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LOW-POWER, MINIMAL-HEAT EXPOSURE SHAPE MEMORY ALLOY (SMA) ACTUATORS FOR ON-BODY SOFT ROBOTICS

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ABSTRACT

In the world of soft-robotic medical devices, there is a growing need for low profile, non-rigid, and lower power actuators for soft exoskeletons and dynamic compression garments. Advanced compression garments with integrated shape memory materials have been developed recently to alleviate the functional and usability limitations associated with traditional compression garments. These advanced garments use contractile shape memory alloy (SMA) coil actuators to produce dynamic compression on the body through selective heating of the SMA material. While these garments can create spatially- and temporally-controllable compression, typical SMA materials (e.g., 70°C Flexinol) consume considerable power and require considerable thermal insulation to protect the wearer during the heating phase of the SMA actuation. Alternative SMA materials (e.g., NiTi #8 by Fort Wayne Metals, Inc.) transform below room temperature and do so using no applied electrical power and generate no waste heat. However, these materials are challenging to dynamically control and require active refrigeration to reset to material. In theory, low-temperature SMA actuators made from materials like NiTi #8 may maintain additional dynamic actuation capacity once equilibrated to room temperature (i.e., the material may not fully transform), as the SMA phase transformation temperature window expands when the material experiences applied stress. This paper investigates this possibility: we manufactured and tested low-temperature NiTi coil actuators to determine the magnitude of the additional force that can be generated via Joule heating once the material has equilibrated to room temperature. SMA spring actuators made from NiTi #8 consumed 84% less power and stabilized at significantly lower temperatures (26.0°C vs. 41.2°C) than SMA springs made from 70°C Flexinol, when actuated at identically fixed displacements (100% nominal strain) and when driven to produce equal forces (~3.35N). This demonstration of low-power, minimal-heat exposure SMA actuation holds promise for many future wearable actuation applications, including dynamic compression garments.

Keywords: Wearable technology, shape memory alloy, compression garments, soft robotics.

BACKGROUND

Compression garments are widely used to treat a variety of conditions, including venous insufficiency and lymphedema [1], and can also be deployed as an intervention for individuals with sensory processing difficulties through deep touch pressure therapy [2], [3]. Conventional compression garments are typically either an inflatable system (wherein air is pumped through the bladder to exert compression on the body) or an elastic system (compression is generated through a snug tight-fitting garment) [1], [4]. Inflatable garments allow customization of compression levels, however, are bulky and may limit mobility [5]. Elastic compression garments are much more portable and less bulky, but they do not allow dynamic variation of compression levels and prove challenging to don/doff [1]. An alternative approach to compression garment development is to use embedded shape memory alloy (SMA) actuators for active compression control [6]. SMA coil actuators are engineered to contract when heated, which is typically accomplished via Joule heating by passing an electric current through the actuators. This actuation can be leveraged to create compressive forces when the actuators (and garment) are wrapped circumferentially around the body [7]. The benefit to using SMA in compression garments is that applied pressure can be adjusted (both spatially and temporally) without requiring inflation, which solves the challenges with mobility and donning/doffing, which in turn enables new forms of dynamic treatment that can be applied in untethered/real-time scenarios. Several versions of upper and lower body SMA compression garments (SMA-CG) with this approach have been previously developed and tested [6], [8], [9].

When developing SMA-based compression garments, selecting SMA actuators with the right actuation properties is crucial to the success of the functional garment. Different shape memory alloy compositions exist (e.g., NiTi, TiNb, AgCd, etc.) each with unique physical and mechanical properties; the

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performance of SMA actuators can be further altered with various shape-setting (i.e., heat treatment) processes. Typically, raw SMA wires undergo actuator formation and shape-setting stages to 'train' the SMA to remember its shape, which involves heat-treating and cooling the SMA. Parameters including heat treatment temperatures, heat treatment exposure times, and cooling mechanisms, as well as the alloy composition itself, each play a role in establishing the actuator's transformation temperature windows (i.e., the temperature range over which the SMA begins and completes actuation). For example, a 0.1% increase in nickel content in a NiTi SMA can cause a 10°C decrease in its transformation temperature [11, 12, 13]). The resultant temperature range required for a particular material actuation will significantly affect the design and performance of an SMA actuator comprised of that material, including the forces generated, the power consumed, and the amount of waste heat generated. These performance elements then influence the design of any system in which the actuators are embedded.

