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Research paper

A review of techniques for embedding shape memory alloy (SMA) wires in smart woven composites

Danish Mahmood Baitab*, Dayang Laila Abang Haji Abdul Majid, Ermira Junita Abdullah, Mohd Faisal Abdul Hamid

Dept. of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
**Corresponding author E-mail: danishbaitab@gmail.com*

Abstract

Metallic structures, in various industrial fields such as transport and aerospace, are mostly replaced by composite structures having less weight and good strength. There is also a need of intensification of the operational dynamic environment with high durability requirements. So a smart composite structure is required that can manifest its functions according to environmental changes. One method of producing smart composite structures is to embed shape memory alloys in composite structures. Shape memory alloys (SMAs) have significant mechanical and thermodynamic properties and are available in very small diameters less than 0.2mm. These SMAs are embedded into composites for obtaining smart composites having tunable properties, active abilities, damping capacity and self-healing properties. Shape memory alloys are available in different shapes as wires, sheets, foils, strips, etc. For smart composites, mostly SMA embedded are in wire shape. Different techniques are used for embedding SMA wires in composites. SMA wires can be embedded between layers of laminates of composites, or embedded directly as reinforcement in matrix and can be woven into fabrics and used as a reinforcement. This paper reviews the different techniques of embedding SMA wires in composite structures, their pros and cons and their applications.

Keywords: *aerospace; damping capacity; shape memory alloys; smart composites; tunable properties.*

1. Introduction

Composite structures replaces the other materials in transport and aerospace industry due to their light weight and high strength [1]. However, there is need of improvement in properties of structures especially in civil, mechanical and aerospace industries. To enhance the mechanical properties of structures and also for morphing of structures, shape memory alloys are introduced in structures due to their promising property to 'memorize, or retain their previous shape when subjected to thermochemical or magnetic variations [2].

Vernon used the term "shape memory" for his polymeric dental material in 1941 but the shape memory alloys were discovered ear-lier in 1932 by Olander [3]. Shape memory alloys are based on various metals such as nickel, titanium, zinc, cadmium, gold and copper. Most used shape memory alloys are composed of nickel and titanium called as Nitinol. With addition of copper in Nitinol, capacity to store a given shape increases [4]. Nitinol are mostly used due to their excellent shape memory characteristics. Other metallic alloys such as CuALNi, NiTiCu and many other alloys also exhibit shape memory effect [2]. In 1962, Frederick Wang and William Buehler described the shape memory effect of Nitinol that signified the importance of these materials [5-6]. From that time, SMAs are used in many commercial fields such as aerospace [7-8], automotive [9], robotics [10], industrial applications [11], structure and composites [12], mini actuators and micro electro-mechanical systems (MEMS) [13], biomedical [14-15] and also in fashion [16].

Shape memory alloys have the ability to regain their shape at certain temperatures even after large deformations. SMAs also provide durability because they can recover their shape many times after deformation upon heating. Adaptive and smart materials are used for improving properties of conventional structures and also make structures smart so that these structures can respond according to environmental changes. Fibre reinforced polymer composites hav-ing high stiffness to weight ratio are made smart structures by em-bedding SMA materials in them. Nowadays SMA wires are availa-ble with diameters less than 0.2 mm. SMAs are preferred over other smart materials because they provide high damping capacity, high reversible strain and have ability to produce extremely high recov-ery stresses [17].

In spite of the tremendous advantages that SMAs can offer, their incorporation into a composite system can be a challenge on its own. These challenges are compatibility of SMA with matrix and fibres, their actuation temperature, position of SMA in composite, and composite curing temperature. Several review papers have reported on the properties, applications of SMA alloys smart structures. None were reported on the techniques for embedding SMA wire, the associated issues and relevant works. This paper seeks to address these needs and provide guidance when embedding SMAs and designing smart composite system.

1.1. Thermo-mechanical behavior and phase transformation of SMA

Shape memory alloys have two phases; austenite and martensite. In austenite phase SMAs behave like metals having higher Young Modulus because of well packed crystalline structure while in martensite phase, SMAs behave like elastomers due to lose packed crystalline structures as shown in Figure 1(a & b). When heat or force is applied to shape memory alloys they change their phase from austenite to martensite or vice versa. SMA materials mechanically behave in two ways, one is the 'shape memory effect' and other is 'pseudoelastic effect' [4].

