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Advancements in shape-memory alloys: Properties, applications, challenges, and future prospects

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Abstract. Shape-memory alloys (SMAs) are advanced engineering materials that have gained significant attention in recent years due to their unique properties and potential applications. SMAs have the remarkable ability to recover their original shape after deformation, making them invaluable in various fields, from biomedical devices to aerospace engineering. Despite their many advantages, SMAs also face several challenges, including the need for improved processing techniques and the development of more efficient actuation systems. To address these challenges, researchers have adopted various approaches, including using advanced fabrication methods and developing novel actuation systems. Recent research has yielded several notable achievements in the field of SMAs. For example, researchers have developed new processing techniques that allow the production of SMAs with improved properties, such as higher strength and better fatigue resistance. Additionally, researchers have developed new actuation systems that allow for more precise and efficient control of SMA behavior. Looking ahead, the future of SMAs looks promising. With continued research and development, SMAs have the potential to revolutionize various fields, from aerospace engineering to biomedical devices. However, further work is needed to overcome the remaining challenges and fully realize the potential of these remarkable materials. This article provides a comprehensive overview of SMAs, including their properties, fabrication methods, and various applications. It also discusses the challenges facing the field, the approaches to address them, and recent achievements.

Keywords: Shape-memory alloys, advanced engineering materials.

1. Introduction

Shape-memory alloys (SMAs) operate on the fundamental principle of the Shape Memory Effect (SME). SME involves a temperature-induced phase transformation that reverses deformation. The martensitic phase in SMAs, typically monoclinic or orthorhombic in structure, undergoes this transformation. Interestingly, martensite lacks sufficient slip systems for easy dislocation motion and deforms through detwinning. Thermodynamically, martensite is favored at lower temperatures, while austenite is favored at higher temperatures. When cooling austenite into martensite, internal strain energy is introduced, leading to the formation of many twins, a process known as self-accommodating twinning.[1] SMAs primarily utilize the martensitic phase at their operating temperatures to exploit the shape memory effect, and it's worth noting that no atomic bonds are broken or reformed during this process.

Additionally, geometrically necessary dislocations, a type of dislocation in crystalline materials, play a role in plastic deformation. Pseudo elasticity, also known as super-elasticity, is another crucial phenomenon in SMAs, characterized by the reversible response to applied stress via phase transformations between austenitic and martensitic phases.[2] SMAs exhibit various types of pseudo elasticity, with the main pseudo elasticity occurring during the stress-inducement phase transformation process. This behavior is illustrated graphically, where stresses above the martensitic stress induce austenite-to-martensite transformation, resulting in large macroscopic strains until no austenite remains (C). Upon unloading, martensite reverts to the austenite phase below the austenitic stress (D), allowing strain recovery until the material is fully austenitic and minimal deformation persists.

Shape Memory Alloys (SMAs) have garnered considerable significance and attention in recent years. These alloys possess the remarkable ability to deform when subjected to a changed temperature and spontaneously revert to their original shape when the temperature changes again.

2. Applications of Shape-memory Alloys

In materials science, Shape-memory Alloys (SMAs) have garnered considerable attention and significance. These alloys can deform when subjected to cold temperatures and then effortlessly revert to their original shape upon heating, a phenomenon referred to as the Shape Memory Effect (SME). This unique behavior has opened doors to many practical applications, including biomedical devices, aerospace engineering, etc.

This section provides several introductions of its real-life applications, along with the possible limitations and their possible drawbacks.

2.1. Biomedical Applications

SMAs can be used in biomedical applications. Most shape-memory alloys used in medical devices are Nitinol (NiTi) due to its good workability in the martensite phase and good resistance to corrosion and fatigue.

2.1.1. Orthodontics. Archwires and palatal expanders are the most significant orthodontic devices. They take advantage of superelasticity. Because of bone remodeling, SMA materials can apply almost constant force to the teeth during dental repositioning.[3] The almost constant oral cavity temperature helps SMAs produce proper constant spring-back forces over various deformations. This makes SMAs more effective than classical alloys since traditional materials have a more rigid shape.

