Studying the influence of technological factors on properties of protective composite materials based on Kevlar fabric and PVB/PF resin

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ABSTRACT

Bullet-resistance and weight are important features of anti ballistic materials. Kevlar fibers are the widest reinforcement material for military and civil systems due to their excellent impact resistance and high strength-to-weight ratio. Kevlar fibre based composites are used for designing personal helmets and body armor to effectively stop both fragmentation and bullets. In this report, the influences of fabrics and technological factors on the properties of the composite made of kevlar and PVB/PF resin were studied. The results showed the composite sample with desired properties could be achieved by using the Kevlar fabric K-129 with the weight ratio of fabric:resin = 0.8:0.2 under the processing conditions: temperature-150 ^oC, pressing pressure-150 kg/cm^2, pressing period-45 minutes. The tensile strength of composite materials is 743.52 Mpa. The composite samples in the shape of plate and helmet passed the ballistic tests with 17 grains (1.1 grams) of Fragment Simulating Projectiles (FSPs) at a speed of 438.92 m/s.

Keywords: Composite material; Kevlar fabric; Fragment Simulating Projectiles (FSPs).

1. INTRODUCTION

Composite materials based on a plastic matrix and high strength, high modulus reinforcement fibers such as kevlar, Spectra, and Zylon fibers have outstanding features for anti ballistic materials [1, 2]. These composites are widely used to create lightweight armor for preventing both fragments and bullets. Advanced fibers absorb the impact of bullets or fragments and disperse their energy across a large area as the projectiles move through successive layers of material. The dispersing of energy of the bullets or fragments makes them can not penetrate the materials [3, 4].

The Kevlar fabric and polypropylene (PP) composite armors with different fabric architecture's ballistic impact response were investigated using testing standard NIJ-STD 0106.01 (Bandaru et al. 2016). Experiments were carried out by Abdul et al. to determine the ballistic limit of coir yarn and Kevlar/epoxy hybrid composites. In their work, the effect of stacking sequences of Kevlar fiber on residual velocity and failure mechanism of the composites was investigated. For the application of body armor, a ballistic impact test on different types of laminated hybrid composites of Kevlar-reinforces polyester resin was conducted by Radif et al. Results showed that the impact ballistic limit, energy absorption, and lifetime rupture were strongly affected by the panel geometry [7].

Aramid fibers were presented in the late 1960s and dominated the market because of their lighter weight in comparison with other polymer fibers, for example, nylon [8]. Aramid fiber, one type of organic fiber, is commonly utilized to reinforce the composite to improve the tensile modulus and strength. They have much better mechanical properties than steel and glass fibers with the same weight [9]. Aramid fibers have particles that are described by generally inflexible polymer chains. These particles are connected by hard hydrogen bonds that help in mechanical loading effectively, making it inconceivable to utilize chains of moderately low molecular weight with a lot higher tenacity and modulus [10]. Aramid-covered textures are broadly utilized for processing military protective helmets and giving spall liners within military vehicles [10].

Phenolic blended with polyvinylbutyral (PVB) resin, originally developed by Debell & Richardson Inc. [11], was the first matrix material system used for ballistic protective body armor. This resin can be fabricated by mixing at a 1:1 weight ratio of phenol formaldehyde and PVB with phthalic anhydride as a catalyst. The phenolic/PVB system was reported to possess superior characteristics to the component alone [12]. When combined with other reinforcing materials, such as nylon, glass fiber, or Kevlar, this resin was found to have an acceptable ballistic resistance level.

Kevlar fiber composite armors using phenolic/PVB resin as a matrix have exhibited superior peel strength compared to other resins, such as phenolic-vinylacetal. Studies on the effect of various compositions of phenolic/PVB system showed that at 40 to 60% PVB, the composite possessed higher interfacial bonding strength than other ratios and had optimized ballistic impact resistance [13]. At lower matrix resin PVB (0-20%), the Kevlar composite exhibited brittle shear failure and inferior ballistic performance [14].

In this study, an attempt was made to design a simple composite material based on Kevlar fabric and PVB/PF resin, as well as realistic ballistics impact tests. The objective of this study is to evaluate the possibility of manufacturing ballistic materials for military applications.