We illustrate this design tradeoff using two SMA-based dynamic compression garments that have been previously developed and tested. As shown in Figure 1, lower body and upper body SMA-based compression garments were designed to selectively apply compression on varying body regions. In these garments, compression was achieved with SMAs (Flexinol 70°C, by Dynalloy, Inc.) that have an activation window of 44–48.5°C to 58.4–69.8°C [7], with full actuation achieved at approximately 70°C (henceforth referred to as 'high-temperature SMAs'). The high actuation temperatures of these SMAs require garment designs that involve fabric combination layers to protect users from heat generated during actuation. In this case, a tri-layered fabric combination was used directly below the SMA actuators (Figure 1 beige regions: cotton aramid, reflective heat shield, and Teflon^{TM}), which compromises the garment flexibility and long-term wearer comfort in order to provide the necessary thermal protection. Additionally, the amount of power needed to sustain a desired compression of 20-30 mmHg levels is 17.1 Watts [17], which presents power management issues.

FIGURE 1: EXAMPLES OF SMA COMPRESSION GARMENTS DEVELOPED WITH HIGH-TEMPERATURE SMA ACTUATORS [6, 10, 15]

While high-temperature SMA presents problems with thermal protection and high power consumption, material manipulation (e.g., modifying the alloy composition) of SMAs can shift the actuator's transformation temperature window. This could, theoretically, drop the actuator's activation temperature window below 37.5°C, equivalent to human skin temperature, offering actuation opportunities with no external power required (we hereafter refer to these alternative actuators as "low-temperature SMAs"). An exploration of this concept was done by Granberry et al. who conducted a preliminary study on using low-temperature SMAs (NiTi #8, by Fort Wayne Metals, Inc.) in compression garments that actuate on exposure to room or skin temperature, illustrated in Figure 2 [10]. This lower body SMA-based compression garment can be directly stored in a freezer and be easily donned on legs, after which environmental and/or body heat can be harvested as an energy source to activate the SMA actuators. This investigation demonstrated a dynamic garment system with no need for a power supply, no complex control system, and no need for heat-protective materials (since it produces no waste heat during actuation).

FIGURE 2: LOW-TEMPERATURE-ACTUATED SMA COMPRESSION GARMENT THAT ACTIVATES AT ROOM/BODY (ORIGINALLY APPEARED IN GRANBERRY ET AL) [10].

While this study presents an exciting development in "powerless" SMAs actuator design, the garment needed to be stored in much colder temperatures to remain unactuated prior to use. This leaves much room for improvement from a usability and user-adoption standpoint. Further, for the scope of the study, the garments were only investigated as a one-time reactive system (i.e., the actuator transformation was only observed with exposure to room/body temperature, and no electrical power was applied to enable dynamic control after donning). However, it is plausible that the specific SMA actuators used in this study were not fully transformed after equilibration to either room or body temperature (i.e., increasing the material temperature above room/body temperature would result in additional stiffening/force generation as the material undergoes additional phase transformation), as it is known that SMA phase transformation temperature windows are dependent on the material stress. If true, this would enable additional and controllable actuation of the low-temperature SMA (and thus, the compression garment in which the SMA was embedded) through incremental applied power and heat exposure above room/body temperature.

This study investigates the intersection between these two paradigms, specifically building upon Granberry et al.'s work to examine whether additional actuation capacity exists in low-temperature SMAs that are equilibrated merely to room temperature. If there is, in fact, additional actuation capacity present in low-temperature SMA actuators which have equilibrated to room or body temperature, this would represent a novel opportunity to create dynamic and controllable actuation with a significant reduction in the power required and heat generated (compared to high-temperature SMAs, which are the typical material used for dynamically-controllable SMA actuators). The following sections describe an initial investigation to determine the magnitude of force that can be generated (via Joule heating) in low-temperature SMA coil actuators once the material has equilibrated to room temperature.

