Developing Complex Shape-Morphing Metallic Structures for Space Applications

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ABSTRACT

This article describes an ongoing Johns Hopkins University Applied Physics Laboratory (APL) fundamental additive manufacturing study to fabricate large-scale (up to 10 × 10 × 13 in.^{3}) shape-memory alloy components with locally tailored actuation stroke, force, and activation temperature.

The goal of the study described in this article is to develop novel structures capable of precise, self-guided shape change under an external stimulus. These materials will be advantageous when used in environments where direct human intervention is impractical (e.g., invasive biomedical devices or deep underwater).[1,2] Perhaps the most exciting application of this concept is for deployable space structures. Owing to launch constraints, spacecraft structures are limited in size, weight, and power. However, once in space, these structures are critically reliant on large, kinematically deployed components—solar arrays, solar sails, radar antennas, etc.—for operational capabilities.[3,4] Current approaches rely on mechanically driven devices to expand and to remain in a deployed configuration, and these devices are heavy and have bulky stowage volumes.[3,4]

To combat these challenges, we have spent the last 2.5 years developing the capability to "program" complex shape change by laser-based additive manufacturing (AM) of shape-memory metals. Shape-memory alloys (SMAs) are a unique class of functional materials with the ability to convert thermal energy into mechanical work by recovering their shape upon an increase in temperature (see Figure 1). When mechanical load is applied to an SMA, it undergoes a unique permanent deformation mechanism (called detwinning), which can only be reversed by heating the material (by a few tens of degrees centigrade) to induce a reversible phase transformation.

Despite their exciting functional properties, SMAs are notoriously difficult to process, shape, and form. The shape-memory effect is highly sensitive to composition variance at the 100-ppm level, impurities (carbon and oxygen), and the underlying material microstructure, all of which can be altered during high-temperature forming processes.[5] As a result, conventional manufacturing of SMAs is limited to wire and flat sheet production methods. AM offers the unique capability for free-form geometry generation, which could overcome this limitation and enable the fabrication of complex shape-changing components. Our ultimate vision is to manufacture structures that will compactly fold into a small volume for launch and expand into complex geometries in space when exposed to the heat of the sun.

In the study described here, we focused on the fabrication of Nitinol (a roughly equiatomic NiTi alloy) components. Nitinol is by far the most widely used SMA because of its excellent mechanical properties, biocompatibility, and corrosion resistance.[6–9] In addition, Nitinol exhibits superior shape memory and superelastic effects, capable of restoring large strains of up to 8%.[5] Our efforts to date have centered on improving the quality of printed Nitinol components, targeting

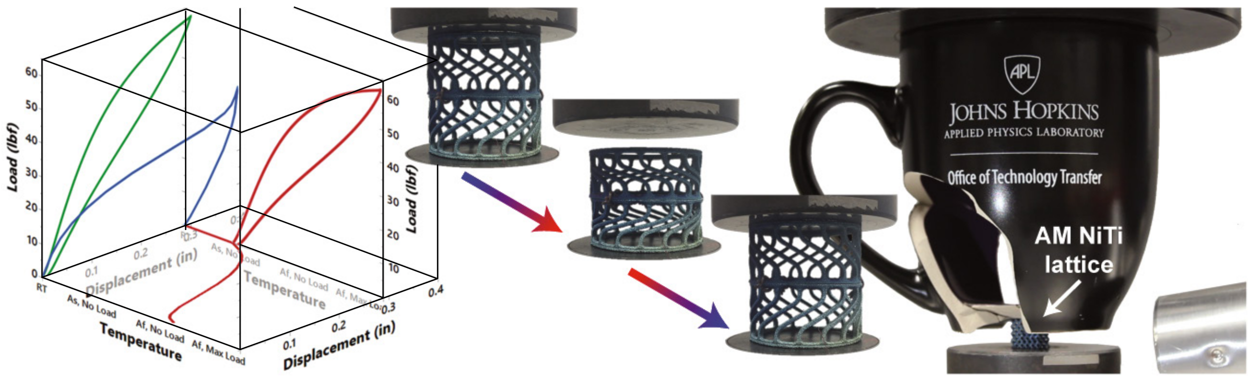

Figure 1. Overview of SMAs. Schematic (left) of the shape-memory and superelastic effects versus load, displacement, and qualitative temperature data for the AM Nitinol structures (middle and right). Blue, Shape-memory loading path, which occurs when the austenite phase transformation of Nitinol is above room temperature. Nitinol starts in the martensite phase and during deformation undergoes a reorientation of the martensite (called detwinning) that results in a permanent macroscopic shape change. Upon heating (red), the material undergoes a reversible phase transformation to austenite and recovers the shape memory strain if left unconstrained (zero load, lower red curve, middle image). If the material is constrained (fixed displacement, upper red curve, right image), the phase transformation during heating creates a large restoration force that can be used to do mechanical work. Green, Superelastic loading path, which occurs when the austenite transition of Nitinol is below room temperature. During deformation, the material undergoes a stress-induced phase transformation to martensite and accumulates shape memory strain via detwinning. Once the load is released, the martensite transforms back to the austenite phase, recovering the shape memory strain.

key metrics such as porosity and crack density; scalable fabrication (i.e., ensuring the AM processing parameters developed for small volumes [~1 mm^3] scales to large volumes [~100 cm^3]); and studying the effects of laser processing parameters on microstructural characteristics, mechanical behavior, and shape-morphing properties. We have successfully printed large parts and demonstrated repeatable shape-memory behavior (see Figure 2) by building on a lattice structure to control the thermal history during fabrication.[10]

