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BALLISTIC PROPERTIES OF POLYETHYLENE COMPOSITES BASED ON BIDIRECTIONAL AND UNIDIRECTIONAL FIBERS*

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The goal of this study is to investigate the behavior of composites made of ultra high molecular weight polyethylene (UHMWPE) woven fabrics and unidirectional tapes under the high speed ballistic impact. UHMWPE fibers are considered to be the strongest fibers in the world and are extensively used in ballistic items (helmets, vests, plates) for personal protection. To investigate their ballistic strength, ballistic composites based on woven fabric and unidirectional tapes are manufactured and subjected to a ballistic test. As ballistic criteria, V_{50} value is used. The test is done in a ballistic laboratory where the speed of the fragment-simulating projectile is measured prior to its impact to the composite. The unidirectional composites have shown a superior performance as compared to bidirectional ones due to their lower extension of the reflective impact wave i.e. the ballistic impact wave is transmitted to a higher composite area. Due to the crossover points in bidirectional composites, a greater extension of the ballistic wave is reflected back, rendering the ballistic impact to a smaller composite area.

Key words: ballistic, UHMWPE, unidirectional, bidirectional, composites

INTRODUCTION

In general, composite materials are formed when two or more chemically distinct materials are combined so that a distinct interface separates the components (as opposed to alloys). Each of the constituent materials has its own specific physical

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properties, but the resulting composite has properties different from each material alone. It is desirable for the composite to take advantage of selected properties from each constituent. Of several types of composite materials, the category of particular interest for the ballistic protection is the continuous fiber-reinforced or fibrous composite. This type consists of one phase, which is usually much stronger (fiber), and the other phase (matrix). This combination leads to anisotropic properties which provide the capability of designing for specific characteristics such as high strength in one critical direction.

Composite materials containing continuous unidirectional high-performance fibers are characterized by a high specific longitudinal stiffness and strength, which makes them especially interesting for weight saving applications. When composites are used for structural applications, usually stacked plies with different fiber orientations are used allowing for considerable stiffness and strength in more than one direction. Composite and textile armor systems are also increasingly being utilized as impact protection materials in weight critical environments. A typical application is personal protective items, a threat either being that of fragments of exploded shells or bullets of handguns. The use of composite and textile armor systems can result in a reduction in weight while maintaining the impact performance, or the increased impact performance for the given weight.

Ballistic impact resistance of fiber-reinforced composites with high modulus and high strength fibers has been under extensive investigation due to specific properties of such fibers [1, 2]. The majority of the composites used in body armor systems take the form of textile fabrics or unidirectional tape of high modulus and high strength fibers embedded in a variety of matrix resins. Fibrous armor has the importance for several reasons. Since a man uses clothing in normal life, protective devices that can be incorporated into such clothing provide the most comfortable, compatible and inconspicuous method of providing such protection. The second reason fibers are important is that they provide the greatest strength and modulus properties that can be obtained from a given material. In the case of polymers, this is due, mainly, to the drawing operation which orients the molecules along the fiber axis, increasing strength and stiffness and providing a natural crack arresting mechanism.

There are many natural and synthetic fibers, which are used for ballistic protection, but only two types of synthetic fibers can be regarded as high-performance – aramid and UHMWPE (Ultra High Molecular Weight Polyethylene) fibers. UHMWPE fibers, also known as HPPE (High Performance Polyethylene) fibers, are characterized with parallel molecules orientation along the fiber axis greater than 95% and a high level of crystallinity as opposed to conventional polyethylene fibers. This results in fibers with a very high strength and modulus of elasticity.

In this study, we have investigated HPPE composites based on woven fabrics and unidirectional (UD) fibers under the high-speed ballistic impact. The fibers we have used were produced by the inventor of these fibers, the Dutch company DSM, and are known under the trade name Dyneema.

EXPERIMENTAL PART

Materials

Plain woven HPPE fabric was used as reinforcement for bidirectional composites and as a matrix polyvinylbutyral (PVB), modified phenolic resin of resole type was used. The impregnation of the fabric with the resin was done on a semi-industrial vertical impregnating machine on the premises of "Eurokompozit" company.

The unidirectional tape, which was pre-processed into prepreg, consists of four layers of unidirectional fibers cross plied at 0°/90° orientation, as shown in Figure 1, and sandwiched with a thermoplastic film.

