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A review of shape memory alloy processing research, uses, and potential applications

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Abstract. Shape memory alloys (SMAs) are unique materials that can revert to a specified configuration upon exposure to thermal stimuli. When this alloy is below the transformation temperature, it demonstrates low yield strength and can be readily deformed into a new shape. Nonetheless, when the alloy experiences a temperature that surpass its transformation threshold, it alters its crystal lattice structure and reverts to its original state. The shape memory effect and pseudo elasticity of SMAs set them apart from other materials. These materials have good biocompatibility, high specific strength, outstanding corrosion resistance, great wear resistance, and exceptional anti-fatigue features due to their unique phase change. Therefore, these materials are widely used in aviation, healthcare, automobiles tubes, hot water valve controllers, the petroleum sector, actuators, sensors, miniature grippers, micro valves, pumps, landing gear systems, eyeglass frames, materials for chopper blades, sprinklers in fine alarm systems, tooth materials, and wrapping devices for electronic materials for many diverse applications. This chapter gives a general review of shape memory alloys and examines their historical applications as well as their present and potential uses. It also elucidates the concept and mechanisms of shape memory materials tailored to specific requirements. Additionally, this article delves into the physics, behaviour, and characteristics of shape memory alloys along with applications.

Keywords: Smart Materials, Shape Memory, Sustainable materials, Smart alloys

1. Introduction

The term "shape memory" was first used by Vernon in 1941 to refer to his polymeric dental material, but Arne Ölander discovered shape memory alloy (SMA), sometimes known as "smart alloy," in 1932. The importance of shape memory materials (SMMs) became evident in 1962, following the discovery of the shape memory effect (SME) in a nickel titanium (NiTi) alloy by William Buehler and Frederick Wang [1]. This alloy, better known as nitinol, is a mixture of nickel and titanium, named after its discovery location, the Naval Ordnance Laboratory. Since then, numerous business sectors have experienced an increase in the demand for shape memory alloys (SMAs) for engineering and technological use. Shape memory alloys are man-made materials with a distinctive capacity to experience induced elasticity and martensitic phase shift at elevated temperatures. These properties allow them to be significantly deformed and subsequently re-formed upon exposure to changes in stress or temperatures. The development of these specialized materials for increasing success in meeting the demands of the engineering sector [2]. These materials display an exceptional shape-memory effect along with super elasticity. SMAs are exceptionally robust, can recover from large elastic stresses (up to 8%), and can sustain large cyclic deformations (without residual strain symptoms) on a hysteretic loop. The exceptional features of SMAs are rapidly being utilized in diverse technological applications, including vibration control devices and energy dissipation in construction sector. Moreover, as due to advancements in technology, More and more components of associated machines are becoming cumbersomely heavy and bulky due to the incorporation of "Smart materials" with adaptive or inventive features, such as sensors, actuators, and micro-controllers for their adaptable and/or intelligent capabilities and features. Therefore, these materials widely used in automotive sensors and control by the integration and miniaturization of integrated micro-controllers and smart software.

2.1 Shape memory effect and Pseudo elasticity

It has recently come to light that many metal alloys display a shape memory phenomenon, which allows a distorted object to recover its original, undeformed shape when heated to a higher temperature. A martensitic phase transition essentially causes this behaviour. Atomic ordering, a crystallographic alloy reversible thermoelastic martensitic transition, and a self-accommodating martensite phase development are shared properties among the different shape memory materials.

2.2. Evolution of SMA Advancements

In 1932, Ölander, a Swedish researcher, first identified the solid phase transformation in shape memory alloys (SMA), demonstrating that gold-cadmium (Au-Cd) alloys can undergo plastic deformation [3]. It cooled and returned to its initial form upon heating. Greninger and Mooradian first observed the shape memory effect (SME) in copper-zinc alloys as well as copper-tin (Cu–Sn) alloys in 1938. The phase change effect was substantially reported over a decade later by Kurdjumov and Khandros in 1949, and subsequently by Chang and Read in 1951.Moreover, some comparable effects in other alloys, including In–Tl as well as Cu–Al–Ni, were also documented in the 1950s. Furthermore, in year 1959, Commercialization potential of shape memory alloys only emerged with William Buehler identification of the shape memory effect in the NiTi alloy. As these alloys are more cost-effective to produce, easier and safer to manage, and exhibit enhanced the mechanical characteristics compared to other shape memory alloys that were accessible at that time