2. EXPERIMENTAL

2.1. Chemicals, instruments, research methods

2.1.1. Chemicals, instruments, equipment

- PVB resin: White powder, butyral group content: 60 ÷ 80%, hydroxyl group content: 18 ÷ 20%;

- PF resin: Light yellow to brown plastic powder (cresol resin), free phenol content ≤ 4.5%, gelation time at 150 ^{o}C: from 65 ÷ 90 seconds;

- Fabric Kevlar K-29: Dupont, density: 200 g/m^2, thickness: 0.25 mm;

- Fabric Kevlar K-49: Dupont, density: 400 g/m^2, thickness: 0.56 mm;

- Fabric Kevlar K-129: Dupont, density: 450 g/m^2, thickness: 0.60 mm;

- Solvents: Acetone, ethanol, butyl acetate, xylene, toluene, methylethylketone;

- Double-stage press: KACHI-QINGDAO, XLB-D, China;

- Injection mold for mechanical measurement: Vietnam.

2.1.2. Samples preparation

In this study, the phenolic resin (PF) is modified by polyvinyl butyral (PVB) resin mixed with PVB:PF ratio of 50/50 by weight, respectively. PVB resin was dissolved in ethanol, forming a solution with a dry function of 10%. PF resin was dissolved in a mixture of ethanol/methylethylketone (by 2/1) solvents by weight, forming a solution with a dry function of 50%. Kevlar fabrics are impregnated with PVB/PF base resin to form semi-finished prepregs with a resin content of 20% (after the solvent in the resin has completely evaporated).

The number of layers depends on the thickness of the fabric to achieve a sample thickness of 1.5 ÷ 2.0 mm. The specimen is compressed in a die measuring the tensile strength in the following machining modes: temperature 120 ÷ 180 ^{o}C, duration 30 ÷ 75 minutes; pressure: 100 ÷ 250 kg/cm^2.

2.2. Research methods

The breaking tensile strength was performed with a Universal Testing Machine GOTECH AI-7000M according to TCVN 4501-4:2009 (ISO 527-4:2012) at a crosshead speed of 5 mm/min. A minimum of five replicate samples were tested for each date reported an average of five specimens.

Ballistic tests were taken according to NIJ-STD 0106.01, using Fragment Simulating Projectiles (FSPs) 17 grains (1.1 g).

3. RESULTS AND DISCUSSION

3.1. Effect of fabrics on properties of composites

Kevlar fabrics K-29, K-49, K-129 were impregnated with PVB/PF base resin to form semi-finished prepregs with a resin content of 20%. The number of layers depends on the thickness of the fabric to achieve a sample thickness of 1.5 ÷ 2.0 mm, usually using 6 ÷ 8 layers of fabric. The tensile strength of composite samples with different Kevlar fabrics under pressing conditions at 150 ^oC, for 45 minutes, pressure 150 kg/cm^2 were investigated, and the results are shown in figure 1.

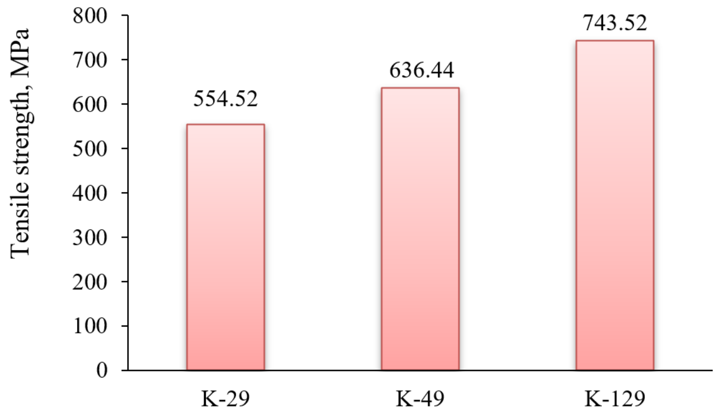

Figure 1. *Tensile strength of composite samples with different fabrics.*

The results in figure 1 showed that, the durability of resin-based Kevlar-reinforced composites (PVB+PF) follows rule: Composite K-129 > Composite K-49 > Composite K-29 (743.52 MPa > 636.44 MPa > 554.52 Mpa). The highest value of tensile strength was 743.52 Mpa: with sample K-129.

3.2. Evaluation of the effect of pressing pressure on the tensile strength of composites

On the basis of the results of the measurement and evaluation of different fabrics, we assessed the influence of pressing pressure on the mechanical and tensile strength of composite samples. The selected fabric is Kevlar K-129 fabric, compared with K-49 model.

Sample processing mode is as follows: Content of base resin for Kevlar fabric composite: 20%; Sample processing temperature: 150 ^oC; Sample pressing time: 45 minutes; Sample scompression pressure: 100 kg/cm^2, 150 kg/cm^2, 200 kg/cm^2, 250 kg/cm^2; Number of layers of fabric: 6 ÷ 8 layers (to achieve a thickness of 1.5 ÷ 2.0 mm).