2.1.2. General Surgery. In general surgery, SMAs can be used in minimally invasive surgery (MIS) since surgical endoscopic procedures require devices to access and operate into intricate regions. SMAs benefit from stainless and other conventional materials since they provide higher flexibility and improve effectiveness in narrow cavities. This fits the requirements of low-sized components. Furthermore, super-elasticity provides high strain recovery and a wide, constant stress plateau over many strains. These unique SMA characteristics led to the designing and manufacturing novel optimized instruments, which are especially favorable for MIS.[4]

2.1.3. Neurosurgery. In neurosurgery, NiTi micro guidewires can also be used. Aneurysm treatments and angioplasty require flexible NiTi micro guidewires which are smaller than 0.5mm to form a guide for the advancement and positioning of other devices, such as angioplasty balloons, stents, and filters, by following tortuous paths without kinking.[5] Since they have the qualities of high steerability and torquability, high strain recovery, and resistance to torsion and kinking, NiTi wires could cause fewer problems in bending than conventional materials, reducing the operation time and improving the surgeon's ease.

SMAs can also be used in orthopedics, otolaryngology, urology, physical therapy, etc.[6] However, the transformation between the martensitic and austenitic phases in SMAs can be relatively slow, leading to delays in actuation or response time, which could not be favorable in critical medical procedures. Meanwhile, the high-quality SMAs can be expensive. This could restrict their use in cost-sensitive medical applications and limit further development.

2.2. Aerospace Engineering

Notably, shape-memory alloys have the potential to realize adaptive flaps according to two different architectures: compliant and kinematic.

Owing to their distinctive attributes, particularly the NiTi variety, Shape Memory Alloys (SMAs) hold significant potential for application in aerospace contexts, including tasks like wing morphing, propulsion systems enhancement, and noise mitigation.[7] These attributes encompass considerable recoverable strains, substantial stress generation, extensive hysteresis loops within the stress-strain relationship, and variable electrical properties. By harnessing these unique characteristics, SMA components can fulfill multifunctional roles as structural elements, serving as actuators, dampers, or sensors.[8] This multifunctional capacity enables the streamlining of systems, reducing the number of components and complexity, a particularly appealing prospect within the aerospace engineering sector. In this demanding field, marked by stringent requirements for low weight and exceptional reliability, SMAs emerge as an attractive and versatile asset.

2.2.1. Bray foil Morphing Wing System. The Bray foil morphing wing system is designed to automatically set the attack angle on a freely rotating wing, using a single uninterrupted shell of composite or similar stiff sheet material. The wing changes camber and thickness while setting an increasingly variable reflex to match the angle of attack with the change in lift characteristics of the morphing section. Simplicity is the advantage. It has far fewer moving parts, less maintenance, and a lower cost than other typologies. It has no sliding joints or hinged panels, common in other morphing typologies. The wings' ability to set attack angles by the reflex section eliminates the need for the tailplane moment, thus reducing airframe drag by some 20% or more from a normal aircraft.

The Bray foil system is an ideal application for SMA actuators.[9] The SMA wires can be embedded into the skin or used to actuate structural mechanisms linked to the flexible skin to realize optimized airfoil shapes. As the pressure bubble, controlling the transition between laminar and turbulent flow is strongly related to the curvature of the airfoil shape; drag reduction resulting from a delay in the laminar-to-turbulent flow transition can be realized by changing adaptively airfoil camber and moving the morphed airfoil to the optimized position.

