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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Investigation on thermo-mechanical behavior of shape memory alloy spring using hot water and laser assisted actuation"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY with specialization in PRODUCTION and INDUSTRIAL ENGINEERING and submitted in the DISCIPLINE OF MECHANICAL ENGINEERING** at **INDIAN INSTITUTE OF TECHNOLOGY INDORE**, is an authentic record of my own work carried out during the time period from July 2014 to July 2016. Thesis submission under the supervision of Dr.I.A.Palani associate professor Discipline of Mechanical Engineering and Dr.B.K Lad, Associate professor Discipline of Mechanical Engineering.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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INVESTIGATION ON THERMO-MECHANICAL BEHAVIOR OF SHAPE MEMORY ALLOY SPRING USING HOT WATER AND LASER ASSISTED ACTUATION

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

Master of Technology
in
Mechanical Engineering
With specialization in
Production and Industrial Engineering
by

Priya Chouhan

DISCIPLINE OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

JUNE 2016

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Priya Chouhan

Dedicated to my Guide –

my mother,

my father,

my teacher,

and my friends

Abstract

Shape memory alloys are relatively a new band of material which have not been utilized to their fullest potential. These materials are alloys composed essentially of Nickel, and Titanium, with possible addition of Copper, Zinc and Aluminum and recover pre-set shapes even after deformation, by heat activation. When deformed in the low temperature, these shape memory alloys rearrange themselves into 'monoclinic' lattice structures, which will give them the shape of a parallelogram. This parallelogram shape converts into more 'cubic' structure upon heating. The heat is supplied by any hot source which mainly is through DC power supply.

In my research, the thermo-mechanical properties of shape memory alloy are studied when the actuation media is changed. Actuation with a laser beam and hot water is focused in this work. Certain key relationships between various physical changes like displacement, load, temperature and time are determined through experiments. These experiments lead to determine the effects of heat over the shape memory alloy spring. . Line laser at a wavelength of 532nm is made to fall over the NiTi Shape memory alloy (SMA) spring and a significant actuation (compression) of 7-8mm is visible. With hot water actuation as the temperature reaches 70-80 ºC, spring gets fully compressed for the first few cycles followed by loss in actuation. The 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 spring when actuated with hot water possesses more life as compared to the one actuated with Laser. Furthermore the rapid actuation shows no sign of fatigue with hot water but with laser, small ablation can be seen after some cycles. Results observed from TGA shows high oxygen content at lower temperature limits with both laser and hot water actuation which suggest the need of conducting experiments in inert atmosphere. As a possible mechanism, actuation medium is changed and various results can be seen in the paper discussed below

LIST OF PUBLICATIONS

International Journal (To be submit)

Chouhan,P., Tameshwer Nath, Lad, B. K. and Palani I A., Detailed Investigation on actuation and thermo-mechanical behavior of shape memory alloy spring using hot water and Laser beam", SAGE, A Journal on Intelligent materials and structures.

Papers in Conference Proceedings

- **Chouhan,P.,** Tameshwer Nath, Lad, B. K. and Palani I A., "Investigation on actuation and thermo-mechanical behavior of shape memory alloy spring using hot water", International Conference in Advancement in materials and manufacturing applications (IConAMMA) 2016, 14–16 July at Amrita University Bangalore, India
- **Chouhan,P.,** Tameshwer Nath, Lad, B. K. and Palani I A, "Investigation on thermo-mechanical properties of Shape Memory Alloy spring under the influence Laser beam", 6th International and 22nd All India Manufacturing Technology, Design and Research Conference, 16th-18th Dec 2016
- Tameshwer Nath, Karthick S,**Chouhan, P.** Lad, B. K**.** and PalaniI I A., **"**Investigation on Actuation and Thermo-Mechanical Behavior of Shape Memory Alloy Spring by comparing On/off and PID Controller for Precise Position Control", International Conference on Advancements in Automation, Robotics and Sensing, (ICAARS 2016), PSG College of Technology, Coimbatore, Tamilnadu, India,23-24 June, 2016.

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Chapter 1 Introduction

1.1 Shape memory alloys

Shape memory alloys (SMAs) are featured by the capability to recover their original shape when a particular stimulus is applied. These materials have attracted considerable attention as potential actuators in the field of robotics, medicine, automotive industries and also as seismic devices.

Smart materials have received increased demand in recent years because of their immense potential in revolutionizing engineering applications. Among the smart materials currently in research, Shape memory alloys predominant for the reason that large recoverable strains occur within it due to crystallographic transformation. A SMA is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. 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) (Sreekumar (2007)) (Wayman (1993)) (Schetky (1982))

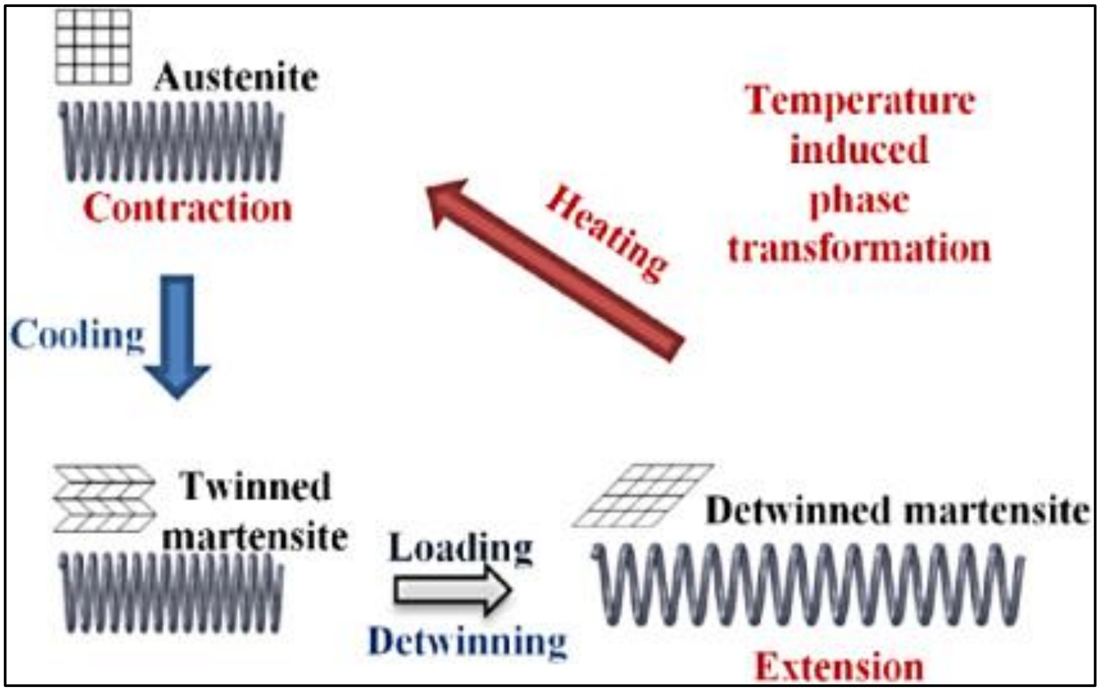


Figure 1 Crystalline arrangement of SMA in different phases (Wikipedia)

The use of smart materials such as Shape memory alloys is becoming increasingly popular in robotics due to their resemblance to muscles (I. W. Hunter and S. Lafontaine 1992) and their biocompatibility (W. Haider 2009). Also its use in actuators has gained popularity, especially in low volume constraint applications, such as medical catheters, stents (thin wires, mesh form) (Flomenblit 1996) (Tung, "Design and fabrication of tubular shape memory alloy actuators for active catheters." 2006) (Tung, "Laser-machined shape memory alloy sensors for position feedback in active catheters." 2008),laparoscope surgical tools (patterned tubing, wires) (Morgan (2004)), micro- robot actuators (coiled wires) (Yoshida 2000) (Matsunaga, "2-D and 3-D tactile pin display using SMA micro-coil actuator and magnetic latch." 2005) and Industrial applications (Wu 2000).

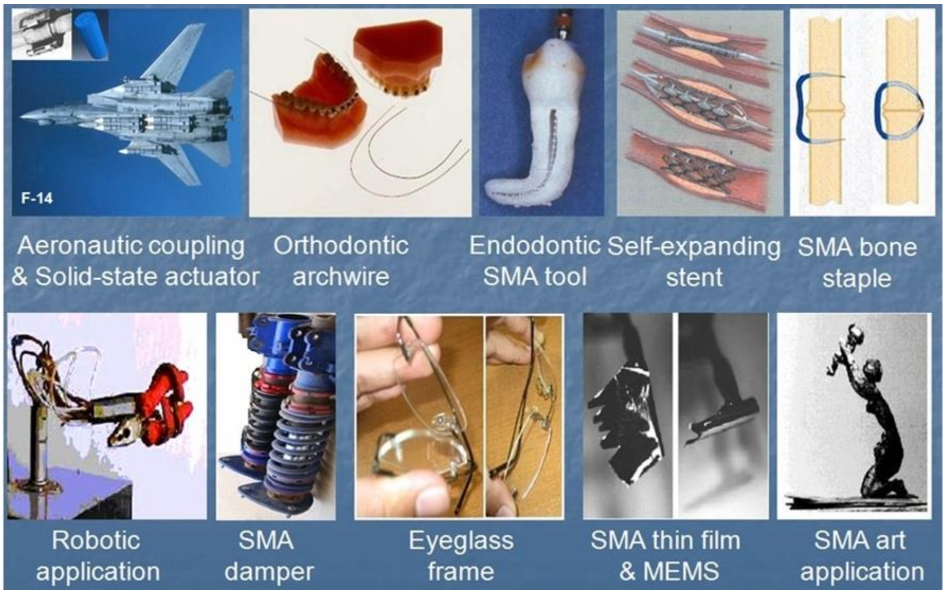


Figure 2 Applications of Shape Memory Alloys (SMA) (Wikipedia)

1.1.1 History

Nickel-titanium alloys have been found to be the most useful of all SMAs because of their stability, practicality and superior thermo-mechanical performance. Other shape memory alloys include copper-aluminum-nickel, copper-zinc-aluminum, and iron- manganese-silicon alloys. The generic name for the family of nickel-titanium alloys is Nitinol. In 1961, Nitinol, which stands for Nickel Titanium Naval Ordnance Laboratory, was discovered to possess the unique property of having shape memory.

William J. Buehler, a researcher at the Naval Ordnance Laboratory in White Oak, Maryland, was the one to discover this shape memory alloy. The actual discovery of the shape memory property of Nitinol came about by accident. At a laboratory management meeting, a strip of Nitinol was presented that was bent out of shape many times. One of the people present, Dr. David S. Muzzey, heated it with his pipe lighter, and surprisingly, the strip stretched back to its original form.

1.1.2 Crystal Structure

Exactly what made these metals "remember" their original shapes was in question after the discovery of the shape-memory effect. Dr. Frederick E. Wang, an expert in crystal physics, pinpointed the structural changes at the atomic level which contributed to the unique properties these metals have.

He found that Nitinol had phase changes while still a solid. These phase changes, known as martensite and austenite, involve the rearrangement of the position of particles within the crystal structure of the solid. Under the transition temperature, Nitinol is in the martensite phase. The transition temperature varies for different compositions from about -50 ° C to 166 ° C. In the martensite phase, Nitinol can be bent into various shapes. To fix the "parent shape" (as it is called), the metal must be held in position and heated to about 500 ° C. The high temperature "causes the atoms to arrange themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase. Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape. This cycle can be repeated millions of times.

Table 1: Comparison of NiTi/CuZnAl alloys (From Funakubo 1987)

Parameters	**NiTi**	**CuZnAl**
Recovery Strain	8%	4%
Recovery Stress	Max 400 MPa	Max 200 MPa
No of cycles	10^5 (ϵ = 0.02) 10^7 (ϵ = 0.005)	10^2 (ϵ=0.02) 10^5 (ϵ= 0.005)
Corrosion Resistance	Good	Problematic, especially stress Corrosion cracking

1.1.3 Shape Memory behavior

1.1.3.1 Shape memory effect

"Shape Memory" describes the effect of restoring the original shape of a plastically deformed sample by heating it. This phenomenon results from a crystalline phase change known as "thermoelastic martensitic transformation". At temperatures below the transformation temperature, shape memory alloys are martensitic, In this condition, their microstructure is characterized by "self-accommodating twins", The martensite is soft and can be deformed quite easily by de-twinning. Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic condition.

