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Fast Track Communication

Standardization of shape memory alloy test methods toward certification of aerospace applications

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Abstract

The response of shape memory alloy (SMA) components employed as actuators has enabled a number of adaptable aero-structural solutions. However, there are currently no industry or government-accepted standardized test methods for SMA materials when used as actuators and their transition to commercialization and production has been hindered. This brief fast track communication introduces to the community a recently initiated collaborative and pre-competitive SMA specification and standardization effort that is expected to deliver the first ever regulatory agency-accepted material specification and test standards for SMA as employed as actuators for commercial and military aviation applications. In the first phase of this effort, described herein, the team is working to review past efforts and deliver a set of agreed-upon properties to be included in future material certification specifications as well as the associated experiments needed to obtain them in a consistent manner. Essential for the success of this project is the participation and input from a number of organizations and individuals, including engineers and designers working in materials and processing development, application design, SMA component fabrication, and testing at the material, component, and system level. Going forward, strong consensus among this diverse body of participants and the SMA research community at large is needed to advance standardization concepts for universal adoption by the greater aerospace community and especially regulatory bodies. It is expected that the development and release of public standards will be done in collaboration with an established standards development organization.

Keywords: shape memory alloy, characterization, standards, experiments, aerospace, actuators



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1. Introduction

The properties of shape memory alloys (SMAs) employed as actuators are especially attractive to engineers and designers

in the aerospace industry [1, 2]; their status as the active material with the highest volume specific actuation energy density has enabled a number of adaptable aero-structural concepts [3, 4]. However, there are currently no industry or government-accepted standardized test methods for SMA materials when used as actuators. While there exists a broad range of potential actuation applications for SMAs on aerospace and automotive platforms, their transition to commercialization and production is hindered by a lack of accepted industry and regulatory testing and certification standards for SMA actuator materials and components. Even the most well-known SMA aerospace application to date, the hydraulic pipe couplers used on the F-14 [5], was limited to a non-actuating role on a military aircraft. Existing public standards are principally related to uses in the medical industry [6–10], which are based primarily on the superelastic response of these materials [11–13].

Due to the lack of universally accepted standards, the various research organizations pursuing the development of SMA actuator applications have been forced to identify and define key properties and institute their own (often conflicting) testing protocols and procedures. To rectify the current situation and provide a path forward, a new collaborative effort has begun⁸ to: (i) identify critical SMA material and actuator requirements, (ii) develop and propose baseline material and shape memory test methods, and (iii) to influence and inform the formation of public standards in collaboration with an established standards development organization (SDO). Note that, while aerospace applications exploiting the superelastic response of SMAs have been proposed, such development efforts have some recourse to the existing superelastic standards; this new effort focuses solely on the use of the material as a thermally induced actuator.

This *pre-competitive* standardization effort, though largely motivated by aerospace needs, should apply to a wide range of applications. The proposed standards are not intended to be directly associated to any specific alloy, family of alloys, or material form, nor are they intended to represent a total airworthiness certification strategy. The standardized experimental methods developed in this program are intended to describe tests that can be used to consistently evaluate new or existing alloys or alloys subjected to new processing steps or techniques, so long as the end use is as an SMA actuator. It is expected that the overall effort will be comprised of three phases requiring one year each to complete (as described in section 3).

The intent of this brief paper is to introduce the current effort to the active materials community at large, to provide a brief review of background motivation, and to encourage the input of other knowledgeable researchers in the area. The initial collaborative tasks are also described and some initial thoughts on material properties to be considered are presented.

⁸ This pre-competitive project has been organized through the Aerospace Vehicle Systems Institute (AVSI; www.avsi.aero) and requires equal commitments from all project participants that include both in-kind and monetary support. For more information or to join the effort, contact Harl.

