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Bulletproof Vests/Shields Prepared from Composite Material based on Strong Polyamide Fibers and Epoxy Resin

[1]Remon A. Mankarious, [1]Mostafa A. Radwan, [2]Mostafa Shazly and [1]Hany A. Elazab
[1]Departmentof Chemical Engineering,
[2]Department of Mechanical Engineering,
Faculty of Engineering, The British University in Egypt, Cairo, Egypt

Abstract: Fiber Reinforced Plastics (FRP) have arisen as a main class of structural materials having high strength and light weight implemented in a large scale of different applications. This study performs a comparison between the enhanced properties of Kevlar 49 fiber and Twaron CT 704 reinforced with epoxy resin to obtain an efficient, light weight and slim body armor capable of resisting high speed projectiles (9 mm bullets). Reinforcing the fabrics adds extra strength to the fabrics instead of using several unreinforced fabrics which increases the weight, thickness and the cost of the final product. The response of the prepared composite material based on the two different fibers was studied by using a test barrel for the penetration test. In addition, indentation test is also applied to compare between the mechanical properties of both laminates and determine which fabric is better for life protection applications. The final results showed that using the technique of reinforcing the fabrics specially Twaron is much better where the final bulletproof shield has less number of layers and was found lighter by 40% than those made by Kevlar.

Key words: Fiber reinforced plastics, Kevlar 49, Twaron CT 704, bulletproof vests/shields, 9 mm bullets

INTRODUCTION

Producing efficient light weight bulletproof vests to replace heavy metallic shields for life protection applications has been a critical issue until the technology of strong synthetic fibers arose in the 1970s. Fibers like kevlar and twaron have been used for ballistic resistance due to their high modulus, energy absorption and strength to weight ratio. Multiple layers of the fabric are aligned for a bulletproof panel manufacturing to absorb the kinetic energy of the bullet and resist the deformation of the panel. Woven fabrics provide strength in two mutually perpendicular orientations which helps in dissipating the energy in both directions during impact. Modern bulletproof vests made of polyamide fabrics have been used since the nineties of the previous century. Since then, the majority of these vests use multiple layers of unreinforced fabric to resist bullets. Karahan (2008) stated that the number of plies or layers of the fabric is the most important factor in absorbing the energy and decreasing the trauma in the panel after impact. The main challenge for the users of the bulletproof vest is the heavy weight and high cost associated with using multiple layers of fabrics without any treatment in addition to extra weight of ceramics added to resist higher calibers. Lee *et al.* (2001) showed that the amount of energy dissipated was relevant to number of plies and could be predicted by empirical equations where for woven fabrics at least 18 plies would dissipate 100% of the energy. The reinforcement of the fibers would target 100% dissipation of energy with less number of plies. Modern body armors are made of composite materials where high strength fibers are joined using high strength resin to achieve certain design criterion (Ramakrishnan *et al.*, 2014). When fiber is reinforced with a suitable resin, the performance of the finished product depends mostly on the fiber properties (Mines *et al.*, 1998).

Experimental data demonstrated that the fibrous reinforcement component carries the majority of the load (Figucia, 1980). Therefore, choosing the right fabric is essential to design composite structures. After reinforcing the fabric, it could be cut into small plates and stuffed inside the vest to achieve flexibility for body motions.

Body armors made of Kevlar, poly-p-benzamide polymer as the reinforcing fabric to resist bullet penetration are widely used for decades (FG, 2013) due to their extraordinary mechanical strength. Alternatively, other candidates such Twaron, a simple form of para polyaramids can be used in body armors. Twaron was

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Corresponding Author: Remon A. Mankarious, Departmentof Chemical Engineering, Faculty of Engineering, The British University in Egypt, Cairo, Egypt

invented by the Akzo team in 1974 and its chemical formula is P-phenylene Terephthalamide (PpPTA). Twaron's main advantage is that it is a light para-amid fiber with a high impact and penetration resistance properties.

