THERMOMECHANICAL BEHAVIOR OF NI-TI SHAPE MEMORY ALLOY WIRE

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Abstract. *Ni-Ti shape memory alloys (SMA) has been the subject of several studies due to its excellent physical and mechanical properties. For this reason, the alloys are used in various applications. In the study, wires were subjected to various heat treatments condition changing the annealing time and the cooling medium. The properties were investigated by means of differential scanning calorimetry and tensile tests experiments. It was observed that the transformation temperature changes more significantly when the samples are quenched in water than in air. Also, the maximum pseudo-plastic deformation reached values as high as 43% for wire annealed at 450ºC for 180min, followed by water quenching.*

Keywords: *Shape memory alloy, Heat treatment, Differential scanning calorimetry, stress-displacement curve.*

1. INTRODUCTION

The shape memory alloys (SMA's) are special materials able to undergo pseudo- plastic deformation and then return to its original geometric shape when subjected to an appropriate temperature variation and/or mechanical stress. This phenomenon is known as shape memory effect (SME) (Lima, 2008).

The shape recovery is due to reversible changes in the crystalline structure provoked by heating-cooling (Lima, 2008; Magela, 2010). Such structural changes occur in most SMA through a phase transformation in the solid state called martensitic transformation which occurs during cooling, beginning at a designated temperature M_S and completed at a lower temperature designated M_F. The reverse transformation of the martensite phase to the austenite promotes the recovery of the shape. Austenite transformation occurs during heating, beginning at a designated temperature A_S and finishing at a higher temperature designated A_F (Dias, 2005).

There are a variety of materials that present the SME, but the alloys that the aroused commercial interest are the that have a significant recovery between 3 and 8% or those that provide considerable significant force during constrained recovering. These features are observed in the copper based alloys such as, Cu- Zn-Al,Cu-Al- Ni, Cu-Al-Be, in Ni-Ti alloys and some ferrous alloys (Castilho and Silva, 2011; Dias, 2005; Farias *et al.*, 2012; Magela, 2010).

Initially, it was established a dispute between the copper-based alloys, ferrous and Ni-Ti. However, the latter have been subject of numerous studies due to their excellent physical and mechanical properties as high resistance to corrosion, the excellent biocompatibility, good ductility, the high damping capacity and consequently is widely recognized as the materials that provide the best properties related to SME (Dias, 2005). For these characteristics, the Ni-Ti alloys have been used in numerous applications as in the naval, aeronautics, aerospace, nuclear, automotive and robotics industry and in the medicine and dentistry (Castilho and Silva, 2011; Lima, 2008; Magela, 2010).

It is well known that the memory effect is a behavior that need to be "Learned" or "Trained". The process of creating a reversible SME usually starts with the heat treatment that is carried out forcing the material into the desired shape, then heating it in a furnace at a suitable temperature, followed by water or air cooling (Luo and Abel, 2007).

The temperatures of the phase transformations are very sensitive to the chemical composition of the alloy which is undesirable in most cases because is a tough task to control precisely the chemical composition (Oliveira *et al.*, 2011).

In this study, the Ni-Ti SMA wires were subjected to various heat treatments condition changing the annealing time and the cooling medium and theirs transformation temperatures and mechanical properties were investigated by Differential Scanning Calorimetry (DSC) and tensile.

2. MATERIALS AND METHODS

Ni-Ti SMA wire of 0.305 mm with a nominal composition of $Ni_{52.95}$-$Ti_{47.05}$ (mass%), supplied by Memory-Metalle company, were used in the present study. The as-received wires were annealed at 450°C for 20, 40, 60, 180 and 360 minutes followed by air and water quenching. Differential scanning calorimetry tests (DSC) were performed using the TA Q20 instrument at a constant heating rate of 10 °C/min under inert gas flux. The tensile tests were carried out in a INSTRON E10000 universal testing machine at a speed rate of 0.5 mm/min in Ni-Ti wire with 50 mm gauge length.

