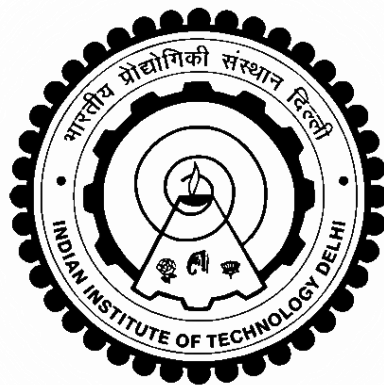


**STUDY ON SHAPE MEMORY FILAMENT INTEGRATED
KNITTED FABRICS**

PRIYANKA GUPTA



DEPARTMENT OF TEXTILE AND FIBRE ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

October 2022

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by

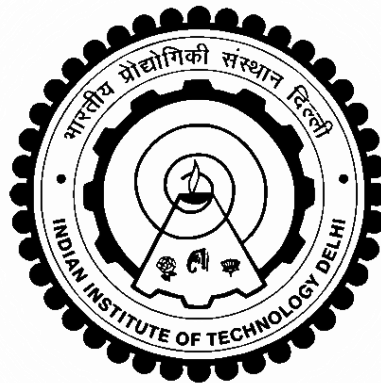
PRIYANKA GUPTA

Department of Textile and Fibre Engineering

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

October 2022

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DEDICATED TO MY PARENTS

In loving memory of my

Uncle (Late Mr. Shri Krishna Gupta)

and

Grandfather (Late Mr. Ram Asrey Gupta)

CERTIFICATE

This is to certify that the thesis entitled “**Study on Shape Memory Filament Integrated Knitted Fabrics**”, being submitted by **Ms Priyanka Gupta** 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 her. Ms Priyanka Gupta has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis which has attained the standard required for a Ph.D. degree of this institute.

The results contained in this thesis are original and 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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Date: 27/10/2022

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Priyanka Gupta

Abstract

Shape memory polymers (SMPs) and their composites are widely explored by researchers due to a wide range of potential applications in civil, aviation, transport, textile, biomedical, sensor, actuator, etc. SMPs possess a unique ability, known as the *shape memory effect*, through which they can fix a temporary configuration from its original configuration via a suitable programming process, and the original configuration can be recovered from the temporary one in the presence of external stimuli such as heat. SMPs have demonstrated innovative applications in textiles such as intelligent curtains, self-fitting garments, wrinkle-free garments, compression garments, smart fashion, patterning, etc. Most research in shape memory textiles has been done by coating and finishing methods. Minimal scientific attention has been received to develop the SMP fabrics by incorporating memory filament in the fabric structure. Particularly, knitted-based SMP textiles could allow large deformation characteristics, more suitable for pliable or extensible systems. But limited understanding is available for describing and predicting the performance of SMP filament in a knit construction under different thermo-mechanical conditions. Moreover, knitting offers tremendous design possibilities to control the fabric's mechanical behaviour and rigidity by employing various stitches, i.e., loop, tuck, and float in a knit design. Examining the performance of different memory knit fabrics would further help in designing and optimising SMP textiles with enhanced shape memory results.

Henceforth, the present study aims to design different memory knitted fabrics using SMP filaments and quantify their shape memory properties under different thermo-mechanical conditions. SMP knitted fabrics are produced by integrating the SMP filaments into double jersey construction using the weft knitting technique. Different knit structures are

systematically developed by varying stitch elements, loop, tuck, and float in the fabric construction. The response of SMP filament and knit structural characteristics on the memory outcome of SMP fabrics are investigated. Several thermo-mechanical parameters, including temperature, strain, and relaxation time, on the memory behaviour of SMP fabrics are thoroughly investigated and compared with the pristine SMP filament. The findings indicate poor response of rib-based SMP fabric compared to SMP filament at various temperatures and strains. Including more tuck or float elements in the structure resulted in more shape fixity of SMP fabrics. Relaxation time during shape fixing is found to be a critical parameter influencing the shape fixity of SMP fabric. The results could help in setting optimal thermo-mechanical conditions for SMP textiles to obtain maximum shape memory performance. This research will further improve understanding of the designing and engineering of SMP fabrics to extend their applications in responsive garments, compression stockings, artificial muscles, soft skins, massage devices, and flexible sensors/actuators.

