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Preparation and Characterization of Bullet-Proof Vests Based on Polyamide Fibers

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Research paper

Preparation and characterization of bullet-proof vests based on polyamide fibers

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Abstract

Fiber reinforced plastics (FRP) is classified as one of the main classes of structural materials. Due to its high strength and light weight, it is considered for being used in a large scale of different applications. Particularly, bullet proof vests are widely used in order to protect the soldiers from being targeted in battle fields, however many modifications are being implemented to enhance the bullet resistivity of the vests for achieving more protection. This scientific paper investigates the enhanced properties of Twaron CT 736 when it is being reinforced with epoxy resin and topped with silicon carbide ceramics. The potential application for this kind of enhancement is to produce body armor plates that would resist the penetration of machine gun 7.62 * 39 mm and 7.62 * 51 mm bullets. A ballistic gun and triggering unit for the penetration test were used and the response of the prepared samples was studied. Vacuum bagging technique was adopted to prepare the samples. The final results of this research study show that, in order to stop a machine gun 7.62 * 39 mm normal bullet the plate should contain 30 layers of Twaron CT736 topped with 2 layers of ceramics, while in order to stop a machine gun 7.62 * 51 mm bullet the plate should contain 70 layers of Twaron CT 736 topped with 3 layers of ceramics.

Keywords: *Fiber Reinforced Plastics; Kevlar 49; Twaron CT 704; Bulletproof Vests/Shields.*

1. Introduction

It is well established that bullet proof vests are widely used nowadays in most military forces in order to protect the soldiers from being injured or targeted during operations in battle fields. There are huge research efforts that are being exerted to investigate several modifications that could enhance the bullet resistivity of the vests for achieving more protection. [1-3] There are several materials such as abalone, spider-silk, silica nano-particles, Kevlar and Twaron that are widely used in the vests' production. [4] Polyamide (PA) is considered as an ideal high performance engineering plastic due to its good fatigue resistance and high strength.
The main characteristics of both Kevlar and Twaron are quite similar as they both can be wetted using a resin in order to produce a new material that is light, rigid, and with high mechanical strength. [5-7] This area of scientific research is currently considered as a hot topic area. The research efforts and progress in this field is currently focused on adopting new methods of preparation and characterization of bullet proof vests based on different materials including polyamide fibres.
In this scientific research we investigated a bullet proof vest due to its importance as a hot topic of research and the historical evolution of bullet proof vests starting from the 16^{th} century and its continuous improvement till now. [8-11] Moreover, a detailed description of the materials used in the production of bullet proof vests including a scientific background for both Kevlar and Twaron that were extensively investigated. It is well known that Twaron is the flag product of Teijin Aramid, and it is classified as a high performance synthetically made fiber. Similarly, Twaron offers an outstanding performance in terms of resistivity to chemical, thermal stability, mechanical properties, and outstanding durability. [12] It is also used in a wide range of applications including ballistic protection and head protection. [13] Particularly, in this research the used resin is EPOXY 150 that is produced by CMB. It is mainly used due to its high performance and it is recommended for being used in light, high strength and stable applications. Vacuum bagging is a technique that is used to generate mechanical pressure on a laminate along its curing process. Applying pressure on a composite removes the trapped air between the layers, makes the fiber layers more compact. Silicon carbide selected is used in the outer face as its hardness is important to destroy and smash the projectile and also its low density offers battle field mobility as silicon carbides have densities of 3.2 g/cm^3 compared with 4 g/cm^3 aluminum oxide ceramics. [14]
There are many different types of Twaron according to their physical properties and chemical structure. A bullet proof vest is a personal armor worn on the chest in order to absorb most of the impact caused by the fired bullet and hence, it can reduce or stop the bullet's penetration to the body. [15]
Soft vests are mainly made of a number of layers of woven fibers or laminated fibers, these vests can protect from shotgun and small explosives' fragments resulting from hand grenades as well. Usually those vests contain a ballistic plate where metal or ceramic plates are mostly used with soft vests as they provide protection against rifle rounds. [16]
The metallic components and the woven layers of fibers enhance the resistance of the armor against stabs and slash attacks resulting from knives and comparable weapons such vests are mostly worn by police officers and citizens that work for security companies. Hard-plate reinforced vests are worn by combat soldiers and others who are exposed to higher risks. Vests designed for military and police usage could also have a ballistic shoulder and components for side protection.
Currently, there is nothing called a bullet-proof vest, however, all the available vests are believed to be bullet resistant simply because there will always be a weapon that has the ability to penetrate the

