Thermomechanical characterisation of NiTiFe for pipe application

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ABSTRACT

In this work, we characterized the functional properties of a NiTiFe alloy pre-selected for application in pipe couplings being currently developed within a ESA ARTES 5.1 project. We realized a set of dedicated experiments in order to map phase transformations in the stress-temperature space. Further experiments were carried out in order to evaluate the performance of the shape memory effect and recovery stresses being the key features of SMAs for couplings. The recovery stresses were evaluated for constant external bias stresses as well as for linearly increasing bias stresses thus mimicking the elastic resistance of the pipe to be coupled. Finally, we characterized the effect of the bias stress, acting during constrained heating, on unrecovered strains critically affecting the built-up of the contact pressure during the assembling operation.

***Index Terms*—Shape Memory Alloy; Material Characterisation; Plasticity; Application SMA;**

INTRODUCTION

Fluid fitting couplings from early 1970s was the first industrial application of shape memory alloy (SMAs). This application takes advantage of the incredible ability of SMA coupling rings to be plastically-like deformed in martensite thus enabling the placement of tubes into the ring, and then to recover the initial shape while subjected to large stress constrains arising the interference of pipes with the SMA ring. Proper design of SMA couplings can be achieved by computational optimization using e.g. the finite element method (FEM). Such optimization requires a reliable model that can capture the key features of the functional behavior of SMAs. The model under consideration [Sedlak2012] is able to capture the key features of the thermomechanical behavior provided that its parameters are properly identified using an appropriate set of experiments. In this work, we selected and realized several thermomechanical experiments in the attempt to properly inform the model about the material behavior critical for the considered application. On the other hand, the functional fatigue itself was not required to be characterized for this application unlike for superelastic applications.

Experiments

The selected $Ni_{47.9}Ti_{49.1}Fe_3$ was machined into round dog bone samples having the gauge length of 15 mm and diameter 3.5 mm. The thermomechanical tests were done within temperature range -180°C to 50°C on 10 kN Instron Electropuls with extensometer Epsilon clipped on the samples using temperature rate 3°C/min. and strain rate 0.05 %/s. The transformation temperatures in stress free conditions were measured using DSC and resistometry within a temperature range from -180°C to 20°C. From the DSC, the transitions between Austenite and R-phase at -50°C were clearly identified unlike the transition to martensite. From the resistometry, the onset of the transition from the R-phase to martensite is noticeable at -180°C, however, the Mf lies below the lower limit of LN2 measurements and, therefore, the Mf lying approximately at -190°C was found by extrapolating thermomechanical tests. The thermal cycles at constant stresses and isothermal tensile tests (e.g. Fig.2) then allowed for construction of a non-equlibrium stress-temperature diagram [Sittner2000] shown in Fig.1.

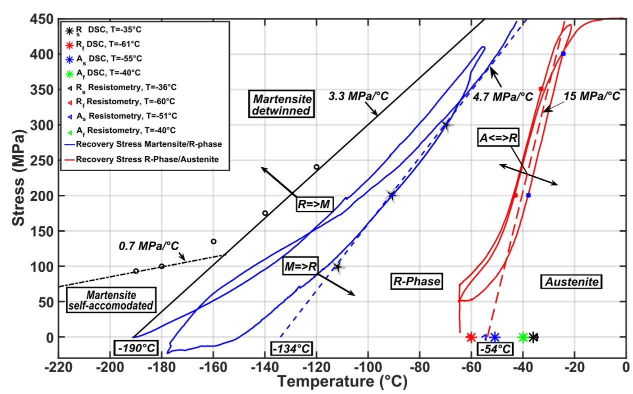

Figure 1: *Non-equilibrium Stress-Temperature diagram identified for tested* $Ni_{47.9}Ti_{49.1}Fe_3$

The assembling operation consists of cooling the SMA material into martensite, using its plastic-like behavior to expand the ring for placement of pipes dimensioned with an interference fit, and heating up to make SMA rings retransform into initial austenite shape while building-up the contact pressure due to the interfering pipes. At a first approximation this operation can be physically simulated on tensile samples by a corresponding thermomechanical sequence (see Fig.2, Cooling, Stretch see blue curve Fig.4) where the heating step is approximated by heating against constant stresses. Three tests with stresses of 100 MPa, 200 MPa, and 300 MPa were realized on virgin samples as seen in Fig.2. These tests bring important information about the temperatures of return into austenite but also about the unrecovered strains, which would decrease the contact pressure affecting the safety of the connection. Inset figure in Fig.2 shows that the unrecovered strain exponentially increases with the stress.

