MULTI-LAYER MATERIAL COMBINATION FOR MANUFATURING STAB-PROOF LIFE JACKETS

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Received: 22 Dec. 2023; Revised: 5 Jan. 2024; Accepted: 20 Mar. 2024

ABSTRACT.

In modern times, individuals working in aquatic environments such as fishermen, fishery inspectors, customs officers, and others require a device that offers protection against punctures and drowning. As a result, a multi-layer composite material consisting of para-aramid 200de woven fabric, Dyneema® SB31 coated plates, and foam was evaluated for the creation of a life jacket that combines stab-proof capabilities with anti-drowning features (stab-proof life jacket). The objective of the research was to determine the optimal number of layers and arrangement of the multi-layer composite materials that would meet the NIJ standard level 1 protection against punctures. The study findings demonstrated that utilizing both types of woven fabric and coated plates yielded the most desirable puncture resistance, considering the thickness and weight of the composite materials. The effectiveness of using only woven fabric ranked second, while relying solely on coated plates produced less satisfactory results. Placing the puncture-resistant material above the foam layer proved to be more effective than placing it beneath the foam layer in all three scenarios. These findings lay the groundwork for the design and development of stab-proof life jackets tailored to the needs of professionals in specific aquatic industries.

Keywords: *Puncture-resistant life vest, puncture-resistant, multi-layer composite, aramid, UHMWPE*

I. INTRODUCTION

Life jackets are mandatory personal protective equipment for those who work on rivers and seas, as they are the minimum tool to prevent drowning and protect human life in case of accidental water immersion. Currently, fishermen who fish far from shore, Fisheries Inspection and Customs forces, as well as other civilian activities on rivers and seas, always face dangers when colliding with sharp objects during work or when encountering weapons from small conflicts. If equipping bulletproof armor or stab-proof armor is very complex, inconvenient for work and requires a large budget. Therefore, the need is to have life jackets that are both buoyant and can resist stabbing in order to protect the lives of those involved during operations.

Bulletproof life jackets have been researched, manufactured, and widely provided to the Navy forces of developed countries. This product is made by adding a ballistic plate to the front and back of a life jacket. The bullet or shrapnel will destroy the material with a large amount of kinetic energy (from hundreds to thousands of joules). Therefore, these bulletproof or stab-proof jackets are usually very rigid and heavy (3-7 kg).

In civilian life, the danger of stabbing is even more dangerous than bullets due to its unpredictability and the availability of stabbing weapons in certain situations. Stab-proof armor is also widely used today, and is often softer and lighter than bulletproof armor. Sharp objects and stabbing weapons (such as knives and spears) may have very low kinetic energy (only a few tens of joules), but their sharp structure means that the material will be destroyed through two processes: puncture by the sharp tip and cut by the sharp edge. Therefore, the outer material will suffer both cutting and puncture, while the inner layers will mainly suffer puncture and less cutting [2].

Many studies by various authors have been published on the anti-stab properties of materials when destroyed by standard penetration testing, such as Vu Thi, Lara and their colleagues who reported on the cut and puncture properties of thin polymer plate materials [3], [4]. Magdi and colleagues studied the cut and puncture resistance of various woven fabrics made from super-strong synthetic fibers under different force, impact direction and weaving parameters [5], [6]. A group of scientists from Kyung Hee University and the Korea Institute of Industrial Technology have published results on the puncture resistance properties and calculations of woven and non-woven materials using super-strong, core and blended fibers, as well as the effectiveness of combining multiple layers of composite materials in producing stab-proof armor [7]-[10].

While there is a necessary demand for stab-proof life jackets, there have been no published results on their production. Similar to the method of producing bullet-proof life jackets, it is possible to create stab-proof life jackets as well. In this study, two commonly used materials with cut and puncture-resistant properties were selected to combine with the buoyant foam of a life jacket to create a stab-proof life jacket. Experiments were conducted to determine the suitable number of layers for each material to create a multi-layer composite anti-stab material that meets Level 1 protection according to the NIJ Standard.

II. EXPERIMENTS

1. The Test Method

Nowadays, there are various standards for testing and evaluating the ability of materials and armor products to resist penetration [2]. After researching relevant studies, we have chosen the NIJ standard (NIJ Standard-0115.00) to manufacture equipment as well as test and evaluate the penetration resistance of the research materials and products [7]-[10].

