DEVELOPMENT OF SOFT BODY ARMOUR BY USING DIFFERENT HIGH-PERFORMANCE MATERIALS

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by

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Dedicated to the “Nation”

CERTIFICATE

This is to certify that the thesis titled **'Development of Soft Body Armour by Using Different High-Performance Materials'**, being submitted by Mr. Mukesh Bajya to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and fulfilled the requirements for submitting the thesis, which has attained the standard required for a Ph.D. degree of this Institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

Lightweight, soft body armour is the current requirement for security forces due to increased terror attacks, civil war and cross border casualties. This research area has become a hotspot for protective textile researchers. For the last five-decade, *p*-aramid and ultra-high molecular weight polyethylene (UHMWPE) fibre is prominently used for bullet resistance material. New high-performance materials and techniques are required, which give better ballistic protection and are eco-friendly. Shear thickening fluid (STF), surface treatment and growth of nanostructures, hybridisation of material and stacking sequences are being explored for impact resistance material. The present research focuses on improving the impact performance in terms of back face signature (BFS) of soft body armour by using hybridisation techniques, STF impregnation and introducing new high-performance material, i.e., disentangled polyethylene (DPE) tape.

In the first part of this research, an attempt was made to develop a hybrid soft armour panel (SAP) using commercial high-performance material such as *p*-aramid woven fabric and UD laminates, UHMWPE UD laminates and polycarbonate sheet. The work shows the role of textile structure for bullet resistance materials. The developed hybridised SAPs were cost-effective solutions with improved ballistic performance.

In the second part of the research, an attempt was made to understand the role of STF impregnation on *p*-aramid woven fabric for SAPs. The areal density of SAP can be reduced further by 10 % (4.5 kg·m^2), while keeping the BFS comparable to or lower than that of an STF impregnated homogenous panel by judiciously placing the STF impregnated fabrics at the rear side while neat fabrics are placed at the strike face of the panel. It was also noted that STF impregnated panels were found to stop the impacting bullet earlier than the neat panel.

In the third part of the research, an attempt was made to understand DPE tapes physical, thermal, and mechanical properties from polymer to highly drawn tape. Thereafter find the possibility of DPE tape as a replacement of existing commercial high-performance material such as *p*-aramid, gel spun UHMWPE fibre. DPE tape has comparable mechanical properties as existing high-performance materials. Basic advantage of DPE, it is manufactured by solvent-free techniques, which is economical and eco-friendly compared to gel spun fibres.

In the last part of this research, an attempt was made to develop the various laminates structures of DPE tape and low-density polyethylene (LDPE), such as woven twisted tape (WTT) based UD laminates, cross-ply laminates at different process parameters and conditions. Thereafter, single layers of various laminates structures were optimised in terms of resin content, structures and process parameters. The prepared laminates structures evaluated for mechanical and low velocity dynamic impact performance. After that, Optimised DPE based structures used for homogeneous SAP configuration using the optimised laminates. Cross-ply laminates-based SAP gives the highest ballistic resistance compared to woven based laminates. Overall, DPE based laminates can be used to produce SAP having areal density of 4.5 $kg \cdot m^{-2}$ which is comparable with the commercial solutions available in the market.

सारांश

बढ़ते आतंकी हमलों, गृहयुद्धों और सीमा पार हताहतों के कारण सुरक्षा बलों के लिए हल्के, नरम रक्षा कवच की वर्तमान आवश्यकता है। यह शोध क्षेत्र शोधकर्ताओं के लिए एक आकर्षण का केंद्र बन गया है। पिछले पांच दशक से बुलेट रेजिस्टेंस मैटेरियल के लिए पेरा-अरमिड और अल्ट्रा-हाई मॉलिक्यूलर वेट पॉलीइथाइलीन (UHMWPE) फाइबर का इस्तेमाल प्रमुखता से किया जा रहा है। नई उच्च-प्रदर्शन सामग्री और तकनीकों की आवश्यकता है, जो बेहतर बैलिस्टिक सुरक्षा प्रदान करने के साथ पर्यावरण के अनुकूल हो। प्रभाव प्रतिरोध को बढ़ाने के लिए शीयर थिकिंग फ्लुइड (एसटीएफ) कपड़े पर कोटिंग और नैनोस्ट्रक्चर की कपड़े की सतहे पर वृद्धि, अलग- अलग सामग्री का उपयोग करके हाइब्रिड पैनलों का निर्माण और स्टैकिंग अनुक्रमों का पता लगाया जा रहा है। वर्तमान शोध हाइब्रिडाइजेशन तकनीकों, एसटीएफ इंप्रेग्नेशन का उपयोग करके और नई उच्च-प्रदर्शन सामग्री, यानी डिसइनटेंगल्ड पॉलीइथाइलीन (डीपीई) टेप का उपयोग करके सॉफ्ट बॉडी आर्मर के बैक फेस सिग्नेचर (बीएफएस) के संदर्भ में प्रभाव प्रदर्शन को बेहतर बनाने पर केंद्रित है।