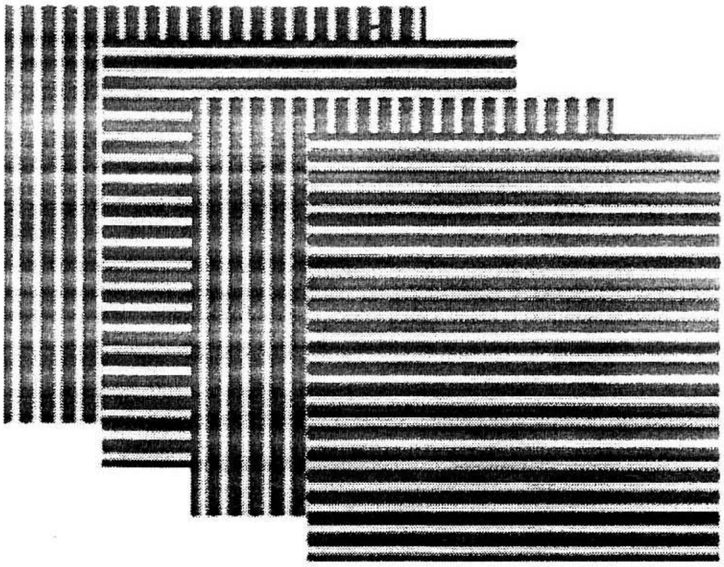

Figure 1. Construction of unidirectional prepreg

The properties of unidirectional and bidirectional prepregs are given in Table 1.

Table 1. The properties of unidirectional and bidirectional prepregs

Property	Unit	Unidirectional prepreg	Bidirectional prepregs
Resin type		thermoplastic	thermoset (phenolic resin)
Resin content	%	20±1	20±1
Gel time at 150°C	seconds	-	96
Areal weight	g/m^2	244±7	240±7
Volatiles content	%	<1.5	<1.5

Molding

The composites were constructed by laying up a multiple number of prepreg plies in accordance to the targeted areal weight and cured at the elevated temperature. Each type of the composite is manufactured in four different areal weights, 3, 5, 7 and 9 kg/m^2. This areal range is chosen because it is common for personal ballistic protection. All composites were molded at 130 ^0C under the molding pressure of 10 MPa.

Ballistic test

Ballistic strength of the composites was assessed by measuring their ballistic strength i.e. V_{50} ballistic limit. V_{50} ballistic limit is a statistical test originally developed by the US military to evaluate hard armor [3]. V_{50} testing experimentally identifies the velocity at which a bullet has a 50% chance of penetrating the test object. Fundamental to the concept of ballistic limit is a relationship between the probability of penetration of the armor and the striking velocity of the projectile. The projectile-armor relationship satisfies the mathematical conditions of probability distribution i.e. for low velocities probability approaches zero; for high velocities the probability approaches one; and between those extremes of velocity, the probability increases with the increase of velocity. When the general model describes physical behavior, the probability of penetration can be treated as a probability distribution and is usually described as a Gaussian or normal distribution. The probability of penetration is illustrated in Figure 2.

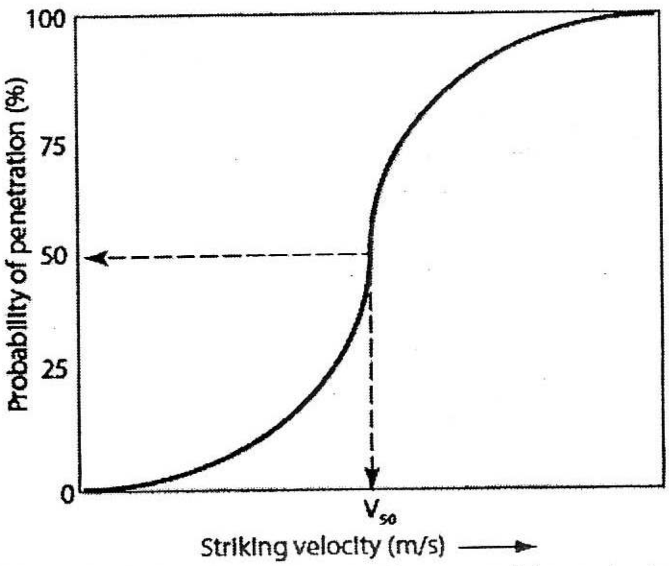

Figure 2. Probability of penetration vs. striking velocity

The normal Gaussian probability distribution curve has been found to give a reasonably good representation of the probability of penetration in many cases [4, 5]. The ballistic test is performed by firing 5.56mm, 1.5 g fragment simulating projectiles on to the composite panel. All test panels (400 mm x 400 mm) prior to testing, are conditioned at 20±2 ^0C and relative humidity of 65±5 %. At least 14 projectiles are being fired at the test panels and their velocities measured. A projectile, which passes

