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EVALUATION OF THE THERMOMECHANICAL BEHAVIOR OF NITINOL WIRES MICRO WELDED BY PLASMA ARC PULSES

Fernando Andrade Amorim
Universidade Federal de Campina Grande (UFCG), Rua Aprígio Veloso, 882 – Bairro Universitário – CEP 58429-140 – Campina Grande – PB, Brazil.
fernandoandradeamorim@gmail.com

Tito Tácio da Silva Sousa
Universidade Federal de Campina Grande (UFCG), Rua Aprígio Veloso, 882 – Bairro Universitário – CEP 58429-140 – Campina Grande – PB, Brazil.
titotacio@gmail.com

Luiz Fernando Alves Rodrigues
Universidade Federal de Campina Grande (UFCG), Rua Aprígio Veloso, 882 – Bairro Universitário – CEP 58429-140 – Campina Grande – PB, Brazil.
luizfarodrigues@gmail.com

Carlos José de Araújo
Universidade Federal de Campina Grande (UFCG), Rua Aprígio Veloso, 882 – Bairro Universitário – CEP 58429-140 – Campina Grande – PB, Brazil.
carlos@dem.ufcg.edu.br

Theophilo Moura Maciel
Universidade Federal de Campina Grande (UFCG), Rua Aprígio Veloso, 882 – Bairro Universitário – CEP 58429-140 – Campina Grande – PB, Brazil.
theo@dem.ufcg.edu.br

Abstract. *The development of welding process for NiTi shape memory alloys (SMA) can allows manufacturing thermomechanical actuators with complex shapes enabling new applications for this class of smart materials. In this work, NiTi SMA wires (ASTM F2063) with 0.9 mm in diameter, in the as-received state (NiTiA) and heat treated at 400°C for 20 minutes (NiTi400) were micro welded using a plasma arc pulse welder. The thermomechanical characterization of the NiTi SMA wires were performed using differential scanning calorimetry (DSC) and tensile tests in order to evaluate the efficiency of plasma welding. The results showed good quality of the plasma arc welding technique. It was verified that a post-weld heat treatment is essential to obtain greater values of stress to failure and high strain properties on welded NiTi SMA wires.*

Keywords: *Shape memory alloys, NiTiNOL, Plasma arc welding, thermomechanical properties.*

1. INTRODUCTION

NiTi Shape Memory Alloys (SMA) exhibits an excellent combination of functional properties, as an thermomechanical actuator that utilize the shape memory effect (SME) and also in applications that requires a behavior of superelasticity (SE). Due to economic and processing reasons, manufacture some types of SMA actuators is not feasible by conventional methods, which makes the welding process an interesting way to produce a new set of these actuators (Falvo et al., 2008).

The micro welding is an efficient way to create great union properties in NiTi SMA. These welding processes locate the heat and minimize thermal distortion for high restriction of the weld zone size (WZ) and heat affected zone (HAZ), providing accuracy and hermetic sealing, factors necessary for the application of this technique in bio implants and micro electromechanical systems (Chan et al., 2012a). In order to improve the quality of welded joints, because the micro welding can also cause the formation of defects, thermally induced residual stress and microstructural changes, which directly affect the mechanical properties of actuators, post-weld heat treatments are often performed in NiTi SMA to reduce residual stress and to ensure a better distribution of grain size (Chan et al., 2012c).

In this context, the study of welding techniques for NiTi SMA have attracted great interest in recent decades, as it is possible to see in some studies: (a) Eijk et al. (2003) in studies of plasma arc welding in martensitic NiTi wires showed a maximum tensile strength of the joint about 150 MPa, (b) Da Silva et al. (2010) obtained about 300 MPa tensile strength resistance of the joint in martensitic NiTi wires micro welded by capacitive discharge, (c) Gugel et al. (2008) using the laser welding process for joining superelastic NiTi wires resulted in about 620 MPa tensile strength of the joint and (d) in a study conducted by Zhao et al. (2010) with NiTi plates was found that addition of Ce and Nb as a weld intermetallic component could increase by 50% the tensile strength of laser welded joint.

