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Shape memory alloys in fibre-reinforced polymer composites

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This article reviews the current state-of-the-art in the applications of shape memory alloy (SMA) wires into high performance fibre reinforced polymer composite materials (FRPs). SMAs have been investigated to date to address four main areas of properties improvement: (i) damping and vibrational response, where SMAs are integrated into composites either in the plane of the neutral axis, or as transverse stitches; (ii) impact, where SMAs are integrated in the neutral axis or as stitches; (iii) crack closure, where SMAs are integrated transverse to the crack, as stitches and (iv) shape morphing, where SMAs are integrated in plane into the composite, but in the non-neutral axis. The critical parameters for successful integration of SMAs to FRPs are highlighted, mostly from a composite processing angle. Finally, this review evaluates some hurdles remaining in the implementation of SMAs to FRPs to create smart and efficient composite structures without compromising their processing route, structural properties, weight and cost.

1. Introduction

The increasing need for weight-saving engineering solutions has led to the development of polymer matrix composite materials, now widely applied to aerospace, wind energy generation, sport as well as automotive applications. Polymer composite materials are man-made combinations of two or more different materials, in general reinforcing stiff inorganic or organic fibres and a polymer matrix that produce unique resulting properties, such as an improved stiffness, but also tailored thermal or electrical conductivity, to some extent mimicking many fibrous structures as found in nature. One of the main initial drivers for the development of composites has been the increasing need for materials with high specific stiffness and strength. More recently, the development of composite materials took advantage of their inherent heterogeneity and anisotropy to combine the traditional load-bearing functions of these materials with novel functionalities in the form of embedded elements. The resulting adaptive or "smart" composite materials may integrate actuators and sensors so that they can adapt and react to their service environment; this enables gains in efficiency not only by reducing structural weight, but also by integrating functions directly into the structure, which may act during processing, during part manufacturing and assembly, and during service, either to adapt to the service conditions, or to detect damage and even to effect repair of the structure in service.

An emerging class of such materials is fibre reinforced polymer composites containing thin Shape Memory Alloy (SMA) wires as functional elements [1–4]. Shape Memory Alloys have been available for 50 years and have found as bulk materials many applications as actuators or dampers, as well as in miniature tooling industry [5,6]. In comparison to other actuating technologies, SMAs provide the following advantages: high reversible strains (up to 6%) and shape recovery, high damping capacity, large reversible change of mechanical and physical characteristics, and the ability to generate high recovery stresses when they are prevented from recovering their shape. They have recently been available as wires with diameters below 0.2 mm, which may thus be integrated into and bring added functionality to a structural composite material, while not strongly disrupting the initial microstructure and structural properties and compromising the light-weighting benefits of composites. As a result, composite materials with SMA wires could demonstrate functions such as a shape change, a controlled overall thermal expansion, a shift in the part natural vibration frequency upon activation, possible damage reduction and repair … In practice, however, limitations have been encountered as the SMA transformation is in general induced by temperature change or

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stress (with the exception of magnetic SMA materials), greatly limiting their response time controlled by heat transfer kinetics. In addition, SMA wires integration must be made compatible with the polymer composite, requiring adaptation to the processing route, as well as to the part design to maintain sufficient structural properties, and to limit the weight increase.

The main goal of this article is to provide an overview of the use of SMA wires in structural, fibre reinforced composite materials, from the composite processing stand-point, as well as the resulting properties, spanning from vibration damping, to shape morphing, crack closure and impact damage mitigation. These aspects were also, but partly, reviewed in Refs. [2,7–10]. In particular, Lester et al. [8] provided a very extensive review of shape memory alloy composite systems, that also covers metal matrix and ceramic matrix composites, as well as the uses of SMA as a matrix, beyond the introduction of SMA into bulk polymers and polymer composites; the reader is referred to this reference for a more general overview on the response of these systems compared to the modelling methods that have been proposed. Here, we consider only SMAs that are embedded (as thin wires, or in rare cases ribbons or powders) into structural composite materials, and will not cover the literature dealing with the external attachment of SMA rods or wires to composite structures [11–13]. We also do not consider the use of SMAs as a single material included in a polymer matrix, a field that is now well developed in biomedical applications, including stents and valves [13,14].

We will first briefly recall the types of SMAs as well as their working principles. We will then review the applications of SMAs into structural composites as found in the literature, and as schematically illustrated in Fig. 1. The method of SMA integration, the choice of polymer and reinforcement material, as well as processing techniques, and the main types of property enhancement and their quantification will be addressed. Finally, we will detail the critical parameters that need to be considered when conceiving a composite with embedded SMA elements: wire positioning methods, interface properties and their change during successive SMA actuation, issues related to thermal effects during cure and during actuation, as well as the optimal positioning of the wire elements for best actuation with minimal impact on weight and other structural properties. Finally, we will review current and potential applications, and the remaining hurdles to address before a wider implementation of these functional materials in industrial applications.

2. Shape memory alloys overview

This class of metallic materials has been discovered in the 20th century, with first observations in 1932 with the expensive and toxic gold-cadmium alloy [15]. In the 1960s [16], nickel-titanium (Ni Ti)-based alloys, which are more affordable and non-toxic, have been established as the main class of Shape Memory Alloys, and attracted interest in a wide range of applications [8,17–19]. For an extensive review of the SMA mechanisms, the reader is referred to the numerous books and articles that describe these materials and their mechanisms [1,2,6,8,17,19]. We provide here only a brief introduction of the main principles, in particular as needed for applications in composite materials. Most SMAs display three main relevant properties: (i) the shape memory upon heating from a deformed martensitic state, with a possible two-way shape memory effect upon training, (ii) damping in the martensitic state, (iii) superelastic behaviour in the austenitic state.

SMAs are metallic alloys, which undergo a diffusionless, thermoelastic solid-state martensitic transformation of their crystal structure, involving a coordinated shear of atomic layers over distances that are on the order of the atomic layer. As a result, when an SMA, under no load, is cooled down from the cubic austenitic

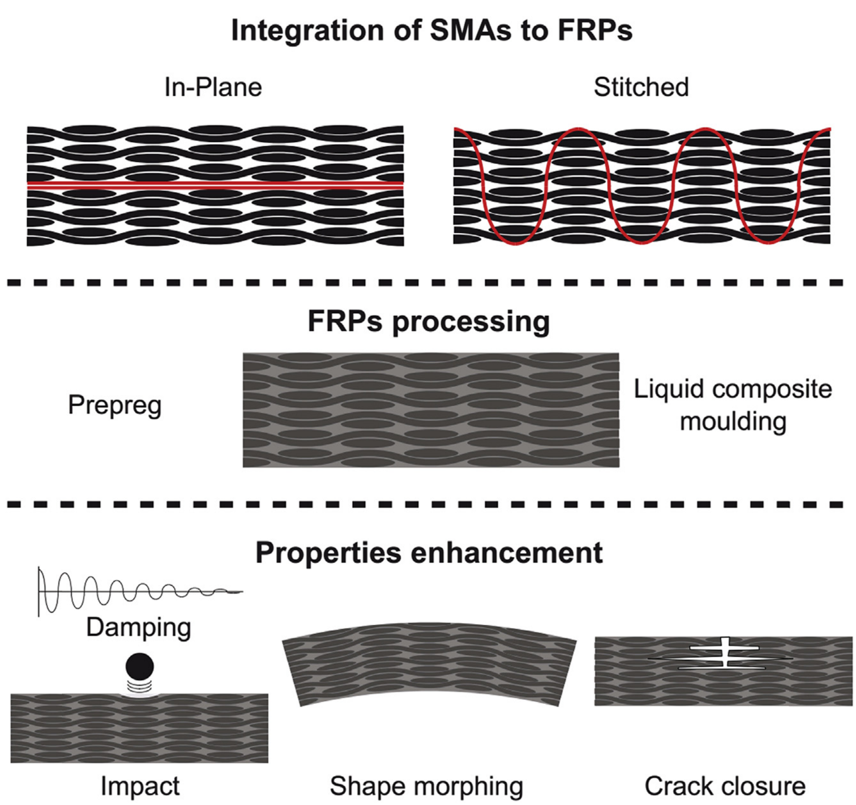

Fig. 1. Schematic concept of SMAs integration and processing in FRPs as well as resulting possible properties enhancement.

(parent) phase through its transition temperature, monoclinic martensitic variants form within the microstructure. As shear of the variants takes place in all directions, no macroscopic shape change is observed. The resulting structure is called self-accommodated martensite (SAM). The interfaces between these variants are glissile: when external stress is applied, the most favourably oriented variants grow at the expense of those which are least favourably oriented, thus forming a preferentially-oriented martensite phase (POM), also known as detwinned martensite, as shown in Fig. 2.

The phase transformation can be analysed based on thermodynamics, as it is driven by a decrease in the Gibbs free energy of the system. Thus, the martensitic phase is present when its Gibbs free energy G_M is lower than that of the parent phase G_A. As shown in Fig. 3(a), Gibbs free energies G_M and G_A are in equilibrium at a given temperature T_0. The martensitic transformation starts however, below T_0, at M_s (martensite start), as undercooling is necessary to initiate nucleation, and finishes at the lower temperature, M_f (martensite finish). While heating, the reverse transformation proceeds starting from A_s (austenite start) and ending at A_f (austenite finish). The resulting martensite fraction versus Temperature plot is shown in Fig. 3(b).

