DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

Shark-Resistant Materials for Combat Diver Use

Report Number:
DSIAC-BCO-2022-205

Completed February 2022

DSIAC is a Department of Defense Information Analysis Center

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
07-02-2022	Technical Research Report	

4. TITLE AND SUBTITLE
Shark-Resistant Materials for Combat Diver Use

5a. CONTRACT NUMBER
FA8075-21-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Taylor H. Knight

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Defense Systems Information Analysis Center (DSIAC)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
Materials and Manufacturing Processes, Human Systems, Advanced Materials

14. ABSTRACT
The Defense Systems Information Analysis Center was asked to identify shark-resistant materials and technology in development or readily available that can be applied to combat diver wetsuits. The most recent breakthrough in this technology comes from the development of the Shark Stop wetsuit by the company SharkStop, located in Australia. These suits were tested and proven to provide protection from shark bites among divers. Testing criteria and research results were published in an international peer-reviewed scientific journal in 2019, which is summarized in this report. The material was developed to resist cuts and punctures and reduce wounds and blood loss, which is the main cause of fatalities from shark attacks. The protective layer is made from ultra-high molecular polyethylene and then bonded to a standard neoprene wetsuit material. There are similar fabrics being tested and developed, including Aqua Armor, Neptunic Sharksuits, and the Blackmaille Sharksuit.

15. SUBJECT TERMS
advanced materials, shark resistant, combat divers, Sharksuit, composite materials

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Ted Welsh, DSIAC Director
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	13	**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U			443-360-4600

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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ABSTRACT

The Defense Systems Information Analysis Center was asked to identify shark-resistant materials and technology in development or readily available that can be applied to combat diver wetsuits. The most recent breakthrough in this technology comes from the development of the Shark Stop wetsuit by the company SharkStop, located in Australia. These suits were tested and proven to provide protection from shark bites among divers. Testing criteria and research results were published in an international peer-reviewed scientific journal in 2019, which is summarized in this report. The material was developed to resist cuts and punctures and reduce wounds and blood loss, which is the main cause of fatalities from shark attacks. The protective layer is made from ultra-high molecular polyethylene and then bonded to a standard neoprene wetsuit material. There are similar fabrics being tested and developed, including Aqua Armor, Neptunic Sharksuits, and the Blackmaille Sharksuit.

Defense Systems Information Analysis Center

Contents

1.0 TI Request

1.1 INQUIRY

What materials and/or technology are being developed, or are available, for shark-resistant wetsuits?

1.2 DESCRIPTION

The inquirer was interested in shark-resistant wetsuit materials and technology that is currently being researched and developed for use with combat divers. Patents, commercial-off-the-shelf technologies, and advanced materials research were of interest.

2.0 TI Response

The Defense Systems Information Analysis Center (DSIAC) staff was tasked with identifying materials and technology being researched and developed for shark-resistant wetsuits. DSIAC staff searched open-source documents, patent publications, and technical papers to find technology and materials to fit the request.

Protecting U.S. combat divers is critical in allowing military missions to be successful. Divers and other water users are at risk of shark attacks. A variety of strategies, electronic shark protection devices, chemical deterrents, and other approaches has been developed to reduce the risk of shark attacks. These have had varied but generally limited efficacy, as well as being heavy, expensive to manufacture, and difficult to maneuver in.

Research into materials that are lighter, less expensive to manufacture, and more readily available has made headway in recent years. This research can also result in developing shark suits that not only deter sharks but are resistant to their bites. The following information summarizes current research in this field, including descriptions of available suits and testing criteria of the material (when available), and relevant patents.