Analyzing the mechanical behavior of NiTi SMA wires (Ni-49, 6at.% Ti) micro welded both in the martensitic state and in austenitic state, joints of the martensitic wire showed lower residual strains when compared with no welded wires (Tuissi et al., 1999). In fact, this occurs because of the appearance of defects during welding that supports the accommodation of strain. For the wires in the austenitic state, the weld process impaired the property of superelasticity, because in this case, the defects caused during welding can affect the atoms return to their original position after charging and discharging cycling.

Some results presented by Yan et al. (2007), that compared superelastic NiTi wires without heat treatment, treated at 400°C and 500°C, have demonstrated that the wire treated at 400°C showed the best mechanical properties and the wire treated at 500°C showed the worst mechanical properties, this behavior happened because at 400°C small Ni_3Ti_4 precipitates are formed, whereas at 500°C, coarse precipitates are formed which hampers the accommodation tension of the welded joint. Therefore, it is necessary to know the behavior of each type of SMA to select the best post welding heat treatment, to obtain better mechanical properties.

Therefore, this study aimed to investigate the thermomechanical behavior of NiTi SMA wires (ASTM F2063) in its natural state (NiTiA) and heat treated at 400°C (NiTi400) micro welded by plasma arc pulses and evaluate the influence of post-weld treatments on the mechanical properties of the welded joints.

2. EXPERIMENTAL

For this work were used NiTi thin wires (0.9 mm in diameter), medical grade, ASTM F2063, polished surface, manufactured in U.S.A. The wires were divided into two groups: (a) wires in their initial, as received, state (NiTiA), (b) heat treated at 400 °C for 20 minutes (NiTi400). After welding some wires were heat treated at 300 ° C for 20 minutes in order to relieve residual stresses resulted and to ensure a better distribution of grain size. All heat treatments were performed in an electric resistance furnace (EDG, model Titan Quartz Platinum).

All NiTi SMA wires were welded using the plasma arc pulse welding process (Micromelt Welder, from EDG). The automatic parameters used in the Micromelt welder were: 01 for deep (related to amperage) and 01 for pulse (related to pulse time). Wires of 40 mm (length) were used and a device for fixing the samples was made to align the wires and improve the accuracy of the welding point. The Figure 1 shows the mounting details of the welding process. Even checking in Fig 1(b) that the tungsten electrode is not protected, the supplier considers the welder as plasma, not TIG (EDG, 2013).

