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On the Torsional fatigue of NiTiCu SMA bars. Experimental results and modeling approach

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Abstract: **The use of Shape Memory Alloys (SMA) as an actuator constitutes a major challenge in terms of their application in innovative products. The present work deals with the torsional characteristics and the modeling of NiTiCu SMA bars to ensure their mechanical performance as torsional actuator. The SMA bars was tested under quasi-static torsional loading and torsional fatigue conditions and their behavior was described using a torsional model based on the modification of Liang-Rogers constitutive relation. Further to torsional mechanical tests, a comprehensive experimental investigation on the torsional fatigue behavior of SMA bars, under the application of given external loading moment, with the temperature to vary from 25^{o}C (well below M_f) to 100^{o}C (over A_s) is provided.**

Keywords: **Shape Memory Alloys, Smart actuator, Smart materials, SMA fatigue, SMA driven mechanism.**

I. INTRODUCTION

Memory is the most important characteristic of SMAs. When the Twinned Martensitic phase of a SMA is deformed at a low temperature until Martensite is Detwinned, and then heated above the temperature threshold for the completion of the transformation to Austenite, the material regains its macroscopic shape. This phenomenon is identified on the micro-structure of the material itself. Martensite may be formed with various crystallographic variants that present different shapes. As Martensite is a structure of lower symmetry and the boundaries between twins are of low energy, the crystal structure can be deformed in various shapes. Nevertheless, Austenite has only one crystal structure and that implies that when the material returns to the parent phase there is only one shape it can obtain. The books of Duerig et al. [1], Fremond & Miyazaki [2], Otsuka & Wayman [3], Lagoudas [4] and Lexcellent [5] constitute substantial bibliography sources.

SMAs actuators can produce linear or rotational motion. SMA actuators have been found field of application in Aeronautics [6-9], biomedical application [10-13], robotics [14-16] and in the sector of commodities. The major reasons for the consideration of SMAs in these fields are mainly the high power to weight and stroke length, the clean, debris-less, the spark-free and silent operation and their capability of operating in zero gravity environment [17, 18].

There are only a limited number of studies addressing the torsional, mechanical, and thermal behavior of SMAs [19-22]. More recently torque tubes of varying geometry including outer diameter, wall thickness, and length were subjected to constant-torque thermal cycling at stresses ranging from 0 to 500 MPa (0–175 Nm), by O Benafan and D J Gaydosh [23] in order to investigate the torsional behavior of high-temperature SMA tubes. This is the first attempt to study the torsional behavior of NiTi or NiTiCu alloys at temperatures over 100^{o}C [23]. In 2017 Han Yuan et al. [24], provided a first review article on rotary actuators triggered by Shape Memory alloys, highlighting the specificities and potentialities of such actuators for new applications in the future.

The most well-known approach for modelling SMAs behavior are the Macroscopic Constitutive Models that are based on Free Energy Potentials. Among them the model which is based on Helmholtz Energy is the model of Tanaka [25], where the rate of stress is a function of the strain, temperature and Martensitic Volume Fraction (MVF), while the assumed kinetics equation correlates the MVF with stress and temperature in an exponential fashion. On the basis of the Tanaka model, Liang and Rogers [26-27] also postulated their constitutive equations based on the Helmholtz free energy, but a cosine function was used to describe the relation between the temperature and evolution of MVF.

Davinson et.al used the Liang and Rogers constitutive model to predict the torsional actuation of SMA rods [28]. Furthermore, Keefe and Carman [29] created an exponential model for the relationship between shear stresses and strains in the SMA alloy by fitting experimental torsional data. Prahlad and Chopra [30], used the Tanaka's model [25] as the representative uniaxial model and extended it to torsional loading. Lagoudas and coworkers formulated the SMA models in a three-dimensional framework [31-32] in order to provide a complete thermodynamic-mechanical framework of understanding the SMA behavior. J. Rejzner et al. studied the moment–curvature hysteresis loops under pure bending of different SMA samples. They compare the experimental results with the theoretical loops using linear strain-hardening and ideal pseudoelasticity models [33].