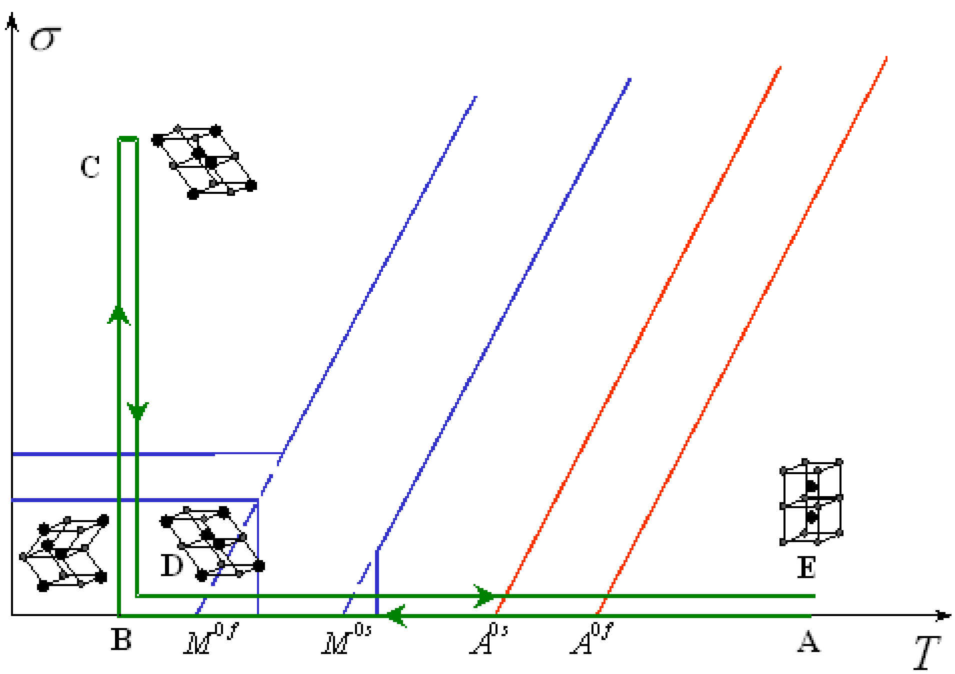


Figure 3: Schematic representation of the thermomechanical loading path demonstrating the shape memory effect in an SMA (Smart lab, Texas)

1.1.3.2 Psuedoelastic

Pseudoelasticity, sometimes called **superelasticity**, is an elastic (reversible) response to an applied stress, caused by a phase transformation between the austenitic and martensitic phases of a crystal. It is exhibited in shape-memory alloys. Pseudoelasticity is from the reversible motion of domain boundaries during the phase transformation, rather than just bond stretching or the introduction of defects in the crystal lattice (thus it is not true superelasticity but rather pseudoelasticity). Even if the domain boundaries do become pinned, they may be reversed through heating. Thus, a pseudoelastic material may return to its

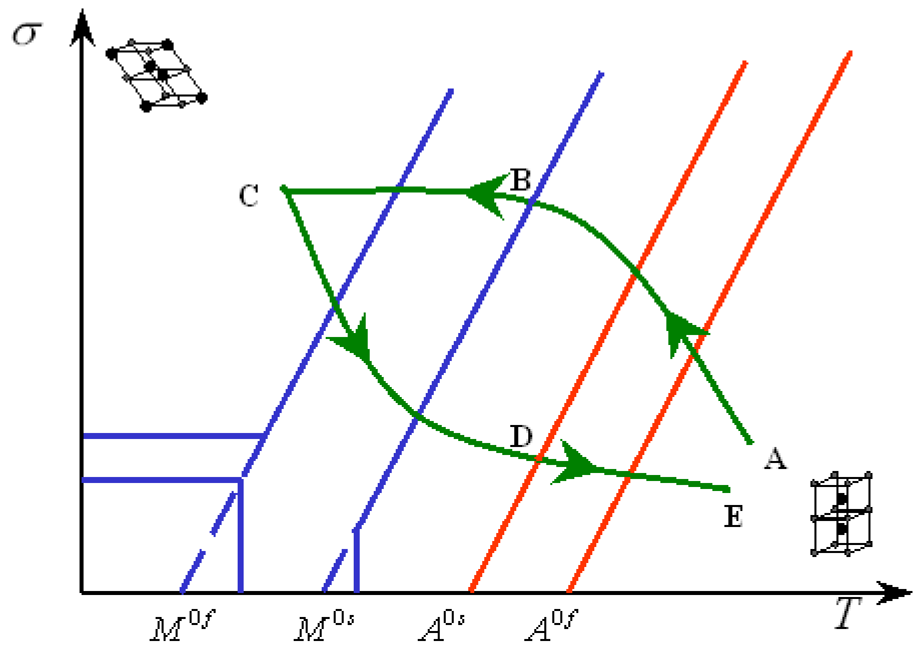


Figure 4: Schematic of a thermomechanical loading path demonstrating pseudoelastic behavior of SMAs. (Smartlab, Texas)

previous shape (hence, *shape memory*) after the removal of even relatively high applied strains.

1.2 Background

In today's world, the technology push, towards 'smart' systems with adaptive and/or intelligent functions and features, necessitates the increased use of sensors, actuators and micro-controllers with precise control. Since the research carried out in past mainly focuses on D.C power supply, thereby resulting in an undesirable increase in connections and makes the setup cumbersome with electrical connections around the micro actuators. (Paik (2010)) presents low-profile torsional actuators applicable for meso-scale and micro-scale robots. The primary actuator material is thermally activated Ni–Ti shape memory alloy

(SMA), which exhibits remarkably high torque density. Also, instead of using conventional Joule heating, an external Ni–Cr heating element is utilized to focus heat on the regions of highest required strain.

The idea of actuating the SMA through a laser came from (Hu (2012)), where the author used a focused laser beam to achieve large amplitude and localized controlled actuation in a microstructure made of ferromagnetic SMA. A significant deformation of about 18µm was achieved at low laser power of 20mW. Various researches have been done on actuation of SMA which is further discussed in the coming chapter. Limited work is done using laser and hot water as actuation and certain gaps were found over which work is done in this project.

1.3 Gaps

Shape memory alloys are used in various fields because of their unique properties they possess. Literature review shows some gaps over which work is done here. Listed below are some of the common challenges faced by most of the researchers.

- Electrical connections near micro-actuator, makes the setup clumsy:
    - Electrical wiring for supplying electricity to the shape memory alloy uses a lot of space near the actuators and makes the whole setup cumbersome.
- Focused spot laser is used:
    - In most of papers, laser is used as actuation medium but the laser used is a spot laser which is effective over the area it is falling i.e. rest of the sample remains ineffective of the heat.
- Laser follows Gaussian curve:
    - In a Gaussian beam, 86.5% of the energy gets concentrated at the center and rest 13.5% lost at the edges leads to inhomogeneous intensity distribution.
- Lack of thermo-mechanical properties:
    - No analysis done on thermo-mechanical behavior i.e. reliability, surface characterization on the spring

- No work to identify operating condition and spring parameters for life prediction models.

1.4 Motivation

Smart materials have received increased demand in recent years because of their immense potential in revolutionizing engineering applications. Among the smart materials currently in research, Shape memory alloys predominant for the reason that large recoverable strains occur within it due to crystallographic transformation. However, performance is restricted over one actuation media. So in this work, we attempted for the first time to actuate NiTi SMA through two different media and then analyzed the effect of these media on the morphology. 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 complex applications in some specific field. In this paper, LASER and Hot water assisted actuation of SMA spring 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 (M. I. Khan (2011)) (Pequegnat, "Dynamic actuation of a multiple memory material processed nitinol linear actuator." 2011) (M. e. Daly 2011) (M. e. Daly (2012)) (M. I. Khan, "Effects of local phase conversion on the tensile loading of pulsed Nd: YAG laser processed Nitinol." 2010) (M. I. Khan, "A method to locally modify shape memory and pseudoelastic properties." The international conference on shape memory and superelastic technologies 2010) (M. e. Daly (2013)). Since one mode of heating here is LASER, so there is a possibility that if higher fluence is used then incident area of SMA spring may get ablated due to absorption of energy. Hence a critical value of fluence must be known below which there is no damage to SMA

1.5 Research Objectives

1.5.1 Overall Objective

The overall objective of this thesis is to "Investigate the thermo-mechanical behavior of shape memory alloy spring using Hot water and Laser assisted actuation."

1.5.2 Intermediate Objective

I. To develop a test setup for performing life cycle analysis of the shape memory alloy actuator for two different mediums.

II. To gain actuation using a laser beam as the heat source. This is tried for the first time and a considerable actuation is gained through a point laser beam.

III. To convert a point laser into a rectangular spot laser beam so as to get distributed laser line than a focused point beam.

IV. To get a homogeneously distributed laser beam.

V. To get a comparison between actuation when done with a nanosecond pulsed laser and a continuous laser.

VI. To optimize operating parameters like Load, laser power, fluence, stand-off distance etc.

VII. Device Application :

- Identifying possible application in device
- Fabricating the prototype
- Performing experiments with the fabricated part

VIII. Performing Life cycle analysis of the spring.

IX. Studying the effects of variables over the spring.

Chapter 2 Literature Review

This Chapter gives detailed information of the research carried out in the past on actuation of shape memory alloys. The research work is broadly classified into three fields based on the actuation media used as shown in Figure 5. The actuation media is divided into three major categories. These are the thermal sources provided to the spring in order to get shape memory actuation which includes Electricity, Hot water and Laser. SMA exhibits different properties like one way effect, two-way shape memory, pseudo-elasticity, high damping capacity, good chemical resistance and biocompatibility. These properties can be altered by changing the thermal source.

Common method of actuation involves electricity. But here work has been performed which focuses more on laser based and hot water actuation.

Literature review starts here with a block diagram showing different heat sources used till now. Important factors in actuation of SMA are discussed through experimental work.

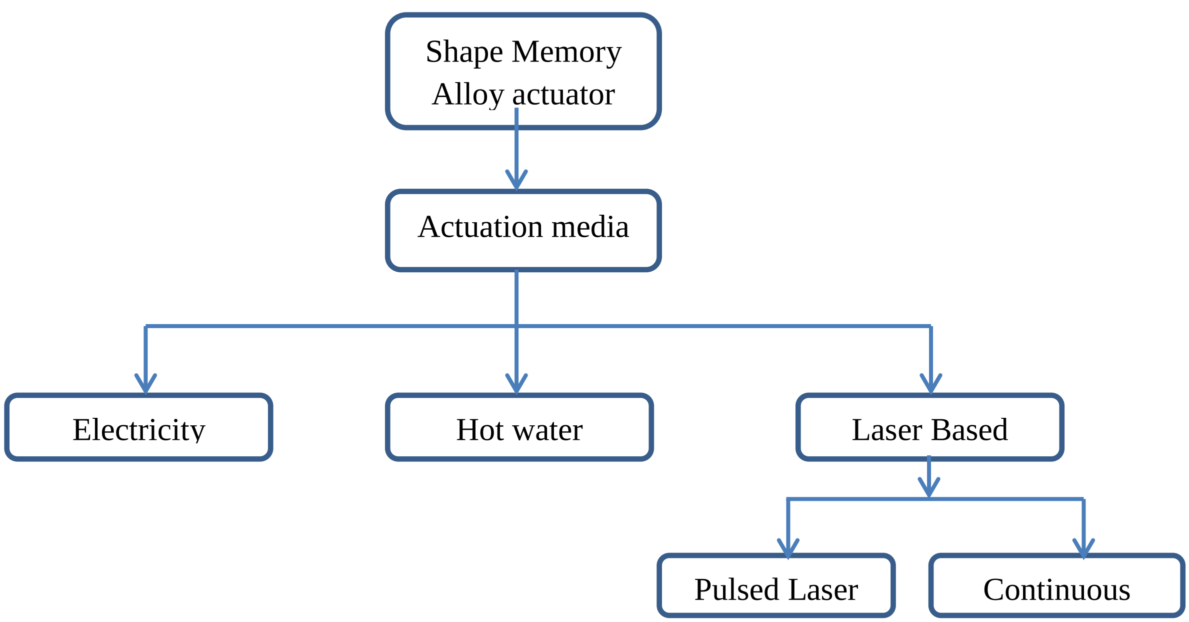


Figure 5 Block diagram for different actuation media

2.1 Past work performed using Electric Current

- **(Pequegnat, "Dynamic actuation of a novel laser-processed NiTi linear actuator." (2012))** Studied a novel laser processing technique, capable of locally modifying the shape memory effect, was applied to enhance the functionality of a NiTi linear actuator. By altering local transformation temperatures, an additional memory was imparted into a monolithic NiTi wire to enable dynamic actuation via controlled resistive heating.. This design will enable new applications to be realized while greatly improving existing SMA devices. This laser-processed actuator will allow for the realization of new applications and improved control methods for shape memory alloys.