METHODS

Low-temperature SMA Actuator Development

Low-temperature SMA wire (0.012" NiTi #8, A_f = 22–40°C) was purchased from Fort Wayne Metals (Fort Wayne, IN, USA) and the raw SMA wire was formed into coils (spring outer diameter = 0.048", spring index C=3) using an in-house coil making device developed by Holschuh et. al. [7]. After coil actuator formation, each coil was exposed to different heat treatment profiles to understand the influence of both heat treatment temperature and duration on SMA actuation behavior. These heat treatment profiles were as follows: 450°C for 5 minutes; 450°C for 10 minutes; 500°C for 5 minutes; and 500°C for 10 minutes. Four corresponding samples were produced, with each sample was tested at the same length of each spring in an Instron 3365 Series tensile testing machine (Instron Inc., Norwood, MA, USA).

Low-temperature SMA Actuator Characterization Test

Blocking force tests were conducted to measure the amount of force generated by the low-temperature SMA springs when held at a fixed extensional strain (100% relative to the fully actuated/compressed spring length) as a function of applied current (i.e., the sample was extended from 1.2" to 2.4" in length). The actuators were powered via a DC power supply (Dr. Meter HY3005F-3) which connected to each actuator using alligator clips, illustrated in Figure 3. Because low-temperature SMA activates at (and below) room temperature, the Instron machine was calibrated at the beginning of each trial to remove the preloading force generated by the actuators at room temperature. The forces measured and the results presented in this paper represent the *relative*, or *additional*, force generated by each actuator when heated above room temperature.

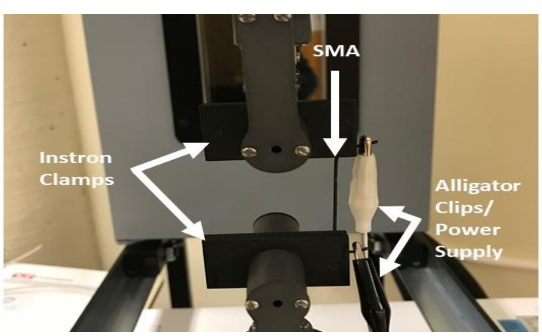

FIGURE 3: LOW-TEMPERATURE SMA CLAMPED INTO THE INSTRON WITH ALIGATOR CLIPS ATTACHED AT THE ENDS.

At 100% extensional strain, each actuator remained at a fixed position (i.e., in a blocking force test configuration), with the baseline force was measured for one minute with no applied current. The current was increased by 0.1 A increments up to 0.6 A and force data were collected for each 60-second window. Each of the four SMA samples underwent five repetitions in a randomized order. Further, we were interested in how the low-temperature SMAs compare to the high-temperature SMAs in terms of power consumption and temperature required to achieve equal force outputs. Therefore, we also conducted a test to compare the power input and thermal output between a single high- and low-temperature SMA (heat-treated at 450°C for 10 minutes), given a similar force range. Both samples were tested separately for force output using the Instron series 3365 machine. Similar to the previous method, each sample was fully actuated and connected at the ends to a DC power supply. The samples were placed into the Instron with a fixed extensional strain of 100%, extending the sample from 1.2" to 2.4". Force output was collected from room temperature up to 0.6 A with 0.05 A increments every 60-seconds. Ten seconds before the end of every increment, a FLIR C2 camera was used to record the temperature output of the SMA.

Additionally, an SMA failure test was conducted where the SMA samples were deliberately overheated to failure (because overheating the SMA ultimately resets its memory), to determine the actuator's maximum force capacity. Replicating the previous test setup (100% strain), a current of 0.25 A was applied with 60-second increments until failure (determined by visible overheating of the material).

RESULTS AND DISCUSSION

Figure 4 shows the average force (relative to room temperature output) generated by each low-temperature SMA actuator type at different current inputs, along with their standard deviations. Figure 5 presents relative force produced by a representative trial of each actuator type over time. The vertical dashed lines denote incremental changes in applied power. Both plots present relative force information (i.e., the baseline force generated at room temperature was removed from all data).