2.3. Recent development in SMAs.

Shape Memory Alloys (SMAs) have experienced notable progress in recent years, expanding their applicability across multiple industries. Significant advancements such as in ultrafine and nanocrystalline shape memory alloys [4]. The production techniques for single-phase ultrafine/nanocrystalline alloys in multicomponent systems are being expanded by these materials' distinctive shape memory effects and super elastic behaviour. Moreover, advancements in Cu-based shape memory alloys (SMAs) have concentrated on improving their transformation temperatures and mechanical characteristics. The significant improvement in processing methods and compositions have enhanced their ability to perform, rendering them viable substitutes for conventional shape memory alloys in many applications. Secondly the high-temperature SMAs are future of aerospace industry. The aerospace industry is investigating high-temperature shape memory alloys for uses including morphing wings and adaptive structures.

3.Designing with SMAs

When designing shape memory alloys, the most important thing is to have reliable and effective form recovery. The material should possess the ability to undergo reversible phase transitions, allowing it to deform and subsequently return to its initial configuration. Consequently, the efficient load transfer is achieved through the strategic design of alloy composition and various surface treatments, which ensures robust bonding. Thermally sensitive SMA exhibits special properties like super elasticity and shape memory effects due to solid-solid, diffusion less phase transitions [5].The integration of sensing and actuation capabilities in these materials enables a system-level response by amalgamating many functionalities inside a singular material system.

The performance of shape memory alloys is highly influenced by the interaction between mechanical and thermal loading. The transformation temperatures for shape memory alloys (SMAs) consist of the austenite-to-martensite transformation temperature (Ms) and the martensite-to-austenite transformation temperature (As). The alloy composition and production circumstances are tailored to achieve the specified temperatures and produce the alloy suitable for its intended application. It is possible to tailor the alloy's mechanical properties to meet the needs of every given application by modifying its composition, heat treatment, and manufacturing processes.

3.1.SMA design advantages and challenges

SMA actuators present a viable technical alternative to traditional actuator types, such as electric motors, pneumatics, and hydraulics as per some recent studies in which materials such as Ni-based alloys, and Satellite alloys are used. The NiTi shape memory alloy (SMA) is an ideal option for actuator designers requiring significant displacement and force capabilities, without the need for rapid response times or high efficiency. As integration of a composite airframe with piezoelectric crystals functioning as vibration sensors and NiTi actuators for vibration mitigation exemplifies a "smart" construction approach.

A considerable proportion of designers integrate engineering effects in application development, frequently using shape memory alloys for actuation and pseudo-elasticity for vibration isolation and dampening. The two distinct pseudo-elastic behaviours of shape memory alloys effectively dampen vibrations. Non-linear behaviour facilitates isolation and significant deformation when recovery, while hysteresis behaviour dissipates energy. Shape memory alloys are capable of producing three-dimensional actuation components, including helical springs, torsion springs, straight wires, cantilever strips, and torsion tubes, which can extend, bend, twist, isolate, or combine[6]. The use of these materials can offer innovative solutions to various technical challenges. Due to its distinct benefits and downsides, it is the sole practical technological answer for complicated applications. The primary challenge lies in the limited operational frequency and narrow bandwidth of SMA materials. Moreover, low actuation frequency, poor controllability, poor precision, and poor energy efficiency are other major limitations for developing SMA applications.

4. Other forms or types of shape memory materials

Due to high manufacturing costs, limited recoverable deformation and low band width some other form of SMAs have been identified. For example, for high temperature applications, High temperature shape memory alloys (Au, Hf, Pd, Pt and Zr) are used in addition to NiTi alloys. The HTSMAs are categorized according to their martensitic transformation ranges, these can operate at temperatures over 100°C but because of their high production costs, low ductility, or poor fatigue resistance at room temperature, most of these HTSMAs are difficult to manufacture and train. Consequently, investigations into substitute, less expensive materials or compositions like copper and cobalt have been conducted. Moreover, TiNiPd, TiNiPt, NiTiHf and NiTiZr alloys are now used at 100-300°C while others face various challenges in commercial implementation. The other form of SMAs are Magnetic shape memory alloys (MSMAs), often referred to as ferromagnetic shape memory alloys (FSMAs), may actuate at elevated frequencies (up to 1 kHz) because the actuation energy is transmitted by magnetic fields, unaffected by their comparatively slow heat transfer process [7].