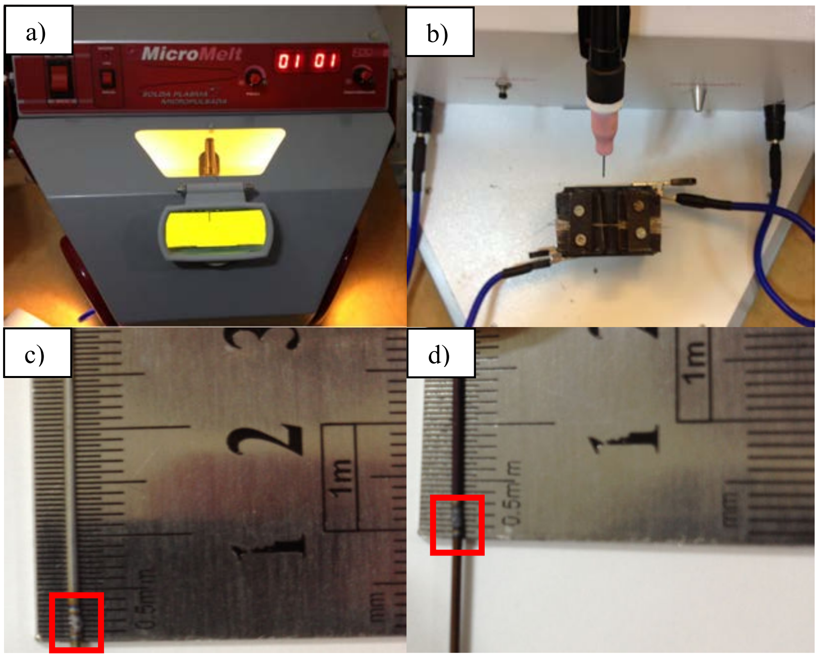

Figure 1. Scheme of welding process: a) Micromelt EDG welding machine. b) Mounting of the fixture for welding the wires. c) Detail of welded wire without thermal treatment. d) Detail of welded wire with heat treatment.

The phase transformations of the NiTi SMA wires were determined from differential scanning calorimetry (DSC) tests using the equipment from TA Instruments, model Q20, in which samples of approximately 5 mm in length were subjected to a temperature range of -60°C to 100°C under heating and cooling rate of 5 °C/min.

The mechanical characterization of the NiTi reference wires and welded wires was performed by the uniaxial tensile test at room temperature (24 °C) using an electromechanical universal testing machine, INSTRON, model 5582. Figure 2 show the assembly for testing of the wires. In the cycling tests was generated a method for controlling displacement during loading and unloading, limiting stain of 4% relative to the useful length of the sample using a displacement rate of 0.5 mm/min.

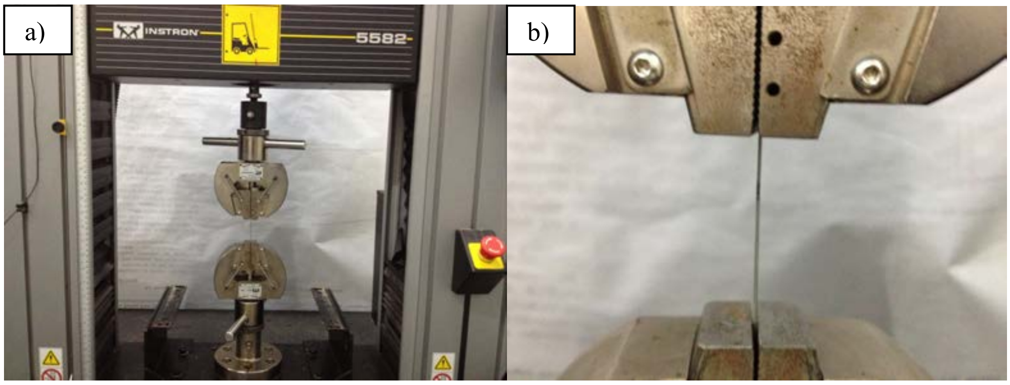

Figure 2. Experimental setup for uniaxial tensile tests. (a) Electromechanical universal testing machine INSTRON, model 5582. (b) Detail of the adjustment of the grips and wires for mechanical test.

3. RESULTS

3.1 DSC measurements

The phase transformation behavior of the NiTi SMA wires can be measured by the DSC method, identifying the peaks during cooling and heating, helping to understanding the thermal properties of these wires. Figure 3 (a) shows the DSC curves for NiTiA reference wire and welded wire, whereas (b) represent DSC curves for NiTi400 reference wire and welded wire. From Figure 3(a) it can be seen that, at room temperature (24 °C), the NiTiA wires are in the austenitic state, however, in Fig. 3(b) NiTi400 reference wire shows a mix of austenitic and martensitic structures. Comparing DSC curves of welded wires to the reference wires, became evident that the welding process reduced the transformation temperatures of austenite and martensite in both wires, consequently NiTiA and NiTi400 shows austenitic structures, at room temperature, after the welding process. The decrease of phase transformation temperatures may originate from: (i) the removal of cold working effect in the base metal (Chan et al. 2012b) and (ii) the presence of thermally induced defects in the weld microstructure, such as residual stress and grain growth (Chan et al. 2013). Hornbogen et al. (2001) also reported that the phase transformation temperatures of NiTi are strongly affected by microstructural defects.

