# CUT-PROTECTIVE PERFORMANCE OF UHMWPE-BASED KNITTED TEXTILES IN REAL WORLD INDUSTRIAL CONDITIONS

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**INDIAN INSTITUTE OF TECHNOLOGY DELHI**
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by

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Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy*

to the




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# CERTIFICATE

This is to certify that the thesis entitled **"Cut-Protective Performance of UHMWPE-Based Knitted Textiles in Real World Industrial Conditions",** submitted by Mr. Shubham Singh to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Textile and Fibre Engineering, is a record of bonafide research work carried out by him. Mr. Shubham Singh diligently pursued his research work under my guidance and supervision and has fulfilled the requirements for the submission of the thesis, which, to my knowledge, aligns with the requisite standards for a Ph.D. degree from this institute.

The results contained in the thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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(Shubham Singh)

# ABSTRACT

Cut-protective textiles are critical components of personal protective equipment used in industrial environments where workers are exposed to sharp tools, abrasive surfaces, thermal hazards, and repeated mechanical loading. Knitted fabrics are widely adopted for cut-protective gloves because of their flexibility, stretchability, and wearer comfort. However, the open-loop architecture of knitted structures can reduce resistance to blade penetration and may lead to performance degradation under realistic service conditions. This thesis presents a systematic investigation into the cut-resistance behavior of knitted textile fabrics by examining the combined influence of yarn reinforcement, knitted structure, cutting direction, thermal exposure, and long-term service-related conditions.

Knitted fabrics were developed using ultra-high-molecular-weight polyethylene (UHMWPE) yarn systems, including 100% UHMWPE yarn and UHMWPE core-spun composite yarns reinforced with stainless steel and glass fibers. Fabric samples were produced on industrial glove knitting machines using controlled knitting parameters and different structural configurations. Cut resistance was evaluated using the ISO 13997 standard, while mechanical properties such as tear, puncture, and abrasion resistance were assessed according to EN 388:2016. Structural and morphological changes were examined using optical microscopy, scanning electron microscopy, X-ray diffraction, and Fourier-transform infrared spectroscopy to establish relationships between material structure and performance.

The study demonstrates that yarn reinforcement has a dominant effect on cut resistance. Stainless-steel reinforced fabrics exhibited the highest cut, puncture, and abrasion resistance at

room temperature due to improved load sharing and enhanced alignment of UHMWPE molecular chains, resulting in higher crystallinity. Cutting direction significantly influenced cut performance, with the highest resistance observed in the widthwise direction, followed by diagonal and lengthwise directions, due to differences in fabric extensibility and loop deformation behavior. Knitted fabric topology was shown to affect both protection and comfort, where selected plain knitted structures provided a balanced combination of moderate cut resistance and high air permeability, improving suitability for prolonged wear.

To evaluate thermal effects, a conventional cut-testing instrument was modified to enable cut testing under controlled contact and radiant heat exposure, for which an Indian patent has been filed. Cut resistance decreased with increasing temperature due to thermal softening and crystallinity loss in UHMWPE. Glass-fiber reinforced fabrics demonstrated better retention of cut performance at elevated temperatures, as the lower thermal conductivity of glass restricted heat transfer and delayed polymer degradation. In contrast, stainless-steel reinforced fabrics showed faster performance reduction under thermal exposure due to more efficient heat conduction.

Service-related performance was examined through repeated rubbing, laundering, fabric stretching, and outdoor environmental exposure. Repeated abrasion and washing caused progressive degradation of cut resistance in all fabrics, with stainless-steel reinforced samples showing superior abrasion durability and glass-fiber reinforced samples exhibiting brittle fracture under mechanical wear. Fabric stretching reduced cut resistance by limiting loop deformation and energy dissipation. Outdoor exposure resulted in chemical and mechanical degradation, particularly in stainless-steel reinforced fabrics due to corrosion-assisted

oxidation of UHMWPE, while glass-fiber reinforced fabrics showed improved environmental stability.

The findings of this thesis establish clear structure–property–performance relationships for knitted cut-protective textiles and provide practical guidance for selecting yarn reinforcement, fabric structure, and protective strategies based on specific industrial service conditions. This work contributes to the advancement of durable, comfortable, and application-oriented cut-protective textile systems and supports the development of testing methodologies that better represent real-world usage.