The strength of body armor depends not only on fabric but also the resin type and its additives and the manufacturing process. Resins such as polyester, vinylester and epoxy are commonly used. Epoxy is chosen due to its high performance and usually recommended for light, high strength and dimensionally stable applications (Njuguna *et al*., 2007). Manufacturing techniques include manual lay-up, vacuum assisted resin infusion and resin transfer molding. Resin Transfer Molding (RTM) is known to produce high quality products but with high tooling cost while manual lay-up produces least quality among all techniques with low tooling cost. Vacuum assisted resin infusion produces relatively high quality products at moderate cost. Vacuum assisted resin infusion optimizes the fiber to resin ratio and produces a stronger, thin and lighter product and therefore adopted in the present study.

The main objective of the present work is to compare between Kevlar and Twaron fabrics after applying a reinforcement technique to enhance both fabrics to provide the vest user with an efficient light weight bulletproof vest made of chemically treated fabrics. The new approach involves the reinforcements of these fabrics using chemical additives (Epoxy adhesive) and the vacuum infusion technique to reach an efficient armor with less number of layers and hence less thickness, weight and cost.

MATERIALS AND METHODS

Experimental

Materials: Kevlar 49 and Twaron CT 704 are selected for the current investigation. Kevlar 49 has "decitex" number of 1270, number of filaments equals 768 with a breaking strength of 264 (N) and elongation at break of 2.4% (Hanif *et al*., 2015). Twaron CT 704 has "decitex" number of 840, number of filaments equals 1000 with a breaking strength of 215 (N) and elongation at break of 3.5%. Both fabrics are plain weaved fabrics and cut into samples of 20×20 cm each. Epoxy resin with a density of 1.11+/-0.02 kg/L, compressive strength equals 500-1000 kg/cm^2 and tensile strength equals 150-250 kg/cm^2 is selected. A hardener (tertiary-amine) is added to epoxy with ratio 1:2, respectively (CMB, 2008; TCC, 2017). All samples are produced using vacuum assisted resin infusion. Samples with 15, 20 and 25 layers of fabric for both Kevlar and Twaron are prepared for testing.

Experimental work: The experimental work here aims to quantitively differentiate between the test materials and compare the effect of number of layers on penetration resistance. Tensile tests are conducted using 100 KN screw driven universal testing machine (WDW-100 D).

Preparing the samples for resin infusion by the vacuum bagging technique include the following steps: cutting the desired samples into the required dimensions, apply some waxing on the lab bench to prevent adherence of the final product to the bench and surround the sample with sealant tape. Fix the peel ply at the edge of the sample near the feeding line of the resign which helps in spreading the resign easily and equally through the whole sample. Fix the bleeder in same position in order to hold the excess resign from entering the laminate part. Fix the release film at the opposite edge in order to retain more resign in the sample and prevent its escape in the hoses rapidly due to vacuum pressure. Remove the upper surface of the sealant tape and fix the vacuum bag carefully without leaving any perforated area which might lead to leakage of air. Make a small opening in the bag to install the vacuum connector which connects the bag with the tubing. Use an ultra-sonic device to check for any air leakage and try to fix it before operation. Connect all the hoses with the resign container from one side and the resign trap from the other side. Make sure to install shut-off valves before and after each connection to ensure safe and easy control on the process during the operation. The resign trap saves the pump from failure, this is because any excess resign coming out of the laminate part will be held in the resign trap instead of being sucked into the pump due to vacuum pressure and cause failure to the pump. The pump is a normal vacuum pump with a capacity of 10 CFM. Pressure gauge should be installed to ensure safe working conditions during the process. Figure 1 shows the procedure steps.

Indentation tests are performed according to ASTM D6264-98 (ASTMI, 2004) on flat panels. The purpose of these experiments is to measure the resistance to damage and penetration under the effect of a concentrated load applied at the center of the specimens by means of an indenter with a hemispherical tip having a 12.5 mm diameter. The rate of loading is slow enough to qualify for quasi-static loading conditions and is kept at a rate of 2 mm/min. Square specimens with a side length of 152 mm are cut from larger panels fabricated by vacuum infusion. Experiments are conducted for fully clamped boundary conditions.

