Study of Tribological Characteristics of Nitife Shape Memory Alloys for Varying Aging Conditions

Sunil Sarangamath1, Ramesh Gowda N.R [2], Chandrakumar D[3], Yellappa M[4], Santhosh N[5], Srinivas M .T[6]
[1]P.G.Student, Department of Mechanical Engineering, Dr. Sri Sri Sri Shivakumara Mahaswamy College of Engineering
[2,4]Assistant Professor, Department of Mechanical Engineering, Rajarajeswari College of Engineering,
[3,6]Assistant Professor, Department of Mechanical Engineering, Dr. Sri Sri Sri Shivakumara Mahaswamy College of Engineering
[5]Assistant Professor, Department of Aeronautical Engineering, Nitte Meenakshi Institute of Technology

***Abstract*— Shape memory alloys are those groups of alloys which have a characteristic phenomenon of exhibiting the property of remembering its shape upon deformation and returning to its original shape when heated. These materials change their properties, for example vibration resonance frequency or modulus in response to a temperature variation. When heated by direct electrical current above the transformation temperature, the pre-deformed shape memory alloy (SMA) try to recover their shape and since they are restrained, a stress is created. The stress thus created can be relieved by aging of the samples at different temperature ranges. Ni Ti Shape memory alloys have a unique behavior of exhibiting maximum super elasticity as compared to other shape memory alloys. However there are certain elements such as Fe, Cu, Al, and Mo which are added to the NiTi as ternary additions to enhance the transformational behavior of these alloys. Alloying Fe is found to have major implications on the shape memory effect of Ni – Ti (Nitinol) based shape memory alloys. The transformational behavior of these shape memory alloys are unique and found to have an impact on biomedical and structural applications. In our work, tribological characteristics of NiTiFe were effectively studied for varying compositions and it was found that hardness increases with the ternary addition of Fe from 3% to 9% and wear drastically reduces as a result of increase in hardness. This is attributed to the fact that the increase in addition of Fe causes precipitation hardening which will ultimately result in improved tribological characteristics. Also in our present work, the samples are subjected to heat treatment and subsequent aging, which has resulted in betterment of wear characteristics, that are compared with the as cast samples.**

Keywords—Shape Memory Alloy, Nitinol, Wear, Hardness, Tribological Characteristics.

I. INTRODUCTION

Shape Memory Alloys (SMAs) are metallic alloys that undergo a solid-to-solid phase transformation which can exhibit large recoverable strains. Shape-memory alloys (SMAs) possess an array of desirable properties: high power to weight (or force to volume) ratio, thus the ability to recover large transformation stress and strain upon heating and cooling, pseudo elasticity (or super elasticity), high damping capacity, good chemical resistance and biocompatibility [1,2]

Shape-memory alloys are functional materials with a variety of applications [3, 4]. Their mechanical properties and their microstructural changes at various strain rates and temperatures have been of considerable interest. The static superelastic properties of shape-memory alloys have been extensively studied [5-7]. In quasi-static loading conditions, the transition stress for stress-induced martensite formation increases with an increase in the strain rate. In addition, in the stress-induced martensite formation regime, the work-hardening rate increases with the increasing strain rate, due to the latent heat of transformation and the heat of deformation [8-10]. Their dynamic properties, however, have not been fully explored, especially their strain-rate sensitivity and their high strain-rate microstructural changes, due to the difficulty in controlling the strain rate [11].

Since the last decade, TiNi shape memory alloy has attracted increasing interest from tribologists due to its high resistance to wear. The excellent performance of this alloy largely arises from its special deformation behaviour, the so-called pseudo elasticity, caused by a thermo elastic martensitic transformation [12-13]. The phase transformation involves a structural change from the parent phase 32(β), to a martensitic phase (monoclinic) [14]. Prior to the martensitic transformation, another phase transformation may also occur, depending on the composition of the alloy and heat treatment. This transformation involves a structural change from the Body centred (B2) phase to a rhombohedral phase (R phase) [15-16].

These two transformations are reversible and can be induced either by changing temperature or by applying stress [17]. The high wear resistance of TiNi alloy has been well demonstrated [18]. A number of researchers have investigated the wear behaviour of TiNi alloy in different wear conditions and compared it to conventional engineering materials such as steels, Ni-based and Co-based tribo-alloys [19-20]. It is observed that TiNi alloy performs better than these conventional wear-resistant materials.