- **(Saikrishna (2009)).** The use of NiTi wire as thermal actuator involves repeated thermal cycling through the transformation range under a constant or fluctuating load. The stability of the material under such conditions has been a concern for the past many years. Experimental results show that for a given alloy composition, the repetitive functional behavior of NiTi wire is largely dependent on the processing schedule/parameters and the stress–strain regime of thermo-mechanical cycling (TMC Resistive heating and forced air cooling with a cycle time of 30 s each was used for the experiments. The temperature range for TMC was fixed in the range 25–100°C. A D.C. current of 2 A was required to heat the wire to ~ 100°C. as shown in Figure 6

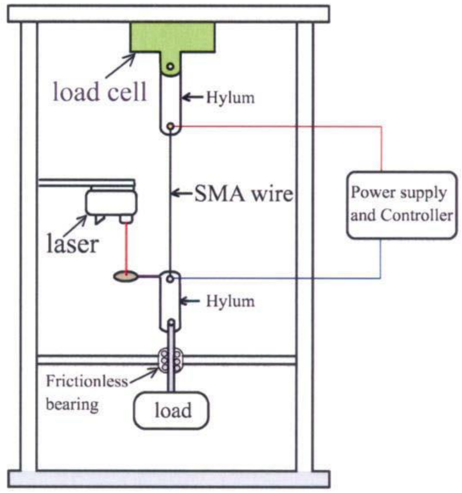


Figure 6: Experimental setup consisting of SMA wire (Saikrishna (2009))

- **(Seguin (1999))** studied about obtaining low temperature crystallised NiTi films which would ensure a good compatibility with microelectronics processes and allow deposition on substrates that could not endure high temperatures, like polymers. Bimorph actuators were obtained by cutting 2*5 mm^2 strips into the NiTi/polyimide composite, which were then clamped on a Si support with electrical contacts. An experimental set up, detecting the NiTi cantilever position by means of a reflected laser beam, allowed us to record its response when heated by a pulsed current.

- **(Paik (2010)).** This paper presents low-profile torsional actuators applicable for meso-scale and micro-scale robots. The primary actuator material is thermally activated Ni–Ti shape memory alloy (SMA), which exhibits remarkably high torque density. Also, instead of using conventional Joule heating, an external Ni–Cr heating element is utilized to focus heat on the regions of highest required strain. Various design parameters and fabrication variants are described and experimentally explored in actuator prototypes. Controlled current profiles and discrete heating produces a 20% faster response time with 40% less power consumption as compared to Joule heating in a low-profile (sub-millimeter) torsional actuator capable of 180◦ motion.

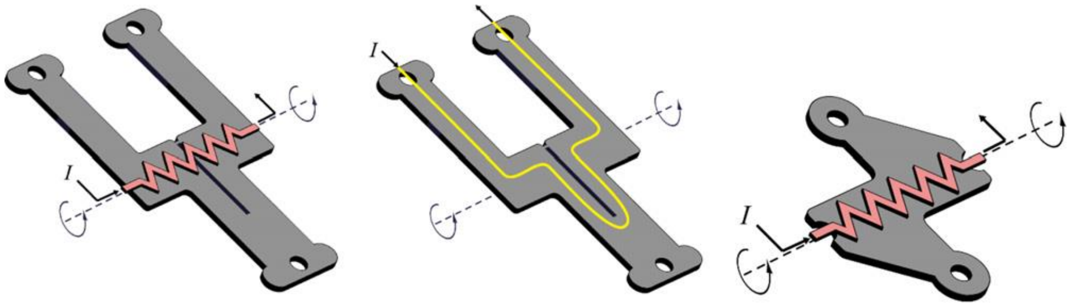


Figure 7: Electrical circuit representation of the models. (a) Y-type: Ni–Cr heating, (b) Y-type: Joule heating and (c) Z-type: Ni–Cr heating(Paik 2010)

(Yin (2012)). Studied the effect on NiTi shape memory alloy when subjected to displacement controlled cyclic deformation, the material exhibits distinctive temperature and stress oscillations due to the release of latent heat and hysteresis heat and the heat transfer with the ambient. In this paper, they establish a model to predict the temperature variation of NiTi SMA wire specimen under the cyclic phase transition by lumped heat transfer analysis. Closed-form solution on the evolution of the temperature is obtained. It is shown that, for all the test frequencies, steady-state cyclic thermal response of the specimen can be reached after a certain number of loading cycles in a transient stage, exhibiting a kind of ‘‘thermal shake down.’’ In the steady state, the temperature profile oscillates around a mean temperature plateau. they showed that the temperature oscillation is mainly due to the release/absorption of latent heat during cyclic phase transition, while the mean temperature rise of the specimen is caused by the accumulation of the hysteretic heat of the phase transition.

2.2 Past work performed using Hot Water

- **(Pierce 2011)** Studied a wet SMA actuator consists of SMA wire enveloped in fluid that is contained within a compliant tube. This compliance allows for the actuator to expand and contract with minimal spring resistance. The fluid inlet of the actuator is connected to a terminal that is supplied with hot or cold fluids and the outlet is connected to a terminal that dumps the used fluid into a lower pressure reservoir. Entire wet SMA actuator arrays have been used to control hand and finger movement and could be used to control other high degree-of-freedom mechanisms as well.

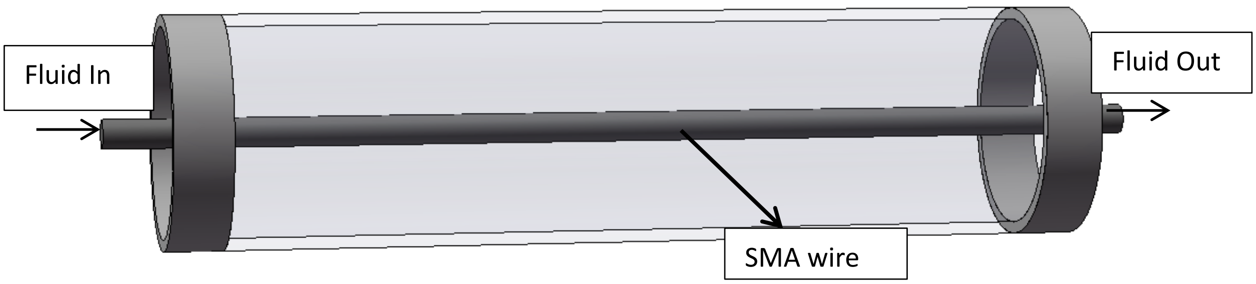


Figure 8: Wet SMA actuator design concept (Pierce 2011)

2.3 Past work performed using Laser source

- **(Hu (2012))** used a focused laser beam to achieve large amplitude and localized controlled actuation in a microstructure made of a ferromagnetic shape memory alloy. Significant deformation (18 µm) was achieved at low laser power (20 mW) and the amplitude of actuation could be linearly controlled with the laser power. The rapid mechanical actuation shows no apparent sign of fatigue even after a million continuous oscillatory cycles. As a possible mechanism, we propose that the deformation of structure was induced by a combination of the thermal effect and the magnetic field of the incident laser light. This is possibly the first such reported visual evidence of microactuation of materials due to the optomagnetic field.

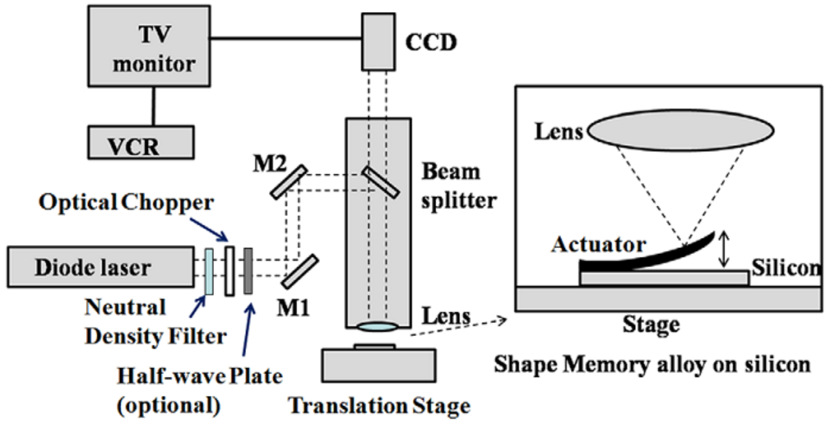


Figure 9: Schematic of the optical-microscope-focused laser beam system (Hu 2012)

Chapter 3 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. Two ways of actuation have been used here that includes Laser based and hot water actuation. Nitinol SMA spring which is equiatomic (50%Ni-50%Ti) in nature is used with specifications as described in Table 2. Heating-cooling cycle is defined for both processes based on the time when steady state is achieved which is different for both processes.

Table 2 Specifications for Nitinol spring

Solid Length (mm)	13.86
Number of turns	18
Wire diameter (mm)	0.77
Mean Diameter (mm)	5.69

3.1 Laser based Actuation:

This is possibly for the first time this work has been reported. Actuation of a shape memory alloy spring with a remotely controlled contactless source like laser beam is the novelty of this project. Laser (Light amplification by stimulated emission of radiations) is used as one of the medium to gain displacement in the NiTi Shape memory spring. Nd:YAG pulsed laser (Quanta Ray) with different wavelengths is used to perform the experiments. The first task for this work is to get an actuation with the help of laser. The laser source is capable of focusing a point beam of diameter range between 1.5-2.5 mm depending upon the stand-off distance (distance between workpiece and laser source).But with a point laser, the actuation attained is very less so next task is to increase the area of the beam. Comparison between point spot actuation and a line spot actuation is also studied in Table 3

Preliminary work has been done by using cylindrical quartz tubes as shown in Figure 12 of different diameters to get a rectangular line beam over the spring. LASER is allowed to pass through a cylindrical quartz tube that diverge the laser beam from a point to a rectangular line beam. Diameter values for quartz tube taken are 5mm, 10mm, 15mm. On performing experiments, it has been found that as the diameter values goes on increasing, the effectiveness of line length obtained decreases. It is because of the reason that loss within the quartz tube increases as it gets more surface area. So work has been done sticking to a optimum value of diameter. Also work is done at different wavelengths of 355nm, 532nm, and 1064nm. It is observed that with 532nm results are better as compared to the other two wavelengths.

3.1.1. Comparison on Point and Line actuation

Table 3: Output Line and Point heating comparison

With Point laser actuation gained (mm)	With line laser actuation gained (mm)
0.38	7.14
2.68	6.92
4.37	6.80
4.59	6.54
4.64	5.65

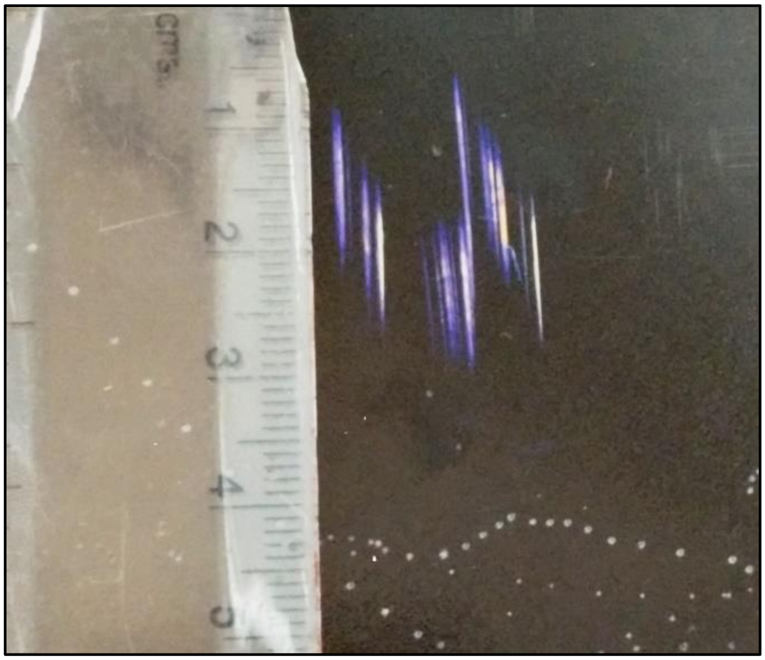


Figure 10: Output line gained when passed through Quartz tube with a scale as reference