2. Background

The unique thermomechanical response of SMAs has made them an attractive option for the development of novel solid-state actuators. Efforts in the aerospace industry in particular have focused on the implementation of these thermally activated SMA actuators in the design of future aircraft and spacecraft actuation systems. SMAs can recover seemingly permanent strains developed under thermal or mechanical load through phase transformation from martensite (the low temperature phase) to austenite (the high temperature phase) and vice versa, where the strain recovery in particular occurs during heating. The attractiveness of SMA actuation components with respect to aerospace, automotive, and oil and gas exploration applications arises from their high actuation work output, low installation volume and silent and/or solid-state (i.e., robust) actuation. However, despite the ubiquitous use of the material in the highly regulated biomedical devices industry and the prior successes of SMA actuators in automotive and especially space applications [14–16], *no SMA-based actuator to date has been certified for use in commercial aircraft*. While the transformation-based properties that underlie the isothermal response of medical devices and the testing methods associated with them have been standardized for some time, the analogous properties associated with actuation have not been similarly standardized. Knowing and understanding the failure mechanisms and fatigue in SMAs is also necessary and useful for design and certification prior to commercial use⁹. Finally, it is expected that such standardized actuation test methods will provide advantages to the SMA modeling community by regularizing the determination of material properties used in the calibration of computational analysis tools.

2.1. Airworthiness certification of materials

The US Code of Federal Regulations in Title 14 (Aeronautics and Space), Part 25 provides guidance on the establishment of airworthiness certification for materials. In Part 25.603 (Materials), we find (emphasis added):

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- The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must:
- be established on the basis of experience or tests;
 - conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
 - take into account the effects of environmental conditions, such as temperature and humidity, expected in service.
-

⁹ Given the diverse input of the various project participants, it was decided that this initial project should address the most fundamental SMA actuation properties prior to considering more complicated issues of SMA behavior. Specific issues such as cyclic fatigue will not be addressed in this initial project, though a statistical understanding of both fatigue and ultimate failure loads is essential to enable the quantitative aspects of system safety analysis (SSA) associated with SMA-based actuation systems. Development of the material testing standards herein represents a first step toward addressing the more difficult and very important issue of cyclic response.

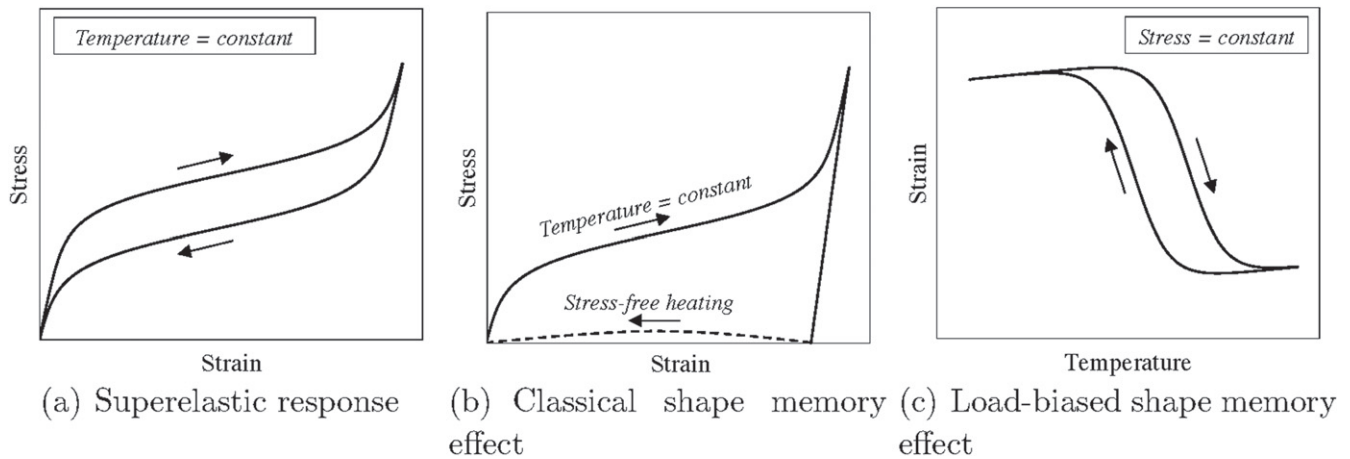


Figure 1. Most important responses in shape memory alloys. A standardized test method exists only for (a); the current effort aims to develop standards for (b) and (c).

In Part 25.613 (Material strength properties and material design values), we also find it stated that ‘Material strength properties must be based on *enough tests of material meeting approved specifications to establish design values on a statistical basis*’ (emphasis added).

