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Applications of Shape Memory Alloy Hybrid Composite for Ballistics: A Review

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ABSTRACT

Shape Memory Alloys (SMAs) are remarkable in that they can regain their previous shape upon exposure to specific stimuli. This unique property has attracted a lot of attention for use in a spectrum of engineering applications. The Shape Memory Alloys (SMAs) have been included in hybrid composite materials in the domain specific to ballistics with the prime intent of improving the effectiveness and durability of protective structures. An examination of the use of Shape Memory Alloys (SMAs) in hybrid composites for use in ballistics applications is presented and briefly discussed in this manuscript. An effort is made to examine the underlying ideas of Shape Memory Alloys (SMAs) and the ballistic performance of Shape Memory Alloy Hybrid Composites (SMAHCs). In this research paper an effort is made to assess as to how well they work to reduce ballistic risks. In this paper, an effort is also made to examine recent advancements and Challenges in utilizing shape memory alloys for ballistic purposes, while addressing issues specific to ballistic performance.

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Introduction

A primary or main goal in the sequence of development process for armour material is to reduce weight of the armour while concurrently enhancing its ballistic impact resistance [1-2]. The material that is chosen for the armour should offer a healthy combination of improved hardness, good stiffness, lightweight while concurrently being affordable in price. Composite materials are often chosen as an attractive and potentially viable material for both bulletproof vests and armour vehicles. In essence, composites are a class of materials that offer a combination of have attractive qualities to include:

(i) Stiffness,
(ii) High specific strength [σ/ρ]
(iii) Low weight [3].

Due on account of their special qualities, these materials, i.e., composite materials, have been chosen for use in a spectrum of engineering applications to include the following [4-8]:

(i) Biomedical
(ii) Sports
(iii) Naval and Even
(iv) Aeronautical

Despite possessing exceptional mechanical properties, such as

(i) High specific strength [σ/ρ]
(ii) High specific stiffness [[E/ρ]
(iii) Good Corrosion Resistance

the composite materials are often not widely chosen for use in critical engineering applications primarily because of their vulnerability to damage from an impact that can arise from out-of-plane loading. When compared with the conventional metallic materials like steel, the composite materials have a noticeably inferior resistance to impact loading or dynamic loading, which results in their susceptibility to damage. Further, the composite materials lack the superior energy-absorbing capability, i.e., toughness, of the metallic materials. This also includes their response to plastic deformation. Also, the composite materials are particularly vulnerable to impact loading for both high-velocity impact loading and low-velocity impact loading primarily because of their brittle nature. During the last few years, several techniques have been tried with the prime intent of improving or enhancing characteristics of the chosen composite material. Several techniques have been tried with the prime intent of enhancing the impact properties of composite materials, to include the following:

(i) The use of toughened fibre and/or matrix
(ii) Nanofillers
(iii) Fabric Thickness Stitching.

The most promising approach appears to be “Hybrid” composite [9,10]. A single matrix phase containing two or more distinct fibers is known or referred to as the “hybrid” composite. These composites have been successfully used to reduce costs while concurrently improving overall quality. Typically, a hybrid composite is made up of the following:

(i) High-cost or high-modulus fibres, such as boron or carbon fibre
(ii) Low-cost or low-modulus fibres, such as glass fibre.

While a lower modulus fibre is more cost-effective and damage-tolerant, a higher modulus fibre does offer the advantages of stiffness and adequate load-bearing capability. Thus, use of the "hybrid" composites instead of metals and even the traditional engineered composites, does result in reduced cost while concurrently achieving increased stiffness, enhanced strength, and improved mechanical qualities [11]. The most common "hybrid composite" is the Shape Memory Alloy Hybrid Composite [SMAHC].