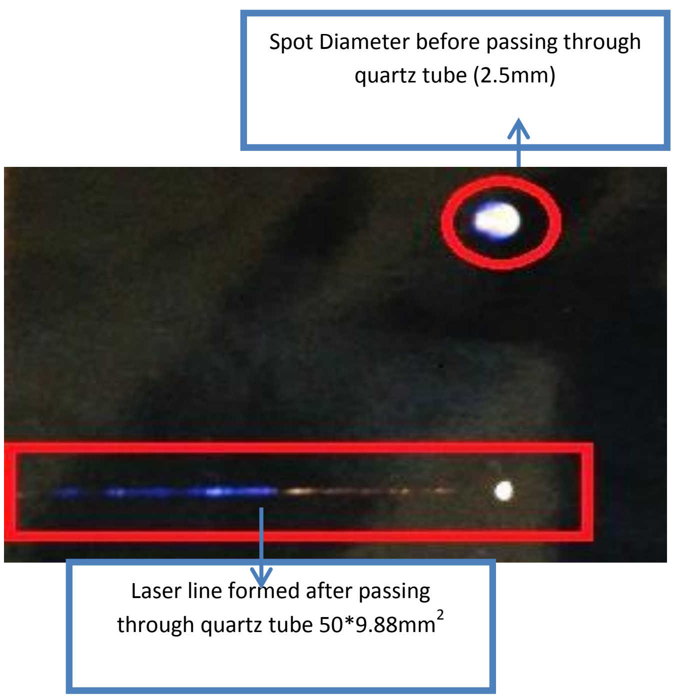


Figure 11: Image captured on a photographic sheet

At first all the experiments were conducted using quartz tubes so as to confirm the actuation through laser. but it is then replaced by Plano concave cylindrical lens that will increase the efficiency of the setup. Hence, the slightest modifications can make drastic changes that can be exploited to enhance component functionality. Dead weights are applied at one end of the spring with the help of frictionless pulley and other end is set fixed. Laser displacement sensor is coupled with the setup to investigate the reliability of Shape memory alloy

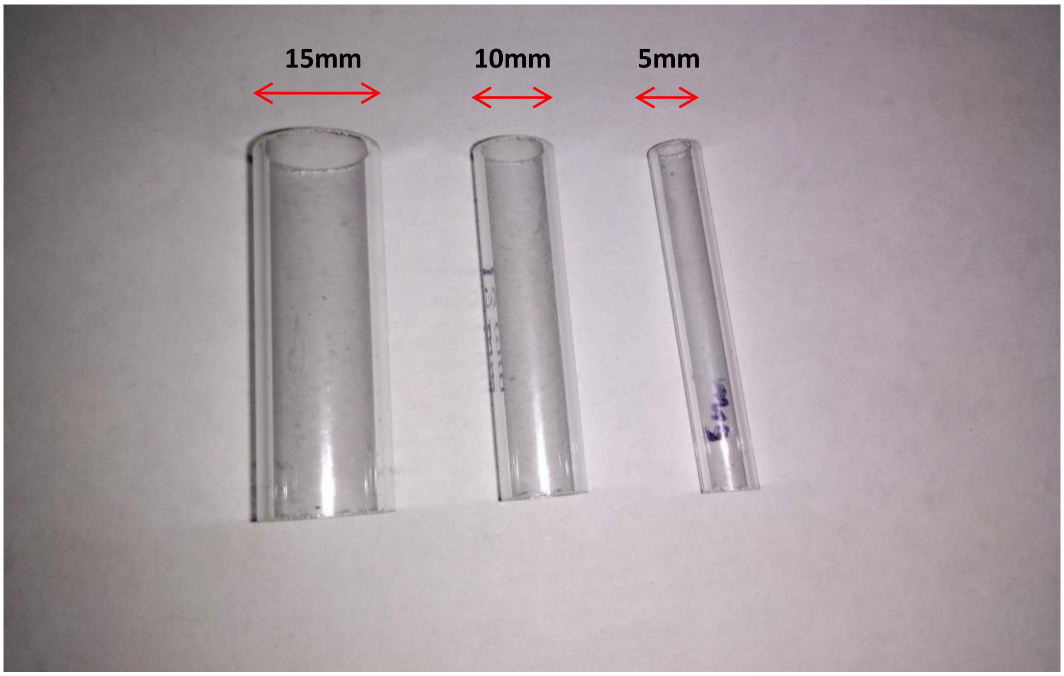


Figure 12 Quartz tubes used with varying diameters

Experimental setup consists of a cylindrical lens and a Shape memory alloy spring. Laser actuation is performed using an Nd-YAG pulsed laser system with varying spot diameter at 532nm. Laser parameters (i.e. peak power, frequency, laser fluence) are altered to control the actuation. Laser is allowed to fall onto the cylindrical lens and then passes to the spring. Spring is fixed at one end and the other end is connected to a varying load through a frictionless pulley. This load tries to elongate the spring. With subsequent heating, this tries to pull back the spring. In the laser actuation, detailed parametric studies have been performed by actuating the SMA at various laser fluences, actuation time, spot diameter and changing the lens arrangement. The programmable power supply is interfaced with the controller, the controller get feedback from the laser displacement sensor. Thermocouple (K-type) is also incorporated to measure the temperature.

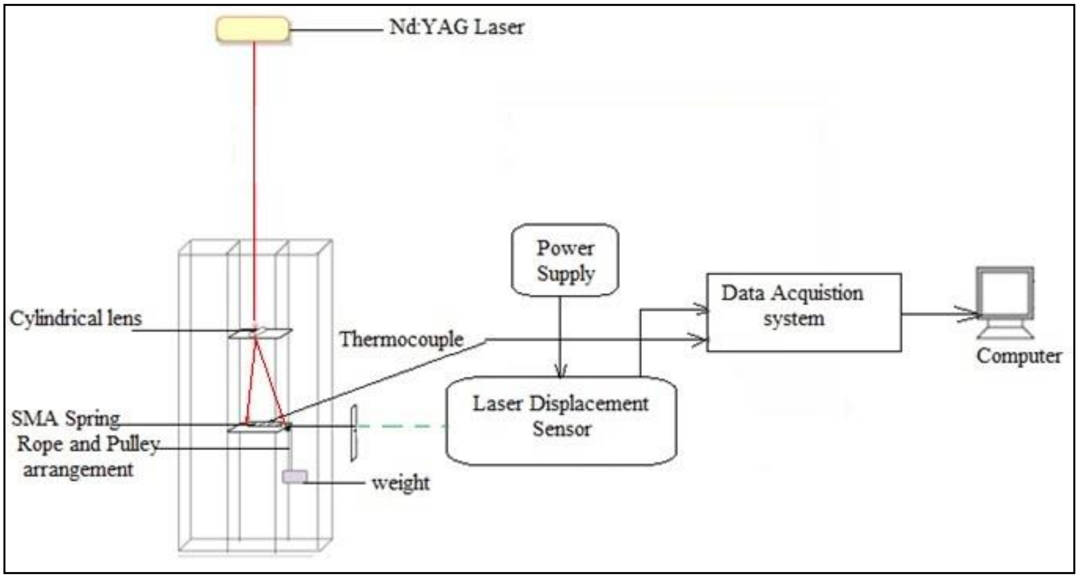


Figure 13: Schematic for laser based actuation setup

The displacement and temperature is monitored continuously using a data acquisition system. Laser displacement sensor (LDS)[Panasonic] with resolution 2.5 microns over a displacement range of 40 mm at a frequency of 664 nm is used to measure the displacement. The sensor head is mounted in the direction towards the measuring target in order to ensure the precise and stable measurement operation of the sensor head. Settings can be stored in the memory. Peak to peak can be used for vibration or eccentricity measurement. Measurement control with external input like timing, zero set, reset and check can be performed easily. A flapper arrangement is made that LDS takes as reference for the calculating the displacement of the spring. 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, Laser is made to fall where spring is held fixed at one end and then cooling is done through natural convection

- During the heating cycle, spring compresses pulling the mass in upward direction against the gravity. This occurs because of martensite to austenite transformation.
- During the cooling cycle, spring elongates and the mass moves in downward direction. This occurs because austenite changes to martensite phase.

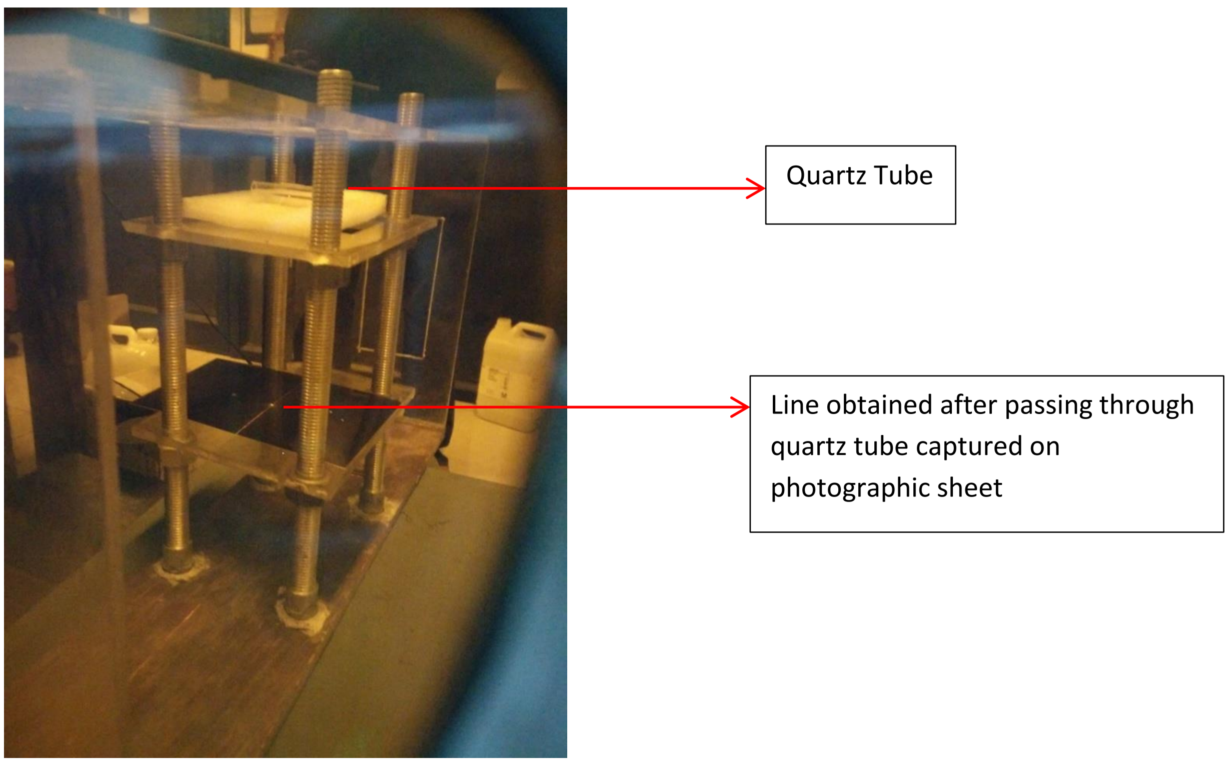


Figure 14: Experimental setup using quartz tubes

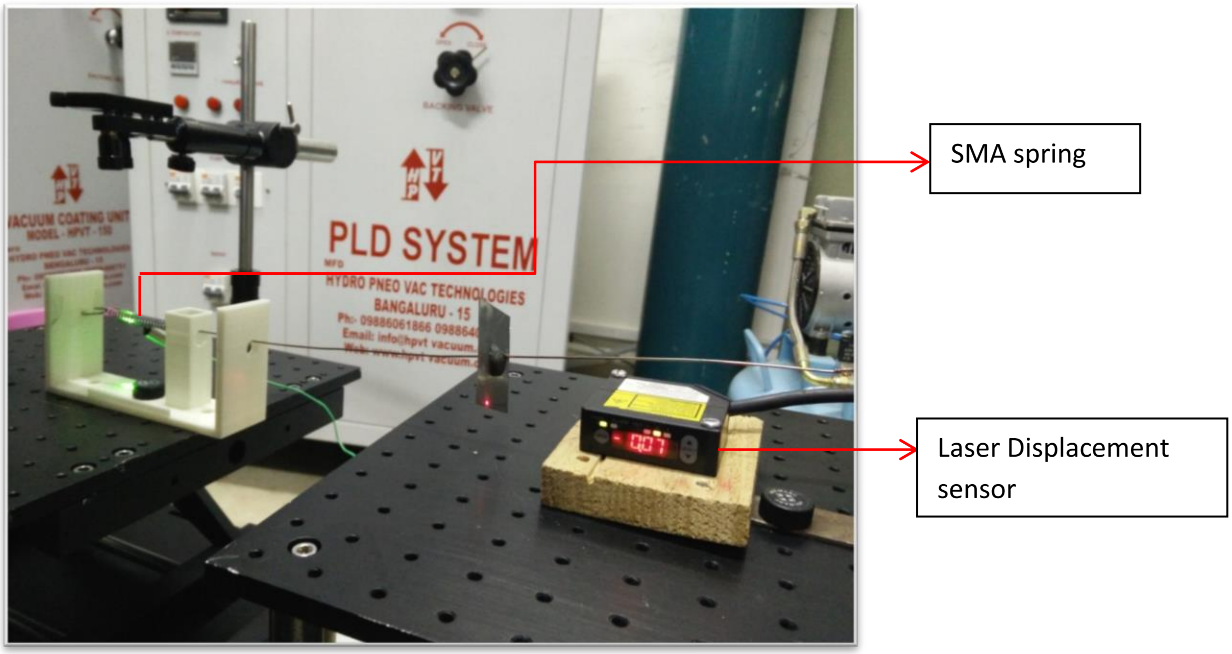


Figure 15: Displacement calculation using LDS and flapper arrangement

The proposed system has a capability to investigate the behavior of SMA springs at varying temperature conditions, load, actuation and displacement conditions. This can be highly helpful in investigating the life cycle in detail.

