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RESIN CONTENT AND MOLDING PRESSURE INFLUENCE ON BALLISTIC PROPERTIES AND TRAUMA EFFECT OF AROMATIC AMIDE FIBERS COMPOSITES*

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The goal of the study is to investigate the behavior of composites made of Aramid (aromatic polyamide) fibers as reinforcements and modified phenolic resin as matrix, under ballistic impact. Aramid fibers are extremely strong and tough and are widely used for manufacture of personal protection items. Besides their inherent resistance to impact, a big influence on the ballistic properties of their composites can have matrix content as well as processing parameters. We have studied two types of woven fabrics composites with the resin content of 20 % and 50 % and the areal weight 2-9 kg/m^2. Some of the composites are molded at on our 200 tons press and we have measured their trauma effect i.e. the deformation of the back face of the panel. The best ballistic strength have shown composites with ~20 % resin content and the worst those with ~ 50 % resin content. Trauma effect was less pronounced by high-pressure composites contrary to the low-pressure ones which have shown the highest trauma effect. Generally, the composites with ~ 20% resin content molded at the highest pressure have shown both, the best ballistic toughness and the lowest trauma on the back side of the panel.

Key words: Aramid, trauma, ballistic, composites

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INTRODUCTION

For a very long time, fabrics have been an extremely important part of modern armors. Also, composite laminates made of fiber sheets stiffened with synthetic resin are extremely important. A fibrous armor has its importance for several reasons. Since a man utilizes 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 [1]. In the case of polymers, this is due, mainly, to the drawing operations which orient the molecules along the fiber axis increasing the strength and stiffness and also providing a natural crack arresting mechanism [2].

Fiberglass is one of the best known, and in a way, the most unusual laminate prepared from glass fabric and used extensively in the construction industry, boats, etc. It is well known in ballistic applications because of the research conducted during World War II, which resulted in a fragmentation protective vest [3]. It is an unusual laminate in that fiberglass, a fabric with poor impact resistance and with especially poor ballistic resistance unlaminated, when combined with polyester resin, another material with poor impact and ballistic resistance, results in a material with excellent ballistic resistance either alone or as a backup for a harder material. The resin, although present in a small percent (~20%), mitigates the defects which can be easily introduced into glass and will lower the strength.

Despite the existence of glass fabrics laminates i.e. composites before World War II, the work of Carothers [4] at DuPont in the early 1930s was necessary to make fabric armor reality. Recognizing the need for molecular weight of at least 12000, a molecular length of 100 nm, and preferably a crystalline morphology, Carothers' research on macromolecules led to nylon fibers which could be prepared uniformly and cheaply with high strength. The second laminate of longtime use is that prepared from nylon fabric in combination with a phenolic resin. At that time, the main advantage of nylon laminates was in their excellent ballistic resistance and lower weight, compared to glass laminates.

The second breakthrough occurred in the early 1960s when DuPont scientists were experimenting with stiff polymers usually considered intractable. They came up with a new Aramid fiber three times as strong as nylon and with a far higher modulus and heat resistance [5]. Even though the fibers had higher modulus, they were so fine that the resulting fabrics possess flexibility and drape. The military seized upon this new material known as Kevlar 29 and produced vests with lighter weight and higher protection values that would have been imagined before.

Kevlar 29 is one of the most amazing synthetic fibers. This para-Aramid fiber is characterized by its high tenacity and modulus of elasticity, low density as well as high energy absorption [6].

When assessing certain material for personal i.e. body protection there are three major properties by which we value the material: ballistic resistance, trauma effect and weight. The aim of every producer of ballistic items is to achieve as high ballistic resistance as possible with as low trauma effect as possible with the lowest possible weight. There is always trade off between the first two characteristics and the last one. In this research we have investigated the behavior of Aramid fabric based composites with different resin/fiber ratio molded under three different pressures and measured their trauma effect at the back of the panels, trying to find the best balance between the make up of the composites (fiber/resin ratio and molding pressure), their ballistic strength (ballistic resistance an trauma effect) and the their weight.

EXPERIMENTAL PART

Materials

Reinforcing fibers, which were used, were ballistic grade, plain woven, Aramid (aromatic amide- Kevlar) fibers with properties as shown in Table 1.