Knowledge of the fatigue life of SMAs is critical, especially when the use of SMA materials entails the role of actuators. During actuation operations, the material is subjected to cyclic thermo-mechanical loads. Cyclic loading can be associated to structural and functional fatigue that both affect the operational life of the SMA material. Functional fatigue refers to repeated actuation with the maximum recoverable strain being of order of 3-5% (in most common polycrystalline SMAs), which results in gradual accumulation of transformation-induced plasticity and low cycle fatigue [34]. Bigeon and Morin [35] reported on the thermal/mechanical fatigue of CuZnAl and TiNiCu SMA wires loaded under slow and high frequency. Based on the results of their experiments they concluded that CuZnAl fails immediately when applied stress exceeds 200 MPa. Their tests also showed that in the case of TiNiCu wires no failure occurred after 11 kcycles when the applied stress was around 50 MPa. For the case of TiNiAl the transformation strain was 2%. Hornbogen [36] related training process of SMA with fatigue because the microstructure of the Martensitic domain is affected when the material is under training. Therefore, an optimum strain exists along with a certain number of cycles. If this optimum combination of strain and number of cycles is surpassed, fatigue is assumed to be initiated. Eggeler et al. [37] have considered structural and functional fatigue of NiTi SMAs in four different cases. One of these cases is the use of SMA spring actuators where the generic features of their functional fatigue are studied. Furthermore, Bertacchini et al. [38] conducted an experimental investigation to account for the thermal/mechanical transformation fatigue of TiNiCu SMA actuators under a corrosive environment. The wire specimens were tested under constant mechanical loading and they were thermally activated under temperature variations. Due to the temperature variations the wires were actuated repeatedly, which consequently lead to accumulation of transformation induced plasticity and reduced fatigue limit of the material to a low-cycle fatigue regime. Fatigue testing and extraction of a life fatigue limit can be a challenging task due to lack of standards and protocols about fatigue experiments for SMAs. In addition, there is a great uncertainty in the reported experimental data due to the large number of parameters influencing the material's response such as environment of testing, gripping mechanism, applied loading path, frequency of actuation etc. Lagoudas et al. [39] have published a consolidated table that summarizes the fatigue life results for some of the NiTi alloys based on different studies.

In the present study the torsional behavior of the SMA bar is investigated. The proposed scheme employs the Liang-Rogers model to describe the thermo-mechanical behavior of the SMA, by exploiting experimental results obtained from torsional and tensile loading. Furthermore, the present work investigates the fatigue behavior of NiTiCu SMA bars under torsional fatigue.

II. BODY OF ARTICLE

1. Materials and Methods

In the present study shape memory alloy bars NiTiCu (Ni48%, Ti46%, Cu6%) were used. This NiTiCu alloy is a commercial product provided by @mt-medical technologies (NTC01). The same alloy in the form of bar or wire was used to carry out all the mechanical experiments. For the tensile tests, the wire received had a diameter of 0,8 mm. For the torsional experiments, the received material was in the form of cylindrical bars, having length of 400mm and diameter of 6mm.

The SMA bars were cut to test samples having a length of 60±1mm using an electrical discharge machine. This length is the nominal length of the samples to be installed into the gripping system of the torsion machine. In all cases the torsional gage length was 50mm. The test samples were annealed at 550°C for 25min and then trained for meeting the requested operational envelope for the biomedical device (45° rotational angle). The measuring accuracy of the torsion device was 0.1° (degree) for angular deformations and 10^{-2} Nm for the applying torque.

Cyclic loading is one of the generic characteristic features for many applications of NiTiCu shape memory alloys, no matter whether they exploit mechanical (pseudo-elasticity) or thermal shape memory (one and two-way effect). Cyclic loading may well be associated with structural and functional fatigue, which both limit the service life of shape memory components. By "structural fatigue" we mean the microstructural damage that accumulates during cyclic loading and eventually leads to fatigue failure. There is a need to understand how microstructures can be optimized to provide good fatigue resistance. The term "functional fatigue" indicates that shape memory effects like the working displacement in a one-way effect (1WE) actuator or the dissipated energy in a loading–unloading cycle of a pseudo-elastic (PE) damping application decrease with increasing cycle numbers. This is also due to a gradual change in microstructure. In both cases it is important to know how fatigue cycling affects shape memory properties [37].