through the panel or causes material to be thrown off the back of the panel, is considered to be a complete penetration. All other impacts are defined as being partial penetrations. The V_{50} ballistic limit velocity for a panel is defined as that velocity for which the probability of penetration of the projectile is exactly 0.5. The subscript 50 designates the percentage of that probability of penetration.
After a number of projectiles have been fired, the V_{50} is calculated as the mean of the velocities recorded for the fair impact consisting of seven highest velocities for partial penetration and seven lowest velocities for a complete penetration providing that all fourteen fall within a bracket of 60 m/s [6].

RESULTS AND DISCUSSION

The results of the ballistic test are given in Table 2.

Table 2. Ballistic strength of the composites, V_{50} (m/s)

Composite	Areal weight of composites			
	3 kg/m^2	5 kg/m^2	7 kg/m^2	9 kg/m^2
BD-HPPE	319.1	412.9	498.2	557.3
UD-HPPE	401.1	517.4	601.9	682.1

In the above table "BD" and "UD" designate bidirectional (fabric) and unidirectional composites respectively.
Textiles are used to protect against two categories of ballistic projectiles. Bullets from handguns and rifles form one category. These bullets are designated to deform when they hit a body or another object, as this is the most effective way to stop a living being. They use a lot of their kinetic energy in the deformation, so they are relatively easy to stop by e.g. bullet-resistant vest. The other category is formed by fragments from exploding shells and grenades. These fragments are smaller than bullets and they have sharp edges and do not deform. For testing purposes (which was done in the ballistic laboratory of the military contractor "Eurokompozit" from Prilep, Macedonia) we used fragment simulating projectiles (FSP) with a well-defined weight and shape in accordance to NATO standard STANAG 2920 [7]
Analyzing the test results, Table 1, one can conclude that there is a distinct difference in ballistic resistance between woven fabric composites and unidirectional tape composites although these composites are similar in many ways. Unidirectional tape composites have performed much better than their counterparts based on woven fabric. In both types of composites:

- the same UHMWPE fibers are used;
- the fiber/resin ratio is the same;
- panels with the same areal weigh are compared
- the same FSP are used for testing

The resin type may have influence the ballistic properties but not in such a big extent, as long as its ratio is the same in both types of the composites [8, 9]. Then, one might ask where this difference comes from?
When a projectile hits a woven, fabric a shock or strain wave is introduced which spreads through yarns. The primary impacted yarns interact with other yarns by means of couplings at the crossover points of the fabric. The strain wave can thus spread over a large number of yarns. The positive effect of this mechanism is that energy will be absorbed over a relatively large area. The velocity of the strain wave and of the energy dissipation is directly related to the modulus of fibers [10, 11].