Table 1. Properties of the reinforcing fabric

Property	Unit	Value
Weave	-	plain (1x1)
Areal weight	g/m^2	280±7
Thickness	mm	0.43
Yarn		
warp	dtex	1260
weft		1260
Tread count		
warp	cm^{-1}	11.0
weft		10.5
Tensile strength,		
warp	N/5cm	10000
weft	N/5cm	9500
Coupling agent		no

For impregnation, we have used phenolic resin the properties of which are shown in Table 2.

Table 2. Phenolic resin properties

Property	Unit	Value
Type		resole
Dry content	%	>98
Viscosity , Höppler, at 20°C		
- 6% solution in methanol	cP	60-110
- 5% solution in n-buthanol	cP	240-300
Density	g/cm^3	~1,1

Thermosetting phenolic resins, naturally, are very brittle and inappropriate for ballistic composites where flexibility of the matrix is required. To make it flexible and resilient i.e. applicable for ballistic composites we have modified it with a fair amount of powdered polyvinylbutyral.

During the impregnation, the following parameters were controlled: resin solution viscosity, temperature, resin pick-up onto the fabric i.e. resin content, volatiles content and gel-time of the prepreg.

Prepreg sheets with the same resin content are sorted, cut to size (400 x 400 mm) stacked together (Figure 1) and molded at 160 ^{0}C under high pressure. Molding temperature varies in accordance with the thickness of the laminate.

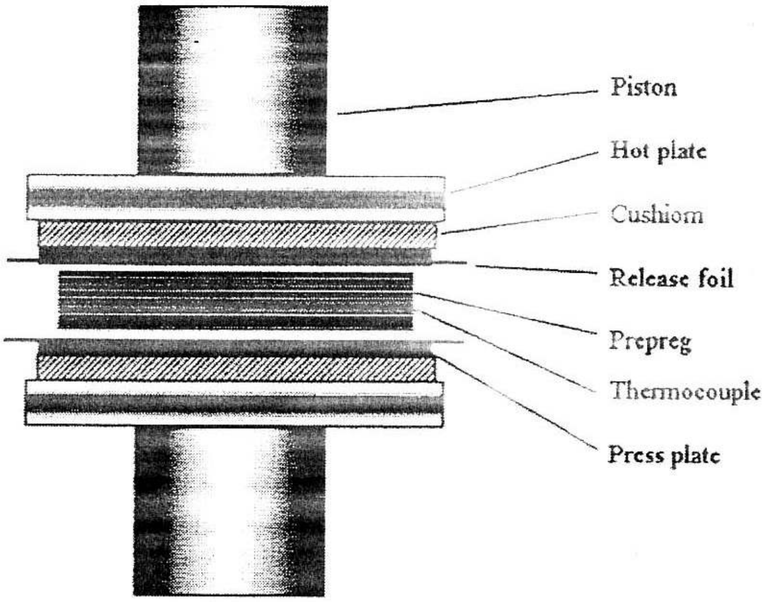

Figure 1. Press stack

To assess the influence of the molding pressure we have molded panels with resin/fabric ratio of 20/80, with 5 kg/m^2 areal weight under the pressure of 2 MPa, 6 MPa and 10 MPa and tested their trauma effect.

RESULTS AND DISCUSSION

The dependence of V_{50} (V_{50} is ballistic test for assessing ballistic resistance and is widely used in the industry) of areal weight, for different resin/fiber ratios of laminates, is shown in Figure 2.