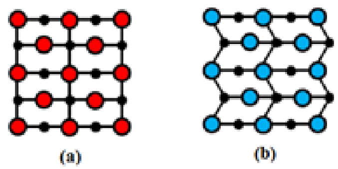

Fig. 1: (a) SMA austenite phase (well packed crystalline structure) (b) SMA martensite phase of (loosed packed crystalline structure) [4]

When a SMA in martensite phase is deformed by applying load its crystal planes unfold the lattice instead of breakage to accommodate the strain. This phenomenon is known as 'detwinning'. When heat is applied, SMA changes phase to austenite and its crystal arrange their lattice in well packed manner so recovering their residual deformation [4]. This is shape memory effect of SMA as shown in Figure 2.

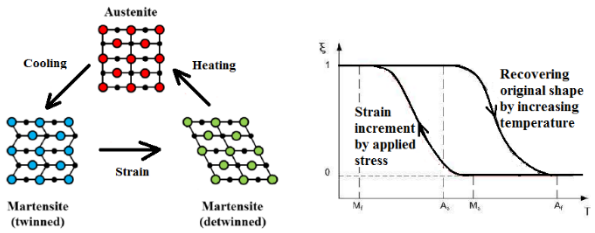

Fig. 2: Shape memory effect of SMA materials [4]

Shape memory effect of SMA can be of two types; one-way shape memory and two-ways shape memory. In one-way shape memory, after deformation of shape, the initial shape is achieved by giving temperature. While in two-ways shape memory, SMA remember two shapes at two different temperatures. So SMA will adopt its specific shape at that temperature without applying any load.

SMA materials changed their phase from austenite to martensite phase by applying external force under appropriate temperature i.e. temperature should be greater than austenite finish temperature. When force is removed SMA recovers its deformation by means of a hysteretic loop and comes to austenite phase. As phase transformation occurs in that temperature where martensite phase is not stable so SMA reverts quickly to stable austenite phase that is its parent phase, exhibiting a quick shape recovery [4]. This phenomenon is known as pseudoelastic effect as shown in Figure 3.

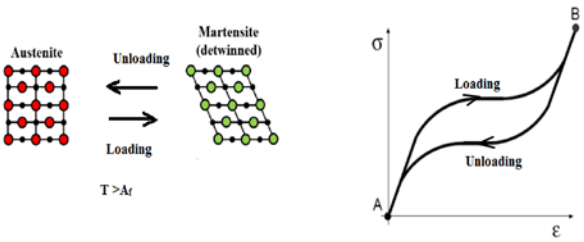

Fig. 3: Pseudoelastic effect of SMA materials [4]

2. Embedding SMA wires into composites

SMA wires are embedded into composites for improving mechanical properties and making structures actively respond to stimuli by changing material's elastic-mechanical behaviour to thermo-mechanical behaviour [18]. Embedment of SMA wires in smart composites can have different objectives such as:

i) For improving mechanical properties
Mechanical properties of structure are improved by embedding SMA wires in composites. Stiffness is improved by SMA wire because when SMA wires are actuated by giving current, this wire gets hot and try contract length-wise. This contraction of wire provide force inwardly to structures and improves stiffness. Generally for improving stiffness SMA wires are place at centre of composite laminates so it can contribute evenly throughout the structure [19]. Damping properties are improved by embedding SMA wires due to their loosely packed crystalline martensite phase in which they have ability to unfold crystal lattice rather than breakage when a load is applied. So they bear the load without breakage and provides damping properties [20]. In aerospace, natural frequencies of the structure are increased by embedding SMA wire so that its vibration and flutter can be controlled for avoiding structural failures [21,22]. Impact resistance can be improved by embedding SMA wires on the lower part of a laminate as this will impart in-plane compressive stresses.

ii) For shape morphing of structures
SMA wires are used for shape morphing purpose. SMA wires are embedded into structures and are heated by giving current. Upon heating these wires change their shape and recovers their original shape when get cool. Morphing structures can change their shape by changing length, width or by twisting itself. Position of SMA wires play a vital role for morphing of structures. Generally SMA wires are embedded away from neutral axis to enable morphing [23].

iii) As actuators
SMA wires are also used as an actuator due to their shape changing properties. As SMA wire gets contracted and provides a pull-force that can actuate any system. SMA based actuators are commonly used in mechatronics and robotics application. In-pipe robot is common example of using SMA based actuators [24].