3.1.2 Framing of the work:

Three major changes that have been done in this work

1.) In the preliminary stages, actuation is tried using a cylindrical quartz tube. But the losses associated with quartz tubes are very high, need cylindrical lens for this purpose.

2.) In the second trial, the quartz tube is replaced by a Plano concave cylindrical lens (Focal length f_1 100mm), which gave better results than the previous one. But in order to further increase the output line, work is done on changing the lens arrangement.

3.) A Plano concave lens (f_1 100mm) along with a convex lens (f_2 100mm) is used to get the required actuation. Comparison between both the arrangements is shown in the Table 4

3.1.3 Lens arrangement used:

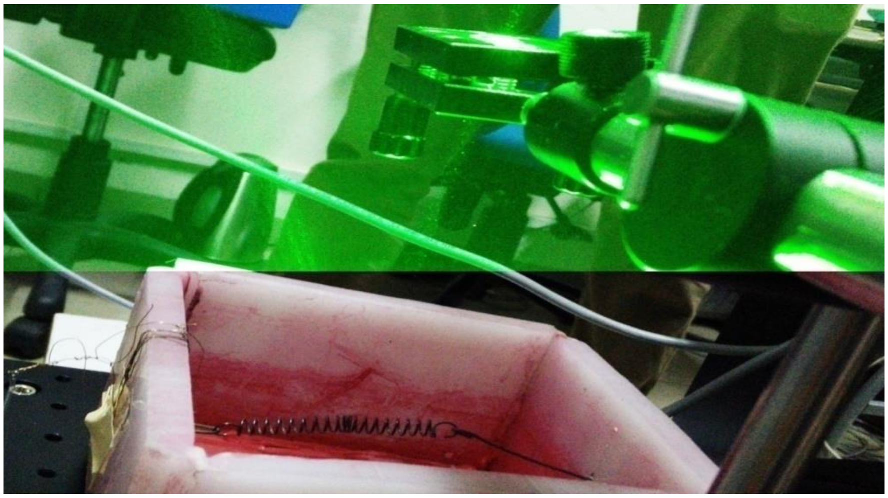


Figure 16: Compressed spring showing effect of cylindrical lens

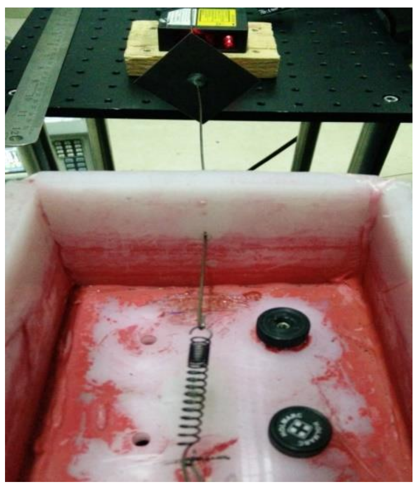


Figure 17: Effect of combination lens on SMA spring

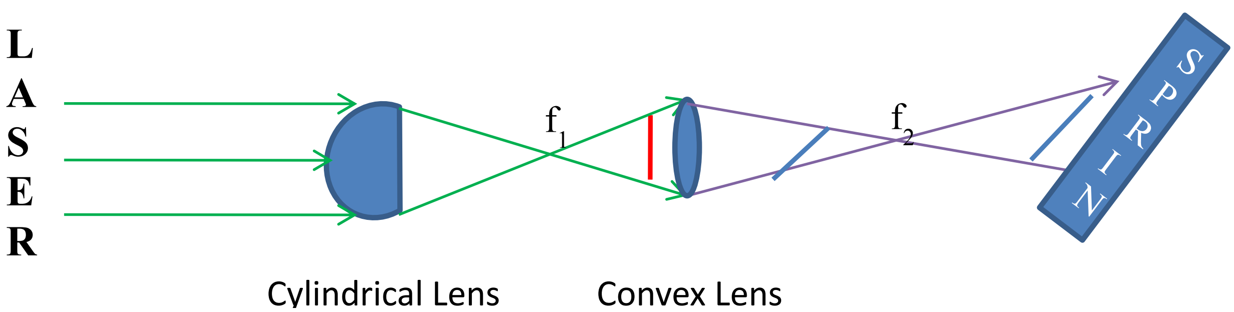


Figure 18: Schematic showing lens arrangement with their focal points

Table 4 Output and input values for both lens arrangements

Parameters	Cylindrical lens	Cylindrical lens + Convex lens
Focal length	100 mm	100 mm
Laser beam diameter	3 mm	3 mm
Laser wavelength	532 nm	532 nm
Output laser line	7-8 mm	13-15 mm

3.2 Hot water based 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 19] which in turn supply thermal energy to the spring. Due to this heat, the temperature of the spring rises and as it reaches transformation limit in turn actuates the spring.

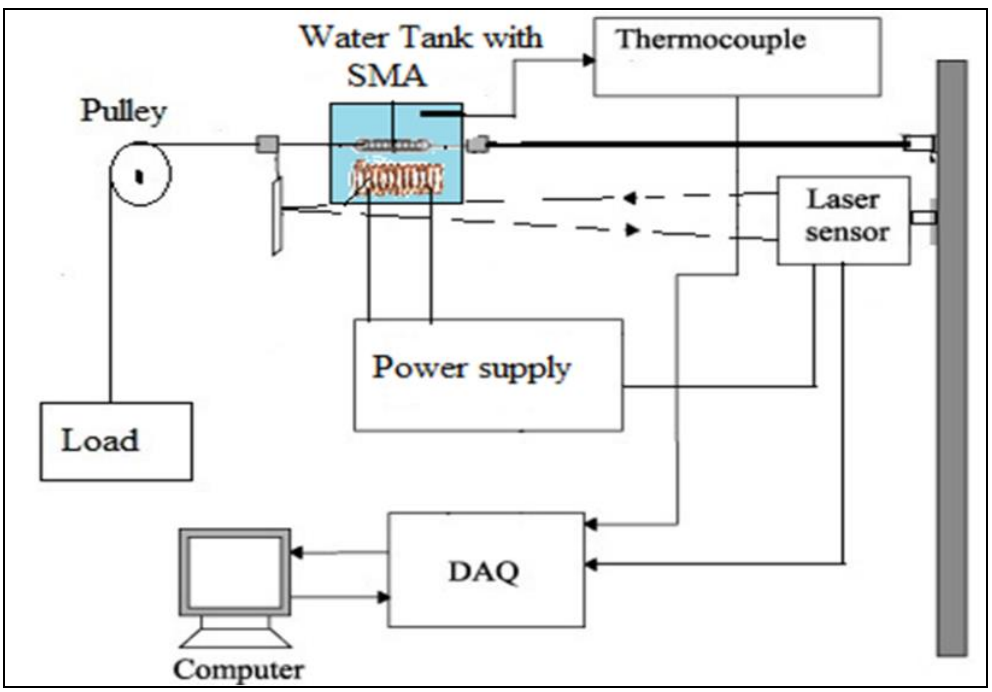


Figure 19: Schematic for hot water actuation setup

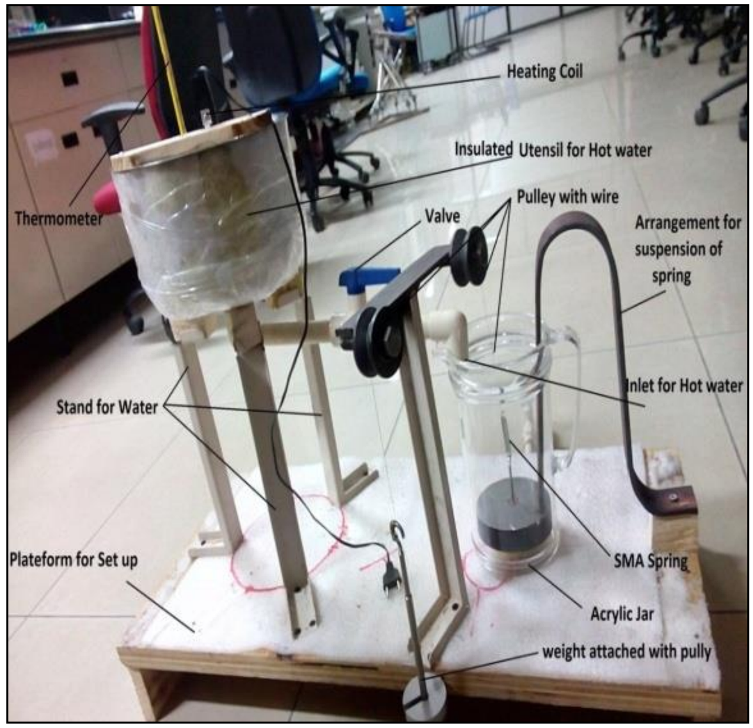


Figure 20: Experimental setup for Hot water actuation method

Experimental setup for hot water actuation is made up of borosil glass with glass molding process in our workshop. Borosil is used because of the reason that it can bear very high temperatures. Current setup consists of inlet and outlet sections for continuous water flow. An electric rod is used that facilitates heating of water. At the base of the setup, a hook is provided that holds the spring from one end and at the other end load is applied through a load-pulley arrangement. Laser displacement sensor (LDS)[Panasonic] with resolution 2.5 microns over a displacement range of 40 mm at a frequency of 664 nm is used to measure the displacement. A flapper arrangement is made that LDS takes as reference for the calculating the displacement of the spring. 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 where spring is held fixed at one end and then cooling is done through natural convection.

Chapter 4 Thermo-mechanical behavior of shape memory alloy spring under Laser actuation

4.1 Laser based actuation

Various changes have been done while performing the experiments based on the results found. At the preliminary stages, work has been started with cylindrical quartz tubes. These tubes generated a line length of about 5-7 mm as shown in Figure 21 captured over a photographic sheet. Though it was found that the laser when passed through this quartz incur heavy loss in the efficiency of the power. Also few experiments were conducted on continuous laser to get a comparison with pulsed laser

4.1.1 Pulsed laser

4.1.1.1 Using Quartz tube:

Results can be seen in Table 5 below when experiments were performed using quartz tube of diameter 5mm with varying spot diameter.

