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EXPERIMENTAL INVESTIGATION OF SHAPE MEMORY ALLOYS: INFLUENCE OF LOADING RATES

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Abstract. Shape Memory Alloys (SMAs) have being used in several applications in areas such as aeronautics, medicine and robotics. Due to that, numerous research efforts are developed trying to obtain a proper understanding of all phenomena involved. Martensitic phase transformation are non-diffusive and, therefore, rate-independent. Nevertheless, SMA response is rate-dependent due to thermomechanical couplings. In this regard, heat transfer process has a significant influence on SMA behavior. Since direct transformation is exothermic and reverse transformation is endothermic, loading rate and convective process establish a competition to define the SMA response. Therefore, for high loading rates, there is less time for convective process. This paper presents an experimental investigation on the influence of the loading rate on the SMA behavior. SMA wires are employed and three different rate conditions are treated: slow, medium and high.

Keywords: *Smart materials, shape memory alloys, experimental.*

1. INTRODUCTION

Shape memory alloys (SMAs) have been studied since the 1930's, but only in 1962, the U.S. Naval Laboratory Ordenance discovered the shape memory effect in NiTi alloy, which was named Nitinol as a tribute to the laboratory. From there, several industrial applications were established in areas such as aeronautics (Lagoudas and Hartl, 2007; Carpenter *et al*., 2001; Kudva, 1999), medicine (Machado and Savi, 2003; Machado and Savi, 2002; Mantovani, 2000; Ryhänen, 1999) .and robotics (Lagoudas, 2008). Several research efforts have been conducted since then, trying to explain all details of the thermomechanical behavior of SMAs (Echchorf *et al*., 2010; Sittener and Sedlak, 2010; Savi *et al*.,2009).

The thermomechanical behavior of SMAs shows a wide variety of responses as pseudoelasticity and shape memory effect (Lagoudas, 2008). Martensitic phase transformations are non-diffusive and therefore, rate-independent. Nevertheless, SMA response is rate-dependent due to thermomechanical couplings. In this regard, heat transfer process has a significant influence on SMA behavior. Mukherjee *et al*. (1985) were probably the first reference to this rate-dependent behavior. Shaw and Kyriakides (1995) conducted experimental tests on SMA wires subjected to different loading rates at different temperatures and environments.

Lin *et al*. (1996) studied the influence of strain rates on SMA wires, observing the increase in the strain rate causes a tendency to temperature increase. Tobushi *et al*. (1999) studied the influence of strain rate on superelastic behavior in stress-strain tests. In these experiments it was observed that the strain rate affects the mechanical properties of SMAs. However, the stress increase cannot be attributed solely to the increase of the strain rate, but also the dynamic effects related to internal friction in the material microstructure.

This paper presents experimental tests performed on SMA wires considering different loading rates, evaluating their effect on the thermomechanical response of the specimen. Basically, three distinct loading rates are treated: slow, medium and high. Material characterization includes DSC tests and pseudoelastic tensile tests. Different training processes are of concern, investigating the stabilization of hysteresis loops under cyclic loadings.

2. SMA CHARACTERIZATION

This section shows the experimental tests used to characterize a shape memory alloy and also to evaluate the influence of thermomechanical couplings. SMA characterization considers differential scanning calorimeter (DSC) tests and tensile tests. Tensile tests consider different loads and temperatures. The influence of loading rates is investigated considering three different rates classified as slow, medium and high.

2.1 Transformation temperatures

The SMA characterization starts from a survey of the phase transformation temperatures. Austenite-martensite transformation and reverse transformation are respectively associated with the release or absorption of latent heat. This latent heat corresponds to a specific transformation temperature that is measured by using the DSC.

Figure 1 shows a typical calorimeter measurement. Basically, it shows the energy required to maintain the constant rate of increase and decrease of temperature of the sample. The upper curve represents temperature increase and therefore, transformation from martensite to austenite. This curves defines temperature A_s and A_f, respectively, start and finish austenite formation temperatures. On the other hand, the lower curve shows the austenite-martensite transformation, defining the temperatures M_s and M_f. The analysis of these curves defines: A_s = 16.7°C, A_f= 30.2°C, M_s = 24.8°C, M_f = 9.1°C.