2.1. Factors considered for embedding SMA wires in composites

Several factors are considered when SMA wires are embedded between fibre layers or laminates. These factors are:

i) Dimension of SMA wires
When embedding SMA wires into laminates, diameter of SMA wire plays a vital role. Diameter of SMA wire should be small enough so that delamination of laminates, having SMA wires in between them, does not occur. Dimension and properties of SMA wires compatible with other fibres enhances the properties of smart structure otherwise structure failure such as cracking of composites occurs [25].

ii) Positioning of SMA wires
Position of embedded SMA wire in composites is very important and it describes the properties of smart composites. If SMA wires are embedded in centre of composites, it will play role to enhance the mechanical properties such as stiffness and modulus of the structure [19]. If SMA wire are embedded asymmetrically (away from centre) to composite structure, it will be responsible for morphing of structures [23]. Special fixtures are needed for the positioning of SMA wires and to avoid inducing unnecessary bending strains due to misalignment.

iii) Actuating temperatures of SMA wires
Phase change temperatures of SMA are very important to consider while embedding SMA wires into composites. Phase transformation temperature of SMA wire should be lower than glass transition temperature of matrix, otherwise it will damage the composite by softening of matrix [17].

iv) Compatibility of SMA wires with matrix
SMA wires and matrix should have good bonding between them otherwise delamination and cracking in composites will occur. Mechanical performance of composite structure decreases due to poor interface adhesion between SMA fibres and matrix [26]. But extremely strong adhesion is also responsible for failure of structures because a crack propagates faster in stiff structure while a slightly weaker adhesion allows to dissipate energy more effectively to slow down propagation of crack [27]. So, interface adhesion strength should be appropriate for preventing structural failures.

Different techniques are used to improve SMA and matrix adhesion. For improving adhesion, surface of SMA is treated with different techniques for making it rough because rough surface provides good bonding strength and it resists pull-out when pull-out forces are applied. Sandblasting [28] is a method to increase surface roughness of SMA wires to improve bonding. Also chemical treatments were suggested for improving bonding and some worth mentioning are use of silane coupling agent [29] and acid etching [30]. Laser etching technique was found to improve surface roughness as well as corrosion resistance [31]. Surface roughness can be improved by imparting a layer of nitride on the surface through laser gas nitriding process [32]. Combined mechanical grinding, polishing and acid etching formed rough surface oxide layer and increased surface roughness [33]. Hybridizing Al_2O_3 with nano-silica particles was found effective for improving bonding and interfacial strength, resulting in higher mechanical performances [34].

v) Thermal cycling (Composite curing)
Different composite manufacturing techniques are used for making smart composites. Mostly used techniques are vacuum-assisted resin injection (VARI) process, autoclave curing, and vacuum infusion and hand layup. Composite fabrication process usually involves a thermal cycling of heating and cooling induced by the chemical reactions of the resin material. Mechanical fixtures are used to restrain the SMA wires during such curing procedure. These fixtures will include the gripping, alignment and base plate for the composite fabrication.

2.2. Techniques for embedding SMA wires in composites

SMA wire are embedded in composites with different techniques. These embedding techniques depend on the required properties of smart composite structure. Every technique has its own benefits and also some disadvantages. Several factors such as dimensions of SMA wire, compatibility of SMA wires with fibre and matrix, actuating temperature of SMA wires and glass transition temperature of matrix are considered when embedding SMA wires in composites. Techniques used for embedding SMA wires into composite are:
i) Embedding SMA wires in between laminates of other fibres
ii) Embedding SMA wires directly in matrix of composites
iii) Embedding SMA woven structure into composites

2.2.1. Embedding SMA wires in between laminates

For smart composites, SMA wires are embedded in between fibres, laminates or fabric layers for producing smart composites also known as SMA hybrid composites (SMAHC). SMA wires are placed on layers of laminates at different positions depending on required properties of structure. SMA wires embedded symmetrically into laminates as illustrated in Figure 4.

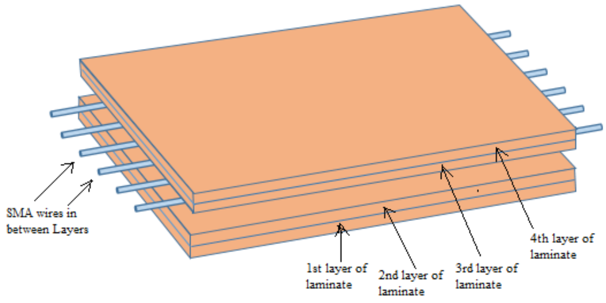

Fig. 4: SMA wires embedded between laminate layers.

Table 1 summarized relevant works related to embedding SMA in between laminates and categorized according to matrix, reinforcement, treatment, SMA positioning, fabrication and SMA types. The matrix used are mostly epoxy based. Reinforcement are generally glass fiber and carbon fiber laminates with embedded SMA wires. SMA wires used are Ni-Ti SMA wires with Nickel content 50 to 56 % by weight and diameter ranging from 0.1 mm to 0.8 mm. SMA are embedded symmetrically or asymmetrically depends on required properties of structure. For improving mechanical properties SMA are positioned symmetrically while for morphing purpose SMA are positioned asymmetrically. Mostly used composite manufacturing process is vacuum-assisted resin injection (VARI) process while in some studies autoclave curing is also used. Thickness of composites varies from 2 to 5 mm depending on SMA wire diameter and numbers of laminates.