इस शोध के पहले भाग में, वाणिज्यिक उच्च-प्रदर्शन सामग्री जैसे कि पेरा-एरमिड से बुने हुए कपड़े और यूडी लैमिनेट्स, यूएचएमडब्ल्यूपीई यूडी लैमिनेट्स और पॉली कार्बोनेट शीट का उपयोग करके एक हाइब्रिड सॉफ्ट आर्मर पैनल (एसएपी) विकसित करने का प्रयास किया गया था। यह शोधकार्य बुलेट प्रतिरोध सामग्री के लिए कपड़े की संरचना की महत्वपूर्ण भूमिका को दर्शाता है। विकसित हाइब्रिड एसएपी बेहतर बैलिस्टिक प्रदर्शन के साथ कम कीमत वाले प्रभावी समाधान थे।

शोध के दूसरे भाग में, एसएपी के लिए पेरा-एरमिड बुने हुए कपड़े पर एसटीएफ संसेचन की भूमिका को समझने का प्रयास किया गया था। एसएपी के क्षेत्र घनत्व को १० % (४.५ किग्रा· मी$^{-2}$) तक कम किया जा सकता है, जबकि बीएफएस को एसटीएफ इंप्रेग्नेटेड होमोजीनियस पैनल की तुलना में या उससे कम रखते हुए विवेकपूर्ण तरीके से बीएफएस इम्प्रेग्नेटेड फ़ैब्रिक को पीछे की तरफ रखकर जबकि बिना एसटीएफ वाले कपड़ों को पैनल के स्ट्राइक फेस पर रखा गया। यह भी नोट किया गया कि एसटीएफ इंप्रेग्नेटेड पैनल बिना एसटीएफ वाले पैनल की तुलना में गोली को पहले रोकने के लिए प्रभावकारी पाए गए थे।

शोध के तीसरे भाग में डीपीई टेप के भौतिक, तापीय और यांत्रिक गुणों को पॉलीमर से अत्यधिक खींचे गए टेप तक समझने का प्रयास किया गया था। इसके बाद मौजूदा व्यावसायिक

उच्च-प्रदर्शन सामग्री जैसे कि पेरा-एरमिड, जेल स्पून यूएचएमडब्ल्यूपीई फाइबर के प्रतिस्थापन के रूप में डीपीई टेप की संभावना का पता लगाया गया। डीपीई टेप में मौजूदा उच्च-प्रदर्शन सामग्री के रूप में तुलनीय यांत्रिक गुण हैं। डीपीई का मूल लाभ, यह विलायक मुक्त तकनीकों द्वारा निर्मित है, जो जेल स्पून फाइबर की तुलना में किफायती और पर्यावरण के अनुकूल है। इस शोध के अंतिम भाग में, डीपीई टेप और कम घनत्व वाले पॉलीथीन (एलडीपीई) के विभिन्न लैमिनेट्स संरचनाओं को विकसित करने का प्रयास किया गया था, जैसे कि बुने हुए ट्विस्टेड टेप (डब्ल्यूटीटी) आधारित यूडी लैमिनेट्स, विभिन्न प्रक्रिया मापदंडों पर क्रॉस-प्लाई लैमिनेट्स। इसके बाद, विभिन्न लैमिनेट्स संरचनाओं की एकल परतों को रेसीन, संरचनाओं और प्रक्रिया मापदंडों के संदर्भ में अनुकूलित किया गया था। यांत्रिक और कम वेग गतिशील प्रभाव प्रदर्शन के लिए तैयार किए गए लैमिनेट्स संरचनाओं का मूल्यांकन किया गया। उसके बाद, डीपीई आधारित लैमिनेट्स का उपयोग करके एसएपी बनाया गये। क्रॉस-प्लाई लैमिनेट्स-आधारित एसएपी बुने हुए आधारित लैमिनेट्स की तुलना में उच्चतम बैलिस्टिक प्रतिरोध देता है। कुल मिलाकर, डीपीई आधारित लैमिनेट्स का उपयोग एसएपी के उत्पादन के लिए किया जा सकता है, जिसका क्षेत्रफल ४.५ किग्रा· मी$^{-2}$ है, जो बाजार में उपलब्ध वाणिज्यिक समाधानों के साथ तुलनीय है।

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AD	Areal density
ANOVA	Analysis of variance
BPJ	Bullet proof jacket
BRJ	Bullet resistance jacket
BFS	Back face signature
CMD	Cross machine direction
CPO	Crystalline plane orientation ratio
CPT	Cross-ply tape
DPE	Disentangled polyethylene
DSC	Differential scanning calorimetry
HAP	Hard armour panel
LDPE	Liner low density polyethylene
MD	Machine direction
PC	Polycarbonate sheet
PEG	polyethylene glycol
SAP	Soft armour panel
SEM	Scanning electron microscopy
STF	Shear thickening fluid
TGA	Thermogravimetric analysis
UHMWPE	Ultra high molecular weight polyethylene
UD	Unidirectional
WAXD	Wide angle X-ray Diffraction
WTT	Woven twisted tape