Level IIA new armor is tested with 9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets with a specified mass of 8.0 g (124 g) and a velocity of 355 m/sec ±9.1 m/sec (1165 ft/sce ±30 ft/sce. Penetration test,

Fig. 1: Sample fabrication by vacuum resin infusion

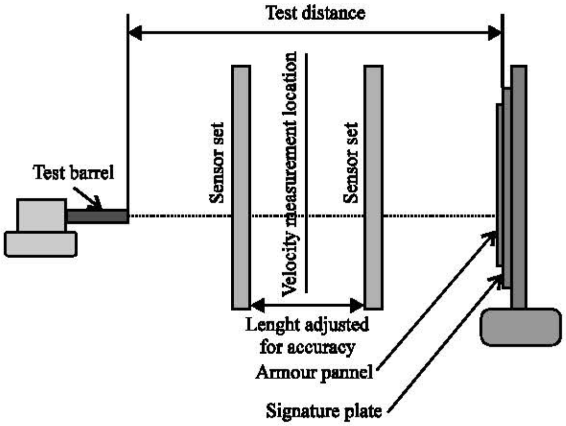


Fig. 2: Penetration test setup

schematically shown in Fig. 1 is a very critical test that must be performed under universal measures usually stated by NIJ Standards-0101.06 (Anonymous, 2008). For handgun rounds, samples are adjusted at a distance of 5±1 m from the muzzle of the test barrel. This test should succeed if no penetration occurs, even if the signature clay sheet shows any dents (trauma), it should not be deeper than 44 mm (Anonymous, 2008) (Fig. 2). Type IIA in the NIJ Standards are intended for a handgun new armor which is tested with 9 mm Full Metal Jacketed Round Nose (FMJ RN) and a velocity of 355s±9.1 m/sce. The signature clay sheet is fixed with inside dimensions of 610×610 mm and a depth of 140±2 mm (Anonymous, 2008).

RESULTS AND DISCUSSION

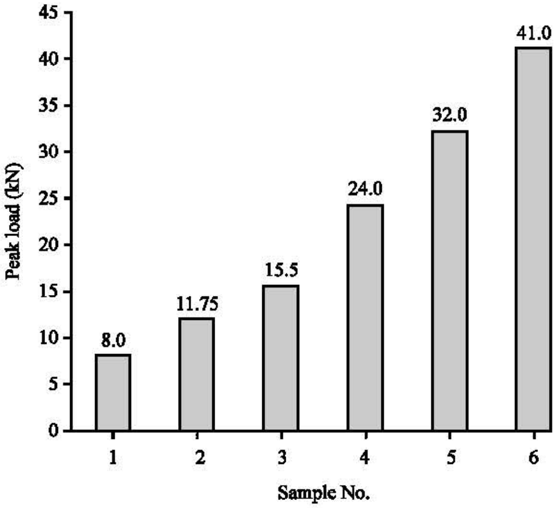


Fig. 3: Samples absorbed energies after indentation

Table 1: Classification of samples

Fabric type	Layers	Resin	Fiber/volume fraction (%)	Thickness of sample (mm)
Kevlar	15	Epoxy	46	6
Kevlar	20	Epoxy	50	7
Kevlar	25	Epoxy	52	8
Kevlar	25	Dry	100	5
Twaron	15	Epoxy	42	6
Twaron	20	Epoxy	45	7
Twaron	25	Epoxy	48	8

Table 2: Indentation test results

Samples	Peak load (kN)
1	8.00
2	11.75
3	15.50
5	24.00
6	32.00
7	41.00

Table 3: Penetration test results

Samples	Sample perforation	Trauma (mm)
1	Yes	-
2	Yes	-
3	Yes	-
4	No	40
5	No	15
6	No	12
7	No	10

Table 1 shows a brief and summarized table showing all samples prepared from different fabrics, number of layers and resign used and thickness of each sample to provide an overall view about the variance of samples and how does each sample was made to suit the different tests and measure a unique property for the fabric solely.

Initial assessment using quasi-static indentation shows that Twaron can withstand higher penetration loads until fracture as shown in Table 2. Kevlar samples are failed due to puncture as shown in Fig. 3 while Twaron samples show excessive deformation under the indenter, wrinkling and finally puncture as shown in Fig. 4 and 5.

