International Journal of Engineering Research and Development, Vol.7, No.4, 2015, 1st International Defense Industry Symposium Special Issue

Ballistic Performance of Kevlar$_{49}$/ UHMW-PE$_{HB26}$ Hybrid Layered-Composite

Mert Onur YAVAŞ, Ahmet AVCI, Mehmet ŞIMŞIR, Ahmet AKDEMIR

Department of Mechanical Engineering,Selçuk University, 42079, Konya, Turkey
Department of Metallurgical and Materials Engineering,Cumhuriyet University, 58140, Sivas, Turkey
Tel:+90 346 219 10 10 (2805); Fax: +90 346 219 11 79, msimsir@cumhuriyet.edu.tr

Abstract— This experimental study investigates the effects of plies number on ballistic performance of Kevlar$_{49}$/ UHMW-PE$_{HB26}$ (ultra high molecular weight polyethylene) layered-hybrid composite. Ballistic performance of the composite samples is explained in terms of trauma depth, energy absorption capacity and the mechanisms that lead to perforation in varied composite samples. Ballistic tests are performed according to NIJ 0101.04 Level-III standards. The results is showed that the produced composite samples excluding Type V-composite provide Level IIIA protection according to NIJ 0101.04 standard. The critical number of ply for Kevlar$_{49}$/ UHMW-PE$_{HB26}$ layered-hybrid composite is obtained as 16 plies consisting of 8 plies for each fabrics. Trauma depth increases with decreasing total number of plies in the composite samples. The energy absorption capability of the layered-composite decreases with decreasing total number of plies. Energy absorption mechanisms are explained by strain energy of the plies due to straining and fracture of yarns, delamination of plies and layers, and friction energy between plies, and the mobility of yarns.

***Index Terms*— Kevlar$_{49}$; UHMW-PE$_{HB26}$; Hybrid composite; Ballistic test**

I. INTRODUCTION

The personal protective armours for military and civilian applications are generally manufactured from woven or nonwoven fabric of fibres due to their lightness, high tenacity, high elastic modulus and good ballistic properties. Aramids, UHMW-PE, poly-benzobis-oxazole (PBO) and poly-pyridobisimi-dazole (PIPD) fibres are widely used fibres in ballistic performance. Ballistic performance means the ability to absorb the kinetic energy of a bullet without injury to a person. Therefore, the armour must be designed not only for nonperforation, but also for a minimum backside deformation [1-15].

Ballistic performance depends on many parameters. Cheeseman and Bogetti [3] carried out studies on important parameters of ballistic protective fabrics. Some of these parameters depends on material properties used in production of armour, such as fibre and yarn properties [2], fabric unit area weight. Some part of parameters are related with fabric construction, such as woven and nonwoven fabrics [3,5,6],, dimension of fabric [3]. Apart from these parameters, bullet geometry [7], shooting angle (Zeng et al., 2005) and bullet speed [12,13] are other parameters affecting ballistic performance.

Many researchers have been worked on the ballistic protection mechanisms. [8] indicated that Twarons CT 716 woven fabric have different energy absorption mechanisms— yarn rupture, fibrillation, failure by friction [24], and bowing. Grujicic [22] worked on UHMW-PE (Spectra) fabrics and the following fracture modes are most often observed sequential delamination [23], plug punch-out induced by the through-the-thickness shear, and combined fiber shearing/cutting and fiber tensile failure [9,10].

The aim of this study is to produce a candidate material used for the personal protective armour and to investigate the effect of plies number on the ballistic performance of Kevlar49/ UHMW-PEHB26 hybrid layered- composite. By changing total ply number, to determine limit of full perforation of Kevlar49/ UHMW-PEHB26 type hybird layered-composite.

II. EXPERIMENTAL STUDY

A. Materials

Kevlar49 (Du Pont PRD-49) woven-fabric, ultra-high molecular weight poly-ethylene, (UHMW-PE, Dyneema® HB26) cross-plied fiber-fabric were used in the present research. Mechanical properties of used materials are shown in Table 1.