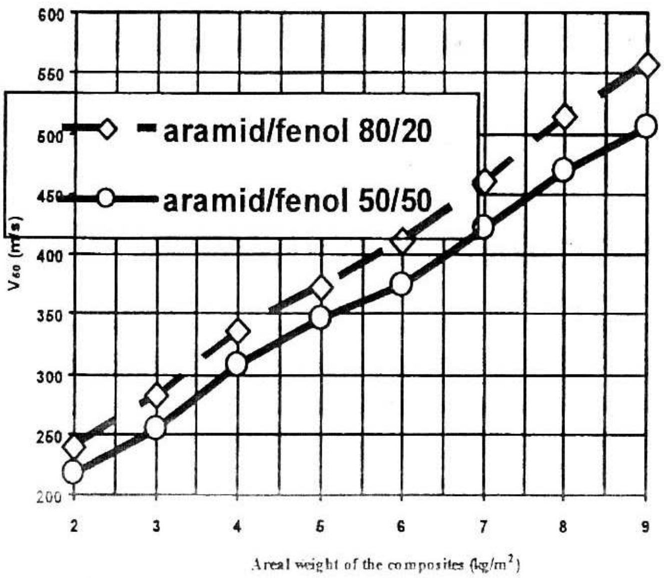

Figure 2. V_{50} vs. areal weight of composites

As it can been seen in Figure 2, with the increase of areal weight the ballistic resistance increases proportionally for both type of laminates. We can also conclude that the composites with the higher fibers content show superior ballistic properties over their counterparts with the lower fiber content. This is something we could have expected having in mind that the fibers are the main load i.e. impact bearing constituent in the composite. The highest ballistic resistance, in both types of laminates, has shown those with 80 % fibers. Our attempt to make laminate with 90 % fibers has failed because there were not enough matrixes to completely transfer the impact load between the layers. The result of that was complete delamination of the composites after the first few shots. According to the NIJ 0101.06 standard at least 14 shots are required for the evaluation of V50 [7].

A trauma effect is a back face deformation of the panel which, if big enough, can cause internal injures to the body or even death although the composite is not perforated. According to NIJ 0101.06 standard this deformation must not exceed 44 mm. Wendlant [8] has made microscopic analysis of the cross-section at the penetration point and he has found out that, when hit, the fibers are tensile strained. Because of the severance of the hit, the first layers are strained over their limit and perforated. As the bullet propagates through the composite it becomes mushroom-like deformed (Figure 3) by which its cross-section area increases and the velocity decreases. Because of the decreased kinetic energy, at last, it is stopped by the remained layers of fabrics. The last layers because tensile strained deform and cause a bulge-like deformation at the back face of the panel which faces the body (Figure 3). This means the one very important property of ballistic resistance is the tensile strength of the fibers [9]

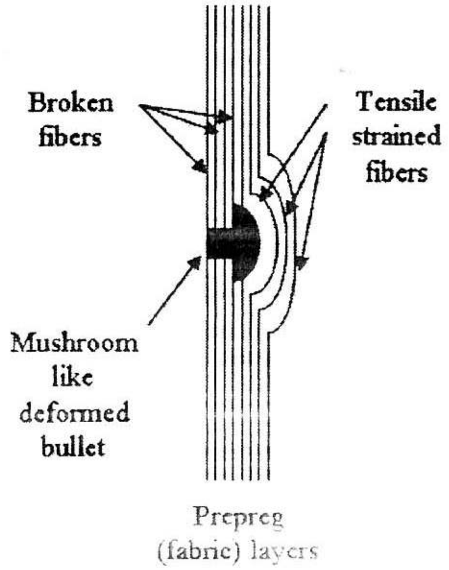

Figure 3. Cross-section at the penetration point of the projectile

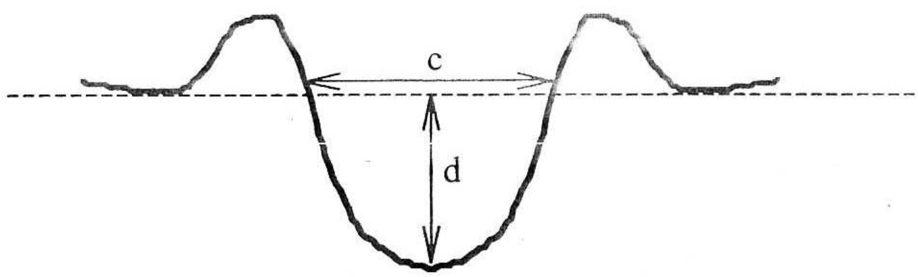

Figure 4. Trauma effect cross-section

At the cross-section of the penetration, the composite deforms as shown in Figure 4. The trauma effect was tested on panels 400 x 400 mm with areal weight of 5 kg/m^2, molded at 2 MPa, 6 MPa and 10 MPa For all panels we have measured the depth of the trauma (d) (Figure 4) as well as its diameter (c) i.e. involved area. The results of the measurements are shown in Figure 5 and Figure 6.

