PRELIMINARY STUDIES ON THE THERMO-MECHANICAL CHARACTERISTICS OF INDIGENOUSLY DEVELOPED SHAPE MEMORY ALLOY WIRES.

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ABSTRACT: Smart materials have received increasing attention in recent years for their great potential to revolutionise engineering applications and design. The technological advantages of using smart materials over traditional materials arise from special capabilities due to unique microstructural or molecular properties. Among different smart materials like piezoelectric, electro-strictive, magneto-strictive, magneto-rheological and electro-rheological, shape memory alloy seems to be a probable candidate for semi-active control of different structural members (rotating or otherwise) in view of the fact that it generates a relatively large deformation and then recover upon heating. Shape memory alloys are deformed while in a low temperature phase and such deformations could be in the form of bending, twisting, contraction or stretching. The so deformed shape memory alloys are then able to return to their original size and shape by undergoing internal phase transformation process through the increase of temperature. This property could be exploited for several useful applications like for example integration of shape memory alloy wires with composite torque transmission tubes utilizing the additional preload to generate an anti-twist so as to enhance the torsional stiffness. As such it becomes important to generate the quantitative values of thermo-mechanical properties of developed shape memory alloy wires and more so for the indigenously developed ones as this information would be extremely useful for aerospace applications in mind. Therefore an attempt has been made here to generate thermo-mechanical properties of shape memory alloy wires defined in terms of deformation recovery as a function of temperature. The study has indicated that the deformation recovery becomes larger and larger as the preload increases which could be exploited for structural applications where on line stiffness change would be beneficial from dynamics point of view.

KEY WORDS
Thermo-mechanical characteristics, shape memory alloys, pre-load, martensite start and finish temperature, austenite start and finish temperature.

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1 INTRODUCTION

Shape memory alloys (SMAs) are a special class of material and exhibit properties very different from normal metals and alloys. They are characterized by shape memory effect and superelasticity also called pseudoelasticity. Though SMAs are known for about past four decades, the applications of SMAs were realized only in mid-eighties. During the last decade, extensive research has been carried out through out the world for the development of smart structures wherein SMAs are considered as the smart element for sensing and actuation.

Buehler and Wiley [1] of the U.S.Naval ordnance laboratory received a united states patent on a series of engineering alloys (nickel-titanium) that possess a unique mechanical memory. The generic name of the series of alloys is 55-Nitinol. Nitinol is derived from Ni(nickel), Ti(titanium) and NOL(Naval Ordnance Laboratories). The most common of the shape memory alloys or transformation metals is a Nickel-Titanium alloy known as Nitinol. C.A. Rogers[2] et.al showed experimentally that the shape memory alloy components embedded or bonded to structures can be utilized in two different ways, the first one is the active property tuning wherein it is based on changes in the stiffness of shape memory alloys and the second one is a technique called active strain energy tuning wherein shape memory alloy are placed in a residual strain state generating additional pre-load as well as changes in their stiffness. The application of shape memory alloys with reference to rotor dynamics was first studied by Nagoya[3]et.al wherein the active control of a metal shaft was done using shape memory alloy bearing supports. They observed that vibration due to whirling were controlled by on/off heat control of shape memory alloy bearing supports. The response of the shaft under the loading caused by eccentricity of a disk was obtained analytically and experimentally. T.Chen [4] examined the performance of a flexible teflon drive shaft activated by shape memory alloy wires inserted in sleeves both by analytically and experimentally. A reduction of 50% in the dynamic response of a rotating flexible Teflon shaft with shape memory activation was achieved. A theoretical analysis of sound transmission/radiation of shape memory alloy hybrid composite panels was presented by C.Liang et al,[5] wherein the new analytical technique was introduced to study the effect of adaptively changing the mode shapes of shape memory alloy hybrid composite plates in order to create the modifications in the radiation efficiencies of modes. They noticed that acoustically excited shape memory alloy hybrid composite plates have the ability to change the radiation efficiency, transmission loss and directivity patterns. An investigation of adaptive hybrid composite cylinders utilizing active shape memory alloy composite layers for use in high pressure vessel applications was presented by Craig A Roger et al [6], wherein the model for the adaptive composite material cylinder and parametric studies were performed to demonstrate the utility of the adaptive composite cylinder concept for various composite materials and pressure vessel configurations. Experimental results on the dynamics of a beam constrained by shape memory wires are presented[7]. It was observed that the damping increases significantly when the shape memory wires are stressed such that they lie within the pseudoelastic hysteresis loop. Theoretical models of the inner hysteresis loop are considered, and modal analysis is used to obtain the dynamic response of the system. These results demonstrate that pseudoelasticity of shape memory wires can be used to augment passive damping significantly in structural systems.