In addition, TiNi alloy also exhibits high resistance to corrosion [21] and this makes TiNi alloy attractive for application in "wet" or corrosive environments, such as cavitations and liquid impact [22].

The contribution of pseudo elasticity to the wear resistance has been directly and indirectly confirmed. Shida and Sugimoto [23] observed remarkable erosion resistance of TiNi alloy during a water-jet erosion test. They found that the optimal composition that corresponded to the minimum erosion was in the range from Ti–55 wt. % Ni to Ti–56.5 wt. % Ni, where the TiNi alloy behaves pseudo elastically. Liang et al. [24] observed that the specimens with pseudo elasticity had higher wear resistance than those with little pseudo elasticity.

Attempts have been made to apply TiNi alloy as a tribo material with success in chemical plants and power stations as reported [25]. Since TiNi alloy is relatively expensive, considerable efforts have been made to develop TiNi coatings using various processes, such as sputtering, plasma spray, explosive welding and plasma ion plating [26].

II. METHODOLOGY

1. Production of Nickel, Titanium and Iron chips by suitable machining process.
2. Weighing of Nickel, Titanium and Iron for varying atomic percentage.
3. Melting of the Weighed proportions of Nickel Titanium and Iron in Vacuum arc remelting furnace to obtain buttons.
4. Suction drawing the buttons in Vacuum suction casting furnace to a diameter of 6 mm and length of 60 mm.
5. Heat treatment of the samples for different aging temperatures (i.e. 300ºC, 350ºC and 400ºC).
6. Abrasive wear test of the samples as per ASTM standards on an alumina (60µ) grinding wheel from M/s carborundum.
7. Hardness test of the samples was carried out as per ASTM Standards on Vickers hardness tester configured and calibrated.
8. Thorough evaluation of the results was carried out and suitable conclusions were drawn.

III. COMPOSITION OF THE ALLOY

The composition of the shape memory alloy is fixed by varying the percentage of iron in increments of 3% up to 9%. But however in this paper, the results for only 3% composition of Fe are discussed.

Element	Ti	Ni	Fe	Total
Alloy	At %	At %	At %	Total (%)
NiTi	50	50	0	100
NiTiFe	50	47	3	100
NiTiFe	50	44	6	100
NiTiFe	50	41	9	100

Table 1: Proportion of different alloying elements

To weigh out the materials, conversions from at (%) to wt (%) are done by using following relation below.

$$\text{Wt }\%A = \frac{(Atomic\ \%\ A * AtomicWtA)}{(Atomic\ \%\ A * AtomicWtA) + (Atomic\ \%\ B * AtomicWtB) + (Atomic\ \%\ C * AtomicWtC)}$$

Table – 2 gives atomic weight of different elements chosen for the project.

Element	Atomic Weight
Ti	47.88
Ni	58.69
Fe	55.84

Table – 2 Atomic weight of constituent elements

III ABRASIVE WEAR TEST

Abrasive wear test for the samples of three different compositions was carried out for both the as-cast and heat-treated samples for different load conditions and track diameter using pin-on-disc apparatus fitted with an AA60 alumina (60µ) grinding wheel from M/s carborundum. The Speed, time and load for which wear test is done is tabulated as shown in table – 3.

Sample	Load (kg)	Speed (rpm)	Time in Seconds
NiTiFe (As Cast)	1	300	600
NiTiFe (HT 300ºC)	1	300	600
NiTiFe (HT 350ºC)	1	300	600
NiTiFe (HT 400ºC)	1	300	600

Table 3: Speed, Wear and Load Conditions

IV. VICKERS HARDNESS TEST

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136º between opposite faces subjected to a load of 5 kg. This load is reasonably big and should give an acceptable hardness for a cast metal. The 3mm diameter castings could not be tested by Brinell. Further the high hardness also precludes the use of Brinell which is the suggested method for cast materials. The full load is normally applied for 10 to 15 seconds. The two diagonals of the square indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kg load by the area of indentation (in square mm). The Vickers Diamond Pyramid harness number is the applied load (kg) divided by the surface area of the indentation (mm^2) Fig 1 shows the Vickers hardness tester used for finding the Vickers hardness number of the given specimens.

