SHEAR THICKENING FLUID REINFORCED UHMWPE FABRICS FOR IMPACT RESISTANCE

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by

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Dedicated to the ‘protectors’ of all countries

CERTIFICATE

This is to certify that the thesis titled **'Shear Thickening Fluid Reinforced UHMWPE Fabrics for Impact Resistance'**, being submitted by Ms. Sanchi Arora 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 her. She has worked under my guidance and supervision and fulfilled the requirements for submission of 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

Increasing instances of terror attacks, civil wars and communal clashes have made body armour a research hotspot for the textile scientific fraternity. New high-performance materials are sought-after to replace the aramids which are in use for almost last five decades. Surface treatments like shear thickening fluid (STF) impregnation, metal oxide nanostructure grafting, plasma treatment, etc. are being explored to augment the impact resistance of high-performance woven fabrics. Improved design of armour panel via judicious arrangement or stacking of constituent fabric layers has also received considerable attention. The present research revolves around improving the impact resistance performance of ultra-high molecular weight polyethylene (UHMWPE) woven fabrics by STF impregnation, zinc oxide nanorod grafting and angular stacking of fabric layers.

In the first part of this research, an attempt was made to develop predictive models for flow curve of STF at various shear rates and temperatures. The developed phenomenological and artificial neural network models were able to represent the typical nature of the flow curve comprising of three distinct zones.

In the second part of research, an attempt was made to understand the role of fabric structure in inducing the effectiveness of STF impregnation. Plain woven fabrics, with three levels of sett (EPI×PPI), namely 22.5×22.5, 25×25 and 27.5×27.5 inch^{-1}; and with seven levels of sett from 25×25 to 55×55 inch^{-1}, in steps of five, were produced using 1350 denier and 400 denier Dyneema® SK75 yarns, respectively. After impregnation with STF, having 65% (w/w) silica in polyethylene glycol, at 2 bar padding pressure, yarn pull-out force and impact resistance increased for all fabrics woven with coarser 1350 denier yarn and loose fabrics woven with 400 denier yarn (i.e. sett ≤ 35×35 inch^{-1}). However, for tightly woven fabrics of 400 denier yarn, having sett ≥ 40×40 inch^{-1}, STF impregnation deteriorated the impact resistance despite increased yarn pull-out force. This fabric structure induced effectiveness of STF was found to be valid at different levels of STF add-on obtained by varying the padding pressure up to 5 bar. Interestingly, STF impregnation was found to be beneficial in less firm weaves (2/2 twill, 3/1 twill and 2×2 matt woven fabrics) even at very high sett (50×50 inch^{-1}) as the number of interlacements was lower than that of plain weave.

An attempt was made in the third part of the research to increase the inter-yarn friction in UHMWPE fabrics by zinc oxide nanorod (Z-NR) grafting with the objective to augment their impact resistance performance. The same plain woven fabrics used in previous part of research, with addition of a fabric with sett of 20×20 inch^{-1}, produced using 1350 denier Dyneema® SK75 yarn, were used in this part of research as well. Z-NR grafting exhibited similar kind of fabric structure induced beneficial effect on impact resistance performance of UHMWPE plain woven fabrics as that of STF impregnation. However, in general, Z-NR grafting exhibited higher or at least comparable impact energy absorption and peak force, with much lower add-on, as compared to STF impregnation. Fabrics grafted with Z-NR also showed lower yarn pull-out as compared to that observed in STF impregnated fabrics during impact failure.

In the last part of this research, an attempt was made to configure soft armour panels by imparting angular orientation to constituent woven fabric plies. Seven sets of 3-, 4- and 5- layered panels were stitched from neat and STF impregnated Spectra®, Kevlar® 363 2S and Kevlar® 802 F fabrics by stacking them in varying angular orientations. An increase in ballistic energy absorption by 15% to 19%, 34% to 58%, and 7% to 27% was observed with increase in number of angular orientations in STF impregnated 3-layered Spectra, 4-layered Spectra and 4-layered Kevlar 363 2S panels, respectively. In 5-layered panels made from neat Kevlar 802 F fabrics, up to 34% improvement in impact energy absorption was obtained with angular orientations.

सार

आतंकी हमलों, गृह युद्धों और सांप्रदायिक झड़पों की बढ़ती घटनाओं के चलते रक्षा कवच वैज्ञानिकों के लिए शोध का अहम क्षेत्र बन गये है। लगभग पाँच दशकों से उपयोग में आ रहे अरामिड फाइबर से भी बेहतर उच्च-निष्पादन फाइबर की आवश्यकता है तथा तलाश ज़ारी है। अत्यधिक मजबूत बुने हुए कपड़ों के आघात प्रतिरोध को बढ़ाने के लिये विभिन्न तकनीकों का पता लगाया जा रहा है, जैसे शियर थिकनिंग फ्लूईड (एस.टी.एफ) संसेचन, धातु ऑक्साइड नैनोस्ट्रक्चर ग्राफटिंग, प्लाज़्मा विकिरण पद्धति, इत्यादि। बेहतर गुणवत्ता वाला रक्षा कवच बनाने के लिए कपड़े की परतों को व्यवस्थित करने के तरीकों पर भी शोध किया जा रहा है। इस शोध प्रबंध में यू.एच.एम.डब्ल्यू.पी.ई से बुने कपड़ों की आघात प्रतिरोध को बढ़ाने के लिए एस.टी.एफ संसेचन, ज़िंक ऑक्साइड नैनोस्ट्रक्चर ग्राफटिंग और कपड़े की परतों के क्रम व कोणीय अभिविन्यास पर शोध किया गया है।

