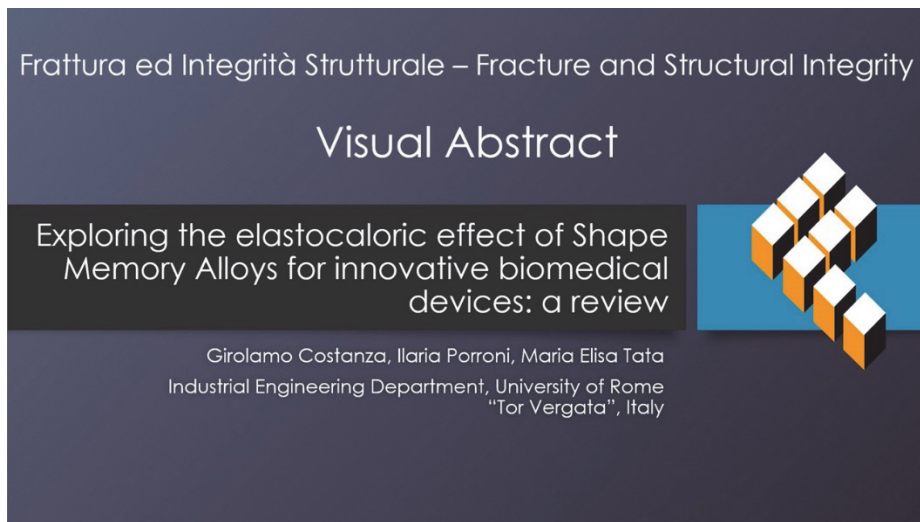


Exploring the elastocaloric effect of Shape Memory Alloys for innovative biomedical devices: a review

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INTRODUCTION

Shape Memory Alloys (SMA) are widely recognized for their ability to revert to the original shape upon changes in temperature or mechanical stress. In recent years, due to increasing environmental concerns, they have garnered growing interest for their ability to dissipate and capture heat because of martensitic phase transformation (MT) when loads are exerted and relieved [1]. The mentioned unique property, also known as elastocaloric effect (EC), found an innovative application in the micro cooling sector, where eco-friendly compact cooling methods have shown the capability to supersede conventional cooling systems that rely on synthetic coolants, which are responsible for high energy consumption and greenhouse gas emissions.

The EC can be categorized based on the external fields used to activate it. Primarily, three categories can be distinguished:

- 1) Stress-induced EC: the most common, where mechanical deformation causes the phase change;
- 2) Magnetic field-induced EC: observed in some ferromagnetic SMA;



3) Electric field-induced EC: less common but studied in some piezoelectric materials.

This review primarily focuses on the stress-induced EC in SMA, given its relevance to biomedical applications.

An analysis of the Scopus database reveals a growing interest in the elastocaloric effect in recent years. From 2010 to 2023, the number of annual publications on EC has increased by over 500%. Notably, publications concerning stress-induced EC constitute about 80% of the total, followed by magnetic field-induced EC (15%) and electric field-induced EC (5%). This trend reflects the increasing interest in EC as an alternative cooling technology, with a particular focus on SMA due to their unique properties and potential applicability in fields like the medical and biomedical ones.

In this context, elastocaloric materials (ECM) provide a substantial effective refrigeration option, also due to minimal workloads needed. The development of solid-state cooling technologies exploiting SMA's elastocaloric property is currently enforced by an extensive span of case studies and research, also with perspective to overcome the low cycle resistance of these materials, enabling the commercialization of this technology [2]. A lot of studies were centered on characteristics and differences of main SMA that can be employed in applications involving thermal regulation, with a particular focus on heat transfer processes, working temperature window, cyclic stability, energy conversion efficiency of these materials and attempts to improve thermal performances and fatigue life limits. Some studies also focus on developing experimental prototype devices, employing different thermal cycles, materials and methods to evaluate the impact of operating conditions on system's performances.

Following this new direction for innovative SMA applications, the authors review progresses of this pioneering technology in the light to import it also in medical and biomedical fields, where precision and minimization of invasiveness are crucial and SMA are already widely employed in multiple devices [3-7]. Some examples include: Self-expanding vascular stents [4], Orthodontic archwires [5], Bone fixation devices [6] and Catheter actuators [7].

These examples demonstrate the versatility and adaptability of SMAs in various biomedical applications, suggesting the potential for integrating the elastocaloric effect in future innovations.

In particular, the authors aim to showcase the potential of SMA's elastocaloric properties as a base to develop novel biomedical devices: compact solid-state refrigerators and heaters can offer the advantages of reduced volume, rapid response, significant caloric effect and simple actuation joined with eco-friendliness. This work points out how SMA, with a particular mention on Nitinol (Ni-Ti), with their biocompatibility and ability to recover a predefined shape at body temperature, can offer promising solutions for the development of advanced medical and biomedical devices employing elastocaloric effect.

THE ELASTOCALORIC PRINCIPLE AND PERFORMANCE PARAMETERS

SMA are becoming more and more popular for cooling applications due to the progress of scientific and technological research, which has revealed their significant advantages over traditional refrigerants [8]. This technology is closely associated with the superelastic properties of SMA, that is material capability to bear high strain (up to 9%), and harnesses SMA's thermal outcome of stress-driven MT for cooling purposes. In detail, EC is a result of the liberation and uptake of latent heat during the alternating application and removal of stress associated with MT in both directions. MT is an invertible solid-state displacive crystalline phase transition governed by a slice among an elevate symmetry and elevate temperature parental stage, and a minimal symmetry and small temperature resultant stage [9]. In particular, the method to obtain solid-state refrigeration via SMA entails triggering MT within alloy through load application, leading to the exothermic release of heat. If this process occurs under isothermal conditions, heat is emitted. Conversely, if the alloy undergoes adiabatic load, MT induces a rise in temperature, thereby heating the alloy. On the other hand, SMA experience forward transformation upon load relief, triggering a heat-absorbing mechanism. If the process happens adiabatically, the alloy undergoes cooling and experience a temperature reduction; if the process occurs isothermally, the intake of heat causes temperature reduction.