Fig 1 Vickers Hardness Testing Machine

V. FORMULAE USED FOR DATA ANALYSIS

1) Sliding distance(S) = $\pi DNT/1000$ (m)

Where D = Diameter of Disc (mm)
N = Speed in rpm
T = Time in minutes

2) Sliding speed (V) = $\pi DNT/(1000\times60)$ (m/s)

3) Specific Wear Rate (SWR) = $\Delta V/(L\times S)$ *(mm3/N-m)*

Where ΔV =Volume loss (mm^3) = ΔLXA
Where ΔL= Loss in length (mm), A = Area of specimen (mm^2)
Where D = diameter of the specimen, L= Load (N), S=Sliding distance (m)

4) Hardness (HV) = $(2F\sin 136/2)/d^2$,
HV = $1.854\ F/d^2$

Where: F= Load in kg
d = Arithmetic mean of the two diagonals, d1 and d2 in mm
HV = Vickers hardness in kg/mm^2

VI. RESULTS

A. HARDNESS

The hardness result for different samples in both as-cast and heat-treated condition is shown as in the table below.

From the table it can be observed that, the hardness values tend to go up with an increase in aging temperature. Aging Temperature ranges from 300ºC to 400ºC, the hardness is found to increase as aging temperature is increased. The hardness value varies from 407 to 509 as the aging temperature vary from 300ºC to 400ºC

It is observed from each of the hardness values that addition of Fe to NiTi matrix has brought about a sufficient amount of solid solution hardening and there is increase in hardness.

Sl. No.	**Aging Temperatures**	**Load (in kg)**	**NiTiFe (VHN)**
1.	As-Cast	05	407
2.	300ºC	05	423
3.	350ºC	05	465
4.	400ºC	05	509

Table –4 Hardness value for different aging temperatures

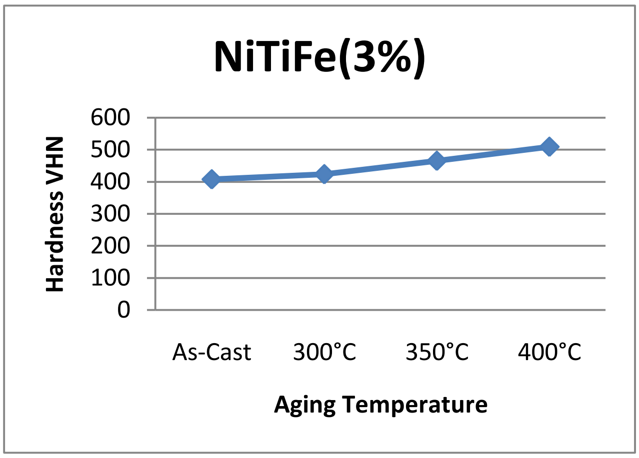

Fig 2 Variation of hardness values for different aging conditions

B. ABRASIVE WEAR

It is clearly observed from the table below that the wear gradually reduces with increase in aging temperature that is as the hardness of a sample goes up; the wear is seen to come down for same load, speed and time.

Specimen	**Load (kg)**	**Speed (rpm)**	**Time (sec)**	**Wear (microns)**
NiTiFe(3%) As-Cast	1	400	600	185
NiTiFe(3%) 300ºC	1	400	600	165
NiTiFe(3%) 350ºC	1	400	600	143
NiTiFe(3%) 400ºC	1	400	600	125