5. Various methods of preparation of shape memory alloys

The fabrication of shape memory alloys (SMAs) encompasses multiple critical stages, ranging from alloy selection to final processing. Shape memory alloys (SMAs), including Ni-Ti (Nitinol), copper-based alloys, and iron-based alloys, are extensively utilized in applications such as actuators, medical equipment, and aircraft components because of their distinctive capacity to "remember" its original shape when subjected to heat.

5.1 Melting

One of the most significant methods for producing SMA is vacuum melting. However, the other methods like electron beam melting and plasma melting are also used. The vacuum induction melting process operates through generating electrical eddy currents in the graphite crucible and the metallic charges while electro-dynamic force is utilized for superior stirring and mixing of the melt. The other alloys such as NiTi are melted by vacuum induction melting (VIM) in graphite crucibles, resulting in increased carbon content that generates titanium carbide (TiC) within the alloy, lowering the transformation temperature. The major advantage of VIM lies in attaining chemical composition homogeneity and the capacity to adjust the chemical composition [8]. The other process vacuum arc re-melting (VAR) eliminates carbon contamination in the alloy due to the absence of a graphite crucible, resulting in high purity. This process is categorized into two types based on the heating system. In first method, the non-consumable electrode, is favoured in laboratories and is suitable for various alloys. In this method, the raw materials to be melted are positioned in a copper Mold and subjected to irradiation by an argon arc generated from a tungsten rod electrode. Upon melting, the alloy assumes a button shape due to the effects of surface tension; this button shape is subsequently remelted multiple times to achieve a homogeneous composition.

5.2 Heat treating

To achieve optimized results NiTi samples must be cold worked before heat treatment. Upon careful analysis of extremely elastic nitinol, heat treatment can be performed at a temperature of 500°C, while for shape memory alloys, the conventional range lies between 350°C and 450°C. The unique attributes of the shape memory effect and pseudo elasticity reach their peak at a nickel composition of 55.5 wt %. At elevated temperatures, these properties are achieved via solution treatment and aging at around 400°C, during which Ni-rich phases emerge as precipitates [9].

5.3 Powder metallurgy

The powder metallurgy technique provides numerous benefits for manufacturing shape memory alloys (SMAs), such as the capacity to produce intricate geometries, accurate compositional regulation, and improved mechanical characteristics. The essential stages in the powder metallurgy production of shape memory alloys. The specified shape memory alloy composition denotes the preliminary phase. The powder size and form can be adjusted to meet the specific requirements of the final product. To augment the desired attributes of the final product and enhance processability, the shape memory alloy powder is amalgamated with supplementary powders, including lubricating or alloying elements, during this stage. To avoid contamination, blending is often conducted in a controlled setting. Various methods, including cold isostatic pressing (CIP), uniaxial pressing, and powder injection moulding, can be employed for compaction. The finished product should closely resemble a net shape.

5.4. NiTi shape memory sintering

When nickel titanium superalloys (NiTiSMAs) are heated to a certain temperature a solid object is formed [10]. This process necessitates a lower thermal input compared to mechanical properties, wherein nickel and titanium powders are amalgamated and subsequently sintered to yield the shape memory alloy, thereby offering diverse methodologies and more advantageous results. Additionally, in order to achieve the highest shape memory transformation enthalpy, the alloying process must take the thermodynamic circumstances into account. A combination of sintering temperature and DC electric charge promoted NiTi particle deformation, resulting in densified products in response to load. This has enabled the production of bulk NiTi materials showing enhanced hardness, strength, and ductility.

5.5. Self-propagating high temperature synthesis

A thermal explosion occurring at one end of a specimen leads to the initiation of powder metallurgy synthesis through auto-propagation at high temperatures. A significant exothermic reaction takes place when two powdered reactants, consisting of a primary metal and a non-metal, are combined. The exothermic reaction generates heat, which is maintained by the heatwave of combustion passing through the material at several meters every second[11].