Initially tensile and thermal loading cycles were used to validate the agreement of the SMA behavior to the results of the analytical Liang-Rogers model [3] and to calibrate the model parameters.

Then, the next set of experiments that investigate the variation of angle recovery of NiTiCu alloy bars versus the numbers of the applied thermal loading cycles for different torque load, were implemented in two steps. During the first step and at temperature range in-between 25-30°C (that is below M_f) the specimen is loaded in torsion clockwise by applying different torsional torque values each time in the range of 1Nm to 5Nm and we measure the (functional) torsional angle of the martensitic phase cylindrical samples. During the second step, the applied toque was removed, and the temperature was increased up to 100°C (slightly over A_f), the recovery angular of the sample was measured again. Five specimens were tested. For each specimen, we repeat this testing process 5 times and we plot the torsional torque-deformation angle diagram. as well as the angle recovery vs number of loading cycles.

The first set of fatigue experiments aims to investigate the effect of torsional fatigue loading on the angular deformation of the SMA bars. For this reason, at temperature range in-between 25-30°C (that is below M_f) the specimen is loaded in torsion clockwise by applying a torsional torque of 5Nm and we measure the (functional) torsional angle of the martensitic phase cylindrical samples. After that, the applied toque was removed, the temperature was increased up to 100°C (slightly over A_f), and the recovery angular of the sample was measured again. This loading process was repeated 100 times.

The second set of fatigue experiment aims to investigate the functional fatigue of NiTiCu alloy bars. The structural fatigue is considered negligible due to the low number of applied cycles. In this case a torsion torque of 5 Nm was applied at the martensitic phase (temperature below M_f) and then the temperature increased (slightly over A_f), without removing the applied torque. The recovery angle due to the phase transformation was measured. This set of experiments was repeated for 1000 cycles. In that way, we measure the specimen's torsional torque vs the numbers of applied loading cycles, using the transformation cycle from the martensitic phase to the austenitic phase and backwards.

The choice of applied torque at 5Nm was driven by the need of using the NiTiCu alloy bars as actuator in the case of a patented intramedullary limb lengthening device [40].

2. Analytical modeling

The analytical modeling used in this work is based on the thermo-mechanical model of Liang-Rogers [26].

The thermo-mechanical constitutive equation for SMAs is:

$$\sigma = \sigma(\varepsilon, \xi, T) \qquad (1)$$

where σ is the stress, ε is the strain, T is the temperature and ξ is the martensite volume fraction. The Liang-Rogers constitutive equation is given by:

$$\dot{\sigma} = \frac{\partial \sigma}{\partial \varepsilon}\dot{\varepsilon} + \frac{\partial \sigma}{\partial T}\dot{T} + \frac{\partial \sigma}{\partial \xi}\dot{\xi} = D\dot{\varepsilon} + \Theta\dot{T} + \Omega\dot{\xi} \qquad (2)$$

where D is the Young's modulus, Θ is the thermoelastic tensor, and Ω is the transformation tensor, a metallurgical quantity [26].

The above equation is an offspring of the constitutive thermodynamic norms.

Integration over time provides a time independent equation, which has the form:

$$\sigma - \sigma_o = D(\varepsilon - \varepsilon_o) + \Theta(T - T_o) + \Omega(\xi - \xi_o) \quad (3)$$

where the index 'o' represents the initial conditions.

Assuming a cosine form for the relation between martensite fraction and temperature during phase transformation and using the relation given in equation (3) [26], we may study the stress-strain behavior of SMA materials quantitatively. The martensite fraction during the phase transformation considered to have the following form:

$$\xi_{A\to M} = \frac{1}{2}\{cos[a_M(T - M_f)] + 1\} \qquad \xi_{M\to A} = \frac{1}{2}\{cos\{[a_A(T - A_S)]1\} \qquad (4)$$

where α_A and α_M are material constants

$$a_A = \frac{\pi}{A_f - A_s} \qquad a_M = \frac{\pi}{M_s - M_f} \qquad (5)$$

and A_s, A_f, M_s, M_f, are the transformation temperatures.

