Shape Memory Materials and its Use in the Textile Industry

Mrunmayee Lingayat, Assistant professor Nikhila Rane

Abstract:

Shape memory materials (SMMs), including shape memory alloys (SMAs) and shape memory polymers (SMPs), possess the remarkable ability to retain and recover significant programmed deformations triggered by external stimuli. This paper explores the utilization of SMAs and SMPs in developing smart textiles, discussing their applications and advancements in various textile sectors. Additionally, recent research on the integration of SMAs and SMPs into fabric structures for responsive textiles is examined, highlighting their potential for enhanced functionality and performance.

Keywords:

Shape memory materials (SMMs), Shape memory alloys (SMAs), Shape memory polymers (SMPs), Smart textiles, Wearable devices, Fabric integration, Responsive textiles.

Introduction

Shape memory materials (SMMs) are intelligent substances capable of retaining and recovering significant programmed deformations when triggered by an external stimulus. These materials find applications in textiles, utilizing either alloys or polymers. In 1932, Arne Oelander discovered that an AuCd alloy could undergo deformation while cold and return to its original form when heated. Shape memory polymers were discovered later than alloys, originating in France and subsequently commercialized by Nippon Zeon Co. in Japan in 1984. Both alloys and polymers have gained traction in the development of shape memory smart textiles, finding diverse applications across various textile sectors. Prior to delving into shape memory textile applications, it is essential to grasp a deeper understanding of the workings of alloys and polymers. [7, 19]

Shape memory polymers (SMPs) belong to a category of smart materials capable of temporarily fixing a programmed shape and then reverting to their original shape when exposed to external stimuli. These unique properties make SMPs ideal for developing smart textiles by incorporating them into fabric structures. Various types of stimuli-responsive SMPs, including thermal, light, pH, and moisture-sensitive variants, have been utilized in textiles to enhance or achieve smart functionalities. The integration of SMPs into fabric brings forth several fascinating and improved properties such as enhanced aesthetic appeal, comfort, soft display, controlled drug release, fantasy design, wound monitoring, smart wetting properties, and protection against extreme environmental conditions. In this chapter, we explore different types of SMPs used for this purpose, their functions, and their applications in textiles, along with discussing their potential future applications [16,20].

Shape Memory Polymers (SMPs) are materials that can be deformed and then revert back to their original shape when stimulated, such as by heat or light. They possess the unique ability to transition from a temporary shape, obtained through deformation, back to their permanent shape when the stimulus is applied. Various stimuli, including heat, light, infrared radiation, immersion in water, and the application of electric or magnetic fields, have been employed to trigger this shape recovery process in SMPs.[18].

Recent advancements in smart materials have inspired researchers to innovate textile products for diverse applications. Utilizing the potential of intelligent materials like Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs) in wire and filament forms, we're integrating them into fabric structures to develop Responsive Textiles. This integration enables fabrics to dynamically respond to external stimuli such as temperature changes, mechanical stress, or electric fields. These Responsive Textiles offer opportunities for shape-changing abilities, self-healing properties, and adaptive functionalities. With applications spanning apparel, medical textiles, automotive textiles, and smart home solutions, Responsive Textiles promise enhanced comfort, safety, and functionality for users.[6].

Shape memory alloys (SMAs) constitute a unique class of alloys with distinctive properties. They possess the remarkable ability to retain their shape at high temperatures, transitioning to a modified shape at lower temperatures within their transition domain, and reverting to their original shape upon heating—a phenomenon known as the one-way shape memory effect. Additionally, SMAs exhibit two other noteworthy properties: super elasticity and damping capabilities, which can be combined to varying degrees with the one-way shape memory effect. To explore the adaptability of SMA wires, specifically Nitinol mesh, in weaving operations compared to stainless wire, and to investigate their potential applications in composite structures, SMA wires were manufactured into technical fabric. Various tests have been conducted or are planned to assess the effects of the weaving process and to measure the efficiency of damping and shape modification capabilities.[4].