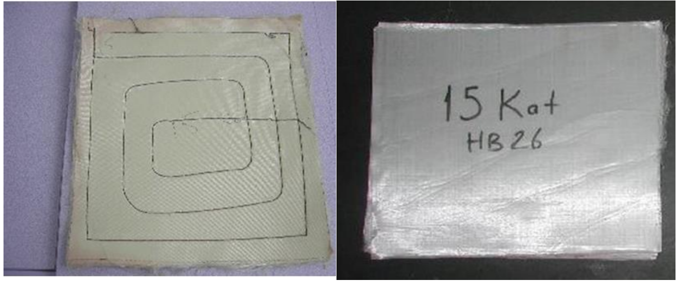
Table I.
Material properties of the Kevlar$_{49}$ and UHMW-PE$_{HB26}$

Materials	Density g/cm^3	Weight g/m^2	UTS GPa	Elastic modulus GPa	Elongation at fracture %	Flameable Temperature ^{o}C	Sound velocity, V_s (1000m/s)
Kevlar$_{49}$	1.44	210	2.9	120	1.9	500	8.2
UHMW-PE$_{HB26}$	0.97	260	3.0	95	3.6	145	10

Karahan [15] concluded that stitching decreases trauma depth. Therefore, before composite samples were produced, the plies of Kevlar$_{49}$ in the layers were stitched together to reduce the trauma of impact loading. Then, all the constituents of the composite sample were stacked and combined in an order

DOI: 10.29137/umagd.379789

without pressing and polyester resin. Fig.1 shows the materials used in the present study



(a) (b)

Figure 1. Materials used in fabricating composites;a)Kevlar$_{49}$ with 15 plies, b)UHMW-PE$_{HB26}$ with 15 plies

In order to determine limit of full perforation of Kevlar$_{49}$/ UHMW-PE$_{HB26}$ type hybird layered-composite, the number of plies in a layer was changed. For this purpose, five different hybrid layered-composites were fabricated as below:

Type I- [(Kevlar$_{49}$)$_{15}$+(UHMW-PE$_{HB26}$)$_{15}$+(Kevlar$_{49}$)$_{5}$+(UHMW-PE $_{HB26}$)$_{15}$]$_{50}$. According to rule of mixture (ROM), volume fractions of Kevlar$_{49}$ and UHMW-PE$_{HB26}$ were calculated as 0.266 and 0.734, respectively.

Type II-[(Kevlar$_{49}$)$_{15}$+(UHMW-PE$_{HB26}$)$_{15}$]$_{30}$

Type III-[(Kevlar$_{49}$)$_{10}$+(UHMW-PE$_{HB26}$)$_{10}$]$_{20}$

Type IV-[(Kevlar$_{49}$)$_{8}$+(UHMW-PE$_{HB26}$)$_{8}$]$_{16}$

Type V-[(Kevlar$_{49}$)$_{5}$+(UHMW-PE$_{HB26}$)$_{5}$]$_{10}$

Volume fractions of Kevlar$_{49}$ and UHMW-PE$_{HB26}$ in the composite samples other than Type-I are the same and were calculated as 0.352 and 0.648, respectively.

B. Ballistic Tests

Test apparatus were adapted to NIJ 0101.04 Level-III standards [Ref]. Speed of the bullet just before it touches the composite sample was measured by a velocimeter called Oehler Research Model 55 (ORM 55). Schematic illustration of ballistic test set up is shown in Fig. 2. In this apparatus, there is 5 m distance between the exit of the bullet from the gun barrel and the target, and 1m distance between two velocity measuring units. The midpoint of the velocity measuring unit is positioned at the midpoint of the distance which is 2 m from the tip of the gun barrel. Passed time of bullet is measured between two velocity measuring units. Velocity of bullet just before it touches the composite sample was read from its digital display after every firing.

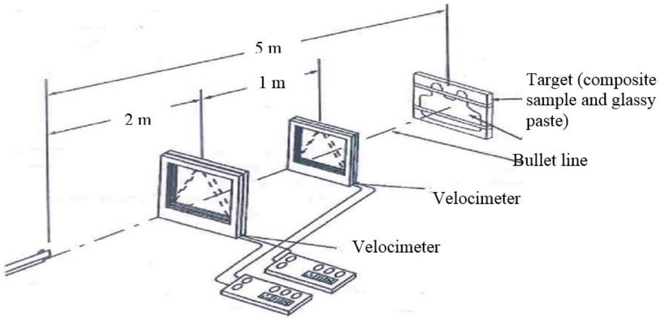


Figure 2. Schematic illustration of ballistic test set up

C. Firing bullets

Full-Metal Jacket (FMJ) bullets were used in present research. Full-Metal Jacket (FMJ) bullets have 7.43 g core weight, 15 mm length and 9 mm diameter. Total bullet weight including core, gun powder and cartridge is 11.64 g.