The reaction that forms a molten or partially molten zone generates enormous heat and pressure. The material is densified, making it easier to make essential goods under pressure. The process is often used to create advanced materials like ceramics, intermetallic compounds, and composites that are challenging to manufacture using traditional processes. The process is popular due of its simplicity, fast output speeds, energy efficiency, and flexibility in manufacturing complicated structures. But regulations and measures should be established to ensure high performance and reliability of the process. Furthermore, it is feasible to conduct periodical assessments of the equipment to evaluate their reliability and integrity. Moreover, these phases substantially diminish the material's corrosion resistance, allowing it to interact with moisture and become compromised [12].

5.6. Different geometries of wire sand plates in shape memory alloys

This study utilizes information pertaining to the geometry of wires and plates. This study analyses the natural frequencies and mode forms of plates that incorporate wire-embedded shape memory alloys. The analysis demonstrates that the inclusion of SMA wires impacts the dynamic behaviour of the plate [13]. Cyclic stress evaluations of SMA sheets we have looked at the mechanical characteristics and behaviour of shape memory alloys in plate form. Shape memory alloys (SMAs) performance and reactivity are likely to be examined in relation to plate layout at different loading levels.

Shape memory alloys demonstrate unique mechanical properties, including the shape memory effect and super elasticity. The study will primarily focus on the mechanical behavior and characteristics of the Plate. Shape-memory alloys are materials that possess the distinctive capability to return to their original configuration following deformation when exposed to thermal conditions. The process is achieved by employing large plates, and the wires within the flexible cycle must demonstrate considerable potential for engineering applications. The objective of this work is to analyze the cycling response of large-sized shape memory plates during the hysteretic cycle. A more comprehensive understanding of this behavior will facilitate the optimization of plate performance in engineering design and execution. Examinations of shape memory alloys typically focus on various geometries, including wires and plates, with an emphasis on their mechanical properties and dynamic applications in practical sectors [98]. Modern methods of shape memory alloy prestressing take advantage of SMAs' unique properties to increase prestressing forces in a number of settings. The use of curved shape memory alloys for local prestressing is one of the innovative options that are currently under development. The unique form-memory effect of SMAs activates this new technology for shape memory applications, which in turn creates additional local prestressing effects in a variety of materials. One possible use of this method is to increase the prestress in concrete structures by taking use of the shape-memory effect of SMAs. This approach uses SMA reinforcement to improve a structural system's performance under continuous tensile stress by inducing prestressing effects. The active mechanism of SMA wires is mostly linked to the suspension shape memory effect and actuation. The shape memory alloy experiences a transformation when varying degrees of reversible changes between austenite and martensite crystallographic phases are induced by external stimuli, like temperature or stress. The shape memory effect in active SMA-based devices is a phenomenon where the device actively alters its properties or dimensions in response to a certain trigger, which, in this instance, is a change in temperature. The controlled phase change of SMA wires enables these devices to actuate and execute mechanical action [14]. The pseudo-elasticity characteristic of shape memory alloys (SMAs) is frequently referred to as the passive mechanism in SMA wires. As soon as the applied load is removed, the passive SMA wire reverts to its original shape, a property known as super elasticity. This remarkable quality does not require any extra energy. Shape memory alloys have outstanding mechanical properties that make them ideal for dampening and sustaining energy. In order to provide controlled actuation, SMA wires first use the shape memory effect. During active operation, by passively responding to mechanical stimuli with the help of the super elastic characteristics.

6. Selective laser melting (SLM)

The use of a laser to liquefy and the specific configuration of fused powdered SMAs are involved in SL-Min. This approach ensures that SMAs have superior mechanical properties by guaranteeing high levels of density and uniformity [15]. Applications where high strength and reliability are paramount include the aerospace and medical equipment production industries, where SLM finds widespread usage. The microstructure and shape memory response of NiTi grown by SLM are two of several variables that could affect it. Martensitic phases, which facilitate the development of SME, may be affected by the growing rate and cooling rate of solidification during the SLM. As the SLM process changes the composition, microstructure, and thermal history, the transformation temperature could change as well. The shape memory qualities can only be guaranteed with well-defined and regulated transformation temperatures. Elastic modulus, yield strength, and deformation behaviour are mechanical properties that influence the shape memory and deformation capabilities of SLM. The specified mechanical properties and SME of the material may be impacted by the circumstances of the SLM process and the structure preparation procedure. It is important to keep an eye on how surface roughness affects SMEs, particularly in applications involving sliding or contact surfaces. Additional post-processing, such as surface treatment, can reduce roughness and increase form recovery efficiency. One way to improve the shape memory response of SLMNiTi is to heat it. The microstructure and alternative phase changeover temperatures can be altered with heat treatments, which can also improve the shape memory qualities.