# सार

कट-प्रोटेक्टिव वस्त्र औद्योगिक वातावरण में उपयोग होने वाले व्यक्तिगत सुरक्षा उपकरणों के महत्वपूर्ण घटक हैं, जहाँ श्रमिकों को तेज औज़ारों, खुरदरी सतहों, तापीय खतरों तथा बार-बार होने वाले यांत्रिक भार का सामना करना पड़ता है। कट-प्रोटेक्टिव दस्तानों के लिए बुने हुए कपड़े व्यापक रूप से अपनाए जाते हैं, क्योंकि वे लचीलेपन, फैलाव क्षमता और पहनने में आराम प्रदान करते हैं। हालांकि, बुने हुए संरचनाओं की खुली लूप संरचना ब्लेड के प्रवेश के प्रति प्रतिरोध को कम कर सकती है और वास्तविक सेवा परिस्थितियों में प्रदर्शन में गिरावट का कारण बन सकती है। यह शोध प्रबंध बुने हुए वस्त्रों के कट-प्रतिरोध व्यवहार का एक व्यवस्थित अध्ययन प्रस्तुत करता है, जिसमें यार्न सुदृढ़ीकरण, बुनी हुई संरचना, कटिंग दिशा, तापीय प्रभाव तथा दीर्घकालिक सेवा स्थितियों के संयुक्त प्रभावों की जांच की गई है।

इस अध्ययन में अल्ट्रा-हाई मॉलिक्यूलर वेट पॉलीइथिलीन (यू-एच-एम-डब्ल्यू-पी-ई) आधारित यार्न प्रणालियों का उपयोग कर बुने हुए कपड़े विकसित किए गए, जिनमें 100% यू-एच-एम-डब्ल्यू-पी-ई यार्न तथा स्टेनलेस स्टील और कांच रेशों से सुदृढ़ किए गए यू-एच-एम-डब्ल्यू-पी-ई कोर-स्पन समिश्र यार्न शामिल हैं। नमूनों का निर्माण औद्योगिक दस्ताना बुनाई मशीनों पर नियंत्रित बुनाई मापदंडों और विभिन्न संरचनात्मक विन्यासों के साथ किया गया। कट-प्रतिरोध का मूल्यांकन आई-एस-ओ 13997 मानक के अनुसार किया गया, जबकि फाड़, छेदन और घर्षण प्रतिरोध जैसे यांत्रिक गुणों का परीक्षण ई-एन 388:2016 मानक के अनुसार किया गया। सामग्री संरचना और प्रदर्शन के बीच संबंध स्थापित करने के लिए ऑप्टिकल माइक्रोस्कोपी, स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी, एक्स-रे विवर्तन तथा फूरियर ट्रांसफॉर्म इन्फ्रारेड स्पेक्ट्रोस्कोपी का उपयोग किया गया।

अध्ययन से यह स्पष्ट हुआ कि यार्न सुदृढ़ीकरण का कट-प्रतिरोध पर प्रमुख प्रभाव पड़ता है। स्टेनलेस स्टील से सुदृढ़ किए गए कपड़ों ने कमरे के तापमान पर सबसे अधिक कट, छेदन और घर्षण प्रतिरोध

प्रदर्शित किया, जिसका कारण बेहतर भार-वितरण और यू-एच-एम-डब्ल्यू-पी-ई अणु श्रृंखलाओं का अधिक समंजन है, जिससे उच्च स्फटिकता प्राप्त होती है। कटिंग दिशा ने भी कट-प्रतिरोध को महत्वपूर्ण रूप से प्रभावित किया, जहाँ चौड़ाई दिशा में सर्वाधिक प्रतिरोध, उसके बाद विकर्ण और लंबाई दिशा में न्यूनतम प्रतिरोध देखा गया। यह व्यवहार कपड़े की फैलाव क्षमता और लूप विकृति से संबंधित है। बुने हुए कपड़े की संरचनात्मक बनावट ने सुरक्षा और आराम दोनों को प्रभावित किया, जहाँ साधारण बुनी हुई संरचनाओं ने मध्यम कट-प्रतिरोध और उच्च वायु पारगम्यता का संतुलित संयोजन प्रदान किया, जिससे लंबे समय तक पहनने की उपयुक्तता बढ़ी।

