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Bi-Metallic Composite Structures With Designed Internal Residual Stress Field

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Abstract

Shape memory alloys (SMA) have a unique ability to recover small amounts of plastic strain through a temperature induced phase change. For these materials, mechanical displacement can be accomplished by heating the structure to induce a phase change, through which some of the plastic strain previously introduced to the structure can be reversed. This paper introduces a concept whereby an SMA phase is incorporated into a conventional alloy matrix in a co-continuous reticulated arrangement forming a bi-metallic composite structure. Through memory activation of the mechanically constrained SMA phase, a controlled residual stress field is developed in the interior of the structure. The presented experimental data show that the memory activation of the SMA composite component significantly changes the residual stress distribution in the overall structure. Designing the structural arrangement of the two phases to produce a controlled residual stress field could be used to create structures that have much improved durability and damage tolerance properties.

Introduction

The shape memory effect has been well documented in the scientific literature [1]. Of particular interest for this work is the one-way shape memory effect in which the alloy is shape set at high temperature (e.g. 500°C), cooled and subsequently deformed plastically, then memory activated at low temperature (e.g. 100°C) in order to recover the initial product shape. The transformation between the high temperature austenite phase and the low temperature martensite phase is the mechanism by which this memory effect occurs. Austenite is the high temperature phase; upon cooling to room temperature, a phase change to martensite occurs. Crystallographically, this martensite phase transformation occurs by twinning. Untwinning of the martensite structure accommodates subsequent mechanical deformation. Finally, heat treatment above the austenite transformation temperature recovers the original crystal structure and the original shape of the part.

There are a wide variety of alloy systems that exhibit the shape memory effect [2]. One of the most prominent is a binary nickel titanium alloy known as Nitinol that was developed at the Naval Ordinance Laboratory in the 1960s [3]. The composition of Nitinol alloys is approximately 55 weight percent nickel and 45 weight percent titanium. Small variations in the ratio of nickel to titanium affect the phase transformation temperatures that govern the memory effect. The start of the martensite transformation can occur from well below room temperature (in this case, deformation at room temperature is recovered as soon as the applied load is removed—a condition termed "superelastic") all the way up to about 70°C. For the application described in this paper, a high temperature composition is necessary to avoid premature transformation due to frictional heating during the deformation step in the processing sequence.

Shape memory alloys have been extensively researched for actuation applications in aero structures [4,5]. It has been well established that these alloys can exert a tremendous amount of force upon memory activation [6]. This paper describes a processing route for creating a metal matrix laminate composite with discrete SMA ligaments that will counteract any applied load and reduce the overall net effective load. A similar concept is routinely used in the construction industry. The tensile load carrying capacity of concrete (a notoriously brittle material in tension) is improved by post-stressing the material with steel wires [7]. These wires pass through a conduit in the concrete and are elastically strained and locked into place once the concrete cures. The contraction of the steel wires is constrained by the concrete, resulting in constant residual compression that mitigates the propagation of cracks due to tensile loads. The proposed concept aims to take this well-proven civil engineering system and apply it to aero structural designs with advanced material combinations.

The enabling feature of this concept is the application of additive manufacturing (AM) methods for the creation of the non-SMA component. Additive manufacturing is used to create the matrix component using a standard titanium alloy, Ti-6Al-4V. This matrix resembles an open-cell foam structure and enables the incorporation of a second phase into the structure. The voids in the matrix structure are filled with Nitinol SMA powder, hot-consolidated and shape-set into a fully dense arrangement. The composite structure is then mechanically worked to introduce recoverable plastic strain into both the matrix and the SMA. Upon memory activation heat treatment, the SMA will attempt to revert to its original shape-set dimensions (i.e. contract) but will be constrained by the titanium alloy matrix. This will result in the development of a static residual stress field within the structure. As cracks generally nucleate at a free surface, the compressive field in front of the crack tip as it grows into the structure will inhibit propagation. The stress intensity factor (K) is related to the local stress field (σ) and crack length (a) by $K = \sigma(\pi a)^{1/2}$. Careful design of the structure and the resultant internal stress field should allow the stress intensity factor to remain below the threshold value, thus inhibiting any cracks from growing. Additionally, by the nature of the interlocking arrangement of the SMA/alloy composite core, any cracks initiating in this area will be contained and isolated from the load-bearing structural layers.