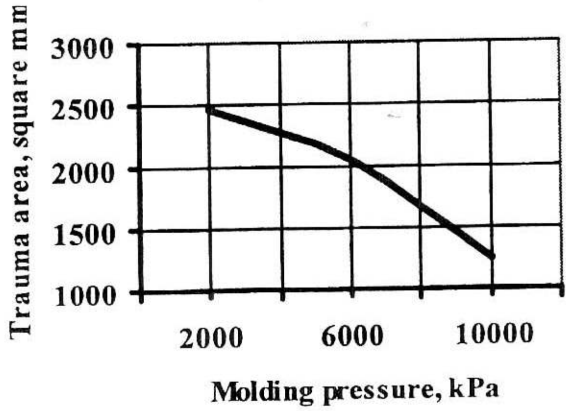

Figure 5. Trauma area vs. molding pressure for 5 kg/m^2 composites

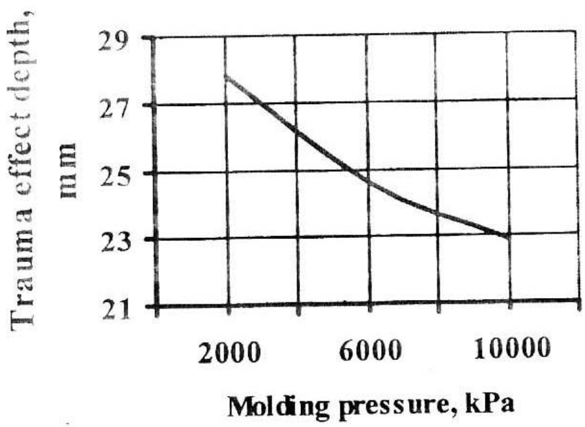

Figure 6. Trauma depth vs. molding pressure for 5 kg/m^2 composites

We have found a significant influence (as shown in Figure 5 and Figure 6) of molding pressure on trauma effect of ballistic composites. Both trauma area and trauma depth decrease with the increase of the molding pressure.

CONCLUSION

All composites made with ~20% resin content have shown the best ballistic strength and the worst those with 50% resin content. Trauma effect was less pronounced by high-pressure composites contrary to the low-pressure ones, which have shown the highest trauma effect. Generally, composites with 20% resin content molded at 10 MPa have shown both, the best ballistic toughness and the lowest trauma on the back side of the panel.

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IZVOD

UTICAJ SADRŽAJA SMOLE I PRITISKA OBLIKOVANJA NA BALISTIČKA SVOJSTVA I EFEKAT OŠTEĆENJA KOMPOZITA OD AROMATIČNIH AMIDNIH VLAKANA

(Originalni naučni rad)

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Cilj rada je da istraži ponašanje kompozita od aramidnih vlakana (aromatični poliamid), kao pojačanja i modifikovane fenolne smole kao matrice, na balistički udar. Aramidna vlakna su izuzetno jaka i široko se koriste za proizvodnju zaštitnih ličnih predmeta. Osim njihove urođene otpornosti na udarce, veliki uticaj na balistička svojstva njihovih kompozita može da ima matrica samog sadržaja, kao i parametri obrade. Proučavane su dve vrste kompozitnih tkanina sa sadržajem smole 20 % i 50 % i površinske mase 2-9 kg/m^2. Neki od kompozita su oblikovani u presi od 200 t, a mereni su uticaj oštećenja, odnosno deformacija naličja panela. Najbolju balističku snagu su pokazali kompoziti sa sadržajem smole ~ 20 % a najgori su bili oni sa sadržajem smole ~ 50%. Efekat oštećenja je manje izražen od strane kompozita pod visokim pritiskom za razliku od kompozita pod niskim pritiskom, koji su pokazavali najveće efekte oštećenja. Generalno, kompoziti sa sadržajem smole ~ 20 % oblikovani na najvišem pritisku su pokazali najbolju balističku žilavost i najniža oštećenja na naličju panela.

Ključne reči: aramid, oštećenje, balistički, kompoziti.

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