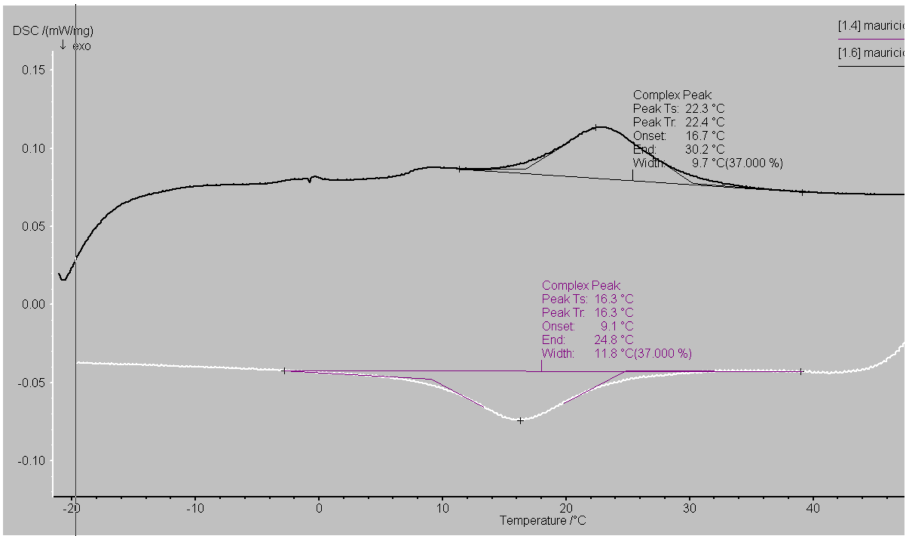

Figure 1. Transformation temperatures.

2.2 Critical Stress

The next step of SMA characterization is related to tensile tests. MTS hydraulic test frames with 30kN load cell are employed, Figure 2. NiTi wires of 1.7 mm (0.066 in) and alloy composition of 50.5 at % Ni are employed. Initially, yield surface position is evaluated considering tensile tests performed till the wire breaks. Tests are carried out in different temperatures: room temperature, 22°C; and 80°C. Figure 3 presents stress-strain curves where it is possible to identify phase transformation, the yield surface position related to plastification, and the specimen break. Note the difference between the two curves, related to different temperatures: 22°C (blue curve) and 80°C (red curve). This analysis defines the yield surface position and therefore, all tests are performed for loads less than 2.5 kN, which corresponds to a 9.7% strain and a stress of 1010 MPa, at 80°C.

Figure 2. MTS hydraulic test frames.

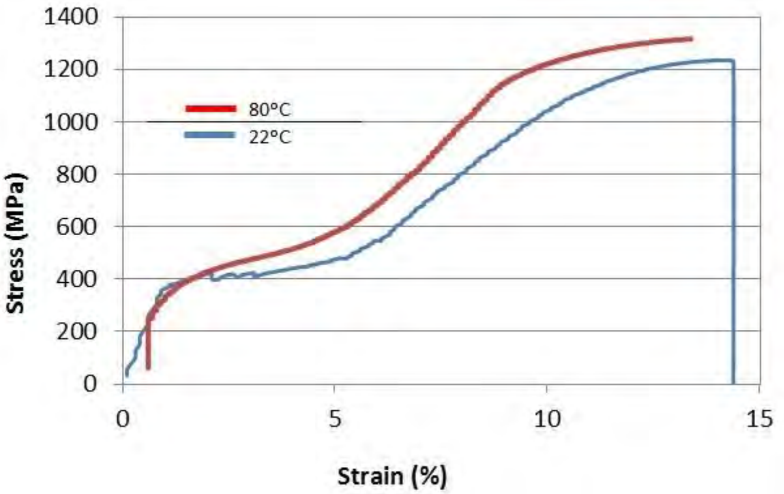

Figure 3. Stress-strain curve in two temperatures.

2.3 Training Process

Transformation induced plasticity (TRIP) is a strain mechanism related to internal stresses resulting from the volume change associated with the phase transformation as well as change of shape (Marketz & Fischer, 1994). TRIP is a type of irreversible strain that occurs inside the yield surface. This phenomenon is associated with a saturation behavior of the SMA where stress-strain curves present a movement till it reaches a stabilized behavior. Therefore, it is important to subject the specimen to a training process responsible for the stabilization of the stress-strain curve. This training process considers several loading cycles to the specimen. Figure 4 presents a training process where the SMA sample is subjected to 20 cycles reaching the maximum value of 2.5 kN load at 60°C. Note that the stress-strain curves tend to stabilize after some cycles.