Shape Memory Alloys (SMAs) can "remember" their initial shape when it is subjected to an external stimulus, such as
(i) Thermomechanical Changes
(ii) Magnetic Changes [12-17].
A few common examples of the Shape Memory Alloy (SMA) are:
(i) Nitinol [Ni-Ti]
(ii) Cu-Zn-Al alloy
(iii) Fe-Mn-Si alloy
(iv) Cu-Al-Ni alloy.
The shape memory alloys (SMAs) have a high endurance in the plastic deformation regime while being incredibly ductile. The internal phase transition processes of the PE-SMA, caused by thermomechanical loading, are thought to be responsible for this unique characteristic [18,19]. Consequently, the shape memory alloy (SMA) embedded composite, also known as the SMA hybrid composite, is a good fit for several applications, such as
(i) Automobile Bumpers
(ii) Helmets
(iii) Bird Strikes on Wings
(iv) Protection of Ballistic Armour Protection
Where resistance to both penetration and damage during ballistic impact is both crucial and essential [20,21]. A pseudo-elastic shape memory alloy [PE-SMA] does exhibit recoverable strains of 6%–8% coupled with a high strain to failure. A stress-induced phase shift that occurs upon loading of the shape memory alloy does give it high-strain capability. A plateau region is created in the stress versus strain curve when the pseudo-elastic SMA is stretched, transitioning from an austenite phase to the martensite phase. It is the phase transformation process that allows the Shape Memory Alloy (SMA) to absorb significantly more energy than the traditional alloy counterpart. To strengthen and concurrently increase the resistance to impact damage of the chosen composite materials, researchers have made every effort to investigate the use of SMA material in conjunction with composites [22]. The shape memory alloy (SMA) wires embedded in composite is shown in Figure 1.

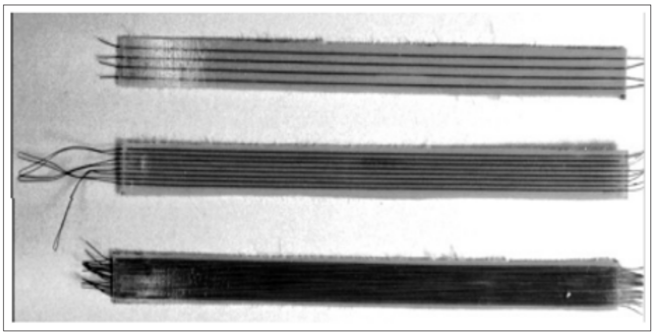

Figure 1: Typical SMA wire embedded in a composite material [23].

Ballistic Performance of Shape Memory Alloy Hybrid Composites [SMAHCs]

A Low-Velocity Impact (LVI) below 11 m/s, a High-Velocity Impact (HVI) below 500 m/s, a ballistic impact below 2000 m/s, and hypervelocity impact beyond 2000 m/s are the four distinct types of impacts that can be classified based on velocity attained by the impactor as is shown in Figure 2 [24,25].

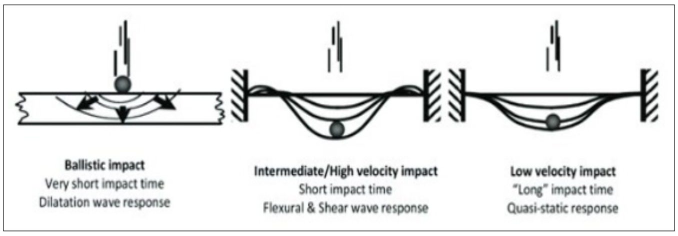

Figure 2: The Types of Ballistic Impact on a Composite Material [24].

Low Velocity Ballistic Impact on Shape Memory Alloy Hybrid Composite [SMAHC]