vests even those produced with the latest technology. For more than thirty years, the synthetic fiber Kevlar has been the main material for producing bullet-resistant vests. The main scientific idea is that the developed bulletproof vest must have the capability to spread the kinetic energy of the projectile as well as to stop the penetration of the bullet. Abalone is one of the materials that inventors believed would meet the requirements as it is made up of many layers of microscopic hard calcium tiles. The layers of abalone are held by a certain sticky protein from the top and bottom while the sides are butting up against each other. When abalone is targeted, it is tough enough to prevent the projectile from penetration and since the tiles can slide back and forth the energy of impact is distributed among the neighboring tiles. Researchers believe that it can stop anything threw at it, but it cannot be used as it will disturb the aquatic life as huge amounts will be needed.

Twaron has been used due to its outstanding properties including resistivity to chemical, thermal stability and mechanical properties. It is also used in the industrial field due to its outstanding durability. It has a wide range of applications that are somehow challenging including ballistic protection and head protection. It is also used in the oil and gas industry as well as automotive industry and in optical fibers production. [17], [18]

Currently, there are new trends to use embedded nanoparticles in materials like polyamide to produce composite nano-fibers with tunable properties for being applied in many applications. [19-26]

2. Experimental

2.1. Materials

Twaron style CT 736 is used in the typical experimental procedure. Epoxy is used as a reinforcement resin to provide the layers with the required stiffness and to preserve their flexibility. The EPOXY 150 comes with its hardener which is usually a tertiary amine and they are mixed together in a ratio of 2:1 respectively by weight.

2.2. Research methodology

In typical experimental procedure, 20 * 20 cm samples of Twaron fibers were prepared using vacuum bagging technique and epoxy for the reinforcement. Five samples were prepared with different number of layers and are piled in a different way while using the same technique. The vacuum bagging technique was used for all of the samples except sample 1. The samples were prepared in a way makes each sample contains a different number of layers and each layer has a dimension of 20 * 20 cm. For the first sample, twenty five layers of Twaron were cut and reinforced with epoxy and then topped with one layer of ceramics (twenty three pieces of ceramics). For the second sample, thirty layers of Twaron were cut and only ten of them were reinforced and twenty are sewed then topped with two layers of ceramics (forty six pieces). For the third sample, thirty layers of Twaron were cut and reinforced with epoxy then topped with two layers of ceramics (forty six pieces of ceramics). For the fourth sample, fifty layers of Twaron were cut and only twenty five are reinforced and the other twenty five are sewed then topped with two layers of ceramics (forty six pieces). Finally, the fifth sample was made up of seventy layers of Twaron at which only thirty five that were reinforced while the other thirty five were sewed then topped with three layers of ceramics (sixty nine pieces). The fusion/reinforcement is done via applying vacuum bagging.

2.3. Experimental work

2.3.1. Fabrication method

An electric scissor was used to cut the Twaron CT 736 Samples 20 cm * 20 cm then, laminate was placed for vacuum bagging and wax was also used in order to avoid the adhesion of the sample to the surface. Moreover, a seal film was used to surround the sample from all sides while, peel layer was used at the corner of the sample adjacent to the resin's feed line to allow a uniform spread of the resin throughout the sample. Then, the bleeder was also added at the corner of the sample that is adjacent to the resin's feed line in order to prevent the excess resin from passing to the laminate area and also added on the side opposite to which the peel layer and bleeder are fixed via using a release film to trap the resin in the sample during the process of applying vacuum.