In light of the above, it is important to note that many properties specific to SMAs are not considered in existing test methods or current definitions and that existing test methods are not sensible or applicable when applied to SMA materials. This issue is addressed in Advisory Circular 25.613-1 [17], which states that other acceptable means for demonstrating airworthiness exist. Thus, industrial partners can define material properties and structural test methods to demonstrate a material meets FAA requirements. The goal of this new effort is to begin to formulate such testing standards toward the establishment of acceptable airworthiness criteria for SMAs.

2.2. Existing ASTM standards for SMA materials applied to medical devices

As SMA materials gained acceptance for use in the medical industry, it became clear that some testing methods should be standardized. ASTM International has addressed this need by publishing standard test methods to guide SMA experimentation efforts [6–10]. Some standards are restricted to the standardization of terminology (ASTM F2005) or suitable compositions of NiTi alloys for medical use (ASTM F2063), but others address experimental methods directly. Standard test method ASTM F2004 addresses the details of differential scanning calorimeter testing, which is an important test for characterizing transformation temperatures in SMAs under zero stress. As an alternative method to estimate only the transformation temperatures in processed materials during heating, specification ASTM F2082 defines the ‘bend and free recovery’ test. This specification makes direct use of the shape memory effect, but is restricted to SMA wires with diameters from within a prescribed range. It is essential to note that both F2004 and F2082 define ‘zero-stress’ tests,

whereby the transformation temperatures are assessed in the absence of externally applied loads. Further, F2063 and F2004 consider properties in the fully annealed state. Each of these restrictions contrasts with the growing use of SMA components as actuators, which are processed beyond an annealed state and by necessity undergo thermally induced transformation in the presence of loads (aero-structural and otherwise).

Finally, specification ASTM F2516 addresses the tensile testing of SMA specimens with a focus on those exhibiting superelasticity at room temperature. While some aspects of the standard might apply to the characterization of material intended to provide thermally induced actuation, the utility of its content in the context of current aerospace and/or automotive industry goals is limited. The current ASTM standards aim for a basic understanding of certain aspects of SMA behavior, mostly relevant to superelastic medical applications; they do not address the full thermo-mechanical characterization of these materials. This is best illustrated in figure 1, which shows the three most important SMA responses (superelasticity, traditional shape memory effect, and load-biased shape memory effect). Only assessment of the first is currently considered in the industry standards described above; our new effort aims to standardized characterization of the second and third responses.

2.3. Prior work on standardization of SMA actuation testing

Elements of this effort have already been initiated within the activities of the Consortium for the Advancement of Shape Memory Alloy Research and Technology. This consortium was established in 2007 by researchers at Boeing, NASA, and Texas A&M University as a venue for discussing issues related to material development and characterization and constitutive model derivation and implementation as they pertain to SMAs (see, for example, resulting works [18, 19]). The consortium eventually grew to include a number of other universities and industry partners, including Rolls-Royce plc. A number of focused experimental, theoretical, and computational team efforts have been documented. One of the more

successful was the initiation of the efforts described herein to determine a standardized characterization approach for actuator material compositions, including specification of testing steps and conditions and specimen configurations.

3. A new collaborative effort

It has been determined that the overall SMA specification and standardization effort will require three phases spread over approximately three years in order to deliver the first ever FAA-accepted material specification and test standards for SMAs as employed as actuators for commercial and military aviation applications. The three phases to be pursued are as follows.

- Phase (1). (Current effort.) Standardized test methods are being developed and documented for determining chosen material and shape memory properties of existing and new alloys. Developed test methods are being assessed via preliminary trial experimentation. Potential SDOs for collaboration will be identified and their level of interest and comments on eventual publication of SMA standards are solicited.
- Phase (2). A draft of the test methods will be submitted to industry, regulatory, and expert organizations for comment and to begin the process toward standards publication. An established SDO will be selected for detailed collaboration and final public release of the test methods. During this process, the test methods will be independently evaluated via a greatly expanded 'round robin' experimental effort (see [20] for a similar example associated with SMA model development). The experimental effort will consider a statistically significant number of samples and a number of laboratories.
- Phase (3). In partnership with a selected standards body, the standardized test methods will be finalized, resulting in a formalized recommendation to regulatory agencies.