D. Backing material

Glassy paste was used as backing material to measure trauma depth. Glassy paste was filled in a mold with 10 mm thick having same dimensions of composite test sample and compressed in order to get rid of air, then conditioned minimum three hours between a temperature of 15-30 ºC . Hardness of glassy paste can show variability depending on temperature and environmental conditions. For this reason, it is important to do the calibration. In the calibration, a cylindrical iron bar with half sphere front tip and having 44.5±0.5 mm diameter and 1 kg weight was used. Calibration test was conducted to determine the trauma depth on the backing material created by the potential energy of semi-sphere iron. In the tests, the cylindrical iron bar was dropped three times on the backing material from 2 m height from inside a hollow tube. Trauma depth were measured for each case. The shape of trauma was taken as the semi-sphere shape of the tip of the iron bar. Validity of the backing material is depends on the trauma depth which must be in the range of 22-28 mm.

III. APPLICATION OF BALLISTIC TEST

Firing tests were carried out according to NIJ 0101.04 Level III standard. The composite sample were fixed along all four edges, and a glassy paste layer was applied to the backside of the sample to measure the backface deformation (trauma depth). Firings at varied speeds, v were performed from a 5 m to the front face of the specimens at 90±1 deg, at least 50 mm from plate edges and at least 80 mm away from any area damaged in previous firing.

Before application of ballistic test, the layered-composite sample sample was conditioned at room temperature. The ballistic tests were performed at a 50% relative moisture and 23 ºC temperature.

IV. RESULTS AND DISCUSSIONS

A. *Trauma Depth*

Trauma depth is so important because a higher trauma depth causes creating large damage on human body. Firing tests were conducted and bullet speed remained in the values given in NIJ standards. Trauma depth were measured for the cases in which panel stopped the bullet. Average values of trauma depth are given in Table 2 together with the bullet speeds and kinetic energies of bullet.

Table II.
The results of ballistic tests of the Composites from 5 m distance

Firing No	Velocity m/s	E_k J	Trauma Depth mm	Absorbed energy J/(g/m^2)	Result
The results of ballistic tests of the Composite-I					
1	426	674.1	18	2.7326	No perforation
2	434	699.4	18	2.8351	No perforation
6	435	702.9	20	2.8493	No perforation
3	436	706.2	19	2.8627	No perforation
5	436	706.2	22	2.8627	No perforation
4	437	709.4	20	2.8757	No perforation
Average	434	699.7	19.5	2.8364	
The results of ballistic tests of the Composite-II					
7	435	702.9	23	2.9000	No perforation
8	438	712.7	25	2.9404	No perforation
Average	436.5	707.8	24	2.9202	
The results of ballistic tests of the Composite-III					
3	386	553.5	25	2.2836	No perforation
2	411	627.5	28	2.5889	No perforation
1	438	712.7	33	2.9404	No perforation
Average	411.67	631.23	28.67	2.6043	
The results of ballistic tests of the Composite-IV					
1	337	421.9	36	1.7404	No perforation
2	380	536.4	38	2.2131	No perforation
3	*418*	*649.0*	*42*	*2.6776*	No perforation
4	435	702.9	*51*	Not calculated due to large trauma	No perforation *but large trauma*
Average	392.5	577.55	41.75	2.3828	
The results of ballistic tests of the Composite-V					
1	340	429.4	-		*Full perforation*

Type I- $[(\text{Kevlar}_{49})_{15}$+($\text{UHMW-PE}_{\text{HB26}})_{15}$+$(\text{Kevlar}_{49})_5$+($\text{UHMW-PE}_{\text{HB26}})_{15}]_{50}$ layered-composite. The composite panel was made of four layers and total 50 plies. The composite plate with 14 mm thick has 300x300 mm dimensions and 1080 g weight. The results of ballistic tests for all produced composite sample were given in Table 2. As it was seen, perforation of composite sample was not observed. Trauma depths were measured in a range of 18-22 mm. The values of trauma depth is less than that of defined value in NIJ 0101.04 standard (maximum trauma depth, 22<44 mm) and the Type-I composite sample provides Level IIIA protection according to NIJ 0101.04 standard.

Fig. 3 shows the front faces of the layers in the Type-I composite sample, respectively. When the layers in the Composite-I sample were inspected, it was observed that there was no perforation up to fifth firing and bullets were stoped at the fourteenth ply of the first layer ($(\text{Kevlar}_{49})_{15}$) of the Composite-I sample. The first layer was dirilled at the sixth firing since the previous firings created large damages in the first layer. However, the bullet was stopped at front face of the second layer (($\text{UHMW-PE}_{\text{HB26}})_{15}$). As it is seen in Fig.3 that plastic deformation was observed on the third ($(\text{Kevlar}_{49})_{15}$) and fourth layer(($\text{UHMW-PE}_{\text{HB26}})_{15}$). During the ballistic test, a shock wave is created on ballistic plane due to kinetic energy of the bullet. Propagating shock energy wave in the composite samples causes fibre breaks and woven fabric deformation. The most of the energy was absorbed by the first and second layer. After these observations, number of layers in the composite sample was reduced since second layer was stopped the bullet.