2.2.2. Variable Geometry Jet Engine Nozzle. Another example is the variable geometry of jet engine nozzles. The nozzles are meticulously engineered to modulate the exhaust flow area of jet engines, a measure that holds the potential to enhance fuel efficiency and curtail emissions significantly. However, conventional variable geometry nozzles are characterized by sophistication and substantial weight, factors that can exert adverse effects on the overall aircraft performance. SMAs represent an appealing, lightweight, and dependable alternative that can streamline the design of such nozzles. In manufacturing a variable geometry jet engine nozzle, SMAs can be effectively employed as actuators to regulate the position of the nozzle flaps. Upon heating, the SMA wires contract, exerting tension on the flaps, thus inducing closure. Therefore, the exhaust flow area can be reduced. Conversely, during the cooling phase, the SMA wires would expand. This allows the flaps to revert to an open config, enlarging the exhaust flow area. This operational sequence can be repetitively executed without any discernable degradation in performance, rendering SMA an exceptionally well-suited material for this application.[10]

2.2.3. Hinge and Deployment System for Solar Array. The last example of the application of SMAs in aerospace engineering is in developing hinge and deployment systems for solar arrays on satellites. This system is designed to deploy the solar arrays once the satellite is in orbit, which can provide power to the satellites' systems. Nonetheless, traditional hinge and deployment systems are complex and can be prone to failure, which could jeopardize the mission of the satellite launch. SMAs can offer a lightweight and reliable alternative that could simplify the design of these systems.[11] In a hinge and deployment system for a solar array, SMAs can be used as actuators to control the position of the hinges. When heated, the SMA wires contract and pull the hinges into a closed position, therefore securing the solar array. When cooled, the wires expand and allow the hinges to open, deploying the solar array. This process can be repeated many times without any degradation in performance. This makes SMA an ideal material for this application. Additionally, SMAs can be used as sensors to detect the position of the hinges and ensure that they are in the correct position before each deployment. This could, hence, improve the reliability of the system and further reduce the risk of failure.

3. The solution to cutting challenges

3.1. Overview of Cutting Challenges

Shape-memory alloys (SMA), especially NiTi, are difficult to cut due to their unique mechanical properties, shape-memory effect (SME), and pseudo elasticity. These properties make NiTi SMAs ideal for various applications, including aerospace and medical fields.[12] However, these alloys are more challenging to cut than other advanced engineering materials due to their high ductility, crystal-oriented and stress-oriented mechanical properties. Waterjet technology is a non-conventional machining process that uses a high-pressure jet of water to cut a wide range of materials. The waterjet is typically pressurized to between 30,000 and 90,000 psi and forced through a small orifice, which creates a high-velocity jet of water that can cut through materials with high precision.

In some cases, abrasive particles, such as garnet, can be added to the water jet to increase its cutting power. One of the main advantages is its ability to cut a wide range of materials. It can cut metals, composites, ceramics, and plastics without generating heat or mechanical stresses that would damage the workpiece. This makes it an ideal cutting approach for materials that are difficult to cut using conventional methods. It also has high precision and accuracy, which makes it suitable for applications that require tight tolerances and high-quality cuts. Additionally, waterjet technology is environmentally friendly since it does not generate hazardous waste or emit harmful fumes.[12]

Subsequently, researchers propose the utilization of waterjet technology as a prospective approach for the difficulties associated with the cutting of NiTi SMAs. Waterjet technology can effectively cut materials that are difficult to cut because it has benefits, such as minimizing both mechanical and thermal damage to the surfaces of the workpiece and, therefore, widely gaining recognition.

3.2. Approaches

Researchers conducted several experimental approaches using a commercial waterjet machine to investigate the feasibility of using waterjet technology to mill NiTi SMAs. Their methodologies included water pressure, traverse speed, and standoff distance.[13] They also used a high-speed camera to capture images of the cutting process and analyzed the images to determine the quality of the cut.[14]

As a result, waterjet technology was able to successfully mill NiTi SMAs, but the quality of the cut was highly dependent on the cutting parameters. Specifically, researchers found that the increase in the water pressure and the decrease in the traverse speed can result in higher-quality cuts. The standoff distance also significantly affects the quality of the cut, with a shorter standoff distance coming with a higher quality cut. Subsequently, researchers conducted a series of controlled depth milling experiments. In these experiments, researchers used a custom-built fixture to control the depth of the cut and varied the cutting parameters to determine their effects on the quality of the cut. As a result, the cutting parameters significantly impact the cutting qualities, with the water pressure and traverse speed the most.