Table – 5 Abrasive wear results for different aging conditions

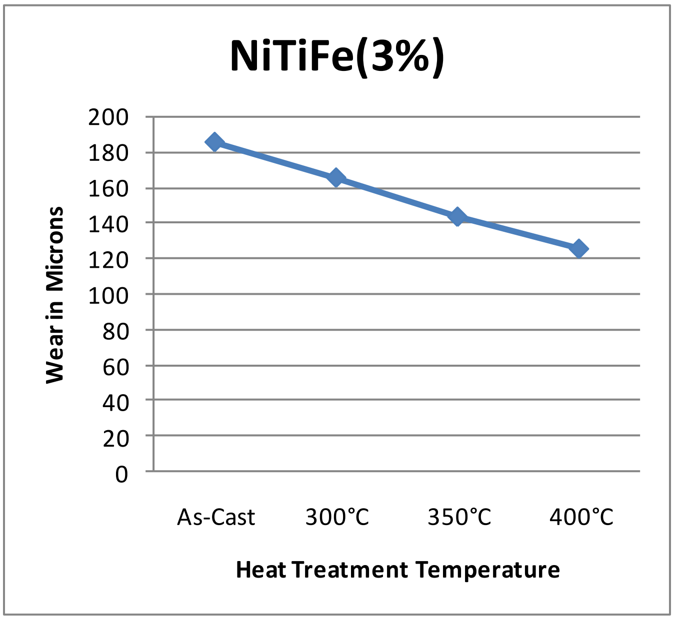

Fig 3 Abrasive wear for 1 kg load for different aging conditions

Basically wear reduces with increase in aging temperature predominantly due to the precipitation hardening that occurs in the samples.

VII MICROSTRUCTURE

In order to distinctly characterize the grain distribution, define the grain boundary and effectively find the inter atomic spacing of the given alloy samples, Micro structural evaluation of NiTi, NiTiFe (3%) as cast, and heat treated NiTiFe (3%) samples are carried out.

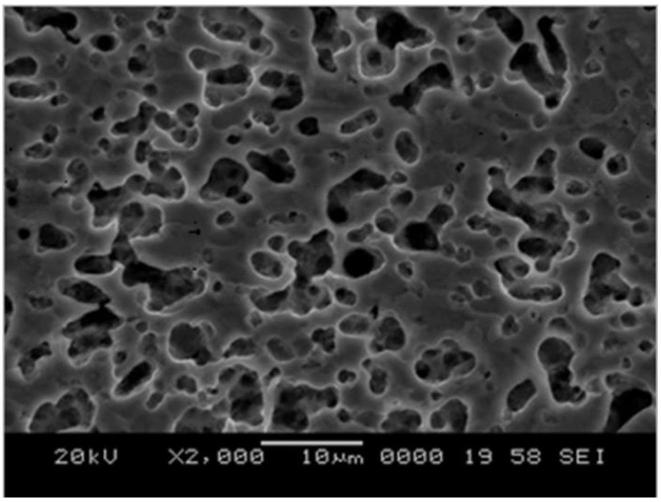

Fig 4 SEM Micrograph of as-cast NiTiFe (3%) sample

From the micrograph shown above it can be clearly seen that the addition of small quantities of Iron in terms of 3 percent, will cause the formation of nodular grain structure. The atomic diameter of Iron is less than the interstices between nickel and titanium atoms and the Iron goes into solid solution of Nickel and titanium. As Iron dissolves in the interstices, it distorts the original crystal lattice of nickel and titanium.

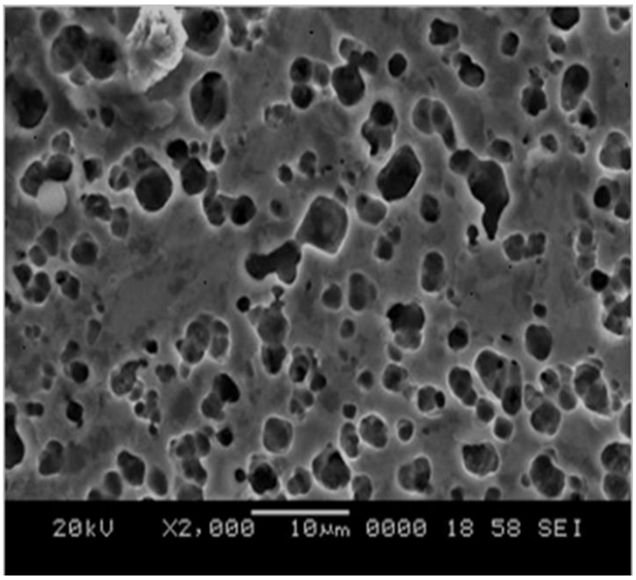

Fig 5 SEM Micrograph of NiTiFe(3%) sample heat treated at 300ºC

At 300ºC, there is distortion of crystal lattice; this distortion of crystal lattice interferes with the addition of Iron to the crystal lattice that is the addition of Iron helps in blocking the dislocation of the crystal lattices. In other words, they avoid the dislocation of the crystal lattices. Obviously adding more and more Iron to NiTi matrix (upto solubility of Iron) results in lesser distortion of the crystal lattices hence increases wear and influences negatively with another important property of NiTi called the hardness. However, solubility of more Iron results in martensitic supression and results in reduction of transformation temperature and increases the superelasticity and shape memory effect.