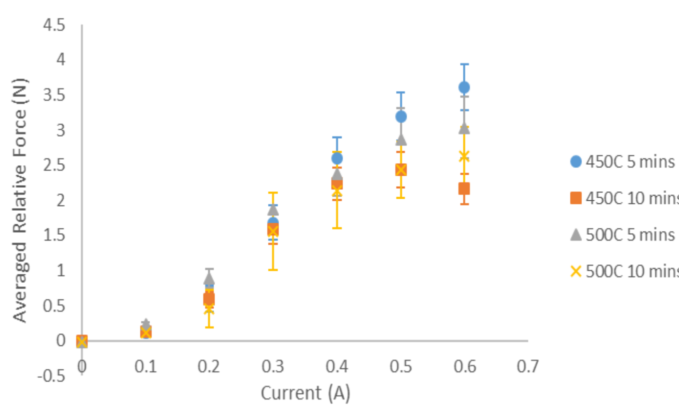

FIGURE 4: AVERAGE FORCE VS. APPLIED CURRENT FOR FOUR LOW-TEMP SMA SAMPLES (CALIBRATED TO REMOVE BASELINE FORCES GENERATED WITH NO APPLIED POWER)

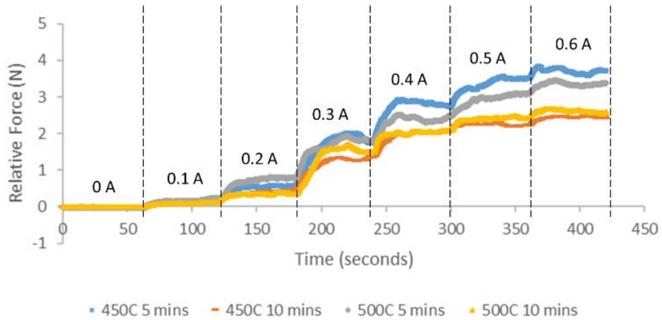

FIGURE 5: FORCE VS. TIME OF A REPRESENTATIVE TRIAL OF EACH LOW-TEMPERATURE SMA TYPE (CALIBRATED TO REMOVE BASELINE FORCES GENERATED WITH NO APPLIED POWER). VERTICAL LINES DENOTE POWER SETTINGS.

From Figure 4 and 5, it is clear that heat treatment settings influence the SMA actuation characteristics, with SMAs with shorter heat treatment periods (5 minutes, shown in blue and gray) generally producing more force than SMAs with extended heat treatment periods (10 minutes). When at maximum applied current of 0.6A, we see that for shorter heat treatment period of 5 minutes, the average force ranges from 3.03 N to 3.61 N, while at extended heat treatment period of 10 minutes, we see 2.16–2.63 N average force. Additionally, as applied power increases, so does the measured standard deviation in force output. All samples demonstrated measurable force generation above the room temperature baseline, up to 3.61 N (achieved by the 450°C/5m sample powered at 0.6 A).

A significant advantage of using low-temperature SMA vs. high-temperature SMA is the amount of heat produced and the power required for actuation. **Error! Reference source not found.** shows the power consumption and temperature differences of low- and high-temperature SMA samples (both heat-treated at 450°C for 10 minutes) when powered to produce the same approximate force (~3.375 N). The low-temperature SMA used 3.29 W less power (0.63 W vs. 3.92 W) and stabilized at a lower temperature (26.0°C vs. 41.2°C illustrated in Figure 6) than the high temperature counterpart.

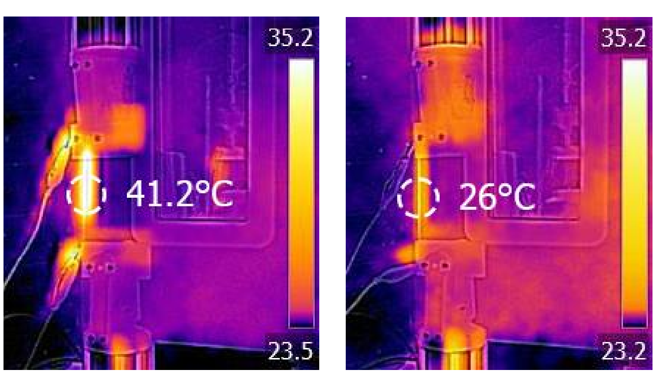

FIGURE 6: TEMPERATURE DIFFERENCE BETWEEN HIGH-TEMPERATURE SMA (LEFT) AND LOW-TEMPERATURE SMA (RIGHT), HELD AT IDENTICAL DISPLACEMENTS AND POWERED TO PRODUCE IDENTICAL FORCE-OUTPUT