The results of measuring the mechanical and tensile strength of the investigated composite samples K-129 and K49 are listed in table 1 and shown in figure 2.

Table 1. *Tensile strength of Kevlar K-129 and K-49 fabric composite samples at different compression pressures.*

Compression pressure, kg/cm^2	**Tensile strength, MPa**	
	K-129	**K-49**
100	684.22	528.14
150	743.52	636.44
200	701.53	583.75
250	667.94	514.05

For sample K-129, when the compression pressure increases from 100 kg/cm^2 up to 250 kg/cm^2, the tensile strength of the composite increases the highest in the compressed sample with a pressure of 150 kg/cm^2 (the tensile strength at break reaches the max maximum value 743.52

MPa with the pressure 150 kg/cm^2) then gradually decrease (to 667.94 Mpa). Similarly, for sample K-49, the tensile strength of composites increases highest in compressed samples with the pressure 150 kg/cm^2 (the tensile strength at break reaches the maximum value 636.44 MPa) then decreases gradually (down to 514.05 Mpa).

It is well-perceived that when the pressure increases higher than 150 kg/cm^2, the tensile strength of the material reduces because of missing resin pushed out by high pressure, the interrupting layers of the matrix, and its bonding with reinforcement fibers.

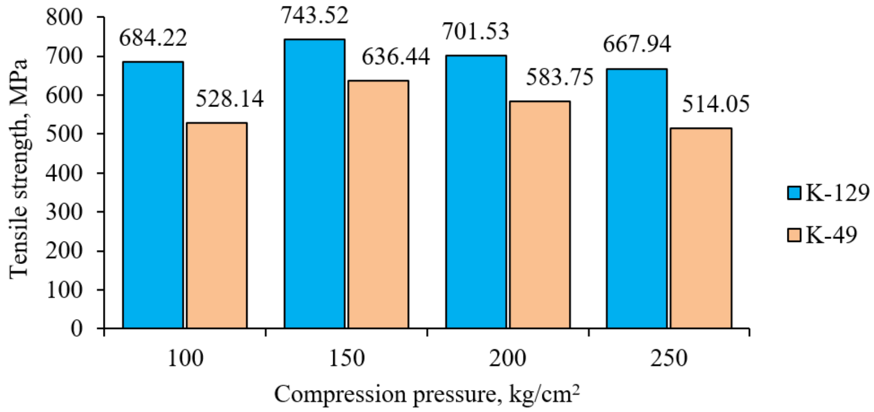

Figure 2. *Tensile strength of Kevlar fabric composite samples K-129 and K-49 at different compression pressures.*

Comparing two types of reinforced fabric, with the same resin content, at the same pressing pressure, the strength of K-129 fabric composite is higher than K-49 fabric composite.

3.3. Evaluation of the effect of pressing temperature on the tensile strength of composites

On the basis of measurement results, the effect of pressing pressure on the tensile strength of a composite made of Kevlar K-129 was evaluated. The sample processing mode: Content of the base resin for Kevlar fabric composite: 20%; Sample pressing time: 45 minutes; Sample compression pressure: 150 kg/cm^2; Sample pressing temperature: 120 ^{o}C, 135 ^{o}C, 150 ^{o}C, 165 ^{o}C, 180 ^{o}C; Number of fabric layers: 6 ÷ 8 layers (to achieve a thickness of 1.5 - 2.0 mm).

The results of measuring the tensile strength of the survey samples are presented in table 2 and figure 3.

Table 2. *Tensile breaking strength of Kevlar K-129 fabric composite samples at different pressing temperatures.*

Fabric	Temperature, ^{o}C	Tensile strength, MPa
K-129	120	705.04
	135	723.02
	150	743.52
	165	727.41
	180	721.55

The survey results showed that in the range of temperature 120 - 180 ^{o}C tensile strength of the composite sample reaches the maximum value of 753.52 MPa at temperature 150 ^{o}C. At the temperature of 120 ^{o}C composite sample had the lowest tensile strength 705.04 Mpa.

For samples pressed at low temperatures (120 ^{o}C, 135 ^{o}C), the curing level of the base resin is not complete. Therefore, the internal adhesion strength of the composite is low, and the stress of the fabric layers is small. This leads to a lower tensile strength of composites than samples that were cured at high temperatures.