According to the NIJ standard [11], the penetration resistance is tested through a penetration test at the drop tower manufactured in Figure 1. This test method simulates the actual impact when using a counterweight with a standard penetrating tip with a weight of 1.8 kg dropped from a certain height onto the target support structure shown in Figure 2. The typical penetrating weapons used are the S1 knife and the spike, as shown in Figure 3.

Depending on the level of energy or drop height applied in the test, the penetrating object will break through and penetrate the material and enter the target support structure. The depth of penetration (DOP) through the material is the distance from the tip of the penetrating object to the back surface of the material when it penetrates (see figure 2). DOP less than 7 mm is considered a necessary condition to meet the NIJ standard for various protection levels (impact energy levels). DOP is measured through a detection layer of paper placed immediately behind the penetrating material and the layers of the target support structure as specified by the NIJ standard.

In this study, we chose two standard penetrating tips, the S1 knife and the spike, with the same protection level of 1 corresponding to a drop energy of 24 J to test the penetration resistance of all sample materials. The test sample must be tested at a perpendicular and a 45^0 angle with the penetrating object, and the average result is taken after 5 tests. When meeting the protection level of 1 (24 J), it is necessary to continue testing with an overload of 36 J, but the DOP at this time only needs to be less than 20 mm for the product to officially meet the requirements at protection level 1 according to the NIJ standard.

2. Materials and Specimens

The product needs to be convenient and comfortable, so it is necessary to choose thin and soft layers with cut-resistant and puncture-resistant characteristics to form a multi-layer composite material with foam that meets the standard. Following the previous research results [7]-[10], we have chosen two component materials, woven fabric and coated sheet, using two super-strong fibers combined with life jacket foam (for technical specifications and images, see Table 1 and Figure 4) as follows:

- High-density woven fabric is woven from continuous Heracron® fibers (para-aramid 200de) from Kolon Corporation (indicated as A), which are layers of materials that are both cut-resistant and puncture-resistant. This

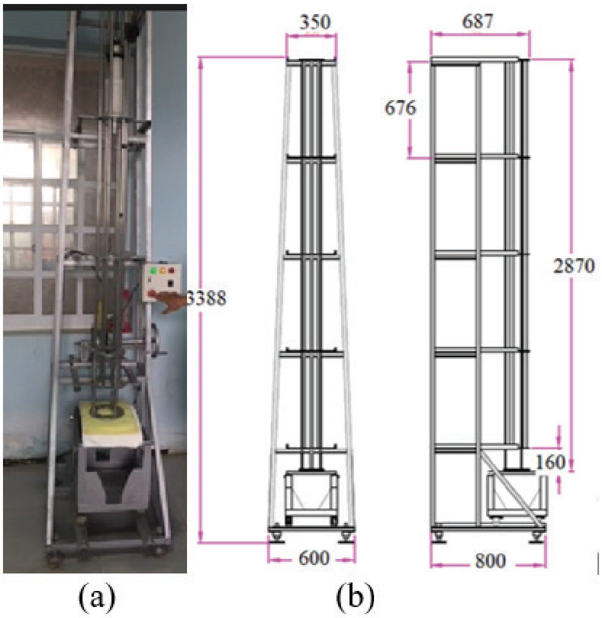

Figure 1. Stab resistance testing apparatus; (a) photograph and (b) dimensional specifications.)

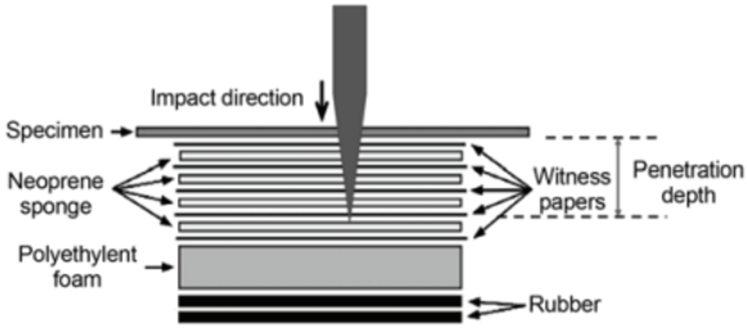

Figure 2. The backing system for stab testing.

type of aramid fiber and fabric made from this basic super-strong fiber are widely used in bulletproof and anti-puncture products.

- Soft, thin coated sheet of Dyneema® SB31 (spectra shield) from DSM Corporation, which is primarily used for puncture resistance and has less cut resistance (indicated as B). The structure of one Dyneema® SB31 panel is made up of two continuous UHMWPE (Ultra High Molecular Weight Polyethylene) fiber layers arranged at right angles to each other, with the two sides covered by two thin PE films that fix the two super-strong fibers inside.

