:4	3	Rib 1×1	20	300	170	2
25	1:4	4	Full-millano	10	200	160	1
26	1:4	4	Full-millano	10	300	160	2
27	1:4	4	Full-millano	20	200	170	1
28	1:4	4	Full-millano	20	300	170	2
29	1:4	4	Rib 1×1	10	200	170	2
30	1:4	4	Rib 1×1	10	300	170	1
31	1:4	4	Rib 1×1	20	200	160	2
32	1:4	4	Rib 1×1	20	300	160	1

[a] These values represent the blending quality: 1: high blending quality and 2: low blending quality (Hosseinalizadeh et al., 2019).

In this study, blend ratio, stitch length, type of the knitting method, melting time, molding pressure, melting temperature and blending quality were considered as production parameters affecting the energy absorption of the composites.

The stitch length (knitting) is the length of the yarn required to produce a complete knitted loop. In this regard, 55 wales in the fabric were marked, then was opened the course and was measured the length in mm scale. The value of the stitch length was calculated by dividing the measured length by the number of loops. The values of the stitch length were categorized into level 3 (average stitch length = 0.99 mm) and level 4 (average stitch length = 1.16 mm) considering the weft-knitted machine setting.

The blending parameterswere developed by Hosseinalizadeh et al. (2019) to determine the uniformity of the blended fibers. Three factors, namely radial distribution, lateral spacing and angular distribution, were considered to evaluate the uniformity of the blended fibers. High-blending quality means that in the cross-section of the co-air-textured yarn for both components (Kevlar and PP filaments), the radial distribution, lateral spacing and angular distribution were uniform, and low-blending quality means that they were not uniform.

To statistically control the production factors and design experiments, the Taguchi approach was used for the least number of experiments. For this purpose, a second-degree polynomial was used. In this study, the seven mentioned factors were considered at two levels of possible values (maximum, minimum). Sintering was considered in the production of these types of composites. The variable parameters were controlled to obtain the desired sample in the initial tests. The values of the factors considered and their levels are shown in Table 2. The experimental designs and sample codes are shown in Table 3, and the process of optimization is shown in Figure 1.