Thanks to this ECM's observed property, two types of thermodynamic cycles can be designed: one driven directly by thermal energy (such as the one of an heat engine), and another driven contrarywise by load (suitable for the development of thermal devices), as shown in Fig. 1a and 1b [10]. In particular, Fig. 1b outline the hysteresis that occurs during a cycle pushed by load when the temperature is kept constant, that can be employed in cooling or heat pump systems. In this figure $\sigma_{AM}(T)$ and $\sigma_{MA}(T)$ represent respectively the austenite to martensite saturation stress, above which martensite transition phase starts in the alloy loaded in austenitic stage, and martensite to austenite saturation stress, below which the forward MT occurs.

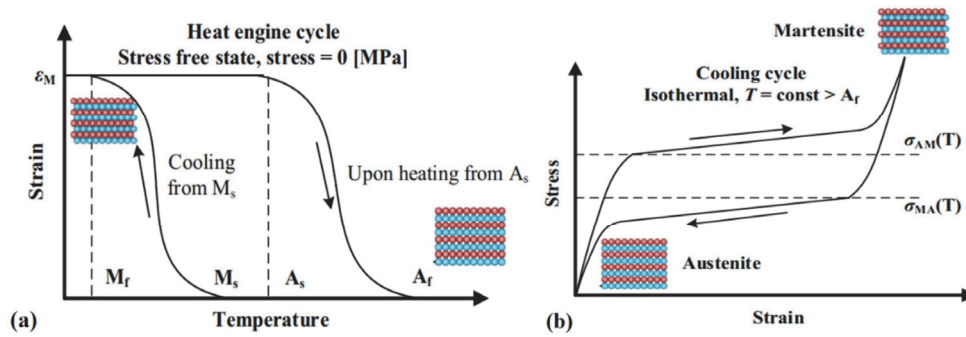


Figure 1: Graphic display of hysteresis curves. (a) A cycle with temperature hysteresis when there is no load applied. (b) The stress hysteresis associated with an isothermal refrigerating process. [10].

The basics of the elastocaloric cycle exploited in thermal devices, theorized with Brayton thermodynamic cycle, can be summarized in four basic steps: (i) the deformation or loading of a SMA in the austenitic stage causes a release of heat associated with advancing MT. Under adiabatic conditions of loading the elastocaloric material heats up. Stressing or straining the alloy at a close-adiabatic temperature growth respect to environment (e.g. an heat sink) requires an elevate deformation frequency [11]; (ii) Heat transfer occurs subsequently from the elastocaloric material to the surroundings, causing the decrease of SMA's temperature. In this stage, ECM remains in touch with environment, and this contact remains until thermal equilibrium is achieved [12]; (iii) In the unloading phase, inverse MT happens, causing an absorption of heat that leads, if the load is removed adiabatically, to the chilling of ECM at a temperature lower than that of the environment (e.g. the heat source); (iv) cold SMA absorbs environment's thermal energy until thermic stabilization. The Brayton series for caloric cooling technologies, including the elastocaloric one, is depicted in Fig. 2.

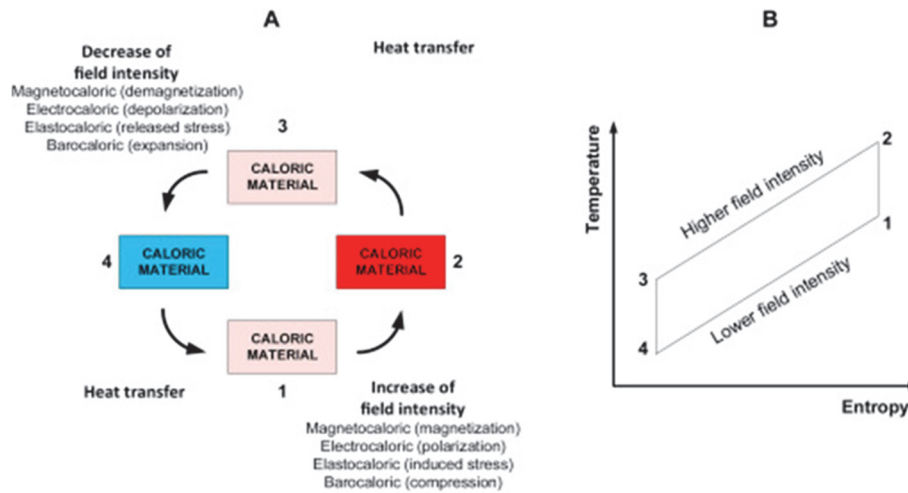


Figure 2: (a) EC-based thermal cycle. (b) Single stage of the caloric Brayton thermodynamic cycle [13].

In the selection of suitable elastocaloric SMA for cooling applications, several parameters must be considered to compare performances.

First of all, the elastocaloric effect (ΔT), that is a term used to refer to the parameter that specifies the highest possible variation in temperature obtainable employing a sollicitation. Higher ΔT are expected when there is a high entropy variation linked to MT [14], and it's possible to measure it directly through infrared thermography. An experimental investigation on the EC property in Ni-Ti testers was performed, demonstrating a temperature change of 17K under a tensile stress of 580 MPa on a tester measuring 3mm in diameter and 1.780mm in length [15]. Another research [16] demonstrates a ΔT of 21K during the unloading phase of Ni-Ti wires trained at different temperatures. Referring also to other SMA, it's possible to obtain during inverse MT a ΔT of 14.2°C in CuZnAl, 15.2°C in NiTiCu, 13.5°C in Ni₂FeGa according to the hysteresis, the variability of the MT and the quantity of cycles performed in superelastic field [17].



Another important parameter to consider in the selection of the right material for solid-state refrigeration scope is the specific heat capacity. This parameter depends on the quantity of thermal energy obtainable per cycle, thus to cycles' number needed to obtain the necessary cooling.