In the present work we use the above described Liang-Rogers equation in order to plot the stress-strain curve during the first transformation cycle for the material under consideration in our experiments, in order to compare the experimental results against the theoretical ones resulted by the application of Liang-Rogers model.

However, it is well known that the Liang-Rogers model covers the case of 1-D tension loading of the SMA material. In the present case, the same model was applied in the case of 1-D pure shear loading by changing all the involving parameters to the ones that correspond to torsional loading. Then equation 3 takes the form:

$$\tau - \tau_0 = G(\gamma - \gamma_o) + \Theta(T - T_o) + \Omega(\xi - \xi_o) \; (6)$$

where: τ is the shear stress, γ is the shear strain, G is the shear modulus, while Θ and Ω considered to keep the same definition and values as in equation 3.

Equation 6 describes the constitutive equation for SMA specimens under pure shear loading.

Considering for the given NiTiCu alloy the critical temperatures to be M_s=45°C, M_f=30°C, A_s=50°C and A_f=70°C, the present study will compare the experimental findings against the theoretical results concluded by the application of equation 6. Thus, plots of the martensite fraction vs temperature coming either by experiments or by the modified Liang-Rogers model for pure shear will be compared, in order among others to check the validity of equation 6 for torsional loading.

III. RESULTS

3.1 Linear deformation – tensile loading

Shape Memory alloys may be used in several geometric forms and utilized in various cases for active control applications. The most common form of SMAs is the form of wires for linear force generators. In the case of SMA force actuators the SMA wire first is elongated at a low temperature (below M_s) at a certain strain and then unloaded to generate some martensitic residual strain; upon heating of the wire, the martensitic residual strain will be restored. During the restoration of the initial length, traction force can be applied.

In the present work, the NiTiCu alloy wire like specimens are pre-strained at 3%, 5%, 7%, at room temperature. Then, the applied load was removed, and the specimens were heated over 100°C. The wire samples return to their initial shape and the residual strain was measured. This is the typical behavior of SMA alloys during their first operation cycle, just after the training/processing of the samples, where a small amount of residual strain is identified upon heating over A_f. However, this amount of residual strain will be negligible after some activation/operation cycles.

Figure 1 shows the loading phase of NiTiCu SMA wires at the different strain levels and the shape recovery after heating over A_f. This represent the first operation cycle of trained NiTiCu alloy wires. The remaining strain after heating is indicated at the lower left edge of the plot. These values are compared against the ones provided by the Liang-Rogers model that are shown at the plots bellow experimental diagrams and are in very good agreement with the experimental findings.

More precisely, the experimental data provides residual strain of the level of 0.27753%, 0.46195% and 0.63744% for initial pre-strain of 3%, 5%, 7% respectively, whereas the Liang-Rogers model predict remaining strain of 0.25005%, 0.45015% and 0.62560, for the same pre-strain values.