Generally, in application, SMAs undergo thermo-mechanical cycling for large number of cycles. The behaviour and response of the material are quite different from that when tested individually for thermal and mechanical properties. It is, therefore, appropriate that the thermo-mechanical behaviour of the material is well understood before designing the structure, which makes use of the thermo-physical and/or thermo-mechanical properties of SMAs. In this respect, the information available in the literature does not appear to be adequate. The present research deals with the study of thermo-mechanical response of Ni-Ti-5at%Cu shape memory alloy wire. Experimental results in terms of contraction as a function of geometry, load and temperature are discussed in this paper.

2 EXPERIMENTATION

To investigate the thermo-mechanical properties of shape memory alloy wires, experiments were conducted in which the effects of various parameters viz., preload, temperature, geometry of the wire on the shape memory properties such as recovery stress and recovery strain were studied. The above study necessitated the development of two test rigs, which were designed, fabricated and instrumented at the laboratory. In the first set up, one end of the shape memory wire was held rigidly and the other end was connected to a spring. A defined preload was applied to the shape memory alloy wire by pulling and fixing the other end of the spring to a predetermined position. Experiments were conducted for 1% and 2% elongation and the shape recovery of the wire (contraction) under a predetermined constant load was obtained as a function of temperature. The photograph of the test rig used for these experiments is shown in figure 1.

In the second set up, the shape memory alloy wire was mounted vertically wherein one end of the wire was held rigidly to a fixed plate and the other end to a plate which could be loaded. The experiment was conducted at various loads, and shape recovery (contraction) as a function of temperature was noted. The photograph of the test rig used is shown in figure 2. Both the rigs were instrumented as required and the shape memory alloy characteristics like contraction in length as a function of temperature, load were noted. The main difference between the two rigs is that while any defined preload/extension could be obtained in first rig, the catenary effects were totally eliminated in the second.

The shape memory alloy wires used in the experiments were indigenously developed in the laboratory and tested in the rigs designed and fabricated in the laboratory. A Ni-Ti-5at%Cu alloy was chosen for the study. The SMA wires of diameter 0.5 and 0.3mm were processed from vacuum arc melted cast ingot by forging, hot and cold rolling followed by wire drawing. The wires used in the present study had a cold deformation of 30% and were heat treated at 450^{0}C for 30min.

3 RESULTS & DISCUSSIONS

The shape memory alloy wire indigenously developed was tested in the rigs designed and fabricated for the purpose. The various parameters affecting thermo-mechanical characteristics is discussed in the following:

load -extension variation of shape memory alloy wire at martensite finish temperature:

In order to understand the behaviour of shape memory alloy wire (0.5mm dia in this case) at martensitic temperature, the wire was tested in a Instron universal tensile testing set up. Figure 3 shows a plot of the load –extension behaviour of shape memory alloy wire in the martensite phase. The load-extension curve exhibits four distinct regions as indicated in figure 3. The first region is classical in nature showing a linear behaviour wherein the extensions are almost proportional to loads and that the material is completely elastic. In the second region, the martensite deforms almost at constant stress by detwinning. Followed by this, there is a third region, which is linear but not necessarily purely elastic. Therefore, upon removal of load at the third stage of deformation may not make the material to come back to the end of second stage. The deformation mechanism in this stage is a mixture of elastic of detwinned martensite, together with formation of new orientation of martensite. The fourth region is where the plastic deformation, as in the case of yielding of all conventional metals and alloys, takes place. Thus theoretically, the maximum amount of recoverable strain or memory strain can be obtained up to the end of second stage. However, the maximum recoverable strain that can be utilized in cyclic applications is much less than this and is normally limited to 2% as against possible about 6% maximum recoverable strain in Ni-Ti-5at%Cu SMA wires. Figure 4 shows the similar results obtained for 0.3mm diameter wire.