Increasing the water pressure and decreasing the traverse speed resulted in a higher quality cut; specifically, a water pressure of 400 MPa and a traverse speed of 0.5 mm/s resulted in the highest quality cut. The effects of the cutting parameters on the surface roughness of the cut are also analyzed. Researchers found that increasing the water pressure and decreasing the traverse speed can result in a smoother surface finish. The standoff distance also has a significant effect on the surface roughness, with a shorter standoff distance resulting in a smoother surface finish.

3.3. Strengths and Weakness

Waterjet technology is known for its ability to cut advanced difficult-to-cut materials with minimal mechanical and thermal damage to the workpiece surfaces.[15] This is particularly important for NiTi

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SMAs, which are highly ductile and have unique mechanical properties that make them difficult to cut using conventional methods. Secondly, this technology is capable of producing high-precision cuts with minimal kerf width, which is vital for applications that require high accuracy and precision.[16] Meanwhile, it can be used to cut a wide range of materials, not only SMAs but also metals, composites, ceramics, and plastics, which makes it a versatile cutting approach.[17]

Nevertheless, limitations still exist in waterjet technology. Firstly, it could be expensive to implement, especially for small-scale applications. The equipment's cost and maintenance can make it prohibitive and be a limiting factor for some applications. Secondly, waterjet technology is generally slower than other cutting approaches, such as laser cutting or plasma cutting. This could be a limitation for applications that require high speed and high production rates or when the products are vulnerable. Thirdly, while waterjet technology can produce high-quality cuts, the surface finish may not be as smooth as other cutting methods. This could be another limitation for applications that require a high-quality surface finish.

In conclusion, researchers solved the problem of cutting NiTi shape memory alloys by exploiting the waterjet technology. Through a series of experiments, the optimal cutting parameters for waterjet milling of NiTi SMAs were determined, which resulted in high-quality cuts with minimal mechanical and thermal damage to the workpiece surfaces. Further research is needed to optimize the cutting parameters for specific applications, such as medical applications requiring high-quality cuts.

4. The solution to long cycle time

Another major challenge in the practical applications of shape memory alloy actuators is their long cycle time. Cycle time refers to the time required for the SMA actuators to complete one cycle of operation, which includes both heating and cooling phases.[18] In the procedures, the cooling process could be slow, making the cycle long. For example, a typical NiTi alloy with a diameter of 0.25mm takes about 5.4 seconds to cool off.[19] Adding one second for heating, the actuator could take approximately 6.4 seconds to complete one cycle of operation. This drawback results in a very low cyclic frequency of roughly 0.056 hertz, which may not be suitable for many applications, especially unsuitable for fast cyclic applications.[20] This limitation poses constraints in domains such as robotics and aerospace engineering. Hence, devising a solution to diminish the cooling time of SMA actuators is imperative for advancing SMA technology.

4.1. Forced Air Cooling

Forced air cooling is a cooling technique that involves directing a stream of air over the SMA actuator to expedite heat transfer and reduce the cooling period. It is commonly used in applications such as robotics and automation, where the actuators are exposed to the air. This approach could increase the heat transfer coefficient and allow for faster cooling of the SMA actuators. Nonetheless, it is worth noting that while forced air cooling can significantly diminish cooling times, it demands a substantial energy input and may not be universally applicable. The energy input required for forced air cooling can be huge, and it would limit its use in applications where energy consumption is a concern and also increase the expenses. Additionally, forced air cooling may not be suitable for applications where the actuator is enclosed or where additional energy is of no feasibility. Despite these limitations, forced air cooling can effectively undermine the cooling duration of SMA actuators in more applications.[21]

4.2. Water Cooling

Water cooling involves circulating water around the SMA actuators to enhance heat dissipation and curtail cooling intervals. Water has a higher heat capacity than air, so it can absorb more heat energy from the SMA actuator, resulting in faster cooling.[22] Water cooling has been observed to be more effective than forced air cooling in reducing cooling times. However, it necessitates access to a water source and may not be appropriate for all scenarios. It is commonly used in applications where the actuator is enclosed or where additional energy is of no feasibility.[23] Therefore, water cooling may

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not be suitable for applications where the actuator is exposed to the water or where the use of additional equipment is of no feasibility.