To assess the thermal properties of ECM, it is important to evaluate the coefficient of performance COP, expressed as the ratio between the thermal capacity (Q) and the work contribution (ΔW): $COP=Q/\Delta W$. This equation shows that to improve cooling performances of SMA the research on material optimization must focus on enhance the obtained latent heat per cycle (Q), that is linked with the cell volume variation that occurs during MT, and reduce cycle hysteresis, that corresponds to ΔW . An efficient transformation is characterized by elevate COP, and elastocaloric analyses of SMA revealed COPs as high as 3.07 [15]. It's fundamental to remember that the theoretical material's COP can be even higher, but the relevant COP is the one of the device [18].

An essential technical parameter to evaluate performances of ECM is the working temperature span (OTW), i.e. the temperature frame in which martensitic transformation takes place, that is recommended to be near to the operating temperature in order to increase heat absorption. In fact, as the working temperature continues to rise above the Austenite finish (A_f) temperature, there is a parallel growth of the load needed to provoke MT, and thus a decrease of resulting EC [19].

The primary challenge in advancing solid-state compact thermal devices exploiting ECM is the fatigue life (or cycle stability). Two major types of fatigue are experienced by ECM: structural and functional fatigue. Cyclic loading leads to structural (mechanical) fatigue, while functional fatigue is caused by thermal loads. The thermal performances of SMA reduces progressively undergoing loading cycles [20], [21], so the endurance limit is pivotal, and finding a compromise between these indicators is essential to enhance the design of industrial scale devices exploiting SMA's EC.

The parameters mentioned are dependent on multiple factors, and as a result, materials for elastocaloric applications must undergo a thorough investigation before they can be translated into a competitive technology. For example, the different type of microstructure impacts on the expected cooling properties [22],[23], and disparate microstructures can be obtained using different processing techniques. Significant efforts have been put into improving thermal performances of ECM by monitoring their structure [24], [25], which lead to improve thermal properties, OTW and efficiency. Understanding all these mechanisms is essential for designing medical devices that require precise control over temperature and mechanical properties.

SHAPE MEMORY ALLOYS' ELASTOCALORIC MATERIALS

Generally, it's possible to regard all SMA as hypothetical ECM depending on application's OTW, that has to be above SMA's A_f in order to get invertible super-elasticity [26]. Among most used ECM there are NiTi-centered, Copper-centered, Iron-centered and Heusler ferromagnetic SMA.

The Ni – Ti based exhibit biocompatibility [27] and pronounced elastocaloric effect due to their martensitic transformation. Ni-Ti alloys have demonstrated high efficiency in converting thermal energy into mechanical work, making them promising for thermal applications, especially in the biomedical field. They can be alloyed with Cu, Co, Pd and Fe [28] and designed with an extensive window of transition temperatures to garb several thermal applications. On other hand, conventional Ni-Ti alloys' lack of fatigue performance and machinability prevent them from being widely used as refrigerants in industrial applications, so the majority of research efforts focus on enhancing the thermal fatigue resistance of this class of alloys, even using doping components or microstructure control. Recently, a significant amount of research has been done to improve performances of Ni-Ti-based SMA, developing new alloys that combinate enhanced stability and lower hysteresis with relevant EC. For example, the properties of Ni-Ti-Cu-Co showed to be durable even after 10^6 cycles [29].

Cu-based SMA also undergo martensitic transformation with a consequent elastocaloric effect. However, even if the forces to generate the EC are lower compared to Ni based ECM, the transition temperature is often higher. For instance, CuZnAl demands an applied stress of about 250 MPa in adiabatic conditions, whereas NiTi requires nearly 400 MPa [30]. Furthermore, Cu is relatively cost-effective compared to Ni and Ti, which can be advantageous for commercial applications [30]. Copper has good thermal conductivity, which can be useful for the even distribution of heat in thermal applications. Nevertheless, efforts are still necessary to enhance cyclic stability and thermal and mechanical properties.

Iron-based alloys are economically attractive, but their application is limited due to the high brittleness and weak caloric effect, causing low cooling capacity.

Heusler-based alloys are characterized by conceivable solid-state thermal application driven combination a magnetic field and an exterior load. Nevertheless, the intrinsic weakness of this class of SMA places substantial constraints on their applications [31].



Tab. 1 offers an illustrative overview of thermal properties of mentioned SMA classes, for use in thermal instruments functioning at ambient conditions.

Material family	ΔS_t (J kg ⁻¹ K ⁻¹)	Hysteresis (MPa)	Critical stress (MPa)
NiTi	-33	100	400
CuZnAl	-17.9	30	250
FePd	-2.2	0	200

Table 1: Elastocaloric properties of SMA classes, for use in thermal instruments functioning at ambient conditions [30].

In general, the choice among the mentioned families of SMA varies according to the particular needs. Ni-Ti alloys are often preferred for high-efficiency and precision applications, while Cu-based alloys may be a more cost-effective choice for some employments. Heusler-based alloys, on the other hand, are ideal for magnetic applications and can be advantageous in particular contexts.

OPEN STRATEGIES TO IMPROVE PERFORMANCES

For commercial applications, the poor thermal fatigue resulting from the distortion among two phases through MT remains a major issue to overcome [32]. Before discussing strategies to improve performance, it's important to understand the mechanisms behind the loss of EC with increasing number of cycles:

- 1) Dislocation accumulation: one of the primary mechanisms for EC effect degradation is the accumulation of dislocations during cyclic loading. Zhang et al. [33] observed that in NiTi alloys, dislocation substructures form and multiply during martensitic transformations, leading to a decrease in transformation temperatures and deterioration of shape memory properties over cycles.
- 2) Residual martensite: Gao et al. [34] found that functional fatigue in NiTi alloys is also related to the formation of stabilized martensite that does not fully transform back to austenite upon unloading. This residual martensite reduces the overall transformable volume fraction, decreasing the EC effect.
- 3) Grain refinement effects: while nanocrystalline structures can improve fatigue resistance, they may also affect transformation behavior. Ahadi et al. [35] reported that nanocrystalline NiTi exhibits a continuous transformation rather than a sharp first-order transition, which can impact the magnitude of the EC effect.
- 4) Compositional sensitivity: the stability of the EC effect is highly dependent on alloy composition. Cong et al. [36] demonstrated that in Ni-Mn-Ti alloys, small variations in composition can significantly affect the transformation behavior and cycling stability.
- 5) Stress state influence: the mode of loading (e.g., tension vs. compression) can affect cycling stability. Chen et al. [25] found that compression-based EC cooling in NiTi cylinders exhibited superior fatigue life compared to tension-based approaches.
- 6) Phase compatibility: materials with better lattice compatibility between austenite and martensite phases tend to show improved cycling stability. Gu et al. [37] demonstrated that alloys with near-zero thermal hysteresis due to good phase compatibility exhibit enhanced functional stability.
- 7) Microstructural heterogeneity: introducing controlled heterogeneity can sometimes enhance stability. Hou et al. [38] showed that additive manufactured NiTi with a heterogeneous microstructure exhibited improved fatigue resistance while maintaining large EC effects.