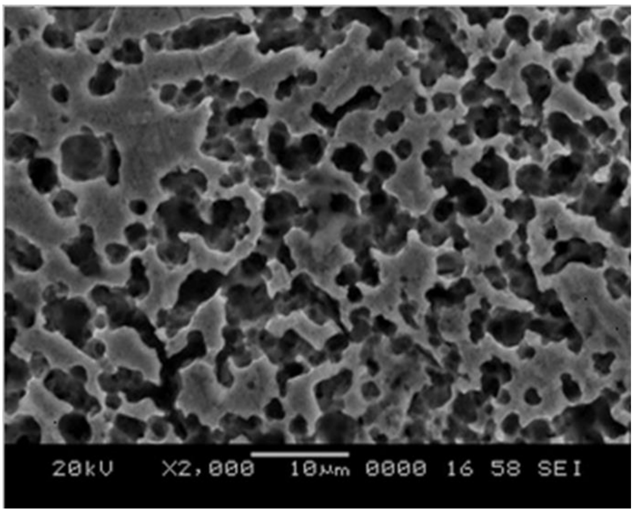

Fig 6 SEM Micrograph of NiTiFe(3%) sample heat treated at 350ºC

From the micrograph as shown in Fig 6, it can be clearly seen that the microstructure of NiTiFe(3%) gives an incipient information about the initial coring that takes place as the aging temperature increases from 300 to 350 degree Celsius, also the coarse grains tend to undergo segregation and result in the formation of dendrites which results in subsequent increase in hardness and reduction in wear of the sample.

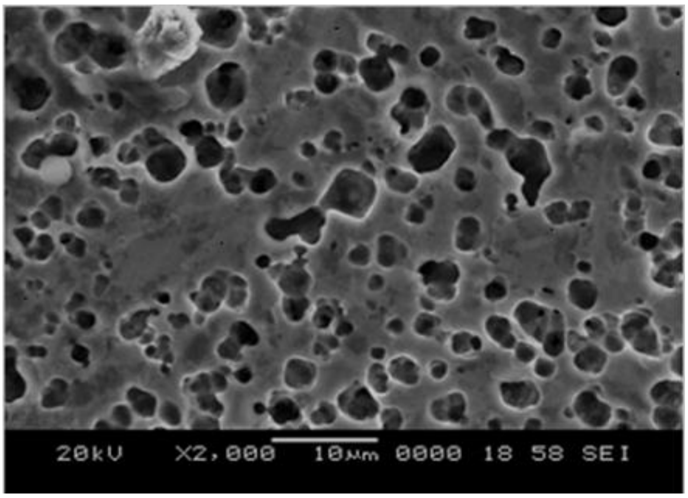

Fig 7 SEM Micrograph of NiTiFe(3%) sample heat treated at 400ºC

The microstructure given above is indicative of the fact that aging causes grain refinement and causes the grains to look like dendrites which eventually results in the formation of tree structure of fine dendrites around the periphery of which one can visualize the deposition of Iron atoms. It can be clearly be seen that the microstructure of NiTiFe(3%) gives a complete knowledge of the grain refinement that tends to take place after the sample is heat treated at 400ºC.