In the following, we briefly describe the efforts *currently* underway toward the completion of phase 1, which initiates the overall effort. Essential to the success of this project is the participation and input from a number of organizations and individuals, which by design includes engineers and designers working in materials and processing development, application design, SMA component fabrication, and testing at the component and system level. Further, strong consensus among this diverse body of participants is needed to advance standardization concepts developed herein for universal adoption by the greater aerospace community and especially regulatory bodies. Additionally, in order to assure broad acceptance of the SMA test methods, the development and release of public standards will be done in collaboration with an established SDO such as ASTM, SAE, etc.

3.1. Determination of SMA properties included in final specification

There are many material and shape memory effect properties that impact SMA component design and performance. These properties depend on alloy composition and thermo-mechanical history (e.g., hot work, cold work, heat treatment, etc). The initial task identifies and defines the most essential material and shape memory effect properties that need to be measured to fully evaluate an SMA. It has begun with a comprehensive review of published information regarding previously accepted SMA material specifications (i.e., in the medical industry), past aerospace applications design efforts, and even the efforts of past collaborative groups. Conventional metals properties such as those addressed in the Metallic Materials Properties Development and Standardization (MMPDS; formerly MIL-HDBK-5) [21] are also being considered. An expanded list of past properties considered (and the justifications for doing so) has been generated. The original expanded list of properties is being reduced via discussion and consensus decision to a critical set for the eventual certification of a new SMA material or component. Such a list will include conventional metals properties (e.g., elastic tensile modulus, shear modulus, etc) and in particular key actuation properties (e.g., transformation/actuation strain, transformation temperatures), which have not been addressed in any previous standard.

3.2. Determination of material characterization methods for assessment of chosen SMA properties

The determination of a final essential material properties list has been highly influenced by the simultaneous consideration of the experimental methods required to measure each proposed property. This will eventually include the specification of the specimen configuration(s), their preparation, the thermal and mechanical conditions applied, and the methods of measurement. Wherever possible, conventional metals testing methods and associated specifications (e.g., ASTM E8 [22]) are being incorporated with necessary modification to determine particular structural properties. The assessment of some SMA properties may be possible using established methods for medical devices, perhaps with modification (i.e., ASTM F2082 on 'bend and free recovery' [9]). However, it is expected that substantial effort will be required to design/determine detailed experimental methods for the quantification of material properties associated specifically with the SMAs performance as a thermally induced actuator. For all tests, special care has been taken to account for material thermal-mechanical coupling and the consequences regarding loading rates, loading axes, and the effects of applied thermal conditions on experimental equipment [23–25]. Finally, methods of interpreting test results to determine quantified material properties are being specified, such as the assessment of slopes, hysteresis heights, etc.