2.1 SHARK-RESISTANT WETSUITS AND MATERIALS

2.1.1 SharkStop

SharkStop, an Australian company, offers surf and dive wetsuits that are shark resistant. The fabric protects divers from puncture wounds from a shark bite incident. The suits are designed with ultra-high molecular weight polyethylene (UHWMPE) and a bio neoprene. The bio neoprene was chosen to be eco-friendly and more durable than petroleum neoprene wetsuits. SharkStop fabrics have been tested on Great White Sharks by researchers at Flinders University of South Australia. A 2019 study was conducted to compare the effectiveness of novel fabrics in resisting punctures and lacerations from the great white shark (*Carcharodon carcharias, or C. carcharias)* and is discussed next.

2.1.1.1 Overview of the Study

A 2019 peer-reviewed study, funded by the New South Wales Department of Primary Industries Shark Management Strategy Competitive Annual Grants Program, was conducted to compare two types of recently developed protective fabrics that incorporated UHMWPE fiber onto neoprene (SharkStop and ActionTX) and compared them to standard neoprene alternatives [1]. Researchers tested nine different fabric variants using three different tests: (1) laboratory-based puncture, (2) laceration tests, and (3) field-based trials involving *C. carcharias*.

Field-based trials consisted of measuring a great white shark's bite force and quantifying damages to the new fabrics following a bite from a 3–4-m-long *C. carcharias*. Researchers determined that SharkStop and ActionTX fabric variants were more resistant to puncture, laceration, and bites from the shark. More force was required to puncture the new fabrics compared to control fabrics (laboratory-based tests), and cuts made to the new fabrics were smaller and shallower than those on standard neoprene for both types of tests. Results showed that UHMWPE fiber increased the resistance of neoprene to shark bites. Although the use of UHMWPE fiber may reduce blood loss resulting from a shark bite, research is needed to assess if the reduction in damages to the fabrics extends to human tissues and decreased injuries.

2.1.1.2 Testing

Nine different fabrics were tested [1] as follows:

- Three standard neoprene fabrics of varying thicknesses used as a control.
- A variety of six fabrics that incorporated UHMWPE fiber onto neoprene.

Fabrics used during testing fluctuated depending on availability, marketability, and performance in the puncture tests. UHMWPE fiber was glued as a top layer or on either side of the neoprene (referred to by manufacturers as SharkStop) or bonded into multiple layers between neoprene layers (known as ActionTX). Table 1 describes the types of fabrics used and their corresponding tests.

Table 1: Fabrics Used for Testing Shark-Resistant Materials [1]

Type	Thickness (mm)	Components	Test used
Control	2	Standard neoprene lined with cotton	Puncture, laceration
Control	3	Standard neoprene lined with cotton	Puncture, field bite
Control	5	Standard neoprene lined with cotton	Puncture
Test	3	Single-lined UHMWPE (SharkStop)	Puncture
Test	3	Double-lined UHMWPE (SharkStop)	Puncture
Test	5	Double-lined UHMWPE (SharkStop)	Puncture, laceration, field bite
Test	3	400 g/m^2 standard UHMWPE (ActionTX)	Puncture, field bite
Test	5	400 g/m^2 ribbed UHMWPE (ActionTX)	Puncture
Test	5	800 g/m^2 standard UHMWPE (ActionTX)	Laceration

https://doi.org/10.1371/journal.pone.0224432.t001

Puncture tests were done using a TestResources 810LE Electrodynamic Test Machine for testing the force required to penetrate each fabric [1]. A gelatinous mix to replicate soft human tissue was covered with squares of each fabric being tested and then stapled onto 20-density Sawbones foam. The foam was used to replicate bone under the skin and tissue. A shark tooth mounted in acrylic was used for all testing in the test machine. Tests were run under the following settings: 25-mm penetration depth at a speed of 100 mm/s. The machine mimicked a straight downward stroke of a single shark bite. Control tests with Sawbones foam alone were used to compare the force needed to penetrate each fabric. A decrease in penetration ability or bluntness of the tooth was not detected.