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

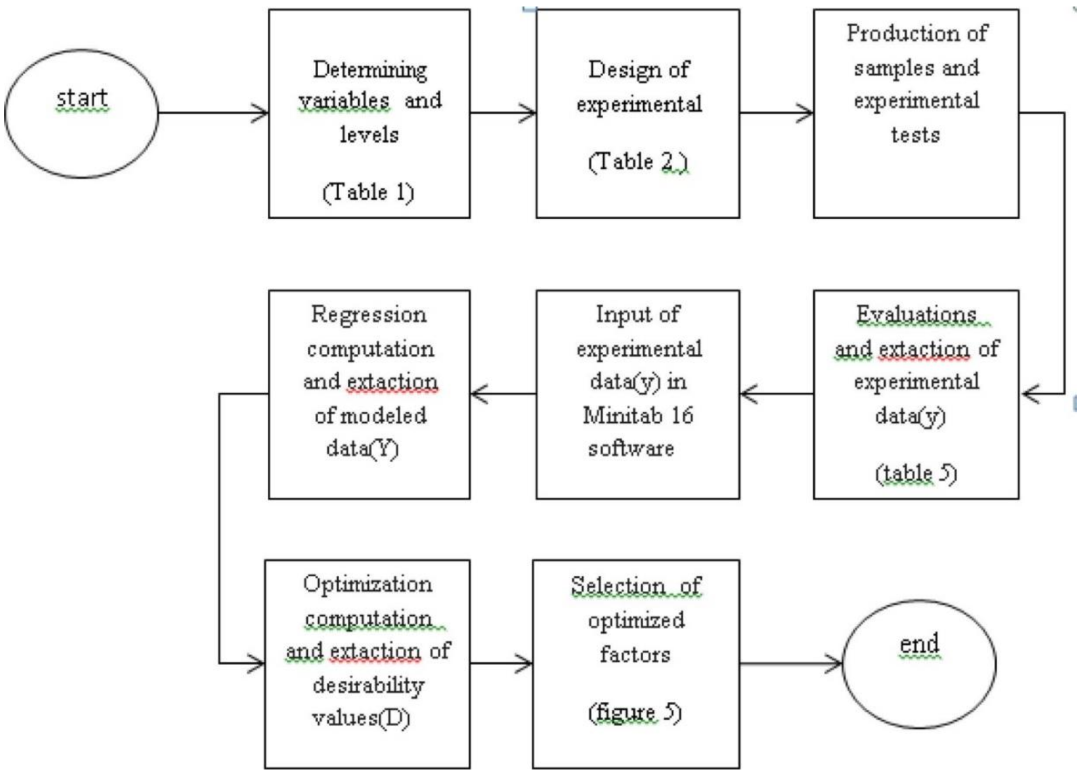

Figure 1. Optimization process.

The specific energy absorption can be calculated with Equations (1)–(3):

$$\mathrm{EA} = \frac{1}{2} M\left(V_{\mathrm{i}}^{2} - V_{\mathrm{r}}^{2}\right) \tag{1}$$

$$\frac{m}{A} = \rho_{\mathrm{A}} \tag{2}$$

$$\frac{\mathrm{EA}}{\rho_{\mathrm{A}}} = E_{\mathrm{e}} \tag{3}$$

where V_i (m/s) is the projectile velocity before perforation (initial projectile velocity), V_r (m/s) is the residual projectile velocity after perforation, M (kg) is the projectile mass, EA (J) is the energy absorbed by the target (Min et al. 2019; Pol et al. 2015), m (kg) is the sample mass, ρ_A (kg/m^2) is the areal density of the sample, A (m^2) is the sample area, and E_e (J m^2/kg) is the specific energy absorption (total energy absorption for each sample divided by its areal density) (Sabet et al., 2011).

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

The initial projectile velocity was recorded by a sensor placed in front of the fixture and this velocity was calibrated for each new test. The impact test device parameters, such as tank air pressure, were set so that the initial projectile velocity for each sample was 140 m/s. Accordingly, V_i was set at 140 m/s for all tests. For the measurement of V_r, 96 composite specimens (32 specimens with 3 trials for each specimen) were tested.

To carry out the impact test, an impact test device was used with an air pressure tank with a capacity of 8 bars; depending on the projectile, this allowed the maximum speed of 140 m/s. The mechanism of velocity recording was realized by the laser gate, where the projectile passed through this laser gate once it was fully deployed and its velocity was recorded by diodes as sensors. By inserting a sample into the fixture and measuring the velocity of the projectile after impact, the amount of energy absorbed by the sample was determined by calculating the velocity at the high-velocity limit and considering the weight and surface parameters of the fabric.

In the impact test apparatus (Figure 2), a composite specimen with an open surface area of 10×10 cm^2 was placed in a fixture. The projectile was made of heat-treated aluminum 7075 and an angle of inclination of 15°, 55 mm height and 21.7 mm diameter with a weight of 21 g (Figure 3) were considered constant for all 96 impact tests. The dimensions and angle of the projectile were determined experimentally after the preliminary penetration test. The boundary conditions also have an important impact on the response. Thus, the test specimen is tightly held on all sides by a fixture designed to prevent slippage of the specimen due to its specific dimensions. At least 2.5 cm of each side is held firmly between the edges of the fixture. Measurements show that the surface roughness of the projectile can be reduced by up to 50% after 96 impact tests. Therefore, the surface roughness of the projectile is an effective factor in the impact test. To this end, the sequence of impact tests was aligned to reduce the influence

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

of this parameter so much so that the 96 samples (32 categories with three trials) were divided into three parts. The first part includes the samples with number one of all categories (32 samples) subjected to the impact test. Then the second part, which includes the samples with number two of all categories, was tested and so on.