2.1. Shape memory effect

If the material is deformed in the martensitic state, creating the POM phase, the stress-strain curve is described as in Fig. 2(c): when the load is released, the material, after some elastic recovery, remains in the deformed state, although this is not a plastic deformation, but the result of the martensitic twins orientation. When reheated above the transformation temperature range, the crystal structure tends to revert back to the original form, and the strain is recovered, provided that there is no irreversible or plastic deformation (as would happen in some steel compositions, which can undergo martensitic transformation but does not exhibit shape memory effect). As a result, when heated, NiTi based materials can exhibit up to 8% recovery strains when free [21]. If the material is constrained, for example if a NiTi wire, that has been strained in the martensitic state, is reheated but fixed at both ends, the material exerts large recovery stresses, up to 700 MPa [1,10,21,22]. In intermediate cases, if a bias force prevents the wire from fully recovering its shape, a mix of strain and recovery stress is obtained. This effect can be exploited in composite materials, either to induce morphing of the part upon temperature change, or to exert a closing force when the material is heated above its transformation temperature and fixed at its extremities in the structure. In some cases, if the material is previously made to deform back and forth between two shapes (this operation is called training), the structure tends to recover its low temperature shape as well without any external bias. This is known as a two-way shape memory effect; however, this is not much exploited in composite applications, as the composite in general is stiff enough to act as the bias force in the cooling down phase. However, as the SMA wires tend to change their behaviour over the first activation cycles, to reach a generally stable stress-strain-temperature behaviour after a rather large number of cycles, it is generally advised to prepare the wires, prior to embedment, even if only one-way SMA is needed.

2.2. Damping of the martensite phase

As the martensite variants are very mobile, their movement and friction between the variant interfaces dissipate a large amount of energy when elastic waves travel into the material. As a result, the intrinsic damping capacity of the martensite phase (in particular in the transformation temperature range) is high; this can be exploited to confer added passive damping to the composite material [6,19].

2.3. Superelastic effect

A fully austenitic material can also undergo a stress-induced phase change, as illustrated in Fig. 3(c). The transformation thus occurs in isothermal conditions, and reverts back when the stress is released. As a result, a stress-strain curve for a material just above the austenitic phase transformation range is as shown in Fig. 2(b): this behaviour is called superelastic. Since energy is dissipated (under the form of heat) when the material is cycled in the hysteretic stress-strain loop, materials in this state can also act as passive dampers.

2.4. Other effects

SMAs can also be used as temperature sensors, since they also change their electrical conductivity, stiffness and damping characteristics when passing the transformation temperature, which is

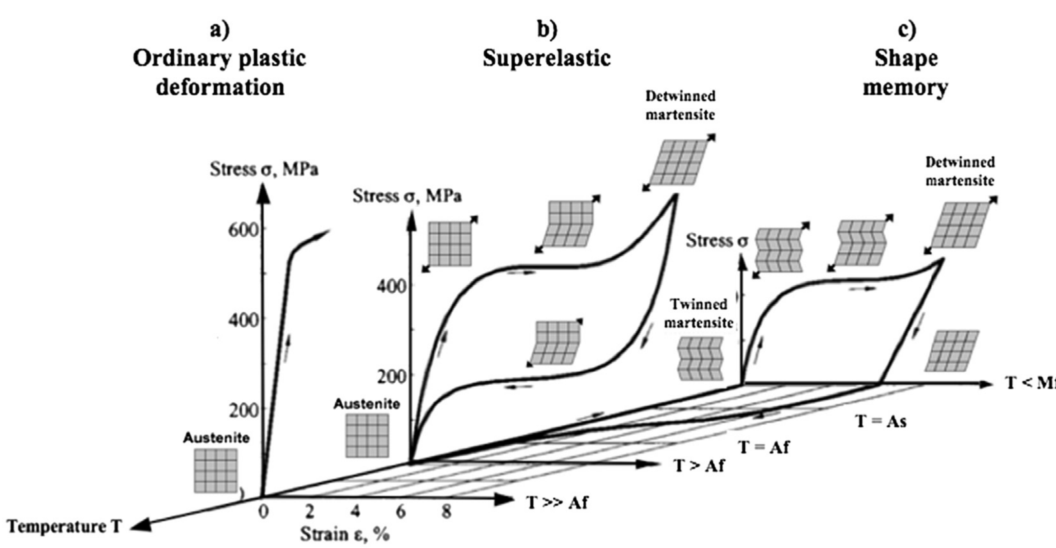

Fig. 2. Stress–strain diagram of shape memory alloys and the schematic crystal structures at three typical temperatures. (a) $T \gg A_f$ (b) $T > A_f$ and (c) $T < M_f$ (adapted from Ref. [20]). Reproduced with permission from ASCE.

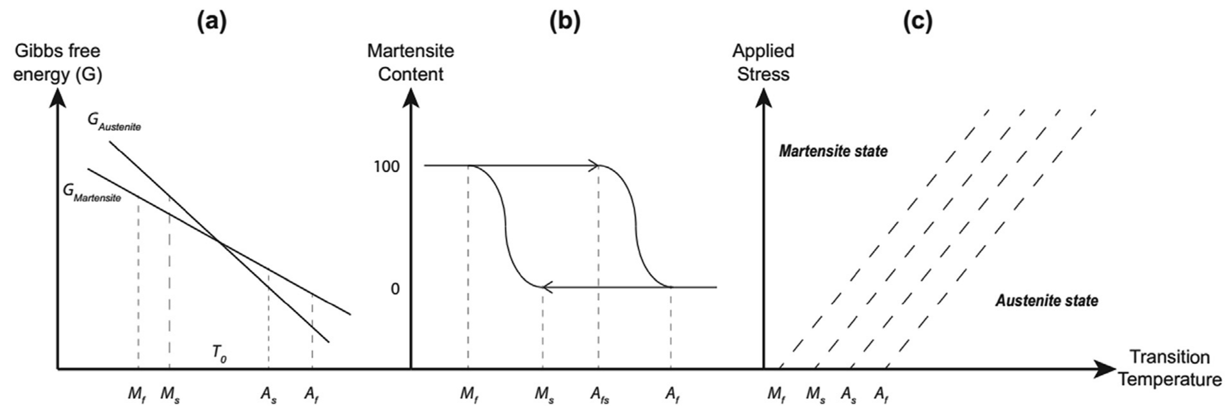

Fig. 3. (a) Gibbs free energy as a function of temperature for austenite and martensite phases. (b) Martensite fraction as a function of temperature, (c) Change in the transformation temperature curves under applied stress, showing the possibility of a stress-induced isothermal transformation from austenite to martensite.

dictated by the alloy composition. Most of the alloys present a rather large transformation range, which makes the change in properties gradual, but specific alloy compositions with narrow hysteretic ranges are found [23,24]. The large change in stiffness between the martensitic and austenitic phases (that can change from about 10 to 30 GPa to about 80 GPa, respectively), can also be exploited to produce structures with variable stiffness [25], simply by changing the part temperature. Another interesting sensing capability of the SMAs, not often mentioned, is the almost linear evolution of electrical resistivity with strain at a constant temperature, which could make these materials also useful as strain sensors [26], although this has not been reported for use in SMA composites.

Shape memory alloys are often exploited for their actuation capabilities, which are most striking and stem from their shape memory. The large recovery strains (up to 8%), or large recovery stresses if constrained (up to 800 MPa), led to their commercial application in fastening or clamping devices, and to the development of self-deploying structures [11,27]. SMA springs have also demonstrated their potential for thermally activated valves, in particular when acting against a steel spring to force their return to the initial position [28]. The two-way shape memory effect could be a solution to make the actuation reversible; however, it is worth noting that high precision in terms of activation magnitude versus the number of cycles is not achieved, as thermal fatigue and drift in the response remain an issue, even though some specific alloy compositions seem to provide better stability [29]. In all cases, accurate prediction of the thermomechanical behaviour of the SMA is needed to design the actuator, taking into account the non-linear and hysteretic behaviour of the alloy, which makes it difficult to control. Another limitation arises from the kinetics of the actuation, which are governed by heat transfer to or from the surroundings. These materials are thus only restricted to very low frequency activation, by opposition to piezo-electric ceramics. A promising competition in terms of frequency is the recent development of Ferromagnetic SMAs. As an example, NiMnGa alloys can achieve magnetically controlled strains up to 10%, with frequencies in the range of 200 Hz or more [30,31]. Applications as linear motors, valves and pumps are now proposed, although these materials are costly, very sensitive to surface quality and do not provide high recovery forces.

2.5. Comparison with shape memory polymers

SMAs being metallic alloys, their density is in the range of 6.45; as a result, they add weight to the structure when used as actuators, sensors and dampers in composite structures. Shape memory polymers, which are polymers exhibiting shape memory when heated above a transformation temperature (in general the T_g), are much lighter than SMAs. Their reversible transformation is not induced by a phase change, but by conformational entropy of the polymer chains, bringing them back to an equilibrium shape when in the rubbery state. The shape memory effect in polymers has been largely reviewed and investigated for shape morphing, crack closure, as well as damping properties improvements in FRPs [32–38]. A comparison of the main mechanical and recoverable properties between SMAs and SMPs is provided in Table 1 (two often investigated SMAs compositions are indicated as of interest for the present review). Intrinsic mechanical properties provide an indication of the capacity to recover high vs. low strain as well as stress. Notice that SMPs have very large recoverable strains, but that their stiffness and hence recovery stress is, as expected for polymer based materials, much lower than for metallic SMAs. In addition, they are activated at temperatures close to in-service temperature of many applications, which may also restrict their use. Recovery stress is crucial to act against the bias force exerted by the composite structure. As a result, SMP are mostly used in the direction transverse to the structural fibre reinforcement direction, or in large volume fraction, even as the matrix material itself. For example, Shape Memory Polymer Composites where the SMP forms the full matrix, impregnating carbon fibre reinforcements, have been investigated for making hinges or deployable light structures for space applications, and have demonstrated their effectiveness for shape change if the bias force is not too high [39],

Table 1
Typical properties of SMAs and SMPs found in various literature. Data are indicative.