Table 5: Results using quartz tubes with varying diameter

Laser Spot Diameter	Power	Length Converted	Fluence(mJ/cm2)
2.5mm	0.15W	30mm	306
	0.30W	35mm	612
	0.55W	40mm	1122
2mm	0.15W	10mm	477
	0.30W	15mm	955
	0.55W	17mm	1751

Fluence calculation is done based on the area of output line (assumed as rectangular spot) at different power values. Figure 21 shows microscopic view of the line formed with the help of portable USB microscope at a magnification of 4X

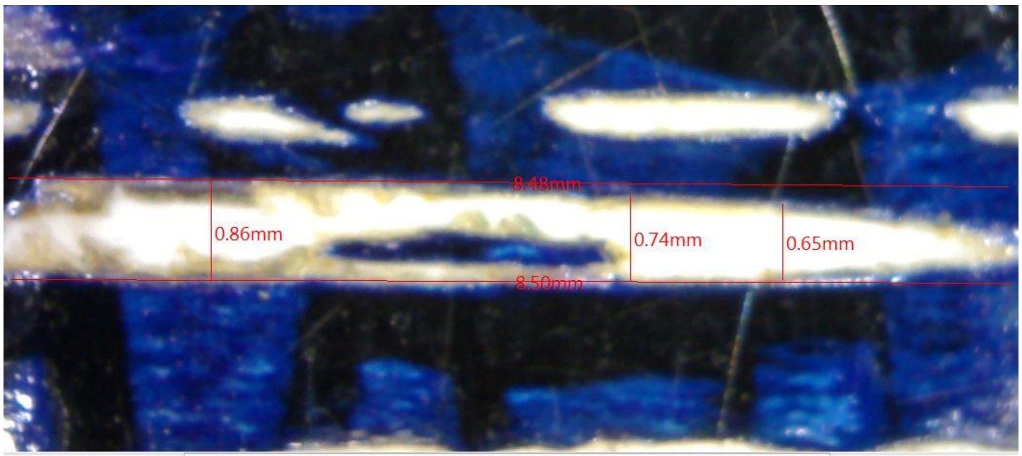
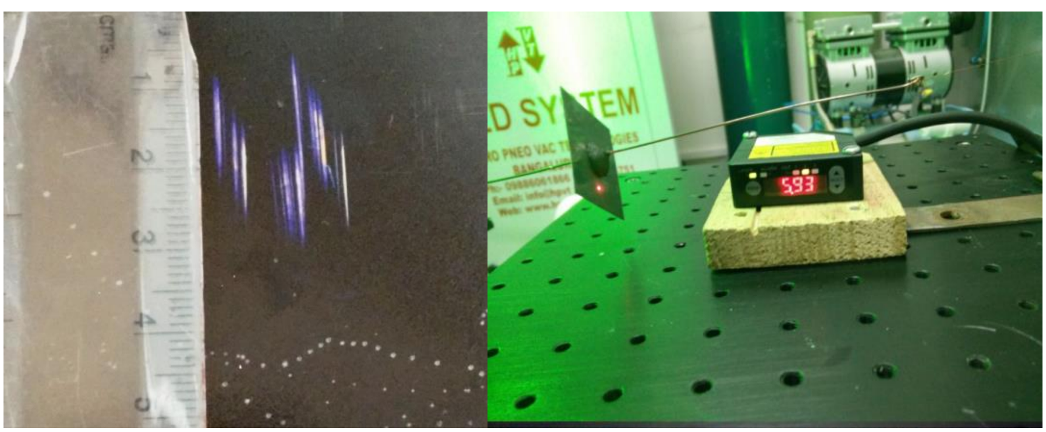


Figure 21: Microscopic image captured over photographic sheet



Above Figure shows the line obtained with quartz tube captured in a photographic sheet in normal view with a centimeter scale kept parallel to it as reference.

4.1.1.2 Cylindrical lens:

The losses with quartz tube are very high, so next set of experiments is performed with a Plano concave cylindrical lens. These lenses will convert the point beam to a rectangular beam with fewer losses when compared with quartz tube.

Cylindrical lens is a Plano concave type lens with a focal length of 100 mm and curvature diameter 25mm. SMA spring is kept after the focal point because at focal point the intensity is very high which may ablate the spring at higher powers.

Table 6: Displacement gain in heating-cooling cycles

Cycle		Time (mins)	Displacement
1	Heating	4.90	7.93
	Cooling	2.00	0.64
2	Heating	4.80	4.56
	Cooling	1.36	0.42
3	Heating	3.90	4.20
	Cooling	1.49	0.40

As it can be seen from the above table where experiments for first three cycles were performed using a cylindrical lens. Heating time required is more than the cooling time because of the inhomogeneous heating due to Gaussian beam.

Displacement for the first cycle is very high which is approx. 8mm and it decreases further. This depends on the length of the line falling and the area over which it is affecting the spring. Even though the line length formed is more but the intensity distribution varies as per Gaussian beam profile.

4.1.1.3 Combination lens

After performing experiments with a cylindrical lens, it is found that the line obtained can further be increased if some kind of combination of lens is used. So a cylindrical lens plus a convex lens is used that increases the output length to 50% than it was before.

All the experiments were then done with this arrangement and different characterization were performed to check the effects of heat over the SMA spring.

A minimum load of 100gms is required to enlarge a fully compressed NiTi spring (original 13.86mm) to about 20mm. Different experiments were carried out by changing power and the results are noted for every heating and cooling cycle.

4.1.1.3.1 Study on Displacement-time relationship

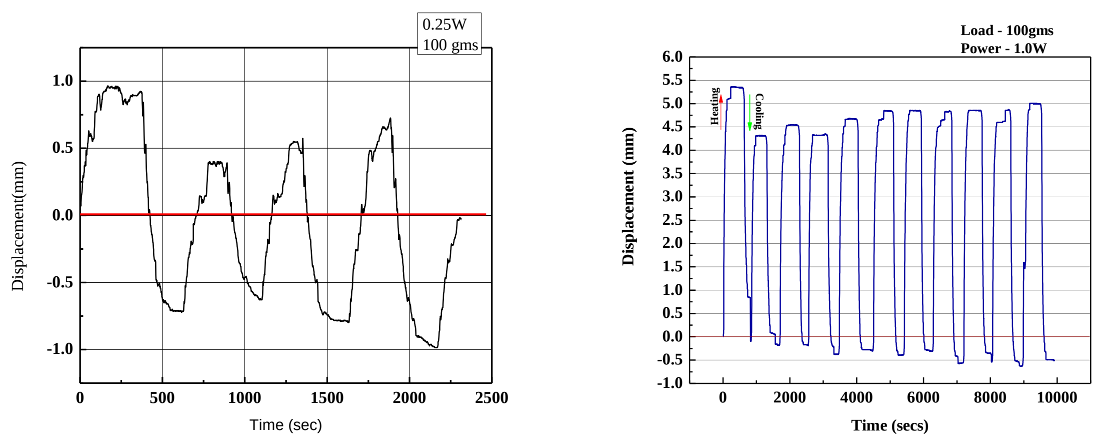


Figure 22: Displacement-Time relationship at 0.25 W and 1.0W

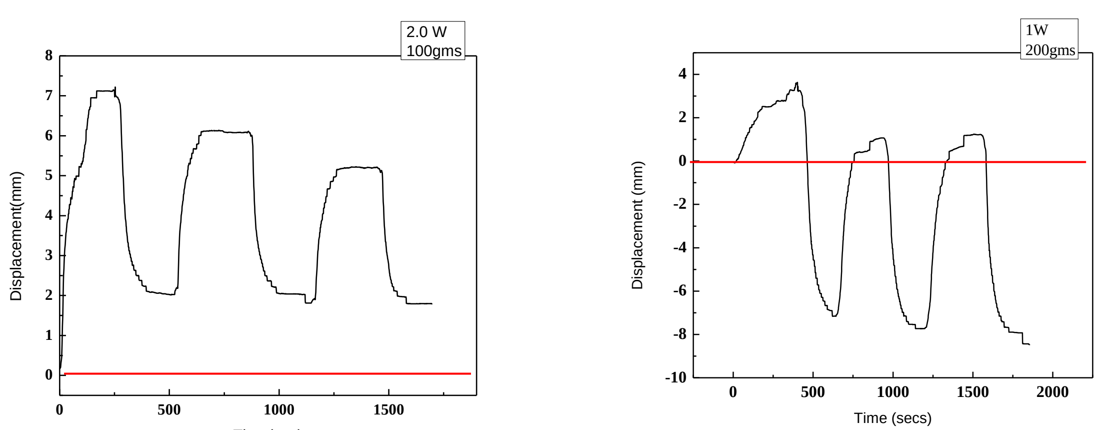


Figure 23: Displacement-Time relationship at varying load and power conditions

Figure 22 above shows heating-cooling cycle for displacement-time relationship Experiment was conducted for NiTi spring at different powers with an applied load of 100gms. Heating time was set as 600secs (threshold for heating displacement) and cooling time as 300secs (threshold).

The LDS reference is taken as zero i.e. when the spring is extended because of applied weight and no thermal energy is provided. Also it can be observed that as the power value increases, displacement gained also increases. As we can see from the above Figure 22, the maximum actuation (compression) when heating is done is about 5.4mm. Running for 10cycles, it can be seen that the actuation is getting stabilized except for the first few cycles (where it decreases). The reading going below zero is because of the load applied which extends the spring more than its compression. One cycle (Heating-cooling) is around 900secs and Data acquisition system captures this data in the terms of voltage.

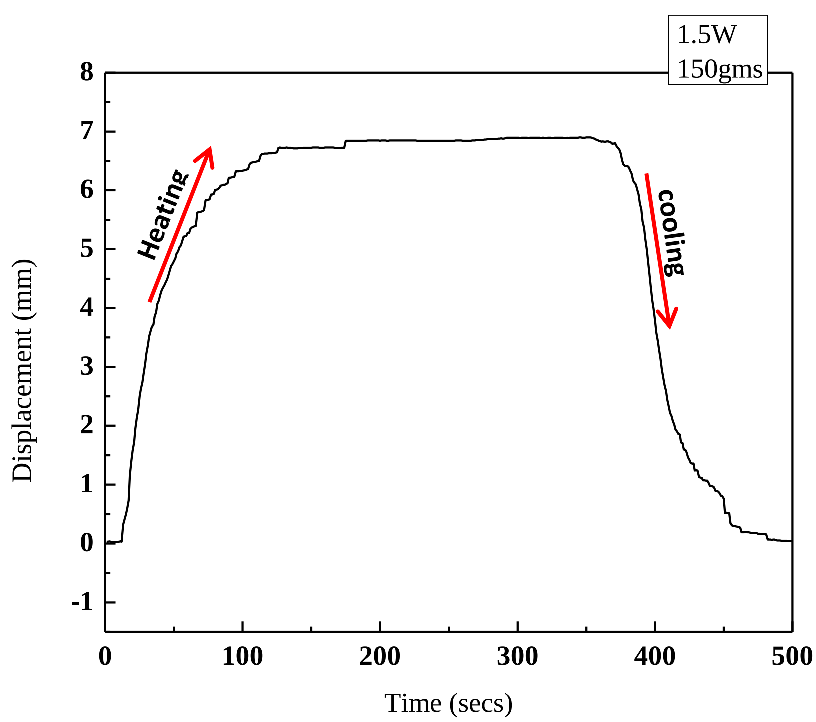


Figure 24: Single Heating-cooling cycle

One Heating-cooling cycle is taken for better clarification. In the Figure 24, it can be seen that the maximum displacement it is gaining is near to 7mm. Also it can be observed that the actuation is gained very fast and it went on increasing till 100secs and then steady state continues for next 300 secs. The heating time here is around 400 secs. This time depends upon the sample to achieve a steady state and then cooling is done. This particular cycle is taken at 1.5 W and at a load of 150gms.

4.1.1.3.2 Surface characterization method

Scanning Electron microscopy

Surface morphology is studied through SEM images. Figure 25 shows scanning electron microscopy done on NiTi shape memory alloy spring taken for different powers and at different magnifications. A 10mm sample is cut from the spring and is analyzed over the region where laser has influenced.

In SEM images shows that at low power (0.25W) the grains are not deteriorating but some debris can be seen over the structure. Also in figure 25(e, f) morphology of NiTi spring shows some tearing feature with downside peaks and valleys clearly visible in the images. Depth in fig 5e shows that at higher powers the laser is ablating the spring. Though even after this, actuation of spring can be seen but the strength of spring decreases drastically.