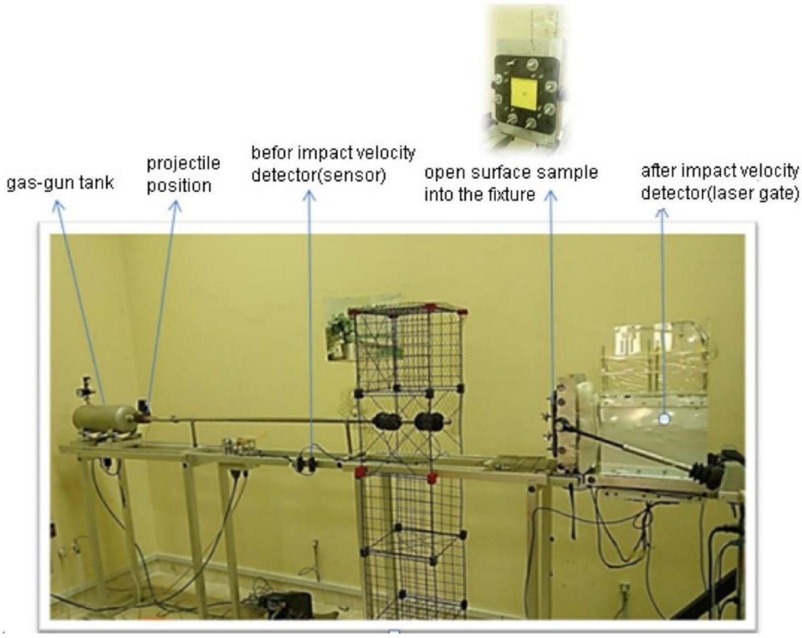

Figure 2. Impact tester device (M211).

Figure 3. Projectile dimension.

To determine the energy absorption, the RSM could be useful. Accordingly, a defined index, namely absorbed energy on areal density (E_e), was considered as the response of the

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

samples to obtain the optimum process factors using the RSM. For this purpose, the absorbed energy on areal density was targeted at 160 (the maximized goal). Table 4 shows the optimal goal for the values. The importance and weight of the response were considered as the unit. A second-degree polynomial was used for the regression.

Table 4. The optimization setup of one response.

Response	Goal	Lower	Target	Upper	Weight	Importance
E_e (J m^2/kg)	Maximize	30	160	160	1	1

3. Results and discussion

The results were related to the specific energy absorption index of the Kevlar/PP. Weft-knitted hybrid composites with different process factors of fabrication have been summarized in Table 5. The bar chart in Figure 4 shows that sample category number 12 has higher specific energy absorption in the experimental test result.

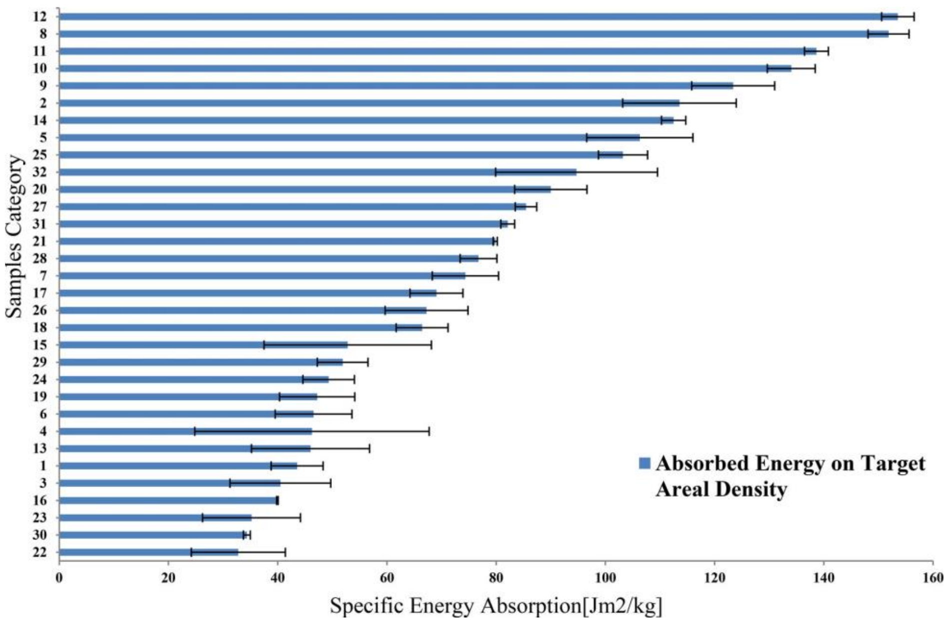

Figure 4. Results of specific energy absorption of the Kevlar/PP weft-knitted hybrid composites.