Effect of heating and cooling on shape memory alloy wire:

In order to study the effect of heating and cooling cycle, one end of the shape memory alloy wire was held rigidly and another end connected to one end of a floating calibrated spring which would provide a defined preload to shape memory alloy wire while the other end of the said spring is pulled and fixed. The shape memory alloy wire was heated and contraction at different temperature intervals were noted down. Figures 5 and 6 show the plot of length of the shape memory alloy wire as a function of temperature for two values of constant loads required for 1% elongation and 2% elongation. It is very clear from the plot that there is a hysteresis between heating and cooling of the shape memory alloy wire which is relatively low at martensite and austenite temperatures and little higher at temperatures in between. Details related to martensite start, martensite finish, austenite start and austenite finish temperatures are depicted very clearly in the figures. A simple comparison made between figures 5 and 6 show that the hysteresis is much lower when the initial constant load is higher. However this factor needs to be verified at higher elongation levels.

Effect of martensitic load on contraction levels of the shape memory alloy wire:

In order to study the effect of martensitic load levels on contraction of the shape memory alloy wire when heated above austenitic finish temperature, the wire was mounted vertically wherein one end of the wire is held rigidly to a fixed plate and the other end to a plate which could be loaded. Initially loading was done to a particular level and loading, unloading cycles were repeated for this load in order to eliminate possible hysteresis due to various reasons. After this loading and unloading cycles, the temperature was increased to above austenitic finish in order to obtain the contraction. Later on the wire was cooled to find out whether the wire has come back to original length. The heating and cooling cycles were repeated at this constant load and region A1 B1 shows the range of contraction in length of the shape memory alloy wire. The wire was again loaded when at position B1(martensite temperature levels) and the extension observed is shown in figure 7(O2). At this point the wire was heated to above austenite finish temperature and cooled to martensite to obtain the level of contraction and extension to which to come back to original position. This heating and cooling cycles were repeated for a number of times and the contraction length variation is shown in region A2B2. The whole process was repeated for various martensitic load levels as shown in figure 7. A close look at figure 7 suggest that the contraction length variation increases as martensitic load levels increases. This indicates that higher level of work recovery can be realised at higher martensitic loads. This is also evident from the widening gap between the lines joining all the austenitic finish temperature points and martensite finish temperature points. The above data is more clearly depicted in figure 8 wherein absolute contraction (defined as the total contraction realised at any load levels when the temperature was raised from martensite finish to austenite finish) is plotted as a function of martensitic load levels indicates the increased contracted length.

Stiffness at martensite finish and austenite finish:

The effect of temperature transformation on stiffness has also been obtained. The stiffness is calculated as load per unit extension at the martensite finish and above austenite finish temperature. The variation of stiffness both at martensite finish and above austenite finish as a function of martensitic load levels is shown in figure 9. The general conclusion that can be drawn is that while austenite stiffness is higher than martensite stiffness, both these values show a slight reduction as martensitic load level increases. A deeper study however is required in this area.

4 CONCLUSIONS

An attempt has been made to get some initial exposure and experience of Thermo-mechanical characteristics of indigenously developed shape memory alloy wires, which would be useful in modifying the system characteristics defined in terms of stiffness and damping. Thermo-mechanical characteristics is being generated in terms of temperature, preload and geometry. The data so generated could be used for the theoretical design and analyses related to increasing the system characteristics of any structural components.

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FIGURE 1.

FIGURE 2.