Furthermore, vacuum bag was fixed cautiously by removing the upper layer of the seal film while making sure that there is no air bubbles under the vacuum bag. Then, the bag was connected to the pump by making a small hole in the bag and connecting them with tubing.

Additionally, ultra-sonic device was used to detect the presence of any leaks and then the tubes were connected with the resin's bucket/container and with the resin trap. Valves were used at the start and the end of every connection in order to achieve an easier control and safety while the process is carried out. A pressure gauge was also used to sustain a safe working environment.

Finally, the vacuum pump was opened to remove all the air. The valves were also opened to monitor the flow of the resin through the tubes and upon the wetting of the whole sample and left to be cured for one day.

2.3.2. Penetration test setup

It is extremely important and essential to perform this test according to the universal adopted protocol which is usually called the NIJ standards. Those measures are to provide the tester with the assistance needed to meet the minimum requirement for carrying out a ballistic resistant test, thus these standards assists in the validation of the tested armor. It is either the armor meets those requirements and considered as a bullet-proof vest or ballistic vest or it doesn't meet those requirements and it fails to be named as a bullet-proof vest.

The test was performed at room temperature 250 ºC, at pressure of 1 atm and relative humidity ranging from 20 % to 50 %. The sample was fixed to the back face signature clay and held in its position using ropes then the triggering unit was adjusted to fit for the bullet to be shot at the sample.

Moreover, the laser of the ballistic unit was used to point the trigger to the middle of the sample; the power supply was turned on while making sure that the door where the unit is present inside was closed properly and then the signal to the triggering unit was sent. After the bullet was shot, the power supply was turned off, the blank was removed from the trigger unit, the sample was also removed from the back face material and the trauma was measured using a caliper, if there was any. Finally, we found out whether the bullet had penetrated the sample or not and the same steps were repeated for all the other samples.

3. Results and discussion

The following table shows the results of performing the penetration test on the samples. The machine gun 7.62 * 39 mm normal bullet was tested on samples 1, 2 and 3. The effect of a machine gun 7.62 * 39 mm piercing incendiary bullet was tested on sample 4 and finally the effect of a machine gun 7.62 * 51mm bullet was tested on sample 5.

From figure 1, we can conclude that sample 1 wasn't able to stop the machine gun 7.62 * 39 mm normal bullet because all of its layers were reinforced. The layer of ceramic was able to absorb some of the kinetic energy of the bullet.

The reinforcement of the layers made all the layers strong and rigid, thus the layers were able to absorb the strength of the bullet but weren't able to dissociate and absorb the remaining kinetic energy of the bullet and stop it.

The resin filled all the layers of the Twaron, thus the acting characteristics of Twaron were these of the Epoxy. While sample 2 was able to stop the bullet because the layer of the ceramic at the front of the sample was able to absorb most of the kinetic energy of the projectile. Not only the layer of ceramic, but the five layers of Twaron reinforced with epoxy had the capability of decreasing the strength of the bullet as the bullet had faced a surface that is strong and rigid.

Table 1: Results of Penetration Test on Different Samples

Sample	Test Results
1	Didn't stop the machine gun 7.62 * 39 mm normal bullet from penetration and caused a 2 cm radius hole in the back face material
2	Stopped the machine gun 7.62 * 39 mm normal bullet from penetration and caused an acceptable trauma with a depth of 2 cm
3	Stopped the machine gun 7.62 * 39 mm normal bullet from penetration and caused an acceptable trauma with a depth of 0.5 cm
4	Didn't stop the machine gun 7.62 * 39 mm piercing and incendiary bullet from penetration and caused a 2 cm radius hole in the back face material
5	Stopped the machine gun 7.62 * 51 mm bullet from penetration and caused an acceptable trauma with a depth less than 0.5 cm