तापीय प्रभावों के मूल्यांकन के लिए एक पारंपरिक कट-परीक्षण उपकरण में संशोधन किया गया, जिससे नियंत्रित संपर्क ऊष्मा और विकिरण ऊष्मा के अंतर्गत कट-परीक्षण संभव हुआ; इस संशोधन के लिए एक भारतीय पेटेंट दायर किया गया है। तापमान बढ़ने के साथ यू-एच-एम-डब्ल्यू-पी-ई में तापीय नरमी और स्फटिकता में कमी के कारण कट-प्रतिरोध में गिरावट देखी गई। कांच-रेशा सुदृढ़ित कपड़ों ने ऊँचे तापमान पर बेहतर कट-प्रदर्शन बनाए रखा, क्योंकि कांच की कम तापीय चालकता ऊष्मा प्रवाह को सीमित करती है और पॉलिमर अपघटन को धीमा करती है। इसके विपरीत, स्टेनलेस स्टील सुदृढ़ित कपड़ों में अधिक ऊष्मा संचरण के कारण तापीय प्रभावों के तहत प्रदर्शन में तेजी से कमी आई।

सेवा-संबंधी प्रदर्शन का अध्ययन बार-बार होने वाले घर्षण, धुलाई, कपड़े के खिंचाव तथा बाहरी पर्यावरणीय संपर्क के माध्यम से किया गया। बार-बार घर्षण और धुलाई से सभी कपड़ों में कट-प्रतिरोध में क्रमिक गिरावट देखी गई, जहाँ स्टेनलेस स्टील सुदृढ़ित नमूनों ने बेहतर घर्षण स्थायित्व प्रदर्शित किया, जबकि कांच-रेशा सुदृढ़ित नमूनों में यांत्रिक घिसाव के दौरान भंगुर टूटन देखी गई। कपड़े के खिंचाव से लूप विकृति और ऊर्जा अवशोषण में कमी के कारण कट-प्रतिरोध घटा। बाहरी पर्यावरणीय संपर्क से रासायनिक और यांत्रिक अपघटन हुआ, विशेष रूप से स्टेनलेस स्टील सुदृढ़ित कपड़ों में, जहाँ जंग-प्रेरित

ऑक्सीकरण के कारण यू-एच-एम-डब्ल्यू-पी-ई का क्षरण बढ़ा, जबकि कांच-रेशा सुदृढ़ित कपड़ों ने बेहतर पर्यावरणीय स्थिरता प्रदर्शित की।

इस शोध प्रबंध के निष्कर्ष बुने हुए कट-प्रोटेक्टिव वस्त्रों के लिए संरचना–गुण–प्रदर्शन के स्पष्ट संबंध स्थापित करते हैं और विशिष्ट औद्योगिक सेवा परिस्थितियों के आधार पर यार्न सुदृढ़ीकरण, कपड़े की संरचना तथा सुरक्षा रणनीतियों के चयन हेतु व्यावहारिक दिशा-निर्देश प्रदान करते हैं। यह कार्य टिकाऊ, आरामदायक और अनुप्रयोग-उन्मुख कट-प्रोटेक्टिव वस्त्र प्रणालियों के विकास में योगदान देता है तथा वास्तविक उपयोग परिस्थितियों को बेहतर रूप से दर्शाने वाली परीक्षण पद्धतियों के विकास का समर्थन करता है।

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## List of Abbreviations

| Terms | Abbreviations |
|---|---|
| Ultra-high molecular weight polyethylene | UHMWPE |
| Relative humidity | RH |
| Polyethylene terephthalate | PET |
| Polypropylene | PP |
| Personal protective equipment | PPE |
| Poly(p-phenylene benzobisoxazole) | PBO |
| American society for testing and materials | ASTM |
| International organization for standardization | ISO |
| European norm | EN |
| Tomodynamometer | TDM |
| Stainless-steel | SS |
| Corrected cut-through distance | CCTD |
| X-ray diffraction | XRD |
| Fourier transform infrared spectroscopy | FTIR |
| Differential scanning calorimetry | DSC |
| Scanning electron microscope | SEM |
| Courses per inch | CPI |
| Wales per inch | WPI |
| Water vapor transmission rate | WVTR |
| Moisture management tester | MMT |

| | |
|---|---|
| Air quality index | AQI |
| Polyurethane | PU |
| IR | Infrared |