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

Table 5. Specific energy absorption of the Kevlar/PP weft-knitted hybrid composites.

Samples category	Specific energy absorption (E_e) ($J\ m^2/kg$)
1	43.57 (4.76)[a]
2	113.57 (10.39)
3	40.49 (9.22)
4	46.27 (21.46)
5	106.30 (9.72)
6	46.57 (7.03)
7	74.37 (6.07)
8	151.86 (3.76)
9	123.40 (7.60)
10	134.04 (4.38)
11	138.66 (2.19)
12	153.56 (2.98)
13	46.01 (10.82)
14	112.50 (2.22)
15	52.82 (15.32)
16	39.94 (0.14)
17	69.07 (4.85)
18	66.45 (4.75)
19	47.23 (6.89)
20	90.01 (6.62)
21	79.85 (0.37)
22	32.79 (8.61)
23	35.21 (8.96)
24	49.33 (4.71)
25	103.23 (4.51)
26	67.25 (7.59)
27	85.47 (1.97)
28	76.77 (3.37)
29	51.90 (4.64)
30	34.36 (0.64)
31	82.13 (1.27)
32	94.72 (14.83)

[a] Bracketed values are the standard deviations.

Based on the RSM optimization of the input data, the best process of air texture factors that corresponded to the optimal response was evaluated. Accordingly, Figure 5 shows the influence of the process factors (X_1: blend ratio, X_2: stitch length, X_3: the type of the knitting method, X_4: molding time(min), X_5: molding pressure (kg/cm^2), X_6: molding temperature (degree), and X_7: blending quality (1: high blending quality, 2: low blending quality) (Hosseinalizadeh et al., 2019)) on the specific energy absorption index (E_e).

Figure 5 is a standard diagram for introducing the optimal variables via the desirability function in the software Minitab 16. The horizontal axis (X) shows the seven variable factors (X_1 to X_7) at three levels. 'High' means level [2] (Table 2) for seven factors, 'low' means level [1] (Table 2) for seven factors and the 'cur' shows the optimized values ([1], [2], [1], [2], [1], [1]) for seven factors. The vertical axis (Y) shows the one response variable with the maximum value of specific energy absorption of the model (166.0581). Based on the target of optimization desirability, the value for each response variable is defined (between '0' and '1'). In this research, one response variable was defined with the target of maximization (Table 4). In the maximum level of the response variable (y = 166.0581), the desirability value is '1'. The composite desirability is the geometric mean of each response variable desirability. In this study, there is one response variable (specific energy absorption), so the composite desirability is equal to the response desirability and is '1'. The red vertical lines refer to the optimized value of each process variable (X_1 to X_7) according to its maximum value of specific energy absorption (the blue horizontal dashed line). The graphs show that when the blend ratio (X_1) is '1:2' or level '1', the stitch length (X_2) is '4' or level '2', the knitting structure (X_3) is full-milano or level '1', the molding time (X_4) is '20 min' or level '2, the molding pressure (X_5) is '300 kg/cm^2' or level '2', the molding temperature (X_6) is '160 C' or level '1' and the blending

This is the accepted manuscript (postprint) of the following article:
Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., & Eslami-Farsani, R. (2022). Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. *The Journal of The Textile Institute*, *113*(6), 1018-1026.
https://doi.org/10.1080/00405000.2021.1914408

quality is 'high' or level '1', the specific energy consumption is the maximum value (166.0581), and the desirability value is '1'.