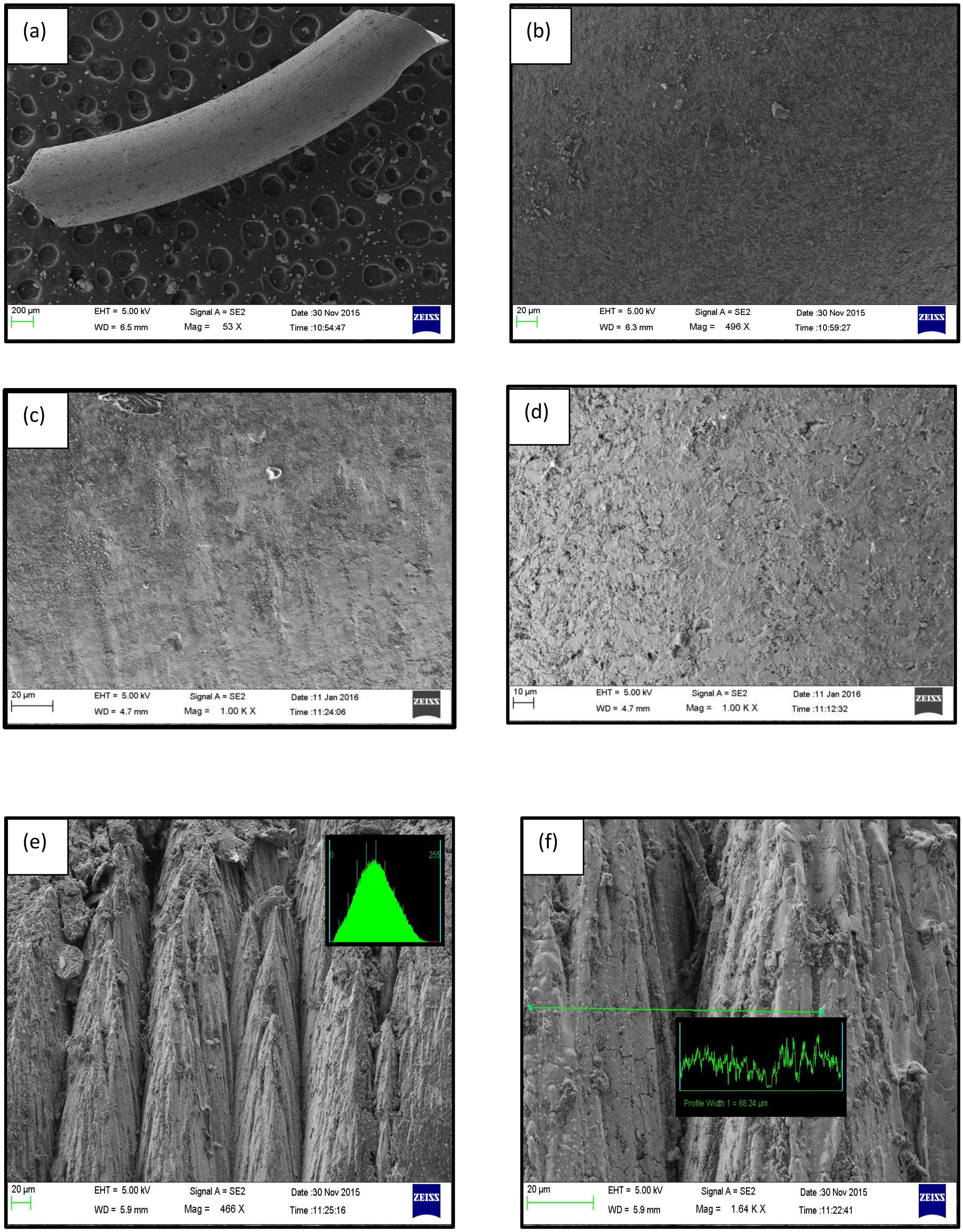


Figure 26: SEM images at different powers (a) Sample cut of 10mm, (b) Original Sample, (c) 0.25W, (d) 1.0W, (e) 2W, (f)Depth created due to high power

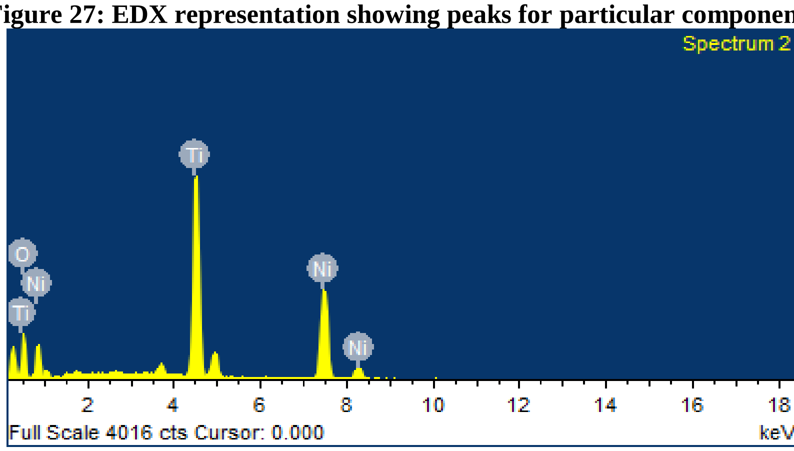
Electro Dispersive analysis:

Spring composition was determined using Energy Dispersive X-ray spectroscopy (EDX). The composition of heat treated spring obtained through EDX is as follows: Ti: 22.62 at. %, Ni: 23.20 at. % and O: 54.18 at. %. It is necessary to do the experiments in inert atmosphere as the NiTi is easily oxidized due to the heat treatment at open atmosphere. Alternatively the oxide formation of NiTi spring which prevent Ni element to release from its alloy surface is beneficial for corrosion resistance and biocompatibility. However it was reported that this passivation layer on NiTi alloy was relatively fragile. This brittle and thin oxide layer may be destroyed during significant deformation or during complex interaction involving wear (Fu (2003))

Table 7: EDX analysis after laser interaction

Element	Weight %	Atomic %
O	11.81	54.18
Ti	14.76	22.62
Ni	18.56	23.20

Figure 27: EDX representation showing peaks for particular components



4.1.1.3.3 Thermal analysis

Thermo Gravimetric measurements were carried out to investigate the kinetics of oxidation. Thus thermal stability of this Shape memory alloy can be revealed by TGA. This test was carried out with a specimen weighing around 20 mg at a constant heating of 5 °C/min purged with nitrogen gas.

Fig 28 (a, b, c) shows the laser actuated spring at intermediate powers and the amount of weight gain goes on increasing with increased fluence. At a low power of 0.25W (Fig 28a), decomposition is seen after 100°C whereas at high powers (i.e., at 0.50 W and 1.0 W), NiTi is severely oxidized. The presence of oxides is then confirmed by Energy Dispersive X-ray spectroscopy. Also it can be seen that in all the graphs, reading again increases after 800°C. Nitridation occurs in NiTi at this temperature limit. As the TGA environment is purged with nitrogen gas, so there are high chances of nitride formation. Normally, titanium is prone to nitridation and forms Titanium nitrides and higher stoichiometric structures (Neelakantan (2009))

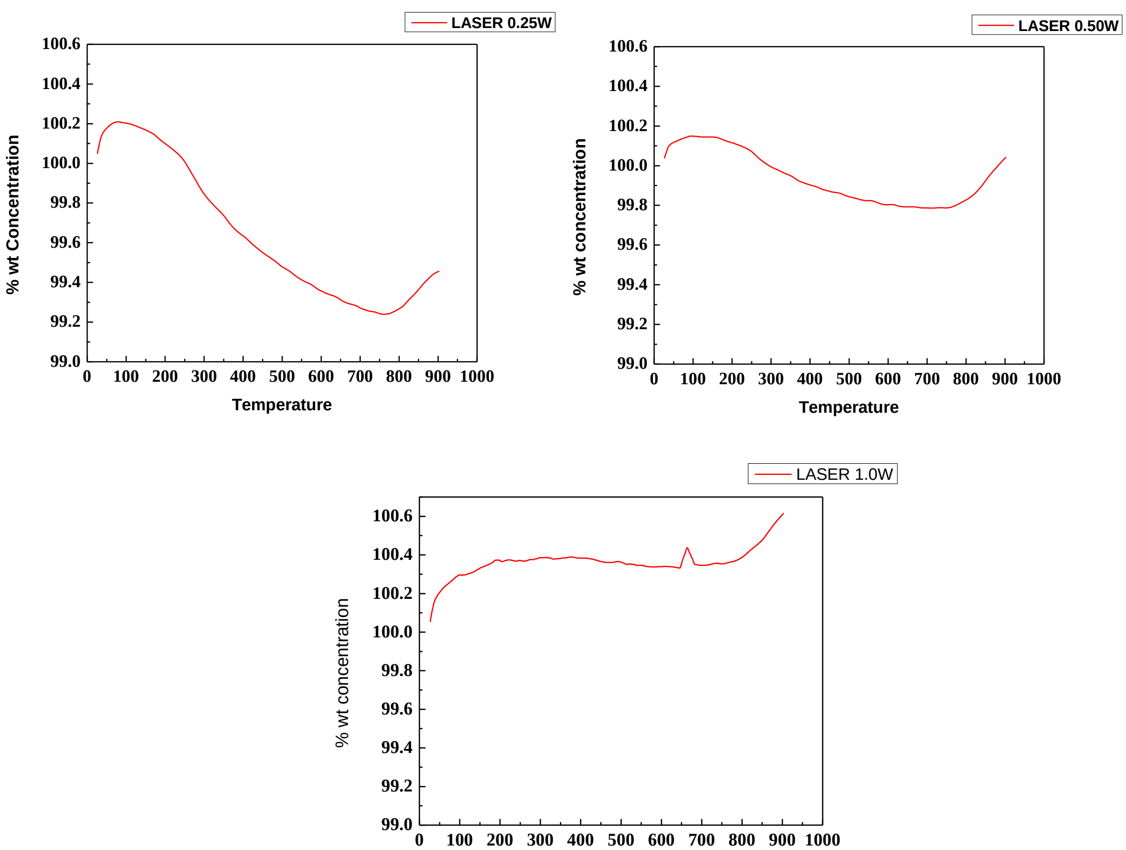


Figure 28: TGA analysis performed for springs undergoes heating at different laser powers (a) 0.25W, (b) 0.50W, (c) 1.0W

4.1.2 Continuous Laser

Experiments were also conducted with continuous laser so that a comparative study can be done with a pulsed laser. Power required to actuate the spring with continuous laser is less than 1.0W. No deterioration in the spring with continuous laser was observed.

Experiments were performed into two categories

- **Case 1:** When the laser is incident on one end.
- **Case 2:** When laser is focused at the center of spring.

Case 1: When the laser is incident on one end.

