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# MECHANICAL BEHAVIOR OF NI-TI SMA HELICAL SPRINGS MANUFACTURED BY INVESTMENT CASTING

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***Abstract.*** *Shape Memory Alloys (SMA) are active metallic materials that have being increasingly studied because the potential applications due to their functional properties of recovering original shape by heating after pseudo plastic deformation. In this context, SMA helical springs can be used as actuators or sensors in several areas. Thus, this work aims to perform thermal and mechanical characterization of Ni-Ti SMA helical springs produced by investment casting process of induction melting followed by centrifugal casting (ICC). Thermal characterization of the springs was performed by Electrical Resistance as a function of Temperature (ERT), while the mechanical characterization in static and dynamic regimes was performed in an Instron Model E10000 machine. The results of thermal analysis by ERT showed that the helical Ni-Ti springs have phase transformation corresponding to the superelastic effect (SE) at room temperature (~23.5±0.5 °C). The reversible deformations under uniaxial tensile were of the order of 80% and the dynamic tests showed that the mechanical properties vary according to the frequency and deformation amplitude. At last, it was verified that the Ni-Ti SMA helical springs produced by IMC process present functional characteristics, which are suitable for superelastic applications such as springs manufactured by conventional processes.*

***Keywords:*** *Helical springs, Shape Memory Alloys, Ni-Ti alloys, Investment casting*

## 1. INTRODUCTION

Engineers have been seeking to improve product efficiency increasing efficiency/weight ratio of systems without compromising costs. Thus, the substitution of systems composed of several components by a simple multifunctional device, using active materials, can be an advantageous and interesting alternative (Rao, *et al.*, 2015).

In the last decades, researchers have constantly sought to develop applications with high performance materials, which provide minimized drive components, weight reduction, silent performance and smart instrinsic functions. Shape memory alloys (SMA) is among these materials, mainly Ni-Ti alloys, due to its more expressive thermomechanical properties compared to other SMA, which can present Shape Memory Effect (SME) or Superelastic Effect (SE) (Czechowicz and Langbein, 2015). Superelasticity was described by Doraiswamy (2010) as an ability of SMA to recover large deformations (~8%) after removing mechanical load that caused deformation. This occurs due to the austenite to martensite (solid-solid) stress induced phase transformation in the material.

Although commercial applications of Ni-Ti SMA have occurred, they have not grown significantly, except in the biomedical field, mainly due to manufacturing difficulties and high costs involved to make projects viable (Rao, *et al.*, 2015). Among the several products possible to be manufactured from Ni-Ti SMA, helical springs are considered interesting designs, allowing applications in thermomechanical valves (Czechowicz and Langbein, 2015) and also for vibration attenuation in a passive or active way, as demonstrated recently by Holanda et al. (2014) and Enemark & Santos (2016). In general, these smart coil springs are manufactured from commercially available Ni-Ti SMA wires by means of a thermomechanical forming process known as "shape setting" (Rao, *et al*., 2015; Heidari, *et al*., 2016). However, this process depends on the preliminary fabrication of the Ni-Ti SMA wires, which is a difficult task. In addition, for customized applications involving larger diameter wire springs (greater than 1mm), it may be more interesting to obtain the helical spring shape directly from a metallurgical conformation.

In this context, this paper aimed to analyze the mechanical behavior of Ni-Ti SMA helical springs manufactured by a novel process, corresponding to investment casting with lost wax technique and centrifugal molten injection into ceramic molds. This manufacturing process can be considered an innovative method for SMA products, including helical coil springs.

## 2. MATERIALS AND METHODS

### 2.1 Manufacturing Process

The helical springs were manufactured using the methodology developed by Simões (2016) for Ni-Ti SMA mechanical components. The SMA used to obtain helical springs was 55.3Ni-44,7Ti (%wt). This composition was selected in order to observe a complete or partial superelastic behavior at room temperature (~25±2 °C). The manufacturing of Ni-Ti SMA ingots (20 to 30 grams) was carried out using the Plasma Skull Push Pull (PSPP) process. This method was validated to manufacture SMA by De Araújo, *et al.*, (2009).

To manufacture the helical springs from the Ni-Ti SMA ingots, a wax model with the design and dimensions of the final product was used to make ceramic molds. Then, ceramic coating, indicated for titanium alloys in dental applications (Microfine 1700), was used to obtain solid molds. The production stages of the Ni-Ti SMA springs are shown in Figure 1.