Experimental Procedure

An Arcam electron beam melting (EBM) AM machine at the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso was used to make the matrix alloy net structure scaffolding coupons. Detailed description of the EBM process are presented elsewhere [8]. Two different designs were constructed; one using a periodic net structure and one using a foamy random structure. The periodic structure was designed using a 3D computer-aided design (CAD) modeling program. The foam structure was reverse-engineered using X-ray computed tomography from a piece of cast aluminum foam. Figure 1 shows cutaway sections of the CAD models, including the periodic structure unit cell and the actual coupons fabricated in Ti-6Al-4V using the Arcam EBM process. The coupons were 1.18 inches wide by 3.90 inches long by 0.48 inch thick. The net structure area was approximately 0.60 inch wide by 2.35 inches long by 0.20 inch thick.

The open cell net structure area of the AM fabricated coupons was filled with nickel-titanium shape memory alloy powder. The physical properties of the SMA powder are given in Table 1. The powder was poured into the void area in the net structure scaffolding and vibrated for a period of 15 minutes such that the powder could achieve peak tap density. A piece of wrought Ti-6Al-4V alloy plate (1.17 inches wide by 3.90 inches long by 0.22 inch thick) was then used to cover the top surface of the coupon and the entire structure was vacuum hot pressed at 930°C for 4 hours at 1,000 psi.

One of the hot pressed samples was examined via X-radiography in order to determine if the filling and consolidation procedure yielded a void-free structure (>99% density). Figure 2 shows the radiographic results and confirms >99% density.

The samples were machined using traditional milling techniques to achieve a final sample width of 0.61 inch and a final thickness of 0.53 inch. This machining operation removed the excess matrix material from the outer edges leaving a two-dimensional laminate of Ti-6Al-4V EBM matrix, Ti-6Al-4V–SMA composite, and Ti-6Al-4V wrought plate. Figure 3 shows a cross-section of the initial coupon configuration with cut lines to indicate the final cross-sectional geometry.

A shape-set heat treatment was performed at 500°C for 15 minutes, followed by furnace cooling. The samples where then cold rolled on a two-high laboratory rolling mill using a multi-pass procedure to an approximate overall reduction of 4%. The samples were monitored between passes to ensure that the overall temperature stayed below the austenite start temperature of 68°C. After the rolling operation, one sample from each of the designs was subjected to a memory activation heat treatment at 115°C for 15 minutes.

Three of the samples were sent to Hill Engineering, LLC, in Rancho Cordova, California, for cut compliance residual stress testing: two of the periodic mesh samples (one as-rolled as a baseline control, and one memory activation heat treated) and one of the foamy mesh samples in the memory activation heat treated condition. Details of the cut compliance residual stress testing methodology are presented elsewhere [9]. Cut compliance testing was performed at the approximate mid-point of the sample and the residual stress on the transverse plane was determined using strain gages.

Results and Discussion

The visual comparison of the cut compliance tested samples is shown in Figure 4. Figure 4a shows the periodic net structure sample that has been cold rolled to 4% reduction but without the memory activation heat treatment. For cut compliance testing, wire electro-discharge machining (EDM) is used to make the cut through the sample beginning at the top surface (relative to the image) and progressing down through the sample. The cut is visible in the sample and the kerf gap at the beginning of the cut is 0.017 inch wide. Also note that the sample has slight concave curvature; this is due to the cold rolling procedure and the elastic/plastic mismatch between the matrix Ti-6Al-4V alloy and the Ni-Ti shape memory alloy. Figure 4b shows the same configuration but with the addition of the memory activation heat treatment. The top of the EDM kerf has opened further (0.033 inch) due to stress relief as material is removed during the cutting process. A longitudinal crack between the bottom surface of the composite net structure area and the Ti-6Al-4V cover plate is also evident, as indicated by the arrow in Figure 4b. These visual indications show that significant residual stress was introduced into the parts that have the SMA activated, and these stresses were relieved through the EDM cutting operation. The sample shown in Figure 4c is the foamy net structure that has been memory activated. This sample shows a much greater release of internal energy as evident by the significant kerf opening on the top of the sample (0.076 inch) and the long longitudinal crack at the net structure/cover plate interface. Also note that the release of residual stress in this sample has turned it from concave to convex.