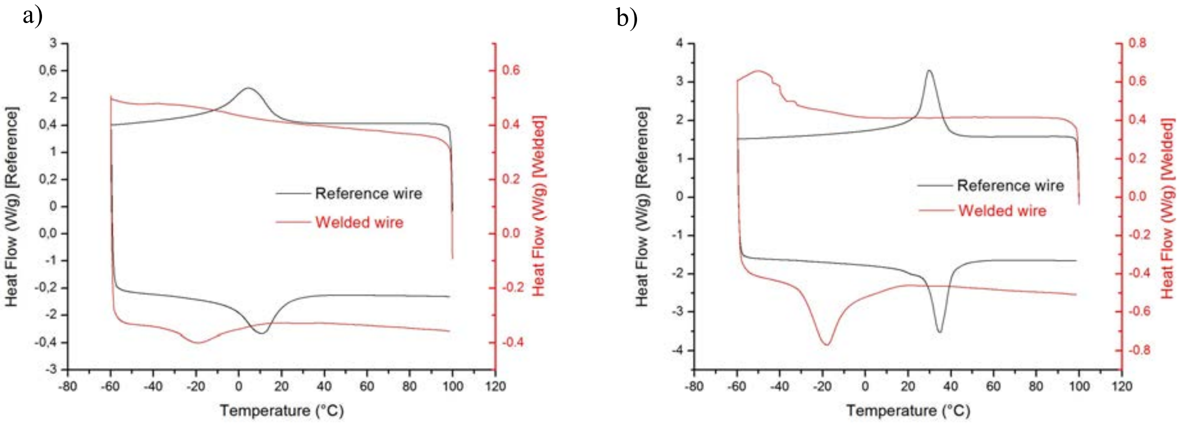

Figure 3. DSC curves for (a) NiTiA reference wire, (b) NiTiA welded wire, (c) NiTi400 reference wire and (d) NiTi400 welded wire.

3.2 Mechanical characterization

3.2.1 Welding effects

The autogenous arc plasma welding enabled the union of NiTi SMA wires in the austenitic state (NiTiA) and also in the wires which coexists martensitic and austenitic phases (NiTi400). It was necessary only one or two welding points to obtain joints with relevant mechanical properties. Figures 4 and 5 shows stress-strain curves that compares the rupture resistance between reference wire and welded wire for NiTiA and NiTi400, respectively. It was verified a premature rupture of the welded wires, which showed similar maximum tension resistance of 450 MPa (NiTiA and NiTi400 welded wires), which implies that the structure of NiTi not affect the tensile strength of the welding point. Looking at Figure 4 it is possible to verify the plateau of stress induced martensite (SIM) initiated approximately 490MPa that is about 40MPa higher than the stress for rupture of weld joint. However, Figure 5 shows that after the heat treatment at 400 ^{o}C for 20 minutes the plateau of SIM starts at about 400MPa, allowing the joint obtain greater values of strain associated to SIM (~ 7%).

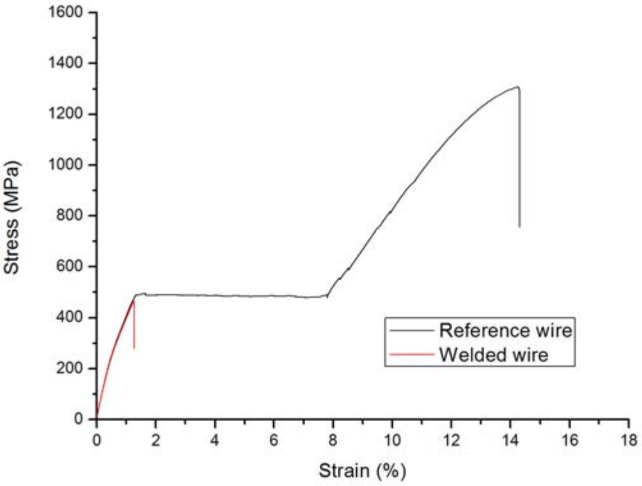

Figure 4. Tensile testing performed until failure for NiTiA reference wire and welded wire.