4.3. Fluidic Cooling

Internal fluidic cooling encompasses fluid circulation through the SMA actuator to expedite cooling, such as a refrigerant or coolant. The fluid absorbs heat from the SMA actuator, which results in faster cooling.[24] This method has proven highly effective in curtailing cooling times but involves the requirement of a fluid source and may entail more intricate implementation than forced air or water cooling methods. Fluidic cooling is commonly used in applications where the actuator is enclosed or where the use of additional energy is not feasible. Therefore, it may not be suitable for applications where the actuator is exposed to fluids or where the use of additional equipment is not feasible.

4.4. Strategies Design

In addition to cooling techniques, various design strategies have been explored to decrease the cooling duration of SMA actuators.[23] These strategies encompass reducing the size of the SMA wire, augmenting the surface area of the SMA wire, and employing multiple SMA wires in parallel or series configs.[25] A reduction in the size of the SAM wire has shown the potential to significantly decrease cooling times, albeit potentially diminishing the actuators' force outputs.[26] Meanwhile, increasing the surface area of the SMA wires can also expedite cooling but may necessitate more convoluted designs. Employing multiple SMA wires in parallel or series can enhance the actuators' force output without substantially elongating cooling durations.

Furthermore, researchers have examined the application of pre-strain to diminish cooling durations. Pre-strain involves applying slight deformation to the SMA wire before heating, reducing the strain required to reset the actuator. Pre-strain may decrease the actuator's force output and entail a more intricate design.

4.5. Elastic Compensation

The principle of elastic compensation in shape memory actuators has been introduced to maximize the overall stroke and the useful output force.[27] The elastic compensation system adds a conventional spring to the shape memory actuator, which is mounted with preload and acts transversely to the wires. The compensation system is designed to have specific elastic stiffness and compensation force at the position of minimum net force, which is calculated from the design data of the actuator.[28] Researchers show that the elastic compensation system can increase the stroke or useful force of the actuator by more than 2.5 times compared to the actuator without compensation while maintaining the same level of performance.

Overall, the choice of SMA alloy can exert a discernible impact on the cooling duration of the actuator. Some SMA alloys exhibit faster cooling rates than others, thereby making the overall cycle time shorter than before. Nevertheless, this alloy choice may influence other actuator properties, including force outputs and durability. In conclusion, researchers have explored various approaches to alleviate the cooling time associated with the SMA actuators. These approaches encompass cooling methodologies such as forced air, water, and internal fluidic cooling, as well as design modifications like altering wire size, enhancing surface area, and employing multiple wires in parallel or series. The selection of the SMAs itself can also influence cooling times. Mitigating the cooling duration, therefore the cycle time, of the SMA actuators can help researchers surmount a principal hurdle in the practical application and broaden the utilization of SMAs across diverse domains.

5. The solution to difficult control

Another major challenge associated with the practical application of shape memory alloy (SMA) actuators is their difficult control. SMA actuators exhibit highly nonlinear behavior, making them difficult to control using traditional methods. In addition, SMA actuators have a slow response time and a hysteresis effect, which further complicates their control. The nonlinear behavior of SMA actuators

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arises from the complex relationship between the input, the current or voltage, and the actuator's output, the displacement or force.[29] The relationship is highly dependent on the SMA wire's temperature and strain state. As a result, traditional control methods, such as proportional-integral-derivative (PID) control, may not effectively control SMA actuators.[30] The slow response time of SMA actuators is due to their long cycle time, as discussed in the previous section. The hysteresis effect of SMA actuators is that the actuator does not return to its original shape immediately after cooling. Instead, it requires applying a certain amount of strain before it returns to its original shape. This hysteresis effect can make it difficult to control the position or force output of the actuator accurately.