3. RESULTS AND DISCUSSION

3.1 Differential scanning calorimetry tests

The Figures 1 to 5 show DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for various times, followed by air quenching.

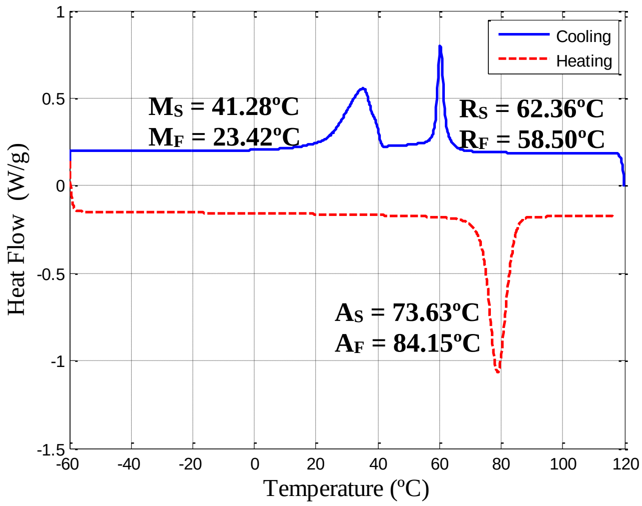

Figure 1. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 20 minutes, followed by air quenching.

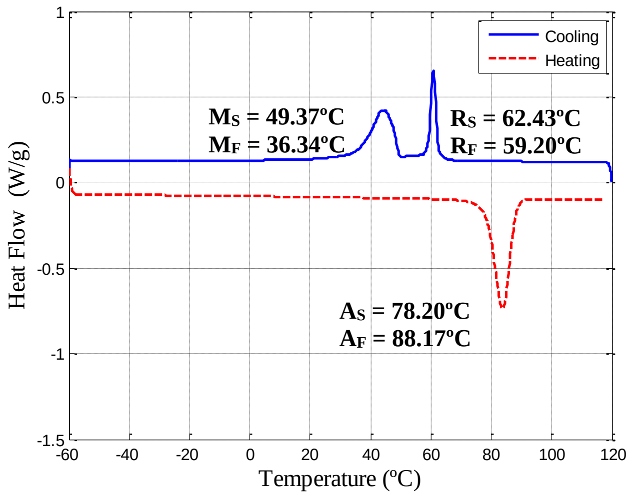

Figure 2. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 40 minutes, followed by air quenching.

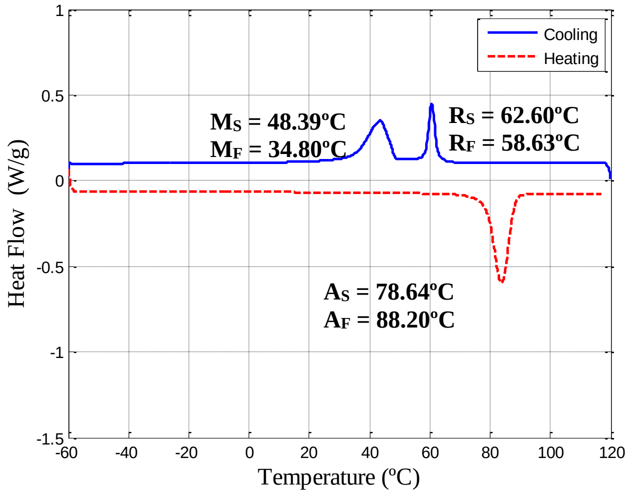

Figure 3. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 60 minutes, followed by air quenching.