The molds obtained with ceramic coating were cured in an electric heat furnace using a thermal cycle consisting of a heating ramp from room temperature to 750 °C at a rate of 20 °C/min, remaing at that final temperature for 20 minutes in order to solidify the ceramic coating and remove the wax completely.

For the final casting of Ni-Ti SMA ingots obtained previously by PSPP, the PowerCast 1700 equipment (EDG) was used. The Ni-Ti ingot was placed in a ceramic crucible, subjected to a flow of argon gas and melted by induction. The injection of the Ni-Ti molten into the ceramic coating mold was performed by centrifugation. After this whole process, the ceramic coating was completely removed by blasting powdered alumina. Further, the as cast Ni-Ti SMA helical springs were heat treated at 850 °C for 1 hour followed by aging at 500 °C for 2 hours.

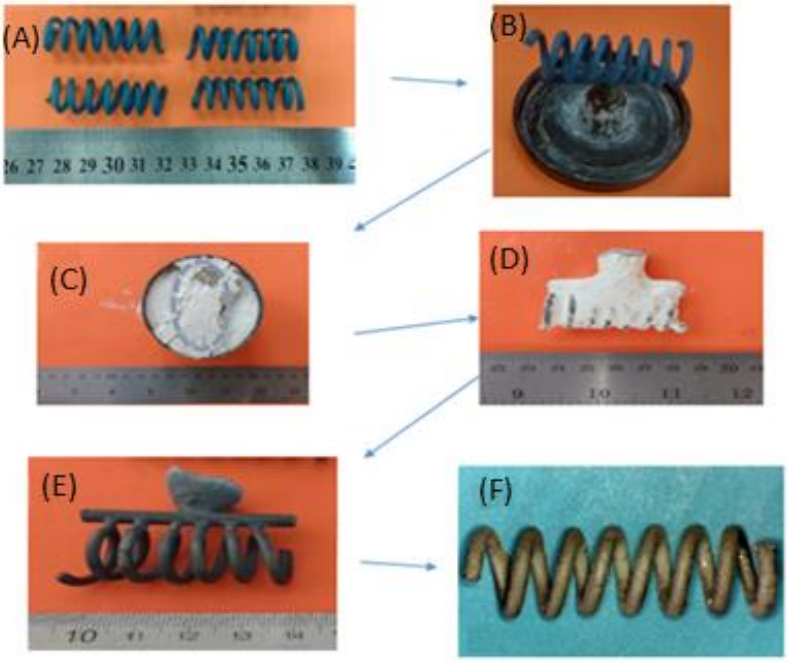


Figure 1. Steps to obtain the Ni-Ti SMA helical springs. (A) Wax models. (B) Model tree. (C) Ceramic mold after casting. (D) Cleaning. (E) Cast tree. (F) Ni-Ti final helical spring.

### 2.2 Thermal Characterization

The phase transformation temperatures of the Ni-Ti SMA helical springs shown in Figure 1(F) were determined by means of Electrical Resistance as a function of Temperature (ERT). This is a non-destructive technique in which the Ni-Ti SMA spring is placed into a thermal controlled silicone oil bath and submitted to a constant electrical current of low intensity to cause a potential difference between two points. Subsequently, the coil spring is subjected to cooling and heating in a temperature range of -60 °C to 120 °C, at a rate of about 3 °C/min. The voltage drop and temperature are captured by a data acquisition system (Agilent, 34970A) and storage in a desktop computer for further treatment. Application of tangents on the ERT curves allow determining the phase transformation temperatures. The advantage of this technique, compared to other thermal analysis (DSC or DTA), is that it allows to determine the transformation temperatures of the entire mechanical component, and not only using a small part extracted from it.

### 2.3 Mechanical Characterization

Mechanical tests were realized at room temperature (~23.5±0.5 °C) using an Electropuls E10000 test machine (Instron) equipped with a 10kN load cell. The Ni-Ti SMA springs were initially subjected to mechanical cycling of 60% deformation to stabilize the superelastic behavior. Then, quasi static tensile tests with 4 cycles of loading/unloading at varied deformations of 20%, 40%, 60% and 80% were taken reliving the applied force to a residual force during the unloading stage in each cycle. A strain rate of 1%/min was used during the loading and unloading stages. Subsequently, tests of dynamic mechanical extension/compression were performed, in which Ni-Ti SMA springs were subjected to loading and unloading cycles varying the excitation frequency at 1Hz, 2.5Hz and 5Hz, with a deformation amplitude of 80% (±40%). The 40% deformation in compression corresponds to the limit to prevent the coils from touching, since the springs are originally open. Figure 2 show the assembly for the mechanical characterization of the Ni-Ti SMA springs with 4 active coils and the springs design with a spring index of 6. During the tests a 100 μm diameter K micro thermocouple was installed in the center of the length of the NiTi spring to monitor the temperature behavior during cycling.