The test data from the cut compliance testing is shown in Figure 5. The depth indicated on the abscissa is relative to the surface of the specimen where the EDM cut began. The interface between the solid Ti-6Al-4V matrix and the composite Ti-6Al-4V–SMA area occurs at around 0.22 inch. The data set labeled “Periodic (control)” is from the sample with the periodic net structure that was cold rolled but not subjected to the memory activation heat treatment. The data indicates that the rolling process itself has introduced a residual stress field in the part. The difference in elastic modulus (16,000 ksi for Ti-6Al-4V versus 5,800 ksi for Ni-Ti) contributes to this residual stress field in the as-rolled condition. The data set labeled “Periodic (memory)” is from the coupon with the same internal configuration as the control with the addition of the memory activation heat treatment after the rolling operation. The memory activation heat treatment changes the residual stress near the surface from +35 ksi to -10 ksi demonstrating a clear effect from the constrained SMA component. The data set labeled “Foam (memory)” is from the foamy net structure, and the data show that the residual stress profile is significantly different compared to the periodic net structure. In this case, the near-surface residual stress is +90 ksi, approximately 75% of the yield stress of Ti-6Al-4V. These data demonstrate two key points: 1) the memory activated, fully constrained SMA material imparts an internal stress to the matrix material, and 2) the structural configuration of the Ti-6Al-4V–SMA composite area can change the character and magnitude of the stress field generated. These results demonstrate the validity of the concept and suggest that a controlled residual stress field could be designed into a structure using bi-metallic composite configurations.

Summary

A bi-metallic composite structure was fabricated using AM and convetional powder metallurgy approaches. The AM process enabled the creation of titanium alloy open cell net structures that were subsequently filled with shape memory alloy powder and hot consolidated. Two configurations were analyzed: one with a periodic net structure and one with a foamy net structure. The fully dense, consolidated coupons were plastically strained using cold rolling and then subjected to a memory activation heat treatment. The interlocking nature of the two discrete phases constrained the memory effect in the SMA and induced a stress field into the matrix material. The two structural configurations showed different residual stress profiles indicating a correlation between stress state and net structure configuration. Further optimization of the net structure configuration should allow for the creation of customized residual stress profiles intended to improve specific properties of the overall structure.

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Table 1: Physical properties of nickel-titanium shape memory alloy powder.

Composition	
Weight percent Ni	54.6
Weight percent Ti	45.4
Mesh size	-140
Austenite transformation	
Start (°C)	68
Finish (°C)	109
Martensite transformation	
Start (°C)	78
Finish (°C)	38