More recently, our focus has shifted to modifying the Ni:Ti ratio within builds to achieve tailored actuation. The impact of laser processing parameters on the microstructure of AM components (size of secondary phases and grain texture) is a very active research area.[11,12] However, the impact of laser parameters is far more nuanced in SMAs because the transformation temperature (i.e., the temperature for recoverable shape change) is highly sensitive to the material composition. For instance, the transformation temperature of a $Ni_{50}Ti_{50}$ (at.%) alloy is ~80°C, while the transformation of a $Ni_{51}Ti_{49}$ (at.%) alloy is ~−20°C.[5] Depending on the laser processing parameters, the thermal history in an AM Nitinol component can vary dramatically, which causes samples from identical feedstock to have transformation temperatures tens of degrees apart.[6,13] Through a combined high-fidelity modeling and experimental effort, we recently developed an analytical tool capable of predicting the transformation temperature as a function of laser inputs.

We are now combining this tool with standard mechanical design approaches to engineer printed components that have local regions with specific transformation temperatures, rates, and displacements. A key challenge in creating a complex deployable space structure is to avoid collision during shape change. Deployment needs to occur sequentially and in a specific order, analogous to origami. Developing the capability for complex shape-morphing kinematics—without the need for and use of specialized and heavy external motors—will require joints to activate at different rates

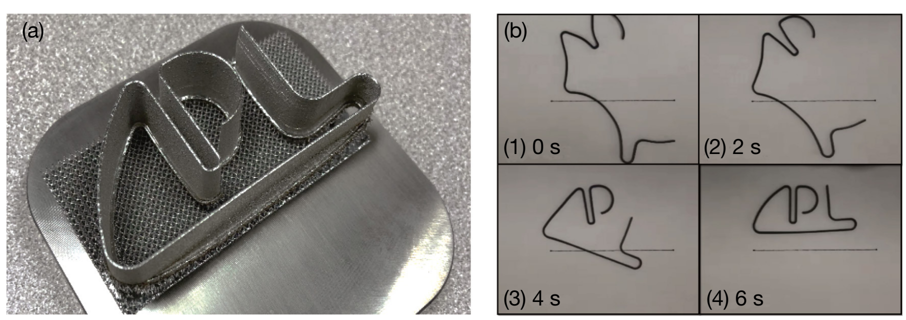

Figure 2. Proof-of-concept demonstration. This figure shows that our optimized processing parameters and lattice support approach successfully translates to complex, large-scale, shape-memory components. (a) APL logo part (65 mm × 32 mm × 20 mm) built on a lattice. (b) Time stamps of deformed logo undergoing shape recovery upon heat exposure. (Reprinted with permission from Ref. 10.)

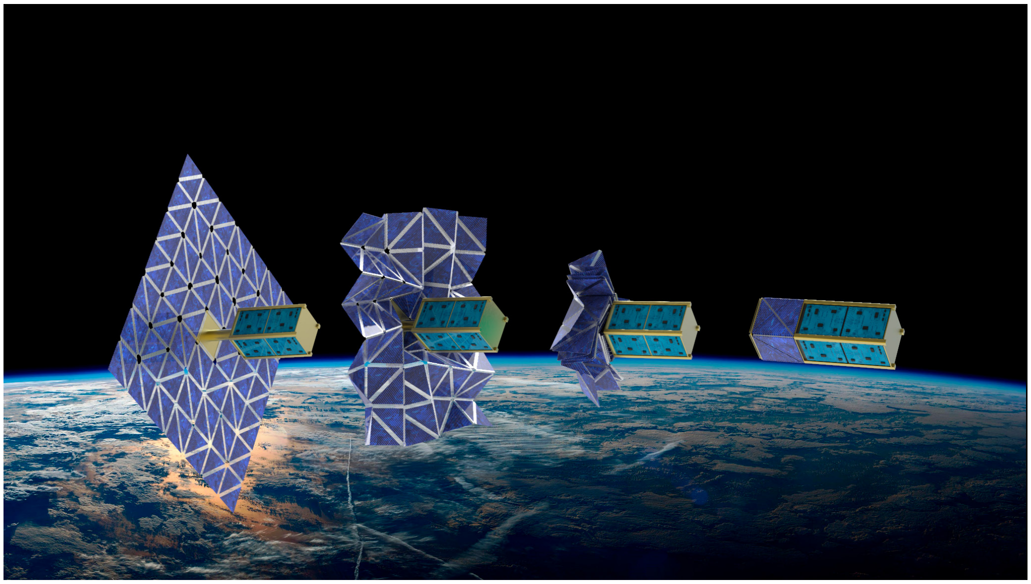

Figure 3. Vision of APL study. Combining the functional properties of shape memory alloys with 3-D printing to develop next-generation deployable space structures.

upon a thermal stimulus. An example of this vision is shown in Figure 3.

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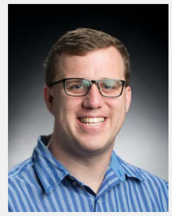

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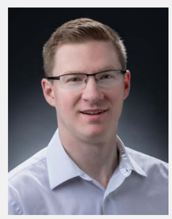

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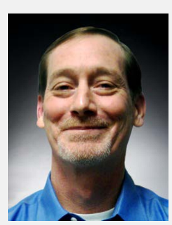

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