6.1. MelT and extrusion for layer deposition (MELD)

The MELD process represents an advanced solid-state technology employed in the 3D printing of metals. The term 'melt and extrusion for layer deposition' suggests that the material does not attain the melting temperature throughout the whole process. This process does not involve costly vacuum equipment or small powder beds.

6.2. Composite fabrication via MELD: characteristic features

Compared to conventional manufacturing techniques, MELD (Melt Emerging Liquid-Phase Diffusion) enables the production of complicated geometries with little post-processing, lower energy usage, and the ability to combine similar materials without the need for extra adhesives or fasteners [16]. The presence of voids or empty spaces within a substance is referred to as its porosity. Porosity in composites can negatively impact the material by weakening its structure and reducing its mechanical properties.

6.3. Thermal spray

Shape memory alloys (SMAs), including nickel-titanium (Nitinol), exhibit distinctive characteristics, such as the capacity to revert to a predetermined shape when subjected to heat, rendering them appropriate for use in aerospace, biomedical, and engineering sectors. This process is primarily utilized for the production of NiTi foils or NiTi tubes, as well as thin-walled mill products and various 3D shapes. The major advantage of this process is, enabling the effective handling of highly reactive materials within controlled environments. Moreover, the low-pressure thermal spraying process technology is poised to decrease lead time in production as well as costs for semi-finished NiTi foils and tubes. Hot rolling can enhance the microstructure of NiTi foils or tubes.

6.4. Thin film fabrication

Shape memory alloy (SMA) thin films are becoming increasingly popular due to their high energy density, superelasticity, and shape memory effect. These materials are commonly used in microactuators, sensors, and biomedical devices. NiTi thin films can be produced using a variety of techniques, such as vacuum sputter deposition, photolithography, and microelectromechanical systems (MEMS). The most effective methods for fabricating medical devices are planar sputtering onto 3D substrates or a multilayer approach. Research on Nitinol thin film composition has concentrated on binary NiTi alloys with nickel content ranging from 48.2 to 51.9 atomic percent, as well as ternary NiTiHf and NiTiCu alloys, using either pre-alloyed or elemental targets.

7. Applications of SMA

Shape memory alloys find applications in diverse fields, including aerospace, automotive, and biomedicine. Nitinol's discovery in 1963 sparked the development of many commercial uses. While biomedical applications of NiTi arose in the 1970s, its use in stents didn't achieve widespread commercial success until the 1990s [17-20]. Today, shape memory alloys (SMAs), including Nitinol, are utilized in a broader range of products, such as air conditioning vents, electronic cable connectors, and valves. The aerospace and hydrocarbon industries have been the driving force behind the recent resurgence of interest in the development of High-Temperature Shape Memory Alloys (HTSMAs) for high-temperature actuation for the past decade. Magnetic Shape Memory Alloys (MSMAs) are a specific area of interest, as they demonstrate shape-changing properties in response to a magnetic field, which is similar to traditional Shape Memory Alloys (SMAs). MSMAs are particularly promising for high-frequency actuation applications. In the same way as numerous SMA applications, MSMAs frequently endure numerous transformation cycles as a result of thermally induced phase transformations under stress or pseudoelastic loading. Nevertheless, as previously mentioned, the material may undergo incremental microstructural alterations as a result of repeated thermomechanical loading. Low cycle fatigue, as opposed to high cycle fatigue, is typically seen in loading routes that operate in a material's entirely elastic regime, is caused by these changes in the SMA behaviour. This section will offer a concise overview of the behaviour of SMAs when subjected to mechanical and thermally induced transformation fatigue. thermally-induced transformation fatigue behaviour of SMAs is extremely important to study for actuation applications,

