Investigation on actuation and thermo-mechanical behaviour of Shape Memory Alloy spring using hot water

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Abstract. In this paper, hot water is used as an actuation media for Shape memory alloy and its impact on the morphology of structure of Nitinol Shape Memory Alloy (SMA), is presented. With hot water actuation as the temperature reaches 70-80°C, spring gets fully compressed for the first few cycles followed by a displacement loss in actuation. This actuation loss is then studied with different characterization methods such as Thermo Gravimetric Analysis (TGA) and Scanning Electron Microscopy (SEM). With SEM results, it can be inferred that the energy source is not deteriorating the structure. Results observed from TGA shows high oxygen content at lower temperature limits with hot water actuation which suggest the need of conducting experiments in inert atmosphere. As a possible mechanism, a new actuation medium is introduced and various results can be seen in the paper discussed below.

KEYWORDS: Shape memory alloy spring, Hot water, Morphological analysis, thermo-mechanical characteristics

1. Introduction

As the field of smart materials evolves, it is imperative to develop new technologies for better ways to actuate and control precisely to perform more complicated tasks. Common methods of actuation involve electricity. The use of smart materials such as Shape memory alloys is becoming increasingly popular in robotics due to their resemblance to muscles [1] and their biocompatibility [2]. Shape memory alloys are prime candidates for actuation applications due to their unique functional thermo-mechanical characteristics, namely the shape memory effect (SME).

A SMA is an alloy that “remembers” its original shape and that when deformed returns to its pre-deformed shape when heated. This material is lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic and motor based systems [1]. These unique properties are achieved through a solid-state phase change (molecular rearrangement) that occurs in an SMA. High temperature parent phase is Austenite and low temperature phase is Martensite. When the phase
transformation occurs between Austenite to martensite, it is referred to as martensitic phase transformation. The property known as the ‘Shape memory effect’, is due to the transition between two crystallographic phases (i.e., the transition between martensite and austenite).[3-5].

A simple SMA actuator has the potential to replace complex electromechanical systems, allowing for reductions in cost, size and weight. Compactness of SMAs allows easy incorporation into mechanical devices of small size and used as actuating elements. Despite the advantages of SMAs for actuator applications—high strain, silent operation, and mechanical simplicity—the response time and Energy efficiency limits overall performance.

SMA materials are readily available in multiple initial forms such as wires, tubes, and sheets. Its use in actuators has gained popularity, especially in low volume constraint applications, such as medical catheters, stents (thin wires, mesh form) [6-8], laparoscope surgical tools (patterned tubing, wires) [9], and micro-robot actuators (coiled wires) [10, 11].

There are many SMA materials and among these, NiTi is the mostly used material in industrial applications [12] and NiTiCu is another SMA that finds wide applications in the medical fields [2]. In this paper, an attempt is to actuate NiTi SMA through hot water and then its effect on the morphology of structure is analyzed. SMA exhibits different properties like one way effect, two-way shape memory, pseudo-elasticity, high damping capacity, good chemical resistance and biocompatibility. All these properties made it suitable for a specific application required. In this paper, hot water assisted actuation of SMA spring [Table 1] is focused. The local functional properties of a NiTi component can be augmented by changing the energy source. These local modifications to thermo-mechanical properties have been attributed to microstructural and compositional changes that subsequently alter transformation temperatures [13-19]. In order to validate the results for heating-cooling cycles and to investigate the cause for depletion in its actuation property, SEM, EDX and TGA were conducted.

SEM (Scanning electron microscopy) gives the information about the sample’s external morphology (texture). EDX (Energy dispersive X-ray spectroscopy) is an analytical technique used for the elemental analysis or chemical characterization of a sample and TGA (Thermo gravimetric analysis) is a method of thermal analysis in which changes in physical properties of materials are measures as a function of increasing temperature and time. It is used to determine selected characteristics of materials that exhibits either mass loss or gain due to decomposition, oxidation.

2. Experimental Setup

Test setup is developed to perform experiments based on the medium used. It comprises of an actuation unit and a displacement sensing unit with a load pulley arrangement. Nitinol spring which is equiatomic in nature is used with specifications as described in Table1. Heating-cooling cycle is defined based on the time when steady state is achieved.

| Table.1: Specification of Ni-Ti SMA Spring |
|------------------------------------------|
| Solid Length (mm)                        | 13.86 |
| Number of turns                          | 18    |
| Wire diameter (mm)                       | 0.77  |
| Mean Diameter (mm)                       | 5.69  |

1.) Hot Water Actuation:

NiTi Shape memory alloy spring which is equi-atomic in nature is actuated using hot water. An immersion rod is used to heat the water kept in the container [Figure 1] which in turn supply thermal energy to the spring. The temperature imparted to the spring with this thermal energy when reaches the transformation limit in turn actuates the spring. But the actuation was not linear indeed drastic.
Spring is held fixed at one end and at the other end load is applied. Laser displacement sensor (LDS) with resolution 2.5 microns over a displacement range of 40 mm at a frequency of 664 nm is used to find the displacement. A flapper arrangement is made that LDS takes as reference for the calculation. The actuator is interfaced to a computer via a data-acquisition system (Agilent 34970 A).