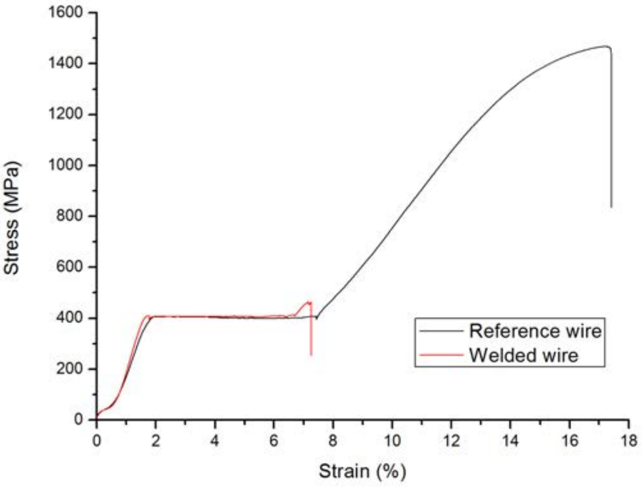

Figure 5. Tensile testing performed until failure for NiTi400 reference wire and welded wire.

By comparing the cycling behavior of NiTi400 for reference wire and welded wire in Fig. 6, it is possible to note that the welded wires exhibit a stress-strain behavior with low residual strain. This behavior occurs because the appearance of defects in the heat affected zone (HAZ), coming from the welding process, supports great accommodation of stress. The stress-strain curve of the NiTi400 welded wire shows a behavior closer to a completely austenitic superelastic SMA, which confirms the results obtained from the DSC measurements corresponding to the reduction of transformation temperatures after the welding process.

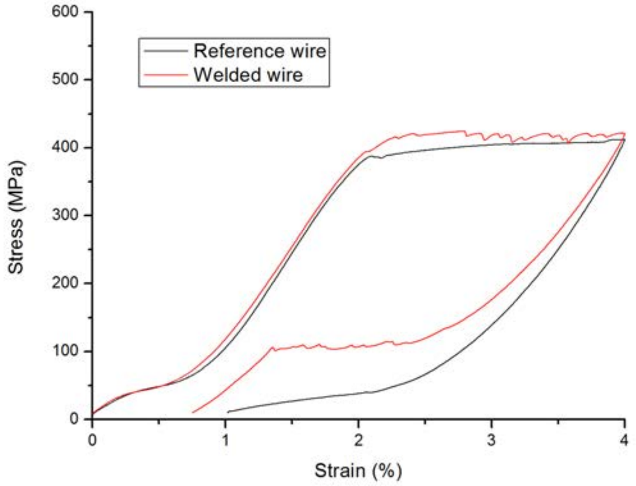

Figure 6. Stress-strain superelastic curves for up to 4% of strain in NiTiA reference wire and welded wire.

3.2.2 Influence of post weld heat treatment

The heat treatment at 300 °C for 20 minutes was performed in order to reduce the welding residual stresses and to ensure a better distribution of grain size, providing an increase of the mechanical properties of the joints. According to Figure 7 the heat treatment carried out in NiTiA wires increased the maximum tension resistance of the joint (520MPa), which also generated a greater deformation supported by the welded wire (5%, increase of 3.8% over the untreated wire).