Shape Memory Alloys (SMAs) are smart materials that can remember and return to a specific shape when deformed under stress or heat. Nitinol (NiTi) is a common SMA composed of nickel and titanium, exhibiting two crystalline phases: Martensite and Austenite. Nitinol can be shaped into wires, tubes, plates, and springs. A unique Nitinol woven fabric has been developed, and the main goal is to predict its apparent elastic modulus. Heat treatment and aging were conducted on the wire and fabric, affecting transformation temperatures. Testing showed that the proposed analytical model had an average error of 6.45%, making it useful for designing woven Shape Memory Alloy fabrics.[14]

Shape memory alloys (SMAs) have the unique ability to return to their original shape when heated, making them ideal for wearable devices. However, traditional heating methods like direct Joule heating have issues like instability and high-power consumption. This research proposes using silver paste for heating, which reduces power consumption. Coating the fabric with carbon nanotubes ensures uniform heating. The study shows that this method achieves higher temperatures with less power and improves heating stability, making SMAs more viable for wearable actuators.[8].

Manufacturing process

Shape memory alloys

In today's advanced and competitive technology landscape, there are multiple processing methods available for different materials. These methods vary in manufacturing, usage, economics, and efficiency. Similarly, for shape memory alloys, various processing methods exist, each with its own challenges such as maintaining shape memory effect, adjusting mechanical properties, and dealing with microstructural changes. Processing can include melting, powder metallurgy, mechanical, and thermo-mechanical methods. Pre-processing steps, like collecting raw materials, cleaning, sizing, and preparing powder forms, are crucial for accurate and efficient production.

Melting route

The melting route for processing shape memory alloys is divided into four methods: Vacuum Induction Melting, Selective Laser Melting, Electron Beam Melting, and Plasma Melting. Vacuum Induction Melting, conducted in graphite crucibles, is a key method for producing Ni-Ti alloys. Its precise temperature control and environmentally friendly process enable close compositional tolerances, leading to increased metal production. Selective Laser Melting is utilized for shaping alloys like Ni-Ti, Cu-Al-Ni-Mn, Fe-Mn-Al-Ni, and Al-Fe-V-Si. This process creates porous shape memory alloys with improved properties, facilitated by its scanning pattern that minimizes distortion during fabrication. Electron Beam Melting employs a layer-by-layer material addition technique using an electron beam in a vacuum chamber. It results in NiTi material with a more uniform chemical composition and reduced carbon and oxygen contamination compared to Vacuum Induction Melting. Plasma Melting prevents contamination by graphite electrodes and achieves homogeneous material composition through high energy concentration, rapid heat transfer, and plasma burner usage instead of electrodes.

Powder metallurgy

Powder metallurgy processing is a method where metal powder is used to create final products without material loss. Ni-Ti, Cu-Al-Ni-Mn, and Fe-Mn-Si-Cr-Ni shape memory alloys are processed using techniques like conventional sintering, hot isostatic pressing, and metal injection molding. Hot isostatic pressing, also called pressure-enhanced sintering, improves density and reduces porosity, addressing a major issue in conventional sintering for shape memory alloys. Sintering involves compacting and forming material with heat or pressure without melting it, commonly used for Nitinol. Factors like applied pressure, diffusion imbalances, shrinkage, and capillary forces affect porosity formation in Nitinol sintering. Metal injection molding, akin to plastic injection molding, consists of feedstock fabrication, injection molding, debinding, and sintering. It offers precise geometrical parts, high production rates, and low costs, making it suitable for NiTi fabrication, especially in biomedical applications.

Mechanical processing

Mechanical processing involves material deformation through mechanical loading, altering its properties. Techniques like equal channel angular extrusion, cold forging, cold rolling, and cold drawing are utilized for shaping shape memory alloys. Equal channel angular extrusion induces severe plastic deformation via high axial pressure, offering benefits like uniform microstructure and control over grain morphology, crucial for shaping NiTi alloys. Cold forging mechanically deforms material without heating, potentially benefiting from a small oxide layer to absorb applied load and protect the underlying material. Cold rolling applies compressive forces via two rollers, leading to nanostructured microstructures in shape memory alloys like NiTi after subsequent annealing, enhancing shape memory and mechanical properties. Cold drawing elongates shape memory alloy rods or wires by pulling them through a die, resulting in elongated grains. The use of lubricants or protective layers is recommended to improve finishing and processing.