Schrooten *et al.* [17] established a basic understanding for manufacturing of SMA composites. Pre-strained SMA wires were embedded into Kevlar prepregs and was cured in an autoclave. All the necessary steps were carried out from selection of material to properties of smart composite. The transformational, dimensional, interfacial, internal stress and strain, tensile and impact behavior, thermomechanical and vibrational behavior of smart composite were investigated. This research provides the knowledge for reliable manufacturing of smart composites and their applications in industries.

i) Recent work for improving mechanical properties of structures by embedding SMA wires in between laminates of composites
Pappadà [25] investigated the improvement in impact properties of smart composites embedded by SMA wires. Properties of two different glass and carbon reinforced composites with embedded SMA wires were compared. It was observed that by embedding SMA wires in composites, there was an improvement in impact energy of composites. It was also found that glass fibre reinforced smart composites are more resistant to crack growth thereby these structures are helpful for blocking this growth. While carbon fibre has higher elastic modulus than SMA wires so this inhomogeneity in behaviour promotes the crack initiation and deformation of structures occurred. Aurrekoetxea *et al.* [28] embedded SMA wires in woven carbon fabric reinforced poly (butylene terephthalate) composite. Effect of embedding SMA wires on impact behaviour of composite was investigated. It was concluded that the dissipated energy is not affected by SMA wires while maximum absorbed energy is positively affected by SMA wires. As SMA wires have ability to absorb energy so contributed in higher impact performance of composites. Zhao *et al.* [35] embedded SMA wires in between layers of glass fibre cloth at different positions. It was concluded that the embedding SMA wires improved the flexural modulus and elastic deformation energy of the smart composites.

Wang *et al*. [36] described the fatigue behavior of glass fiber reinforced composites containing SMA wires in between the layers of glass cloth. By embedding SMA wires in between layers, the fatigue life of composite structure increased two time then the composite structure without SMA wires. So, it was concluded that embedding SMA wires into layers of laminates of composites is an effective method to improve the tolerance and anti-fatigue damage of smart structures. Kang *et al.* [37] embedded SMA wires in between glass epoxy laminates at the centre of the composite and compared its impact behaviour with a base composite without SMA wires. It was found that impact damage behaviour of smart composite is more affected by SMA and temperature than base composite and residual strength of composite is affected by impact damage.

Table 1: Summary of previous work on embedding SMA wires in between laminates of composites

Application [References]	Matrix System	Reinforcement	SMA Type	Treatment	SMA Positioning	Composite Fabrication Method	Thickness of Composites
Manufacturing guidelines for SMA embedded smart composite [17]	Epoxy resin	Kevlar prepregs and SMA wires	NiTi, NiTi-R-phase and NiTiCu. wires with diameter of 0.15 mm	Pre-strained on special frames	In between layers of Kevlar prepregs	Autoclave curing	2 mm
Transportation and aerospace [25]	Vinylester resin	Carbon fibre fabric, Glass fibre fabric, SMA wires	Superelastic SMA wires with 56% nickel content and 0.1 mm diameter A_f = -15°C	-	Four layers of SMA wires were embedded into laminates at different distances from the neutral axis.	Vacuum-assisted resin infusion process	-
High impact performance structures [28]	cyclic butylene terephthalate oligomer	Carbon fibre fabric and SMA wires	Superelastic SMA wires (50.9 % Ni) of diameter 0.5mm (M_s = -31.4°C M_f = -51.9°C)	Sandblasted surfaces	Composites structure is 3.2mm thick and the SMA wires were embed between carbon fibre laminates at 0.8 mm from the skin layer of the structure	Vacuum assisted RTM	3.2 mm
Aerospace, automobile structures [35]	Epoxy resin	Glass fibre cloth and SMA fiber	NiTi SMA fibres	Acid and nano-silica particles treatment.	Symmetric (centre) and asymmetric SMA positioning	Vacuum-assisted resin injection (VARI) process	2.4 mm and 3 mm
Aerospace, civil, automobile industries [36]	Epoxy vinyl resin	Glass fibre cloth and SMA wires	Super elastic NiTi wires (0.2 mm)	Sand-Polished and acetone-cleaned	In between layers of glass fabric cloth	Vacuum-assisted resin injection (VARI) process	1 mm
Structural integrity [37]	Epoxy resin	Glass/epoxy laminates and SMA wires	0.4 mm Ni–Ti SMA wire	-	SMA wire are embedded at neutral plane of the layers of glass epoxy laminates	Autoclave curing	5 mm
Morphing structures, aerospace, actuators [38]	Epoxy resin	Glass fabric, Silicon rubber and SMA wires	Nitinol wires (50.4 % Ni content by weight) with diameter of 0.4mm (M_f = 17.4°C, A_f = 96.9°C)	Pre-strained at 8%	Asymmetric SMA positioning	SMA wires and glass fabric were placed on an n-shaped mould and then this assembly was cured for 72 hours at 25° C in a vacuum.	4 mm
Morphing structures, aerospace, actuators [39]	Epoxy resin	Glass fibre laminates and SMA wires					
Morphing structures, aerospace, actuators [40]	Epoxy resin	Carbon/ epoxy laminates and SMA wires , E-glass/ epoxy laminates and SMA wires	Binary nitinol wires with 55.3% Ni and diameters of 0.25mm and 0.51mm (M_f = 16°C, A_f = 55°C)	Pre-strained at 5.5%	1-In between carbon fibre laminates 2-In between glass fibre laminates	Autoclave curing	2-3 mm
Structural integrity [41]	Epoxy resin	Carbon fibre fabric and SMA wires	The superelastic SMA with nickel content 55.8% by weight, wire diameters 0.47, 0.66 and 0.89 mm)	-	In between two layers of carbon fiber fabric.	Hand lay up	-