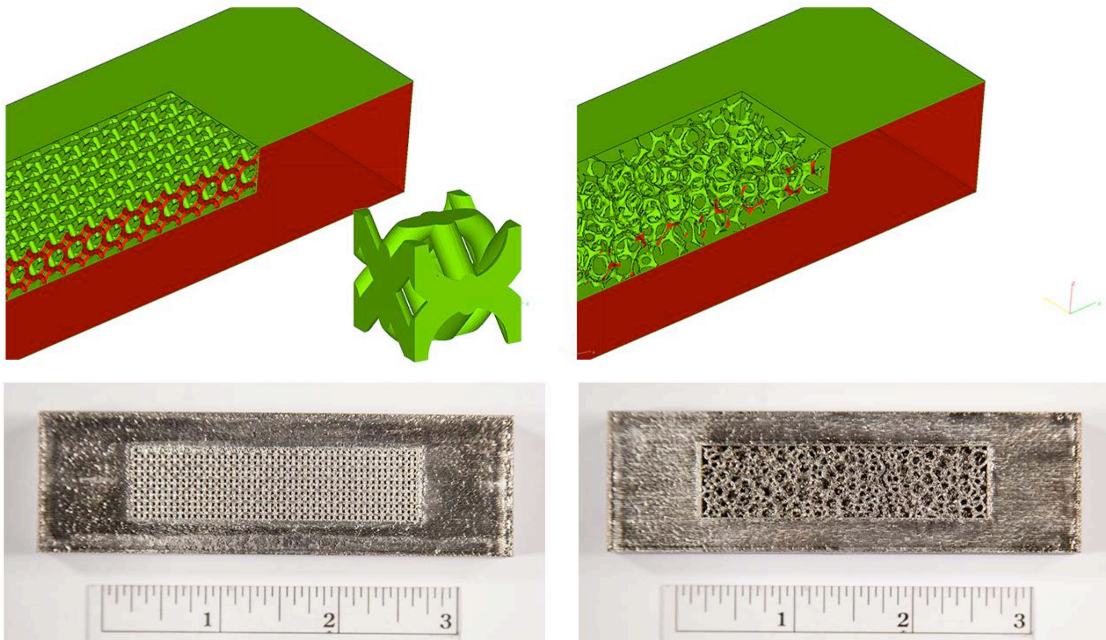

Figure 1: Test coupon designs (top) showing section cut through net structure area. Periodic design unit cell shown in inset, upper left. Actual as-fabricated test coupons made via electron beam melting shown on bottom.

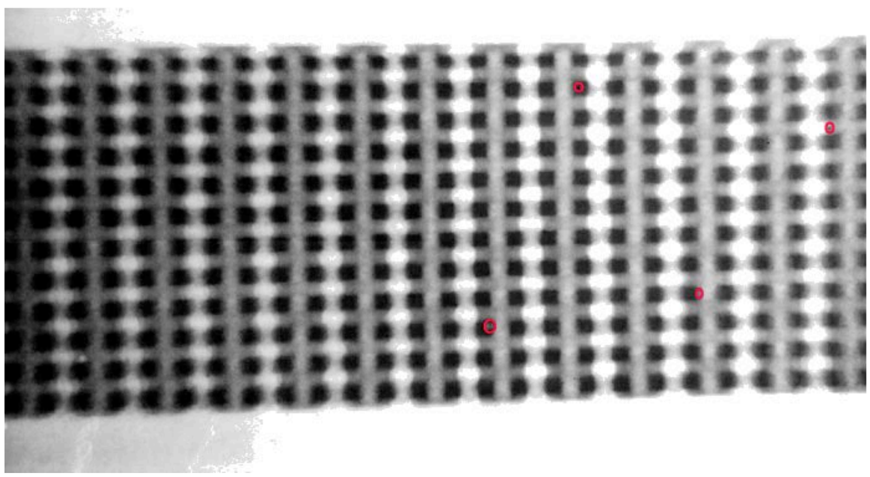

Figure 2: X-radiograph of as-consolidated periodic net shape structure. Red circles indicate isolated porosity.