Thermo-mechanical

Thermo-mechanical processing combines mechanical deformation with thermal effects. Methods like friction stir processing, hot forging, and hot rolling fall under this category. Friction stir processing achieves solid-state fabrication, allowing for homogeneous distribution of NiTi powder in aluminum matrix by controlling process parameters. Hot forging deforms materials using heat and forging force to shape them. Ni-Mn-Ga shape memory alloy exhibits excellent shape memory effects with favorable hot forging parameters. Hot rolling involves heating materials and pressing them with rollers. Control over parameters like heating temperature, pulling tension, lubricant type, and number of passes is crucial for shaping shape memory alloys and ensuring desired mechanical properties.[21]

Shape Memory Polymer

Shape memory in polymers offers remarkable versatility, with activation methods including heat, electric current, force application, light radiation, and hydration. This adaptability extends to both thermoplastic and thermosetting polymers, utilizing various structures like crosslinked polymers, block copolymers, blends, or IPNs (Interpenetrating Polymer Networks), often reinforced with fibers. Though diverse in structure and activation mechanisms, commonly used shape memory systems are typically copolymers or crosslinked types, with thermal activation being predominant. In thermal activation, a material's behaviour is characterized by a "switch" temperature between phases. For instance, a material with a switch temperature of 60°C can deform into its temporary form when heated above this temperature and revert to its original shape when cooled below it. The presence of two phases, one with a higher transition temperature (the "hard phase") and the other with a lower transition temperature (the "soft phase"), allows for the existence of temporary and permanent forms. The temporary form, often associated with an amorphous phase, undergoes modification above its glass transition temperature but below the transition temperature of the permanent phase. After molding, cooling below the temporary temperature fixes the temporary shape, and reheating initiates a rapid return to the original form. Although theoretically repeatable, repeated cycling may lead to a loss of recovery of the permanent form over time.[22]

Applications

Application of Shape Memory Polymer

Thermally Formable Yarn:

Luxion Industries NV and Massebeuf have developed a novel substance called thermo-formable yarn. This innovative polymer, when spun into a monofilament, adopts a bi-stable nature, transitioning between flexibility and rigidity upon activation. It can be incorporated into clothing by weaving or knitting into yarn. Remarkably, the thermo-formable yarn softens upon heating for approximately a minute at 65°C, and then stiffens upon cooling. Furthermore, it can be reshaped by reheating.[9].

Comfort Fitting Footwear:

A dynamic shoe last, crafted from shape memory polymer (SMP) material, is revealed for comfort fitting footwear. This innovative SMP footwear last can be adjusted repeatedly to transform into any size and shape accurately and reliably. This feature significantly reduces the total inventory of footwear lasts required at a footwear manufacturing facility, offering greater efficiency and flexibility in production processes.[9]

Damping Fabrics:

Fabrics that excel at absorbing energy include Shape Memory Polymers (SMPs), thanks to their superior damping characteristics, especially around their glass transition temperature (Tg). Allied Signal Inc. developed automotive seatbelt fabric using SMP fibers known as Securus fibres, effectively enhancing passenger safety by absorbing kinetic energy during accidents. These fibers, made from shape memory poly (ethylene terephthalate)-poly (caprolactone) block copolymers, are reported to absorb energy from the body's forward motion, thus enhancing safety.[9].

Self-adaptability of Shape:

SMP fibers are utilized to create self-adaptive textiles capable of managing structural changes in response to environmental temperature fluctuations. While a fiber's shape memory effect (SME) typically involves changes in length, when incorporated into fabrics, SMP fibers can exhibit various shape changes, including bending, shrinkage, and thickness growth, dictated by the fabric's structure. Clothing made from SMP fibers can adapt appropriately to accommodate the wearer's body, as demonstrated by vertical pressure testing, which indicates lower vertical tension stress compared to elastic fiber-made clothing. This is attributed to the SMP fibers' ability to deform and assume temporary shapes, thereby reducing unwanted pressure on the wearer.[9].

Deodorant Fabrics:

Special fabrics with the ability to release deodorant agents at specific temperatures are created by coating a stimuli-responsive polymeric hydrogel onto the textile surface. This hydrogel is attached to the fabric through chemical cross-linking using a functional monomer like acrylamide and a cross-linking agent such as 2-(diethylamino) ethyl acrylate. Deodorant is typically incorporated into the hydrogel during or after the cross-linking process. β-cyclodextrin, which has a hydrophobic interior cavity and a hydrophilic external surface, is often loaded with the polymeric gel to further enhance controlled release properties. While some body-responsive deodorant hydrogel products are available on the market, the full potential of deodorant fabrics remains underexplored. Issues such as maintaining softness and product stability need to be addressed for further development. Controlling the hydration level of the product in open environments is another crucial factor to consider.[9].