Data from LDS is measured in terms of voltage with the help of data acquisition system and then the reading can be seen on the system. To generate a displacement, hot water is poured in the container and then cooling is done through natural convection.

- During heating, the martensite changes to austenite; the length of the spring reduces and the mass moves upward.
- During cooling, the austenite changes to martensite; the length of the spring increases and the mass moves downward.

![Schematic and experimental setup of Hot water actuation](image)

**Figure 1:** Schematic and experimental setup of Hot water actuation

3. Results:

**Surface Characterization:**

1.) **Hot water actuation:**

Figure 2a shows displacement Vs Time graph when spring is loaded with 4.5 N. Heating time (25 secs) is very less compared to cooling time (1200 secs). Hysteresis (figure 2c) is plotted which shows dynamic lag between input and output stage i.e. heating-cooling cycle. As the temperature reached 83°C, a deflection of 2.8 mm can be seen from figure 2c. Data from LDS is measured in terms of voltage with the help of Data acquisition system and reading is transferred to the system. For the same cycle temperature versus time curve (figure 2b) is plotted, in that fluctuations in gaining the temperature can be seen which may be due to release/absorption of latent heat and heat transfer with the ambient. [22]
Figure 2(a): Heating-cooling cycle for Hot water actuation

Figure 2: (b) Temperature-Time response and (c) Displacement-Temperature response for Hot water

Hot water actuation is gained when the temperature of water reaches near about 70-80°C and then cooling happens through natural convection.

SEM and TGA was performed over samples which are subjected to 10 cycles of Heating-cooling.

Figure 3: (a) Scanning Electron microscopy images and (b) Thermo gravimetric analysis on Hot water actuated springs
Figure 3a shows Scanning electron microscopy when performed on NiTi SMA spring which is hot water actuated. Here it is observed that the structure shows elongated grains where black part is for Titanium and grey ones for Nickel as it is with higher atomic weight. Nickel content is more than Titanium content (Figure 4). Though Elongated grains may result an increase in strength and hardness but it is also observed that the alloy becomes more brittle and more liable to fracture due to this actuation. The spring over which SEM is conducted is actuated with hot water for 10 cycles (1 cycle is equal to heating+cooling).

Figure 3b shows Thermo gravimetric analysis [20] which is done to find kinetics of oxidation. The loss or gain of material can be because of decomposition or oxidation. Here, it is shown that an increase in %weight concentration is observed at temperature range of 0-100°C, which may be due to the oxide formation of NiTi alloy. This is further verified with EDX data [Table 2] which shows 52.46 at % of oxygen content in the sample. Between 100°C-200°C, NiTi spring is severely oxidized and then decomposes after this limit. At about 800°C, there is an increase of NiTi %weight concentration (figure 3b) which may be because of nitridation in NiTi alloy. [21]

| Table 2: Results for Electro Dispersive X-Ray |
|-----------------------------------------------|
| Element | Weight % | Atomic % |
|---------|----------|----------|
| O       | 12.79    | 52.46    |
| Ti      | 12.56    | 17.20    |
| Ni      | 27.14    | 30.33    |

Figure 4: EDX data performed on Hot water actuated spring

4. Conclusion

Here a different thermal source as actuation media for shape memory alloy has been proposed. It has been found that actuation gained by hot water is good enough to use in practical applications. It is capable of actuating the spring once the temperature reached transformation limit. Thermo gravimetric results shows weight gain i.e. oxidation till 100°C and then decomposition starts. Oxygen content is further validated with Electro dispersive X-ray spectroscopy (EDX), also weight gain after 800°C can be because of NiTi nitridation phenomenon. Results showed high oxygen content in the samples with about 50% of oxygen by atomic weight and rest is Nickel and titanium.

We see that by changing thermal source, we can control the displacement for different load values. Hot water can be used at places where we cannot go for electrical connections, as it makes the setup clumsy. Applications can be micro valves for drug delivery, also in engines it can replace thermostat valves. The present study could represent the vital observations and results when actuated with Hot water. Further study for life cycle analysis of spring is underway.

5. Acknowledgement

The authors are grateful to the Centre for Material Science and Engineering department, Mechanical Engineering department and Sophisticated Instrumentation Centre (SIC) of IIT Indore, India for the financial support and facilities they have provided to carry out the above investigations.
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