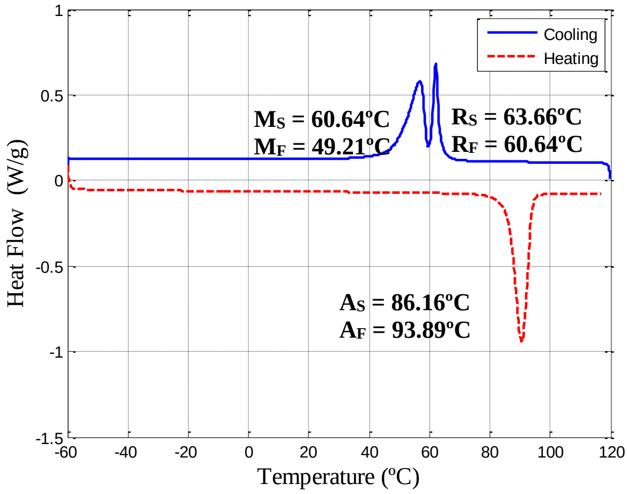

Figure 4. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 180 minutes, followed by air quenching.

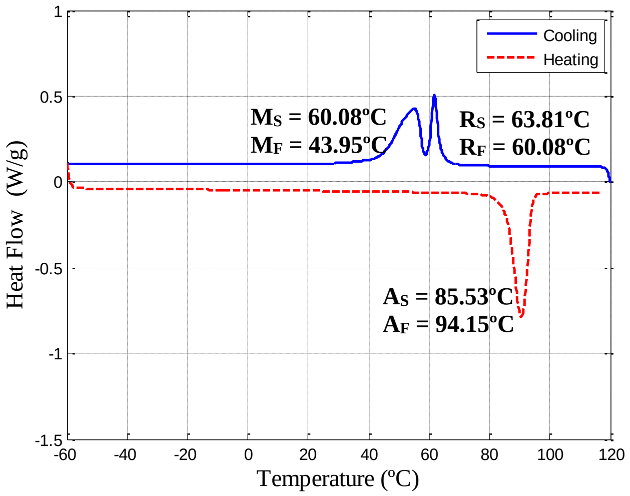

Figure 5. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 360 minutes, followed by air quenching.

The Table 1, shows the values of the phase transformation temperatures of the Ni-Ti SMA wire annealed at 450°C for various times and air quenching. These values were obtained by applying the tangents method.

Table 1. Phase transformation temperatures of the of the Ni-Ti SMA wire annealed at 450°C for various times, followed by air quenching.

Time (min.)	A_S (°C)	A_F (°C)	R_S (°C)	R_F (°C)	M_S (°C)	M_F (°C)
20	73.63	84.15	62.36	58.50	41.28	23.42
40	78.20	88.17	62.43	59.20	49.37	36.34
60	78.64	88.20	62.60	58.63	48.39	34.80
180	86.16	93.89	63.66	60.64	60.64	49.21
360	85.53	94.15	63.81	60.08	60.08	43.95

It can be observed in Tab. 1, that the values of the phase transformation temperatures increase with increasing the annealing time up to 180 minutes ad them reached a constant values. The Fig. 6 to 10 show DSC cooling and heating curves for wires annealed at 450°C for various times, followed by water quench.

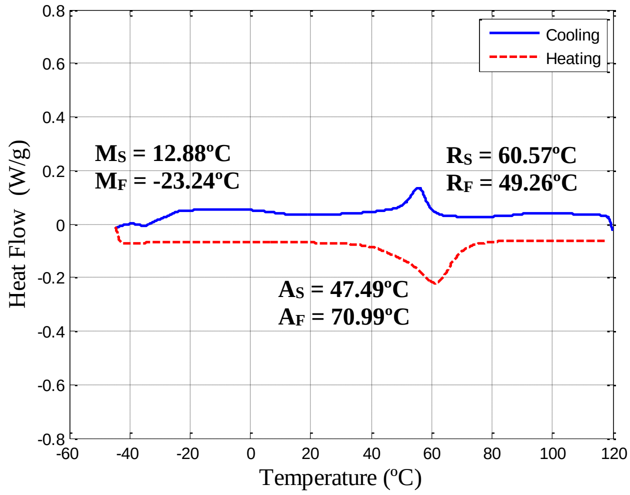

Figure 6. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 20 minutes, followed by water quench.