The results indicated that the higher composite desirability (D = 1) of specific energy absorption could be achieved by controlling process factors such as a lower level (1:2) of the blended fiber ratio (Kevlar: PP), a higher level (4) of stitch length, a full-milano weft-knitting process, a higher level (20 min) of molding time, a higher level (300 kg/cm^2) of molding pressure, a lower level (160 °C) of molding temperature and a higher level (1) of blending quality. Category 12 (Table 3) was produced with the above optimum factors.

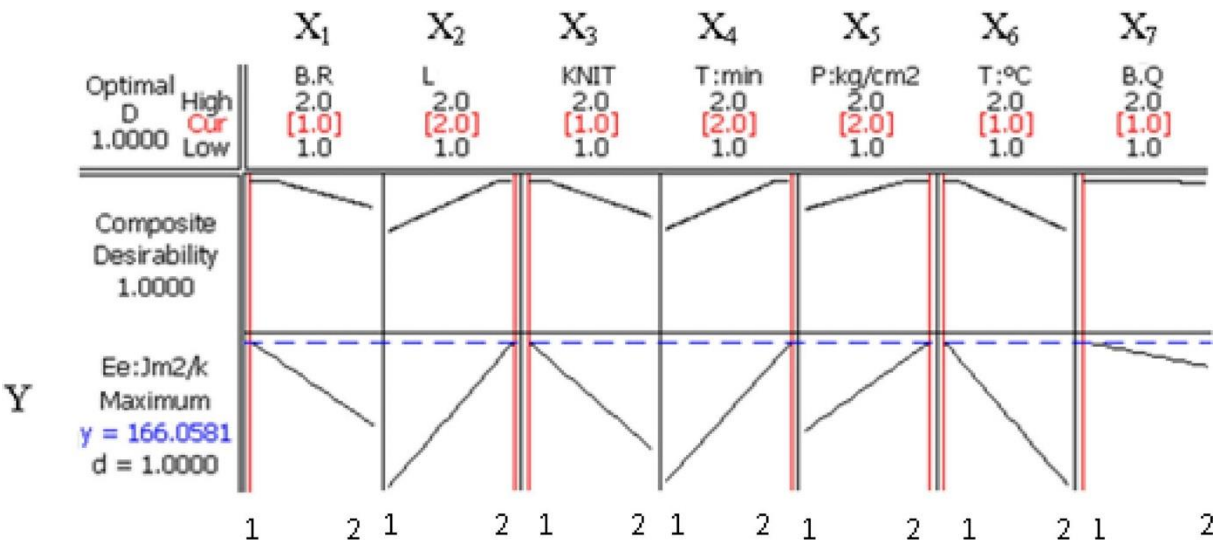

Figure 5. Optimized process parameters for the energy absorption index.

Table 6 summarizes the experimental values of the absorbed energy of the optimized sample (category 12) and the values estimated by the model and the absolute error. It could be concluded that the model value was trustworthy.

Table 6. The energy absorption of the optimized sample, experimental and model.

Responses	Experimental	Model	Abs. error (%)
E_e (J m^2/kg)	153.56	166.05	8.13

In the optimization process, all seven variable parameters were interdependent, so that with the variation of one parameter in the manufacturing process, the other parameters could be adjusted to achieve the desired energy absorption by considering the one affected index. According to the objective of this study, the desired energy absorption occurred when the absorbed energy on the areal density of the composite had the maximum value.

The co-air-textured yarn with the blend ratio of 1:2 had a finer structure, so about 60% of the Kevlar fibers had this yarn cross-section. Thus, there were more Kevlar fibers in this area of the composite. This increased the energy absorption of the composites. On the other hand, in the blend ratio of 1:4, about 60% of the PP fibers exhibited this yarn cross-section. Thus, more PP fibers were present in the specific region of the composite. This increased the adhesion and tensile strength and a decrease in the toughness and stiffness of the composite. In this situation, the amount of force per unit time at the moment of collision with the ballistic impact of the composite caused the fibers to fail before they began to stretch, which reduced the energy absorption in the composite.