		Elastic modulus [GPa]	Strength [MPa]	Recoverable strain [%]	Recovery stress [MPa]	Activation temperature [°C]	Reference
Shape memory alloys	NiTi	10–35	800–1100	5–8	<500 MPa	85	[1]
	NiTiCu	19	1200	5	<800 MPa	67	[44]
Shape memory polymers		0.01–3	0.1–100	<800	1–3	10–50	[45]

with some reservations concerning the potential microbuckling of the reinforcement fibres in the folded state, and the lack of high temperature solutions, which may better survive in a space environment. SMAs, owing to their much higher recoverable stress and temperature ranges, appear suited to use in low volume fractions for shape morphing, crack closure as well as damping properties improvement in FRPs. As an example, they have found use in active stitches to close cracks and improve the mechanical property recovery in self-healing composites [40–43].

3. Shape memory alloys in fibre reinforced polymers

The use of SMA wires into FRP structures was initiated in the early 90's by Rogers et al. [46,47]. By embedding NiTi SMA wires (5, 10 and 15 vol%) into a carbon-epoxy prepreg parallel to the reinforcement layers, they demonstrated that upon heating, the Young's modulus of the structure as well as the yield strength increased by a factor of 4 and 10, respectively. They further showed that the natural frequency of these systems could be tuned by heating the SMAs, which allowed tailoring the vibration properties of the FRPs. Since then, SMAs into composites were investigated by many researchers, including for impact damage resistance and suppression, as reviewed in Refs. [2,7–10]. In what follows, studies embedding SMAs into FRPs are detailed to cover the four main areas of properties improvements (see Fig. 1): (i) damping and vibration, where SMAs are integrated in-plane to the composites in the neutral axis, but also as stitches; (ii) impact, where SMAs are also integrated in the neutral axis or as stitches; (iii) crack closure, where SMAs are integrated transverse to the crack, as stitches and (iv) shape morphing, where SMAs are integrated in-plane to the composite, but in the non-neutral axis.

3.1. *SMAs in FRPs for damping and vibrational properties improvement*

SMAs embedded into composites have been used since many years to improve damping and vibrational properties using a variety of approaches. As mentioned above, SMAs in the martensitic phase have a high intrinsic damping capacity [48], and can thus be introduced as a second phase for passive damping increase without any need to pre-strain the SMA [23,49–51]. If this material is heated above the austenitic transformation temperature, the change in Young's modulus of the SMA phase and its decreased intrinsic damping can also contribute to a modification of the vibrational properties, this is often referred to as active modal modification. It is also possible to consider the use of superelastic SMAs, initially pre-strained to reach the stress-strain plateau, if the strain induced by the elastic wave propagation is large enough to dissipate energy through the hysteresis loop (as shown in Fig. 2) [52]. In both cases, a loss factor increase of 100% or more was obtained in carbon-epoxy composite plates, albeit to the penalty of a weight increase, of at least 20% [49]. A more efficient approach is to use the shape memory effect of SMAs to introduce an active damping effect, obtained through a change of temperature above the austenitic transformation temperature, leading to a recovery force. This is particularly striking if the part itself is constrained. Considerable research efforts have been carried out on this topic in the years 2000, in Japan [53,54], and in Europe in the scope of a European effort to provide a fundamental understanding for the manufacturing and design of SMA FRPs for active vibration control [29,55–61]. Balta et al. [59] first produced FRPs made of Kevlar/epoxy prepregs with embedded ternary NiTiCu SMA wires, which were 150 μm in diameter. NiTiCu wires, straight annealed (to provide them with a straight shape upon heating), were selected as they had a transformation temperature close to 50 °C, i.e. above room temperature, but not too high to remain below usual softening temperatures of the polymer matrix. Pre-strained wires (3%) were embedded in the middle plane of the reinforcing fibres, as shown in Fig. 4(b); a frame was designed to maintain the wires and avoid recovery of the wires during processing of the FRPs at 70 °C. The SMA-matrix interfacial shear strength was first assessed and was found optimal for SMA wires having a thin oxide layer on the surface. The recovery force and vibration response of the enhanced composites further showed a narrow hysteresis loop, as illustrated in Fig. 4(a). Recovery force measured on a clamped composite, upon heating, increased with temperature after the transformation temperature, and also increased linearly with the volume fraction of wires; this led to a resonance frequency shift upon actuation at 80 °C of more than 30% above the initial value directly related to the recovery force measured in a clamped-clamped condition, for a composite containing 3 vol% wires. Further characterisation of the vibration response is found in Ref. [61]. This research further led to the processing of an adaptive aircraft aeroelastic profile demonstrator, demonstrating the possible industrial use of adaptive composites [28,57,62]. Modelling and material design was adapted to take into account the interaction between the wire and the host materials response upon actuation. Šittner et al. [60,63] carried out simulations to find optimal parameters in terms of: (i) SMA wires (i.e. Young's Modulus, thermal expansion coefficient, transformation temperatures, hysteresis etc.); (ii) polymer matrix (i.e. Young's modulus and thermal expansion coefficient) and (iii) composite structure (i.e. composite layout, wires volume fraction, SMA pre-strain). Modelling, processing and characterisation of these adaptive structures are also reported in Refs. [29,55,56].

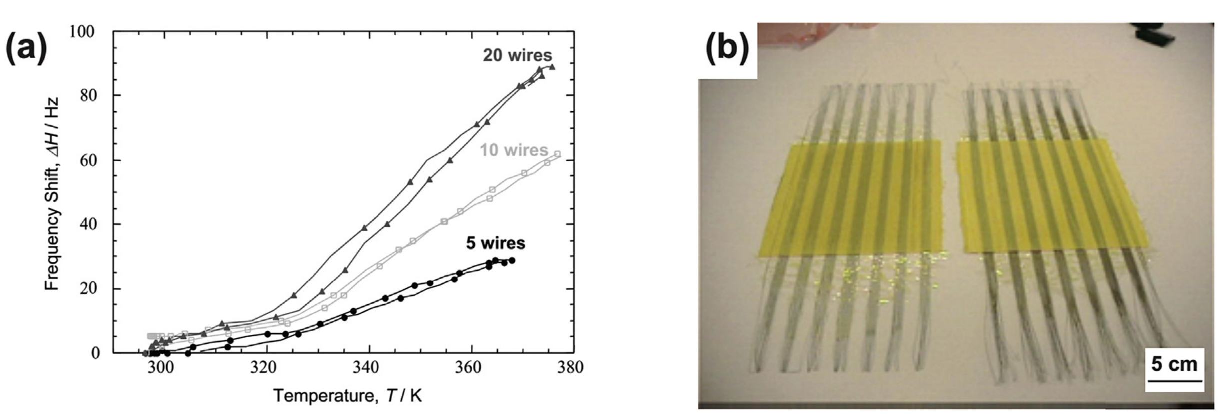

Fig. 4. (**a**) Resonance frequency shift as a function of temperature for clamped kevlar-epoxy composites with 4 prepreg plies but different number of wires (20 wires corresponds to 5% volume fraction wires); (**b**) Example of Kevlar epoxy composites, with embedded SMA wires. Reproduced with permission [29]. Copyright 2002, The Japan Institute of Metals.

Recently, De Matos Junior [64] proposed a semi-analytical model to predict the flutter of a Carbon/Epoxy composite containing embedded SMA wires, providing a tool to assess the effectiveness of vibration reduction, as a function of ply sequence, part aspect ratio, and other geometric parameters, in addition to the SMA properties versus Temperature. Finally, some realistic part concepts have been considered [25,65], in particular exploiting the fact that the SMA stiffness strongly changes between the martensitic and the austenitic state, thereby easily producing parts with variable stiffness.

3.2. SMAs in FRPs for impact resistance

Following their capacity to improve damping and vibrational properties into FRPs, SMAs can also supress, or at least decrease the damage area subsequent to an impact event. Two ways to integrate the wires have been studied: (i) in-plane in the FRPs and (ii) through the thickness of the FRP, as stitches.