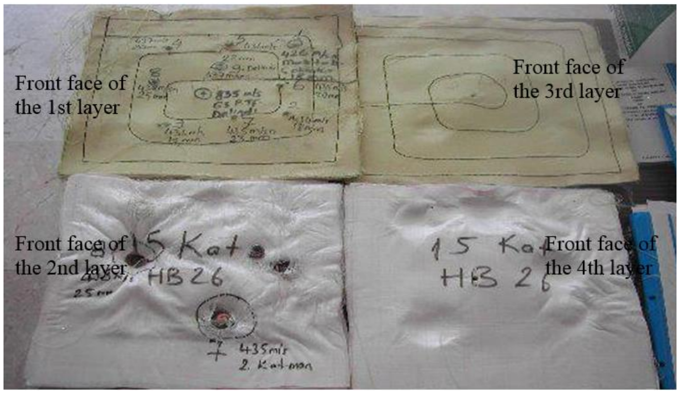


Figure 3. The front faces of the layers in the Composite-I sample

Type II-$[(\text{Kevlar}_{49})_{15}$+($\text{UHMW-PE}_{\text{HB26}})_{15}]_{30}$ hybrid layered-composite. The composite panel was obtained by separating two layers from Type-I composite sample. The composite plate with 8.5 mm thick has 635 g weight and 300x300 mm dimensions. The results of ballistic tests are given in Table 2. Average trauma depth was measured 24 mm. The maximum value of trauma depth is less than that of defined value in NIJ 0101.04 standard (max. trauma depth 25<44 mm) and the Composite-II sample provides Level III A protection according to NIJ 0101.04 standard.

Fig. 4 shows the front faces of the layers in the Composite-II sample, respectively. When the layers in the Composite-II sample were inspected, it was observed that there was no fully perforation on the composite panel. However, the first layer ($(\text{Kevlar}_{49})_{15}$) was drilled and the bullet was stopped at front face of the second layer (($\text{UHMW-PE}_{\text{HB26}})_{15}$). This is due to that second layer of the composite samples, which is the $\text{UHMW-PE}_{\text{HB26}}$. This layer has lager area due to its construction, i.e. $\text{UHMW-PE}_{\text{HB26}}$ is not produced in the form of woven-fabric and it is produced by unidirectional layers of filaments. These layers are used in 0-90° constructions in the ballistic packet. Under the impact loading, shock wave travels through filaments. The impact energy is distributed faster and efficiently in the UHMW-PE_{HB26} layer [14].

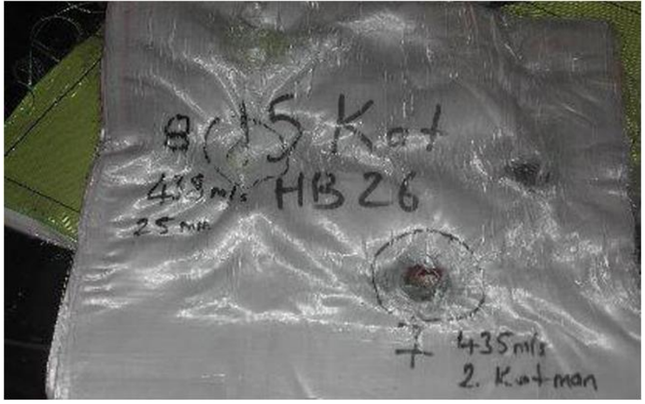


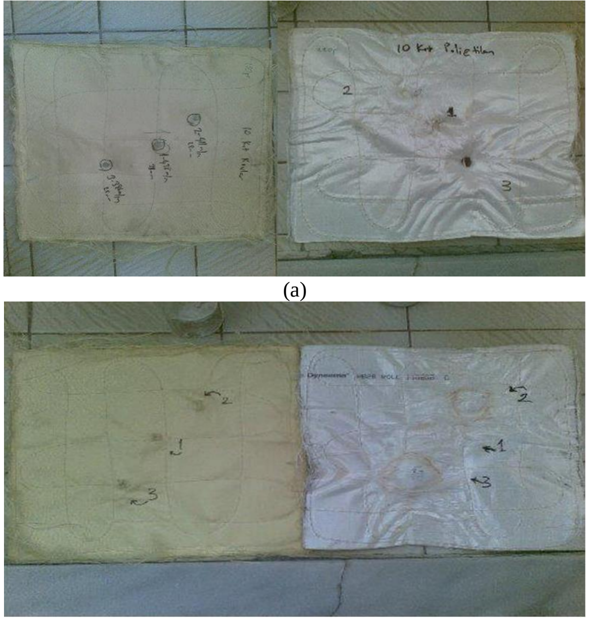
Figure 4. The front face of the second layer of the composite