Table 3 and Fig. 6 show bullet penetration tests. The results show that all Kevlar samples reinforced with

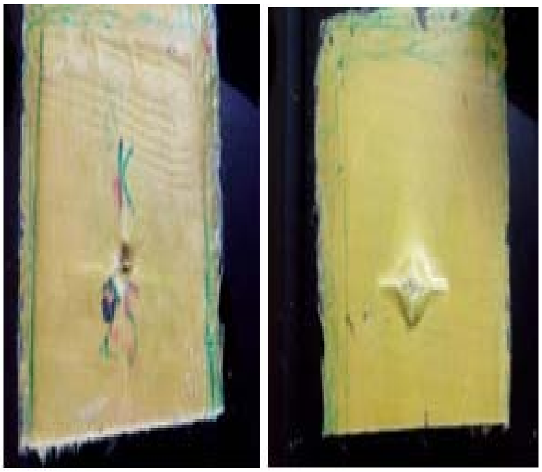
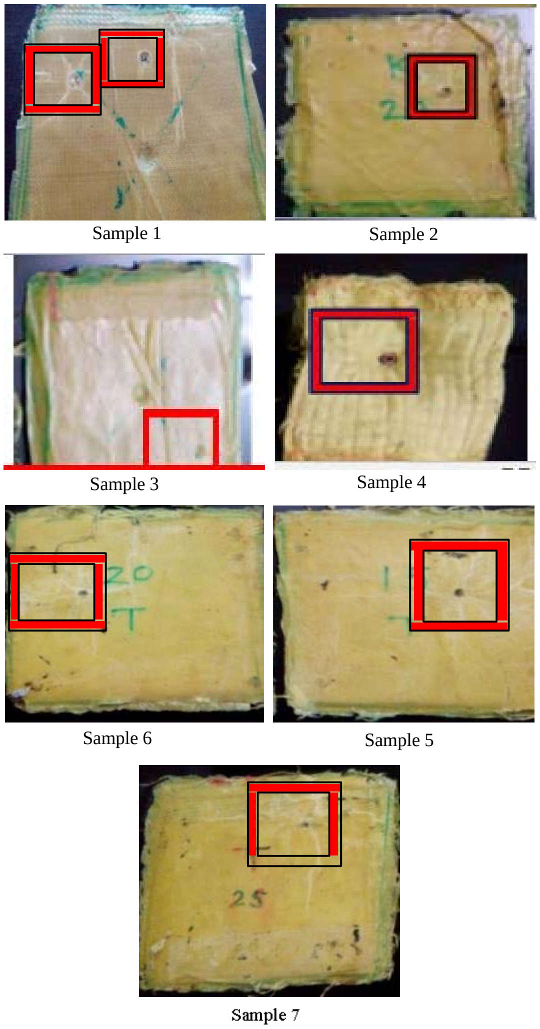


Fig. 4: Sample 3 after indentation

Fig. 5: Sample 7 after ondentation

resin couldn't resist the 9 mm bullets, instead complete perforation of the armor occurred without resistance. sample #4 made of dry Kevlar fabric resist the bullet but with serious trauma reaching 40 mm while the maximum range is 44 mm according to NIJ standards (Anonymous, 2008).

Twaron samples showed better resistance to bullet penetration test as shown in Table 3. Results show that all three samples of Twaron resisted the bullet with good range of trauma. This is obvious even sample #5 fabricated with 15 layers which resulted in a trauma of only 15 mm. The following pictures shows the sample after the penetration test where the red boxes determine the point of impact of the bullets.



Sample 1

Sample 2

Sample 3

Sample 4

Sample 6

Sample 5

Sample 7

Fig. 6: Samples after penetration test. Samples 1-4 are for Kevlar while samples from 5-7 are for Twaron

CONCLUSION

In conclusion, producing a light weight efficient bulletproof armor using the fiber reinforced laminates was the target of the present work. Experimental work showed that Kevlar samples punctured under quasi-static indentation while Twaron samples were excessively deformed, wrinkled and finally punctured. Under bullet penetration test, all Kevlar samples reinforced with epoxy failed to stop the bullet while dry Kvelar fabrics resulted in trauma under the limit set by standards. In this sample, the whole filaments of the fabric contributed to the absorption of bullet's energy in an even and equal way. Twaron CT704 showed better resistance to bullets in which no perforation occurred at all with very little number of layers which reached 40% less than Kevlar 49, hence less weight, thickness and cost over Kevlar.

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