7.1. Space applications

The application of shape memory alloys in space seeks to tackle the specific challenges associated with actuation, release, and vibration attenuation during spacecraft launch and operations in microgravity and vacuum environments [21]. To meet the mission objectives and get high-quality photographs, it is essential to isolate the micro-vibrations generated by a cryocooler. The proposed technique incorporates a spaceborne cryocooler micro-vibration isolator that employs a pseudo-elastic mesh washer, guaranteeing adequate vibration isolation under the harsh circumstances of launch. The micro-vibrations produced by the cryocooler in orbit have been mitigated. Static testing and free vibration assessments have been performed on the assembly, confirming the design's effectiveness. Spacecraft launches and operations in microgravity and vacuum provide unique issues that shape memory alloys (SMAs) are designed to tackle [22-23].

Lot of work has been done on evaluating the effectiveness of compressed mesh washer isolators in pyro shock isolation. The fabrication and evaluation of shape memory alloy compressed mesh washer isolators have been completed. Another area that has been studied is the dynamic reaction of compressed mesh washer isolators to pre-compressive displacements. The results showed that by modifying the isolator's pre compressive displacement, the damping capacity and natural frequency may be changed. Intelligent isolation systems that rely on the isolator's dynamic flexibility could benefit from these characteristics. Current solar array deployment mechanisms offer specific energies between roughly 20 and 40 W/kg. The Lightweight Flexible Solar Array (LFSA) technology proposed by Carpenter and Lyons has the potential to achieve specific energies exceeding 100 W/kg. For some missions, photovoltaic arrays may offer superior power-to-weight ratios than traditional solar arrays. As a result, more of the scientific cargo may be utilized. An array of solar cells made of copper indium diselenide and placed on a flexible substrate. One potential component of the hinge's deployment mechanism is shape memory alloys. The device is activated by heating the shape memory element to the transition temperature. Thus, the elements can continuously regain their predetermined configuration without stress. A prototype of the invention pertains to a technique for assessing the integrity and readiness of the low-shock separation device, as well as a method for calibrating the actuator's release point. The significance of the argument is attributable to the frequent identification of the pyrotechnic release mechanism as the primary cause of failure and mission termination [41]. Fixing problems with low-shock release devices is one of the best uses of SMA in space. As can be seen from Johnson's Patent [24-25], these procedures have been planned and developed for use in spacecraft design for quite some time. The SMAs are activated slowly but surely using continuous, quick, and inexpensive methods. It would appear that the best approach for designing compact mechanisms is to use novel technology in conjunction with simple designs and applications. A micro burn wire release, a mini rotary actuator, a separation nut (microdomain), a SMA linear actuator, and a SMA redundant release mechanism are some of the approaches that have been put into practice.

8. Future directions of SMA applications

Many potential research areas exist for shape memory alloys (SMAs), Although most studies have focused on their metallurgical properties, neglecting design considerations.

1. Effective use of SMAs requires closer collaboration between material scientists and design engineers. Currently, the information provided by material scientists, while specialized and valuable, is often difficult for design engineers to directly apply due to its technical nature. The difficulties in the sharing and application of information are the primary source of the challenges associated with the design of shape memory alloy (SMA) actuators, rather than the material's inherent limitations [26].

2.Three primary design challenges: the development of design equations for proper dimensioning, the expansion of actuator stroke, and the establishment of a straightforward and dependable material model. Consequently, it is imperative to establish a database or information infrastructure that is effective for SMA applications. This resource would reduce the time and cost of development, mitigate the risk of failure, and simplify the identification of prospective applications through patent analysis [27-32]. In the final analysis, it is imperative to furnish design engineers with the necessary procedures and guidelines to ensure the optimal design of SMA actuators.

3.While there are many innovative ideas for shape memory alloy (SMA) applications, bringing them to market remains a challenge. Marketing professionals play a vital role in social media marketing communities, helping to adapt social media applications for commercial success. "Smart marketing" is key to achieving significant market penetration. To this end, several social media marketing (SMM) communities have developed standards and requirements as guidelines for various aspects of SMM, including terminology, testing, fabrication, and treatments.

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