Paine and Rogers [66] first demonstrated the use of SMA wires (0.4 mm diameter) to improve the FRP response to low velocity impact damage. They integrated NiTi wires into carbon prepregs, parallel to the fibres in the 0° plies that are below the neutral axis of the structure. Overall, the volume fraction of the wires was 2.8%. This strategy allowed a 25% increase in the delamination resistance upon impact as compared to composites without SMA wires. The wires also allowed stopping the perforation of the structure by the impactor. To further benefit from the SMA wires properties, a pre-strain can be applied to the wires before integrating them into the structure. Birman et al. [67,68] used a micromechanical model based on the multi-cell method to model pre-strained SMA enhanced FRPs. Their results confirmed the effectiveness of SMAs embedded within the composite layers to improve low velocity impact characteristics, if these are pre-strained and their contraction is prevented during composite manufacturing, thus creating tensile stresses. The improvements can be further tailored by optimizing the wires' distribution throughout the FRP plate. Similar modelling was provided by Roh and Kim [69,70] and confirmed these conclusions. For further modelling of SMAs embedded in composite structures to improve impact damage characteristics, the interested reader is referred to the following references [71,72]. Tsoi et al. [73] experimentally investigated the potential of SMAs, pre-strained, into FRPs to improve impact damage properties. They integrated superelastic NiTi and NiTiCu SMA wires (0.15 mm diameter), as well as stainless steel wires for comparison, into glass fibre epoxy prepregs. To allow pre-strained wires to be integrated into the structure, a special frame was designed to maintain the strain during the composite curing process (which was above the transformation temperature of the wires). Pre-strain levels of 0, 1.5 and 3% were investigated for NiTiCu wires. The influence of the position and volume fraction of SMAs was investigated with NiTi wires, which were integrated in between the reinforcing layers, at different positions, and with volume fractions of 0.45, 0.89 and 1.8%, corresponding to 0.5, 1 and 2 wires/mm in the structure, respectively. Overall, results showed that (i) the delaminated area decreased when increasing the SMA pre-strain level; (ii) the SMAs needed to be integrated in between the 0° plies, in the bottom half of the laminate, and especially in the bottom layer to decrease fibre breakage damage; and (iii) increasing the wire density increased the resistance to delamination. From these tests, the authors could create an impact performance map (Fig. 5), comparing the PDA slope (the slope of the damage area versus the incident energy), an indication of the damage resistance of the material (the greater the slope is, the easier the damage accumulation is), with the IEC slope (the slope of the absorbed energy versus the incident energy), a measure of the materials' energy absorption capacity (the greater the slope is, the greater the capacity for internal damping and impact energy absorption capacity). From this map, reference specimens, without embedded wires, show obviously high slopes, indicating high energy absorption capacity and easy damage accumulation. Steel and NiTiCu wires, have low slopes, representative of better damage accumulation; however these do not have high damping capacity. For improved performance, NiTi wires thus show a good compromise, and the choice of the wire volume fraction depends on the targeted application. The authors further studied the thermomechanical behaviour of a series of NiTi and NiTiCu wires to better understand their capacity to recover stress and strain when varying the temperature [22]. It is important to highlight at this stage that the study of Tsoi et al. [73] is the only one, to the author's knowledge, taking advantage of the SMA pre-strain benefit on the impact characteristic in SMAs enhanced FRP structures. In the remainder of this section, all studies thus not consider pre-straining of the wire before composite manufacturing. Considering the cumbersome processing route needed when integrating pre-strained SMAs in composites (the use of frames to prevent recovery during matrix curing), it is in fact not surprising that many of the studies do not consider such a route.

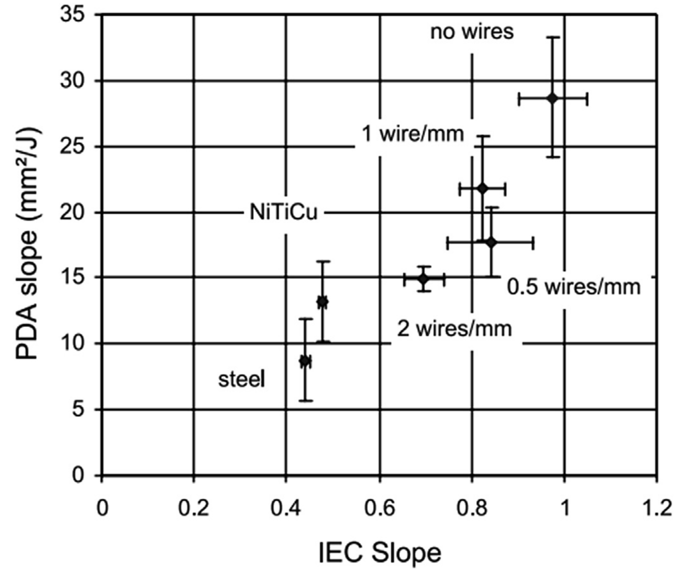

Fig. 5. Impact performance map [29,73]. The PDA slope is the slope of the damage area versus incident energy, and the IEC slope is the slope of the absorbed energy versus the incident energy. Where not indicated, SMA wires are NiTi superelastic wires. Reproduced with permission [73]. Copyright 2003, Elsevier.

In a set of two papers, Pappada et al. [74,75] assessed damping, mechanical and impact characteristics of SMAs (0.1 mm diameter) enhanced composites (the damping properties of these modified systems have been already discussed in Section 3.1). The authors first produced three types of hybrid glass-reinforced composites with a vinylester matrix for Charpy impact tests [74]: (i) plates with unidirectional superelastic NiTi SMA wires; (ii) plates with unidirectional steel wires to understand the influence of the SMA martensitic transformation; and (iii) plates with knitted SMA wires. All plates contained about 1% of reinforcing wires and were produced by vacuum infusion. While knitted samples showed a 37% enhancement in impact energy, samples containing unidirectional steel and SMA wires did not show a significant change in the impact characteristics. The improvement in the knitted configuration was related to the lower elastic modulus as compared to SMAs integrated in the plane of the structure. For both configurations, static flexural properties were affected by the hybridisation; this was attributed to fibre crimping and fibre-matrix adhesion. The authors continued their investigation by low-velocity impact tests on SMA enhanced laminates, produced again by vacuum infusion moulding with a vinylester resin and a plain glass fabric [75]. Aluminium frames were used to align the superelastic NiTi SMA wires in the 0° and 90° directions and the achieved wire volume content was about 3%. Impact testing curves, measured for incident energies varying between 1 and 500 J, showed a slight, but marginal, increase in the onset of delamination for the modified composites. However, when measuring the resulting damage area by light scattering under back illumination, infrared thermography as well as C-scanning, a considerable decrease in the damage area (up to 60%) was observed, especially for impact energies lower than 10 J. Similarly, Pinto and Meo [76] studied low-velocity impacts of 20, 30 and 40 J on composite plates made of an aramid warp knitted tape reinforced with SMA wires within a thermoplastic/carbon fibres laminate (SMAs were placed in the 0° and 90° directions). From the impact data curves, stiffness of the modified composites was increased, thus shifting to higher levels the maximum force values. Even though the energy absorbed by the samples was the same in reference and modified specimens, the hybridisation process changed the energy dissipation mechanism, leading to a reduction up to 300% in the damage area measured by C-scan tests. The authors also highlighted the difficulty to draw clear conclusions for the high incident energy levels due to progressive SMA breakage. In order to observe an influence of SMA wires on composite structures' energy dissipation for lower energy levels, Aurrekoetxea et al. [77] proposed to use a thermoplastic matrix (as opposed to thermoset resins seen with the previous studies), since it is tougher and more ductile and should allow earlier stress-induced martensitic transformation of the SMAs. In their study, superelastic NiTi wires (0.5 mm diameter), with a volume fraction of 2.3%, were integrated into a plain weave carbon fibre fabric with a poly(butylene terephthalate) matrix. The laminates were produced by vacuum assisted resin transfer moulding at 230 °C to allow thermoplastic impregnation. Impact tests were then carried out with energies ranging from 0.1 up to 6.8 J. Results showed that there is threshold energy level of 1.1 J, above which a non-negligible contribution of SMAs is found on the dissipated energy and strength of the laminate. This lower contribution, as compared to thermoset composites reported before, is well explained by the use of a thermoplastic matrix, but also from the lower reinforcement fibre volume fraction achieved with such resin (34% as compared to around 50% with thermoset resins). The environmental conditions of tests may also change the impact response of the laminates. Kan and Kim [78] produced a 24-ply glass/epoxy prepreg and embedded SMA wires in the neutral axis of the laminate. Impact tests were then carried out on modified and unmodified systems at three different temperatures: 293, 263 and 233 K. While the embedment of SMA wires showed obviously improved impact characteristics, the decrease in temperature increased the laminates brittleness and thus reduced the impact energy absorption capabilities.

Research efforts have been provided by Harbin University to study the effect of SMAs position on the impact behaviour [79,80], the influence of interface performance on mechanical behaviour of the enhanced laminates [81], and the fatigue behaviour of SMAs enhanced FRPs [82]. Sun et al. [79] embedded superelastic NiTi wires (0.2 mm diameter) into a unidirectional glass fibre reinforcement with a vinylester resin. The laminates were produced by vacuum assisted resin infusion moulding and the achieved fibre volume fractions were slightly above 50%. One or two layers of SMAs were inserted at different positions in the composites, each time at 1/8, 1/2, 14/16 and 15/16 of the laminates thickness. Specimens were all impacted at an energy of 28 J. Similarly to Tsoi et al. [73], the best impact performances were observed when SMA wires were integrated in the bottom layer of the composite (i.e. 15/16 of the laminate thickness) to reduce fibre breakage. Additionally, Sun et al. [79] showed that integrating a second SMA layer in the middle composite layer (i.e. 1/2 of the laminate thickness) improved the energy storage capacity of the system. Notice however that such integration has a cost in terms of weight increase as one and two SMAs layers represent a composite mass fraction of around 8 and 14%, respectively. These authors used similar specimen configurations to further study the impact characteristics in terms of critical energy absorbed during tests and observed a similar behaviour as in the above mentioned research [80]. Finally, using the optimum configuration with one layer of SMAs at the bottom of the composite laminate (i.e. at 15/16 of the laminates thickness), the authors studied the effect of different surface treatments provided to the SMAs on tensile, three-point bending and low-velocity impact of enhanced FRPs [81]. The SMAs treatments provided improvement on the composites mechanical properties in all three categories mentioned, in the following order: untreated wires, wires polished with sand paper, wires treated with H_2SO_4 followed by NaOH to respectively remove the oxide layer and promote hydroxyl attachment, and finally wires treated with a silane coupling agent. It is not surprising, considering the usual sizing found in fibre reinforced composites, that the silane coupling agent showed best properties. The authors lastly assessed the fatigue life of SMAs composites, which was more than twice higher than for unmodified systems [82].