Wound-dressing Products

Chitin and chitosan derivatives are widely employed in the fabrication of wound dressing products due to their excellent antibacterial and wound-healing properties. Chitosan hydrogel, for instance, aids in restoring skin architecture, making it an effective wound dressing material. Additionally, chitosan-treated alginate filaments and cotton fabric have been created for advanced wound dressings. Apart from chitin and chitosan, various biopolymer-based hydrogel products have also been developed for wound dressing applications. These smart wound dressing materials can offer a novel drug release system that responds to changes in pH or temperature, thereby promoting quicker wound healing.[9].

Breathable Fabrics:

Shape memory polyurethanes (SMPUs) are utilized for creating breathable fabrics. The water vapor permeability (WVP) of SMPUs can be adjusted according to the wearer's body temperature. Incorporating hydrophilic segments like dimethylpropionic acid and diol-terminated poly (ethylene oxide) in SMPUs can significantly enhance their WVP. Additionally, forming microfoams in SMPUs can notably improve their overall WVP.[13].

Fabric Finishing:

Thermo-responsive SMPs find utility in textile finishing for apparel. Wrinkle-free, crease-retaining, anti-shrinkage, and visually dynamic textiles are produced by applying SMPs onto fabrics. Studies have shown that cotton fabrics treated with SMP exhibit superior wrinkle-free properties. Cotton fabrics treated with SMPU can quickly return to their original flat shape (wrinkle-free) within a minute when exposed to steam. SMP-treated fabrics retain good crease and pattern retention abilities, resulting in an aesthetically pleasing appearance.[13].

Ergonomic Textiles:

Violins made from a combination of shape memory polymer and carbon fibers utilize a specific SMP known as "Veriflex". This design aims to reduce neck and shoulder pain for the player by allowing the material to be reshaped as desired.[13].

Other applications

Shape memory textiles find applications in various fields due to their unique properties. They serve as actuators, making them valuable in soft robotics, where they can replace electric actuators by using stimuli-responsive shape memory materials. In smart clothing, they enable the adjustment of fabric dimensions or orientations, allowing for tailored pressure on the body, useful in sports and wound care. They can also control air and water vapor permeability or enhance crinkle recovery in garments. In biomedical applications, shape memory textiles are used in devices like stents, which can be inserted into the body in a compact shape and then expanded at the desired location. Overall, shape memory textiles offer innovative possibilities in textile and clothing design, opening up new avenues for creativity and functionality.[5].

Temperature-Dependent Shape-Memory Textiles

This review delves into recent progress and challenges surrounding intelligent fabrics, focusing particularly on temperature-dependent shape-memory metamaterials. The potential impact of innovative smart textile materials on augmenting the overall functionality and usefulness of traditional fabrics is considerable, especially within fields like medical devices, fashion, entertainment, and defence. A key consideration in these applications is ensuring user comfort to encourage widespread adoption of wearable devices. The development of smart textile devices requires a multidisciplinary approach, combining expertise in circuit design, knowledge of smart materials, proficiency in microelectronics, and a deep understanding of chemistry and textile manufacturing processes. Synergy across these diverse fields is crucial for unlocking the full potential of smart fabrics and facilitating their widespread use. Embracing this comprehensive approach holds the promise of groundbreaking advancements in smart textile technology, fostering innovation and progress in the field.[12].

Self-sensing shape memory polymer

In this study, a thermally reduced graphene oxide coated glass fabric (TRGO-GF) was utilized as both a sensing element and reinforcement in the production of a thermo-responsive polyurethane-based self-sensing shape memory polymer composite (SSMPC). This novel composite was shown to possess the ability to detect changes in temperature and shape recovery simultaneously, rendering it applicable in various scenarios. To demonstrate the temperature sensing capability of the manufactured SSMPC, as well as the correlation between temperature and electrical resistance, heating and cooling cycles were induced using a heating film attached to the sample. The experiments confirmed that the SSMPC could detect temperature variations occurring within the composite. Specifically, the SSMPC exhibited a negative temperature coefficient (NTC) of resistance, measuring -14.80 × 10^-3 (°C)^-1 and -7.25 × 10^-3 (°C)^-1 for testing regimes I (30–40 °C) and II (40–50 °C) respectively. Furthermore, experiments demonstrated the SSMPC's ability to monitor the recovery ratio and rate of shape recovery during the thermally induced shape recovery process. It was revealed that the extent and rate of shape recovery could be controlled by manipulating the thermal stimulus.[1].