ii) Recent work for morphing shapes and actuating properties of structures by embedding SMA wires in between laminates of composites

Embedment of SMA wires into composites is also responsible for shape morphing and due to thermomechanical behavior of SMA wires. Jung *et al.* [38] embedded the SMA wires in between the glass fabric layers and silicon rubber for fabrication of smart composites. For producing large deformations, the shape of structure was n-shape. It was observed that the smart composite shown 36 percent lower bending strength and 28 percent lower bending modulus than the glass fiber reinforced composite without SMA wires. Due to lower bending strength and modulus of smart composite structure, it morphs easily. It was observed that radius of curvature of smart composite structure changed 3.25 times larger than simple composite. So these smart composite structures can be used as large deflection smart materials. Jung *et al.* [39] embedded Nitinol wires in glass fibre reinforced composite to develop an actuator for air intake. After heating SMA wires by providing current it was found that the smart structure deflected 15°. This structure with 15° deflection can be easily used for making an air intake structure. Zhou and Lloyd [40] embedded SMA wires in between layer of glass fiber epoxy laminates and also for other sample, SMA wires embedded in between layers of carbon fiber epoxy laminates. The smart E-glass/epoxy beams shows significant end deflections of up to 41 mm while the smart carbon epoxy beams show very limited deflections because SMA wires were not shielded against carbon fibres those are semi-conductor and create hindrance to activation of SMA wires. So smart E-glass/epoxy composite is useful for morphing purpose.

iii) Recent work to improve bonding between SMA wires and matrix for embedding SMA wires in between laminates of composites

When embedding SMA wires in between layers, it is very important to understand the bond behavior of SMA wires with polymer composites. Dawood *et al.* [41] embedded a single SMA wire of different diameters and different lengths in between two layers of carbon fabric to describe the bond behavior of SMA wires to carbon fibre reinforced polymers. Different modelling techniques were used for modelling of SMA wires and interface behaviour. For modelling of SMA wires, a built-in superelastic material model was used while for behaviour of interface, cohesive zone model was used. A methodology is suggested to quantify the parameters of these modelling techniques. For improvement of bonding between SMA wires and the host material, Zhao *et al.* [35] treated SMA wires with acid and nano-silica particle. It was concluded that the bonding strength between SMA wires and the host material is significantly improved after treating SMA wires with nano-silica particles. For improving adhesion between SMA wire and the matrix, Wang *et al.* [36] polished the surface of the wires by sanding. After polishing acetone is used for cleaning before embedding SMA wires into composites.

iv) Pros and cons of embedding SMA wire in between laminates of composites

Embedding SMA wire in between layers of laminates gives special properties to composites. Position of SMA wires in composites can be manipulated for desired properties, i.e. SMA wires are symmetrically embedded for improving stiffness while asymmetrically embedded for morphing purposes. In embedding SMA wires in between laminates, positioning of SMA wires in between laminates can be adjusted easily by adjusting stacking sequences and number of layers of laminates.