Using SMAs to tailor impact properties in composites structures has been also assessed by using the wires as stitches. Such stitches are commonly named as translaminar reinforcements; a detailed review of these materials and their behaviour as compared to conventional FRPs is given by Dickinson [83]. A translaminar fibre-reinforced composite is defined as a composite with up to 5 vol% of fibre reinforcement oriented in the through-thickness direction. Inserting this kind of reinforcement considerably disturbs the behaviour of the FRP, however it has been observed to provide several advantages including: improving the compression after impact (CAI) response, increasing interlaminar fracture toughness in Mode I and II, restricting impact damage and edge delamination. The penalty to these improved properties is the decrease of in-plane properties. Inserting these translaminar reinforcements (i.e. SMAs) to an FRP are of course accessible, but time consuming on a laboratory scale. On an industrial scale, this can be achieved through conventional stitching machines for FRPs with minor changes as SMA wires down to 0.2 mm in diameter can be produced [10]. Lau et al. [84] manufactured by RTM a ten layers E-glass epoxy woven composite stitched with NiTi SMA wires of 0.22 mm diameter. Through impact tests (at about 3.4 J impact energy), they demonstrated that SMA stitches decreased the delamination energy and the number of translaminar cracks, and also increased the tensile modulus as well as the damping ratio of the composites as compared to unstitched systems. These property variations were enhanced when increasing the volume fraction of SMA wires. Vachon et al. [85,86] manufactured SMA (or Kevlar) stitched FRPs made of a 16 plies uniaxial carbon fabric and epoxy resin; a cross-section of the resulting structure, showing the SMAs (or Kevlar) stitches is given in Fig. 6. The authors observed a 7 and 19% decrease in the impact delamination area (with energy level of 1 J/mm) for SMA and Kevlar stitches which was translated in a 1, respectively 8%, increase of the CAI response as compared to unmodified systems. Finally, Cohades et al. [87,88] used NiTiCu SMA wires (diameter of 0.15 mm) as stitches (with a similar pattern as Vachon et al. [85,86]) in a woven glass fabric. SMA wires were inserted through a semi-automatic sewing process in the dry fabric preform before composite processing. Laminates were produced by vacuum assisted resin infusion moulding with an epoxy resin as well as a healing matrix (see Section 3.4 for further details); the resulting

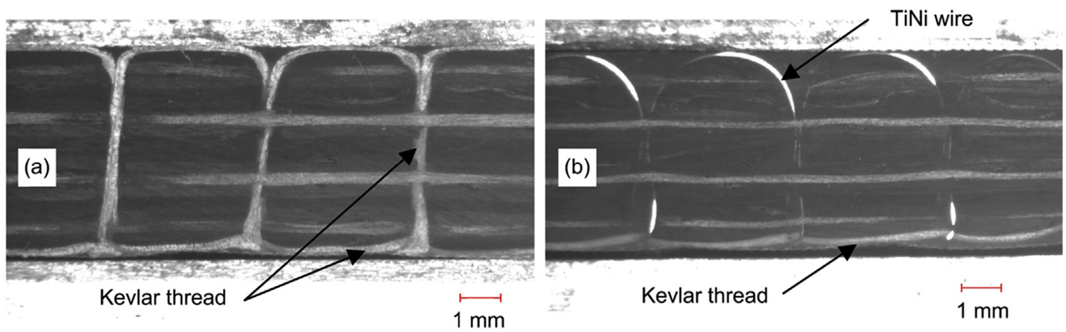

Fig. 6. Micrographs of (a) Kevlar-stitched and (b) TiNi-stitched laminates [86].

volume fractions of fibres and SMAs were respectively of around 47 and 0.4%. Following impact tests at energy levels up to 34 J, the delaminated area changed significantly only for the highest impact energy and for the composite containing the healing matrix (a softer resin). Considering that with SMA wires placed in between the laminate layers, the delaminated area can be reduced up to 60% [75], stitching SMA wires into FRPs did not induce the expected energy absorption effect. Notice however that volume fractions used for stitching are much lower (<1%) as compared to structures studied with SMAs in−plane in the laminate (>4%).

3.3. SMAs in FRPs for structural shape morphing

Shape morphing, whether by control of in plane strain (if the wires are embedded in the neutral plane of the composite part), or by control of bending properties (if the wires are embedded off the neutral plane) is a very promising application for SMA composites (often called SMAHC for SMA hybrid Composite), and has led to many studies, both experimental and numerical, to evaluate the benefits of integrating the wires inside the composite, instead of simply anchoring free wires (which may give more freedom and reach faster actuation, but are more difficult to protect and scale up) [2,8,11,25,65,89]. In this case, the shape memory effect of the SMA is exploited through a change in temperature. When a pre-strained SMA wire is embedded into a host composite material, the force balance between the elastic properties of the host and the recovery stress in the wire creates an overall strain in the composite, given in simple terms (in one dimension) by:

$$\varepsilon(T) = \frac{V_w}{1 - V_w}\,\frac{\sigma_w(T)}{E_c} - \alpha_c(T - T_0) \tag{1}$$

where T_0 is the temperature at which the thermal load starts, E_c and α_c are the host composite Young's modulus and coefficient of thermal expansion, respectively, V_w is the volume fraction of wires in the host composite. The stress imposed by the wires, $\sigma_w(T)$ is obtained through modelling or directly from a stress recovery curve of a single clamped wire.

Extensive effort was carried out in the early 2000s at NASA LaRC, with the aim to embed SMA ribbons or wires in the neutral axis of host composite structures, in general glass epoxy prepregs, to evaluate the in-plane (and out of plane buckling effects) and vibration properties of the beams, and to develop the corresponding in-house predictive models [90–95]. Davis et al. [90] proposed further refined models, and introduced them into the commercial FEM software Abaqus, with good comparative results. Since the GFRP has a positive thermal expansion, thermal actuation created first an expansion, then a contraction of the beam. Balta et al. [58] and Yoon et al. [96,97] embedded fibre Bragg grating sensors into the FRPs made of Aramid/Epoxy unidirectional prepreg with SMA wires to monitor in-situ the strain during production and shape memory activation, thus allowing self-triggering of the shape memory effect, for example to keep the strain constant even when the beam is loaded in tension, thereby creating an adaptive system. They demonstrated that significant negative linear strain of the structure takes place upon heating of the SMAs by Joule effect, which is directly related to the host material properties (with a contribution from the negative thermal expansion of the Aramid/Epoxy composite), the wire behaviour and wire volume fraction. As an example, a reversible contraction of 0.1% was obtained from heating a sample with 16 embedded NiTiCu wires (about 5% volume fraction), pre-strained by 3%, from 20 °C to 85 °C. Araujo [98] performed similar experiments, with a carbon-epoxy host composite and NiTi wires embedded in the neutral plane of the samples, and proposed methods to limit the part buckling during thermal activation.

It is also in principle possible to create an out-of-plane shape change, by careful positioning of the wires in the part, associated with the corresponding modelling tool, as many geometric parameters then contribute to the final shape; this is often named Active Shape Control. Due to the complexity in the control of both the modelling parameters, and the precise positioning (and pre-strain which is in these cases difficult to maintain) of the wires, only few studies compare theory and experimental results. Jung et al. [99] produced U-shaped glass-epoxy composites by wet lay-up, with embedded pre-strained NiTi wires out of the neutral axis, and could verify the effectiveness of a FEM based analysis (using the model of Lagoudas [19]) by comparing the variation in radius of curvature of the beams (as a function of wire position, for a given actuation temperature) with the model results. Fig. 7 illustrates their sample geometry, a view of their actual samples during measurement, and the change in radius of curvature of the beam as a function of wire location, both experimentally and numerically. Daghia and co-workers also proposed a FEM model that evaluated the SMA (Nitinol, pre-strained 4%) and host carbon fibre composite properties separately [100]; they monitored stiffness evolution, or tip displacement in a cantilever beam, heated in a chamber, and attributed the discrepancies with theory to the precision of the SMA model. In subsequent work on the actuation of NiTi embedded into polyester/glass fibre composites manufactured by vacuum infusion, they pointed out the need to carefully control the glass transition temperature of the matrix, to ensure a reproducible behaviour [101]. Naghashian et al. [102], with a simple analytical model, predicted the curvature of SMAs embedded into glass fibre composites, made from prepregs, as a function of temperature. Fig. 7 shows the comparison between the model results and measurements of the curvature as a function of temperature for several types of composites, with different wire volume fraction and position. They then derived rules to determine the maximum radius of curvature, normalized by the beam thickness that can be obtained in these composites. Lacasse et al. [103], and Simoneau et al. [104] also