The results of the test-to-failure experiments are illustrated in Figure 7. As seen, each sample increases in force until a plateau is reached (indicating complete material phase transformation), above which increasing current provides little additional force. This plateau occurs for each different sample, with the earliest plateau experienced by 500°C for 10 minutes at 0.75A and the latest being 450°C for 5 minutes at 1.25A. In addition, failure occurred between the ranges of 2.5A (500°C heat-treated for 10 minutes) and 3.5A (450°C heat-treated for 10 minutes) and for both 450°C & 500°C heat-treated for 5 minutes occurred at the same point at 3A. Note that in contrast to previous tests, here, preloading force generated at room temperature (22°C) by the low-temperature SMAs was not removed prior to running the test. The force generated at room temperature ranged from 1.9–2.5 N.

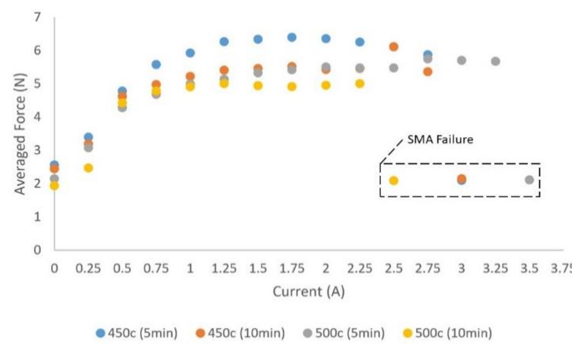

FIGURE 7: FAILURE TESTING OF THE FOUR DIFFERENT SMAS BY INCREASING CURRENT OVER TIME.

Overall, the low-temperature SMA samples from this study produced a relative force between 0 N to 3.61 N (i.e., an *additional* force generated by each actuator when heated above room temperature). The temperature outputs ranged from room temperature 22°C to 37°C and power consumption ranged from 0 to 2.7 W. Though preliminary, these results show promise in demonstrating that low-temperature SMA actuation is a plausible solution to the high power/high-temperature limitations associated with high-temperature SMAs. By achieving similar force outputs with lower power consumption and lower temperature exposure, wearable systems using low-temperature SMA can, in theory, be dynamically controlled without the need for large batteries or bulky thermal insulation, representing a significant step forward in actuated garment wearability and usability.

SMA Type	Electrical Power Consumed	Observed SMA Temperature
High-temp	3.92 W	41.2°C
Low-temp	0.63 W	26.0°C

TABLE 1: COMPARISON OF HIGH AND LOW-TEMPERATURE ACTUATOR POWER CONSUMPTION / TEMPERATURE GENERATED FOR APPROXIMATELY CONSTANT FORCE-OUTPUT (~3.375 N)

While these results provide some fundamental insight into how low-temperature actuated NiTi SMA coils performed when Joule heated above room temperature, it is necessary to perform experiments with more samples with different heat-setting temperatures and durations to fully map the design space and functional tradeoffs. Since these actuators partially transform without control authority (up to the forces generated at room/body temperature), there is a functional penalty to this approach – in which we lose control authority for the force regime that exists at temperatures below room temperature.

CONCLUSION

In this study, we demonstrated that low-temperature SMAs have a number of useful characteristics in terms of initial unpowered actuation (i.e., room temperature force ranging from 1.9 N to 2.5 N and displacements generated as the material equilibrates to room temperature), while simultaneously possessing additional dynamic control and force generation that can be accomplished through additional, minimal Joule heating. Because these additional actuation steps occur immediately above room and body temperature, less power is required (and less heat is generated) to achieve the dynamic effect, compared to higher temperature SMA. This makes low temperature SMA (e.g., NiTi #8 from Fort Wanye Metals) better candidates than high power actuators for on-body soft robotic applications, as they would not require large batteries or bulky thermal insulation to protect the wearer. Several different wearable soft-robotic applications (e.g., exoskeletons) and medical device applications (e.g., dynamic compression garments) would particularly benefit from this type of technology.

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