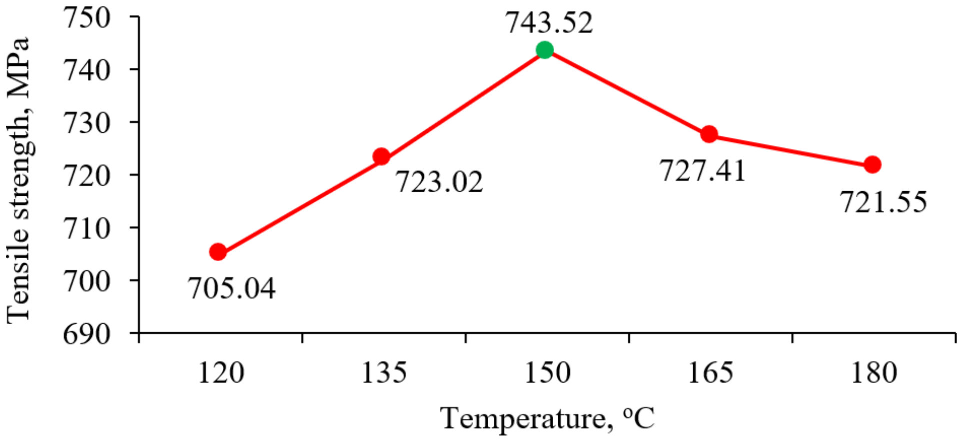

Figure 3. *Tensile strength of Kevlar 129 fabric composite samples at different pressing temperatures.*

With samples pressed at high temperatures (165 ^oC, 180 ^oC), even though it has completely cured, after the curing stage, high heating levels will age the base resin, leading to a decrease in the internal adhesive strength. This causes a decrease in the tensile strength of composites.

3.4. Evaluation of the effect of pressing time on the tensile strength of composites

Similar to pressing temperature, pressing time was investigated to evaluate its effect on the tensile strength of a composite made of Kevlar K-129. Sample pressing time: 30 minutes, 45 minutes, 60 minutes, 75 minutes. The results of measurements of the tensile strength of samples are illustrated in figure 4 and table 3.

Table 3. *Tensile strength at break of Kevlar K-129 fabric composite samples at different pressing times.*

Fabric	Time, min	Tensile strength, MPa
K-129	30	711.17
	45	743.52
	60	741.52
	75	719.39

The survey results showed when increasing the pressing time from 30 minutes to 75 minutes, the tensile strength gradually increased and reached the highest value of 743.52 for the sample pressed in 45 minutes, then gradually decreased. Samples pressed at 30 minutes gave the lowest tensile strength (711.17 Mpa).

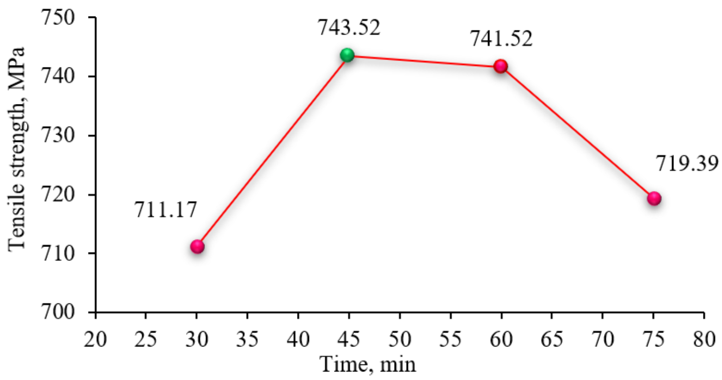

Figure 4. *Tensile strength of Kevlar 129 fabric composite samples at different pressing times.*

For samples pressed at a short time (30 minutes), the curing reaction of the base resin occurs incompletely. Therefore, the internal adhesion strength of the composite is low, and the stress of the fabric layers is small.

For samples pressed for a long time (60 minutes, 75 minutes), after the time of complete curing (45 minutes), the base resin will be aged by a high heating level, leading to a decrease in the internal adhesive strength.

3.5. Actual test of fragment resistance of composite materials made of kevlar K-129 fabric and PVB/PF resin

Based on the fabricated samples, the actual ballistic testing was performed on 02 types of samples: 1- the sample in the shape of a plate: size: 20x20 cm; thickness: 7 mm; 2- the sample in the shape of a helmet: thickness ≤ 9 mm. The results are presented in figure 5 and figure 6.