VIII REFERENCES

[1] Lagoudas, D., ed. Shape Memory Alloys. 2008, Springer Science and Business Media, LLC: New York, NY.
[2] Philippe P.Poncet., Application of super elastic nitinol tubing, Memory Corporation, USA.
[3] Elahinia, M. H. and Ahmadian, M., An Enhanced SMA Phenomenological Model. Part I. The Shortcomings of the Existing Models, Journal of Smart Materials and Structures, December 2005, 14 (6): 1297-1308.
[4] Elahinia, M. H. and Ahmadian, M., An Enhanced SMA Phenomenological Model. Part II. The Experimental Study, Journal of Smart Materials and Structures, December 2005, 14(6): 1309-1319.
[5] Graesser, E. J. and Fozzarelli, F. A., A proposed three-dimentional constitutive model for shape memory alloys, Journal of Intelligent Material Systems and Structures, January 1994.
[6] Lombardi, S. and P. Poncet, Metallurgical principles of Nitinol and its use in interventional devices. C2I1, 2004: p. 24-26.
[7] Williams, E., and Elahinia, M., An Automotive SMA Mirror Actuator: Modeling, Design and Experimental Evaluation, Journal of Intelligent Material Systems and Structures, December 2008 19(12):1425-1434.
[8] Williams, E., Shaw, G. and Elahinia, M., Control of an Automotive Shape Memory Alloy Mirror Actuator, Mechatronics, June 2010, 20(2010): 527-534.
[9] Kadkhodaei, M., et al., Modeling of Shape Memory Alloys Based on Microplane Theory. Journal of Intelligent Material Systems and Structures, 2008. 19: p. 541-550.
[10] Brinson, L.C., One-Dimensional Constitutive Behavior of Shape Memory Alloys: Thermomechanical Derivation with Non-Constant Material Functions and Redefined Martensite Internal Variable. Journal of Intelligent Material Systems and Structures, 1993. 4: p. 229-242.
[11] Elahinia M., Hashemi, M., Tabesh, M., and Bhaduri, S., Manufacturing and processing aspects of NiTi implants: a review, Journal of Progress in Materials Science, June 2012, Pages 57(5): 911–946.
[12] Wang, X. M., et al., Finite element analysis of Psuedoelastic behavior of NiTi shape memory alloy with thin-wall tube under extension-torsion loading. J Mater Sci, 2006
[13] Peng, X., Pi, W. and L. Fan, A microstructure-based constitutive model for the pseudoelastic behavior of NiTi SMAs. International journal of plasticity 24 (2008).
[14] Blanc, P. and C. L'Excellent, Micromechanical modeling of a NiTiAl shape memory alloy behavior. Materials Science and Engineering A, 2004. 378: p. 465-469.
[15] Tanaka, K., A Thermomechanical Sketch of Shape Memory Effect: One Dimensional Tensile Behavior. Res Mech., 1986. 18: p. 251-263.
[16] Tanaka, K. and S. Nagaki, A Thermomechanical Description of Materials with Internal Variables in the Process of Phase Transformations. Ing. Arch., 1982. 51(287-299).
[17] Liang, C. and C.A. Rogers, One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Material. Journal of Intelligent Material Systems and Structures, 1990. 2(207-234)
[18] Brinson, L.C. and M.S. Huang, Simplifications and Comparisons of Shape Memory Alloys and Constitutive Models. Journal of Intelligent Material Systems and Structures, 1996. 7: p. 108-114.
[19] Sun, Tsuan Li, Phase transformation in superelastic NiTi polycrystalline micro-tubes under tension and torsion-from localization to homogeneous deformation. International Journal of Solids and Structures, 2002. 39: p. 3797-3809.
[20] Tabesh, M., M. Elahinia, and M. Pourazady. Modeling NiTi Superelastic-Shape Memory Antagonistic Beams: A Finite Element Analysis, In The ASME 2009 Conference on Smart Materials, Adaptive Structures, and Intelligent Systems SMASIS 2009. 2009. Oxnard, California, USA.
[21] Andrew C Keefe and Gregory P Carmon, Thermomechanical characterization of shape memory alloy torque tube actuator. Smart Materials and Structures, 2000.
[22] Shishkin S V, On theoretical interrelations between thermomechanical diagrams in tension, compression, and torsion for alloys possessing the shape memory effect Industrial Laboratory, 1994.
[23] Prahlad, H. and I. Chopra, Modeling and Experimental Characterization of SMA Torsional Actuators. Journal of Intelligent Material Systems and Structures, 2006. 18: p. 29-38.
[24] Mirzaeifar, R., R. DesRoches, and Y. Arash, Exact solutions for pure torsion of shape memory alloy circular bars. Mechanics of Materials, 2010. 42: p. 797-806.
[25] Boyd, J.G. and Lagoudas, D.C. 1998. ''A Thermodynamic Constitutive Model for the Shape Memory Materials Part I. The Monolithic Shape Memory Alloys,'' International Journal of Plasticity, 12(6):805–842.
[26] Lexcellent, C. and Rejzner, J. 2000. ''Modelling of the Strain Rate Effect, Creep and Relaxation of a Ni-Ti Shape Memory Alloy under Tension (Compression)-torsional Proportional Loading in the Pseudo elastic Range,'' Smart Materials and Structures, 9:613–621.