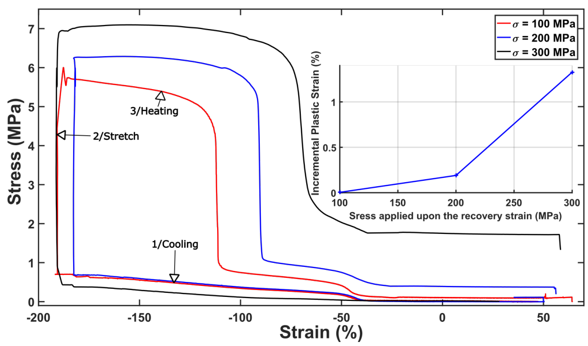

Figure 2: *Evolution of strains during shape memory tests using different stress constrains, which results in different unrecovered strains, measured well above Af, plotted in the inset figure.*

In a better approximation, the shape return in heating step is accompanied with a linearly increasing stress thus mimicking the elastic resistance of the pipes. Such an experiment was done using a closed-loop control simulating the spring with a stiffness of 50 MPa/°C. The sample responded to such conditions as seen in Fig.3, where also a second cycle of cooling and heating is shown. The second cycle allows to evaluate the critical temperature upon cooling at which the connection pressure sharply drops due to initiation of the forward transformation.

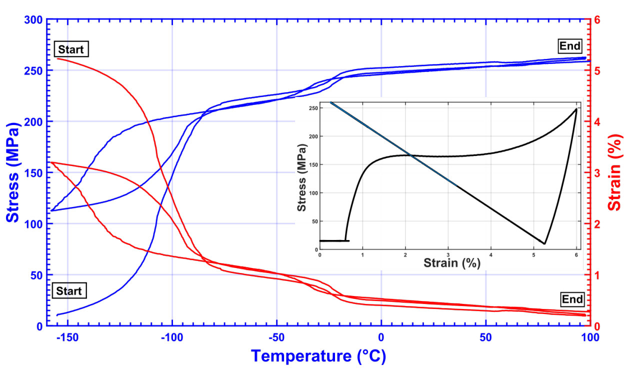

Figure 3: *Evolution of stresses and strains during thermal cycling of the sample biased by a virtual spring changing the applied stress 50 MPa/°C. Inset figure shows evolution of bias stress in the stress-strain space of tested material.*

The recovery stresses arising from the reverse transformation under constraints are responsible for contact pressure build-up. The increase in recovery stresses per temperature increment is the key parameter of SMAs as it should in principle correspond to the slope of lines for reverse transformations in stress-strain diagram (Fig.1). Recovery stresses were measured for both the transformations occurring in the tested material. The blue curve in Fig.1 shows the increase and decrease in recovery stresses from the transformation between martensite and R-phase due to constrained 6% of deformation induced at -185°C. Similarly, the red curve in Fig.1 corresponds to recovery stresses from the austenite to R-phase transformation constrained by 0.7% induced at -70°C. Here, the constrained strain was sufficiently low to allow for a complete conversion between transformation and elastic deformations as indicated by stabilization of the stress above -20°C. The mean slope is in good agreement with the corresponding transformation lines (the dot lines in Fig.1).

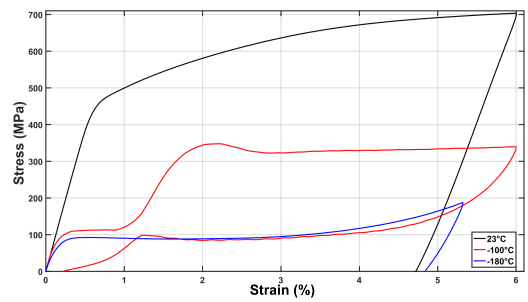

Figure 4: *Isothermal tensile responses at temperatures above Af, within the R-phase region, and near Mf temperature.*

CONCLUSION

The thermomechanical behavior of $Ni_{47.9}Ti_{49.1}Fe_3$ SMA material was investigated and characterized with regard to its application in pipe couplings. The non-equilibrium stress-temperature diagram was constructed based on a set of dedicated experiments. The diagram reveals pronounced intermediate R-phase that appears upon cooling from austenite as well as upon heating from martensite.
The material shows Mf well below LN2 temperature, which extend enormously the temperature window for safe operation. On the other hand, the material has low resistance against slip, which must be taken into account when optimizing the interference fit as it will increase the unrecovered strain and decrease the contact pressure.
The safe temperature window for operation was identified by measuring the recovery stresses under constrains simulating elastic resistance of pipes to be coupled. The exponential evolution of unrecovered strains with applied stress during constrained heating was measured and should be taken in consideration in design as it directly affects the contact pressure.

References

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