Type III-$[(\text{Kevlar}_{49})_{10}+(\text{UHMW-PE}_{\text{HB26}})_{10}]_{20}$ layered-composite. The composite panel was made of two layers and each layer has 10 plies and total 20 plies. The composite plate with 5.6 mm thick has 423 g weight and 300x300 mm dimensions. The results of ballistic tests are given in Table 2. Average trauma depth was measured 28.67 mm. The values of trauma depth is less than that of defined value in NIJ 0101.04 standard (max. trauma depth 33<44 mm) and the Type–III composite sample provides Level III A protection according to NIJ 0101.04 standard.

Fig. 5 a and b shows the front faces of the layers in the Composite-III sample, respectively. When the layers in the Composite-III sample were inspected, it was observed that there was no fully perforation on the composite panel. However, the first layer ($(\text{Kevlar}_{49})_{15}$) was drilled and the bullet was stopped at front face of the second layer ((UHMW-$\text{PE}_{\text{HB26}})_{15}$). As it is seen (Fig.5b) that plastic deformation was observed on the second layer((UHMW-$\text{PE}_{\text{HB26}})_{15}$). Amount of deformation on the back face of the composite panel increases with increasing in the number of firings.

Type IV-$[(\text{Kevlar}_{49})_{8}+(\text{UHMW-PE}_{\text{HB26}})_{8}]_{16}$ hybrid layered-composite. The composite panel was made of two layers and each layer has 8 plies and total 16 plies. The composite plate with 4.5 mm thick has 339 g weight and 300x300 mm dimensions. The results of ballistic tests are given in Table 2. Average trauma depth was measured 41.75 mm. The maximum value of trauma depth is greater than that of defined value in NIJ 0101.04 standard (max. trauma depth 51>44 mm) and the Composite –IV sample did not provide Level III A protection according to NIJ 0101.04 standard. It was observed that there was no fully perforation on the composite panel but high deformation was observed in result of the fourth firing.

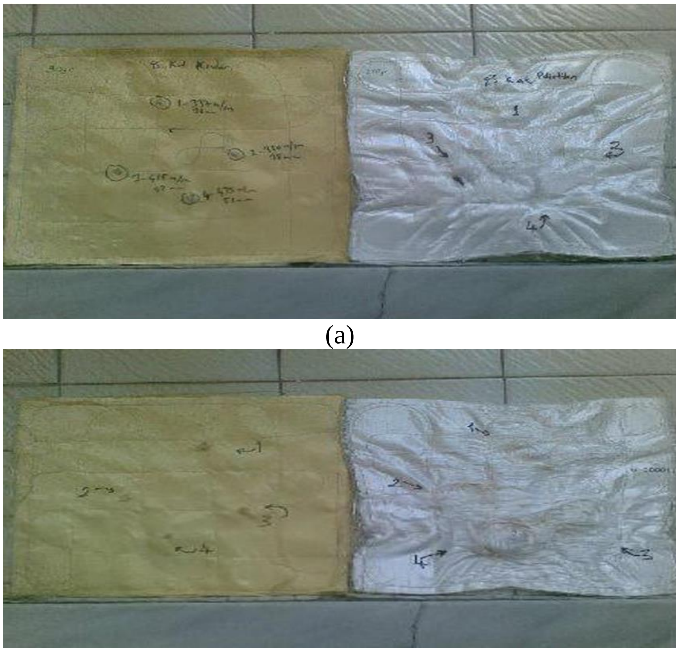
Fig. 6 a and b shows the front and back faces of the first and the second layers in the Composite-IV sample, respectively. When the layers in the Composite-IV sample were inspected, it was observed that the first layer ($(\text{Kevlar}_{49})_{15}$) was dirilled and the bullet was stopped at the front face of the second layer ((UHMW-$\text{PE}_{\text{HB26}})_{15}$). As it is seen (Fig.6b) that very large plastic deformation was observed on the back face of the second layer((UHMW-$\text{PE}_{\text{HB26}})_{15}$). Amount of deformation on the back face of the composite panel increases with increasing in the number of firings.