Lidan Xu et al found from their independent study that the Shape Memory Alloy Hybrid Composite [SMAHC] has a substantially higher impact resistance than the Glass-Fiber (GF)/epoxy composite material [26]. They also found that under the influence of a low-velocity impact failure of the SMAHC was noticeably greater than that of the Glass Fibre (GF)/epoxy composite due on account of the excellent energy absorption capacity of the Shape Memory Alloy (SMA). The low-velocity impact response of a composite plate to include SMA wires was examined [27]. Results of their independent study demonstrated that the SMA wires, primarily at energies below 10 J, can increase the damage tolerance capability of the glass fiber-reinforced laminates. Low-velocity impact properties of the carbon fibre-reinforced polymer (butylene terephthalate) and the Shape Memory Alloy (SMA) wires produced by resin transfer moulding were studied by Aurrekoetxea et al. [28]. They discovered that due on account of a higher maximum permissible load, the SMA does have a beneficial impact on the maximum absorbed energy. The low-velocity impact response of a doubly curved, symmetric cross-ply laminated panel containing embedded SMA wires was investigated [29]. An examination of their model provided results that demonstrated the benefits of using Shape Memory Alloy (SMA) wires in composite panels especially when there is a transverse low-velocity impact. Meo et al studied using both numerical method and experimental method to examine the response of a smart hybrid thermoplastic composite plate to a low-velocity impact [30]. In comparison to the traditional composite constructions, an observable increase in the damage resistance and ductility of the composite structure was noted upon the embedding of Shape Memory Alloy (SMA) wires. The impact of biaxial loading on the low-velocity impact performance of a E-glass/epoxy-laminated composite plates was investigated both experimentally and numerically by Kursun et al. [31]. The variation of force with time, variation of energy with time, and even failure of the composite laminate obtained from finite element stress analysis did reveal a good correlation with the experimental test results. Rim et al performed a series of low-velocity ballistic experiments by varying the positions of the Shape Memory Alloy (SMA) through the thickness [32]. It was found that the impact resistance of the SMAHC revealed significant improvement. Ling et al showed that the SMAHC did have lesser delamination energy when compared one-on-one with their regular counterpart [33]. A similar study was conducted to evaluate the damage behaviour and residual strength of the glass-fiber reinforced plastic (GFRP) laminates with embedded shape memory alloy (SMA) wires [SMA-GFRP] by Kang et al. under conditions of low-velocity impact and fixed temperature condition [34-35]. They discovered the primary cause of impact damage to the SMA-GFRP laminate was delamination of the reinforcing fibers, with the major axis aligned well with the orientation of the reinforcing fibers. Gou-Cai Yu et al. investigated the impact behaviour of carbon fibre aluminium laminates (CARALL) at low velocities [36]. Primary goal of their independent study was to determine and/or to establish if the carbon fibre could be used as a reinforcement and characteristics of the chosen aluminium alloy did affect or influence the low-velocity impact response of the Carbon Fiber Aluminum Laminate (CARALL).

Besides numerical investigations, the dynamic behaviour of Shape Memory Alloy (SMA) – Fibre-Reinforced Plastic (FRP) laminate under the influence of low-velocity impact was also investigated by both theoretical analysis and modelling [37-42]. The experiments clearly demonstrated that the Shape Memory Alloy (SMA) wires can increase both the damage resistance and impact resistance of the Fiber-Reinforced Plastics (FRPs) while concurrently making them tenacious. Low-velocity impact on a SMAHC in comparison to a traditional composite counterpart is summarized in Figure 3.

Figure 3: The advantages of shape memory alloy hybrid composites (SMAHCs) for the study of low velocity impact.

High Velocity Ballistic Impact on Shape Memory Alloy Hybrid Composite [SMAHC]

Several researchers have successfully conducted a study on high-velocity ballistic impacts on the Shape Memory Alloy Hybrid Composites (SMAHCs). At ballistic speeds, the contact period between the projectile and the composite is significantly reduced, resulting in essentially a localized response from the impact loading rather than global deformation. When struck at low velocity, it was discovered that size of the damage decreased as length of the beam grew. On the other hand, at a higher speed, the damage-induced did not depend on length of the beam [43]. At greater velocities, an extra damaging mechanism known as the "shear plug" is present primarily because the high-velocity impact energy is distributed across a much smaller space. The material surrounding the perimeter of the projectile is sheared and forced forward due on account of the high pressure that is produced at the point of impact, resulting in the creation of a hole or "plug" that is slightly larger than diameter of the projectile and does tend to grow larger as it penetrates into the chosen composite material. Until such time the impact energy of the projectile is reduced to a point where the fibres do begin to offer some shear resistance, this procedure is repeated for the subsequent plies [44]. Ahmadi et al. investigated the resistance to high-velocity impact of the glass fiber-reinforced laminates having various thickness ratios [i.e., thickness of the glass/epoxy ply to the thickness of the aluminium sheet) [45]. Verma et al found from their independent study that the ballistic limit of PE-SMA graphite-fiber reinforced plastics GFRPs) (maximum 72.72%) is much higher than that of the homogeneous counterpart [46]. They also showed that the PE-SMA did experience maximum strain and thereby getting damaged at the point of impact. This is shown in Figure 3.