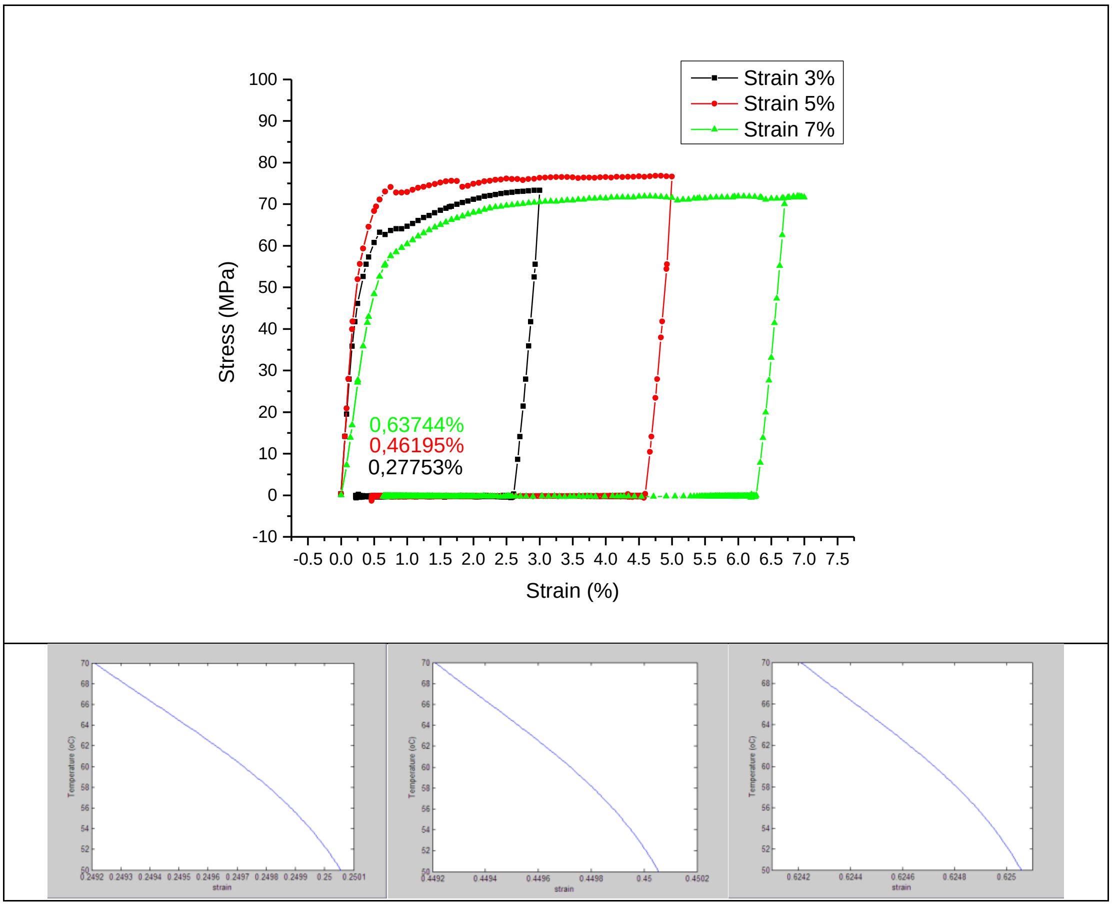


Fig. 1: The first thermomechanical cycle after processing/training of the NiTiCu alloy used both for the experimental and the theoretical analysis.

The difference between the experimental and the theoretical values of the remaining strain after heating over A_f is close to 3% in all the cases, and this is a first strong indication for the correct choice of the material constants α_A and α_M.

3.2. Torsional deformation

The main purpose of the present study is to investigate the behavior of NiTiCu alloy cylindrical bars subjected to torsion. The test samples used for the torsional tests had a length of 60±1 mm (50 mm gage length) and a diameter of 6 mm. 5 samples were used at this step of work.

Initially monotonic quasi-static introduction of the torsional load applied on the cylindrical SMA bars and the results are presented in Figure 2, in the form of Torsion torque versus angular deformation in degrees. Furthermore, Figure 2 presents the modeled behavior of torsion using the modified form of Liang- Rogers constitutive equation (6). For gaining this curve the mean values of the developed shear stress and the mean value of the resulted shear strain have been used. Also, all the material parameters have been taken from the 1-D tension tests.