(a)

(b)

Figure 5. Front faces of composite layers; a) first and second layers, b) third and fourth layers



(a)

(b)

Figure 6. a) Front faces of first and second layer, b) Back faces of first and second layer

Type V-$[(\text{Kevlar}_{49})_{5}+(\text{UHMW-PE}_{\text{HB26}})_{5}]_{10}$ hybrid layered-composite. The composite panel was made of two layers and each layer has 5 plies and total 10 plies. The composite plate with 2.9 mm thick has 212 g weight and 300x300 mm dimensions. The result of ballistic test is given in Table 2. When the layers in the Composite-IV sample were inspected, full perforation was observed on the composite panel. The Composite –IV sample did not provide Level III A protection according to NIJ 0101.04 standard.

Fig. 7 a and b shows the front and back faces of the layers in the Composite-V sample, respectively.

(a)

(b)

Figure 7. a) Front faces of first and second layer, b) Back faces of first and second layer

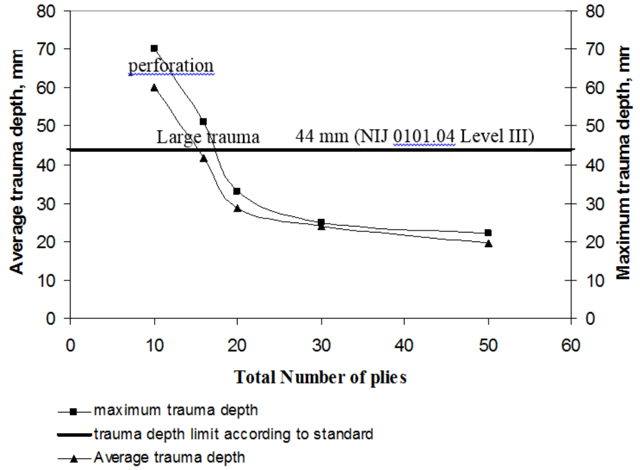


Figure 8. Trauma depth versus total number of plies in the composite panels

As it is seen in Fig. 8, increasing in the number of plies decreases the trauma depth. The critical trauma depth of 42 mm was carried out when the total number of plies in the composite reaches a critical value of 16 plies (Type-IV). Critical bullet velocity was observed as 418 m/s for Kevlar$_{49}$/ UHMW-PE$_{HB26}$ composite (Type-IV). For all composite samples, it was observed that when a composite sample stoped a bullet, it was deformed and decreased in its strength. In firing tests, it can be said that trauma depth generally increases with increasing number of firing (Table 2).

B. Absorbed Energy

In the current study, absorbed energy was calculated in terms of kinetic energy of bullet and energy absorbing capacity. Karahan [15] stated that when a bullet strike to composite panel, a part of kinetic energy bullet is absorbed by composite panel and the rest is transmitted to the glassy paste and creates a trauma on the glassy paste. Also, the energy expended by the bullet in perforating the fabric specimens is regarded as the energy absorbed by the fabric [8]. It is found by subtracting the residual energy of the projectile from its initial impact energy. When no perforation occurs, the energy absorbed by the fabric is taken as equal to the initial impact energy. In the current study, transmitted energy was neglected since there is no perforation in the composite sample, and also trauma depth was smaller than critical trauma depth (44 mm). Kinetic energy of a bullet is calculated using following equation:

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

m is the mass of a bullet, v is the velocity of bullet. The kinetic energy values were given in Table 2. Kinetic energy of bullet increases with increasing velocity of bullet. As it was seen that absorbing kinetic energy of composite samples decreases with decreasing total number of plies in the composite samples and reaches limit value as 649 J when the total number of plies is 16 plies in composite (Type-IV composite sample). It is desired that lesser energy forms lesser trauma on glassy paste.

Energy absorbing capacity is more suitable for determining absorbed energy than kinetic energy of bullet term since it is calculated on the basis of weight per area. Therefore, energy absorbing capacity of a composite panel is important to determine ballistic resistance of a composite panel. Energy absorbing capacity is calculated according to weight per area of the composite panel using following equation;