Understanding these factors is crucial for developing strategies to improve the long-term stability and performance of elastocaloric materials.

Improving cooling and heating performances of elastocaloric SMA while enhancing thermal fatigue resistance involves multidisciplinary strategies, combining material design, process control and ongoing innovation to maximize the efficiency and applicability of these materials in refrigeration scopes.

Several approaches have been investigated to improve the cycling stability and fatigue resistance of elastocaloric materials:

- 1) Microstructural engineering: techniques like thermal treatment [39] or adding doping elements can be exploited to augment geometric dissimilarities between structures, thereby improving the elastocaloric (EC) effect. For instance, Hou et al. [38] developed a NiTi-based nanocomposite with TiNi₃ precipitates that exhibited stable elastocaloric performance over millions of cycles. The precipitates act as barriers to dislocation motion and help maintain reversibility.



- 2) Grain refinement: nanocrystalline structures have shown improved fatigue life. Lin et al. [40] produced nanocrystalline NiTi through severe plastic deformation, achieving one million stable cycles. The high density of grain boundaries impedes dislocation accumulation.
- 3) Compositional tuning: alloying additions can modify transformation behavior and enhance stability. Yang et al. [41] found that boron micro-alloying in Ni-Mn-In alloys improved cyclic stability of the elastocaloric effect through grain refinement.
- 4) Thermomechanical treatments: proper heat treatments and training procedures can optimize microstructure. Chen et al. [21] used localized laser surface annealing to create a gradient structure in NiTi, improving both elastocaloric effect and fatigue resistance.
- 5) Transition pathway engineering: Liang et al. [42] demonstrated a two-step $B2 \rightarrow R \rightarrow B19'$ transition in Ni-rich NiTi that exhibited cyclic-stable superelasticity with large recoverable strain and elastocaloric effect. The intermediate R phase helps reduce hysteresis and fatigue.

While these strategies can improve cyclic stability, they may also cause a reduction in the thermal capacity of the elastocaloric material. For example, introducing self-accommodated structures, toughening via secondary ductile phase, strengthening via grain refinement or texturing through directional solidification could improve the cyclic stability but potentially at the cost of reduced thermal capacity. Therefore, implementing a blend of various approaches is essential to strike a balance among conflicting needs.

Despite these advances, gradual degradation of the elastocaloric effect with cycling remains a challenge in many systems. This is often attributed to the accumulation of defects like dislocations that hinder reversible transformation. Strategies that can mitigate defect generation or promote their annihilation during cycling are needed to further improve long-term stability. The effectiveness of different approaches varies depending on the material system. Comparative studies examining multiple strategies on the same composition could provide valuable insights into optimizing elastocaloric performance and fatigue resistance for specific applications.

Current studies are also focusing on manipulating the microstructure of alloys through heat treatment processes to achieve uniform and controlled martensitic transformation or suitable transition temperatures for specific applications. Additionally, the optimization of manufacturing and production processes is another open issue. The use of geometric design and the optimization of component shapes and dimensions to maximize the contact surface area between the alloy and the cooling fluid can enhance heat transfer efficiency.

Continued research and development efforts are essential to identify new alloys, technologies and approaches to further enhance elastocaloric thermal performances of SMAs and assess the practical applicability of this new thermal solution in medical and biomedical fields. As the field progresses, a holistic approach considering material properties, production methods, and application requirements will be crucial for realizing the full potential of elastocaloric cooling technologies.

STATE-OF-ART ABOUT ELASTOCALORIC DEVICES

Despite SMA's emission and uptake of thermal energy throughout MT, along with the related temperature variations, have been recognized for many years, the recognition of the elastocaloric effect as an effective cooling or heating pumping mechanism has only recently occurred [43]. Modern thermal technologies must be tight, efficient and prompt; for this reason solid-state thermal technologies are typically linked with minor size refrigerating or heating implementations. In this situation, aside from studying ECM, researchers are focusing on designing and developing elastocaloric cooling/heat-pumping devices, as well as numerical models to simulate and optimize their performance. Several innovative elastocaloric devices have been developed in recent years, even if the elastocaloric devices in the literature are not yet commercialized as they are still in an experimental phase [44].

Elastocaloric devices in literature exploit two main techniques to obtain the needed heat transfer: through a solid-to-solid contact, involving single elastocaloric elements, and by employing a convective thermal exchange through permeable EC architectures. Moreover, devices can realize the cooling/heating cycle with a single-stage or multi-stages, reaching larger temperature spans. The majority of experimental applications involve an active regenerative thermodynamic cycle, based on permeable EC architectures where a fluid that transfers thermal energy is circulated. In designing such elastocaloric thermal devices, the key components are the permeable architecture and the actuator that applies the load on ECM [28]. The permeable EC architecture can be realized with several elementary SMA forms (for example cables, sheets and bricks).