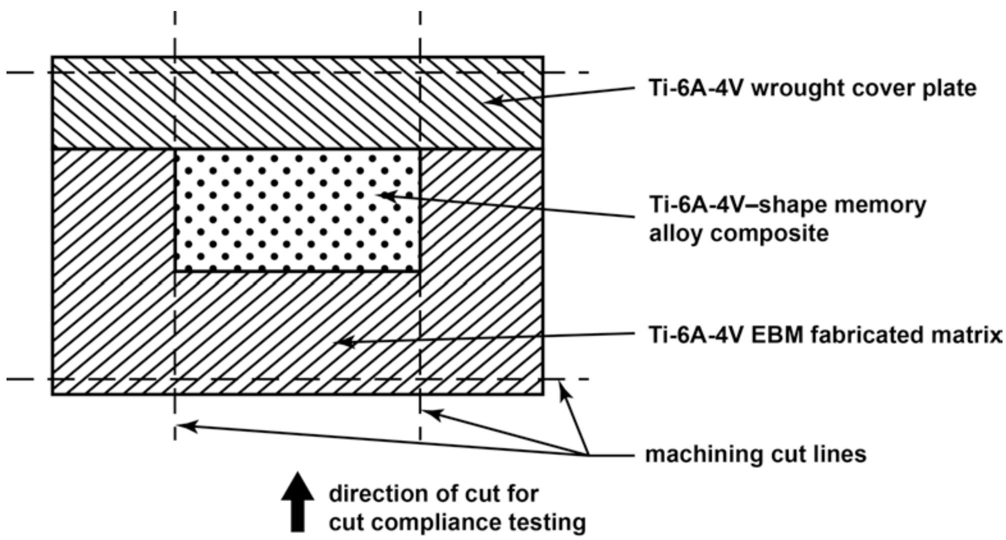

Figure 3: Schematic of the cross-section configuration of the coupons. The dashed lines show approximately how much material was machined away in order to prepare the coupons for cut compliance testing. Also note the arrow showing which direction the cut was made with respect to the coupon orientation.

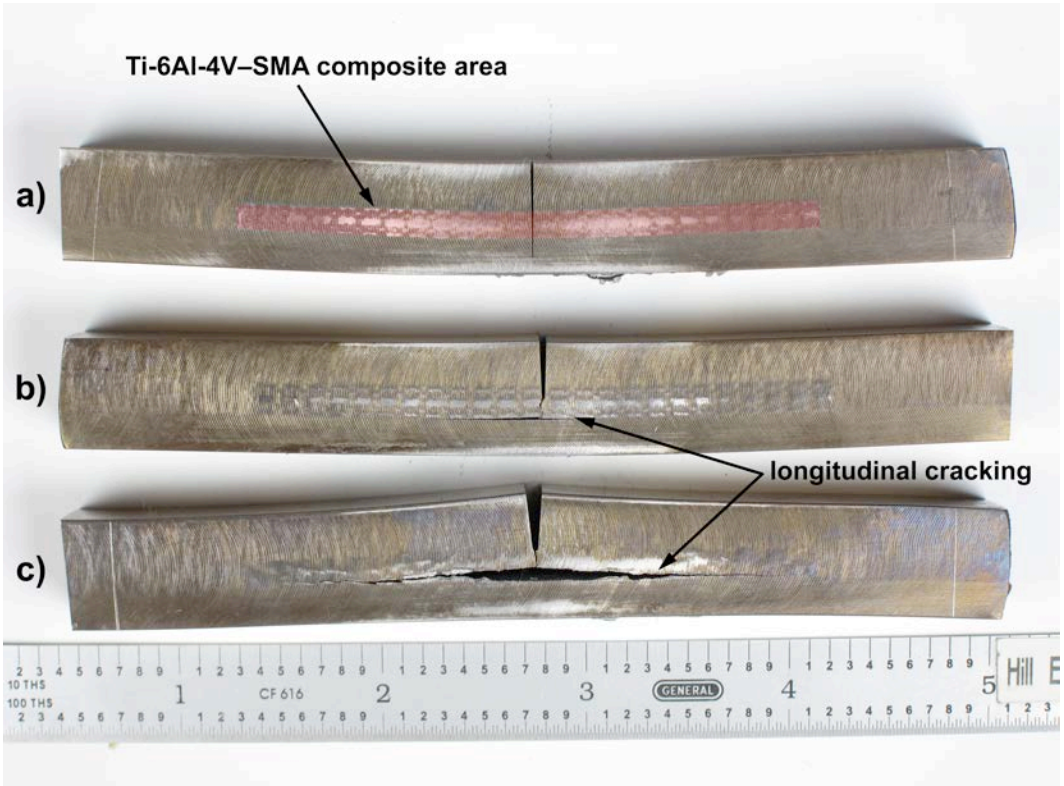

Figure 4: Side view photograph of as-tested cut compliance coupons: a) periodic mesh, cold rolled to 4% reduction, no memory activation heat treatment, b) periodic mesh, cold rolled to 4%, memory activation heat treatment, c) foam mesh, cold rolled 4%, memory activation heat treatment. For clarity, the Ti-6Al-4V–SMA composite area is highlighted by the red overlay in sample (a).