Laceration tests were conducted with a six-degree-of-freedom hexapod robot used to test the force required to cut the fabrics. The machine was designed to mimic the “head shake” action exhibited by white sharks when biting prey. The fabrics were affixed in a horizontal plane and consisted of a round 140-mm diameter plastic top secured with clamps and a polycarbonate ring. Teeth were mounted so serrated edges were horizontally exposed, and a sawing motion was created by the hexapod robot. Based on the outcome of the puncture tests, three fabrics were tested: (1) 5-mm, double-lined SharkStop, (2) 5-mm, 800 g/m^2 ActionTX, and (3) a control fabric of 2-mm neoprene. A minimum of 10 tests was conducted for each fabric. Tooth bluntness was visible over time, so only six repeat tests were conducted using any one tooth.

Field-based testing was conducted to measure the *C. carcharias* bite force and the effectiveness of the wetsuit fabric. To test the bite force, the maximum force (N) for shark bites was measured using two Futek LTH350 2000-lb donut load sensors placed between two steel plates surrounded by foam. To encourage sharks to bite, pieces of bluefin tuna were attached to the foam while the setup floated behind a vessel. Bite values recorded from the tests were adjusted using calculations from laboratory calibrations and then compared to theoretical maxima calculated from previous studies.

C. carcharias were enticed to bite the tested fabrics (3-mm control neoprene, 3-mm double-lined SharkStop, and 3-mm 400 g/m^2 ActionTX), with 10–12 trials for each fabric type. Bite sequences were filmed with the overall intensity, intensity of head shakes, and number of bites recorded for each sequence. A minimum of nine individual sharks ranging 3 to 4 m total length (TL) was involved in the field testing. Analysis did not include shark identification due to some bites occurring too fast for sharks to be identified. No single shark dominated the trials, and the randomization of fabric type ensured that results were not biased by individual sharks.

2.1.1.3 Results

Puncture tests showed the mean force required to puncture the fabric was similar between the control fabrics but significantly different between fabric types (control vs. SharkStop vs. ActionTX), with SharkStop requiring the highest force to puncture the fabric and ActionTX requiring more force than the control neoprene [1]. Researchers found the force required to penetrate SharkStop fabric was significantly higher for SharkStop (1150N) compared to standard neoprene (264N) [2].

Laceration tests showed the mean length of the cut was similar across fabric types, but the depth was significantly different, with both test fabrics having shallower cuts than the control and SharkStop having the shallowest cuts [1]. The length of cut was affected by teeth size. The average depth of a bite from a great white shark on SharkStop was approximately 50% less than on standard neoprene [2]. This also resulted in a reduction of puncture length, as the teeth could not penetrate as deeply.

Overall, the study showed consistent trends across the different tests and revealed that UHMWPE fiber incorporated onto neoprene was more likely to withstand damages from *C. carcharias* bites than standard neoprene. This resulted in a reduction of punctures and cut depth and length. Laboratory tests undertaken in a controlled setting showed that SharkStop and ActionTX fabrics required a stronger force to be punctured and were less damaged by laceration trials than control neoprene. When tested in the field with 3 to 4 m TL *C. carcharias*, the neoprene with UHMWPE fiber was more resistant to bites than standard neoprene and had less damage. There were little statistical differences between the two fabric types tested, but the SharkStop fabrics required a higher force to puncture than the ActionTX, which also had depth of cuts and punctures in between those of the SharkStop and control neoprene. The results showed that both fabrics tested may provide some protection against shark bites and could be used as part of a shark bite mitigation strategy if properly implemented.

2.1.2 Aqua Armor

Aqua Armor is a fiber-reinforced composite intended for integration into neoprene wetsuits in the form of protective pads by integrating Kevlar fibers into an elastic matrix. Uniaxial testing using shark teeth replicas was conducted on a specially designed test rig to quantify the effectiveness of the material, and the degradation of the material due to ultraviolet (UV) and seawater exposure was monitored [3].

Tested samples contained five layers of plain weave Kevlar with an overall thickness ranging from 1.17 to 1.37 mm or eight layers from 1.92 to 1.98 mm [3]. Prior to testing, some samples were subjected to UV exposure and saltwater immersion to test for changes in the material's performance. Samples were provided by the company Aqua Armor (Newcastle, Australia).