Properties of smart composites are the combination of properties of fibres and embedded SMA wires. Both fibres and SMA wires improve the properties of smart composites. But there is also a problem that SMA wires should be compatible with fibres for achieving required results otherwise structural failure can occurs. If modulus of fibre is not compatible with wires it will create fractures and cracks in composite when SMA wires will actuated. Delamination between SMA embedded layers is another big problem encountered during heating of SMA wires. When SMA wire actuated it changes its shape so create forces on matrix and weakens the bonding between laminates where these wire are embedded and delamination of laminates occurs.

2.2.2. Embedding SMA wires as reinforcement of composites

Smart composites containing only SMA wires as a reinforcement as shown in Figure 5 provide mechanical properties as well as actuating capabilities to structures. Special frames are required for placing SMA wires and matrix is applied on wires in specific molds.

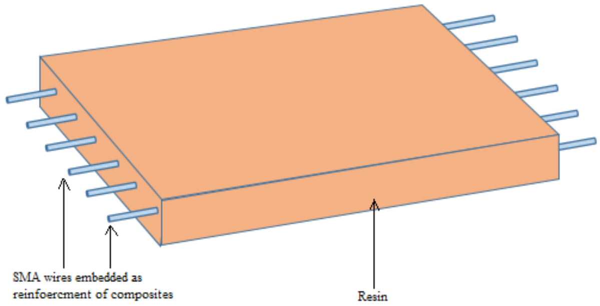

Fig. 5: SMA wires embedded as reinforcement

Table 2 summarized relevant works related to embedding SMA directly in matrix and SMA works as reinforcement of composites. The matrix used is epoxy and in some studies for high impact resistance property ER3 epoxy is used. SMA wires are used as reinforcement providing mechanical properties as well smart behavior to composites. SMA wires are treated for improving bonding of SMA wires to matrix. Thickness of composites varies from 1.2 mm to 4 mm. These composites are thin because SMA are embedded directly in resin without any laminate layers.

i) Recent work for improving mechanical properties of structures by embedding SMA wires directly in matrix of composites

Embedding SMA fibers directly as reinforcement into epoxy composites provides increased mechanical properties. Sharifishourabi *et al.* [18] joined two composite layers for producing smart composite. The first laminate layer was carbon/epoxy layer and the second layer was laminate having SMA wires embedded in epoxy. It was found that by increasing the number of SMA wires, the Poison's ratio and shear and elastic moduli of smart composites improved. It was concluded that mechanical properties of smart composites are directly affected by number of SMA wires. Donadon *et al.* [19] embedded SMA wire along with carbon fibers into resin simultaneously. It was found that stiffening effect induced by the changes in the transformation phases of the shape memory alloy controls the rate of occurrence of flutter hence stabilizing the plate. So amount of flutter speed can be controlled by adjusting the temperature of the SMA wires in the smart composites. Raghavan *et al.* [20] designed a single-fibre winder, for winding SMA wires well-aligned preforms then transferred these wires in mould and resin was applied. Mechanical properties of composite as tensile, impact and damping properties were improved by using SMA wires as reinforcement for smart composite. Daghash *et al.* [42] described that embedding SMA wires into resin for smart composite improves mechanical properties as ultimate strain, damping property, ductility and re-centering capability of the smart composites. It was also mentioned that superelastic properties of composite depend on fiber volume ratio and can be increased by increasing fiber volume ratio. Ni [43] embedded short SMA fibers simply dispersing into epoxy resin, then the SMA mixed epoxy resin was transferred into a mould where it was cured for 24 hours at room temperature. It was found that by adding SMA short fibres, the vibrational characteristics of smart composites are increased. It was also found that by increasing amount of SMA short fibres, the attenuation coefficient of smart composite is also increased. Zhang [44] investigated the mechanical properties of the smart composites by embedding SMA short fibres and SMA particles in resin. It was found that by addition of SMA fibres and particles storage modulus, loss factor and flexural rigidity of smart composites remarkably increased. Kuo [45] used finite element method to investigate the effect of shape memory alloy (SMA) on the buckling behaviour of a smart composite plate. It was concluded that buckling performance of the composite plate is improved by using Active Strain Energy Tuning method and placing SMA fibres in centre of the composite. If more concentration of SMA fibres is at centre so composite have more load carrying capacity so buckling performance improves. It was also concluded that Active Strain Energy Tuning method is better than Active Property Tuning method for improving buckling performance of smart composites.

ii) Pros and cons of embedding SMA wire directly in matrix of composites

For embedding SMA wires directly in matrix, a mould is required for placing SMA wires at specific position in composites. Positioning of SMA wires in composites is a difficult task when SMA wires are directly embedded in matrix. It requires special frames for positioning of wires and pre-conditioning processes to avoid excessive thermal strain. SMA wires as reinforcement are the sole contributor to the strength of the composite, however, number of wires embedded as reinforcement is limited due to their relative high cost as compared to other typical fibre reinforcement thereby limiting the properties of composites. SMA wires should be compatible with matrix for avoiding structural failures. Embedding SMA wires directly in matrix, thin and fine composites can be produced as only SMA wires are used in these structures for reinforcement.