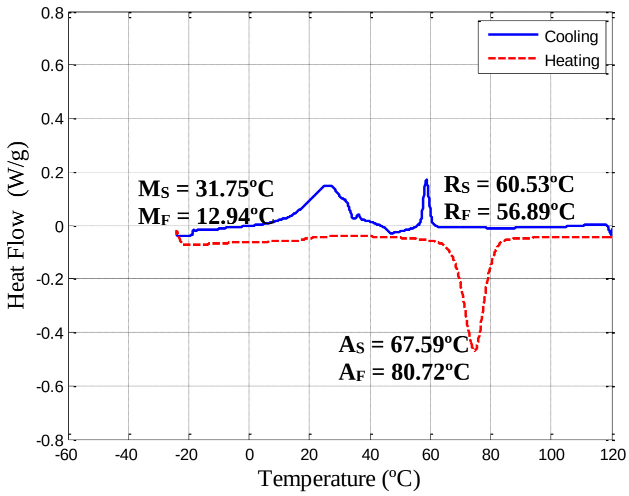

Figure 7. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 40 minutes, followed by water quench.

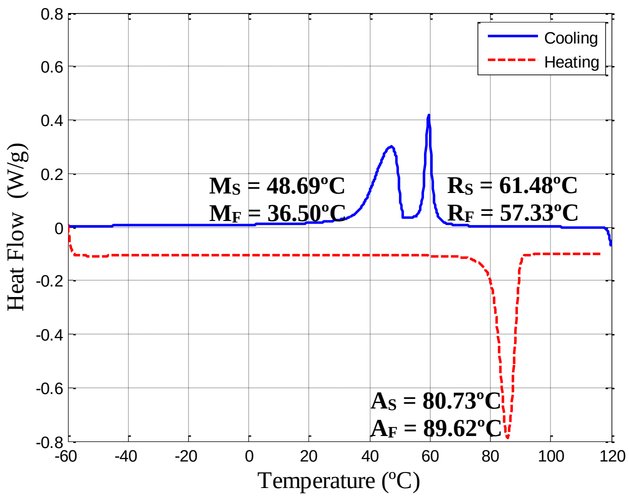

Figure 8. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 60 minutes, followed by water quench.

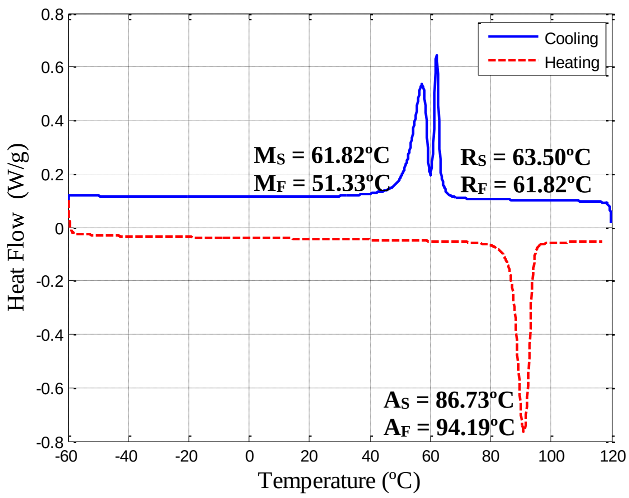

Figure 9. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 180 minutes, followed by water quench.

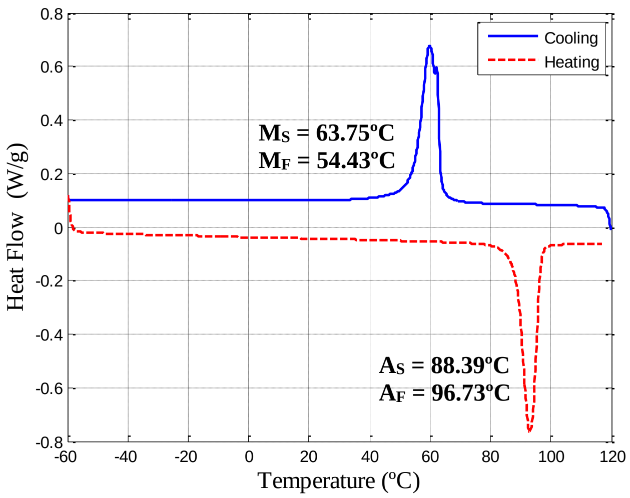

Figure 10. DSC cooling and heating curves of the Ni-Ti SMA wire annealed at 450°C for 360 minutes, followed by water quench.