Stitch length is an important factor determining the properties of the weft-knitted fabrics. As the stitch length increased, the stitch density in the specific dimensions of the fabric decreased, and thus the intersection of the stitches was slacker. This resulted in a more direct threading path and the fabric became more elastic. In this case, due to the nature of the fiber structure, there was no possibility of resonance and tension waves at the intersection points; so, reaching the maximum stretching of the fibers and cutting them were unlikely. Therefore, when the ballistic impact was applied to the weft-knitted composite with more stitch length, without applying much tension to the fibers, projectile attenuation occurred; consequently, the absorbed energy increased on the areal density.

In the full-milano weft-knitted fabrics, the amount of yarn consumed was similar on the back and front of the fabric, and the fabric was balanced. Some missing stitches in the full-milano fabrics reduced the thickness, width, weight and load on impact due to the direct yarn path of the fabric. The friction between the Kevlar fibers was very low, so they could shift a lot during an impact. Therefore, the energy was not properly absorbed by these fibers. In the full-milano structure, the displacement of the Kevlar fibers in the yarn and the composite structure is reduced and limited due to the higher dimensional stability compared to the rib fabric, so that there is good energy absorption by the Kevlar fibers. Therefore, in the full-milano structures, the local movement of the fibers was reduced, resulting in good energy absorption compared to the fabricated composite with rib structures.

In the fabrication of the composite, by decreasing the time and temperature of the melt and increasing the molding pressure, the sintering of the PP fibers and their adhesion with Kevlar in the co-air-textured yarns and the weft-knitted composites became more uniform and the flexibility of the composite upon impact increased, improving the energy absorption.

By using the matrix and reinforcement in the substrate of the blended yarn as fiber in the composite production, it is possible to control the Kevlar of fiber displacement in the wide range of the manifold; in fact, the PP fibers in a tiny Kevlar can reinforce fibers; in this way, a lot of control could be reduced due to the rise in the blow.

As the blending quality of each blend ratio increased in the co-air-textured yarns, so did the number of PP filaments. Therefore, the movement of Kevlar filaments through the yarn and the composite structure with PP filaments could be limited after the melting process due to the effect of the ballistic impact. The Kevlar fibers could easily overcome the friction force and move from their place; otherwise, they could cause holes and more convenient projectiles, which reduced the energy absorption of the composite.

A higher value of co-air-textured yarn blending quality means that the radial, lateral and angular distribution in the yarn and composite cross-section was uniform, which improved the energy absorption of these composites.

4. Conclusion

In this study, the specific energy absorption of hybrid weft-knitted composites fabricated from the Kevlar/PP co-air-textured yarn was investigated using the RSM statistical method. The co-air-textured yarn with the blend ratio of 1:2 had a finer structure so that about 60% of the Kevlar fibers consist of this yarn cross-section. Thus, there were more Kevlar fibers in the specific area of the composite. This increased the energy absorption of the composites. Stitch length is an important factor that determines the properties of the weft-knitted fabrics. When the ballistic impact was applied to the weft-knitted composite with more stitch length, without applying much traction on the fibers, damping of the projectile occurred; consequently, the absorbed energy on the areal density increased. In the full-milano structure, due to the higher dimensional stability compared to the rib fabric, the displacement of the Kevlar fibers in the yarn and composite structure is reduced and limited, so there is good energy absorption by the Kevlar fibers. In the manufacture of the composite, by reducing the time and temperature of the melt and increasing the molding pressure, greater uniformity was achieved and the flexibility of the composite increased upon impact, improving energy absorption. This was attributable to the sintering of the PP fibers and their adhesion with Kevlar in the co-air-textured yarn and the weft-knitted composites. As the blending quality of each blend ratio in the co-air-textured yarns increased, so did the number of PP filaments around the Kevlar fibers. Therefore, the Kevlar filament-free movement through the yarn and composite structure could be restricted with PP filaments after the melting process. A higher value of co-air-textured yarn blending quality means that the radial, lateral and angular distribution in the yarn and composite cross section was uniform, which improved the energy absorption of these composites. The results showed that the better desirability of specific energy absorption could be achieved by controlling process factors such as blend fiber ratio 1:2 (Kevlar:PP), higher level (4) of stitch length, full-milano weft-knitting structure, longer (20 min) melting time, higher level (300 kg/cm^2) of the molding pressure, lower level (160 °C) of the melting temperature, and higher level of the blending quality. The optimization setup of one response was very important as it could affect the desirability results. To reveal the objective of this study, the specific energy absorption was targeted as the maximized objective. The experimental values of the energy absorption index and the values estimated by the model showed that the model values were trustworthy with an 8.13% error.