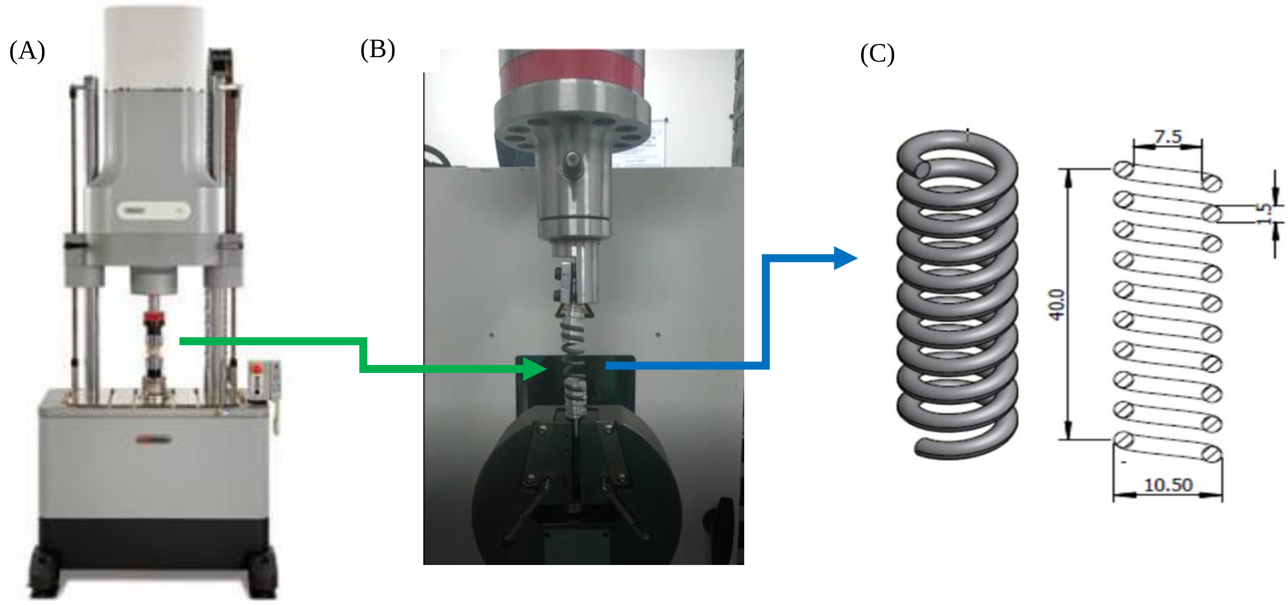


Figure 2. Mechanical tests of the Ni-Ti SMA springs. (A) Electro Pulse E10000 Dynamic Machine. (B) Experimental Assembly for test. (C) Mechanical design and dimensions in mm of the Ni-Ti SMA helical springs: height (H) - 40, inner diameter (Di) - 7.5, outer diameter (De) -10.5, wire diameter (d) -1.5.

## 3. RESULTS AND DISCUSSION

### 3.1 Thermal Characterization of Ni-Ti Springs

Figure 3 show the aspect of the ERT curve for the Ni-Ti SMA springs obtained by investment casting. The ERT behavior was typical of Ni-Ti SMA presenting a two-step phase transformation during cooling, from austenite to R-phase and then to martensite (Otsuka and Wayman, 1998). This transformation behavior is characterized by an ERT peak during cooling. The phase transformation temperatures obtained by ERT for the Ni-Ti SMA springs were: Martensite Finish Temperature ($M_f$) = -24.6 °C; Martensite Start Temperature ($M_s$) = 8.1 °C; R-Phase Finish Temperature ($R_f$) = 21.0 °C; R-Phase Start Temperature ($R_s$) =29.0 °C; Austenite Start Temperature ($A_s$) = 25.8 °C; Austenite Finish Temperature ($A_f$) = 38.4 °C.