Table 2: Summary of previous work on embedding SMA wires directly into matrix

Applications [References]	Matrix System	Reinforcement	SMA Type	Treatment	Embedding SMA wires in Matrix and Composite Fabrication Process	Thickness of Composites
Structures, automotive and aerospace, aircraft wings [18]	Epoxy resin	Carbon/epoxy laminate and SMA/epoxy laminate	Nitinol wires with diameter 0.5mm (A_s = 45°C, A_f = 60°C)	1- Pre-strained at 5% 2- Knotting at ends for avoiding slippage	Hand layup for SMA/epoxy laminate (SMA wires at center) and vacuum infusion process for carbon/epoxy laminate. Then bonding of both laminates	2 mm
Structures, automotive and aerospace, aircraft wings [19]	Epoxy resin	Carbon fibers and SMA wires	Nitinol wire (A_s = 57°C, A_f = 75°C)	-	SMA wires embedded along with carbon fibers into resin simultaneously	3 mm
Civil, automobile, aerospace structures.	Vinyl ester	Superelastic Nitinol SMA fibres	Nitinol wires with diameter 0.102 mm	Sandblasted surfaces	The resin was applied on a SMA pre-form in a mould and then cured at room temperature for 24 hours	0.9 mm
Aircraft structures	Epoxy resin	NiTi wires	Nitinol wires with diameter 0.495 mm (M_f = -6.6°C, A_f = 24°C)	-	Resin was applied on SMA wires placed at center in a mold. Then mould was sealed by layer of peel ply for 24 hours and then specimen was cured in air for 6 days.	4 mm
Structures having good vibrational control [20]	ER3 epoxy resin due to its high impact resistance property	Ti–Ni alloy short fibres	Ti–Ni alloy fibres with diameter 0.2mm	-	SMA fibres dispersed in epoxy resin and poured into a mould and cured at room temperature for 24 hours then moulding was heated up to 140°C.	1.2 mm
High damping control structures [42]	ER3 epoxy resin due to its high impact resistance property	Ti–Ni alloy short fibres	Ti–Ni alloy short fibres with diameter of 0.2mm and SMA particles with diameter 0.425 mm (Austenite Phase transformation temperature = 58°C)	-	SMA particles and fibres were well dispersed into epoxy resin and dried for 20 min by a vacuum pump. Then poured into a mould and cured at room temperature for 24 hours and then molding was heated up to 140°C.	-

2.2.3. Embedding SMA woven structures into composites

SMA wires are woven into fabrics for using it as reinforcement of composites. Special weaving techniques are used for weaving of SMA wires. Appropriate wire tension and wire space during weaving requires special arrangement. SMA wires are woven in different methods according to requirements. One methods is weaving of SMA wires into fabric by placing all SMA wires in one direction and other yarns at other direction as shown in Figure 6 (a). Second method is placing some SMA wires with other yarns in one direction interlaced with yarns at other direction as shown in Figure 6 (b) and the third method is weaving of a SMA mesh with all SMA wires without using any other yarns or wires as shown in Figure 6 (c).

Table 3 summarized relevant works related to embedment of SMA wires as a woven structure in composites. Matrix used is Polydimethylsiloxane (PDMS) due to its isotropic properties and elasticity [23]. SMA woven structures are used as reinforcement of composites. More thick composites due to woven laminates and thickness of composites structures varies from 2.1 mm to 8 mm.

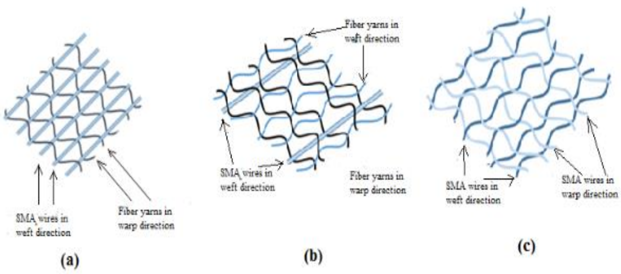

Fig. 6: (a) SMA wires in weft direction interwoven with warp yarns **(b)** SMA and yarns in weft direction interwoven with warp yarns **(c)** SMA woven mesh (Warp and weft are SMA wires)

i) Recent work on embedding woven SMA structures in composites

Zhang *et al.* [46], embedded woven SMA mesh between epoxy layer and carbon-fiber cloth. It was found that developed laminates possess high natural frequency particularly at high temperatures.