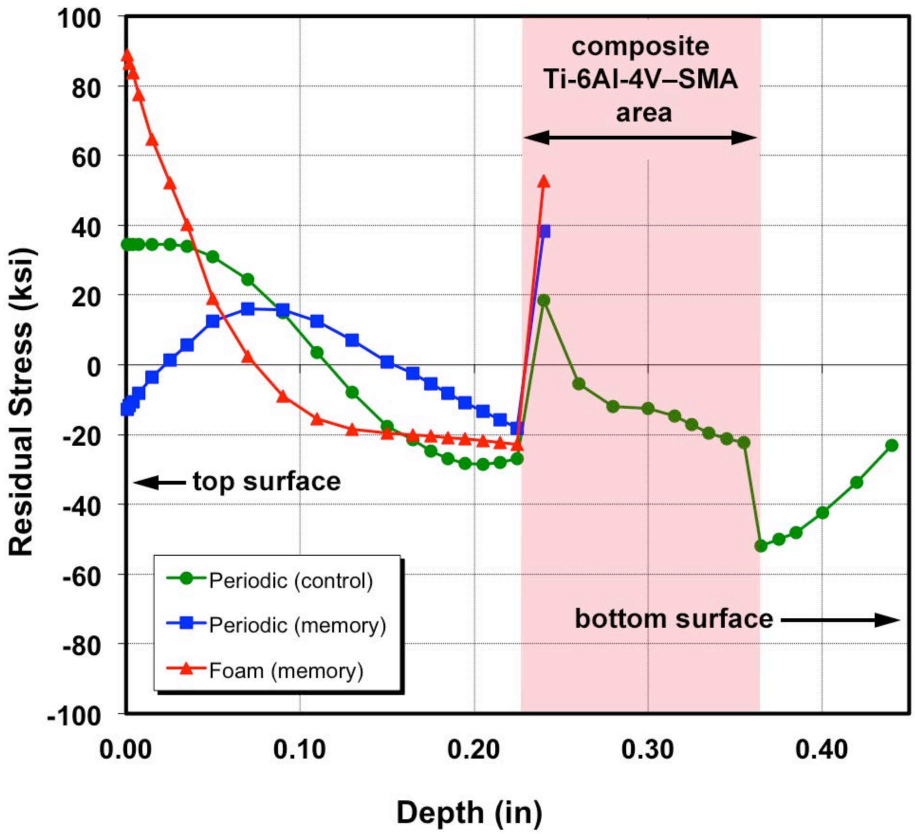

Figure 5: Residual stress results from cut compliance testing. The cut progresses from the top surface (on left at 0.00), through the matrix Ti-6Al-4V material (up to 0.22 inch), and then into the Ti-6Al-4V–SMA composite area (denoted by red shaded area).

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Shape memory alloys (SMA) have a unique ability to recover small amounts of plastic strain through a temperature induced phase change. For these materials, mechanical displacement can be accomplished by heating the structure to induce a phase change, through which some of the plastic strain previously introduced to the structure can be reversed. This paper introduces a concept whereby an SMA phase is incorporated into a conventional alloy matrix in a co-continuous reticulated arrangement forming a bi-metallic composite structure. Through memory activation of the mechanically constrained SMA phase, a controlled residual stress field is developed in the interior of the structure. The presented experimental data show that the memory activation of the SMA composite component significantly changes the residual stress distribution in the overall structure. Designing the structural arrangement of the two phases to produce a controlled residual stress field could be used to create structures that have much improved durability and damage tolerance properties.

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