The easiest production technology currently employed to obtain this kind of structures is additive manufacturing, with whom producers can overcome Ni-Ti alloys low machinability and welding properties and obtain homogeneous structures in terms of quality. Recent advancements in additive manufacturing (AM) techniques, particularly Laser Powder Bed Fusion (L-PBF), have opened new avenues for fabricating NiTi-based elastocaloric devices. The microstructure of NiTi alloys



fabricated by additive manufacturing techniques like laser powder bed fusion (L-PBF) or laser directed energy deposition (L-DED) significantly influences their elastocaloric performance. Unlike conventionally manufactured NiTi, AM-produced alloys exhibit distinct features that can both enhance and challenge their elastocaloric properties:

- 1) **Heterogeneous Microstructure:** L-DED fabricated NiTi often displays a heterogeneous grain structure with a combination of equiaxed and columnar grains [38]. This microstructural heterogeneity can lead to enhanced fatigue resistance while maintaining large elastocaloric effects. The varied grain structure creates multiple nucleation sites for phase transformation, potentially improving the stability of the elastocaloric response over repeated cycles.
- 2) **Precipitate Formation and Distribution:** The rapid cooling rates in AM processes can result in a fine dispersion of Ni-rich precipitates like Ni₃Ti and Ni₄Ti₃ [45]. These precipitates play a crucial role in the elastocaloric effect by acting as nucleation sites for martensitic transformation, enhancing the yield strength of the material, which is essential for achieving reversible transformations and stable elastocaloric effect and influencing the transformation temperatures and hysteresis.
- 3) **Defects and Porosity:** AM processes can introduce defects such as lack-of-fusion pores and internal stresses [46]. While these defects can potentially degrade mechanical properties, they can also act as nucleation sites for phase transformation, altering the elastocaloric response. Careful control of processing parameters is crucial to minimize detrimental defects while potentially leveraging beneficial ones.
- 4) **Texture and Anisotropy:** AM processes often result in textured microstructures due to the directional solidification inherent in layer-by-layer fabrication [38]. This texture can lead to anisotropic elastocaloric properties, potentially enhancing the effect in certain orientations while diminishing it in others.
- 5) **Compositional Control:** AM techniques offer precise control over composition, allowing for the creation of functionally graded materials with tailored elastocaloric properties [47]. This capability enables the design of NiTi components with optimized performance for specific applications.
- 6) **Grain Size Effects:** The grain size in AM NiTi can be controlled through process parameters and post-processing heat treatments. Finer grain sizes generally lead to improved fatigue resistance and can enhance the stability of the elastocaloric effect over multiple cycles [38].
- 7) **Transformation Behavior:** The unique microstructure of AM NiTi can result in a more gradual martensitic transformation compared to conventionally processed alloys. This can lead to a broader temperature range for the elastocaloric effect, potentially beneficial for certain applications [38]. Different elastocaloric driver mechanisms can be exploited. The applied load can be a tension, compression, bending or torsion. The first two mentioned loads are preferred for applications since they result in a homogeneous strain distribution in elastocaloric material. Moreover, the compression load often determines longer fatigue life compared with tensile load, but necessities of less slim forms to prevent bucking, while, conversely, slim forms are better to increase thermal exchange. In this context it's important to mention once again that an elastocaloric device should be able to undergo more than 10 million loading/unloading cycles in an estimated lifetime of 10 years, and that elastocaloric elements' fatigue life increases under smaller applied cyclical stresses, but smaller stresses are related to an incomplete phase transformation, and thus to limited adiabatic temperatures changes. All mentioned themes are at the base of current challenges in the design of elastocaloric devices, that need to find an optimum compromise between maximizing an effective and fast thermal exchange and guarantee fatigue resistance for practical applications.

Another crucial aspect for this kind of devices is the actuator required. Ideal criteria for actuators are a mechanical applied load sufficiently high to make the phase transformation happen and the exploiting of work recovery during unloading phase to increase device's efficiency. The actuators can often be pneumatic, hydraulic or linear motors. The pneumatic ones operate with a maximum pressure of 10 bar, requiring small contact surfaces to generate sufficiently high forces in the elastocaloric material. The pressure value can be increased up to 300 bar using hydraulic actuators, suffering of poor efficiency. On the other hand, linear motors, working with higher efficiencies, face challenges in supplying the necessary elevate loads. For all this reasons, a suitable alternative can be employing an actuator based on a rotary motion, for example coupled to a shaft, installing ECM circumferentially or longitudinally.

Investigating outlined assumptions, in recent years researchers developed and tested many different single and multi-stage cooling or heating elastocaloric devices.

One of the first elastocaloric prototypes was developed by Tušek et al. [48]. Their regenerator, built using NiTi plates and water as the working fluid, achieved temperature spans of 15.3 K and a maximum COP of 7. The regenerator consists of SMA plates enclosed between two clamps on which the loading/unloading cycle is applied. Two circuits (hot and cold) are connected to the regenerator in which the working fluid flows, transferring heat with external exchangers.

Bruederlin et al. [49] introduced a design using SMA foil deflection as a heat sink with tilted geometry (Fig. 3). Their device achieved a temperature span of 14 K and a COP of 3.3 using air as the working fluid.