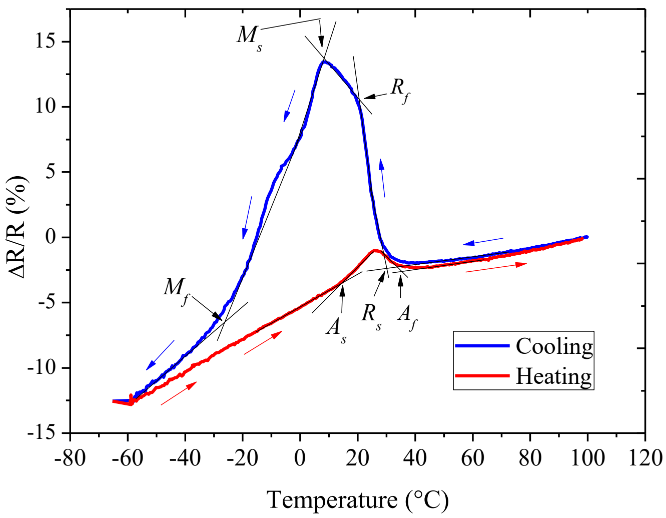


Figure 3. ERT behavior of $HS_{SMA}$.

From the analysis of the ERT curve, it can be observed that the Ni-Ti SMA springs will present complete or partial superelasticity because room temperature (~25±2 °C) is located between $R_s$ and $A_f$. Therefore, in order to confirm this SE behavior, before the mechanical tests the SMA springs were heated to a temperature higher than $A_f$ (up to 60 °C) and then cooled down at room temperature, which is near than the $R_s$ temperature.

### 3.2 Mechanical Characterization of Ni-Ti Springs

The results of the mechanical uniaxial quasi-static tensile tests are shown in Figure 4 while the dynamic extension/compression tests are shown in Figures 5, 6 and 7 for different frequencies, highlighting the first (1st) and last cycle (128th).

In the static tensile tests (Fig. 4), it was verified that Ni-Ti springs manufactured by ICC reached a force of 120 N, when subjected to deformation of 80 %. It can be observed that the superelastic deformation was of the order of 65 %, due to a residual deformation of 15 % after unloading in the last cycle.

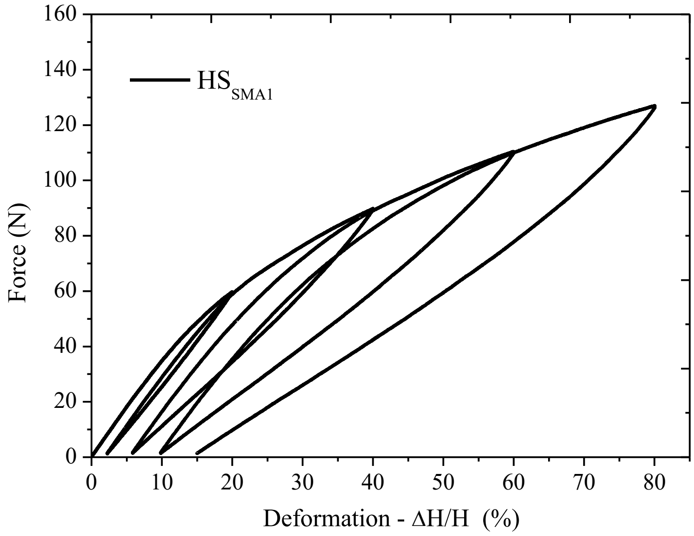


Figure 4. Static mechanical cyclic behavior of the Ni-Ti springs.

In the dynamic tests, for all frequencies, it was verified an asymmetry between extension and compression, in order to require more force to reach the 40% deformation in compression than in extension. This asymmetry decreases as the frequency increases to 5Hz. Qualitatively, it can be observed that stiffness increases slightly when the frequency increase from 1 Hz to 5 Hz for a constant deformation amplitude of 80 % (-40 % to +40 %). This behavior of increasing the load to reach the same final deformation during the cycling up to ±40% can be attributed to the phenomenon of self-heating of the Ni-Ti SMA spring due to the fact that the phase transformation is endothermic during loading and exothermic in the unloading, generating an accumulation of latent heat that is not fully dissipated by natural convection. This accumulation of heat along the cycles causes a rise in temperature of the spring leading, by Clausius Clayperon's law for SMA, to increased loading to achieve the same final deformation. This behavior of self-heating was shown experimentally by Oliveira et al (2012) during strain controlled cyclic tensile tests of Ni-Ti SMA wires of 0.5 mm diameter cycled in superelasticity between 0.5 Hz and 25 Hz.