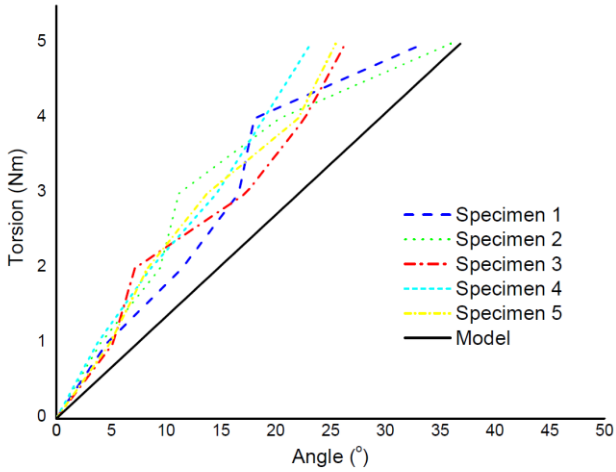


Fig. 2: Comparison of the experimental results of torque vs rotation angle for the five tested specimens against the modified form of Liang-Rogers constitutive relation (6).

The difference between the torsion torque-deformation angle behavior of the tested samples as well as the difference between the theoretical and the experimental results showed on Figure 2 can be easily explained.

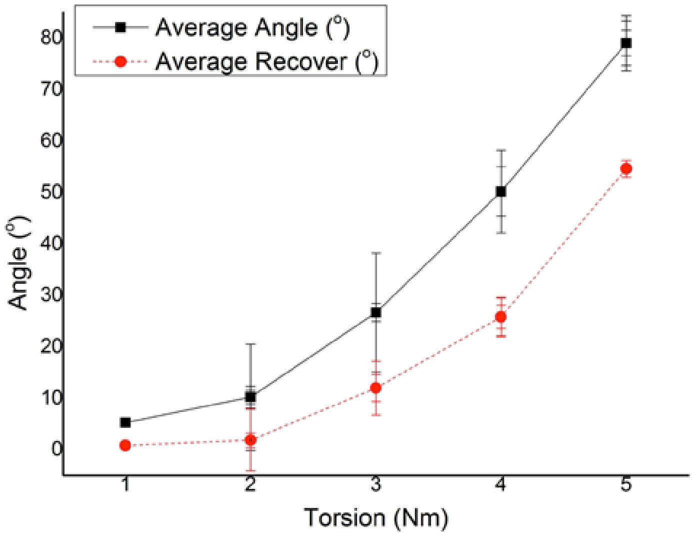
- No specimen thermal pretreatment was applied prior of torsional loading. In case a thermal pretreatment would be applied at a temperature level slightly over A_f for a certain period, the SMA material expected to have slightly different behavior and the variation between the subsequent loading cycles of the different samples expected to almost disappear. This is because SMA's seems to "null" their past shape memory, since the specimens orientate along a different habit plane (Otsuka [3]).

- Modified Liang-Rogers equation (6) stands for 1-D homogenous shear loading of the SMA material, which is not the case of the used SMA bars, where the shear deformation variates along the radius. To have a homogeneous shear loading of the SMA material under torsion thin SMA tubes must be used.

- The theoretical results were concluded by using the material characteristics given by the manufacturer of the SMA bars and verified under 1-D tensile loading conditions.

The next set of experiments that is was followed is described analytically in the next.

For each sample, at the first step of the experiment an 1Nm torsional torque in the clockwise direction was applied. After the application of the torque we measure the deformation/rotation angle. Then, the torsional torque is removed, and the specimen is heated slowly over the temperature of 100°C (>A_s), measuring the recovery angle. After that initial step, we cool the specimen at room temperature (<M_s) and then we repeat the same loading process by applying subsequently a torsional torque of 2Nm, 3Nm, 4Nm, and 5Nm and after the application of the torsional torque we repeat the procedure described above (measurement of the angular deformation, removal of the torsional torque, heating up the specimen, measurement of the recovery angle and cooling down the specimen at ambient temperature). Each loading step is applied for 5 times and 2 specimens were tested in total. All specimen was not subjected to any type of treatment prior or during loading cycles.



Figures 3: Angle-torque diagrams for 4 of the specimens used

Figure 3 summarizes the deformation angle versus torsional torque diagram concluded by the testing procedure described in the previous paragraph. The solid line shows the angle vs torque due to martensitic transformation and the dash line shows the recovery angle after heating over As. It is obvious that the deviation between the initial angular deformation and the recovery angle increases, increasing the applied load. In parallel, it is evident that there is a decrease in standard deviation of the measurements increasing the applied torsional load (and the loading/unloading cycles) of the SMA material. This is due to the 'training' of the material by the applied load.