The Table 2 show the values of the phase transformation temperatures of the Ni-Ti SMA wire annealed at 450°C for various times, followed by water quench. These values were obtained by applying the method of the tangents in DSC curve shown in Fig. 6 to 10.

Table 2. Phase transformation temperatures of the of the Ni-Ti SMA wire annealed at 450°C for various times, followed by water quench.

Tempo (min)	AS (ºC)	AF (ºC)	RS (ºC)	RF (ºC)	MS (ºC)	MF (ºC)
20	47,49	70,99	60,57	49,26	12,88	-23,24
40	67,59	80,72	60,53	56,89	31,75	12,94
60	80,73	89,62	61,48	57,33	48,69	36,50
180	86,73	94,19	63,50	61,82	61,82	51,33
360	88,39	96,73	-	-	63,75	54,43

It can be observed in Tab. 2, that the values of the phase transformation temperatures increase continually with annealing time. In addition, it can also be observed the superposition of the R and martensitic phase when annealing time reaches 360 minutes.

3.2 Tensile tests

The stress-displacement curve for Ni-Ti SMA wire annealed at 450°C for various times quenched into water and in air are shown in Fig. 11 and 12.

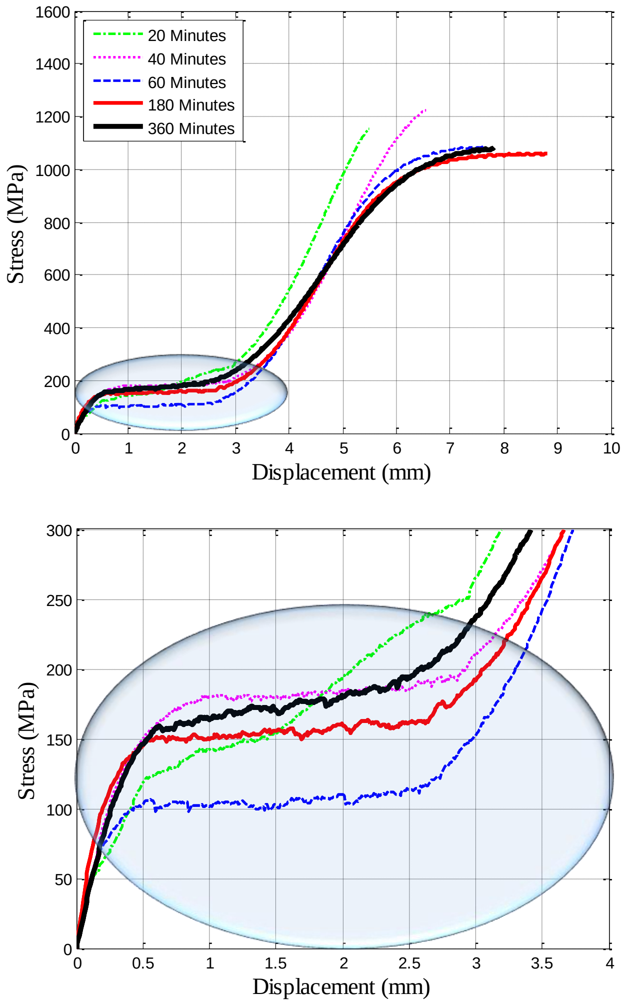

Figure 11. Stress-displacement curve for Ni-Ti wire annealed at 450°C followed by air quenching.