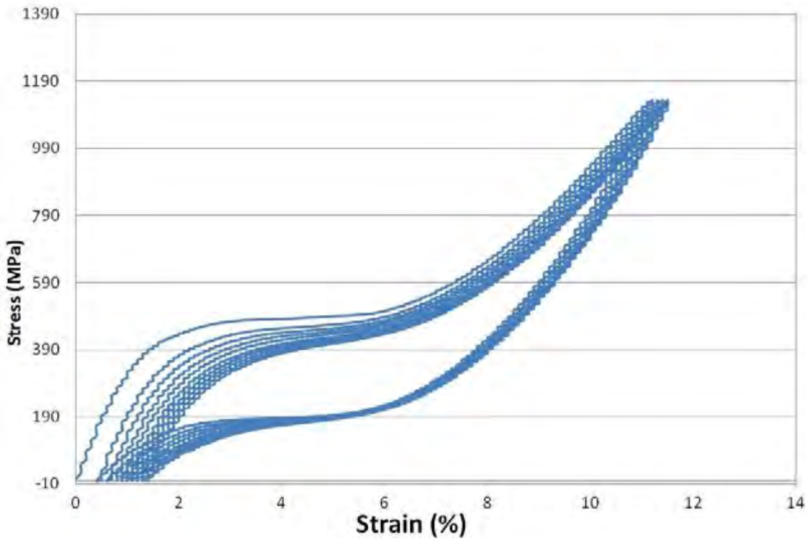

Figure 4. Training process of 20 cycles reaching the maximum value of 2.5 kN load at 60°C.

2.4 Critical Stress Temperature Dependence

In this section, pseudoelastic tests are performed at different temperatures. Basically, five levels of temperatures are of concern: 50°C, 60°C, 80°C, 90°C and 100°C. Figure 5 shows pseudoelastic responses for these temperatures. Note that the higher the testing temperature, the higher the critical stress transformation.

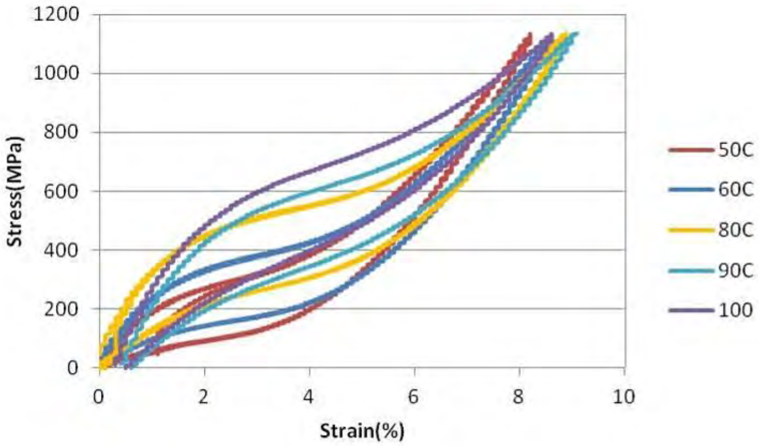

Figure 5. Pseudoelastic tests at different temperatures.

An important way to characterize the SMA thermomechanical behavior is the definition of the critical phase transformation stresses at different temperatures. Therefore, one can define four levels at each temperature: σ^{Ms} and σ^{Mf}, start and finish of martensite formation; σ^{As} and σ^{Af}, start and finish of austenite formation. Figure 6 presents the plots of these critical stresses for different temperatures. Moreover, it is plotted the DSC test result that corresponds to a zero stress level. Regression analysis shows the linear tendency of this general behavior. It uses the least square fit to a line and is that best fits the data points. The number R^2 is one factor ranging from 0 to 1 showing with precision that the estimated values for the trend line correspond to actual data.