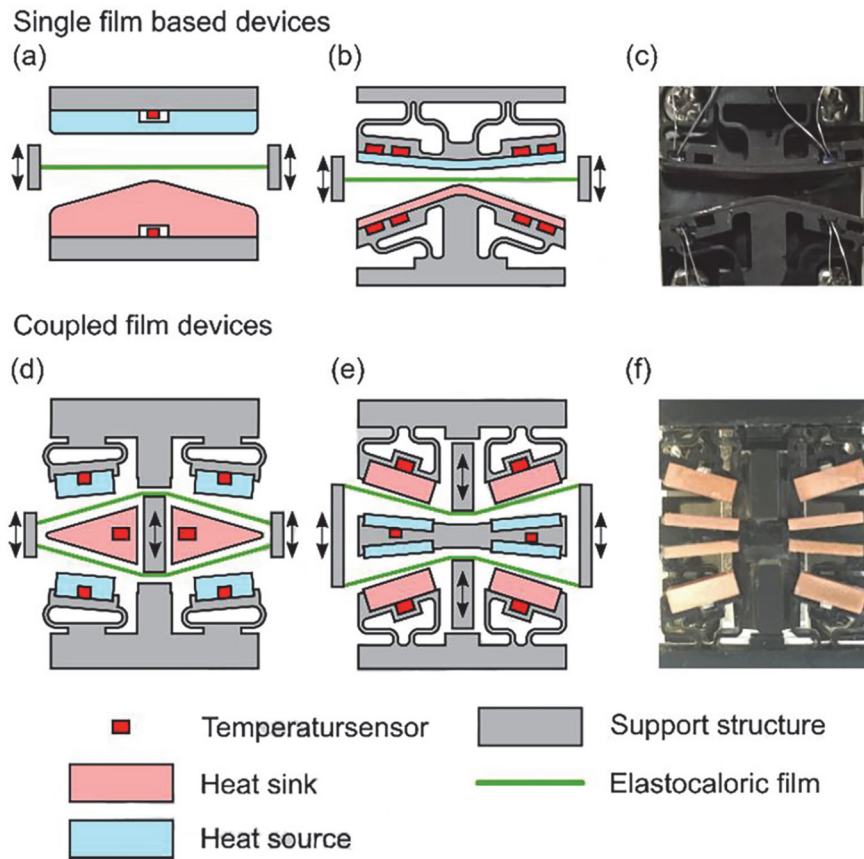


Figure 3: Thin films-based miniaturized eCE prototypes and their basic layouts [49].

More recently, Kirsch et al. [50] developed a rotary elastocaloric prototype using $\text{Ni}_{45}\text{Ti}_{47.25}\text{Cu}_{5}\text{V}_{2.75}$ wires. This device demonstrated a temperature span of 28 K, a COP of 8.4 and a cooling power of 250 W with 50 g of elastocaloric material. Fig. 4 shows a schematic prototype of the rotary cooling device made up of wires. Tab. 2 summarizes key performance metrics of several recent elastocaloric devices.

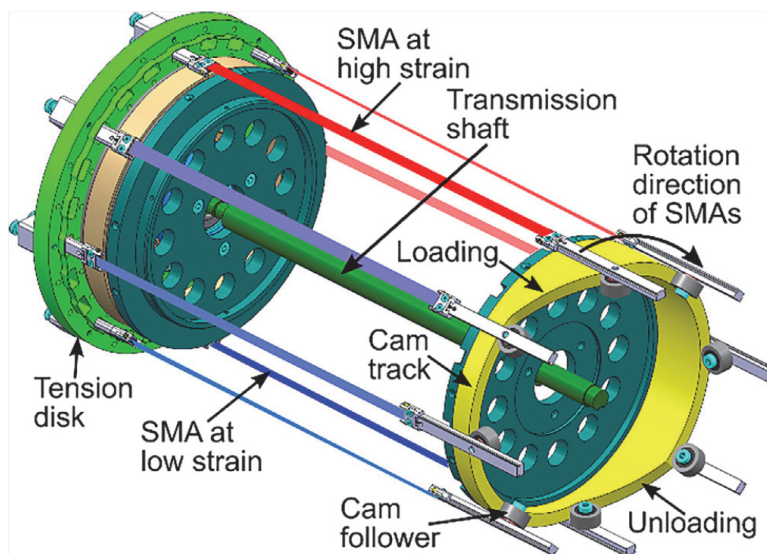


Figure 4: A schematic prototype of the rotary cooling device made up of wires [49].



Device Type	Material	Max Stress (MPa)	Working Fluid	ΔT_{ad} (K)	COP	Reference
SMA tube	NiTi	1100	Water	24.6	11	[51]
SMA plate	NiTi	440	Water	15.3	7	[52]
SMA foil	NiTiFe	-	Air	14	3.3	[49]
SMA wire	NiTiCuV	400	Air	28	8.4	[50]

Table 2: Performance comparison of elastocaloric devices.

These examples demonstrate the range of designs and performance levels achieved in recent elastocaloric devices. The COPs reported range from 3.3 to 11, with temperature spans of 14–28 K, showcasing the potential of this technology for efficient solid-state cooling. However, further optimization of materials, device designs, and thermodynamic cycles is needed to improve performance and move towards commercial viability.

All mentioned devices can be crucial in the integration of engineering technologies with biomedicine, even finding a solution to the biomedical requirement for compact thermal technologies that can allow extremely targeted temperature management.

EXPLORING THE POTENTIAL OF ELASTOCALORIC SMA FOR INNOVATIVE BIOMEDICAL DEVICES

SMA, particularly NiTi alloys, have been widely used in various biomedical applications since their properties were first revealed in 1962. Their exceptional capabilities, including shape-memory behavior and superelasticity, combined with high corrosion resistance and biocompatibility, have made them invaluable in applications ranging from implants to surgical instruments. Recently, the elastocaloric effect of SMAs has garnered interest for potential use in medical and biomedical applications. This section explores the advantages and challenges of elastocaloric NiTi devices in several biomedical contexts.

Temperature management systems in microfluidic technology

Microfluidic technology, a growing field that blends multiple disciplines and focuses on fluid handling at micro and nano levels, is crucial in various biomedical applications, including blood analysis, surgical microsystems and drug delivery. Elastocaloric NiTi devices offer promising solutions for temperature control in these systems.

Advantages:

- 1) Compact size: elastocaloric NiTi elements can be miniaturized, making them ideal for integration into microfluidic devices.
- 2) Rapid response: the elastocaloric effect allows for quick temperature changes, essential for precise control in biological processes.
- 3) Energy efficiency: these devices potentially offer higher efficiency compared to traditional Peltier elements.
- 4) Biocompatibility: NiTi alloys are already widely used in medical applications, ensuring compatibility with biological samples.

Challenges:

- 1) Cyclic stability: ensuring long-term performance over many heating/cooling cycles remains a challenge.
- 2) Integration complexity: incorporating the mechanical loading mechanism into microfluidic devices may require innovative design solutions.
- 3) Cost: initial development and production costs may be higher than existing technologies.

Compared to current joule heating or thermoelectric cooling methods, elastocaloric NiTi devices offer the potential for more precise temperature control with lower power consumption. For instance, a thermal management system based on elastocaloric SMA elements could replace current designs using cartridge heaters, providing a more compact and energy-efficient solution for controlling temperature in microfluidic devices.

As example, the employment of ECM was recommended for the design of innovative biomedical electromechanical devices operating at microscale (MEMS) or nanoscale (NEMS) [18], [126], even considering that the research on heat impact on cell activities has shown substantial improvements thanks to devices based on these innovative technologies [53].