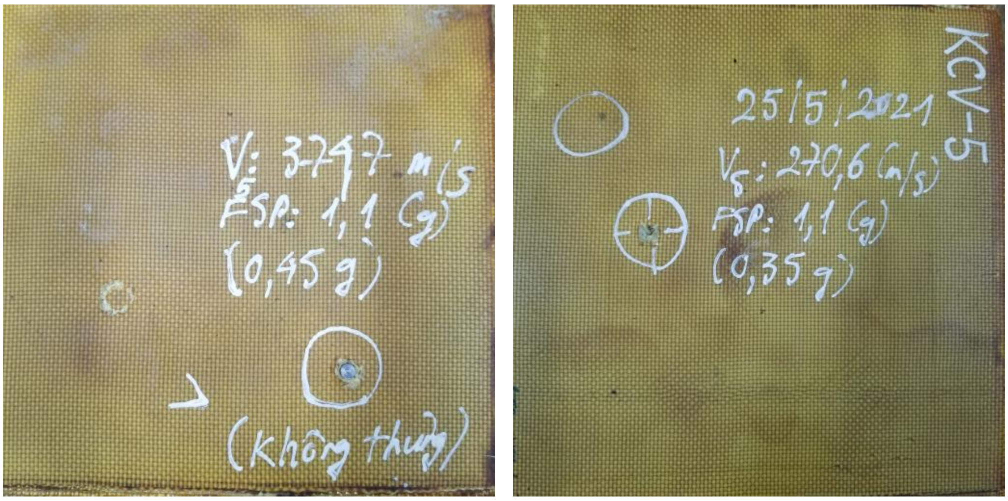

Figure 5. *Images of ballistic resistance of composites in the shape of flat plate.*

Figure 6. *Images of ballistic resistance of composites in the shape of the helmet.*

As shown in figure 5 and figure 6, on a flat plate, with a thickness of 7 mm, this composite can withstand Fragment Simulating Projectiles (FSPs) 1.1 g (17 grains) at 374.7 m/s. As for the helmet, the FSPs speed up to 438.9 m/s still does not have a penetration phenomenon. This means that the manufactured composite material is resistant to FSPs 17 grains (1.1 g) at a speed of about 430 m/s.

4. CONCLUSIONS

The article presents some research results on the influence of fabrics and technological factors on the properties of composite materials made of Kevlar fabric with PVB/PF resin. The optimal machining mode has been determined: temperature: 150 ^{o}C, pressing pressure: 150 kg/cm^2, pressing time: 45 minutes. The material sample has a tensile strength at break: 743.52 MPa.

In addition, the actual test of FSPs 17 grains (1.1 g) resistance of the composite material made of kevlar K-129 fabric and the PVB/PF matrix showed no penetration at 438 m/s.

Lời cảm ơn: *Nghiên cứu này được thực hiện nhờ sự tài trợ kinh phí của Đề tài nghiên cứu khoa học cấp Viện Khoa học và Công nghệ quân sự năm 2021:"Nghiên cứu thiết kế chế tạo mũ chống đạn và mũ chống mảnh văng bằng vật liệu Compozit, trang bị cho bộ đội".*

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TÓM TẮT

Nghiên cứu ảnh hưởng của các yếu tố công nghệ như nhiệt độ, áp suất, thời gian ép đến tính chất cơ lý của vật liệu compozit chống mảnh văng

Khả năng chống đạn và trọng lượng là những đặc điểm quan trọng đối với vật liệu đạn đạo. Sợi Kevlar là sợi gia cường rộng rãi nhất cho các hệ thống quân sự và dân dụng do khả năng chống va đập tuyệt vời và tỷ lệ độ bền trên trọng lượng cao. Vật liệu compozit dựa trên sợi Kevlar được sử dụng để thiết kế mũ bảo hiểm cá nhân và áo giáp để tránh hiệu quả cả mảnh vỡ và đạn. Trong bài báo này, ảnh hưởng của các loại vải và các yếu tố công nghệ đến tính chất của vật liệu compozit được chế tạo từ vải kevlar với nhựa nền PVB/PF đã được nghiên cứu. Kết quả cho thấy vật liệu compozit với các đặc tính mong muốn có thể đạt được bằng cách sử dụng vải Kevlar K - 129 với tỷ lệ về khối lượng của vải:nhựa = 0,8:0,2 trong các điều kiện xử lý: Nhiệt độ - 150 ^oC, áp lực ép - 150 kg/cm^2, thời gian ép - 45 phút. Độ bền kéo đứt của vật liệu compozit thu được 743,52 Mpa. Các mẫu vật liệu compozit dạng tấm và mũ bảo hiểm đã vượt qua các bài kiểm tra đạn đạo với đạn mô phỏng phân mảnh (FSPs) 17 grains (1,1 gram) ở tốc độ 438,92 m/s.

Từ khóa: Vật liệu compozit; Vải kevlar; Đạn mô phỏng phân mảnh (FSPs).