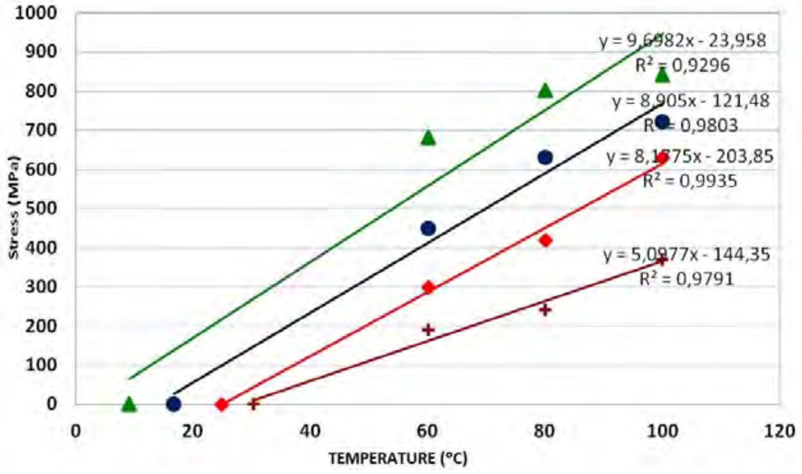

Figure 6. Characterization of the SMA from critical phase transformation stress.

3. INFLUENCE OF LOADING RATES

Despite the martensitic transformations are non-diffusive and therefore does not depend on the loading rate, the SMAs exhibit rate-dependent behavior as a result of thermomechanical couplings. Since austenite-martensite transformation is exothermic and reverse transformation is endothermic, the sample temperature can vary if the heat generated in the exothermic transformation is not removed by convective process.

In order to check the influence of the variation of the loading rates on the thermomechanical responses, SMAs are tested for pseudoelastic behavior considering a maximum value of 2.5 kN load and three distinct strain rates: slow rate; medium rate; high rate. Each test is associated with displacement driving test with the following rates: slow rate (0.5 mm/minute); medium rate (3 mm/minute); high rate (18mm/minute). Tests are conducted at different temperatures for each rate: -5°C, 22°C, 40°C and 80°C.

A comparison of these experimental results is now in focus. Figure 7 presents results at $T = -5°C$. Note that at the stress level of 1132 MPa, the high rate response has a strain of 4.8%, while the slow rate response presents 5.5%, corresponding to approximately 15% increase.

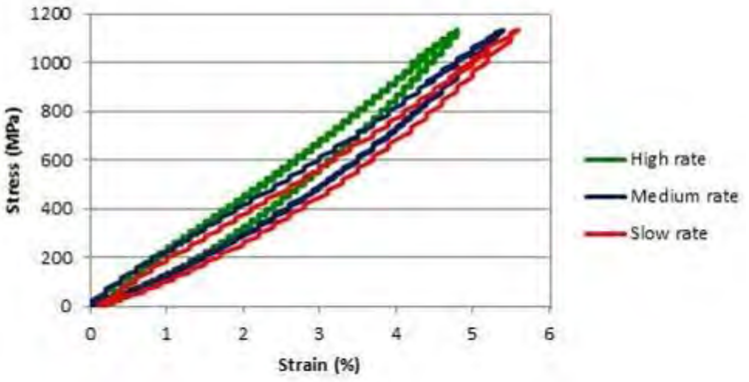

Figure 7. Influence of loading rates at $T = -5°C$.

Figure 8 presents the same response for $T = 22°C$. For stress level of 1132 MPa, the slow rate response has a strain of 7%, whereas at medium rate and high rate presents 6% and 5.6% of strain, respectively. Here, the difference between slow and high rate is 25%.

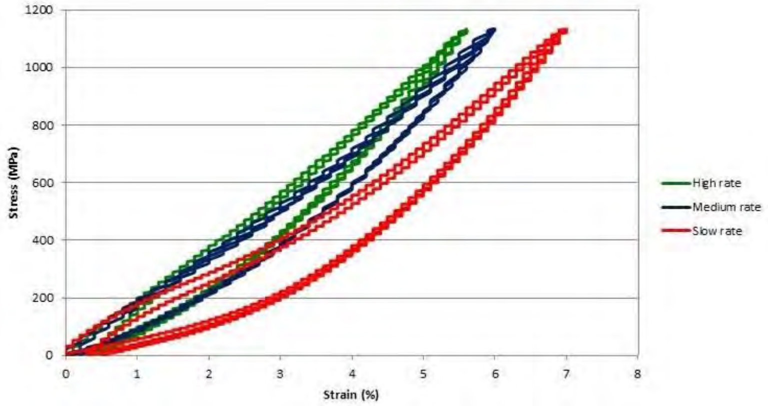

Figure 8. Influence of loading rates at $T = 22°C$.