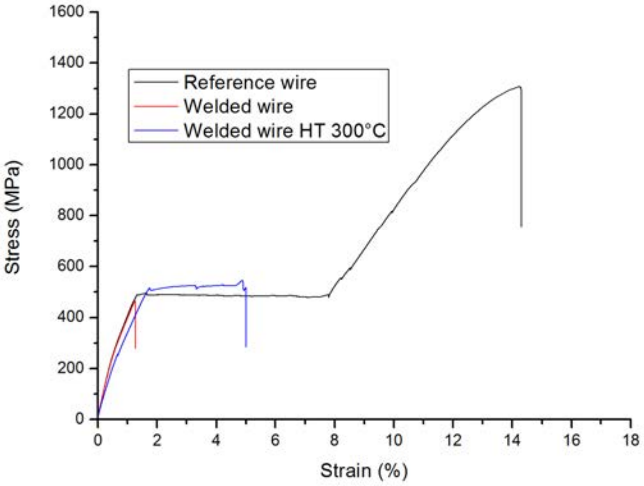

Figure 7. Tensile testing performed until rupture in NiTiA reference wire and welded wire (untreated and post-weld heat treatment of 300 °C for 20mintes).

The influence of the heat treatment after the welding process for NiTi400 wires is shown in Fig. 8, where it is possible to note a higher strain supported by the wire which was heat treated after welding. However, the plateau of SIM for this wire did not finish at about 8% of strain. Thus, it is clear that the defects caused during the welding process hampers the induction of the martensite, requiring a longer time to complete this transformation (SIM).

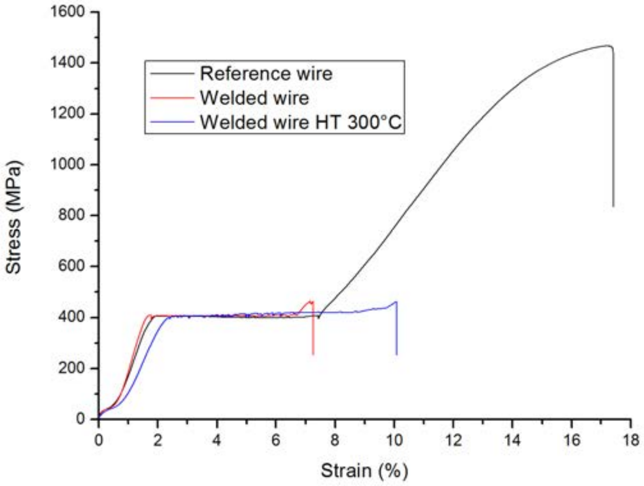

Figure 8. Tensile testing performed until rupture for NiTi400 reference wire and welded wire (untreated and post-weld heat treatment of 300°C for 20min).

Figure 9 shows stress-strain cycling up to 4% of strain, comparing NiTiA reference wire and welded wire (heat treated post-weld, 300°C for 20 minutes). The superelastic curves show great similarity, however the welded wires showed a small increase of the residual strain. Some authors attribute this behavior to the presence of defects in the heat affected zone (HAZ) resulting from the welding process (Tuissi et al., 1999 and Chan et al., 2012b).

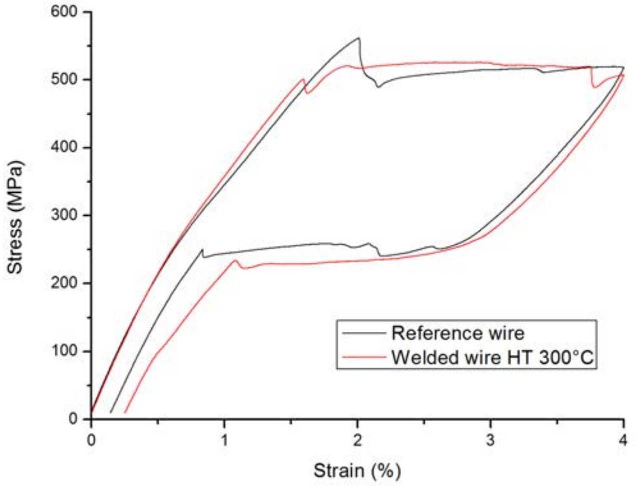

Figure 9. Stress-strain superelastic curves up to 4% of strain for NiTi400 reference wire and welded wire (heat treated after welding).