$$E = \frac{E_k}{W} \tag{2}$$

E_k= Kinetic energy of bullet, J, and W=Weight of the composite panel, g/m^2. Weight of composite per area is calculated using Rule of Mixture (ROM). The weight per area for the Type-I composite, W_I, was calculated as 246.69 g/m^2. For other composite samples, W_{II}, W_{III}, W_{IV} and W_V were calculated as 242.38 g/m^2 since the volume fractions of Kevlar$_{49}$ and UHMW-PE$_{HB26}$ in the composite samples are the same. Energy absorbing capacity values of the composite samples were given in Table 2. Energy absorbing capacity of composite samples decreases with decreasing total number of plies in the composite samples and reaches limit value as 2.6776 J/(g/m^2) for Type-IV composite sample. For Type-V composite sample was not calculated since fully perforation of the composite was observed. It is concluded that the amount of absorbed energy depends on the number of stretched yarns and number of broken yarns in its fabric constituent during impact loading. In addition to that, fibers having high-tensile strengths and large failure strains increases considerable amounts of absorption energy. Roylance and Wang [17] worked on high velocity impact loading of Kevlar and spectra laminates. They showed that materials having high-wave velocities were advantageous since the stresses and strains could propagate more quickly to neighboring fibers and layers, thus involving more material in the ballistic event. This can be seen in the high-speed photographic study conducted by Field and Sun [18] who examined the transverse wave speeds of a number of different fibers, Kevlar fabrics and Spectra laminates impacted with steel balls fired at velocities of up to 1000 m/s.

The energy absorption of the composite samples were explained by three mechanisms. Delamination was observed by stroking a bullet to composite sample. It becomes incosistency in bending of plies in the impact direction causes delamination between plies in layers and also between layers. Furthermore, delamination in the composite sample occured easily since the composites were produced without any resin matrix. There is no any restriction on the movement of yarns and plies. By this way, high impact energy is dispersed away from the impact point and distributed over a wider area and prevents large strains from developing at the impact point. In contrans to that, Grujicic [16] have told that stiffer resin matrices (e.g., vinyl ester versus polyurethane) tend to constrain the yarn movement to a greater degree and to force the penetrator to engage and fracture more yarns during penetration. The reason is that armor-grade composites reinforced with woven-yarn fabric are generally found to possess a higher energy-absorption potential than their resin-free fabric counterparts. In addition to delamination, the energy absorbed by the plies are converted into strain energy created from straining and broken of the number of yarns in its fabric constituent. Some of the yarns in direct contact with the penetrator head are strained and broken. Some of the yarn along the periphery of the bullet head strains but not broken and slip off from bullet head. More details on impact energy dissipation of strings was reported by Smith [11]. In the current study, yarn tensile straining/fracture and delamination is the major mechanisms for absorption of the bullet kinetic energy. Similar results was obtained by Lee [9]. They have indicated that fiber straining is the primary mechanism of the energy absorption in the penetration failure of ballistic textile.

Some part of the impact energy is also converted to frictional energy. The frictional energy causes some melt of UHMW-PE$_{HB26}$ plies (Fig.4). Similar melt damage such as fiber fusion, bridging and contraction has also been observed in impacted panels of UHMWPE [19-21]. Mobility of yarn is not restricted by any resin matrix. Relative motion between the orthogonal yarns while the yarns deflects outwards results in friction between the yarns at the crossover points. Some energy is dissipated as frictional energy when the bullet penetrates the plies and squeeze through the perforation. Also, friction takes place between bullet and yarns along the periphery of the bullet head and also by the side-way movement of the yarns. These yarns slip off from the penetrator. Movement of the yarns partly prevented by stitching of Kevlar$_{49}$ plies.

V. CONCLUSION

In this study, Kevlar$_{49}$/ UHMW-PE$_{HB26}$ layered-hybrid composites were produced with resin free matrix in order to use at personal defense against to light weapons. The results showed that the produced composite samples (except Type-V composite sample) can be used for protective purpose according to NIJ 0101.04 Level-III standards. The trauma depths of the composite samples were measured lower than that of defined NIJ standards.

The effects of plies number on ballistic performance of Kevlar$_{49}$/ UHMW-PE$_{HB26}$ layered-hybrid composite were investigated. Increase in ply number decreases the trauma depth and increases the energy absorbing capacity. Critical total ply number was found as 16 plies consisting of 8 plies for each textile fabrics, and also the critical velocity of bullet was measured as 480 m/s for the Type-IV composite.

Ballistic performance of the composite samples was assessed in terms of energy absorption mechanisms. Three mechanism were observed; delamination, fiber straining and fracture, friction between yarns, plies and layers. It can be said that delamination and fiberstraining and fracture are the major energy absorption mechanisms for the Kevlar$_{49}$/ UHMW-PE$_{HB26}$ layered-hybrid composites.

VI. REFERENCES

[1] O. Soykasap and M. Colakoglu, Ballistic performance of a Kevlar-29 woven fiber composite under varied temperatures, Mechanics of Composite Materials, Vol. 46, No. 1, 2010

[2] Chitrangad, Hybrid ballistic fabric. United States patent no. 5,187,003, 16 February 1993.