References

Atiqah, A., Jawaid, M., Sapuan, S. M., & Ishak, M. R. (2019). Dynamic mechanical properties of sugar palm/glass fiber reinforced thermoplastic polyurethane hybrid composites. Polymer Composites, 40(4), 1329–1334. https://doi.org/10.1002/pc.24860

Carrillo, J. G., Gamboa, R. A., Flores-Johnson, E. A., & Gonzalez-Chi, P. I. (2012). Ballistic performance of thermoplastic composite laminates made from aramid woven fabric and polypropylene matrix. Polymer Testing, 31(4), 512–519. https://doi.org/10.1016/j.polymertesting.2012.02.010

Cheeseman, B. A., & Bogetti, T. A. (2003). Ballistic impact into fabric and compliant composite laminates. Composite Structures, 61(1–2), 161–173. https://doi.org/10.1016/S0263-8223(03)00029-1

Chou, S., & Wu, C. J. (1992). A study of the physical properties of epoxy resin composites reinforced with knitted glass fiber fabrics. Journal of Reinforced Plastics and Composites, 11(11), 1239–1250.

Czigany, T., & Karger-Kocsis, J. (2001). A comparison of the mechanical behaviour of weft-knitted glass and carbon fiber fabric-reinforced polyamide-12 composites produced with commingled staple yarns. Polymers and Polymer Composites, 9(8), 491–498. https://doi.org/10.1177/096739110100900801

Dabiryan, H., Hasanalizade, F., & Sadighi, M. (2019). Low-velocity impact behavior of composites reinforced with weft-knitted spacer glass fabrics. Journal of Industrial Textiles, 49(4), 465–483. https:// doi.org/10.1177/1528083718787533

Dimeski, D., Bogoeva-Gaceva, G., & Srebrenkoska, V. (2011). Resin content and molding pressure influence on ballistic properties and trauma effect of aromatic amide fibers composites [Paper presentation]. Faculty of Technology in Leskovac Conference Proceedings. Faculty of Technology in Leskovac.

George, G., Joseph, K., Saritha, A., & Nagarajan, E. R. (2018). Influence of fiber content and chemical modifications on the transport properties of PP/jute commingled biocomposites. Polymer Composites, 39, E250–E260. https://doi.org/10.1002/pc.24306

Hosseinalizadeh, M., Dolatabadi, M. K., Najar, S. S., & Farsani, R. E. (2019). Blending quality of co-air-textured yarn: Optimization parameters of Kevlar/polypropylene applicable for thermoplastic composites. Journal of Composite Materials, 53(13), 1791–1802. https://doi.org/10.1177/0021998318811510

Leong, K. H., Falzon, P. J., Bannister, M. K., & Herszberg, I. (1998). An investigation of the mechanical performance of well-knit Milano-rib glass/epoxy composites. Composites Science and Technology, 58(2), 239–251. https://doi.org/10.1016/S02663538(97)00128-0

Li, T.-T., Fang, J., Huang, C.-H., Lou, C.-W., Lin, J.-Y., Lin, M.-C., Chen, Y.-S., & Lin, J.-H. (2017). Numerical simulation of dynamic puncture behaviors of woven fabrics based on the Finite Element Method. Textile Research Journal, 87(11), 1308–1317. https://doi.org/10.1177/0040517516652343

Loganathan, T. M., Sultan, M. T. H., Gobalakrishnan, M. K., & Muthaiyah, G. (2019). Ballistic impact response of laminated hybrid composite materials. In M. Jawaid, M. Thariq & N. Saba Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites (pp. 171–191). Woodhead Publishing.