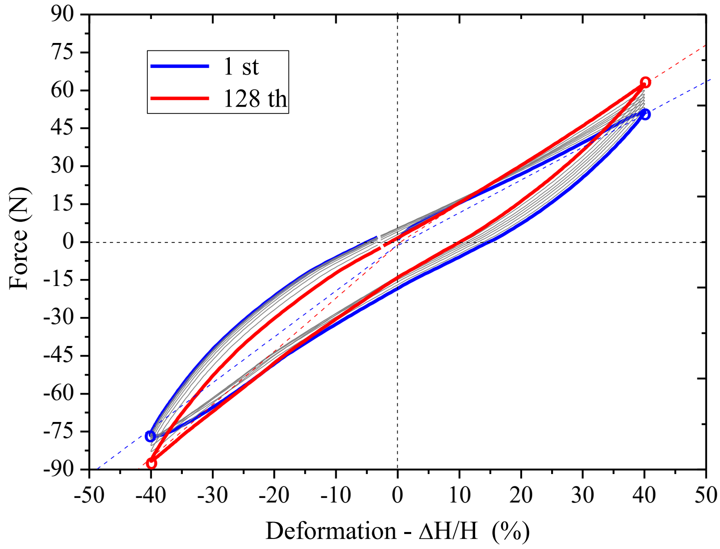


Figure 5. Dynamic mechanical behavior at a frequency of 1Hz and amplitude of 80%.

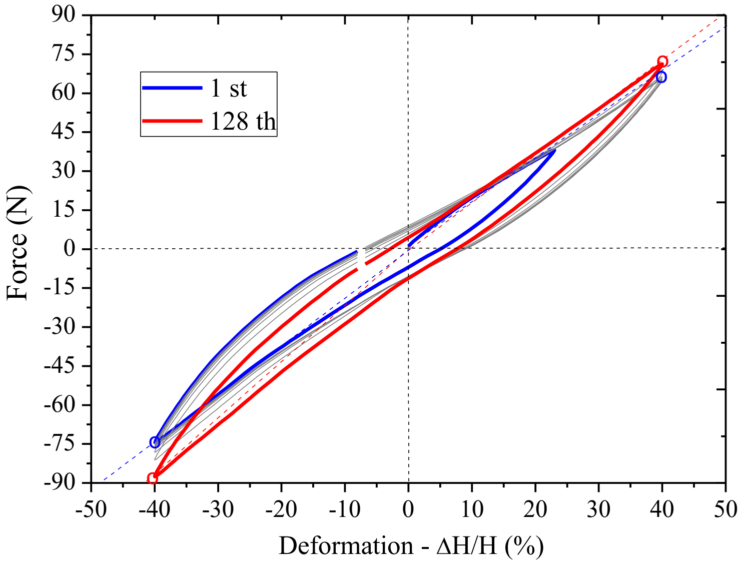


Figure 6. Dynamic mechanical behavior at a frequency of 2.5Hz and amplitude of 80%.

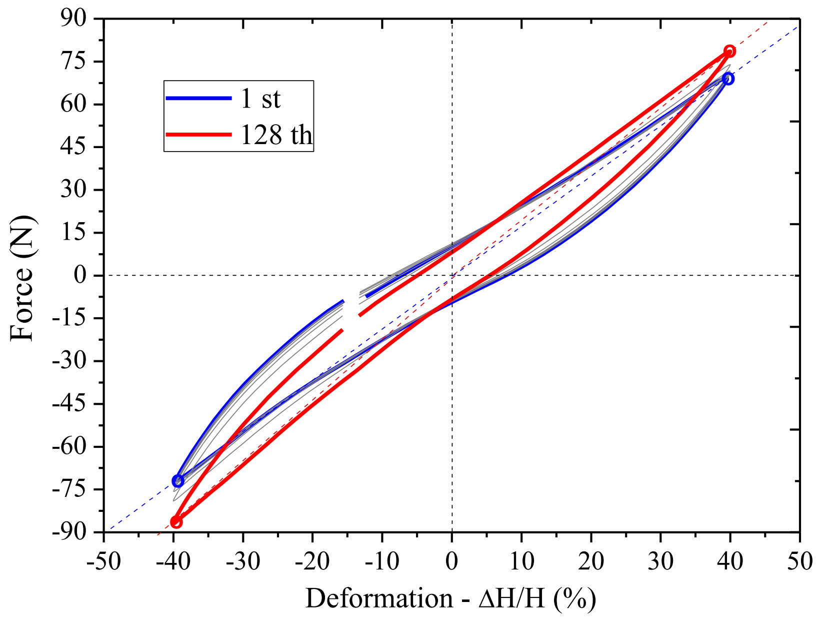


Figure 7. Dynamic mechanical behavior at a frequency of 5Hz and amplitude of 80%.