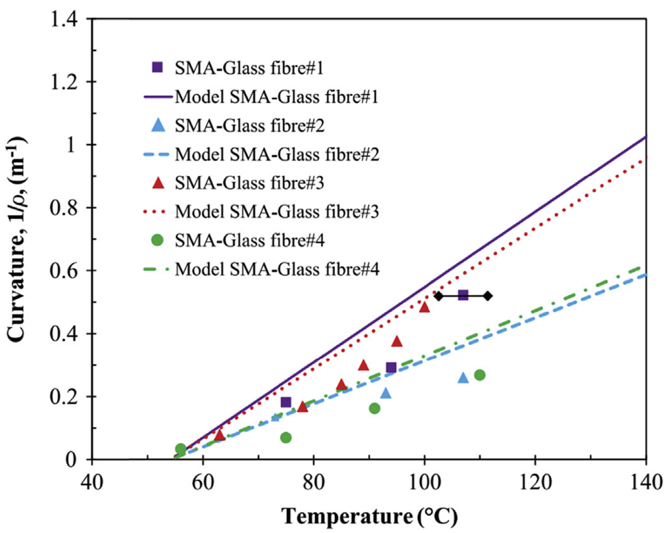

Fig. 7. Curvature changes as a function of temperature for SMA-glass fibre composites and their models. Only first heating is shown. The error bar is shown to indicate the ±5 °C uncertainty in the temperature [102]. Reproduced under the Creative Commons Attribution 3.0 licence.

proposed the design (using Finite Element Analysis methods) and manufacturing of curved carbon composite panels, this time produced by Vacuum Assisted RTM; they did not really embed the wires, though, and preferred to leave the wires free to slide into embedded tubes, so as to avoid interfaces issues and to maximize the strain, as if the wires were attached onto the part surface. This is a potential solution if the panels are not subjected to fatigue or transverse loads, as large pockets of resin resulted from this geometry.

A main limitation of these systems is their frequency of actuation, which is in general, lower than a few Hz, as it is controlled by the diffusion of heat in the generally not highly conductive polymer composite host. A potential alternative, which has unfortunately yet not been proven in the case of structural composites, but only for pure polymer matrices, is the use of magnetic SMA, which can reach up to 5%strain at much higher frequency [51,105–108]. However, activation may also be limited by the viscoelastic nature of the polymer host.

3.4. SMAs in FRPs for crack closure and self-healing improvement

SMA stitches in FRPs have also been used to provide autonomous (upon SMA triggering by heating) crack closure after a damage event, thus improving the self-healing capability of the structure. The design key to achieve such capability is to insert SMA wires perpendicular to the crack direction (i.e. perpendicular to the reinforcement layers in FRPs).

Wang [12] first demonstrated this concept by modelling the integration of pre-strained SMA wires into polymer composites patches to enhance repair efficiency thanks to the compressive stress provided by the SMAs that have been strained during damage, and then activated by heating. The model provided an estimation of the optimum SMA volume fraction to produce the required closure stress given by the part design as well as the maximum pre-strain of the SMAs before they are embedded in the composites. The model also demonstrated that increasing patch thickness and reducing matrix modulus is beneficial to increase the closure stress, which is also affected by the bonding strength between SMAs and the composite matrix. Thus, the patch thickness and the SMA wires' surface treatment are key in such a concept.

Crack closure modelling by SMAs directly embedded into composites has been further modelled by Brinson et al. [109] and Bor et al. [110]. In particular, Bor et al. [110] modelled FRPs with SMA wires as translaminar stitches with the aim to determine if the SMAs can provide crack closure after heat treatment. From their model simulation, it was concluded that SMA wires can compress delamination interfaces when a heat treatment is applied on the composite part. However, they also concluded that this crack closure behaviour might be obtained with other wire materials as the heat treatment applied in their simulation was above the matrix T_g, which softened the system and allowed such compressive stresses. Applying heat treatments above the matrix T_g needs careful composite design, as the structural integrity of the system might be lost. Nevertheless, this study showed a good promise to close delamination cracks when SMA wires are integrated as stitches into FRPs.

Experimental crack closure through the use of SMAs was first studied by Kirkby et al. [111–115]. They showed that the addition of pre-strained SMA wires into an epoxy resin containing the microcapsules of DCPD-Grubb's healing system improved the healed peak fracture load during tapered double cantilever beam testing by a factor up to 1.6. This improvement was attributed to: (i) the pre-strained SMAs, which upon heat activation, allowed crack closure and therefore reduced the crack volume; (ii) the heating of the healing agent during its polymerisation, which increased the degree of cure. Notice that Kirkby [113] stitched SMA wires into FRPs to provide crack closure and improve the healing process, however, the beneficial effect of SMA wires could not be concluded at that time.

Neuser [116,117] then showed that the addition of SMAs into an epoxy resin where solvent microcapsules based healing systems were added, improved, upon heating of the SMAs, the healing efficiency up to 78% (as compared to 24% without SMAs). He also pointed out the need to anchor the SMAs away from the crack path, for example by introducing a knot in the wires, and to take advantage of interface debonding to spread the deformation field in the SMA wires.

Through the combination of stitched SMA wires with an epoxy-polycaprolactone (PCL) healing matrix in FRPs, Cohades et al. [87,88] demonstrated that such a smart structure, through heat treatment at moderate temperature, has the ability to first close a crack before sealing it. Pull-out testing results first indicated that wires can debond in FRPs when placed perpendicular to the fibres whereas the wire deformation was completely blocked in the stitch bends, which is ideal to provide controlled debonding and thus the highest crack closure ability after a damage event. For a crack opening of 200 μm, SMA wires were overall able to bring the crack faces in close contact when activated through heat treatment and this over at least three cycles. The repair capacity of these smart systems was then demonstrated for low-velocity impacts at increasing energy levels. SMA stitched glass fibre-reinforced epoxy-PCL composites showed the ability to almost fully heal impact damage events from low energy up to 17 J. This achievement was possible through the combined effect of: (i) the epoxy-PCL healing matrix that could repeatedly expand and fill microcracks after multiple damage events; (ii) the stitched SMA wires, which autonomously closed cracks that were above a threshold thickness of PCL expansion. These smart materials can thus be of high interest in composite structures that are subjected to moderate loading events resulting in matrix microcracks, even though further work is now still needed to assess other relevant properties such as conventional in-plane and fatigue tests.

4. Critical parameters to integrate SMAs to FRPs

From the studies integrating SMAs into FRPs presented in Section 3, several issues and critical parameters to select, produce, and test such systems have been encountered. Even though variations are found for each specific systems, all reported articles produce the smart FRPs either by using prepregs, or by Liquid Composite Moulding (LCM) techniques. The matrix of the FRP is usually a thermoset (mainly epoxy, sometimes polyester or vinylester) and the SMA is NiTi eventually with Cu addition, with a shape memory activation temperature close to ambient temperature. Issues and critical parameters highlighted can thus be divided in different categories as follows.

4.1. Selection of adapted wire

The type of wire needs first to be carefully selected depending on the targeted property improvement. Two parameters are of importance: the wire size and the transformation temperature. In terms of wire length, continuous wires are most often used as they can be positioned and pre-strained through devices that are placed around the part, and as sufficient length is required to provide the crack-closure or activation that is sought. Short wires/particles could be used if passive martensitic damping is considered, as reported in Refs. [51,105,107]. The diameter of the SMA wires generally varies between 0.1 and 0.5 mm and should be carefully selected to: (i) provide the least possible intrinsic property modification to the FRP; (ii) allow its integration to the FRPs, especially for stitches, so the diameter should be as low as possible; and (iii) tailor the required quantity of SMAs needed into the system and avoid too much weight increase. The type of wire then needs to be carefully selected depending on its exact chemical composition and the resulting transformation temperatures to reach the desired effect, and to remain stable after several actuation cycles. For the studies reported above, integrating SMA wires in FRPs, NiTi wires had an Austenite finish temperature below room temperature while NiTiCu wires had an Austenite finish temperature of around 60 °C as well as a Martensite finish temperature above room temperature. If the wires need to be activated for shape morphing or crack closure, it is a necessary condition to have an Austenite finish temperature well above room temperature. If the wires are pre-strained, their activation temperature also needs to be compatible with the temperature cycles required to process the composite, in order to avoid annealing of the wire. Some authors have however proposed flash heating techniques to circumvent this issue [118,119].

4.2. Selection of adapted host material

Carefully selecting the host material is also of high importance to exploit at best the properties of SMAs. The host material should have the required stiffness, strength, toughness for the given application, but if these are too different from those of the wires, incompatibilities may occur such as premature delamination of the wire, early failure of the structure or the impossibility to sustain temperature differences due to large differences in thermal expansion. As a result, some compromises may be necessary, for example, a negative coefficient of thermal expansion of the host (and thus of the reinforcing fibres) will favour the negative strain needed for active damping or shape morphing. This is the reason why carbon and aramid are most generally chosen over glass. However, carbon is an electrical conductor, which may cause issues if Joule heating is selected. The host material polymer matrix, and its process condition requirements, also need to be compatible with the phase transformations of the SMAs to avoid any annealing of the SMA or unwanted shape recovery during processing.