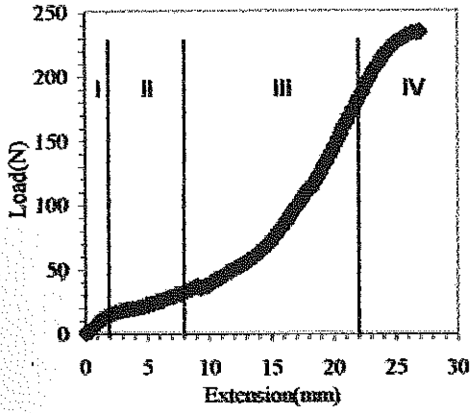

FIGURE 3: The plot depicting Load V/s Extension of a SMA wire of diameter 0.5mm at martensite finish temperature

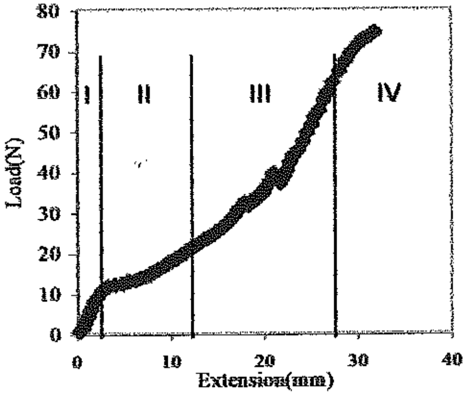

FIGURE 4: The plot depicting load V/s extension of a SMA wire of dia 0.3mm at martensite finish temperature

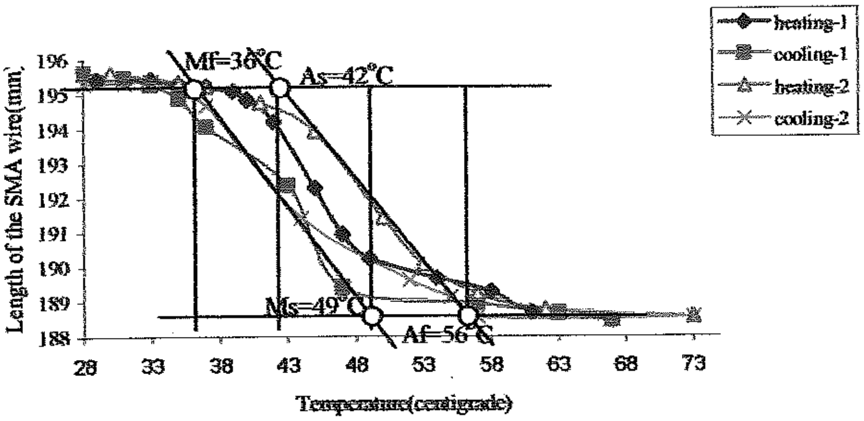

FIGURE 5:A plot depicting temperature versus change in the length of the SMA wire for 1% elongation initial length=193.5mm, stretched length=195.5mm, load=43N

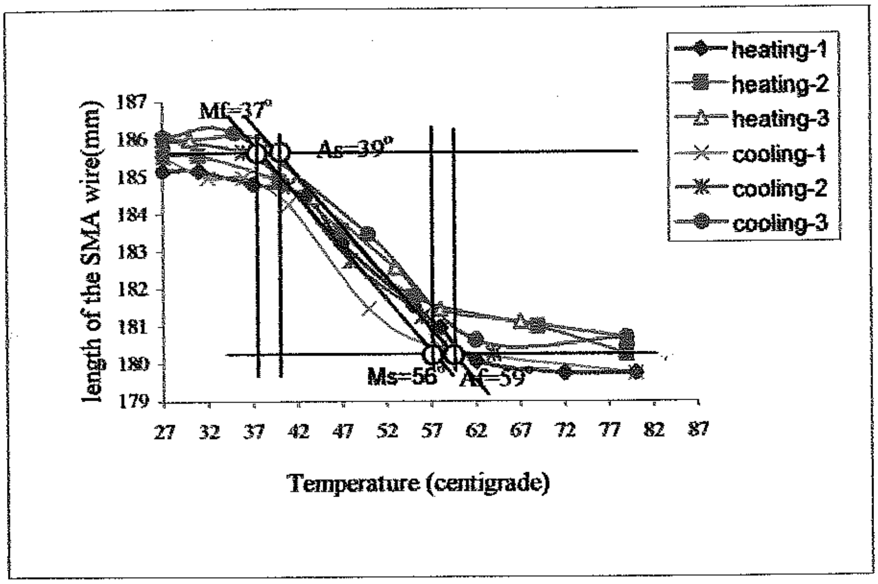

FIGURE 6:A plot depicting the change in the length of the SMA wire at various temperatures for 2% elongation. Initial length=181.2mm, stretched length=185.2mm, load =81N