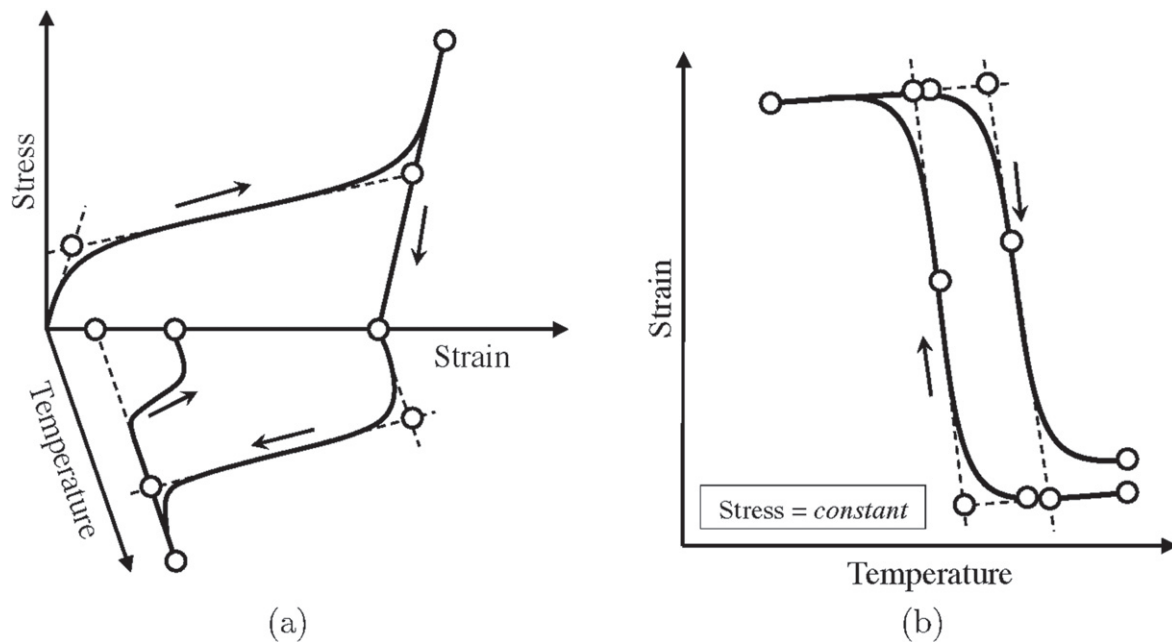


Figure 2. First two SMA actuation tests to be standardized: (a) tension/compression free recovery, and (b) constant force thermal cycling. Stress-strain-temperature points of interest are schematically illustrated.

3.3. Preliminary experimental assessment of proposed tests

In order to validate the feasibility of proposed experimental methods, trial experiments will be performed on a range of alloys at multiple laboratories experienced in the particular complexities and nuances inherent in the testing of SMA materials. Given that this is a preliminary assessment, only a relatively small number of specimens (50–100 total, provided by project participants ATI Specialty Metals, SAES Group, and NASA-GRC) will be tested for each experiment proposed. The effectiveness of these tests in quantifying the target properties in alloys of varying behaviors and the consistency of the results obtained from the two labs will be used to plan the larger testing effort of the subsequent phase 2.

3.4. Evaluation of existing SDO for collaboration

Successful acceptance of the SMA test methods developed during this project will require that they be evaluated, endorsed, and publicly released by an accepted and established SDO. To this end, potential SDOs are currently being identified (e.g., ASTM, ASME, SAE, etc). They are being contacted, engaged, and briefed on the aims and approaches of the collaborative project. Each SDO will be evaluated and assessed on their suitability for development and release of SMA actuator standards

4. Initiation of efforts and concluding thoughts

As this SMA testing standardization effort begins, researchers have focused on properties and associated tests. Property discussions have addressed the need of material suppliers and application developers to consider fundamental properties

such as element composition (including trace elements) and microstructural properties such as grain morphology and inclusion characteristics. The effect of these on actuation performance and even fatigue is especially strong in phase transforming materials such as SMAs. Further, standard thermoelastic properties such as tensile and shear moduli and thermal expansion coefficient have also been discussed, though it is evident that recourse will be made to the existing testing standards for metals (e.g., ASTM E8 for Tension Testing for Metallic Materials).

However, of greatest interest to the SMA research community is the determination and description of important thermally induced shape memory response features. Two experiments (and the response features they elucidate) have been down-selected as being both the most critical and most common characterization methods used throughout the aerospace community: (i) the tension/compression free recovery test, and (ii) the constant force thermal cycling test. The former is associated with the conventional shape memory effect (cf figure 1(b)) and is analogous to ASTM F2082 on ‘bend and free recovery,’ while the latter directly addresses the capability of an SMA material or processed component to perform actuation work (i.e., to recover strain under load). The two loading paths associated with these first tests to be standardized are shown in figure 2, where the critical stress-strain-temperature points to be obtained from these tests are schematically illustrated. Note that such aspects as recoverable and irrecoverable strains and critical transformation temperatures are measured in various ways.

Draft testing standards associated with these two tests are currently being authored, and these have been and will continue to be shared with the wider SMA actuation community via conference presentations and articles such as this. Preliminary experimentation is also being initiated to assess the

robustness of these methods across a range of specimen types, materials systems, experimentalist experience levels, etc. In the coming years, and especially as the SDO process begins, it will be essential that more organizations with a vested interest in the ability of these important materials to be flight-certified choose to participate in these developments, in addition to those in the areas of automotive applications and even consumer goods. This article has provided a description of the effort in its current form and serves as an invitation to other interested entities to join and contribute. It is only through such community-wide effort that SMA actuator applications will reach their full market potential and functional impact.

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