Min, S., Chai, Y., Chu, Y., & Chen, X. (2019). Effect of panel construction on the ballistic performance of multiply 3D through-the-thickness angle-interlock fabric reinforced composites. Polymers, 11(2), 198. https://doi.org/10.3390/polym11020198

Naik, N. K., & Shrirao, P. (2004). Composite structures under ballistic impact. Composite Structures, 66(1–4), 579–590. https://doi.org/10. 1016/j.compstruct.2004.05.006

Naik, N. K., Shrirao, P., & Reddy, B. C. K. (2005). Ballistic impact behaviour of woven fabric composites: Parametric studies. Materials Science and Engineering: A, 412(1–2), 104–116. https://doi.org/10. 1016/j.msea.2005.08.019

Pandita, S. D., Falconet, D., & Verpoest, I. (2002). Impact properties of weft knitted fabric reinforced composites. Composites Science and Technology, 62(7–8), 1113–1123. https://doi.org/10.1016/S02663538(02)00057-X

Patil, P. S., & Naik, N. K. (2018). Ballistic impact performance of spaced multilayered and monolithic composite targets: Analytical and experimental studies. International Journal of Damage Mechanics, 27(9), 1352–1379. https://doi.org/10.1177/ 1056789517732376

Pol, M. H., Liaghat, G., Zamani, E., & Ordys, A. (2015). Investigation of the ballistic impact behavior of 2D woven glass/epoxy/nanoclay nanocomposites. Journal of Composite Materials, 49(12), 1449–1460. https://doi.org/10.1177/0021998314535010

Priyanka, P., Dixit, A., & Mali, H. S. (2019). High strength Kevlar fiber reinforced advanced textile composites. Iranian Polymer Journal, 28(7), 621–638.

Ramakrishna, S., & Hull, D. (1993). Energy absorption capability of epoxy composite tubes with knitted carbon fibre fabric reinforcement. Composites Science and Technology, 49(4), 349–356. https:// doi.org/10.1016/0266-3538(93)90066-P

Sabet, A., Fagih, N., & Beheshty, M. H. (2011). Effect of reinforcement type on high velocity impact response of GRP plates using a sharp tip projectile. International Journal of Impact Engineering, 38(8–9), 715–722. https://doi.org/10.1016/j.ijimpeng.2011.03.004

Safri, S., Sultan, M., Yidris, N., & Mustapha, F. (2014). Low velocity and high velocity impact test on composite materials –A review. International Journal of Engineering Science, 3(9), 50–60.

Salman, S. D., Leman, Z., Sultan, M. T. H., Ishak, M. R., & Cardona, F. (2017). Effect of kenaf fibers on trauma penetration depth and ballistic impact resistance for laminated composites. Textile Research Journal, 87(17), 2051–2065. https://doi.org/10.1177/ 0040517516663155

Selver, E., Potluri, P., Hogg, P., & Soutis, C. (2016). Impact damage tolerance of thermoset composites reinforced with hybrid commingled yarns. Composites Part B: Engineering, 91, 522–538. https:// doi.org/10.1016/j.compositesb.2015.12.035

Sevkat, E., Liaw, B., & Delale, F. (2012). Ballistic performance of hybrid and non-hybrid composite plates. The Journal of Strain Analysis for Engineering Design, 47(7), 453–470. https://doi.org/10.1177/ 0309324712457897

Vijaykumar, G. (2018). Hybrid biocomposites. Polymer Composites, 39(S1), E30–E54.
Wiegand, N., & Mäder, E. (2017). Commingled yarn spinning for thermoplastic/glass fiber composites. Fibers, 5(3), 26.

Zaera, R. (2011). Ballistic impacts on polymer matrix composites, composite armor, personal armor. In S. Abrate (Ed.), Impact engineering of composite structures (pp. 305–403). Springer.

Zaixia, F., Zhangyu, Yanmo, C., & Hairu, L. (2006). Tensile properties of glass fiber knitted fabric reinforced polypropylene composite made from GF/PP commingled yarn affected by prestretching. Journal of Reinforced Plastics and Composites, 25(5), 553–560.