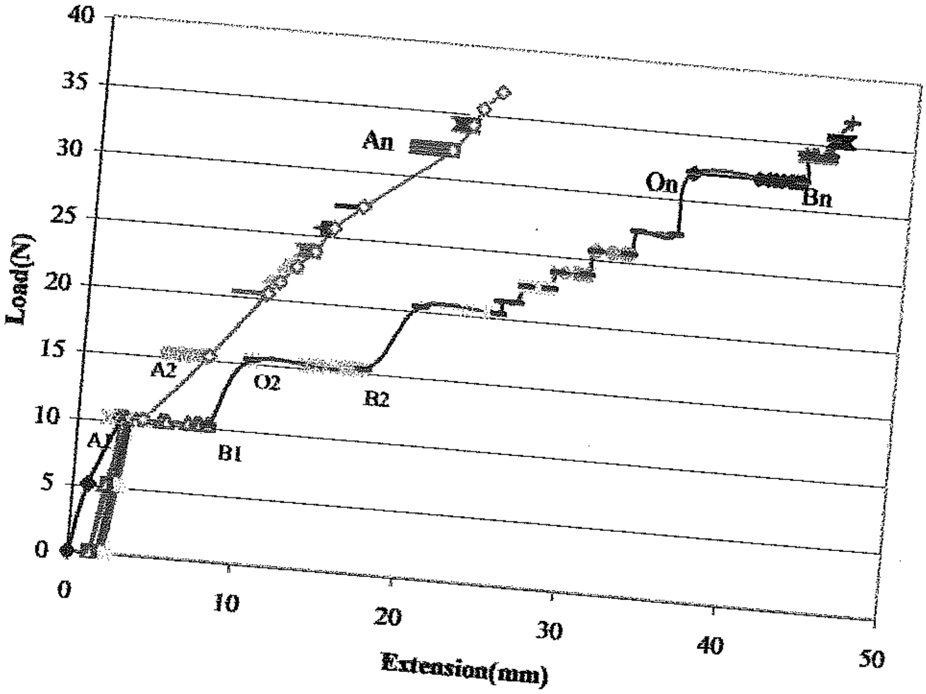

FIGURE 7: The plot depicting Load V/s Extension of a Shape memory alloy wire of dia 0.5mm at martensite finish and above austenite finish temperature.

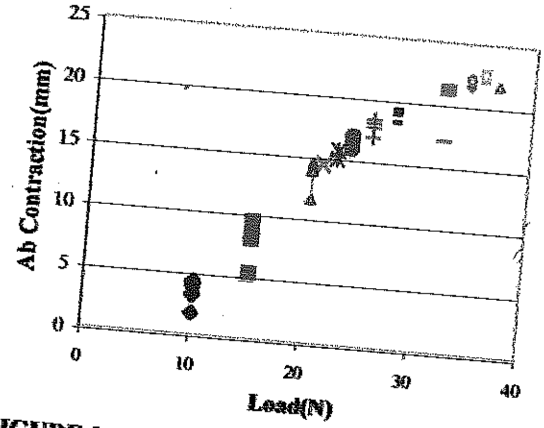

FIGURE 8: The plot depicting load V/s Absolute Contraction Of SMA wire of dia 0.5mm

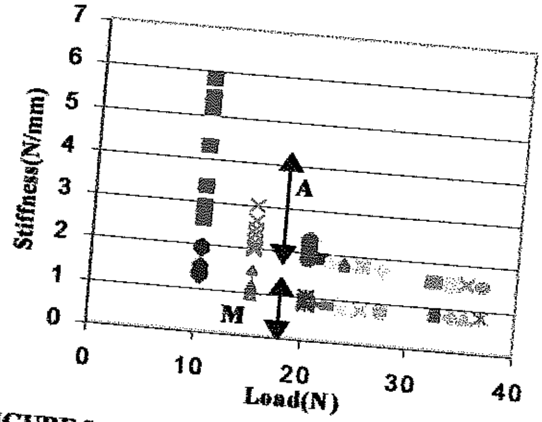

FIGURE 9: The plot depicting Load V/s Martensite stiffness,Austenite stiffness of SMA wire of dia 0.5 mm