Elastocaloric elements enabling transdermal drug delivery

Transdermal drug delivery (TDD) is an important area where elastocaloric NiTi devices could make significant contributions, particularly in the development of advanced microneedles technologies (MNs).

Advantages:

- 1) Temperature-controlled drug release: the elastocaloric effect can be used to trigger thermo-responsive drug delivery systems.
- 2) Enhanced skin permeation: localized heating can increase the permeability of the skin, potentially improving drug absorption.
- 3) Painless administration: the rapid and localized temperature changes could be used to create a numbing effect, reducing discomfort during needle insertion.
- 4) Multifunctionality: NiTi alloys can serve both as structural materials for MNs and as thermal actuators.

Challenges:

- 1) Precise temperature control: ensuring uniform and controlled heating/cooling across the MN array may be challenging.
- 2) Safety considerations: the potential for tissue damage due to excessive heating must be carefully managed.
- 3) Drug stability: the impact of temperature cycling on drug stability needs to be thoroughly investigated.

Compared to passive MNs or electrically heated systems, elastocaloric NiTi-based MNs could offer more efficient temperature control, potentially leading to improved drug delivery efficacy and patient comfort.

Additional potential biomedical applications

-Thermal neuromodulation therapies

Advantages:

- 1) Localized cooling: elastocaloric NiTi devices could provide precise, localized cooling for treating neurological conditions like epilepsy.
- 2) Rapid temperature changes: quick cooling could be crucial in stopping seizures effectively.
- 3) Miniaturization potential: suitable for developing compact devices for use in animal models or future human applications.

Challenges:

- 1) Biocompatibility for long-term implantation: while NiTi is generally biocompatible, long-term implantation for neuromodulation may present additional challenges.
- 2) Power requirements: ensuring sufficient cooling power in a compact and implantable device may be challenging.
- 3) Integration with neural interfaces: combining cooling functionality with neural recording or stimulation capabilities adds complexity.

-Selective cooling of biological tissue

Advantages:

- 1) Precise temperature control: elastocaloric devices could offer more accurate and localized cooling compared to current methods.
- 2) Rapid activation: the elastocaloric effect allows for quick temperature changes, useful in time-sensitive procedures.
- 3) Potential for integration in surgical tools: the compact nature of these devices could allow for incorporation into existing surgical instruments.

Challenges:

- 1) Tissue contact: ensuring good thermal contact with the target tissue while maintaining sterility may be challenging.
- 2) Depth of cooling: achieving sufficient cooling at depth in tissues may require innovative device designs.
- 3) Durability in surgical environments: devices must withstand sterilization procedures and be reliable in operating room conditions.

-Dermatological applications

Advantages:

- 1) Controlled cooling/heating: elastocaloric devices could provide precise temperature control for various dermatological treatments.
- 2) Rapid temperature cycling: useful for treatments that require alternating hot and cold therapies.
- 3) Portable designs: potential for developing handheld devices for in-office or at-home treatments.

Challenges:

- 1) Large area coverage: scaling up devices to cover larger skin areas efficiently may be challenging.



- 2) User-friendly designs: developing easy-to-use devices for non-medical personnel or patients may require significant engineering efforts.
- 3) Competition with established technologies: elastocaloric devices will need to demonstrate clear advantages over existing cryotherapy or heat therapy methods.

Application	Advantages	Challenges
Microfluidic temperature management	Compact size, Rapid response, Energy efficiency, Biocompatibility	Cyclic stability, Integration complexity, Initial costs
Transdermal drug delivery	Temperature-controlled release, Enhanced skin permeation, Painless administration, Multifunctionality	Precise temperature control, Safety considerations, Drug stability
Thermal neuromodulation	Localized cooling, Rapid temperature changes, Miniaturization potential	Long-term biocompatibility, Power requirements, Integration complexity
Selective tissue cooling	Precise control, Rapid activation, Surgical tool integration	Tissue contact, Cooling depth, Durability in surgical settings
Dermatological applications	Controlled cooling/heating, Rapid temperature cycling, Portable designs	Large area coverage, User-friendly designs, Market competition

Table 3: Summary of advantages and challenges of elastocaloric NiTi devices in biomedical applications

In conclusion, while elastocaloric NiTi devices show great promise for various biomedical applications, significant research and development efforts are still needed to overcome the challenges associated with their implementation. The potential benefits in terms of precise temperature control, energy efficiency and miniaturization make this an exciting area for future innovation in medical technology.

Reliability and fatigue life considerations in biomedical applications

Considering the critical nature of biomedical applications, the reliability and durability of elastocaloric NiTi devices are of paramount importance. The cyclic loading inherent in the elastocaloric effect poses significant challenges in terms of fatigue life, which is crucial for the long-term viability of these devices in medical settings. This aspect is particularly relevant, as the structural integrity and durability of materials are fundamental considerations in biomedical engineering.

Several studies, which results are summarized in “open strategies to improve performances” section of this paper, have investigated the fatigue behavior of NiTi alloys under conditions relevant to elastocaloric applications. Despite these advancements, several challenges remain in ensuring the long-term reliability of elastocaloric NiTi devices specifically for biomedical applications:

- 1) Biocompatibility of Fatigue-Resistant Alloys: while modifying NiTi compositions can enhance fatigue resistance, the biocompatibility of these new alloys must be thoroughly evaluated for medical use. This is particularly critical for implantable devices or those in direct contact with biological tissues.
- 2) Environmental Factors: the impact of bodily fluids and varying temperatures on the long-term performance of elastocaloric devices needs further investigation. Corrosion resistance and stability in physiological environments are crucial for biomedical applications.
- 3) Scaling Effects: many fatigue studies are conducted on small samples or thin films. Translating these results to larger, practical devices remains a challenge, especially for applications that may require larger temperature changes or more substantial cooling/heating capacities.
- 4) Combined Mechanical and Thermal Fatigue: in real-world biomedical applications, devices may undergo both mechanical cycling and thermal fluctuations, necessitating studies on combined fatigue effects. This is particularly relevant for devices that may be subject to both body movements and temperature variations.