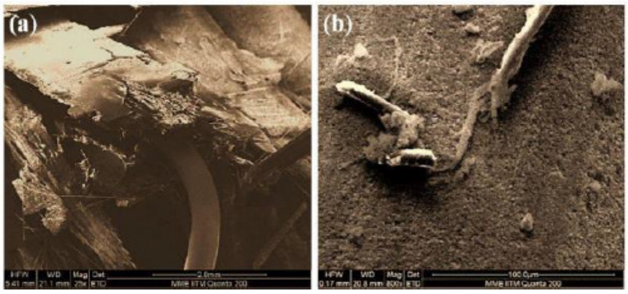

Figure 4: Micrographs Showing:
(a) Pull-Out of Shape Memory Alloy (SMA)
(b) Evidence of Different Damage [46].

Eslami et al studied the insertion of a shape memory alloy (SMA) wire into a composite does cause the elasticity modulus to increase and the compressive stress to be released or decrease, both of which tend to improve overall mechanical properties of the resultant composite material [47,48]. A few impact experiments with high ballistic velocities have been carried out to both determine and understand the post-impact structural strength of the chosen and studied composite material [49]. It was discovered that for a certain type of impactor the severity of damage increases with an increase in impact energy up to the penetration velocity, which is often referred to as the ballistic limit, when the projectile barely perforates the intended target [50,51]. The post-impact structural strength of the resultant composite material reduces in proportion to the degree and/or severity of the damage. Nevertheless, the degree of damage does reduce when the level of impact energy does rise above the penetration velocity. There is adequate documentation in the published literature on high-velocity impact dynamic studies on Shape Memory Alloy Hybrid Composites {SMAHCs}.

Conclusions

Shape memory alloy hybrid composites find themselves useful for a spectrum of applications in the defence field, particularly in the domain of impact dynamics. In this paper, low-velocity impact dynamics and high-velocity impact dynamics of Shape Memory Alloy Hybrid Composite (SMAHC) is presented and the following conclusions are drawn:

1) Despite their excellent strength-to-weight [σ /ρ] ratio, high specific strength [σ /ρ], high specific stiffness (E /ρ), and good corrosion resistance, composite materials are not widely chosen for use in critical engineering applications primarily because of their vulnerability to damage arising from an impact that resembles out-of-plane loading, an overall inferior resistance to impact loading, coupled with lower energy-absorbing capability.
2) The pseudoelastic shape memory alloy does exhibit a recoverable strain of 6 % –8 % coupled with a high strain to failure. The stress-induced phase shift that occurs upon loading does give the shape memory alloy (SMA) its high-strain capability. A plateau region is created in the stress versus strain curve when

the pseudoelastic Shape Memory Alloy (SMA) is stretched, transitioning from an austenite phase to the martensite phase. This phase transformation process is what allows the SMA to absorb significantly more energy than the other competing materials. To strengthen and increase the impact damage resistance of a composite material, researchers have made an attempt to investigate the use of a shape memory alloy (SMA) material in conjunction with the desired composite material.

3) In comparison to the traditional composite materials, the SMAHCs possess the following:

(i) Higher ballistic impact resistance
(ii) Increased damage tolerance
(iii) Good ductility
(iv) Less delamination energy
(v) Excellent energy absorption capability.

These qualities make them a better substitute to the traditional composite counterpart.

4) Insertion of a shape memory alloy (SMA) wire into the chosen composite Material does cause the elasticity modulus to increase and the compressive stress to be gradually released, both of which contribute to improving the mechanical properties of the composite.

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