Table 3: Summary of previous work on embedding SMA woven structures into composites

Applications (References)	Matrix Type	Reinforcement	SMA Type	Method of Embedded SMA wires	Composite fabrication method	Thickness of composites
Morphing wings and spoilers [23]	Polydimethylsiloxane (PDMS)	SMA wires and glass fibers woven structure	SMA wires (55 % Ni content by weight) of diameter 0.2 mm	SMA wires interwoven with glass fibers	The woven SMA/glass fiber structure, glass-fiber fabric and PDMS was cured in an oven.	8 mm
Damping control in aerospace and civil structures [46]	ER3 epoxy resin	Carbon cloth and SMA woven mesh	SMA wires of diameter 0.2 mm and 0.4 mm	SMA wires were woven into a mesh.	SMA mesh with carbon cloth prepregs were vacuumized, and cured by using hot press at 130 °C for 2 hours..	2.1 mm
Bio-mimicking, soft morphing actuators, spoilers and wings of micro air vehicles [47]	Polydimethylsiloxane (PDMS)	Glass fibers and the SMA wires woven structure	SMA wires FLEX-INOL with a diameter of 0.2 mm (M_f = 31.52°C, A_f = 72.63°C)	SMA wires interwoven with glass fibers	Woven structures and PDMS was placed in mold and cured at room temperature for 48 hours.	3 mm
Morphing winglet of an unmanned aerial vehicle (UAV) [48]	Polydimethylsiloxane (PDMS)	Glass fibers and the SMA wires woven structure	SMA wires FLEX-INOL (55 % Ni content by weight) with diameter range of 0.2 mm to 0.5 mm	SMA wires interwoven with glass fibres	The PDMS was poured on SMA woven structure in a mold. Then whole assembly was vacuumized and cured at 55°C.	-

Thus, these smart structures containing woven SMA mesh can be practically used for damping control purpose.

Han *et al*. [23] fabricated a woven type smart soft composite (SSC) for a car spoiler. SMA wires were woven with glass fibres and used as reinforcement of smart composite. Woven smart structure was added with two layers of glass fabric for improving stiffness and also provide eccentricity to SMA wires. SMA wires are eccentrically embedded for morphing purpose so that smart structure can easily morph. It was concluded that the smart structure can deform easily, it can regain its original shape and can bear the external forces of airflow around spoiler. Wu [47] embedded SMA wires into composite beam by weaving of SMA wires with glass fibre for using it as an actuator that can morph randomly and maintain its deformed shape without additional power. From results it was observed that the maximum tip deflection of smart composite beam was about 21 mm and it retains its deformed shape at 16mm. So these smart structure can be used for morphing purpose as in wings of Micro Air Vehicles and in spoilers. Han [48] embedded SMA wires woven with glass fibre in a soft polymer matrix. Smart composite was used for morphing winglet and implemented on an unmanned aerial vehicle (UAV) for observing morphing behaviour and its effect on the aerodynamic properties of vehicle. After testing, it was observed that lift to drag ratio of smart structure increased 5.8 percent when actuated than flat wing geometry. By using this smart structure, the aerodynamic performance of UAV is improved.

ii) Pros and cons of embedding woven SMA structures in composites

In SMA woven structure, fibres bind the SMA wires so their stresses on matrix are controlled by fibres interlaced with SMA wires thereby improving the integrity of structures. Positioning of SMA wire is more versatile in SMA woven structures because it can be used in weft direction, warp direction or in both directions simultaneously. SMA woven structure needs additional weaving mechanism for weaving of SMA wires. Special techniques are used for weaving of SMA wires so their tension, spacing and position can be controlled during weaving. The compatibility of fibres woven with SMA wires has importance in performance of smart composites. For example, the whole structure will change its shape when SMA wires are actuated so compatibility in terms of stiffness and elasticity is very important.

3. Conclusion

It is concluded that, for embedding SMA wires in composites, it is very important to consider the factors such as dimensions of SMA wire, position of SMA wire, compatibility of SMA wires with fibers and matrix, actuating temperature of SMA wires and composite curing method. SMA wires can be embedded in between layers of laminates of composites, can be directly embedded in matrix as reinforcement and can be embedded as woven structure depending on properties. Furthermore, SMA wires are embedded in composites symmetrically for improving mechanical properties and asymmetrically for morphing of structures. Last but not least, for avoiding damages of smart composites and improving their properties, some special treatments are carried out with SMA wires such as pre-straining, sand basting and acetone cleaning for improving bonding between SMA wires and the host materials.

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