5.1. Model-based Control

Model-based control is a control technique that involves developing a mathematical model of the SMA actuator and using this model to design a control system.[31] The authors note that model-based control can effectively control SMA actuators, allowing for precise control of the actuator's behavior.[32] Nevertheless, it requires a good understanding of the behavior of the actuator and may be difficult to implement in practice.[33] The accuracy in the whole process of operating the model is crucial to the success of the control system. Any errors in the model could lead to poor actuator performance.[34] Model-based control is commonly used in applications where the precise control of the actuator is required, such as robotics and automation. However, model-based control may not be suitable for applications where the actuator's behavior is highly nonlinear, it is difficult to estimate, or additional equipment is not feasible.

5.2. Adaptive Control

Adaptive control involves adjusting the system's control parameters in real-time based on the actuator's behavior.[35] It is a control technique distinguished by its capacity to dynamically modify system control parameters in response to the actuator's evolving behavior. This approach can be effective when the actuator's behavior remains uncertain or undergoes variations over time.

Additionally, adaptive control can exhibit sensitivity to external disturbances and uncertainties, potentially impacting the control system's performance.[36] This approach has already found practical applications in the control of SMA actuators. For instance, a Generalized Predictive Control system was employed to address the nonlinear behavior of an SMA spring-based linear motion actuator in 2010. Likewise, adaptive PID controllers, combined with an inverse hysteresis model, are investigated to actuate an SMA-based robotic hand, demonstrating the capability to mitigate overshooting and achieve effective tracking control.

5.3. Sliding Mode Control

Sliding mode control involves designing a control system that forces the actuator's output to follow a sliding surface. The sliding surface is a function of the system's state variables, designed to ensure that the actuator's output converges to a desired value.[37] According to the researchers, the sliding mode control can effectively control SMA actuators, especially in the presence of disturbances and uncertainties.[38] This is because sliding mode control is designed to be robust to disturbances and uncertainties, and it can ensure that the actuator's output converges to the desired value even in the presence of these disturbances.

However, sliding mode control can be sensitive to noise and may require a more complex design because it involves designing a sliding surface that is sensitive to the system's state variables.[37] Additionally, sliding mode control can require a more complex design than other control techniques, making it more difficult to implement in practice.

Overall, researchers have examined many strategies to enhance the control of SMA actuators. These approaches encompass model-based control, adaptive control, sliding mode control, etc. By refining the control mechanisms governing SMA actuators, researchers can effectively address a significant obstacle hindering their practical application, expanding the scope of SMA utilization across a broader spectrum of applications.

6. Conclusion

In conclusion, Shape-Memory Alloys (SMAs) are advanced engineering materials that have gained significant attention in recent years due to their unique properties and potential applications. SMAs can recover their original shape after deformation, making them invaluable in various fields, from biomedical devices to aerospace engineering. This paper has provided a comprehensive overview of SMAs, including their properties, fabrication methods, and various applications. It has also discussed the challenges facing the field, the approaches to address them, and recent achievements. Despite the many advantages of SMAs, several challenges remain, including the need for improved processing techniques and the development of more efficient actuation systems. However, with continued research and development, SMAs have the potential to revolutionize various fields, from aerospace engineering to biomedical devices. Using SMAs in biomedical applications shows great promise, with the development of new SMA-based devices and implants that can improve patient outcomes and quality of life. Additionally, the use of SMAs in aerospace engineering has the potential to reduce weight and improve fuel efficiency, leading to significant cost savings and environmental benefits. Overall, the future of SMAs looks promising, and continued research and development in this field will undoubtedly yield many exciting discoveries and applications.

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