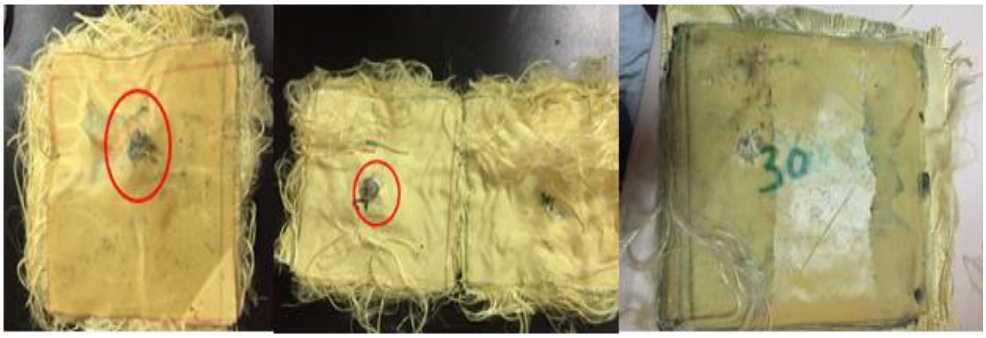

Fig. 1: Penetration Tests Showing Holes Formed for Samples 1, 2, and 3 Respectively.

Fig. 2: Penetration Tests Showing Holes Formed for Samples 4 and 5 Respectively.

Moreover, the twenty sewed layers were able to dissociate the rest of the kinetic energy of the bullet, since these layers were unreinforced the tensile strength of Twaron which was five times greater than steel enabled the bullet to dissociate the rest of its kinetic energy in these layers.

The twenty layers were quite flexible, thus the fibers were able to move back and forth decreasing the kinetic energy of the bullet. The bullet was stopped at the 15^{th} layer and didn't even reach the final 5 reinforced layers of Twaron.

Finally, the trauma caused is due to the static movement of the sample. As in sample 3, this sample was able to stop the machine gun 7.62 * 39 mm normal bullet and resulted in an acceptable trauma of 0.5 cm in the back face material, however all the layers of this sample were reinforced. The presence of a second layer of ceramics assisted the first layer of the ceramic to absorb most or nearly all the kinetic energy of the bullet and allowing the bullet to pass through the next thirty layers of reinforced Twaron just to decrease its strength and to dissociate remaining kinetic energy of the bullet.

Sample 4 wasn't able to stop the machine gun 7.62 * 39 mm piercing and incendiary bullet as the main characteristic of this bullet is to penetrate and burn the body or the object it is directed to. Even though this bullet was scheduled under the 39 mm bullets, its strength is five times the strength of a normal 39 mm bullet. Not only the strength but also the speed and the characteristics of this 7.62 * 39 mm bullet were much greater than the normal 39 mm bullet and sometimes greater than the 7.62 * 51 mm bullet.

Even though the Twaron fibers have high thermal resistivity and can withstand high temperatures, it couldn't withstand this bullet. The twenty five reinforced layers and the twenty five sewed unreinforced layers supported by two layers of ceramics weren't able to absorb neither the kinetic energy of the bullet nor its strength. Two 7.62 * 39 mm bullets were tested on this sample.

Finally, sample 5 was able to stop the machine gun 7.62 * 51 mm bullet due to the presence of three layers of ceramic that were able to absorb most of the bullet's strength. Upon detaching the thirty five reinforced layers from the thirty five unreinforced layers, it was found that the bullet didn't reach the thirty five reinforced layers. Therefore, the thirty five unreinforced layers assisted with the performance of the three layers of ceramic at the front were able to absorb all of the kinetic energy and the strength of the 7.62 * 51 mm bullet.

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Thus, the thirty five reinforced layers of Twaron could be decreased in number in further tests to decrease the weight of the sample, their presence is important as they could be the reason of preventing a big trauma to occur. Two 7.62 * 51 mm bullets were shot on the sample.