To address these challenges and improve the reliability of elastocaloric NiTi devices for biomedical applications, future research directions should include:

- 1) Long-term in vivo studies to assess the performance and biocompatibility of elastocaloric devices under physiological conditions, focusing on both material degradation and biological responses.
- 2) Development of accelerated testing protocols specific to biomedical elastocaloric applications, simulating the unique stresses and environmental conditions these devices would face in medical use.
- 3) Integration of self-healing or fatigue-resistant microstructures in NiTi alloys to further enhance durability, potentially drawing inspiration from other biomedical materials with self-repairing capabilities.



- 4) Investigation of hybrid materials or composite structures that could combine the elastocaloric properties of NiTi with enhanced fatigue resistance and biocompatibility.
- 5) Exploration of surface modification techniques to improve both fatigue resistance and biocompatibility, which is crucial for long-term implantable devices.

The reliability and fatigue life of elastocaloric NiTi devices are critical considerations for their adoption in biomedical applications. Recent advancements in materials science and manufacturing techniques have shown promising results in enhancing the cyclic stability of these materials. However, translating these improvements into practical, long-lasting biomedical devices remains an active area of research.

As the field progresses, a multidisciplinary approach combining materials science, mechanical engineering and biomedical expertise will be crucial in developing elastocaloric devices that meet the stringent reliability requirements of the medical field. The potential benefits of these devices in terms of precise temperature control, energy efficiency and miniaturization make this an exciting area for future innovation in medical technology, but their success will ultimately depend on achieving the necessary durability and reliability for safe, long-term use in biomedical applications.

Outlook and challenges

In medical and biomedical fields heat system design is likely to persist contributing significantly in enhancing actual small size technologies and fostering the creation of novel technologies. SMA elastocaloric devices hold promise for delivering high thermal efficiency and serving as alternative engineering solutions for conventional cooling and heating processes.

However, despite the potential manifold benefits of ECM in the aforementioned fields, the path to market adoption appears to be lengthy. This is primarily due to the fact that the widespread scientific interest in ECM's thermal properties has not yet translated into a surge of applied research specifically tailored to medical and biomedical applications. Within these sectors, ECM technology still seems to be predominantly laboratory-oriented rather than industrial, exacerbated by a dearth of large-scale manufacturing techniques.

For these reasons, biomedical devices harnessing the elastocaloric effect are still in nascent stages, with most technologies confined to proof-of-concept demonstrations. Achieving a more comprehensive understanding and conducting dedicated research efforts are imperative to ascertain how ECM perform in real-world biomedical thermal instruments and how operating conditions are tunable. Only then can scientific findings accrued thus far be effectively translated into clinical applications, marking the initial strides toward commercialization.

The integration of ECM into biomedical devices represents a promising frontier with vast potential for innovation and advancement. By bridging the gap between fundamental research and practical applications, we aim to catalyze further exploration into the utilization of ECM in diverse medical and biomedical contexts. Through collaborative efforts and interdisciplinary research, we envision the creation of novel ECM-based biomedical devices that not only address existing challenges but also pave the way for transformative breakthroughs in healthcare. This proactive engagement with ECM technology holds the promise of revolutionizing medical diagnostics, therapies, and patient care, ultimately enhancing the quality of life for individuals worldwide.

CONCLUSION

This comprehensive review has explored the elastocaloric effect of Shape Memory Alloys (SMA) and its potential applications in the medical and biomedical industry. The key points and findings of this review are summarized as follows:

1) Elastocaloric Effect and SMA Materials:

-The principles and mechanisms have been examined, underlying the elastocaloric effect in SMAs, focusing on the martensitic phase transformation.

-Key performance indices for elastocaloric materials have been discussed, including temperature change (ΔT), specific heat capacity and coefficient of performance (COP).

-Various elastocaloric SMA families have been compared, with NiTi-based alloys showing particular promise for biomedical applications due to their biocompatibility and pronounced elastocaloric effect.

2) Performance Enhancement Strategies:

-Current strategies to improve the performance of elastocaloric SMAs have been explored, including microstructural engineering, compositional tuning and thermomechanical treatments.

-The challenge of balancing enhanced cyclic stability with maintaining high thermal capacity has been highlighted as a key area for ongoing research.



3) State-of-the-Art Elastocaloric Devices:

-Recent developments in elastocaloric cooling devices have been reviewed, showcasing various designs and their performance characteristics.

-The potential for these devices to provide efficient, compact cooling solutions has been demonstrated, with COPs ranging from 3.3 to 11 in recent prototypes.

4) Biomedical Applications:

-Several promising areas for elastocaloric SMA devices in biomedical applications have been identified, including: Temperature management in microfluidic technology, Transdermal drug delivery systems, Thermal neuromodulation therapies, Selective cooling of biological tissue and Dermatological applications.

-For each application, we have discussed potential advantages and challenges, emphasizing the need for further research and development.

5) Reliability and Fatigue Life:

-The critical importance of durability and fatigue resistance for biomedical applications has been emphasized.

-Recent advancements in improving the cyclic stability of elastocaloric SMAs have been highlighted, along with the challenges that remain in translating these improvements to practical biomedical devices.

6) Future Outlook:

-While elastocaloric SMA devices show great promise for revolutionizing cooling and heating systems in the biomedical sector, significant challenges remain.

-Key areas for future research include enhancing cycle resistance, developing efficient actuation methods, improving thermal capacity, and ensuring biocompatibility for long-term use.

-The integration of elastocaloric elements with other components in biomedical devices presents both challenges and opportunities for innovation.

In conclusion, the elastocaloric effect of SMAs holds significant potential for creating more sustainable and efficient medical devices and applications. However, the transition from laboratory research to practical, commercially viable biomedical devices requires continued interdisciplinary efforts. This review aims to encourage further studies into the applications of SMA's elastocaloric effect, supporting the future development of biomedical solid-state refrigeration and heating technologies. By disseminating this foundational knowledge, we hope to inspire researchers and practitioners to delve deeper into the realm of biomedical applications of elastocaloric materials, ultimately leading to innovative solutions that enhance patient care and medical capabilities.

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