Figure 8 shows that this self-heating phenomenon also occurs in the Ni-Ti springs during cycling. It has been found that the higher is the loading frequency, the higher is the temperature rise of the spring, which reaches more than 30 ºC to 5Hz, corresponding to an increase of 6.7 ºC from the room temperature (23.5 ºC).

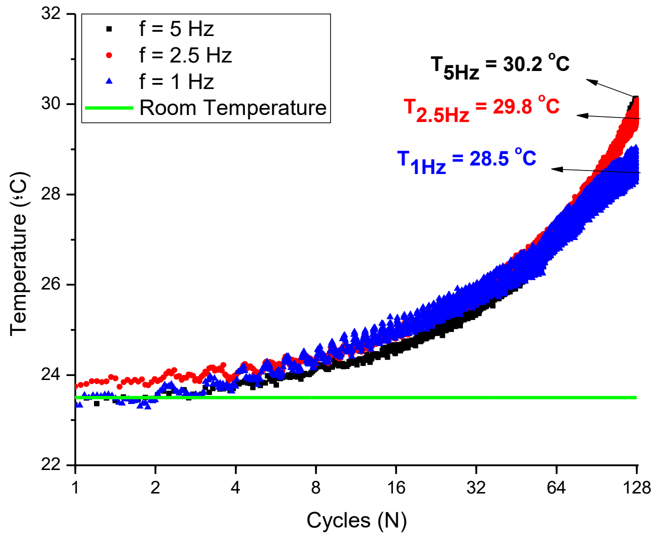


Figure 8. Temperature behavior of the Ni-Ti SMA spring during cycling.

By converting the deformations of Figures 5, 6 and 7 for displacement in meters and integrating force vs. displacement loops it is possible to obtain the energy dissipated (Savi et al., 2016) by the Ni-Ti springs in the first and last complete cycles of extension and compression. Figure 9 shows the behavior of the dissipated energy as a function of the loading frequency, for two complete cycles (cycles 2 and 128).

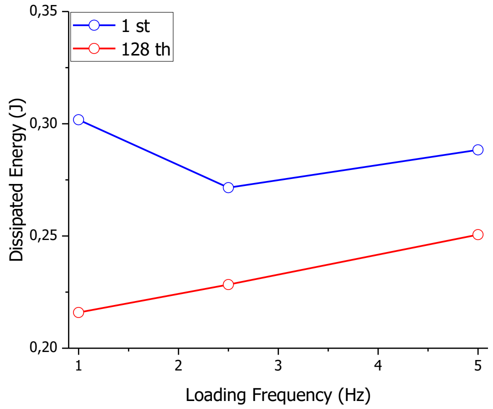


Figure 9. Dissipated energy as a function of the loading frequency for complete cycles 2 (1$^{st}$) and 128 (128$^{th}$).

There is a reduction of energy dissipated during the transient period (from cycle 1 to 128) for all frequencies. After stabilization, corresponding to cycle 128, it is verified that the dissipated energy tends to present a linear increase with the frequency. This is due to the fact that hysteresis loops become more symmetrical with increasing frequency. In general, for superelastic Ni-Ti wires under tensile loading the dissipated energy tends to decrease with increasing frequency (Oliveira et al., 2012). However, this is a complex behavior that needs to be better investigated especially in Ni-Ti springs because it is associated with the existence or not of an important self-heating of the material due to phase transformation in the presence of shear stresses.

## 4. CONCLUSIONS

In this study, the mechanical characterization of Ni-Ti shape memory alloy springs obtained by investment casting as an alternative to shape setting was performed for the first time.

The Ni-Ti SMA helical springs manufactured by investment casting present phase transformation temperatures between -30 °C and +40 °C. In the mechanical tests, the springs supported static deformations up to 80% of extension with no rupture. It was verified that the maximum force to produce controlled extension and compression between ±40 % in dynamic tests is dependent of the loading frequency, increasing with frequency in the range of 1Hz to 5Hz. This behavior was attributed to a self-heating of the Ni-Ti spring during the cycling, due to the accumulation of heat generated by the successive cycles of phase transformation. This behavior causes dissipated energy to increase with frequency when the Ni-Ti spring is in a permanent cycling regime (cycle 128).

## 5. ACKNOWLEDGEMENTS

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