[3] Cunniff P.M., An analysis of the system effects of woven fabrics under ballistic impact. Textile Res J 1992;62(9):495–509.

[4] Cheeseman B.A, Bogetti TA. Ballistic impact into fabric and compliant composite laminates. Compost Struct 2003;61:161–73.)

[5] Briscoe BJ, Motamedi F. The ballistic impact characteristics of aramid fabrics: the influence of interface friction. Wear, 1992;158:229–47.

[6] Bazhenov S. Dissipation of energy by bulletproof aramid fabric. J Mater Sci 1997;32(15):4167–73.

[7] Tan VBC, Tay TE, Teo WK. Strengthening fabric armour with silica colloidal suspensions. Int J Solids Struct 2005;42:1561–76

[8] V.B.C. Tan, C.T. Lim, C.H. Cheong. Perforation of high-strength fabric by projectiles of different geometry, International Journal of Impact Engineering 28 (2003) 207–222

[9] Lee BL, Walsh TF, Won ST, Patts HM, Song JW, Mayer AH. Penetration failure mechanisms of armor-grade fiber composites under impact. J Compos Mater 2001; 35 (18) :1605–33.

[10] B.L. Lee, J.W. Song, and J.E. Ward, Failure of Spectra_ Polyethylene Fiber-Reinforced Composites Under Ballistic Impact Loading, J. Compos. Mater., 1994, 28(13), p 1202–1226

[11] Smith JC, McCrackin FL, Schiefer HF. Stress–strain relationships in yarns subjected to rapid impact loading. Part V: wave propagation in long textile yarns impacted transversely. Text Res J 1958;28:288–302.

[12] Lyons WJ. Impact phenomena in textiles. Cambridge, Massachusetts: MIT Press; 1963.

[13] Shim VPW, Tan VBC, Tay TE. Modelling deformation and damage characteristics of woven fabric under small projectile impact. Int J Impact Eng 1995;16(4):585–605.

[14] M. J. N. Jacobs, J. L. J. Van Dingenen, Ballistic protection mechanismsin personal armour. J Mater Sci 36 (2001) 3137 – 3142

[15] Mehmet Karahan, Abdil Kus, and Recep Eren, An investigation into ballistic performance and energy absorption capabilities of woven aramid fabrics, International Journal of Impact Engineering 35 (2008) 499–510

[16] M. Grujicic, P.S. Glomski, T. He, G. Arakere, W.C. Bell, and B.A. Cheeseman, Material Modeling and Ballistic-Resistance Analysis of Armor-Grade Composites Reinforced with High-Performance Fibers, JMEPEG (2009) 18:1169–1182

[17] Roylance D and Wang SS. Penetration mechanics of textile structures. In: Laible RC, editor. Ballistic Materials and Penetration Mechanics. NewYork: Elsevier Scientific Publishing Co; 1980.

[18] Field JE and Sun Q. A high speed photographic study of impact on fibres and woven fabrics. In: The Proceeding of the 19th International Congress on High-Speed Photography and Photonics Part 2, 16–21 September 1990. p. 703–12.

[19] Prosser RA, Cohen SH, Segars RA. Heat as a factor in the penetration of cloth ballistic panels by 0.22 caliber projectiles. Text Res J 2000;70(8):709–22.

[20] Iremonger MJ. Polyethylene composites for protection against high velocity small arms bullets. In: Proceedings of the 18th International Symposium on Ballistics, San Antonio, Texas, 15–19 November 1999. p. 946–53.

[21] Prevorsek DC, Kwon YD, Chin HB. Analysis of the temperature rise in the projectile and extended chain polyethylene fiber composite armor during ballistic impact and penetration. Polym Eng Sci 1994;34(2):141–52.

[22] M. Grujicic, G. Arakere, T. He, W.C. Bell, B. A. Cheeseman, C.-F. Yen, and B. Scott, A Ballistic Material Model for Cross-Plied Unidirectional Ultra-High Molecular- Weight Polyethylene Fiber-reinforced Armor-Grade Composites, Mater. Sci. Eng, A, 2008, 498(1-2), p 231–241

[23] N. Critescu, L.E. Malvern, and R.L. Sierakowski, Failure Mechanisms in Composite Plates Impacted by Blunt-Ended Penetrators, Foreign Object Impact Damage to Composites, ASTM STP #568, ASTM, Philadelphia, PA, 1975, p 159–172

[24] Y. Duan, M. Keefe, T. A. Bogetti, and B. Powers, “Finite element modeling of transverse impact on a ballistic fabric,” Int. J. Mech. Sci., 48, 33-43 (2006).

[25] NIJ 0101.04 Level-III standards