Thermal-moisture

Maintaining optimal thermal and moisture levels has become a fundamental human need, significantly impacting comfort. Personal thermal-moisture management textiles play a vital role in regulating the microenvironment of the skin, enhancing overall comfort. However, conventional thermal-moisture management fabrics typically have static structures or functions, lacking the ability to adapt to real-time environmental changes. Active fabrics, on the other hand, possess the capability to dynamically respond to environmental stimuli, offering promising prospects in intelligent thermal-moisture management. Among active fabrics, shape memory active fabrics stand out as they can sense external stimuli and adjust their morphology or structure accordingly, presenting significant advantages. This review focuses on shape memory active thermal-moisture management fabrics, providing insights into the mechanisms of shape memory and thermal-moisture management. It also summarizes research findings and applications of related textiles. Furthermore, the review identifies existing challenges and envisions future developments, including enhancing shape memory properties, exploring multimodal thermal-moisture management approaches, and integrating multidisciplinary technologies. These advancements are expected to enable smart textiles with substantial potential in enhancing personal comfort, developing intelligent wearable devices, and more.[17].

Temperature and moisture responsive

Recently, there's been a push for clothing that's not only comfortable but also adapts to changing conditions, especially in sports and functional wear. Researchers developed a new treatment using shape memory polyurethane and cellulose nanowhiskers, applied to polyester fabric. This treatment creates smart fabric that responds to both moisture and temperature changes. Tests showed improved breathability, sweat absorption, and durability, making it ideal for sports clothing with enhanced comfort and performance.[10].

Temperature stimulating the study explores using temperature-responsive shape memory polyurethane (SMPU) for smart breathable clothing. It delves into the principle behind temperature-stimulating polymers and investigates the shape memory behaviour of SMPU in relation to its temperature-sensitive water vapor permeability, crucial for smart clothing. Comparisons were made between the water vapor permeability of SMPU and regular polyurethane (PU). Results showed a temperature-sensitive change in water vapor permeability at the phase transition temperature of SMPU, unlike ordinary PU. The study suggests potential applications of temperature-stimulating SMPU in creating smart breathable textiles.[11].

Application of Shape Memory Alloys

Applications of Shape Memory Alloys

Shape memory alloys (SMAs) find diverse applications across various industries due to their unique properties. Some notable applications include: Biomedical Engineering, Aerospace Engineering, Robotics and Automation, Consumer Electronics, Automotive Industry, Civil Engineering and Infrastructure and lastly

Textile industry: Innovations in the textile industry include the integration of shape memory alloys (SMAs) into fabrics to create shape-changing garments. Smart clothing embedded with SMAs can dynamically adapt to temperature changes, providing wearers with enhanced comfort in various environments.[2].

Application to Soft Grippers

In recent years, there has been a growing interest among researchers in developing soft robotic grippers capable of handling delicate or irregularly shaped objects without causing damage. This study introduces a novel approach utilizing a smart textile-composite actuator for such grippers. The actuator is crafted by combining an active fiber with an inactive fiber through knitting techniques. The active fiber, made of a shape memory alloy (SMA), is wrapped around conventional fibers, while the inactive fiber is a standard knitting yarn. This combination results in a flexible textile structure with excellent shape retention and high compliance, making it ideal for constructing soft grippers. The driving force behind the actuator is the SMA wire, which undergoes deformation when heated due to its shape memory properties. Through experimentation, the study investigates various factors such as the ratio of course-to-wale, the number of bundled SMA wires, and the required driving current to achieve maximum actuator deformation. To construct the soft robotic gripper, three of these actuators are stitched together to form each finger. Research on layer placement is conducted to determine the optimal bending angle for grasping objects. Finally, the gripping performance of the gripper is evaluated by testing its ability to grasp objects of different shapes, demonstrating its successful handling of flat, spherical, and uniquely shaped items.[15].