Tables 3 and 4 illustrate the weights of the samples and compare them with the weights of the already available vests. Sample 1 wasn't able to stop the machine gun 7.62 * 39 mm normal bullet because all of its layers were reinforced. The layer of ceramic was able to absorb some of the kinetic energy of the bullet. Sample 2 was able to stop the bullet because the layer of the ceramic at the front of the sample was able to absorb most of the kinetic energy of the projectile, the 20 sewed layers were able to dissociate the rest of the kinetic energy of the bullet as the fibers were able to move back and forth decreasing the kinetic energy of the bullet.

Table 2: Comparison between Different Weights of the Used Samples* and the Actual Weights in the Available Vests**

Sample Number	Weight (Kg)/0.25 m^2 *	Weight (Kg)/m^2 **
1	6.35	25.4
2	5.5	22.38
3	7.2	29.03
4	9.04	36.16
5	12.8	51.25

As for sample 3, the presence of a second layer of ceramics assisted the first layer of the ceramic to absorb most or nearly all the kinetic energy of the bullet. Sample 4 wasn't able to stop the bullet because it is much powerful than the normal 7.62 * 39 mm bullet so it needs a design that is more advanced. Finally for sample 5, this sample was able to stop the bullet due to the presence of 3 layers of ceramic that were able to absorb most of the bullet's strength.

The thirty five unreinforced layers assisted with the performance of the three layers of ceramic at the front were able to absorb all of the kinetic energy and the strength of the bullet. Thus, the thirty five reinforced layers of Twaron could be decreased in number in further tests to decrease the weight of the sample.

Table 3: Comparison Tests Between the Used Samples Weight* and the Actual Weights in the Available Vests**

Bullet Resistivity of the Plates	Weight (Kg)/0.25 m^2 *	actual weights**
Machine gun 7.62 * 39 mm normal bullet	7.2	8-10
Machine gun 7.62 * 51 mm	12.8	not evidence of presence of such plates that could stop this bullet

4. Conclusion

In conclusion, the aim of the research study was fulfilled as through the experimental work, it was able to design the optimum plate for two different types of machine gun bullets that are being used by military forces. The preparation of the samples was done after studying the theoretical background and the available revealed information that would facilitate the decision making process.

We report here the design of a bullet-proof vest that could stop the machine gun 7.62*39 mm normal bullet. The plates of this vest were prepared as follows; for one plate there are thirty layers of Twaron fiber reinforced with Epoxy and are piled together using the vacuum bagging technique and finally on top of the layers of Twaron there are two layers of the dragon ceramics.

The weight of this plate is 25.4 Kg/m^2 which is tolerable as the soldiers might only carry two plates in a vest, one in the front and one at the back each having dimensions 20 * 20 cm. thus the soldier would only carry a total weight of 2.323 Kg. Sample 2 wasn't considered as it caused a greater trauma than sample 3. As for the machine gun 7.62 * 51 mm bullet the plates are prepared as follows; for one plate thirty five layers of Twaron were reinforced and thirty five other layers were unreinforced topped with 3 layers of ceramics. The weight of this plate is 51.255 Kg/m^2, this could be a bit heavy but it would protect the soldiers from the strong 7.62 * 51 mm bullets.

Since the soldiers would only carry two plates of with dimensions of 20 * 20 cm, thus they will be carrying a total weight of 4.1 Kg. The plate prepared for the 7.62* 51 mm bullet could weigh less by decreasing the number of the reinforced layers because as previously mentioned the bullet didn't reach the reinforced layers.

In brief, The experimental results showed that samples 2,3 and 5 were able to stop the penetration of the bullet, however, samples 1 and 4 couldn't stop the bullet's penetration. For the futuristic work, the preparation of the samples could start from where this research has ended.

However, the presence of the reinforced layers is important to absorb the remaining strength of the bullet and causing an insignificant trauma. Finally, for futuristic work other materials that would cost less than epoxy and Twaron but having the same properties could be used.

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