Shark teeth replicas were used due to degradation of real shark teeth limiting the repeatability of testing [3]. Replicas were conical steel penetrants topped with a cone that approximated the geometry of a shark tooth. All penetration tests were conducted with a quasistatic machine-crosshead displacement velocity of 10 mm/min. Tests were conducted on a 30-kN Shimadzu uniaxial testing machine, with a mounting block attached to the machine-crosshead moving downward toward the samples.

The tested material decreased the penetration of shark teeth replicas into vulnerable tissue and mitigated injury severity due to shark attacks [3]. Based on the results, exposure had no significant impact on material performance. However, a desirable decrease of penetration depth was observed due to residual curing of the polymeric matrix of the composite. For cured samples, penetration of two sharpened steel rods resembling the teeth of *C. carcharias* was reduced to ~5 mm by including additional Kevlar layers into the protective materials.

2.1.3 Jeremiah Sullivan Sharksuits

Jeremiah Sullivan is the founder of Neptunic and SharkArmor Technologies. His shark suits are available to professional divers in the scientific, military, public safety, commercial/salvage, and film/television markets. The earlier generation Neptunic suits incorporate stainless steel mesh, designed by MailleTec, and are offered in booties, gloves, pants, and sleeves and tunics [4]. The newer Blackmaille by SharkArmor Sharksuit is comprised of 500,000 individually welded, blackened, stainless steel rings.

2.2 PATENTS

The following patents are in chronological order, with the most recent listed first. The patent abstract is summarized to provide a brief description of the material and technology.

2.2.1 Shark-Resistant Composite Fabric

This 2022 Australia patent was filed by the founder and developer of the SharkStop wetsuit [5]. It describes a shark-resistant composite fabric with an outer layer of a woven or knitted UHMWPE material, an intermediate layer of neoprene, and an inner layer of woven or knitted UHMWPE. In test environments, sharks found the texture and feel of the outer layer unsatisfactory, in some cases ceasing their attack. If an attack penetrated the outer layer, it was observed that penetration of the inner layer was unlikely since it was spaced apart from the outer layer by a neoprene intermediate layer.

2.2.2 Anti-shark Garment and Method of Use

A shark-repellent fabric garment was researched from one or more fabric panels prepared from natural and/or synthetic yarn, where one or more fabric panels were configured to form a garment [6]. The garment contained at least one strand of nickel or stainless steel wire of 30 gauge or higher, and at least one strand of nickel or stainless steel wire was configured to provide a continuous electrical circuit throughout the garment. The garment was connected to a signal generator configured to supply a frequency of 0.25 MHz to 10 GHz, preferably 1 MHz ±100 Hz to the circuit, along with a method for using the garment to repel sharks.

2.2.3 Wetsuit System With Shark Deterrents

This 2013 patent was filed by one of the field testers of the SharkStop suit. It describes a wetsuit composition made of a first layer of neoprene and a weave made of a plurality of layers comprising UHMWPE [7]. The weave was found to be useful for stopping shark teeth. A layer of denatonium benzoate can be placed between the weave and a second layer of neoprene. The second layer of neoprene may have an outer surface coated with pigment or material having a bright color, such as yellow, orange, or pink. The new wetsuit composition is sometimes used with a new shark repellant made of three parts red wine vinegar to one part of a specially processed habanero pepper mixture. The new shark repellant may be stored and propelled by use of a variety of implements, including a disclosed squirt device.

2.2.4 Puncture- and Cut-Resistant Material

An Australian patent from May 2012 describes an elastic, cut/puncture-resistant material that was researched for use in garments [8]. This material contains a variety of protective elements, at least one elastic base layer, and minimal connective area or no connective area between the protective element(s) and the elastic base layer(s). The attachment can be a point attachment or an attachment of layers of elastic materials to form pockets to capture the protective elements. The protective elements can be flexible or (semi) rigid.

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