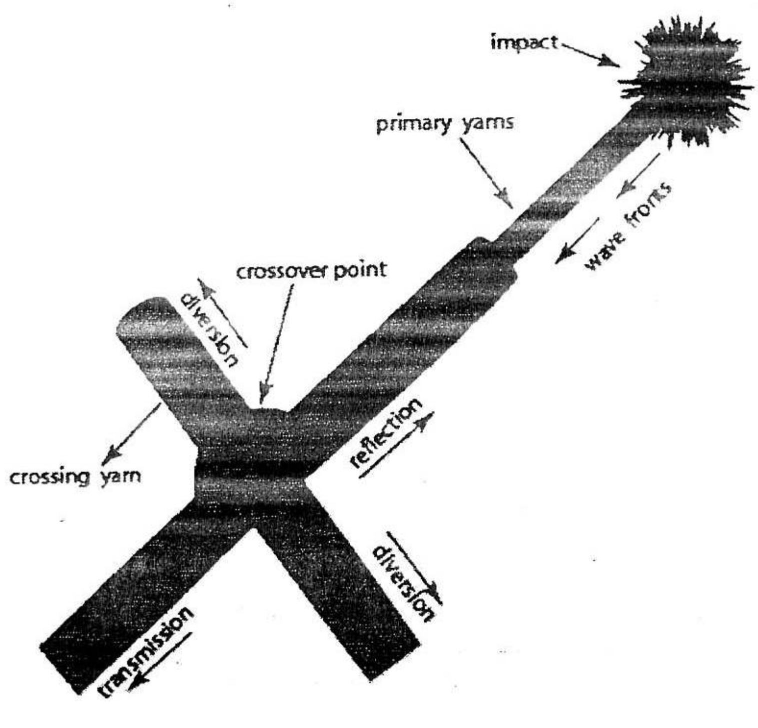

Figure 3. Longitudinal wave propagation in a fabric after the ballistic impact

The disadvantage of a woven fabric is that the crossover points reflect part of strain waves and somehow hamper the propagation of the wave, Figure 3. The crossover points can be seen as fixed ends. At fixed ends, the amplitude of the reflected wave has the same direction as the amplitude of the original strain wave and must therefore be superposed. Thus, a large number of strain waves, travelling in both directions, are introduced into the yarn. The resulting effect is that the elongation in the yarn can reach its maximum, the elongation-at-break, and the projectile can perforate the first few layers.
Therefore, the effect of crossover points in fabrics is not always positive. This was the reason for the development of UD materials. In UD material the fibers are laid unidirectional, bonded with a thermoplastic matrix and then cross-plied, Figure 1. In this unidirectional construction, the yarns have no real crossover points as in woven fabric. There are crossover points only between the different layers, Figure 4, but not within a single layer.

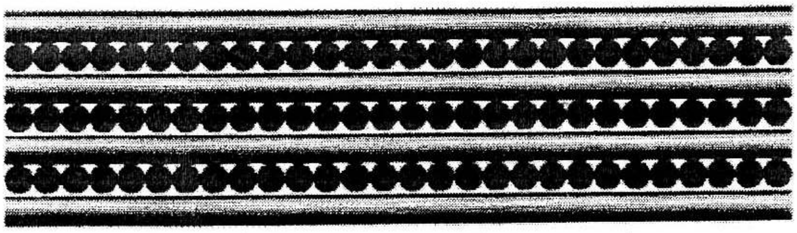

Figure 4. Cross-section of UD composite

There is, definitely, an interaction between the cross-plied layers of fibers, but the part of the strain wave that is reflected is much smaller [12, 13]. Thus, in UD composites, due to the lack of cross-over points, the strain wave can travel unhampered at greater distances from the impact point and engages a greater surface i.e. mass of the composite in stopping the projectile. This means that the kinetic energy of the projectile will be absorbed over a larger area compared to fabric composites, which results in a better ballistic performance by UD composites.

CONCLUSION

The textile form that the fibers are processed into has a very great influence on the ballistic resistance in the ballistic composites. When a projectile hits a ballistic fabric, the risk of the yarn break is the highest at the crossover points of warp and fill. Because of the lack of the crossover points, unidirectional materials are superior in ballistic performance over the woven fabrics.

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IZVOD

BALISTIČKA SVOJSTVA POLIETILENSKOG KOMPOZITA NA BAZI DVOSMERNIH I JEDNOSMERNIH VLAKANA

(Originalni naučni rad)

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Cilj ovog istraživanja je da ispita ponašanje kompozita od polietilenske (UHMWPE) tkanine i jednosmerne trake ultra visoke molekulske mase, u uslovima brzog balističkog udara. UHMWPE vlakna se smatraju najjačim vlaknima u svetu i intenzivno se koriste za balističku namenu (šlemovi, prsluci, ploče) kod lične zaštite. Balistički test je iskorišćen za ispitivanje balističke snage proizvedenih kompozita na bazi tkanine i jednosmerne trake. Za balistički kriterijum uzeta je vrednost V_{50}. Test se izvodio u balističkoj laboratoriji gde je brzina simuliranog fragmenta projektila merena pre njegovog udara u kompozit. Jednosmerni kompoziti su pokazali superiorne performanse u odnosu na dvosmerne zbog slabijeg širenja odbojnog udarnog talasa, odnosno udarni balistički talas se prenosi dublje u kompozitnu oblast. Zbog propustnih tačaka u dvosmernom kompozitu veće širenje balističkog talasa se odbija nazad, prevodeći balistički udar na manju kompozitnu oblast.

Ključne reči: balistički, UHMWPE, jednosmerni, dvosmerni, kompoziti.

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