सार

मानवीय, उड्डयन, परिवहन, कपड़ा, जैव चिकित्सा, संवेदक, प्रवर्तक, आदि में संभावित अनुप्रयोगों की एक विस्तृत श्रृंखला के कारण आकार स्मृति बहुलक (एसएमपी) और उनके सम्मिश्र का व्यापक रूप से शोधकर्ताओं द्वारा पता लगाया जाता है। एसएमपी में एक अद्वितीय क्षमता होती है, जिसे आकार स्मृति प्रभाव के रूप में जाना जाता है। जिसके माध्यम से वे एक उपयुक्त प्रोग्रामिंग प्रक्रिया के माध्यम से अपने मूल विन्यास से एक अस्थायी विन्यास में परिवर्तित हो सकते हैं, और मूल विन्यास को बाहरी उत्तेजना जैसे गर्मी की उपस्थिति में अस्थायी विन्यास से पुनर्प्राप्त किया जा सकता है। एसएमपी ने वस्त्रों में अभिनव अनुप्रयोगों का प्रदर्शन किया है जैसे स्मार्ट पर्दे, स्व-फिटिंग वस्त्र, शिकन/सिकुड़न मुक्त वस्त्र, संपीड़न वस्त्र, स्मार्ट पोशाक/वेश-भूषा, फैशन, विभिन्न आकृति (पैटर्निंग) इत्यादि। आकार स्मृति वस्त्रों में अधिकांश शोध लेप/ आवरण और परिष्करण विधियों द्वारा किया गया है। वस्त्र संरचना में स्मृति तंतु/रेशे को शामिल करके एसएमपी वस्त्र को विकसित करने के लिए न्यूनतम वैज्ञानिक ध्यान दिया गया है। विशेष रूप से, बुना हुआ एसएमपी वस्त्र बड़ी विरूपण विशेषताओं का प्रदर्शन कर सकता है, जो व्यवहार्य या विस्तारणीय निकाय के लिए अधिक उपयुक्त है। लेकिन विभिन्न ऊष्म-यांत्रिक स्थितियों के तहत एक बुनाई द्वारा निर्मित कपड़े में एसएमपी तंतु/रेशे के प्रदर्शन का वर्णन और भविष्यवाणी करने के लिए सीमित समझ उपलब्ध है। इसके अलावा, बुनाई (निट) के लिए विभिन्न टांके, यानी, लूप, टक, और फ्लोट द्वारा एक बुनी हुई रचना में नियोजित करके कपड़े के यांत्रिक व्यवहार और कठोरता को नियंत्रित करने के लिए जबरदस्त संरचनाओं की संभावनाएं प्रदान करता है। विभिन्न स्मृति निट वस्त्र के प्रदर्शन की जांच करने से एसएमपी वस्त्र को बेहतर आकार स्मृति प्रभाव के परिणामों के साथ बनाने और अनुकूलित करने में मदद मिलेगी।

वर्तमान अध्ययन का उद्देश्य एसएमपी तंतुओं का उपयोग करके विभिन्न स्मृति निट वस्त्रों का निर्माण करना और विभिन्न ऊष्म-यांत्रिक स्थितियों के तहत उनके आकार स्मृति गुणों को निर्धारित करना है।

एसएमपी निट वस्त्र एसएमपी तंतुओं को वेफ्ट निटिंग तकनीक का उपयोग करके डबल जर्सी निर्माण में एकीकृत करके उत्पादित किया जाता है। कपड़े के निर्माण में अलग-अलग सिलाई तत्व, लूप, टक और फ्लोट द्वारा अलग-अलग संरचनाएं व्यवस्थित रूप से विकसित की जाती हैं। एसएमपी तंतु की प्रतिक्रिया और एसएमपी वस्त्र के स्मृति परिणाम पर निट संरचनात्मक विशेषताओं की जांच की जाती है। एसएमपी वस्त्रों के स्मृति व्यवहार पर तापमान, तनाव और विश्राम समय सहित कई ऊष्म-यांत्रिक मापदंडों की पूरी तरह से जांच की जाती है और इसकी तुलना मूल एसएमपी तंतु से की जाती है। प्राप्त हुए निष्कर्ष विभिन्न तापमानों और तनावों पर एसएमपी तंतु की तुलना में रिब-आधारित एसएमपी वस्त्र की खराब प्रतिक्रिया का संकेत देते हैं। संरचना में अधिक टक या फ्लोट तत्वों को शामिल करने से एसएमपी वस्त्रों की अधिक आकार स्थिरता प्राप्त हुई। आकार स्थिरीकरण के दौरान विश्राम समय एसएमपी वस्त्र के आकार की स्थिरता को प्रभावित करने वाले एक महत्वपूर्ण मापदंड के रूप में पाया गया। अधिकतम आकार स्मृति प्रदर्शन प्राप्त करने के लिए एसएमपी वस्त्रों के लिए इष्टतम ऊष्म-यांत्रिक स्थितियों को स्थापित करने में परिणाम मदद कर सकते हैं। यह शोध एसएमपी वस्त्रों की डिजाइनिंग और इंजीनियरिंग की समझ को और बेहतर करेगा ताकि क्रियाशील वस्त्र, कंप्रेशन स्टॉकिंग्स, कृत्रिम मांसपेशियां, मुलायम आवरण, मालिश उपकरण और लचीले संवेदक/प्रवर्तक में एसएमपी तंतुओं के अनुप्रयोगों का विस्तार किया जा सके।

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List of Abbreviations

Terms	Abbreviations
Stimulus-responsive material	SRM
Shape memory material	SMM
Shape memory alloy	SMA
Shape memory polymer	SMP
Shape memory effect	SME
Polyurethane	PU
Shape memory polyurethane	SMPU
Polyester	PET
Nickel-titanium	NiTi
Glass transition temperature	T_g
Melting temperature	T_m
Transition temperature	T_s
Deformation temperature	T_d
Poly (ϵ -caprolactone)	PCL
Polyethylene glycol	PEG
Poly (tetramethylene) glycol	PTMG
Poly (ethylene adipate)	PEA
1,6-hexane diisocyanate	HDI
4,4'-diphenylmethane diisocyanate	MDI
2,4-toluene diisocyanate	TDI
1,4-butane diisocyanate	BDI
Isophorone diisocyanate	IPDI

Carbon nanotube	CNT
Carbon nanofiber	CNF
Dimethylol dihydroxyethyleneurea	DMDHEU
Poly(1,6-hexamethylene adipate) diol	PHA
Polytetrafluoroethylene	PTFE
Parts per million	ppm
Thermogravimetric analysis	TGA
Differential scanning calorimetry	DSC
Derivative thermo-gravimetric	DTG
Fourier transform infrared spectroscopy	FTIR
Nuclear magnetic resonance	NMR
Wide-angle X-ray diffraction	WAXD
Attenuated total reflection	ATR
Scanning electron microscopy	SEM
Course per inch	CPI
Wales per inch	WPI
Standard linear solid	SLS