4.3. Positioning of the SMAs into the system

SMAs have been used for damping, impact, shape morphing and crack closure in composite structures. In each of these cases, the wires need to be carefully placed to obtain the desired effect. To improve the damping properties of composites structures, the SMAs need to be inserted in the neutral axis of the FRPs. For impact properties improvement, somehow linked to the damping case, the increase in impact energy absorption is also achieved with SMAs placed in the middle plane of the laminate. However, it was demonstrated that SMAs need to be inserted bottom part of the laminate to reduce fibre breakage [73]. For shape morphing, the wires positioning depends on the desired effect and shape change, as described in Section 3.3. In order to efficiently close a crack, one SMA (or more) should cross it perpendicularly. However, damage to be closed can be oriented in the three dimensions of the reinforcement, which requires a cumbersome integration. An efficient way for closing every crack arrangement has been achieved by inserting SMAs through the thickness of the reinforcement as a continuous stitch [88]. The wires need to partially debond and be anchored to limit their strain when the crack opens, and to provide enough recovery stresses to close cracks upon heating (see Section 4.5 for further details on the wire-matrix adhesion). Stitching SMA wires into FRPs has also been assessed to improve impact damage properties, but this configuration in general did not lead to the expected energy absorption effect as compared to SMAs placed in the plane of the structure. Finally, the wire placement is also of high importance in terms of FRP architecture disruption. When SMAs are placed in the plane of the structure (i.e. in between two layers of the laminates or fabric) and if a unidirectional reinforcement is used, the fibres surround the wires (see Fig. 8(a)). If the

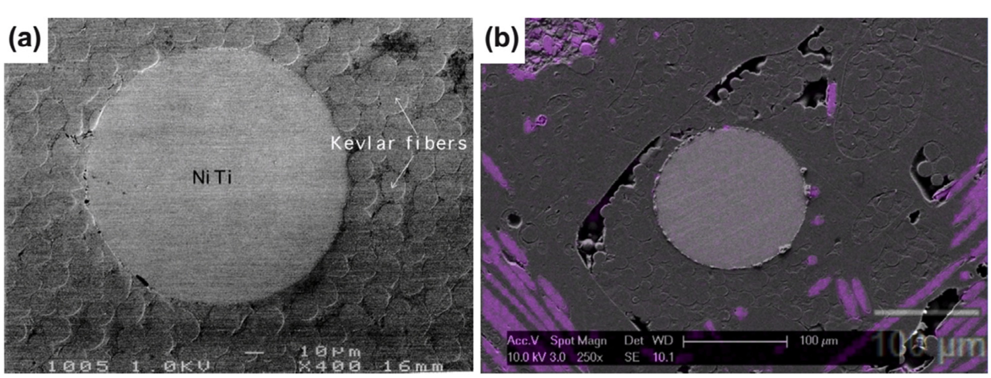

Fig. 8. (a) Cross section of a Kevlar fibre composite with embedded 3% pre-strained TiNiCu wires, showing the fibre distribution around a wire [44]; (b) SEM image of the cross-section of a polished specimen of an *Epoxy-PCL* blend containing glass fibre reinforcement; the pink areas indicate the presence of Si (determined by EDX analysis) and hence the location of the glass fibres [88]. Reproduced with permission [88]. Copyright 2018, Elsevier.

reinforcement is a weave pattern, the wires may not surround well the fibres, thus preventing efficient compaction of the reinforcement during composite processing. Oppositely, if SMAs are stitched into the structure, the fibre architecture disruption is larger due to the need of using a needle for stitching (see Fig. 8(b) where a channel of 0.5 mm was created inside the reinforcement [88]). Positioning of the wires needs thus to be carefully controlled to avoid the degradation of FRPs mechanical properties if the wires are affecting too much the reinforcement architecture.

4.4. Cure schedule selection to prevent undesired shape recovery

When used for passive damping (i.e. with the wires in the austenitic or martensitic undeformed state at room temperature), the cure schedule of the composite system is not of high importance as it will not affect the SMA properties, as long as annealing temperatures are not reached. However, for active damping as well as shape morphing and crack closure purposes, the cure schedule is essential to preserve the highest possible shape memory effect. Balta et al. [59] showed that 3% of pre-strain of the NiTiCu SMA wire provided the highest recovery stress upon activation. Moreover, in order to provide an efficient (and reproducible) load transfer during strain recovery of the wire, the activation temperature of the SMA must remain below the T_g of the matrix. However, composite processing with thermoset matrices implies post-cure temperatures that are close to the desired final T_g and therefore above the wire activation temperature. If pre-strained, the wire may therefore recover its initial strain already upon curing, preventing its use when needed. This problem is also present for two-way shape memory alloys. The use of frames [29,59,112] or of some preliminary treatment of the wires [118,120] (to raise A_s), or of an adapted resin curing schedule [111–113] were demonstrated as efficient methods to prevent early strain recovery, however this does not necessarily scale-up well towards industrial manufacturing. Increasing the interfacial shear strength was also demonstrated as possible [112], but this can lead to problems of load dissipation during damage (see Section 4.5). Inserting the SMA wires as stitches may solve this problem as the resulting 3D network and its adhesion to the matrix (without raising it too much) may prevent strain recovery upon heating; however, this is not in-line with the requested SMA effects for damping and shape morphing properties. A last solution is to perform curing below A_s; load transfer as well as wire strain recovery may not be obtained in this case due to poor matrix properties but can be solved by a tailored post-curing treatment [112]. Notice however that if SMAs are used for crack closure, no pre-straining may in general be required as the crack opening will strain the wire, thus preventing these cure schedule complications.

4.5. SMA-matrix adhesion

Improving the damping or impact properties as well as providing the highest recovery of SMAs upon heating into the FRPs (for shape morphing or crack closure) requires an efficient load transfer from the SMA to the surrounding matrix. In particular, thermal actuation of pre-strained SMA wires leads to the formation of high shear stresses at the interface between the wires and the host composite, which must not lead to premature failure of the part. Repeated actuation cycles also require that the interface sustain the resulting shear for a large number of cycles. Therefore, wire/matrix adhesion is a key parameter. For crack closure, the adhesion level should be high enough to avoid wire debonding during recovery, but should not be too high to avoid permanent plastic deformation and failure of the wire, which prevents efficient strain recovery. Upon crack opening, the wire should therefore partially debond, to provide enough wire length to be strained to the appropriate level, but should also be able not to debond later upon activation in order to provide crack closure. Neuser [116] introduced wire knots, which allowed a controlled debond length through anchoring, and uniform strain over a significant length of wire to efficiently close the crack upon activation. This technique, not suitable for industrial purposes, however indicates what happens with translaminar stitched wires as the top and bottom bends of the stitch may act as knots. This last has been confirmed by Cohades et al. [88], where pull-out testing results indicated that wires can debond in FRPs when placed perpendicular to the fibres whereas the wire deformation was completely blocked in the stitch bends. For damping, mechanical and impact properties, it was demonstrated that several wire pre-treatments (wires polished with sand paper, wires treated with H_2SO_4 followed by NaOH to respectively remove the oxide layer and promote hydroxyl attachment, and finally wires treated with a silane coupling agent) are efficient to provide improvements in the structure [81]. In addition, controlling the adhesion level goes through the control of the wire surface properties and especially the wire roughness. Several techniques are available to vary the adhesion strength, including chemical treatments [44,81,121], polishing (sand blasting) [81,122], the presence of oxide layers [44,59,81], wire twisting [123], control of the martensite twinning amount [124] or the SMA phase condition [125], and even application of a mechanical indentation on the wire [126]. An example of wire with and without the presence of an oxide layer is shown in Fig. 9, where the presence of an oxide layer was found to lead to a cohesive interface failure. The adhesion level can also be increased by curing the system above the wire A_s level [127], which induces thermal shrinkage of the austenite phase, and subsequent thermal expansion of the martensitic phase upon cooling, therefore creating

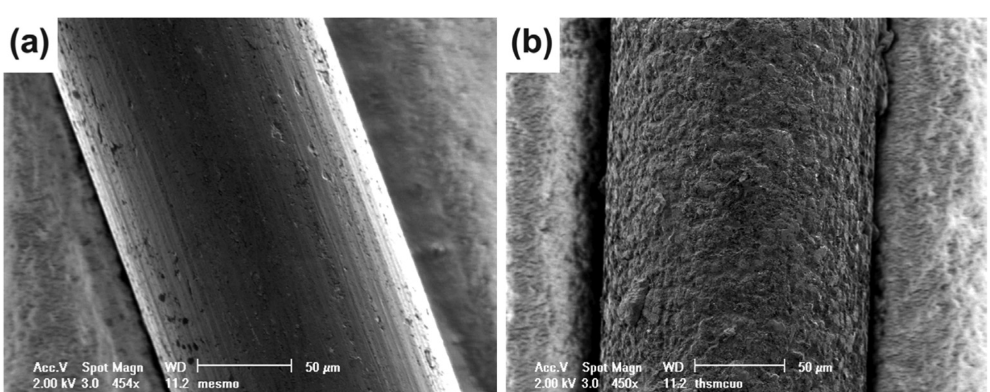

Fig. 9. SEM images of (a) NiTiCu wire cold-worked and straightened; and (b) NiTiCu wire straight annealed (leading to a rough oxide layer) [44].

compressive stresses of the wire. Notice that many studies consider interface properties between SMA wires and a polymer matrix, not necessarily for composite structures; overall, similar treatments as mentioned above are applied and the interested reader is referred for example to the following studies [128–130].