In this penetration test, the samples with a size of 35x40 (cm^2) correspond to the area of one anti-penetration panel attached to the life jacket and are clamped by two nylon straps. The test sample is prepared by stacking the layers of materials on top of each other according to the selected multi-layer composite structure.

When using only one type of material, such as the A woven fabric or B coated sheet above, the number of layers combined with foam required to meet the NIJ standard for various protection levels can be easily determined by gradually increasing the number of layers until the requirement is met. However, when using both types of component materials A, B, the order and quantity of each type of component material will greatly affect the penetration resistance. Many experiments have been conducted with various test samples with

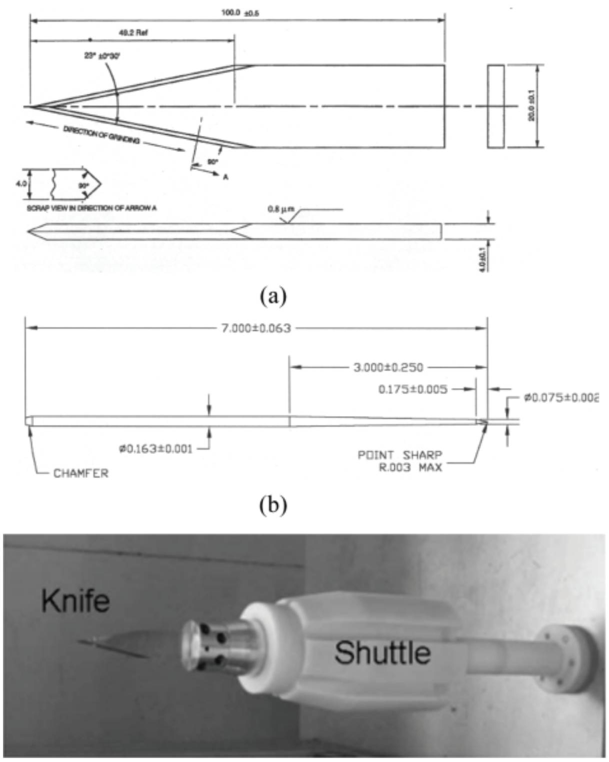

Figure 3. Blades for stab testing; (a) knife (S1), (b) spike and shuttle.

changing ratios of % A, % B, and the position of the foam to find the most advantageous combination of weight and thickness for the anti-penetration panel. However, the experimental results are presented only for a few typical samples to compare the advantages of combining two types of materials versus using only one type when meeting the NIJ penetration resistance standard.

Table 1. Technical specifications of woven fabric and coated sheet

Name	Fineness (denier)	Thread count (yarns/in)	Thickness of 1 layer (mm)	Areal density of 1 layer (g/m^2)
A: Woven fabric (Para-aramid 200de)	200	70x70	0.2	130.7
B: Thin coated sheet (Dyneema® SB31)			0.2	132

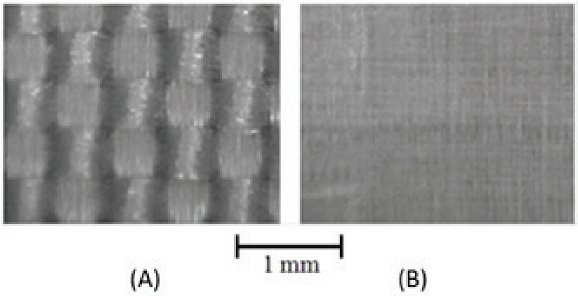

Figure 4. Image of two types of penetration-resistant materials
(A): Woven fabric using Heracron® fibers (para-aramid 200de);
(B): Thin coated sheet (Dyneema® SB31).

III. RESULTS AND DISCUSION

Table 2 presents the results of the experiment on seven multi-layer composite material samples made up of the number of layers and arrangement of two types of soft, thin, A and B component materials combined with life jacket foam to form multi-layer anti-penetration composite material. The penetration resistance test was performed at the NIJ protection level 1 (24 J) on a drop test stand with two types of penetrating objects, the S1 knife and the spike, at perpendicular and 45° angles. If the test order meets the requirements with energy of 24 J, continue to tilt 45°, if it passes, continue with the vertical test (overload) with energy of 36 J. If the previous test step fails, do not perform the following conditions. From the results above, we make the following observations:

When the stabbing angle is at 45°, the penetration resistance of the test materials will be lower than the case of perpendicular stabbing compared to the surface of the product. The stabbing object usually slides off the test sample, sometimes the awl is bent due to the reactive force causing sliding. The test sample when stabbed perpendicularly to the surface of the product meets the requirements, then when tilted 45°, it also meets. The case of penetration-resistant material placed on the life jacket foam will be more effective than underneath. This result is easy to understand because the penetration resistance of this case will be limited by the thickness of the foam (30 mm).