3.3. Fatigue Experiments

The fatigue experiments were executed at the same torsion machine. Two type of fatigue tests were conducted. During the first type of fatigue tests, the test sample was places into the grips of the torsion machine and a torsional torque of 5Nm was applied on the sample. The angular deformation was measured. Then the sample was released from the loading grip and the applied torsion was removed, then the sample was heated up to100^{o}C (>A_s), it returned to its initial phase and then it was cooled down to ambient temperature. This loading cycle was repeated for 100 times and the results of the deformation angle versus the number of loading cycles are given in Figure 4. It is obvious that initially the deformation angle decreases increasing the fatigue cycles. However, after a certain number of fatigue cycles (65 cycles) the deformation angle stabilized and remained almost constant until the end of the experiment.

During the second type of Fatigue test, the specimen was placed into the grips of the torsion machine, at a room temperature. After that we apply a 5Nm torsional torque to the specimen. Due to the applied torsional load, a deformation angle is resulted and monitored.

Then, we heat the specimen homogeneously via a locally applied radiation furnace, and the SMA pulled back the applied load. We measure recovery angle. Thus, we have the pure angle difference due to the SMA transformation under torsional load, and this is a first experimental calculation of the SMA's pull capacity to torsion. At the next step, we remove the applied torque and leave the system to cool naturally. After proper cooling, we apply again the torque of 5 Nm and repeat the process as described above. 5 samples passed through the torsional fatigue process.

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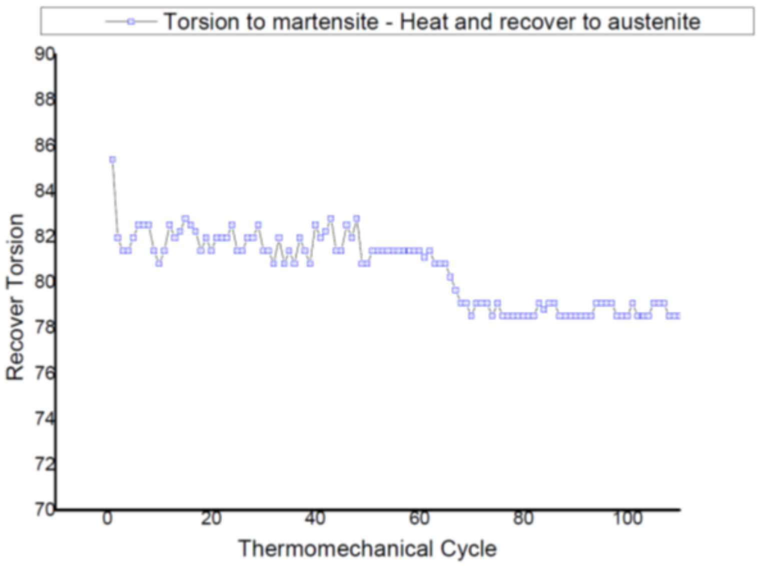

Fig. 4: Fatigue Experiment on SMA bars. Deformation angle versus number of torsion cycles for an applied torsional torque for 5Nm.

Figure 5 shows the recover torsion angle versus the applied loading cycles. There is a significant reduction of the recovery angle as a function of fatigue cycles close to 25%, due to imposed plastic deformation that results by the permanent changes of internal discontinuities of the crystal structure of the SMA alloy due to fatigue.