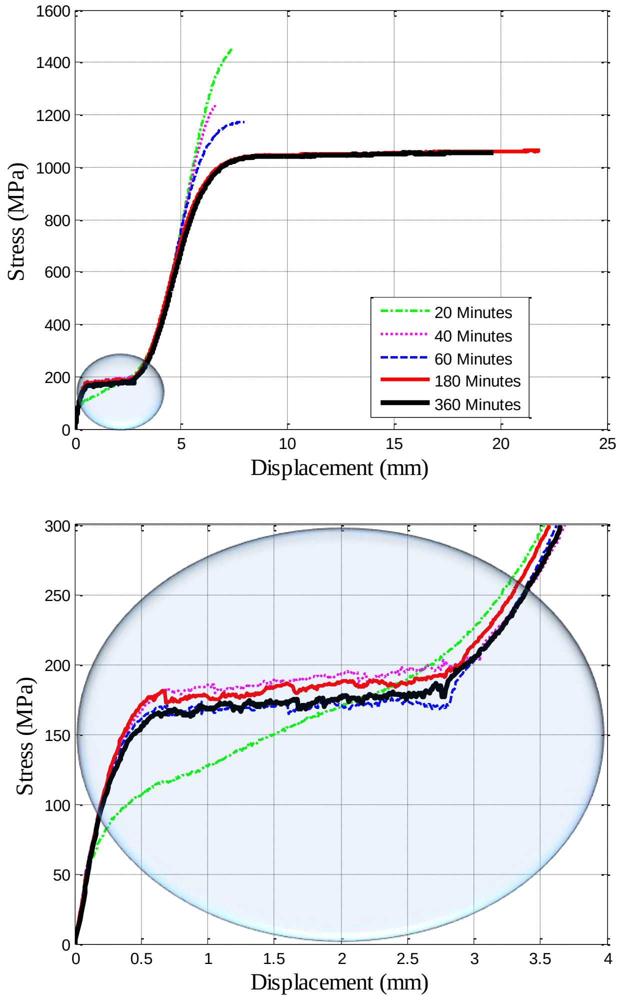

Figure 12. Stress-displacement curve for Ni-Ti wire annealed at 450°C followed by water quench.

The Table 3 and 4 show the mechanical properties of the Ni-Ti SMA wire annealed at 450°C followed by air and water quenching respectively. These characteristics are obtained from the tensile curves shown in Fig. 11 and 12.

Table 3. Mechanical properties of the Ni-Ti wire annealed at 450°C as a function of annealing time for air quenched specimens. Where: yield stress (YS), ultimate stress (US) and maximum strain up to rupture (MSR).

Time (min.)	YS (MPa)	US (MPa)	MSR (%)
20	150	1155	11.00
40	180	1224	13.13
60	105	1086	15.23
180	150	1062	17.63
360	170	1082	15.66

It can be observed in the Tab. 3 and 4, that the Ni-Ti SMA wires annealed at 450°C followed by water quench have a higher ductility than those wires quenched in air, especially for annealing time higher than 60 minutes. The ultimate stress decreases with increasing annealed time in both conditions. The medium yield stress for the Ni-Ti wire annealed quench is 151 MPa e 168.8 MPa for specimens annealed in air and water, respectively.

Table 4. Mechanical properties of the Ni-Ti wire annealed at 450°C as a function of annealing time for water quenched specimens. Where: yield stress (YS), ultimate stress (US) and maximum strain up to rupture (MSR).

Time (min.)	YS (MPa)	US (MPa)	MSR (%)
20	150	1448	14.76
40	185	1232	13.23
60	164	1174	15.91
180	175	1064	43.70
360	170	1057	39.35

4. CONCLUSIONS

In this study the thermomechanical properties of Ni-Ti SMA wires annealed at 450°C for 20, 40, 60, 180 and 360 followed by air and water quenching were investigates. The mains conclusion can be summarized as follow:

1. Irrespective to quenching medium, the phase transformation temperatures increase with increasing the annealing time. Additionally, is was observed the superposition of the R and martensitic phase.
2. The Ni-Ti SMA wires annealed followed by water quench exhibit a higher ductility.

5. ACKNOWLEDGEMENTS

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