Figure 10 show that the post weld heat treatment did not affect the residual strain of NiTi400 wires subjected to welding process. Thus, it is possible to suppose that the morphology of this type of wire does not suffer modifications after heat treatment at 300°C.

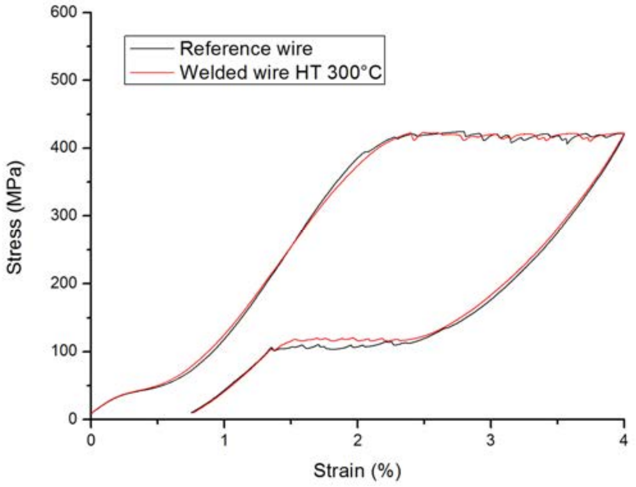

Figure 10. Stress-strain superelastic curves up to 4% of strain for NiTi400 welded wire (untreated and heat treated after welding).

Figure 11 shows superelastic behaviors for NiTiA wires heat treated after welding, comparing the first cycle to the eighth cycle up to 4% of strain. After eight stress-strain cycles the wire accumulates almost no residual strain. This behavior confirms that the joint of this type of wire has an austenitic structure with superelastic property. It can be also verified that the plateau of SIM is reduced of about 50 MPa after cycling, as commonly verified for non-welded superelastic NiTi SMA (Lagoudas, 2008).

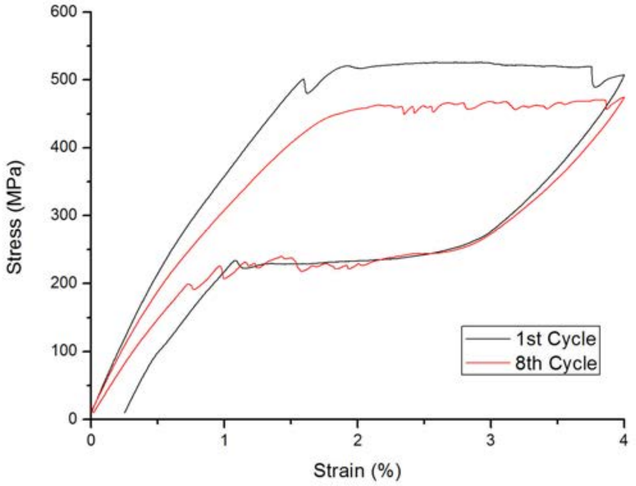

Figure 11. Stress-strain curves for the first and eighth cycle up to 4% of strain in NiTiA welded wires and post-weld heat treated.

4. CONCLUSIONS

Considering the results obtained in this experimental study which analyzed the thermomechanical behavior of NiTiNOL wire micro welded by plasma arc pulse, it follows that:

- The process of plasma arc welding is efficient for joining commercial NiTi SMA wires, since it took only one or two points to obtain a resistant joint in these wires;
- DSC tests have shown that the welding process reduced the transformation temperatures, so that the welded wires (NiTiA and NiTi400) showed an austenitic structure at room temperature;
- The NiTi400 welded wires showed better results of residual strain when compared to the non-welded wires;
- To obtain a joint with higher mechanical strength for NiTiA wire was necessary to perform a heat treatment (300 °C for 20 minutes) after welding process.

5. ACKNOWLEDGEMENTS

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