इस शोध के पहले भाग में विभिन्न शियर दरों और तापमान पर एस.टी.एफ के प्रवाह वक्र का अनुमान लगाने वाले मॉडेलों को विकसित करने का प्रयास किया गया। विकसित किए गये फिनोमिनोलॉजिकल और आर्टिफीशियल न्यूरल नेटवर्क मॉडल एस.टी.एफ के प्रवाह वक्र के तीन विशिष्ट क्षेत्रों का अनुमान लगाने में सक्षम पाए गये।

अनुसंधान के दूसरे भाग में, एस.टी.एफ संसेचन की प्रभावशीलता में कपड़े की संरचना की भूमिका को समझने का प्रयास किया गया। १३५० और ४०० डेनियर के डायनीमा एस.के. ७५ यार्न का उपयोग करके क्रमश: तीन घनत्व के यानि २२.५×२२.५, २५×२५, २७.५×२७.५ प्रति इंच, और पाँच के चरणों में २५×२५ से ५०×५० प्रति इंच तक के सात स्तरों के साथ, सादी बुनाई वाले कपड़ों को उत्पादित किया गया। इन कपड़ों पर २ बार पैडिंग दबाव के साथ एस.टी.एफ (पॉली-इथायलीन ग्लाइकोल में ६५% सिलिका) संसेचन किया गया। अवलोकन करने पर एस.टी.एफ संसेचन से १३५० डेनिअर

यार्न से बुने सभी कपड़ों में और ४०० डेनिअर यार्न से बुने ढीले कपड़ों (घनत्व ≤ ३५×३५ प्रति इंच) में यार्न पुल-आउट बल और आघात प्रतिरोध में वृद्धि पाई गई। दूसरी ओर, ४०० डेनिअर यार्न के कसकर बुने हुए कपड़ों (घनत्व ≥ ४०×४० प्रति इंच) में एस.टी.एफ संसेचन ने यार्न पुल-आउट बल में वृद्धि के बावजूद आघात प्रतिरोध को खराब कर दिया। कपड़े की संरचना पर निर्भर एस.टी.एफ संसेचन की इस प्रभावशीलता को विभिन्न ऐड-ऑन स्तरों पर (जो कि पैडिंग दबाव बदल कर पाए गये), ५ बार पैडिंग दबाव तक वैध पाया गया। दिलचस्प बात यह है कि एस.टी.एफ संसेचन कम दृढ़ बुनाई (२/२ ट्विल, ३/१ ट्विल और २×२ मैट) वाले कपड़ों में बहुत अधिक घनत्व (५०×५० प्रति इंच) होने पर भी फायदेमंद पाया गया, क्योंकि इसमे जिल्द की संख्या सादी बुनाई की तुलना में कम थी।

अनुसंधान के तीसरे भाग में ज़िंक ऑक्साइड नैनोरोड (ज़्-न.र.) ग्राफ्टिंग द्वारा यू.एच.एम.डब्ल्यू.पी.ई कपड़ों में अंतर-यार्न घर्षण को बढ़ाने के लिए प्रयास किया गया ताकि उनके आघात प्रतिरोध को बढ़ाया जा सके। अनुसंधान के पिछले भाग में उपयोग किए समान सादे बुने हुए कपड़ों का तथा १३५० डेनियर डायनीमा एस.के. ७५ यार्न से २०×२० प्रति इंच घनत्व में बुने कपड़े का उपयोग अनुसंधान के इस भाग में भी किया गया। ज़्-न.र. ग्राफ्टिंग ने भी एस.टी.एफ संसेचन के रूप में यू.एच.एम.डब्ल्यू.पी.ई के सादे बुने हुए कपड़े के आघात प्रतिरोध प्रदर्शन पर उसी तरह के कपड़े संरचना से उपजे लाभकारी प्रभाव का प्रदर्शन किया। हालांकि, सामान्य तौर पर, ज़्-न.र. ग्राफ्टिंग ने एस.टी.एफ संसेचन की तुलना में बहुत कम ऐड-ऑन के साथ उच्च या कम से कम तुलनीय आघात ऊर्जा अवशोषण और शिखर बल का प्रदर्शन किया। इसके अतिरिक्त ज़्-न.र. ग्राफ्टिंग के साथ तैयार किए गए कपड़े में एस.टी.एफ संसेचित कपड़े की तुलना में आघात होने के बाद कम यार्न पुल-आउट भी पाया गया।

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