4.6. Pre-strain level

Pre-straining the wire to an optimal amount before embedding it into the polymer is of interest to provide the highest recovery capacity. For example, the highest recovery force arises when the NiTiCu wire is strained to 3% [59], but the pre-strain should be adapted to the expected effect. Indeed, for large damage volumes in impact, no initial pre-strain may be needed (preventing processing complications) whereas it would be required for small damage volumes. For damping or shape morphing however, the pre-strain level providing highest shape memory upon heating is necessary to limit the volume fraction of wires. Zheng and coworkers demonstrated with elegant modulated DSC experiments [131] that embedded pre-strained NiTiCu wires exhibit a different thermal transformation as they are in a constrained state, and could identify the point at which interface debonds, as this released the internal stress and related heat flow. Finally, to prevent interface debonding, the use of anchoring knots [116] or of frames [29,59,112] can overcome the pre-strain recovery, but makes the scale-up to complex shapes difficult.

4.7. Activation type

The method to heat up the SMA to reach the austenitic transformation temperature is also of importance. Heating can be performed using an oven, however this limits part size and potential applications; also local heating can be desired and may require an external insulation of the part, which leads to further design complications. The other possibility is by Joule heating thanks to the high electrical resistivity of the wires, however this also requires electrical insulation if carbon fibres are present in the system. The type of wire activation therefore depends on the system of interest.

4.8. Influence of SMAs on FRPs intrinsic properties

Adding SMA wires to the FRPs influences their intrinsic properties, in a similar way as any additional fibre reinforcement, due to the intrinsic stiffness of the SMA (in the order of 10–80 GPa depending on the crystallographic state and composition), as compared to the intrinsic stiffness of the host composite, to the strength and strain to failure of SMA wires, and to the interface properties as described in Section 4.5. Lau et al. [84] showed that the tensile modulus of their modified composite structures was higher than that of the reference, as the tensile modulus of the SMA wires, around 30 GPa, was higher than that of the host material, which was about 15 GPa. However, their results also showed that the SMA's beneficial presence was limited at higher volume fractions due to misalignment of the wires when large quantities are used. Linked to the tensile properties, the authors also demonstrated that the natural frequency of the composite plates decreased when increasing the amount of SMA wires, and thus the damping ratio increased for the modified composite plates. With their high damping capacity, the appearance of SMA wires into composite structures can also provide an improvement in impact energy absorption. Cohades et al. [88] demonstrated up to 34% improvement in energy absorption for an incident impact energy of 8.5 J. Care needs however to be taken when considering the resulting damage delamination area after impact. Indeed, Cohades et al. [88] and Vachon et al. [85] demonstrated that the impact damage area of the composites is almost insensitive to the presence of the SMA wires (stitched) up to a certain damage threshold, above which these wires can limit the growth of fibre dominated damage. For low damage energies, the compression strength after impact has also demonstrated no influence of the SMA wires [85]. Finally, Cohades et al. [88] demonstrated a three-fold improvement in the Mode I delamination resistance when stitched SMA wires were used; this improvement is also linked to the SMA-matrix adhesion discussed above (see Section 4.5).

5. SMAs enhanced FRPs: design and validation

The use of SMAs in FRP structures has been highlighted as efficient for improving damping and impact properties, to close crack and assist healing mechanisms, but also to provide shape morphing upon activation of the wires. However, in these four categories, design, processing, SMA activation type as well as the resulting cost and mass increase related to the use of SMAs are crucial parameters that can limit the introduction of these enhanced structures into commercial applications.

In terms of design, the choice of the SMA wire type, the fibre-matrix system as well as their compatibility in the structure should prevent early failure of the structure while providing the desired effect, as reviewed through Chapter 4. Some solutions have been devised to enable an adapted processing of these composites, but may require the need to adapt the cure schedule, and to develop frames to align wires and potentially maintain their strain during the process. All of these are quite difficult to scale up, and no example, so far, is found where SMAs embedded into composites are commercially used for active damping or shape-morphing purposes. A critical point that often remains for this type of composite structure, lies in the prediction of the potential variation of the response of SMA wires batches and of the part life-time as related to the degradation of the interface upon the high shear stresses/fatigue created by repeated actuation cycles as encountered in service. In terms of crack closure, the process complications lie in stitching of the SMA wires. However, Cohades et al. [88] demonstrated that thin SMA wires (0.15 mm) can be easily sewn through a semi-automatic process, which can be easily scaled up to conventional manufacturing processes. Chapter 4 also highlighted the two different possibilities to activate the wires when needed: heat treatment of the part or Joule heating of the wires. These two activation types need also to be carefully validated as applying heat to an entire structure or passing a current through it is not necessarily compatible with applications. While inserting an entire part application in an oven is not realistic, it is important to remember that activation temperatures of SMAs are not too high and can be reached easily with simple tools like heat guns. Notice that if temperature activation is chosen, it is also required to validate the heat resistance (even if below 100 °C) of the structure (i.e. design an FRP with a glass transition temperature above the activation temperature). If Joule heating is chosen for the application, heat is applied locally to the structure, therefore the resistance of this last to temperature is less crucial; however, the system needs to be electrically insulated, which can provide complications for carbon fibre reinforced structures. In cases of passive use of SMA composites, for example for intrinsic damping cases, applications may be restricted by the temperature range for optimal damping of the martensitic (or pre-strained superelastic) phase.

Finally, the addition of SMAs to an FRP structure increases its cost as well as its weight. Fig. 10 shows the variation of these quantities as a function of the SMA volume content in the structure, for a use in glass, aramid or carbon reinforcements. The example is given for a 1 m^2 plate of 5 mm thickness with structural fibre

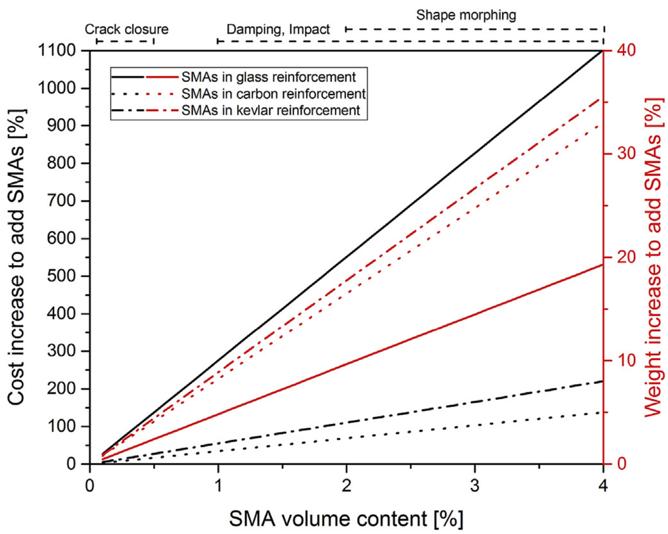

Fig. 10. Cost and weight increase when adding SMAs to a glass or carbon fibre composite, as a function of the SMA volume fraction. Ranges of SMA volume content used for crack closure, damping, impact and shape morphing are also shown.

reinforcement of around 400 g/m^2, leading to around 16 plies in the laminate and with a fibre volume fraction of 50%. Densities of SMAs (6.4 g/cm^3), carbon (1.5 g/cm^3), aramid (1.4 g/cm^3) and glass (2.6 g/cm^3) are taken into account. The following cost parameters are assumed based on [45,132]: the cost of standard SMAs wires is about 500 €/kg, that for glass fibres is about 4 €/m^2, for aramid fibres 20 €/m^2, and for carbon fibres it is about 32 €/m^2. Notice that these costs can vary depending on the reinforcement choice as well as the SMA type and quantity. The results in Fig. 10 demonstrate that the insertion of SMA wires affects less a carbon structure in terms of cost as this last is already more expensive than glass or aramid fibre reinforced composites. This increase is different depending on the intended application (i.e. crack closure, damping, impact or shape morphing), and can lead to very large cost increase for the highest volume content of SMAs, especially for glass reinforcements. In terms of weight increase, the influence of SMA wires is less critical for glass fibre composite structures as these are already heavier than carbon or aramid ones (for the same amount of fibres, to reach the same stiffness, less carbon reinforcement would be needed and this difference would be even higher). This raises the question of the benefit of using SMAs in a carbon structure if they increase the weight of the structure by 30% for shape morphing applications for example. However, the answer remains specific to each application, as no other simple mechanism can enable shape morphing, and the added cost and weight should be considered as a replacement for otherwise needed hinges and pneumatic or hydraulic systems.

6. Conclusion

Shape memory alloys in the form of thin wires have successfully been integrated in composite structures to provide a variety of potential effects. If SMA wires are integrated in-plane in the neutral axis of the laminates, these provide passive as well as active damping to the structure. Directly related to damping, these materials found applications to enhance impact properties of the laminates, again when integrated in the plane of the structure. With their high strength, these contribute in addition to reduce fibre breakage and puncture after an impact damage event. Furthermore, SMAs allow shape morphing of active composites. Finally, with a tailored placement of the wires through the thickness of the laminate, SMAs close cracks after a damage event and enhance the self-healing processes of these bio-inspired materials. In spite of the promising laboratory scale results, these hybrid composites are not yet found in commercial applications. The need to adapt the composite manufacturing process and position the wires is a possible reason, although we believe that these can be overcome by a careful selection of materials and processing routes. The cost and weight increase remains a main limiting factor, however, this could be addressed by minimizing the amount of SMA to act only in selected areas, and should be carefully evaluated and compared to the full benefits found in practical applications, so as to develop adequate niche applications. Finally, SMA could be exploited to reach higher performance/weight ratio in combination with shape memory polymers (SMP), which are lighter, cheaper and can be used as the whole matrix, but which have lower stiffness and intrinsic recovery force, by careful combined design and matching of the actuation temperatures.

Conflict of interest

The authors of this manuscript certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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