Figure 9 and 10 present the same analysis for $T = 40°C$ and $T = 80°C$, respectively. The same qualitative changes are observed showing how loading rates influence the thermomechanical behavior of SMAs. In Figure 9, at stress level of 1132 MPa, the slow rate response and medium rate response have the same strain of 7.4%, whereas at high rate presents 6.8% of strain. Therefore, the difference between slow and high rate is 8.8%. Figure 10 shows the response for $T = 80°C$. At the stress level of 1133MPa, the high rate response has a strain of 7.6%, while the slow rate and medium rate response present 8.8% and 8.5%, respectively. Note that the difference between slow rate and high rate is 15.8%.

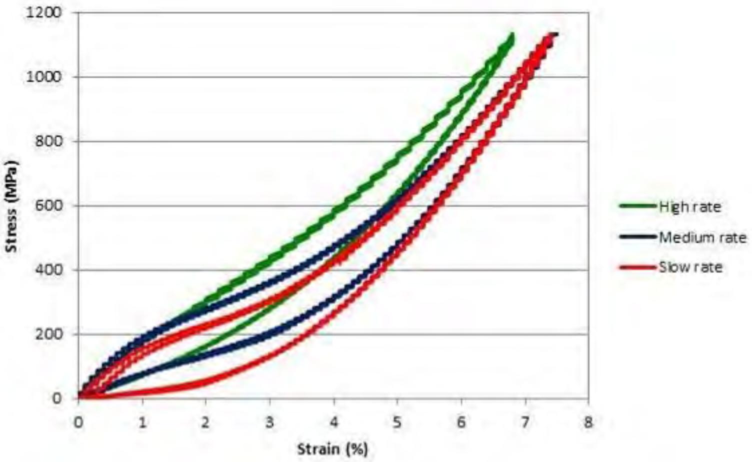

Figure 9. Influence of loading rates at $T = 40°C$.

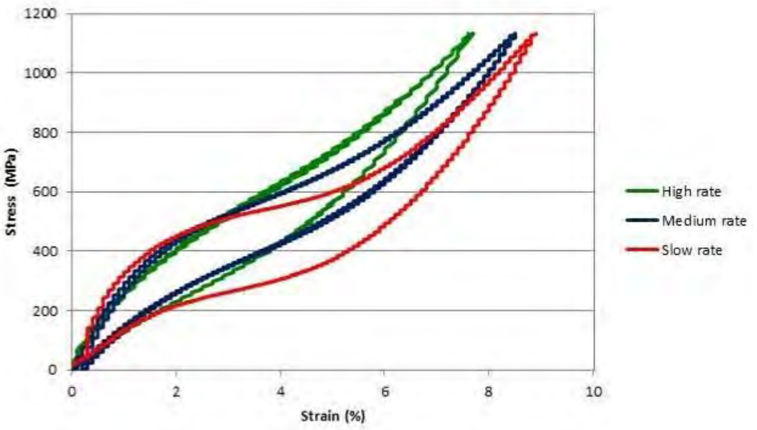

Figure 10. Influence of loading rates at T = 80°C.

4. CONCLUSIONS

This work presents experimental tests on SMAs. Initially, SMA characterization is of concern considering DSC and tensile tests. Characterization considers temperature dependence of critical phase transformation stresses. Training process is another important aspect to be considered. The influence of loading rates is investigated considering three conditions: slow, medium and high rates. In general, the loading rates have great influence on the SMA thermomechanical response. Results show quantitative differences that illustrate the great influence of loading rates. By considering maximum stress (1132 MPa), at T = 22°C, the slow rate response shows 7% of strain. By increasing the temperature to T = 80°C, the slow rate response shows 8.8% of strain at the same stress level, corresponding 25.71% of strain increase. On the other hand, at T = 22°C, the high rate response shows 5.6% of strain and at T = 80°C the strain reaches 7.6%, increase of 35.71%.

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