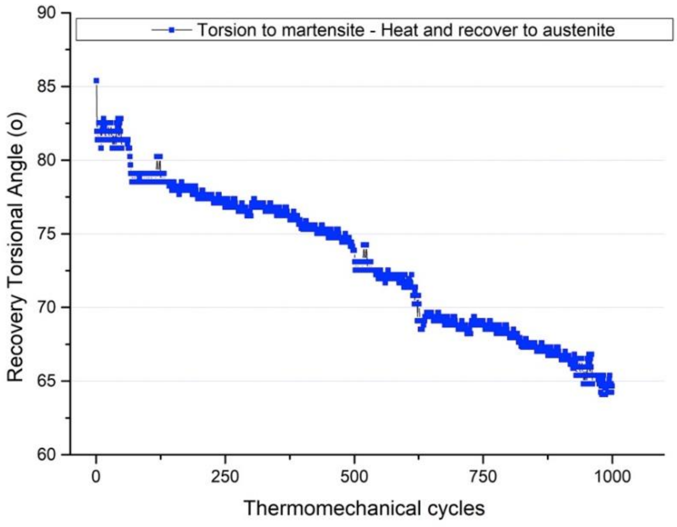

Fig. 5: Fatigue Experiment for SMA bars to recovery torsion angle for 1000 cycle

After finishing the loading fatigue process, we remove the sample from the machine and examine its outer surface using Scanning Electron Microscopy SEM analysis (EDS-WDS & default Standards), in order to investigate possible defects and the surface roughness after torsional deformations.

Figure 6 presents the typical SMA outer surface before and after fatigue.

As it is shown in Figure 6 the SMA specimens shows the internal stresses generated as a result of the mechanical-thermal cycling during torsional loading in shape memory alloy bars. The direction of the surface traces corresponds to the shear loading of the bar. The formation of the traces can be attributed to surface oxidation during mechanical/thermal torsional cycling in the direction of maximum shear stresses applied on the specimen.

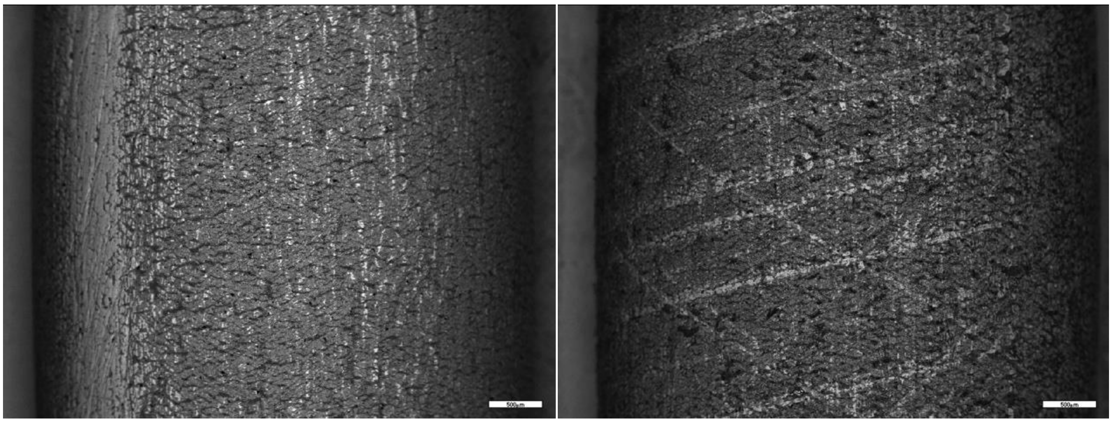

Fig. 6: SEM photos of the SMA sample before and after the torsional experiments

IV. CONCLUSION

The investigation of the torsional characteristics of NiTiCu SMAs bars is carried out at the present article to gain fundamental understanding for the behavior of SMA as torsional actuators.

Based on the results of the above-mentioned experiments, we can assume that the SMAs behavior to torsion can easily be “trained” even if this is torsion, and this behavior can be predicted using a modified form of Liang-Rogers constitutive equation. The difference between the theoretical and the experimental results can be addressed to several parameters that were discussed analytically. Regarding the fatigue experiments it can be seen is that there is a decrease of the pulling capacity (angle) vs number of loading cycles because of the permanent internal discontinuities of the crystal in the structure of SMA. This decrease of the pulling capacity in torsion (recovery of angular deformation) seems to be close to 25% when 1000 fatigue cycles are applied under a torsional load of 5Nm. This effect must be taken into consideration whenever an actuation mechanism is designed based on SMA materials.

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