The latest research in protective clothing design focuses on integrating smart materials to enhance protective performance. This paper presents findings on a smart textile material incorporating shape memory alloys (SMAs) and its resistance to thermal factors such as flames, radiant heat, and molten metals. Laboratory tests revealed significant improvements in resistance: Resistance to Radiant Heat: The application of SMA elements led to over a twofold increase in resistance, with a Radiant Heat Transfer Index (RHTI24) of 224 seconds. This improvement was observed with a thickness increase of 13 mm, with the sample positioned vertically under load. Resistance to Flames: The resistance to flames increased to 41 mm when the sample was positioned vertically without any load. Resistance to Molten Metal: The resistance to molten metal reached 17 mm when the sample was positioned horizontally. These results demonstrate the effectiveness of integrating SMAs into the textile material, significantly enhancing its protective properties against various thermal hazards.[3].

Conclusion

In conclusion, the utilization of shape memory materials (SMMs), including shape memory alloys (SMAs) and shape memory polymers (SMPs), holds immense promise in the field of smart textiles. These materials offer unique properties such as the ability to retain and recover programmed deformations in response to external stimuli. Through advancements in fabric integration and research into responsive textiles, SMAs and SMPs are poised to revolutionize various textile sectors. The integration of SMAs and SMPs into fabric structures enables the development of smart textiles with enhanced functionality and performance. From wearable devices to medical textiles, automotive textiles, and beyond, the applications of shape memory materials are diverse and far-reaching. By incorporating SMAs and SMPs into fabric structures, responsive textiles can dynamically adapt to changes in temperature, mechanical stress, or electric fields, offering users greater comfort and convenience. Moving forward, further research and development in this field are essential to unlock the full potential of shape memory materials in textile applications. Continued exploration of fabric integration techniques, optimization of material properties, and advancements in manufacturing processes will drive innovation and expand the capabilities of smart textiles. With ongoing advancements, shape memory materials are poised to play a central role in the next generation of intelligent textiles, offering unprecedented functionality and versatility across a wide range of applications

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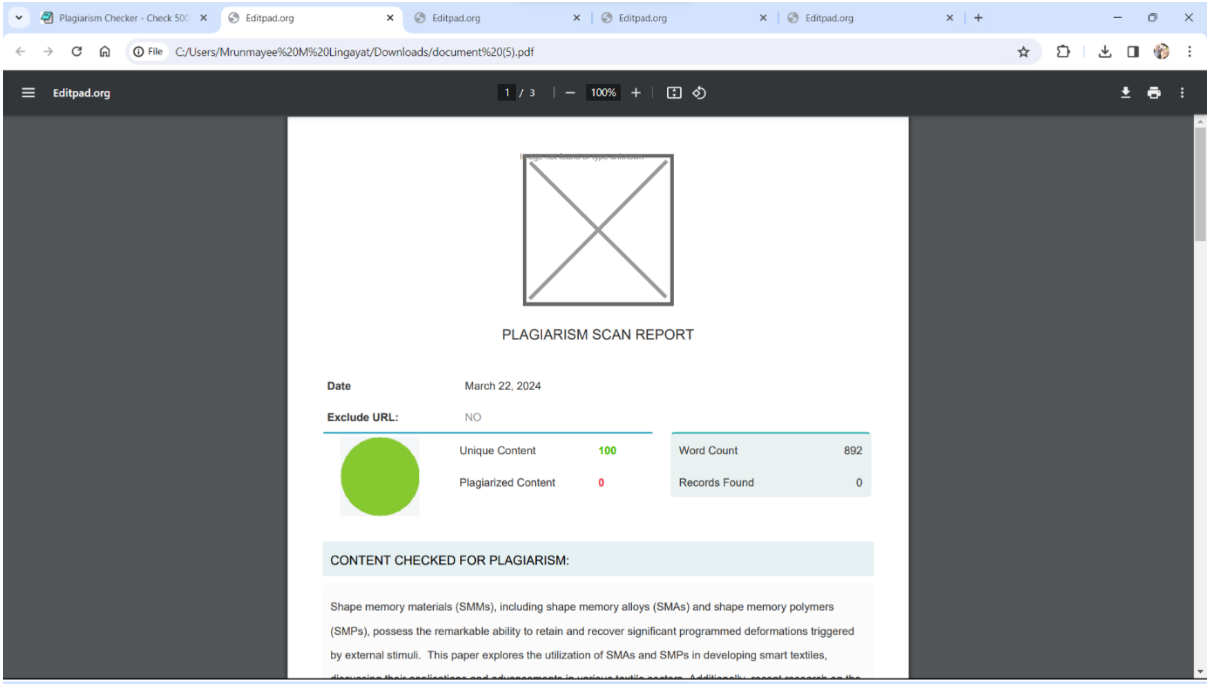