Comparing the criteria of weight and thickness of material A and B in the composite sample when achieving protection level 1 (24 J) according to NIJ standards: When using only one type, A is more effective than B; when using both materials A and B, penetration resistance is better than using only type A or B; arranging the component materials in order of A-B achieves better penetration resistance than arranging in order of B-A. This shows that each type of material has a certain penetration resistance characteristic. When arranging cutting and penetration-resistant materials on mainly penetration-resistant layers, good penetration resistance will be achieved with the opposite arrangement.

Based on the test results, we can select and determine the sufficient amount of material to manufacture an anti-stabbing life jacket that is buoyant and puncture-resistant, achieving Level 1 protection according to NIJ standards, in a way that is advantageous in terms of thickness and weight of the product. This is also a basis for comparison and evaluation with other stab-proof materials or anti-stabbing life jacket products during production.

Table 2. Results of puncture tests on multi-layer composite materials with perpendicular and inclined 45^0 impact angles, surface contact, impact energy of 24 J, and overload of 36 J.

Composite material sample for penetration resistance	Impact projectile testing	Number of layers of each type of material used in combination to create the penetration-resistant plate		Specifications of the penetration-resistant plate (0.14m^2)		DOP through the sample when tested at energy level 1 (normal, overloaded) and impact angle (mm).		
		Number of Type A layers	Number of Type B layers	Thickness (mm)	Mass (g)	Perpendicular, 24 J	Inclined 45^0, 24 J	Perpendicular, 36 J
Sample **1**	Knife S1	29	0	5.8	531	0	0	13
	Spike					0	0	15
Sample **2**	Knife S1	0	31	6.2	573	0	0	13
	Spike					0	0	15
Sample **3**	Knife S1	16	11	5.4	496	0	0	16
	Spike					0	0	15

Composite material sample for penetration resistance	Impact projectile testing	Number of layers of each type of material used in combination to create the penetration-resistant plate		Specifications of the penetration-resistant plate ($0.14m^2$)		DOP through the sample when tested at energy level 1 (normal, overloaded) and impact angle (mm).		
		Number of Type A layers	Number of Type B layers	Thickness (mm)	Mass (g)	Perpendicular, 24 J	Inclined 45^0, 24 J	Perpendicular, 36 J
Sample 4	Knife S1	Number of layers A, B as Sample 3 but with B placed on top of A		5.4	496	17		
	Spike				15			
Sample **5**	Knife S1	Number of layers A, B as Sample 3 but placed behind foam		5.4	496	>30		
	Spike				>30			
Sample **6**	Knife S1	Number of layers A as Sample 1 but placed behind foam		5.8	531	>30		
	Spike				>30			
Sample **7**	Knife S1	Number of layers A as Sample 2 but placed behind foam		6.2	573	>30		
	Spike				>30			

IV. CONCLUSION

In this study, high-density woven fabric made from para-aramid 200de fibers (A) and a thin layer coated with Dyneema® SB31 (B) were chosen, along with the foam of a life jacket to create a composite material to test for puncture resistance. The experiment identified three samples with the appropriate number of layers and arrangement of component materials for composite to meet NIJ Level 1 puncture resistance. This serves as a basis for manufacturing anti-stabbing life jackets for specific workers who work on water, where the material must be both anti-drowning and resistant to puncture.

When compared to the criteria of thickness and weight of composite material or product, using both types of materials is more advantageous than using only one type, with the order being type A on top and type B on the bottom like sample 3. If only using one type of material, type A is more effective than type B like sample 1. In all cases, placing the puncture-resistant material on top of the foam of a life jacket is more effective for puncture resistance than placing it below.

There are currently many commercial puncture-resistant materials available on the market with varying quality and prices. Research and testing are necessary, particularly in combining these materials with the characteristics of cut resistance, puncture resistance, and other traits to achieve the best puncture resistance effectiveness according to set goals. Materials that have met NIJ standards in testing conditions also require the development of specific puncture resistance characteristics and the demonstration of the relationship between the thickness, weight of the material, and the energy absorbed from different types of striking objects to observe the behavior of composite puncture-resistant material.

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