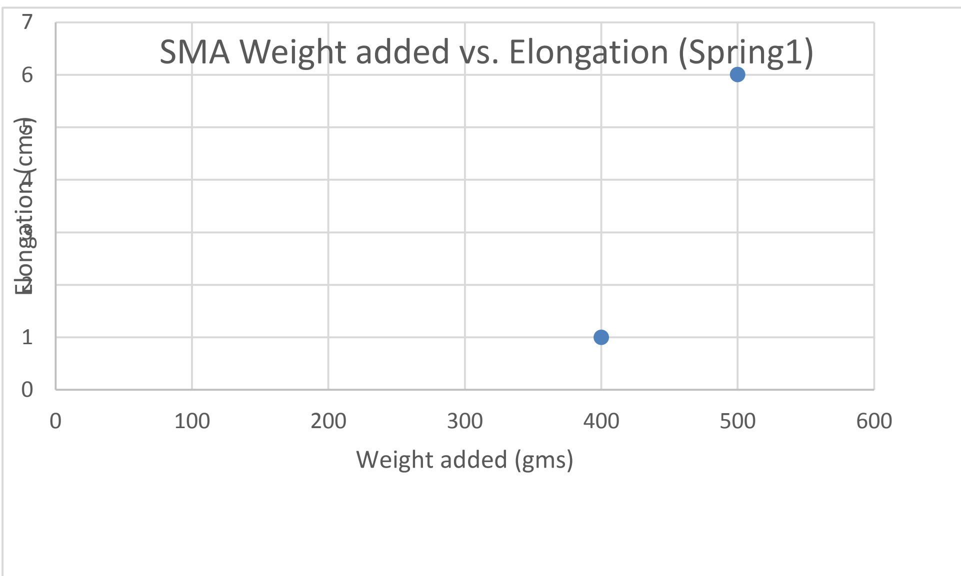


Figure 29: SMA Weight added vs. Elongation

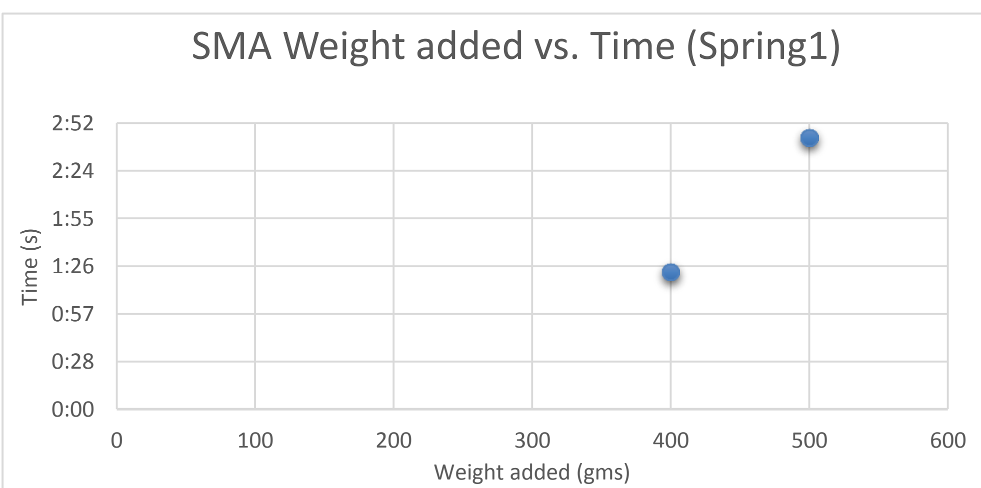


Figure 30: SMA Weight added vs. Time

Case 2: When laser is incident at the center

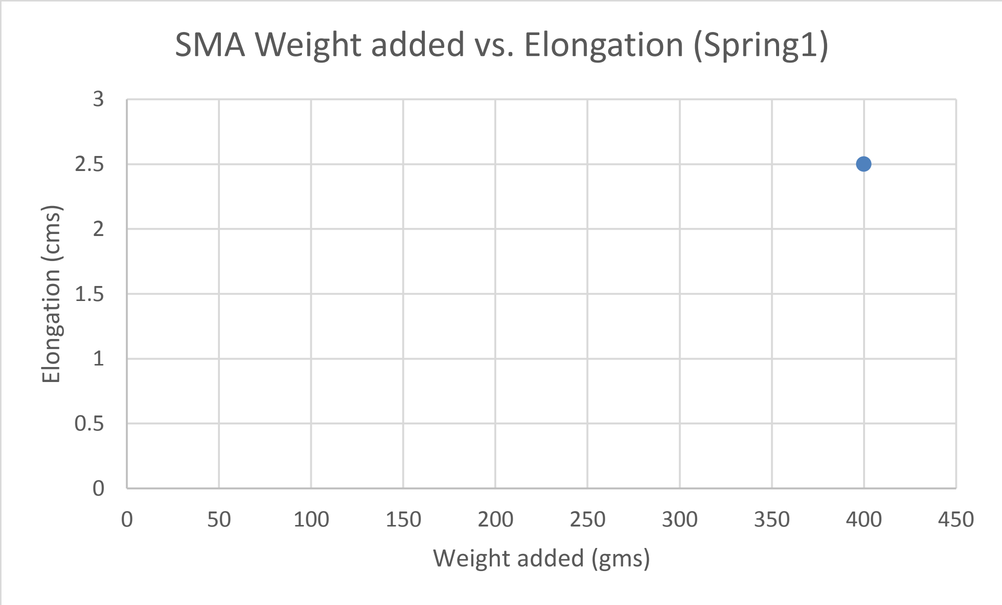


Figure 31: SMA Weight added vs. Elongation

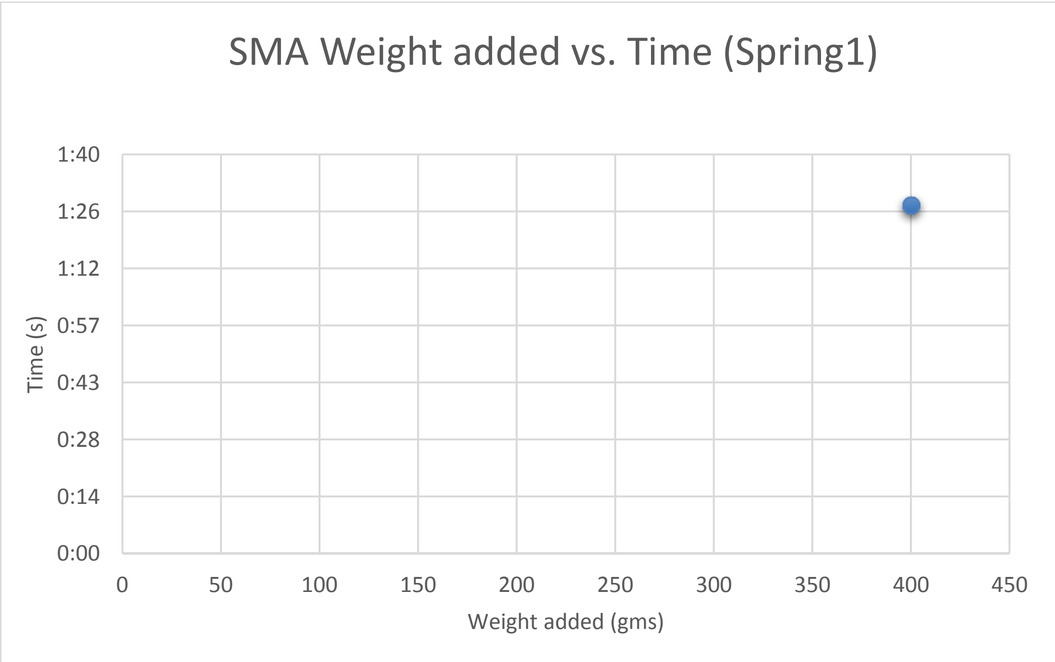


Figure 32: SMA Weight added vs. Time

Chapter 5 Thermo-mechanical behavior of Shape memory alloy spring under Hot water actuation

5.1 Hot water based actuation

Using hot water, same characterization is performed as done with laser source. Effects of heat are analyzed for various numbers of cycles and studied life cycle analysis of the spring.

5.1.1 Study on Displacement-Time-Temperature relationship

Figure 33 shows displacement Vs Time graph when spring is loaded with 4.5 N. Heating time (25 secs) is very less compared to cooling time (1200secs). Hysteresis (figure 34) 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 28 mm can be seen from figure 34. For the same cycle, temperature versus time curve Figure 34 is plotted, fluctuations while gaining the temperature can be seen which may be due to absorption or dissipation of latent heat and heat transfer with the ambient. (Yin (2012))

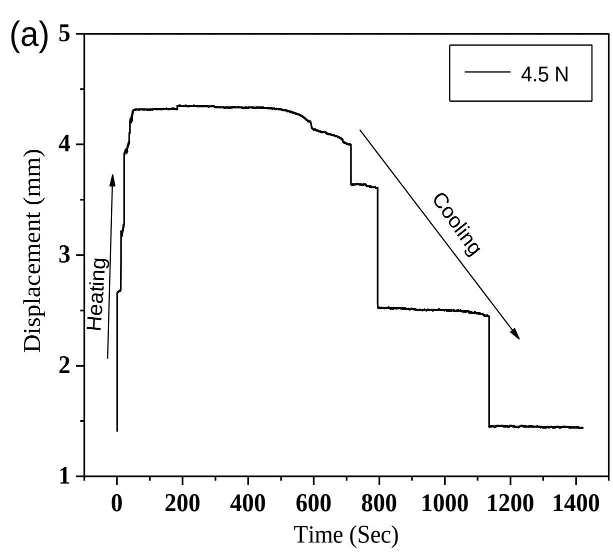


Figure 33: Displacement Vs. Time relation for Hot water actuation

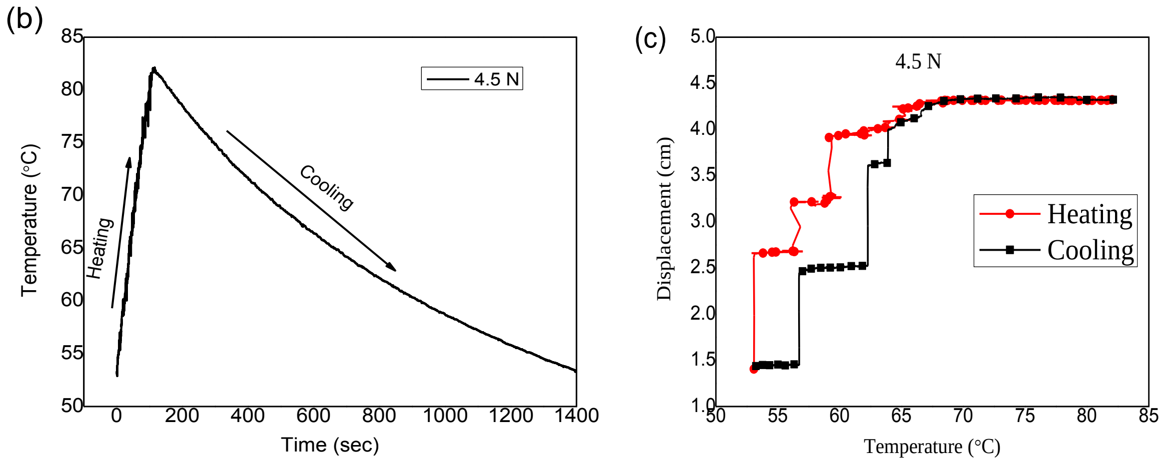


Figure 34: Displacement-Time-Temperature relationship

5.1.2 Surface characterization

Scanning Electron microscopy

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.

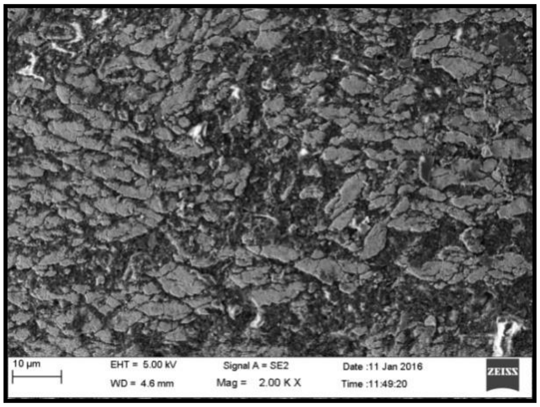


Figure 35: SEM image for Hot water actuated spring

Figure 35 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 since heavier atomic weight. Nickel content is more than Titanium content (Table 8). Though Elongated grains result in 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)

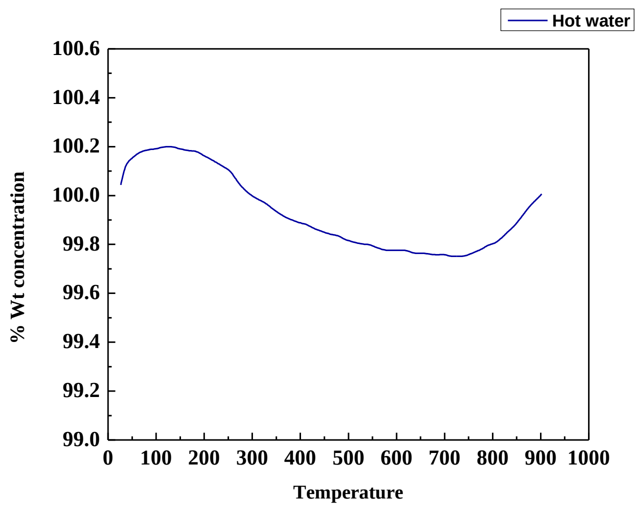


Figure 36: TGA analysis for Hot water actuated spring

Figure 36 shows Thermo gravimetric analysis which is done to find kinetics of oxidation.

The loss or gain of material may be because of decomposition or oxidation. Here, it is shown that an increase in %weight concentration is observed at temperature range of 0-100^{o}C, which may be due to the oxide formation of NiTi alloy. This is further verified with EDX data which shows 52.46 at % of oxygen content in the sample. Between 100^{o}C-200^{o}C, NiTi spring is severely oxidized and then decomposes after this limit. At about 800^{o}C, there is an increase of NiTi %weight concentration (Figure 36) which may be because of nitridation in NiTi alloy. (Neelakantan (2009))

Table 8 EDX Data over Hot water spring

Element	Weight %	Atomic %
O	12.79	52.46
Ti	12.56	17.20
Ni	27.14	30.33

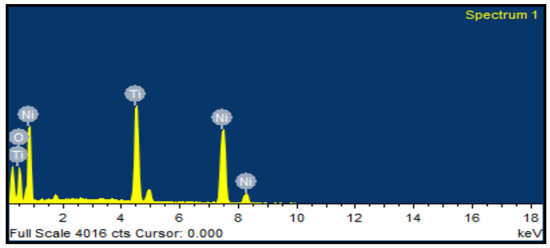


Figure 37: EDX showing peaks for different components

Chapter 6 Conclusion and Future Scope

In conclusion, we proposed two thermal sources as actuation media for shape memory alloy. It has been found that actuation gained by both the medium is good enough to use in practical applications. Laser at 532nm is used and optimum power of about 1.0W is analyzed which gives fluence of $49 mJ/mm^2$. Hot water actuation is capable of actuating the spring once the temperature reached transformation limit. Thermo gravimetric results shows weight gain i.e. oxidation till 100℃ and then decomposition starts. Oxygen content is further validated with Electro dispersive X-ray spectroscopy (EDX). Also weight gain after 800℃ can be because of NiTi nitridation phenomenon.

We see that by changing thermal source, we can control the displacement precisely. Thus it can be concluded this mediums can be used at places where human interference is not advisable to consider human safety. The present study could represent the vital observations and results when actuated with two different mediums. Further study for life cycle analysis of spring can also be done over this work.

Future scope for Laser based actuation:

- Leads to development of solenoid's and micro valves in harsh environment such as nuclear reactors, thermal power plants etc.
- Also can be used at places where flow control should be precisely monitored. By changing laser power, displacement can be controlled effectively
- A detailed comparative study between pulsed laser and continuous laser will be helpful in investigation behavior of spring based on different parameters

Future scope for Hot Water actuation:

- Engine's thermostat valve can be replaced with a SMA spring that is economical and less complex arrangement than a thermostat device
- Micro Drug delivery device is yet another application with hot water based actuation
- As hot water does not deteriorate the spring, so maintenance required is also less compared to other actuation mediums

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