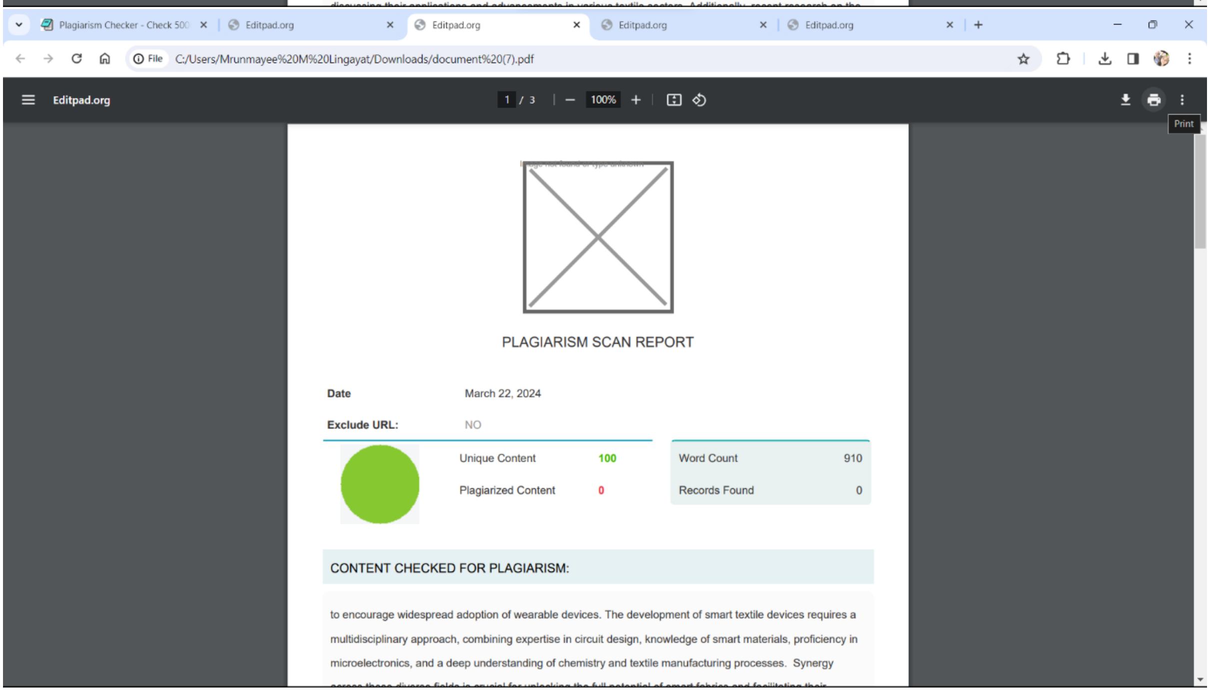

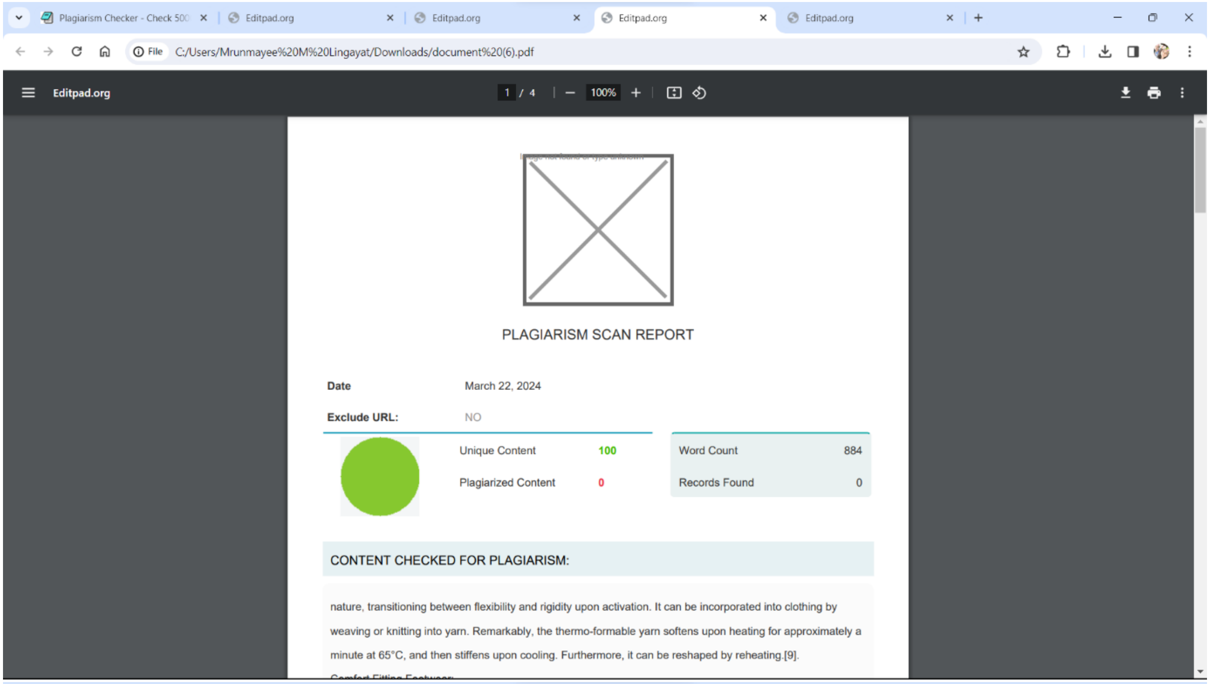
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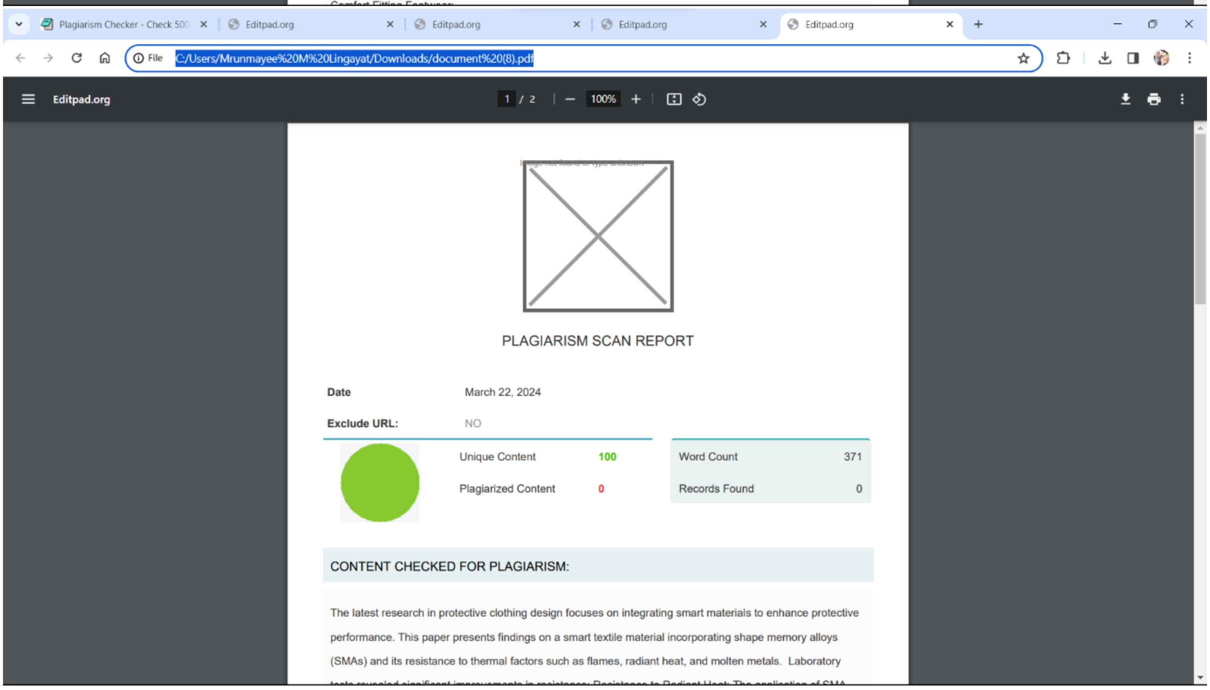
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The latest research in protective clothing design focuses on integrating smart materials to enhance protective performance. This paper presents findings on a smart textile material incorporating shape memory alloys (SMAs) and its resistance to thermal factors such as flames, radiant heat, and molten metals. Laboratory